AN ABSTRACT OF THE THESIS OF

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Title: A Wireless Sensor Network Approach for Estimating Individual Task Time.

Abstract approved

J. David Porter

Most existing methods for generating individual task time estimates in production systems where jobs move through various manually operated workstations remain tedious and time consuming. For existing systems, average task times may vary considerably from prior estimates causing system inefficiencies, poor scheduling and poor planning decisions. Accurate and up-to-date estimates are also extremely valuable when planning and designing future assembly lines.

In this study, a wireless sensor network (WSN) based indoor positioning system (IPS) is proposed as a potential alternative for estimating individual task times. Several network design factors were varied in the experiments conducted to assess the ability of the WSN-based IPS to determine an operator's position within the workstation so that the total production time can be allocated to the appropriate

tasks. The main response variable utilized to determine the location of the operator within the workstation was the link quality indicator (LQI). Accurately measuring LQI levels is not a straightforward process since radio frequency (RF) signals can change over time depending on many conditions, including physical obstructions and electromagnetic interference (EMI).

The results show that a WSN-based IPS is a viable approach to estimating individual task times. Additionally, the analysis of the experimental data showed that certain WSN design factors need to be set carefully to ensure good quality in the estimation of individual task times.

A Wireless Sensor Network Approach for Estimating

Individual Task Time

by
Tanawat Atichat

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Tanawat Atichat, Author

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This thesis is dedicated to my parents Tasanai and Wilawan Atichat, two outstanding educators, as well as great inspirations to me. I would also like to thank my grandmother Nong-nuch Suwanakarn, my sister Chonfun and all of my family members for their support and patience as I have pursued this degree.

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A Wireless Sensor Network Approach for Estimating Individual Task Times

1. INTRODUCTION

The use of wireless network technologies for data collection has increased dramatically in the last 10 years in the manufacturing sector (Ngai et al., 2008). Many companies have integrated their traditional information systems with wireless network technologies due to the minimal wiring efforts required to create a networked enterprise in manufacturing environments. Additionally, a wireless network based information system can potentially improve decision-making processes by providing accurate up-to-date data.

Many different types of wireless network technologies can be used in manufacturing applications including simple infrared-based systems for short range, point-to-point communications; wireless personal area networks (WPAN) for short range, point-to-multi-point communications (e.g., Bluetooth); wireless local area networks (WLAN) for mid-range, multi-hop communications; and wireless sensor networks (WSNs).

Recently, WSNs have been receiving popularity in industrial segments (Akyildiz et al., 2002). A WSN is typically deployed as an ad-hoc network consisting of small sensor nodes. Each node in a WSN can operate as a router to effectively increase the communication range and the size of the network without sacrificing network performance. WSN sensor nodes are also equipped with self-forming and self-healing properties which allow them to rapidly leave and join the network. The other main advantage of WSNs over other wireless network technologies is the ability to operate with low power consumption. This feature allows WSN nodes to operate with a pair of AAA batteries for years. An example of a basic WSN architecture is depicted in Figure 1.

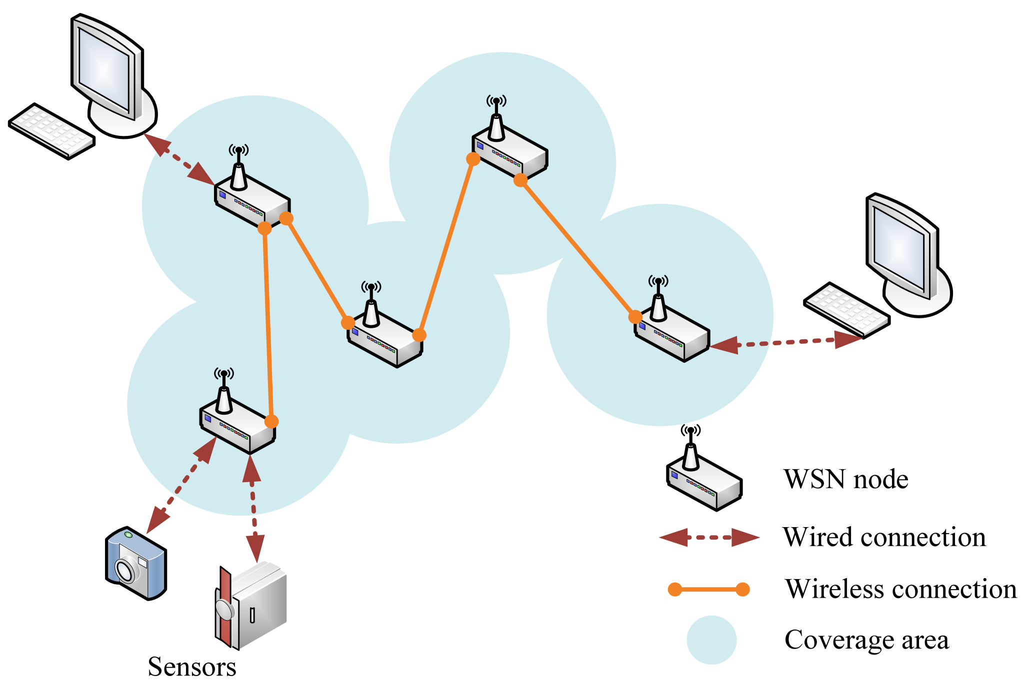


Figure 1: A Basic WSN architecture.

Due to the advantages of WSNs over wired networks and other wireless network technologies, these systems have already been utilized in healthcare and industrial process control applications and are currently gaining acceptance in new market segments such as home security, asset management, and building automation.

For example, WSN nodes can be deployed in a house to consistently measure temperature, humidity and light levels and then automatically make adjustments to optimize the power consumption of the house while still maintaining comfortableness for the inhabitants.

There are also unlimited possibilities to integrate WSNs with existing industrial systems. As a result, WSNs enable incremental value for a number of additional usages including:

- Environmental control for power savings in heating, cooling, and lighting.
- Device and machine monitoring to prevent accidents and failures, or limit their consequences.
- Inventory control and asset tracking.
- Workers' tracking and monitoring.

1.1 Research Motivation

Most existing methods for generating individual task time estimates in production systems where jobs move through various manually operated workstations remain tedious and time consuming (Kim et al., 2008). Automotive assembly lines are a good example of these production systems. Tasks within workstations in automotive assembly lines must have low variability in their average completion times to ensure a continuous and smooth operation of the entire system. Therefore, engineers must estimate the time of every task by studying, measuring and calculating the task times of all workstations and assign tasks to the workstations such that each will execute (on average) the same amount of work. For existing systems, average task times may vary considerably from prior estimates causing system inefficiencies, poor scheduling and poor planning decisions. Accurate and up-to-date task time estimates are also extremely valuable when planning and designing future assembly lines.

Bar coding is arguably the most prevalent automatic identification and data collection (AIDC) technology employed in industry, but still requires the operator to activate a trigger to signal the start and end of job processing. Therefore, an indoor positioning system (IPS) based on a wireless network technology is a more viable solution to alleviate some of the problems associated with estimating individual task times because more data can be collected more often, thus potentially increasing the accuracy of the task time estimation process.

To setup a wireless IPS, three main steps have to be considered: (1) the placement of the wireless data collection devices in the network; (2) the sensing technique; and (3) the location estimation methods. Since many types of wireless network technologies are available, the focus of this research was on WSN technology. To the best of our knowledge, there is no previous work in the literature that has focused on utilizing a WSN-based IPS for time and motion study.

1.2 Research Objective

The main objective of this research was to assess whether or not a WSN-based IPS is a viable technology to perform task time estimation. To accomplish this objective, several WSN design factors were varied in a designed experiment to assess the ability of the WSN to accurately determine an operator's position within a workstation so that the production time could be allocated to the appropriate tasks. The metric utilized to infer the location of the operator within the simulated assembly area was the link quality indicator (LQI).

Accurately measuring LQI levels is not a straightforward process since factors such as temperature, physical obstructions, and electromagnetic interference have an effect on radio frequency (RF) signals, thus affecting the ability of the WSN to accurately estimate task times.

1.3 Research Contribution

The results obtained in this research show that a WSN-based IPS is a viable approach to estimating individual task times.

More specifically, the analysis of the experimental data showed that the WSN design factors *number of tag nodes* and *orientations at each grid location* need to be set carefully to ensure good quality in the estimation of individual task times. Most of the prior research done in wireless IPS area considered only one tag node and no more than four orientations at each site survey location when defining a radio fingerprinting map. Therefore, demonstrating that by using two tag nodes and eight orientations reasonable results can be obtained when determining the location of the operator is considered one of the main contributions of this research.

2. BACKGROUND

This research explored the feasibility of using a wireless sensor network (WSN) to estimate individual task times. Therefore, there are several industrial engineering knowledge areas (e.g., work measurement and shop floor data collection systems) that are combined with areas more typical of the computer science and/or electrical engineering fields (e.g., indoor positioning and wireless network technologies).

This chapter is intended to provide an introduction to some of the topical areas mentioned above and is organized as follows. Section 2.1 presents an introduction to work measurement. Section 2.2 covers the topic of computerized shop floor data collection systems. Section 2.3 reviews indoor positioning technologies and algorithms. Finally, section 2.4 presents several wireless networking technologies, including wireless wide area networks (WANs), wireless local area networks (WLAN), and wireless personal area networks (WPANs).

2.1 Work Measurement

Industrial and manufacturing systems have become more complex and the skills necessary to manage and operate those systems have also increased. To effectively control and manage these systems, engineers must study and fully understand the information generated by them. Normally, this information may include the time required for a person to complete a task or operation at a defined rate of work. This completion time is known as a *standard time* or *standard task time*.

To effectively measure a standard time for a task, engineers have to consider the following three key variables:

- **Observed Time**. The time required to complete the task.
- **Rating Factor**. The pace at which the person is working. A rating factor of 100% means that a person is working at a normal pace. If a person is working slowly than normal or faster than normal, then rating factors of less than 100% or more than 100% would be used, respectively. The rating factor is typically calculated by an industrial engineer trained to observe and determine the rating.
- **Personal, Fatigue, and Delay (PFD) Allowance**. Important questions to answer in this category may include whether or not the workers stand all day or whether or not they work in a cold environment.

The standard time is then calculated by applying the following formula:

$$\textit{Standard Time} = (\textit{Observed Time})*(\textit{Rating Factor})*(1+\textit{PFD Allowance}) \quad (1)$$

Reductions in the standard time are the key to increasing the throughput and the performance of a manufacturing system. For this reason, many researchers have developed techniques for measuring the standard time in a process and have applied time reduction techniques to decrease cycle time and task time (Niebel, 1982).

2.1.1 Time-motion Study

Time-motion study is a work measurement technique, which generally uses direct observation to record the actual elapsed time for performing a task, adjusted for any observed variance from normal effort or pace, unavoidable or machine delays, and rest periods. This observed information is then converted into standard times for those particular tasks (Smith, 1978).

2.1.2 Work Sampling

Work sampling is a work measurement technique where observations about work are collected at discrete time intervals, either periodic or random. Work sampling is a particularly useful technique whenever time study data collection is not possible or is cost prohibitive. The main advantage of the work sampling technique is the reduction in the amount of data collected during the time study. This technique employs statistical methods, such as multiple regression (Mundel & Danner, 1994; Smith, 1978) and maximum likelihood estimation (Kim et al., 2008) to allow quick analysis, recognition, and enhancement of job responsibilities, tasks, and organization work flow.

Practically, both methodologies have advantages and limitations, some of which are a function of the type of observation done for each. In some situations, work sampling studies that rely on self-reported logs are generally considered the least reliable, as workers may not record their activities in a timely fashion, and they may not be totally honest concerning what activities were being done at the specified sampling times. Work-sampling approaches that use an observer or observers to record the activities of several workers are employed most frequently when workers are in a circumscribed area, e.g., factory workers on a floor, or nurses in a medical unit. If workers are not in a circumscribed area (e.g., residents traveling throughout the hospital) then the time-and-motion approach of one observer for each subject may be more feasible (Finkler et al., 1993).

2.2 Computerized Shop-Floor Data Collection Systems

In a manufacturing process, a shop-floor data collection (SFDC) system plays an important role in systematic improvement. Therefore, manufacturing companies must effectively implement information technology with SFDC techniques to improve SFDC processes. Such a system is referred to as a computerized SFDC system. A basic computerized SFDC system includes data capture devices, data storage, data processes, and presentation and implementation, as shown in Figure 2.

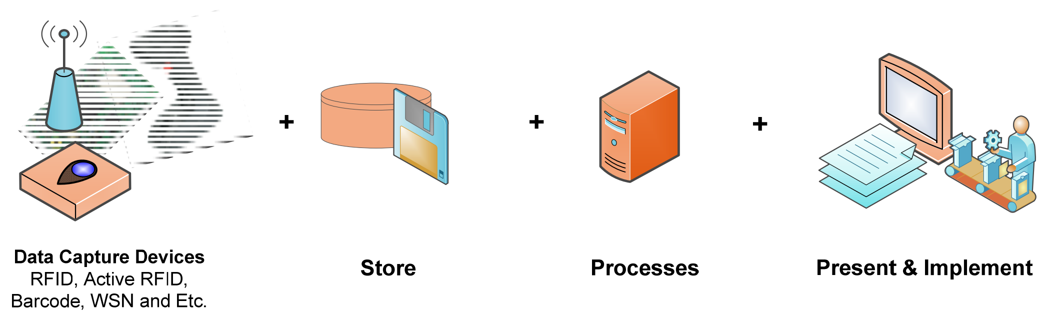


Figure 2: The concept of computerized SFDC.

Generally, the technologies used to implement a computerized SFDC system include automatic identification and data collection (AIDC) technologies, such as bar codes, radio frequency identification (RFID) and WSNs. These technologies were created to overcome the disadvantages of manual data collection (Palmer, 2001).

In large production systems, combinations of AIDC technologies have been implemented to increase productivity and performance by controlling and monitoring the condition and working times of workers and machines at workstations. In addition, these implementations support other industrial management systems, such as material requirements planning (MRP) and enterprise resource planning (ERP) systems, by providing accurate and real-time data of shop floor conditions and inventory system levels. These actions help engineers and supervisors to organize, plan and schedule their production systems effectively (Palmer, 2001).

Some product manufacturers and suppliers are required to attach RFID tags or bar code labels onto their products individually or on the packaging. As a result, product movement can be tracked throughout the supply chain and logistics (SCL) processes. Such real-time traceability and visibility are important to increasing the efficiency and quality of supply chain operations such as distribution, wholesale, and retail (Ehrenberg et al., 2007). Potential benefits, such as improved traceability, information accuracy, operation efficiency, reduced labor costs, increased speed, greater responsiveness, and better product quality control, have been widely expected, reported, and recognized (Akyildiz et al., 2002).

2.3 Indoor Positioning Technologies and Algorithms

An indoor positioning system (IPS) is a system for locating and tracking objects and/or persons inside a building or in a small open area. Currently, most of the systems have been implemented with wireless technologies, including IEEE 802.11 WLANs, Bluetooth, and WSNs. In an IPS, locations normally refer to coordinates that describe each node in a network. The coordinates of these locations can be described by *physical location coordinates* and *data location coordinates*. These two types of coordinates can be defined as follows:

- **Physical location coordinates**. The physical coordinates of nodes or devices that are estimated or measured in units of length.
- **Data location coordinates**. The non-physical coordinates of nodes or devices that are sensed or measured based on radio signal property units (e.g., signal strength and propagation delay time) by other stationary devices in a system.

For example, assume that an object node is placed into a space which has three dimensions with three perpendicular planes, as depicted in Figure 3. Thus, the physical location coordinate of this object node is *(x,y,z)* and the data location coordinate of the object node is the value of the radio signal strength measured by tw receiever nodes, indicated in Figure 3 as *(-90dB,-50dB)*.

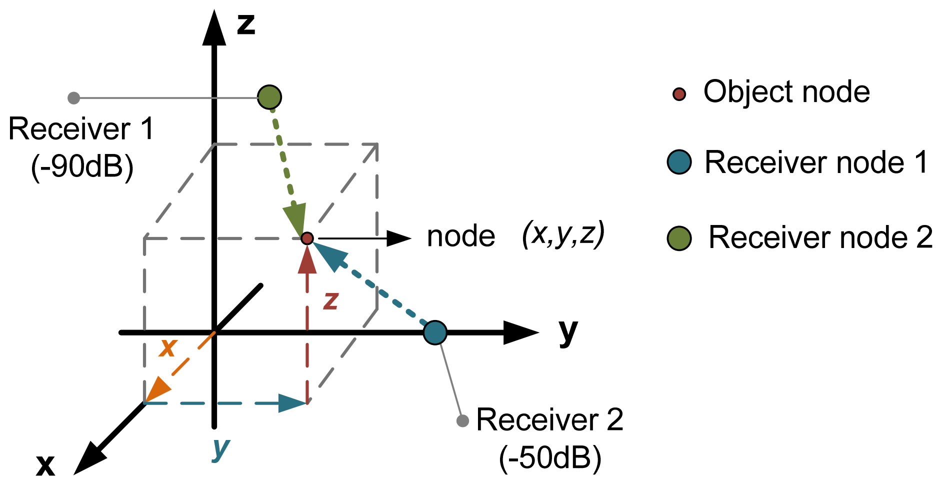


Figure 3: Physical location coordinate and data location coordinate.

Figure 4 depicts a basic block diagram for a wireless IPS system, as suggested by Pahlavan et al. (2002). It can be seen that a wireless IPS consists of three main components: a number of location sensing devices; a positioning algorlithm; and a display system. First, the strength of the signal received from mobile devices is mesured by a number of sensing devices that have pre-defined physical locations via a location sensing tecnique. This received signal metric can be based on the angle of arrival (AOA), the received signal strength (RSS), the carrier signal phase of arrival (POA), and the time of arrival (TOA). If the received signal is sufficiently strong, then a location estimation algorithm is applied to estimate the physical position of the mobile device. Finally, the estimated physical location is displayed by the system.

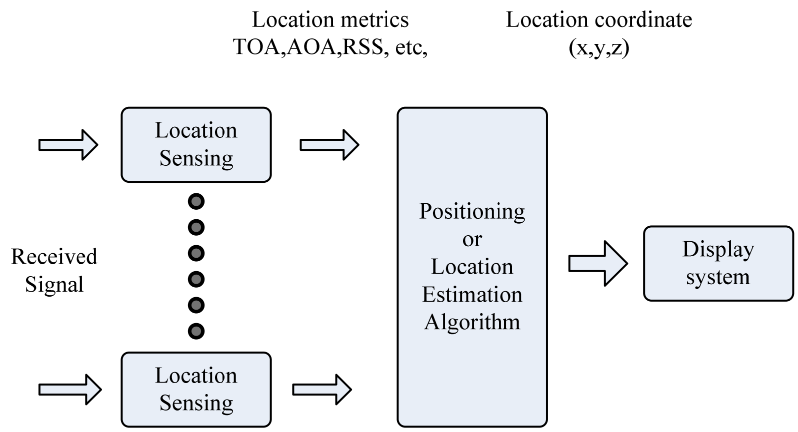


Figure 4: The functional block diagram of a wireless indoor positioning system.

2.3.1 Sensing Methods

To effectively estimate the location of a wireless node, sensing methods should be considered. Sensing methods are processes used to collect data coordinates to form statistical models based on a variety of sensing techniques, such as TOA, AOA, and RSS. These techniques can be combined to achieve more accurate localization.

2.3.1.1 Time of Arrival

Time of Arrival (TOA) is the measured travel time of a radio frequency (RF) or acoustic signal from a single transmitter to a remote receiver. Due to the typical behavior of RF signals, the propagation delay time should be considered. The propagation delay time is caused by the separation distance between a transmitter and a receiver (Stojmenovi 2005). The speed of an RF signal is approximately the speed of light (i.e., 3 x 10^8 m/s).

The main advantage of the TOA technique is that it allows a receiver to accurately estimate the arrival time of the received signal. As the travel time plus the delay time are measured and estimated by the receiver, location coordinates can be calculated utilizing the speed of the RF signal (Stojmenovi 2005).

2.3.1.2 Angle of Arrival

Angle of Arrival (AOA) employs the propagation direction of an RF signal among transmitters and receivers rather than the distance between them. When a receiver utilizes AOA, the direction of the RF signal is determined by measuring the time difference of arrival (TDOA) using multiple antenna elements, as depicted in Figure 5 (Stojmenovi 2005). The combination of measured TDOA values and estimated AOA values are then calculated to approximate the location coordinates of a node in a network.

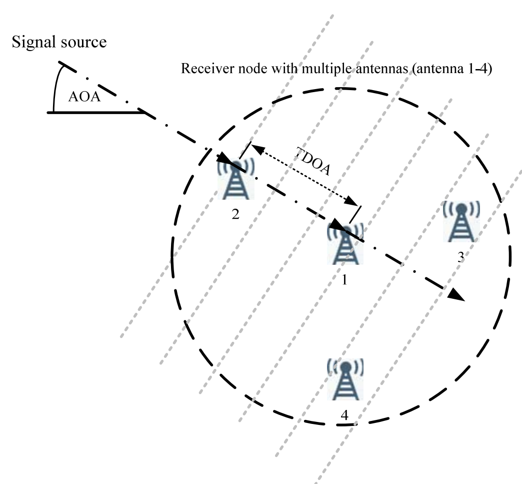


Figure 5: The Angle of Arrival (AOA) estimation method.

2.3.1.3 Received Signal Strength

Received signal strength (RSS) is defined as the voltage measured by a received signal strength indicator (RSSI) circuit. Most wireless network devices are equipped with an RSSI circuit (Stojmenovi 2005). In some wireless network devices, RSS is equivalently reported as measured power. Normally, RSS works as an indicator for wireless network devices to identify neighboring nodes during normal data communication. The process to measure RSS does not require additional bandwidth and/or energy. Moreover, it is considered an inexpensive and simple measurement to implement in hardware. For these reasons, RSS is the preferred measurement technique in the majority of wireless indoor positioning research.

2.4 Wireless Network Technologies

Nowadays, industrial and manufacturing companies are confronted with increasingly higher wiring costs to install and/or expand their network systems. This situation brings opportunities to replace and expand wired systems with a wireless technology. This approach results in a significant improvement in terms of cost reduction and installation time for network systems (Flickenger, 2007).

A wireless network uses an RF signal for communication among devices, which are called network nodes. Based on their physical area coverage, wireless network technologies can be categorized as either wireless personal area networks (wireless PAN or WPAN), wireless local area networks (wireless LAN or WLAN), or wireless wide area networks (wireless WAN or WWAN). Figure 6 depicts the aforementioned wireless network technology classification, along with specific examples of these. Appendix A includes a glossary of terms where the acronyms shown in Figure 6 are defined.

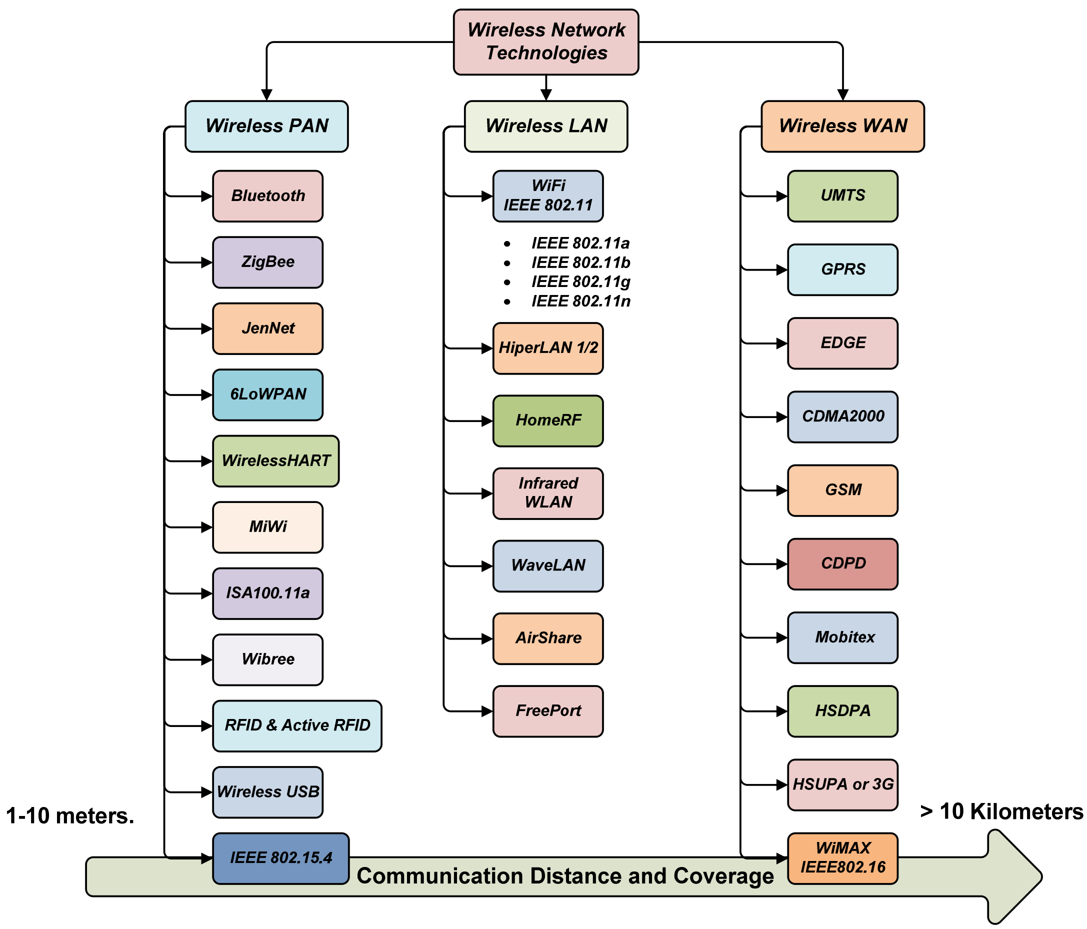


Figure 6: Wireless network technologies arranged by physical area coverage.

WPANs, WLANs and WWANs do have some overlap in terms of coverage area and throughput, as depicted in

Figure 7. More specifically, the differences among these technologies can be specified as follows:

- WPAN: Low throughput, short range coverage area, and low mobility.
- WLAN: High throughput, short range coverage area, and low mobility.
- WWAN: High throughput, long range coverage area, and moderate mobility.

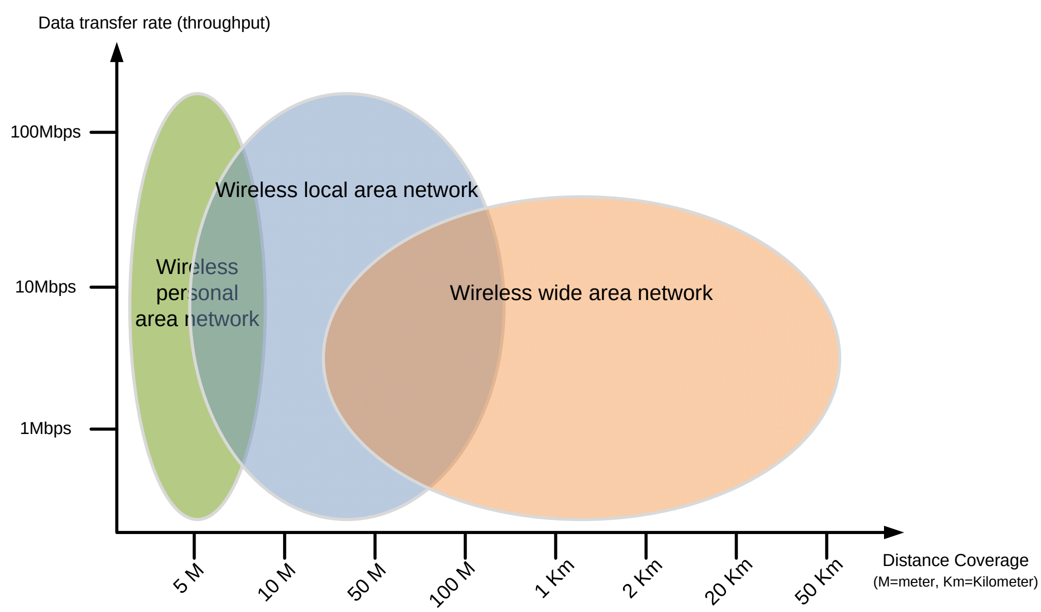


Figure 7: Comparison of area coverage and throughput among WPAN, WLAN and WWAN (adapted from N. H. Kim, 2008).

2.4.1 Wireless Wide Area Network Technology

A Wireless Wide Area Network (WWAN) provides connectivity to high-mobility users over a large coverage area. In general, a WWAN consists of a number of base stations mounted on towers, rooftops, or atop mountains to create large coverage areas. These base stations can then be connected to a backbone wired network system to provide useful data services for multiple users. Additionally, a multi-hop ad hoc wireless network system can be set up to expand the coverage of the WWAN by repeating the signal from a group of base stations to other groups (Goldsmith, 2005). Figure 8 depicts a simplified WWAN system.

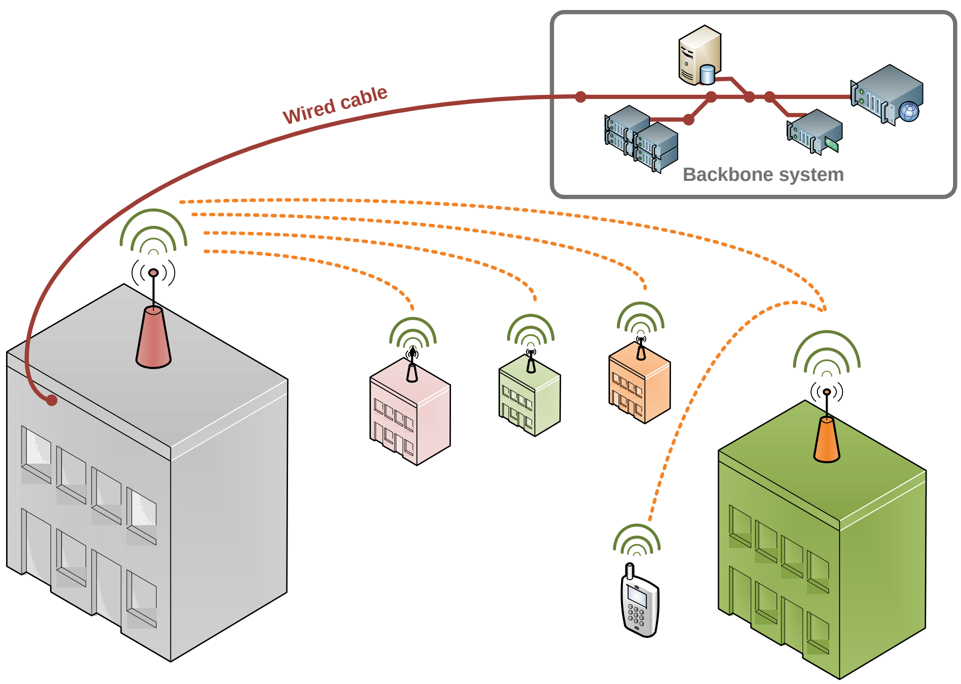


Figure 8: A simplified wireless wide area network diagram.

Examples of WWANs are cellular network systems or mobile phone network systems. Currently, these cellular network systems are not only able to transmit analog voice data, but also transmit digital data including voice, video and text (Goldsmith, 2005).

A WWAN technology considered to be a fourth generation mobile phone technology is WiMAX (IEEE 802.16e). WiMAX has many advantageous features such as its support of multiple-input, multiple-output technology (MIMO), operation in the unlicensed industrial, scientific and medical (ISM) radio frequency bands, and support of high data rate communications (Ghosh et al., 2005).

2.4.2 Wireless Local Area Network Technology

Wireless local area networks (WLANs) generally feature high-speed communications within a small to medium region (e.g., a house, small office or small building). A WLAN system is usually an extension of a wired network system. Figure 9 depicts a practical network system used in a small office or a house.

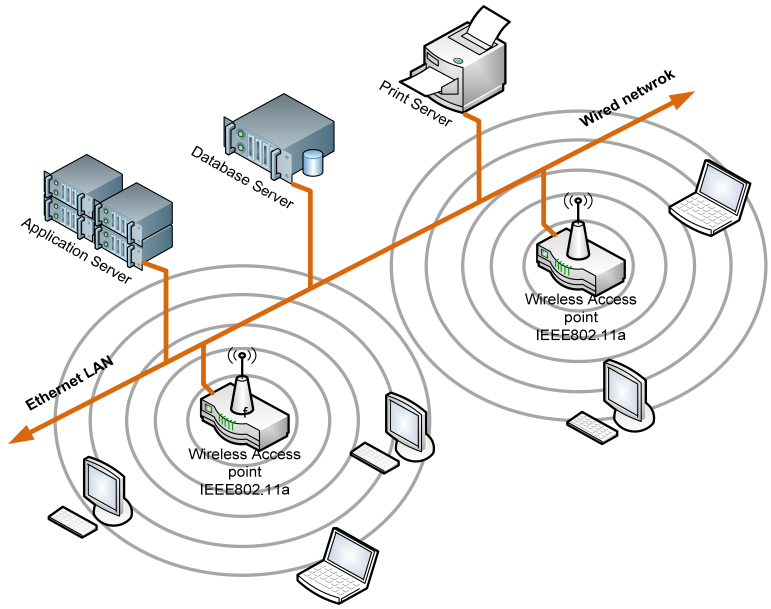


Figure 9: A wireless local area network combined with a wired system.

The WLAN system depicted in Figure 9 is equipped with two IEEE 802.11 standard-based access points. These access points manage mobile wireless devices and facilitate the transfer of data over the network.

WLAN technologies are based on many different standards. However, most of those standards have become obsolete except for the IEEE 802.11 standard, which was originally developed in 1997 (Flickenger, 2007). Compared to other WLAN technologies and standards, IEEE 802.11 has more advantages in terms of throughput and production cost (Goldsmith, 2005). These reasons make all computer companies and research groups focus on developing applications and improving protocols for the IEEE 802.11 standard.

2.4.3 Wireless Personal Area Network Technology

A wireless personal area network (WPAN) is a short-range wireless network system with a typical coverage area of about five to ten meters. However, the coverage area can be extended to over 100 meters, depending on the circumstances. One of the key features of a WPAN is its low power consumption, which allows a WPAN device to operate with a single AAA battery for a couple of years without replacement. The other key advantage of a WPAN is improved ad hoc network connection over traditional WWAN and WLAN technologies. This improvement increases stability and expandability on the ad hoc connection of WPAN systems.

While traditional wireless networks (e.g., a WLAN) usually have a preexisting infrastructure (e.g., a wireless access point acting as a centralization node), ad hoc wireless networks can be described as multi-hop wireless networks with mobile nodes. This type of network can be explained as a decentralized wireless network. With this advantage, a personal wireless networked system is able to operate in a large area without using any access points. Figure 10 depicts a comparison between an ad hoc network connection and a normal centralized network connection, known as a star network connection.

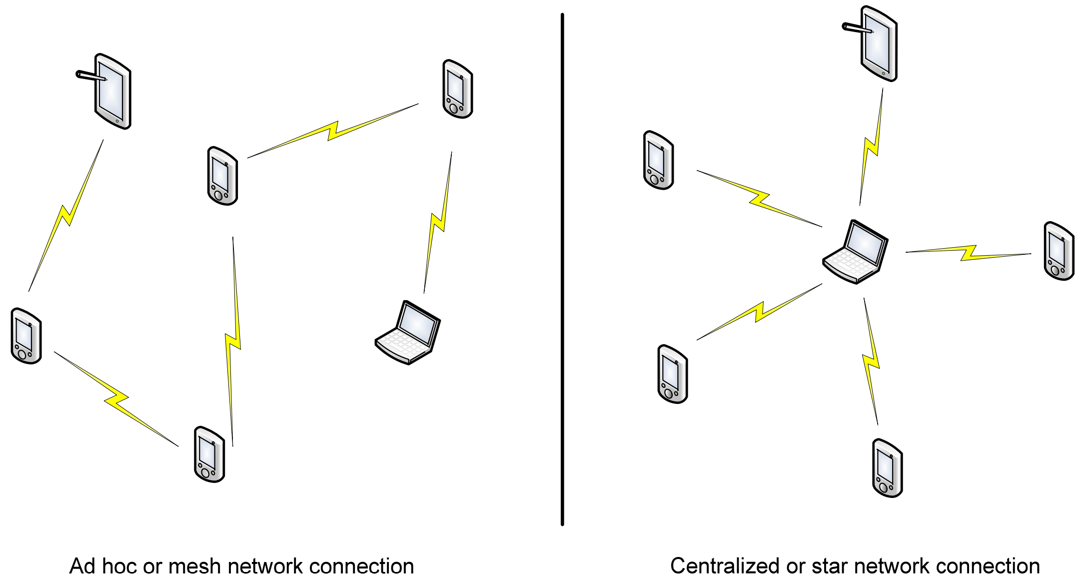


Figure 10: Comparison between mesh network topology and star network topology.

Applications of WPAN have been developed in many sectors, such as the military, supply chain, and agriculture and manufacturing industries. These expansions have resulted in the development of many standards for WPAN technologies, as shown in Figure 11. However, the foremost WPAN technology category is radio frequency identification (RFID). As some WPAN applications have complexities that exceed the abilities of RFID, other technologies such as active RFID, Bluetooth and Wireless Sensor Networks (WSNs) have been independently developed to effectively suit those applications. Due to the independent development of those technologies, their standards are different. Figure 11 depicts a diagram developed by Jongwoo et al. (2007) that illustrates the evolution of RFID to WSN.

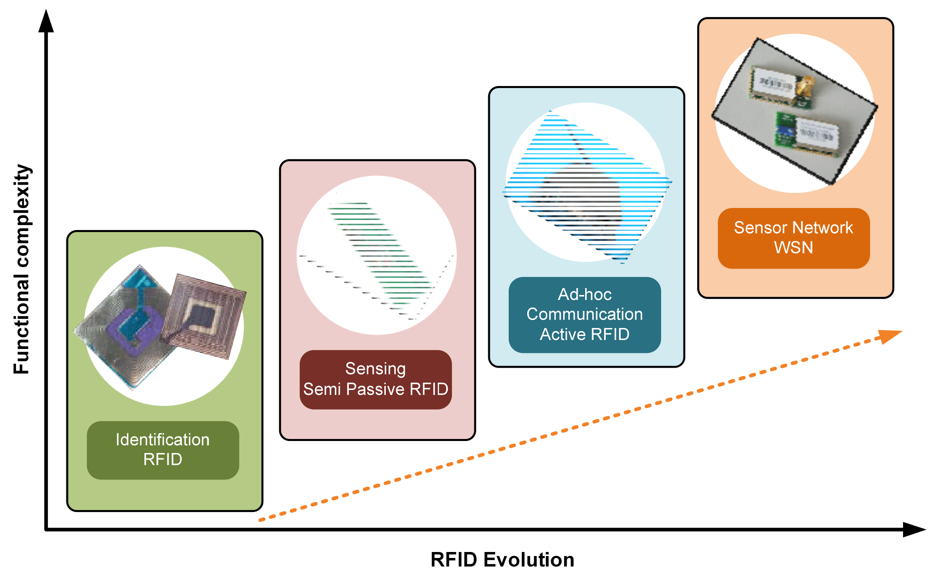


Figure 11: Evolution of RFID to WSN.

2.4.3.1 Radio Frequency Identification

Radio frequency identification (RFID) technology provides the ability to identify and sense the condition of objects. In general, an RFID system consists of interrogators (also known as readers) and tags, as depicted in Figure 12.

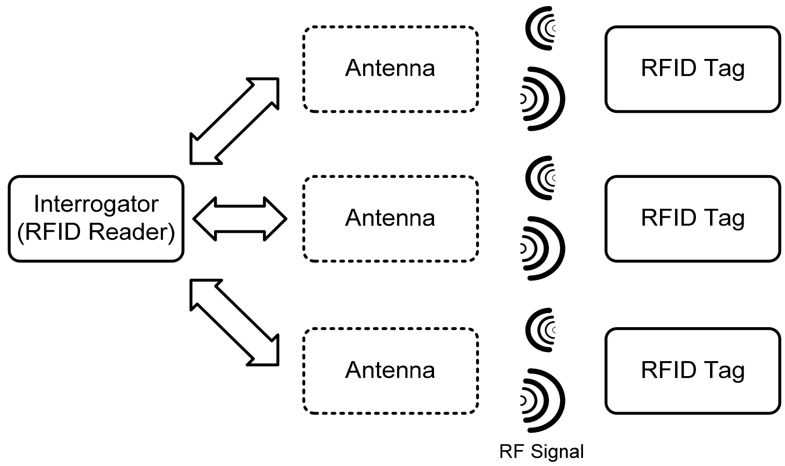


Figure 12: Diagram of a basic RFID system.

There are three main types of RFID tags:

1. Passive RFID tag:
   - This RFID tag uses an external electromagnetic field from an interrogator to power itself up and respond to the interrogator.
2. Active RFID tag:
   - This RFID tag is equipped with a battery as a power source for signal transmission.
3. Battery-assisted passive (BAP) RFID tag:
   - This RFID tag is equipped with a battery as a power source for signal transmission. However, it also requires an external electromagnetic field to initially power itself up.

Table 1 provides a more detailed comparison of the different types of RFID tags.

Table 1: Comparison among passive RFID, Active RFID and BAP RFID tags (modified from Nathanson, 2007).

	RFID tag types		
	Passive	**Active**	**BAP**
Read Range	Up to 40 feet (fixed reader) Up to 20 feet (handle reader)	Up to 300 feet or more	Up to 160 feet or more
Power	No power source	Battery powered	Battery powered
Tag Life	Up to 10 years, depending upon the environment in which the tag is located	3-8 years, depending upon the tag broadcast rate	2-3 years or more, depending upon the tag broadcast rate
Tag Costs	$.10-4.00 or more, depending upon quantity, durability, and form factor	$15-50, depending upon quantity, options (motion sensor, tamper detection, temperature sensor), and form factor	$3-10, depending upon quantity, durability, and form factor
Tag Durability	Poor durability	Excellent durability	Medium durability
Ideal Use	For inventorying assets using handheld RFID readers. Can also be used with fixed RFID readers to track the movement of assets.	For real-time asset monitoring at choke-points or within zones and other real-time tracking applications. Typically necessary when security is a requirement.	For tracking and monitoring applications. Security can be implemented to be used, if required.
Data Storage Read/Write	128 Kb	128 Kb with data search and access capabilities.	8 Kb to 64 Kb

2.4.3.2 Bluetooth

Bluetooth is currently managed by the Bluetooth Special Interest Group (SIG). This technology was developed in 1994 to support applications with a communication range of about 10 meters. Bluetooth was intended as a replacement for infrared short-range communications typically found in cell phones, personal digital assistants (PDA) and laptop computers (Muller, 2001). The communication range of Bluetooth is classified into three classes, which are detailed in Table 2, including data rate specifications from the Bluetooth Versions 1.2 to 3.1.

Table 2: Comparison between each class and version of Bluetooth technology.

Standard Version	**Data Rate**	**Class**	**Maximum Permitted Power**		**Range**
			mW	**dB**	**(meters)**
1.2	1 Mbit/s	1	100	20	~100
2.0 with enhanced data rate (EDR) feature	3 Mbit/s	2	2.5	4	~10
3.0 with high speed (HS) feature	24 Mbit/s	3	1	0	~1

2.4.3.3 Wireless Sensor Network Technology

A Wireless Sensor Network (WSN) system consists of spatially distributed wireless autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, power or location. Currently, this technology is used in many industrial and civilian application areas, including asset tracking, roadside traffic pattern and open parking spot detection, individual plant monitoring for precision agriculture, habitat monitoring in nature preserves, and advanced building security and automation (Akyildiz et al., 2002).

WSN technology facilitates the automatic collection and processing of real-time field data in processes and has the potential to reduce (and perhaps eliminate) errors in tedious manual activities. In addition, each node in a WSN is typically equipped with a radio transceiver or other wireless communications device, a small microcontroller, sensors and an energy source, usually a battery. The cost of sensor nodes varies from a few pennies to hundreds of dollars, depending on the size of the sensor network, the type of sensors embedded within the nodes, and the complexity required of individual sensor nodes. Figure 13 depicts the major components of a WSN device.

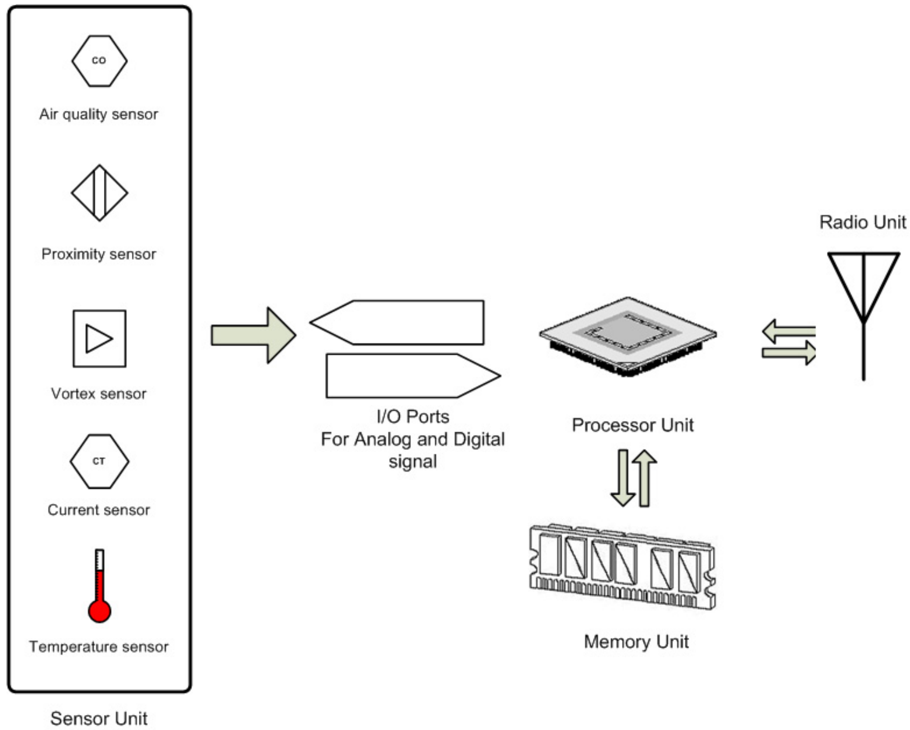


Figure 13: Wireless sensor network device system.

When developing and implementing applications using WSN systems, engineers and developers are confronted with many challenges, such as installation and setup costs, system complexity, network topologies, network protocols, power consumption and signal interference (Akyildiz et al., 2002). However, the major area that engineers and researchers must consider initially is the type of WSN standard and platform that should be used for their applications. There are many WSN standards and platforms, most of which are based on the IEEE 802.14.5 standard. Figure 14 shows the different WSN standards and platforms, and identifies the main protocol layers based on the Open Systems Interconnection (OSI) model.

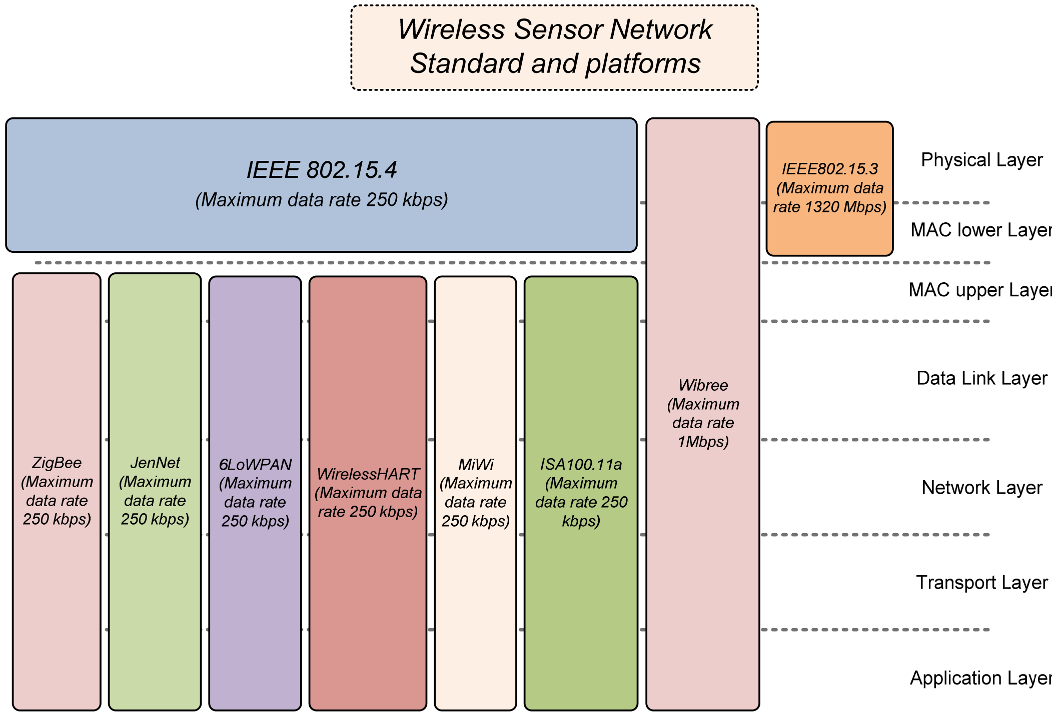


Figure 14: Comparison of WPAN technologies based on OSI standard layers.

As illustrated in Figure 14, IEEE 802.15.4 is a standard that specifically addresses the physical layer and the low level of the medium access control (MAC) layer. This standard supports many stack protocols, such as ZigBee, JenNet, 6LoWPAN, and MiWi. Although all of these stack protocols function from the upper level of the MAC layer through the application layer and have the same maximum data rate, they do not exactly have the same functionalities. Table 3 presents a comparison between these stack protocols based on their functionality.

Table 3: Detailed comparison of stack protocols based on IEEE802.14.5 standard.

Criteria	ZigBee	JenNet	6LoWPAN	WirlessHART	MiWi	ISA100.11a
Recommended Topologies	Mesh	Tree Star Linear	Linear Star	Tree Mesh Star	Tree Star Linear	Mesh Star
Licensing Cost	Yes	No	No	Yes	No	No
Hardware Restriction	No	Yes (only hardware from Jennic)	No	Yes	Yes (only hardware from Microchip)	No
Reliability	Medium	Medium	Medium	High	Medium	High
Security	Medium	Medium	High	Medium High	Medium	Medium High
Special Features	Bridge networks together capability	Supports up to 500 nodes in a network	IPV6 package protocol standard (Internet connection capability)	Strong and quick network managing protocol	Small foot-print protocol stack & easy to understand software programming	Very reliable stack protocol with easy scalability

Note: All technologies shown in this table have low power consumption

3. LITERATURE REVIEW

A review of prior work was conducted on four main areas and the relevant findings are synthesized in this chapter. These areas were work measurement; automatic identification and data collection (AIDC) technology; indoor positioning systems (IPSs) that utilize different wireless technologies as a basis; and position estimation algorithms.

The chapter is organized as follows. Section 3.1 presents the review of the literature focusing on work measurement. Section 3.2 describes studies of AIDC technology and their application in different areas. Section 3.3 is divided into three subsections based on types of wireless technology utilized in IPSs. Section 3.4 presents the reviews of position estimation algorithms. Finally, Section 3.5 presents the summary of the literature review.

3.1 Work Measurement

Work measurement is considered an application in the field of industrial engineering (Smith, 1978) and a considerable amount of research has been published mainly in two areas. The first area is applying work measurement techniques to enhance existing systems. For example, in some environments such as healthcare, effectively measuring the performance of nurses and physicians can be a challenge because these individuals perform inconsistent tasks in the same situation, which results in unquantifiable work measurement information (Irad et al., 2010). Finkler, et al. (1993) provided solid evidence that a work sampling technique requires a large number of work sampling observations to reach the same accuracy level as the time-motion study technique. However, in some situations, the time-motion study techique requires an excessive number of observations, which can become a labor-intensive procedure. With these arguments, Finkler, et al. (1993) sugessted a guideline to properly choose between the two techniques for a variety of problems.

Another research area is work measurement technique improvement, in which the main purpose is to apply other techniques, such as statistical techniques and automatic data collection techniques, to improve the performance of work measurement in terms of data interpretation and data collection (Kim et al., 2008; Mundel & Danner, 1994; Palmer, 2001; Porter et al., 2004; Smith, 1978). Smith (1978) and Mundel et al. (1994) introduced an approach to estimate task times. This method utilized work sampling to randomly collect the operation times of workers in the system and then applied a multiple regression method to estimate task times of the operators engaged in a variety of tasks. Kim et al. (2008) applied the least-squares method and maximum likelihood estimation to the total job-processing times at a workstation to extract the mean and variance of the individual task times from each workstation. Furthermore, this research also attempted to improve the old multiple regression method proposed by Smith (1978) and Mundel et al. (1994) by developing a computational formula to effectively and accurately update estimated individual task time from additional data.

3.2 AIDC Technology Based Inventory Tracking Applications

AIDC technology is employed in many applications, including inventory management, shop floor control, healthcare management and transportation tracking systems (Baker, 2005; Ehrenberg et al., 2007; Porter et al., 2004; Weinstein, 2005; Zhekun et al., 2004).

Porter et al. (2004) developed a framework for integrating legacy information systems with bar code technology. This study provided information about implementing a wireless bar code tracking system with an existing warehouse management system. The case study in this research showed the benefits of the wireless bar code tracking system, which included improved productivity and reduced waste in terms of time and excessive inventory levels. However, there are some drawbacks to bar code technology, such as requiring an operator to trigger the bar code registration process to initiate the data collection procedure.

Weinstein (2005) provided an example of an RFID-based system used for tracking tools and equipment in a healthcare environment. This system helped to increase the utilization of tools and equipment by reducing the time needed to locate these objects. Ehrenberg et al. (2007) developed an inventory management system deploying RFID technology. In addition, the research provided valuable information about location estimation accuracy with RFID tags in a nearby environment. The results indicated that this system can correctly estimate the locations of objects equipped with RFID tags within a few centimeters' error.

Huang et al. (2008) proposed a wireless manufacturing framework that integrates RFID technology with a wireless information system to solve typical problems in manufacturing environments, such as excessive work in process, unnecessary inventory, and waste in the production process. The combination of the RFID system and wireless information system enabled increased visibility in the shop floor and inventory management systems, which in turn increased production rates while decreasing production costs.

Baker (2000) investigated the strengths and weaknesses of Bluetooth technology in comparison to ZigBee technology, focusing on industrial applications. The results indicated that ZigBee has more advantages than Bluetooth technology in terms of long-term battery life, multiple networking architectures, and communication range, and these perfectly match the broader requirements of industrial applications.

3.3 Wireless Indoor Positioning Systems

Besides the ability of wireless network technologies to seamlessly transfer data and information from one place to another, researchers and engineers also apply measurement and estimation techniques to extract other information from radio frequency (RF) signals, such as the position of a network node in the network system.

The Active Badge System (ABS) based on an infrared (IR) model is the oldest and one of the most famous localization systems. In the ABS, a badge that emits a unique infrared signal every 10 seconds is worn by a user. This IR emission is made on an on-demand basis by the sensors placed at different locations. The sensors recognize the IR signal emitted by the badge and immediately report the location information to a central server. Although this system provides fairly accurate location estimation, it suffers from some major drawbacks, such as the limited range of the IR sensors and the usage of diffused infrared for location estimation, which could generate incorrect estimates in direct sunlight (Want et al., 1992).

Technological alternatives for IR-based sensing include the use of angle of arrival (AOA) and time difference of arrival (TDOA) techniques, commonly used by global positioning system (GPS) based systems. While GPS-based systems work effectively in outdoor environments, they suffer from the limitations of multiple reflections and path loss of RF signals in indoor environments (Hightower et al., 2002). Due to these problems, most of the technologies deployed in IPSs are wireless network technologies that can be set up and developed with GPS system techniques. However, some studies have also developed their own localization techniques and algorithms to enhance system performance in terms of position accuracy and location computation speed (Denby et al., 2009; Lin & Lin, 2005; Ocana et al., 2005; Patwari et al., 2003; Wallbaum & Spaniol, 2006).

3.3.1 Positioning Systems Based on Wireless Wide Area Network Technology

Wireless Wide Area Network (WWAN) technologies have been used for over a decade. However, most research in this area is not publicly available due to the following reasons:

- WWAN technologies require a large infrastructure. Thus, an individual researcher cannot practically setup a WWAN system to conduct research.
- Most WWAN technologies are patented. This causes some difficulties for a researcher to access these technologies.
- Most WWAN operate on licensed frequencies.

However, WiMAX technology is an example of a WWAN technology that has overcome these problems because it operates on unlicensed industrial, scientific, and medical (ISM) frequencies, and the price per unit of the WiMAX chip is inexpensive compared to previous technologies. Since WiMAX does not require a license, it allows researchers to change and to develop their applications and technologies based on the WiMAX standard. Thus, the majority of publications available on WWAN positioning are based on WiMAX technology (Bshara et al., 2010; Bshara & Van Biesen, 2009; Bshsra et al., 2008; Denby et al., 2009; Mayorga et al., 2007).

Bshsra (2008) introduced a WiMAX location-based service provided through the mobile network and features the ability to use the geographical position of mobile devices. This service utilizes WiMAX technology with received signal strength (RSS) distance interpolation technique, which measures RSS values and then compares them to the geographical distance to form a statistical model between these two variables. Then, a location estimation technique was applied to obtain the location of the mobile devices. The results showed that WiMAX provides higher accuracy location reports than the location-based service utilizing traditional Global System for Mobile Communications (GSM) cellular technology.

Bshara et al. (2009) improved their WiMAX location-based system by incorporating a location fingerprinting technique into the system, which translated into more accurate locations reported by the system. Subsequently, a case study was conducted based on WiMAX and the location fingerprinting technique (Bshara et al., 2010). This study implemented a dynamic RSS location model to increase the robustness of the location estimation for moving mobile devices. The results of this study indicated the possibility of applying this technology for real-world applications.

Mayorga et al. (2007) proposed a positioning system using a 4^{th} generation (4G) GSM cellular network as a basis. This system combines TDOA and RSS techniques to achieve the location-based service. The least-square algorithm was applied to convert TDOA and RSS data into the geographical positions of the mobile devices. Furthermore, this study utilized additional information obtained from in-mobile phone short–range communications such as WiFi to increase the accuracy of the system. The results indicated that the combination of RSS and TDOA information from multiple technologies can be employed to achieve higher precision of location estimation with WWAN for both outdoor and indoor environments.

3.3.2 Positioning Systems Based on Wireless Local Area Network Technology

RADAR was the first RF-based technique for location estimation and user tracking, developed at Microsoft Research (Bahl & Padmanabhan, 2000). It is primarily based on an IEEE 802.11 Wireless Local Area Network (WLAN) for building a single monolithic radio map for the network site and uses a *k*-nearest neighbor algorithm to search the signal space. Fundamentally, this study applied a similar RSS distance interpolation technique to that of Bshsra (2008). This study was one of the first to provide localization via WiFi technology, and documented the impact of node orientations and the number of sampling data points. An accuracy of 80 percent was achieved in location estimation with a position error smaller than three meters. However, the *k*-nearest neighbor algorithm consumed significant amounts of computing power and time, which would prevent the implementation of this technology in a real-time tracking system (Honkavirta et al., 2009). Other researchers have attempted to improve on this study by implementing other algorithms and sensing techniques to enhance the performance of localization-based WiFi technology (Honkavirta et al., 2009; Rong-Hong & Yung

Rong, 2003; Wallbaum & Spaniol, 2006).

Rong-Hong & Yung Rong (2003) applied a radio fingerprinting technique with the RADAR system. This research also compared the performance of the traditional RADAR system against the applied radio fingerprinting RADAR system. The results indicated that the radio fingerprinting technique increased the resolution of the traditional RADAR system in the range of two to three meters.

Wallbaum & Spaniol (2006) developed the probabilistic RSS Markov Localiser method to reduce the time required to create a radio fingerprinting map, which normally requires a lot of RSS data to achieve a satisfactory level of location accuracy. The probabilistic RSS Markov Localiser method theoretically is the application of a stochastic Markov model with an RSS fingerprinting map to create a distribution of the radio map. Then, this distribution map was utilized with the *k*-nearest neighbor algorithm to convert RSS data to geographical positions. The results of this study indicated that the median error of the average of the reported positions improved by 30% compared to the RADAR system.

3.3.3 Positioning Systems Based on Wireless Personal Area Network Technology

Hightower et al. (2001) developed a three dimensional (3D) location sensor based on RFID technology known as SpotON. This technology deploys the RSS distance interpolation technique including a unique calibration technique that results in a high precision radio map between RSS values and the distance between an RFID reader and the tag. In the calibration phase, the custom design of the SpotON RFID device allowed the researchers to fine-tune the radio signal level for both the readers and the tags to achieve a linear relationship between distance and RSS in the radio map. This study claimed that the system can achieve very precise 3D location accuracy within a small area. However, a complete system has not been made commercially available yet.

Ehrenberg et al. (2007) developed an RFID two dimensional (2D) location sensor based on the scheme of the SpotON system and tested it in an inventory system. This research applied a high level of detail in the calibration process, including the deployment of a higher number of readers and tags than the traditional SpotON system. The result obtained from the experiment proved the capability of the traditional SpotON system in a real inventory application and demonstrated the superior precision of the 2D location report within 2-8 centimeters, with more than 80% accuracy.

Priyantha et al. (2000) proposed one of the most unique location estimation systems based on WSN technology. This system, developed at the Massachusetts Institute of Technology (MIT) and referred to as the Cricket indoor location support system, uses ultrasound transmitters and objects with embedded receivers. It employs RF signals for time synchronization and delineation of the time, during which the receiver considers the sound waves it receives. It is based on a decentralized system of sensors, but this caused a huge burden on the tiny power-constrained mobile receivers due to distributed computation and processing of ultrasound pulses and RSS data. Based on the results obtained from testing, it was concluded that the combination between the ultrasound and RSS data positioning approach can be an alternative solution for an IPS that requires cost-effective installation and maintenance.

Whitehouse (2002) used a WSN ad hoc localization system to estimate the distance between wireless nodes using RSS and the acoustic time of flight (TOF), therefore eliminating the need for the ultrasound transmitters used in the Cricket IPS. However, this system required extra procedures for the calibration process to optimize the overall system performance. The results indicated that this method reduced the average error of the reported positions from 74.6% to 10.1% compared to the traditional calibration process as proposed in the RADAR system.

Fischer et al. (2004) proposed a high precision Bluetooth indoor localization system with an accuracy of ±1 meter. This study suggested the measurement of the differential time differences of arrival (DTDOA) technique to achieve the required level of accuracy. However, standard Bluetooth technology does not have the capability to measure DTDOA of the received signal, so this study specifically developed a unique integrated circuit to precisely measure DTDOA values. The results indicated that a high precision localization system with Bluetooth technology is feasible. However, additional research is still needed.

Zhongcheng et al. (2009) developed a WSN location algorithm based on simulated annealing. This study employed the free-space path loss equation, which is expressed as:

$$P_t = P_r \left[\frac{4\pi d}{\lambda\sqrt{G_l}}\right]^2 \tag{2}$$

P_t is transmitted radio power, while P_r is received radio power at a distance d from a transmitter. $\sqrt{G_l}$ is the product of the transmit and receive antenna field radiation patterns in the line of sight direction. λ is the ratio of the speed of light to the frequency of the signal used in the transmission (Goldsmith, 2005). This study combined the free-space path loss equation with the RSS map to form a distribution of RSS values and distance. Then, the simulated annealing method was introduced to improve the accuracy level of the positions. The results obtained from the experiment indicated that the positions reported by this system have higher accuracy than the system without applying the simulated annealing process.

3.4 Position Estimation Algorithms

Indoor positioning system (IPS) applications normally operate inside and close to the locality of a building. The area of operation of IPS applications is usually relatively small compared to that of an outdoor positioning system. These conditions allow an IPS to construct a comprehensive plan for the placement of wireless sensors to effectively estimate locations of mobile devices in the coverage area. Additionally, the small area to be covered by the IPS makes it possible to conduct extensive pre-measurement, also known as the *offline* data collection phase. The offline data collection phase provides templates of data locations, which can be used to construct statistical models of the location coordinates (Bahl & Padmanabhan, 2000). To achieve indoor localization, pattern recognition techniques should be considered. These pattern recognition techniques are applied after the online data collection phase is completed in order to identify physical locations based on the templates generated during the offline data collection phase. The offline data collection phase, the online data collection phase and the pattern recognition techniques are collectively referred to as *location fingerprinting*. Figure 15 depicts the location fingerprinting process.

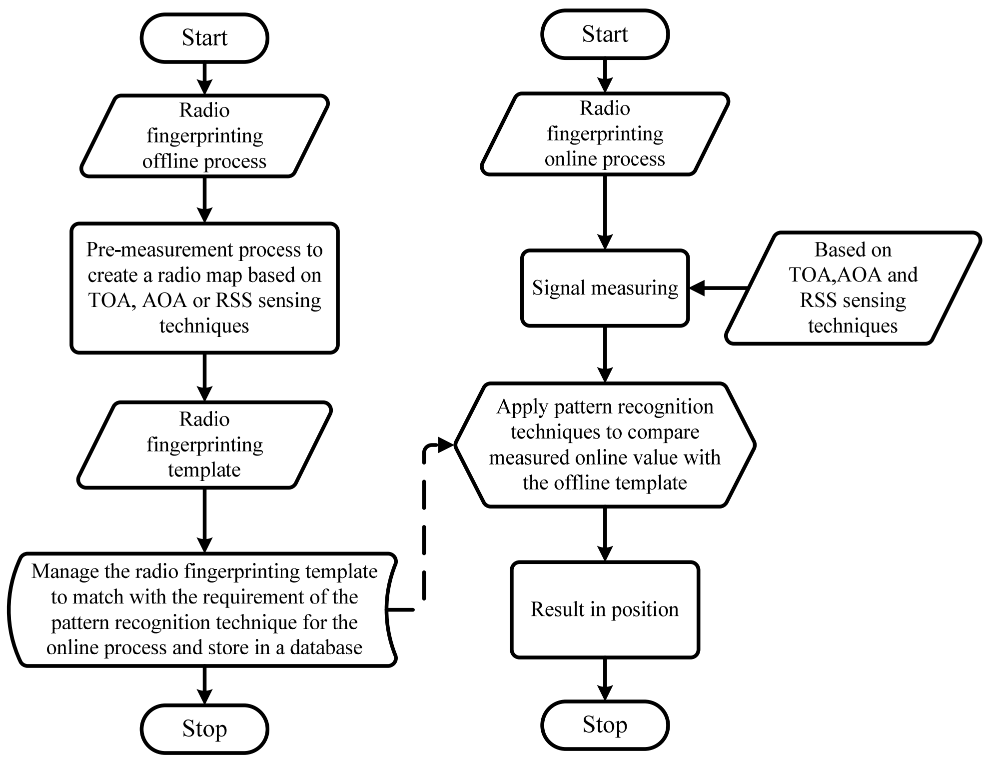


Figure 15: Radio fingerprinting.

Bahl et al. (2000) suggessted that the *k*-nearest neighbor algorithm is the simplest pattern recognition algorithm for IPS applications. This method utilizes the Euclidean distance calculated from the offline and online data by utilizing the RSS, TOA or AOA techniques. The estimated location is determined based on the minimum Euclidean distance between the offline and online data. This technique achieves 80% accuracy in location estimation and a position error smaller than three meters. The steps of the *k*-nearest neighbor algorithm are as follows:

1. Calculate the distance between the query instance (online data) and all the training samples (offline data).
2. Sort the distance values calculated in step 1 in ascending order to identify the nearest neighbors based on the value of *k*.
3. Tally the nearest neighbors based on location and orientation.
4. The estimated location of the query instance is the one that corresponds to the largest tally calculated in step 3.

As the coverage area of an IPS increases, the number of wireless nodes must be increased significantly to properly maintain the functions of the system. This reduces the calculation speed for some uncomplicated data pattern recognition algorithms, such as the *k*-nearest neighbor algorithm. Thus, many complex approaches such as neural networks (Battiti et al., 2002), the probalilistic approach (Ekici et al., 2006), and the statistical learning approach (Brunato & Battiti, 2005) have been researched and implemented to improve performance of the pattern recognitions for IPS.

Honkavirta et al. (2009) conducted a survey of different wireless positioning-based fingerprinting methods, including deterministic and probabilistic methods for static estimation, as well as filtering methods based on the Bayesian filter and Kalman filter. A series of tests were conducted to measure the performance of each method. The results indicated that both the Bayesian filter and Kalman filter significantly increased the accuracy of the average of the reported positions determined with the *k*-nearest neighbor algorithm and the weighted *k*-nearest neighbor algorithm.

3.5 Summary of the Literature Review

From the review of the work measurement literature, it is evident that the amount of data collected is one of the most important factors for both time-motion studies and work sampling techniques. The increase in data points proportionally enhances the accuracy of the estimated time (Irad et al., 2010). However, in some situations, the data collection process can be a tedious task because it requires observations conducted by humans.

Thus, wireless technologies can be used as the foundation for an IPS to automatically collect the necessary data for work measurement applications. For example, the location of a person relative to certain areas in a workstation can be identified, so that the period of time spent by that person in these areas can be allocated to the appropriate positions. A number of wireless IPS publications are available that address many technologies and techniques to increase the accuracy of the system and attempt to reduce the time required to convert signal information into a position. However, very few studies addressed the effects of network system design factors, such as the orientation of the receiver and transmitter, the number of data samples, and the number of receivers for a tracked object.

Presently, there is no evidence of research employing WSN-based IPSs to support task time estimation applications. Moreover, time accuracy in WSN IPSs has never been addressed for this particular application. It is expected that this research would fulfill this gap in the body of literature.

4. RESEARCH METHODOLOGY

The methodology followed in this research consisted of several steps, as illustrated in Figure 16.

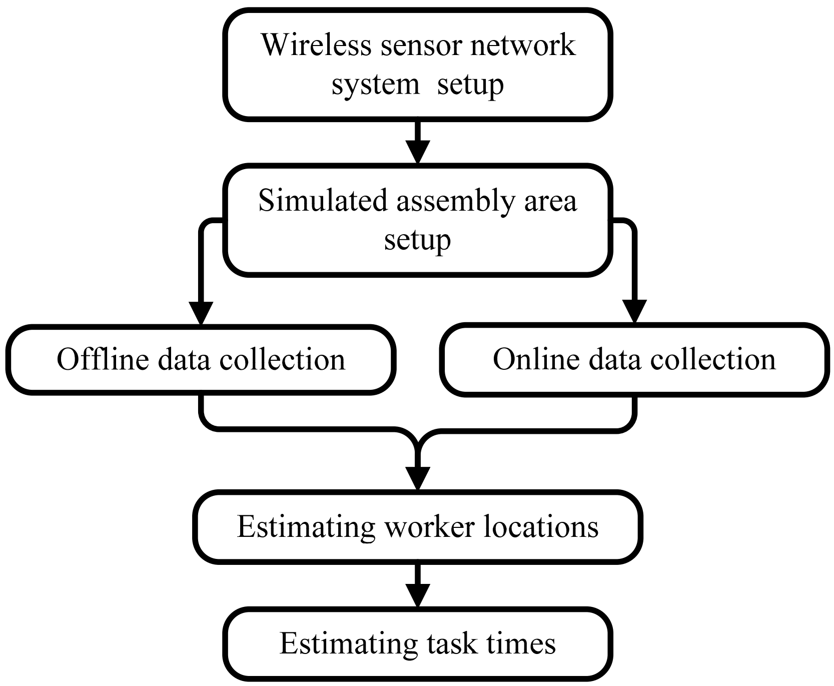


Figure 16: Research methodology for task time estimation utilizing a WSN.

First, a wireless sensor network (WSN) and a simulated assembly area were setup in the Mobile Technology Solutions (MTS) laboratory at Oregon State University (OSU). The simulated assembly area consisted of three individual workstations, each equipped with a beacon node to capture the LQI levels emitted by the mobile sensors carried by the operator.

By varying several key design factors of the WSN, a total of 16 templates were developed during the offline data collection phase. Each template represented an individual *radio fingerprinting map* (see section 3.3.3). Next, a total of 20 runs were conducted during the online data collection phase. The purpose of the online data collection runs was to mimic a manual assembly line with one operator working on each workstation for a period of time and then traveling to other workstations until the completion of the process.

The data gathered in the online data collection phase was used to assess the ability of the 16 offline data collection templates to estimate the location of the operator within the simulated assembly area. In this process, the *k*-nearest neighbor algorithm was utilized with three different levels of *k*. Finally, individual workstation task times were estimated based on the operator location determined in the previous step.

The rest of this chapter is organized as follows. Section 4.1 describes the hardware and software used to setup the WSN. Section 4.2 details the steps taken in setting up the simulated assembly area and placing the beacon nodes for data collection. Section 4.3 explains both the offline and the online data collection processes. Section 4.4 presents the LQI value data collection software application. Section 4.5 details the process utilized in estimating the locations of the operator within the simulated assembly area using LQI values. Finally, section 4.6 presents the LQI data processing and data management software application.

4.1 WSN Hardware and Software Requirements

4.1.1 Jennic JN5139 IEEE802.15.4 Wireless Microcontroller

Six Jennic JN5139 wireless microcontrollers were employed to construct the WSN utilized in this research. The Jennic JN5139 is a 2.4 GHz, low power wireless microcontroller compliant with the IEEE802.15.4 standard for wireless personal area networks (WPAN). Other relevant specifications of the Jennic JN5139 wireless microcontroller are shown in Table 4.

Figure 17 depicts two JN5139 modules with different antenna options. The JN5139 module is available with either an internal antenna or a standard Sub Miniature version A (SMA) connector.

Table 4: Relevant specifications of JN5139 wireless microcontroller system (Jennic, 2008a).

Transceiver Specification	Microcontroller Specification
• 2.4GHz IEEE802.15.4 compliant • 128-bit AES security processor • Integrated power management and sleep oscillator for low power • On-chip power regulation for 2.2V to 3.6V battery operation • Deep sleep current 0.2µA • Sleep current with active sleep timer 1.3µA • Rx current: 34mA • Tx current: 34mA • Receiver sensitivity: -97dBm • Transmit power: +3dBm	• 32-bit RISC processor sustains 16MIPs with low power • 192kB ROM stores system code, including protocol stack • 96kB RAM stores system data • 48-byte OTP eFuse, stores MAC ID on-chip, offers AES based code encryption feature • 4-input 12-bit ADC, 2 11-bit DACs, 2 comparators • 2 Application timer/counters, 3 system timers • 2 UARTs (one for debug) • SPI port with 5 selects • 2-wire serial interface

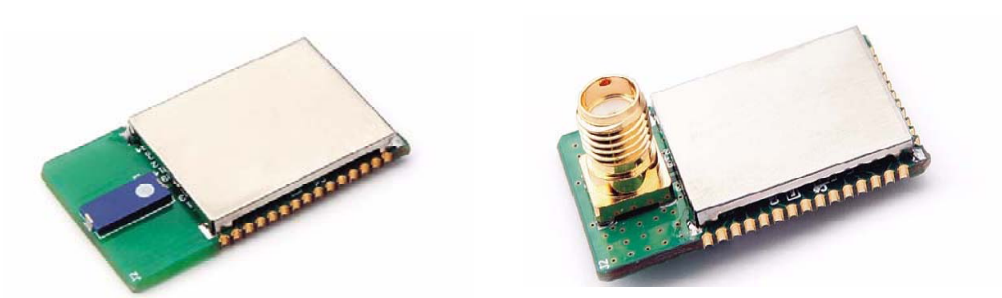


Figure 17: JN5139 modules: (a) with integral ceramic antenna, (b) with standard SMA connector (Jennic, 2008a).

The radiation pattern of the JN5139 module’s internal antenna is depicted in Figure 18. With the standard SMA connector, different types of external antennas can be used such as a half-wave dipole (depicted in Figure 19) or a Yagi (depicted in Figure 20). This interchangeable antenna feature allows engineers to choose the type of antenna that better suites their application.

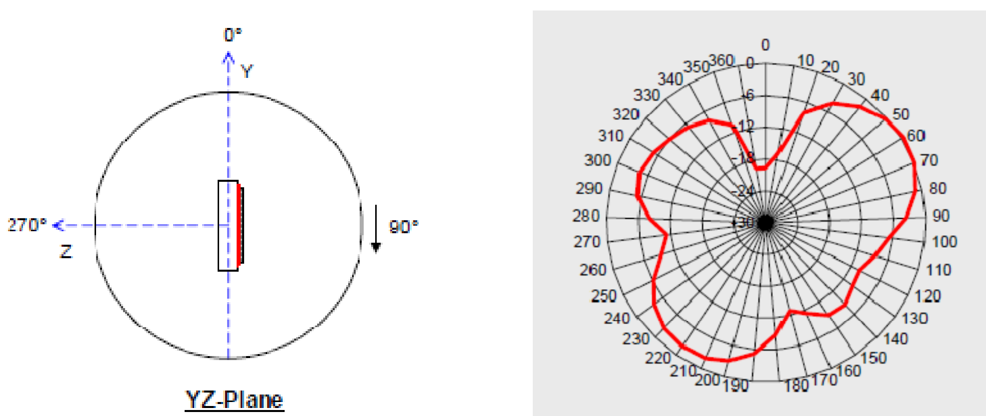


Figure 18: Internal antenna (Jennic, 2008b).

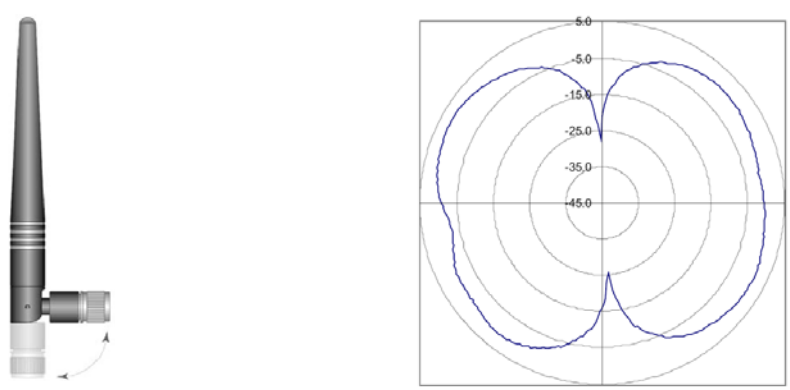


Figure 19: Half-wave dipole antenna (Jennic, 2008a).

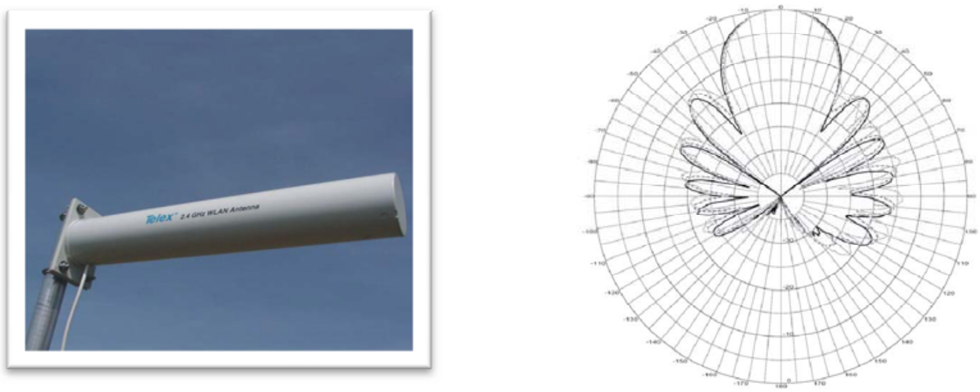


Figure 20: Yagi antenna with external enclosure (Jennic, 2008a).

4.1.1.1 JN5139 with expansion print circuit board

To operate the JN5139 module, an expansion print circuit board (PCB) is needed. The expansion PCB provides the proper electrical power lever to operate the JN5139 module. In addition, several input and output (I/O) devices and ports are included in the expansion PCB such as buttons, connectors, light emitting diodes (LEDs) indicators and some extra sensors. The details of the expansion PCB (including a JN5139 module) are depicted in Figure 21.

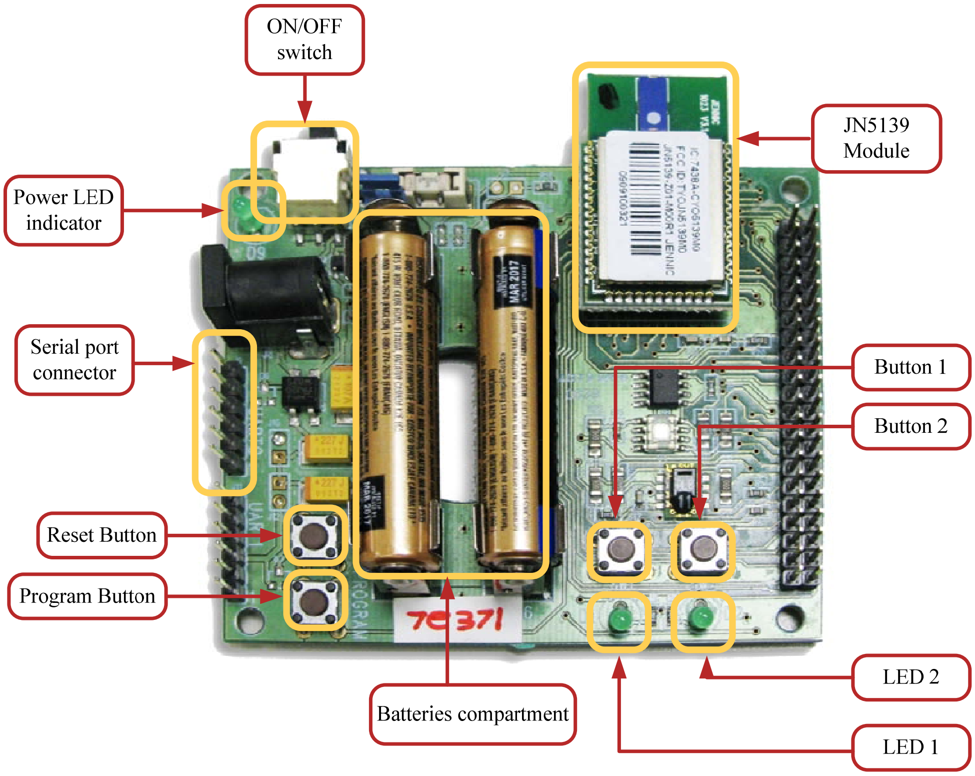


Figure 21: JN5139 module with expansion PCB.

4.1.2 JenNet Network Protocol Stack

The JenNet network protocol stack is needed to create wireless sensor networks using the JN5139 platform. Figure 22 depicts the layers of the JenNet network protocol stack.

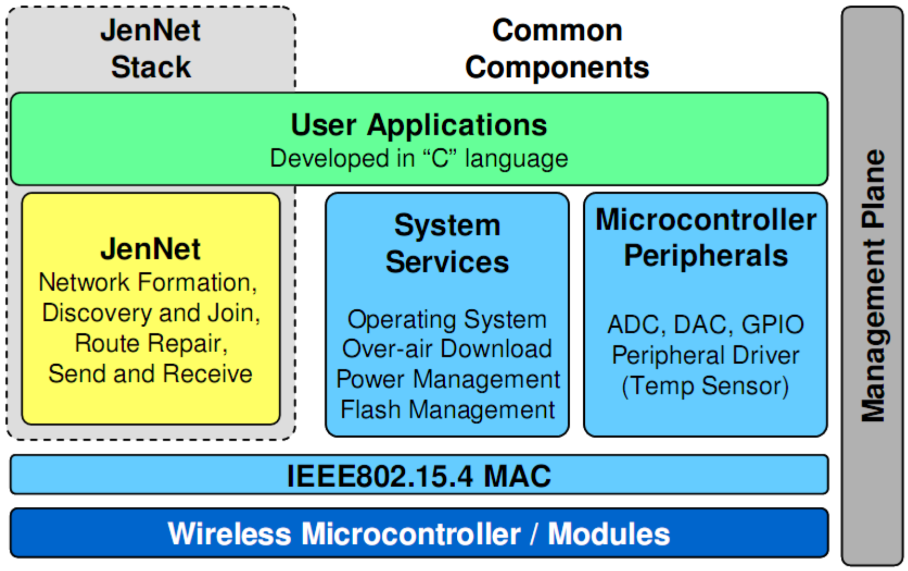


Figure 22: The overview diagram of Jennet stack protocol (Jennic, 2008a).

Interaction with JenNet is achieved via code written in the C programming language and the Jennic application programming interface (API). As depicted in Figure 22, the JenNet network protocol stack utilizes the IEEE802.15.4 MAC sublayer, thus allowing the JN5139 wireless microcontroller to handle other network stack protocols such as ZigBee and 6LoWPAN by simply changing the API provided by the Jennic company (Jennic, 2008a).

Under the JenNet network protocol stack, a wireless sensor network constructed with JN5139 modules can be setup utilizing a wide variety of network topologies based on the IEEE802.15.4 standard such as star, tree and mesh. Figure 23 depicts examples of these network topologies.

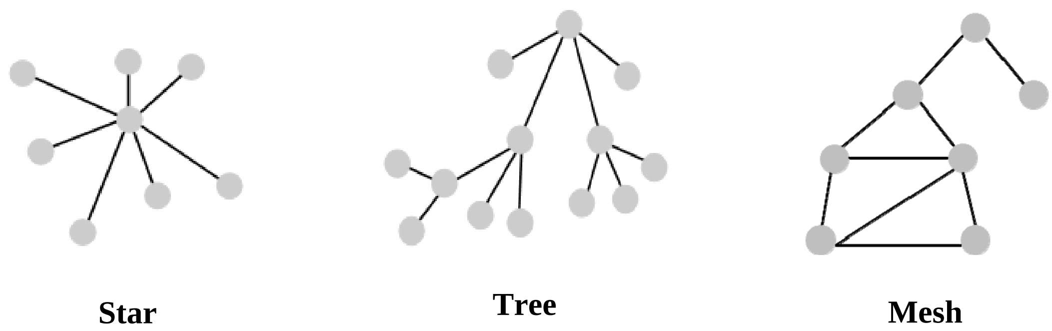


Figure 23: Alternative JenNet network topologies.

The star, tree and mesh network topologies may include a combination of the following three node types:

- **Coordinator Node**. The coordinator node is the network's most capable device, forms the root of the network tree, and might bridge to other networks. There is only one coordinator node in each network since it is the device that originally starts the network. It is able to store information about the network, including acting as the trust center and repository for security keys. For the remainder of this document, coordinator nodes will be referred to as *centralization* nodes.
- **Router Node**. A router node can act as an intermediate router, as well as running an application function, passing on data from other devices. For the remainder of this document, router nodes will be referred to as *beacon* nodes.
- **End Device Node**. An end device node contains just enough functionality to talk to a single or multiple parent nodes (i.e., either the

centralization node or a beacon node). However, it cannot relay data from other devices. For the remainder of this document, end device nodes will be referred simply as *tag* nodes.

4.1.3 Measuring Radio Frequency Signal Strength

In telecommunications, received signal strength indicator (RSSI) is a measurement of the power present in a received radio frequency (RF) signal (Ahson & Ilyas, 2011). The JN5139 module measures RSSI in terms of a link quality indicator (LQI) value on an integer scale that ranges from 0 to 255, where 255 represents the strongest signal. The LQI value is updated every time the module receives new data packets from other nodes. This reported LQI value is stored in the main memory of the JN5139 module and can be accessed using code written in the C programming language via the JenNet API. To translate the LQI value to an RSSI value expressed in units of decibel-milliwatts (dBm), equation 3 is used:

$$RSSI = \frac{(LQI - 305)}{3} dBm \tag{3}$$

4.1.4 WSN System

As mentioned before, a total of six JN5139 modules were used in this research to construct a WSN. The WSN employed a tree network topology consisting of one centralization node, three beacon nodes and one or two tag nodes. The centralization node constantly reported LQI values sent from the beacon nodes to the main computer via a universal asynchronous receiver/transmitter (UART) serial port connection with a connection speed of 115,200 bits per second (bps). The three beacon nodes measured the LQI values of the data signals consistently broadcast by the tag nodes. The network structure of the WSN is depicted in Figure 24.

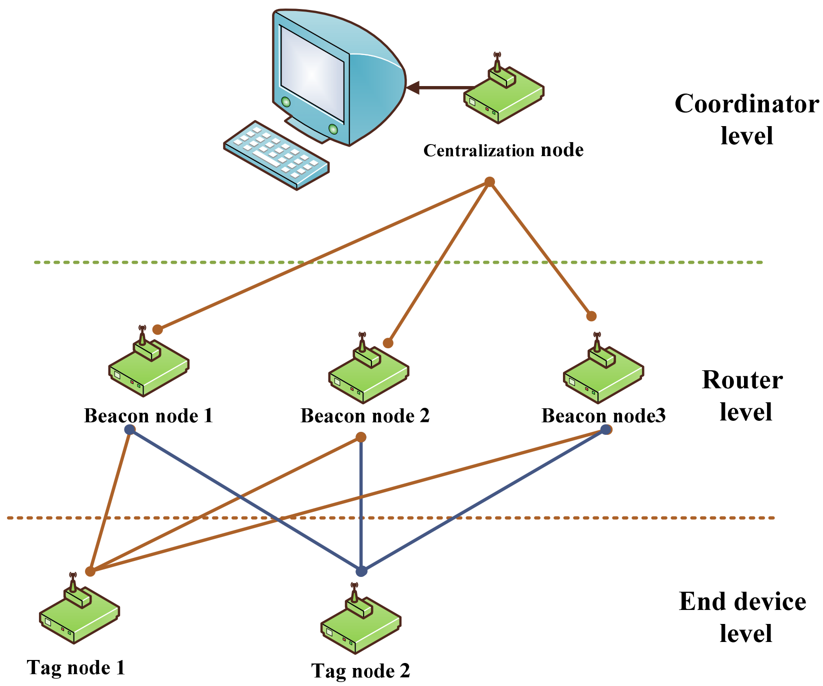


Figure 24: The tree structure of the network for the actual experiments.

4.1.4.1 Process to Establish the Wireless Sensor Network

In order to establish the WSN using all six JN5139 modules, the source code specifically written for each node type had to be uploaded to the devices using Jennic's Flash Programmer application. The source code written in the C programming language for the centralization node, three beacon nodes and two tag nodes is included in Appendix B, Appendix C and Appendix D, respectively.

Once the source code was uploaded to the specific node types, the procedure to establish the WSN was performed. First, the centralization node was initiated by turning on the power switch on the expansion PCB (see Figure 21). Next, the pairing process to set routing tables between the centralization node and the beacon nodes was performed by turning on each individual beacon node and waiting until the LED1 stopped flashing.

Finally, the tag nodes were paired with the beacon nodes. This process was performed by activating the pairing authorization feature on one of the beacon nodes and deactivating the pairing authorization feature on the centralization node. The activation and deactivation of the pairing feature is done by pressing the “Program” button on the expansion PCB (see Figure 21) followed by switching on the tag nodes. If the WSN is successfully established, then the LED1 on the expansion PCB needs to stop flashing on every module. Figure 25 depicts the complete process to establish the WSN.

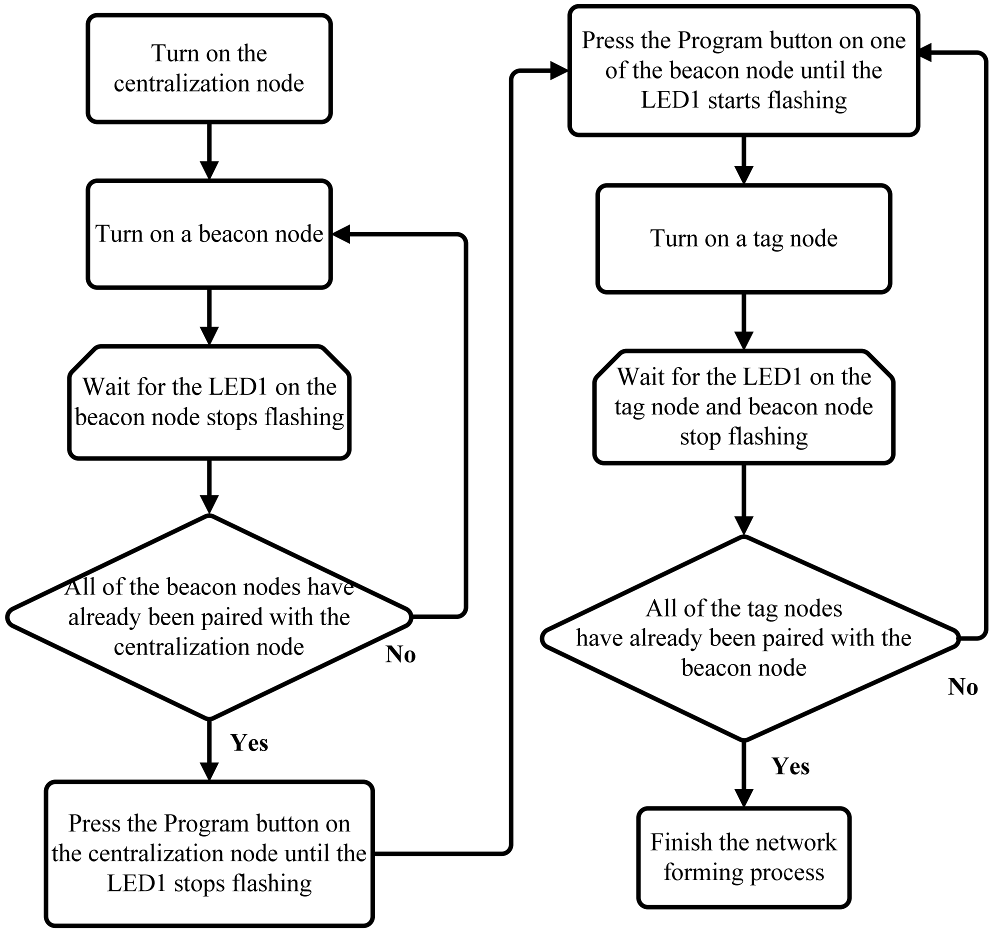


Figure 25: Process steps to form the WSN.

4.2 Simulated Assembly Area

A simulated assembly area was set up in OSU's MTS laboratory to mimic a manual assembly line. The simulated assembly area consisted of three individual workstations tended to by a single operator. The operator spent different amounts of time at each workstation performing specific product assembly tasks.

4.2.1 Simulated Assembly Area Layout and Dimensions

The simulated assembly area consisted of three workstations setup in an area 100 inches long by 180 inches wide. Each individual workstation was equipped with a beacon node, as depicted in Figure 26. The three workstations were setup following a U-shaped layout due to the limited physical space available in the MTS laboratory.

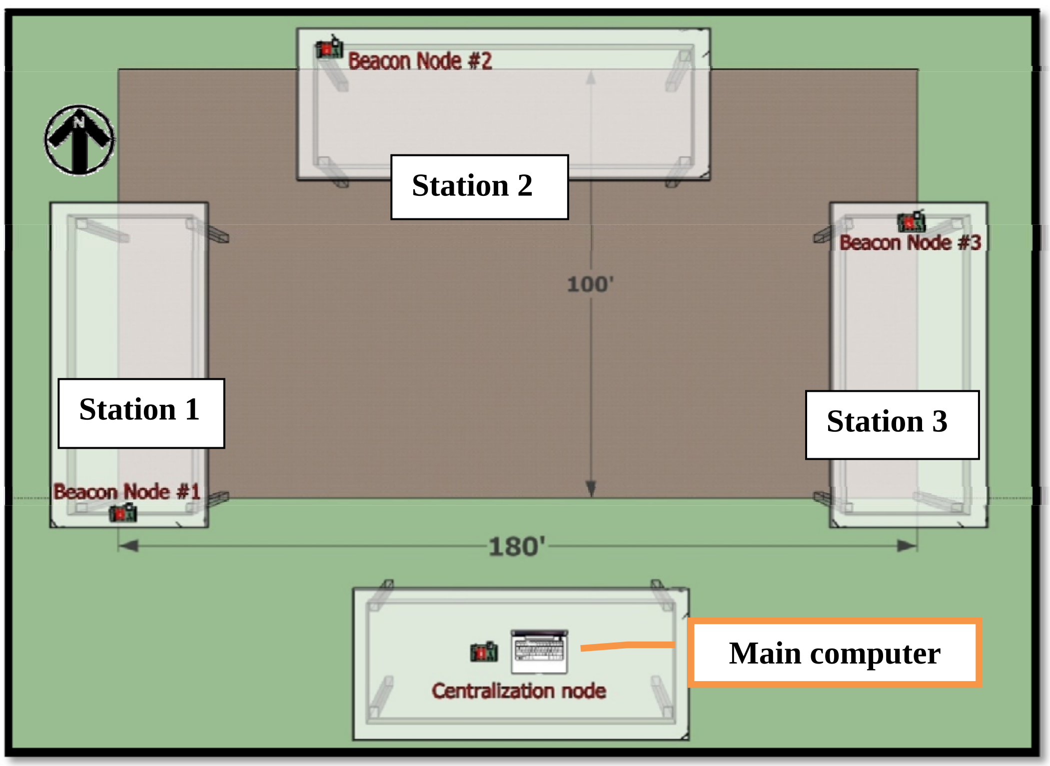


Figure 26: Layout of the simulated assembly area and placement of beacon nodes.

4.2.2 Arrangement and Placement of WSN Nodes in Simulated Assembly Area

4.2.2.1 Centralization Node

The centralization node could have been located anywhere within the envelope of the simulated assembly area. However, to effectively communicate with the beacon nodes, the centralization node was placed in an open area near the workstations with an unobstructed line of sight (see Figure 26).

4.2.2.2 Beacon Nodes and Workstations

Within a workstation, beacon nodes were placed at strategic locations to maximize the likelihood that the LQI value sent from the tag node(s) could be uniquely identified. Furthermore, the orientation of the beacon nodes was guided by the position of their antennas which were always pointed north within the simulated assembly area. The specific location of each beacon node within its respective workstation is depicted in Figure 27.

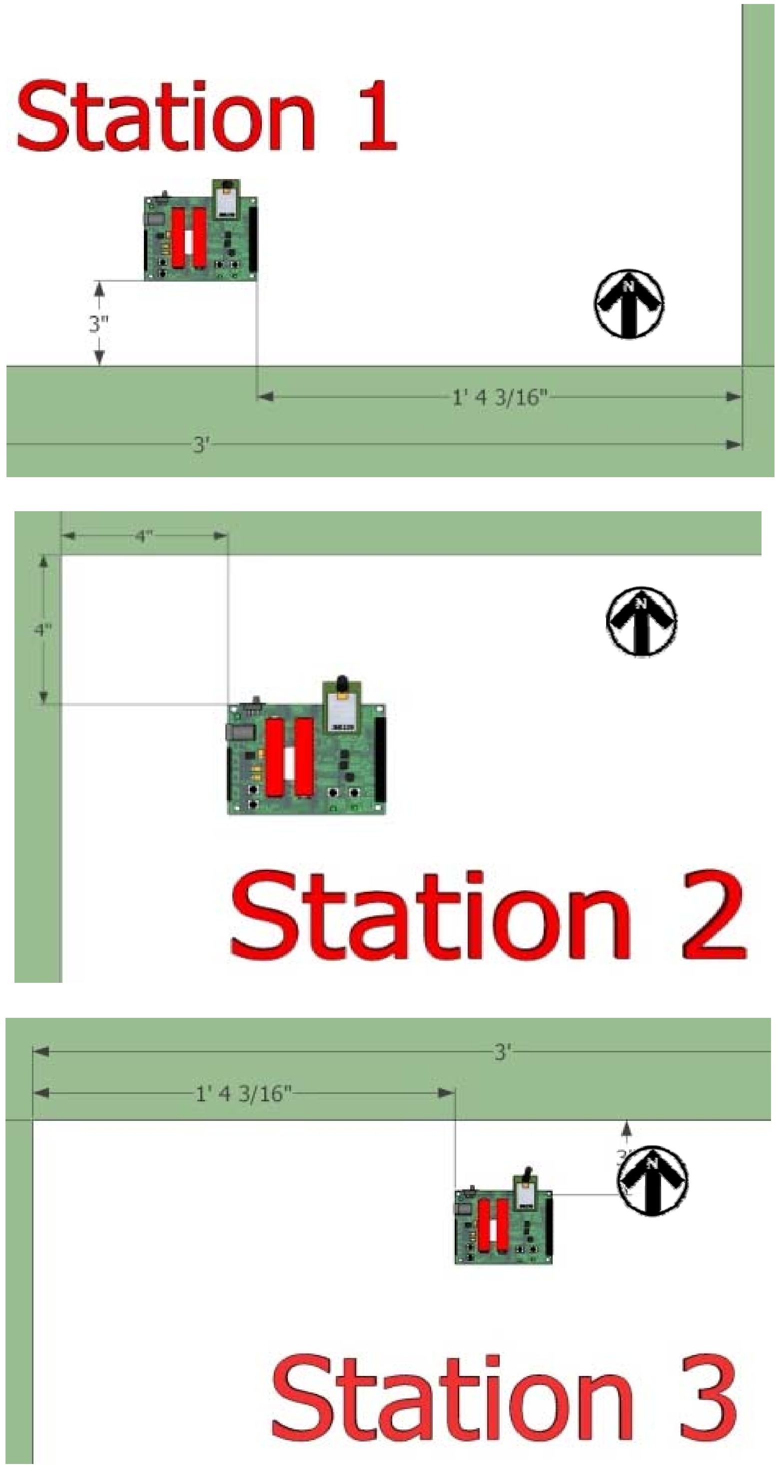


Figure 27: Placements of the beacon nodes within workstations.

4.2.2.3 Tag Nodes

The tag nodes were the only node type that could move within the simulated assembly area. During the data collection process, tag nodes were attached to an operator, as depicted in Figure 28. Tag nodes could be attached to the front of the operator only, or to both the front and back of the operator depending on the conditions of the experimental run. Also, the antenna of the tag node was kept perpendicular to the ground plane.

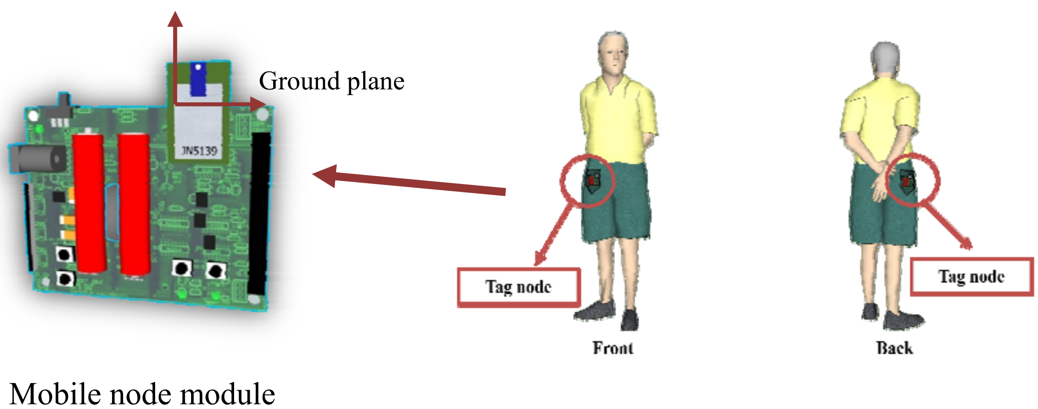


Figure 28: Attachment location for the tag nodes.

4.3 Data Collection Process

After the WSN nodes and the simulated assembly area were setup, the data collection process was conducted. In this research, the specific data collection method employed is referred to as *location fingerprinting*. Location fingerprinting consisted of two phases: the *offline* data collection phase (or calibration phase), and the *online* data collection phase. In these two phases, the location of the centralization node and the beacon nodes within the simulated assembly area were identical.

4.3.1 Collecting LQI Values with the WSN

Once the WSN was successfully established, LQI values were collected during both the offline and the online data collection phases. To accomplish this, the tag nodes were first forced into the packet broadcast mode by pressing "Button1" on the expansion PCB (see Figure 21) to allow the tag node to continuously broadcast data packets. LQI values were measured by the beacon nodes located at each workstation as soon as data packets sent by the tag node(s) were received. Finally, the beacon nodes sent the LQI value measured to the centralization node.

Each LQI value sent by a beacon node to the centralization node included the media access control (MAC) address of both the beacon node and the tag node. These MAC addresses (also known as *physical addresses*) are uniquely assigned to every node by the manufacturer (Flickenger, 2007). The centralization node then transferred individual LQI values to the main computer where a time stamp (i.e., date and time of day) was added before the data was organized and stored in a database or a text file depending on the data collection phase.

Figure 29 depicts an example of the data saved in the main computer. Additionally, a diagram that describes the operation of the WSN nodes during the location fingerprinting process is shown in Figure 30.

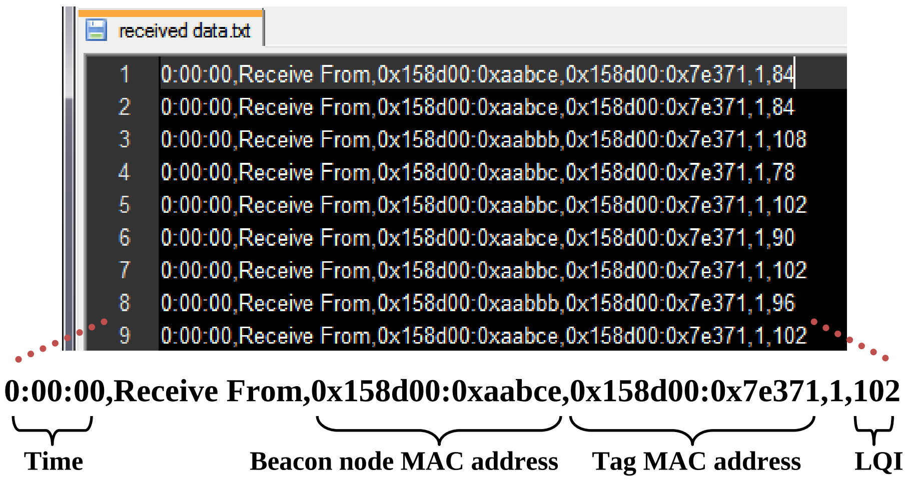


Figure 29: LQI values reported by centralization node to main computer.

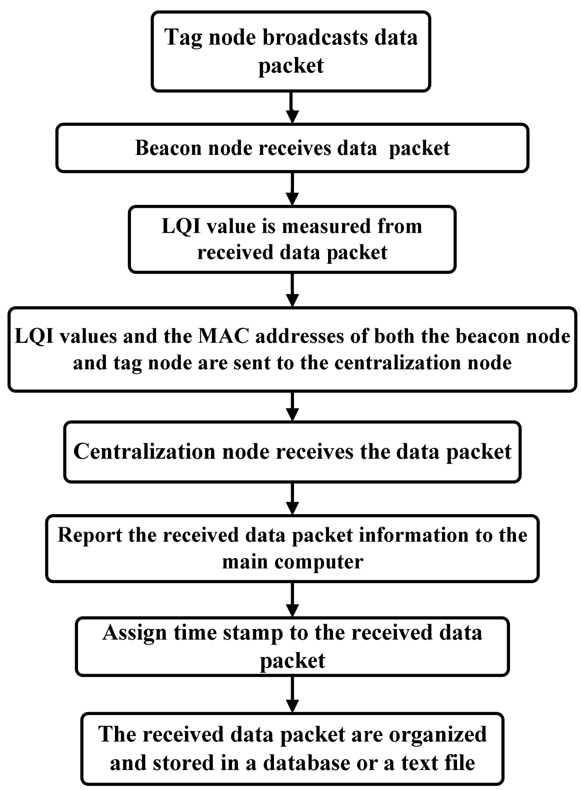


Figure 30: The operation of the WSN nodes during the location fingerprinting process.

4.3.2 Offline Data Collection Phase

The main propose of the offline (or calibration) data collection phase is to generate a radio signal map of the area covered by the indoor positioning system (IPS). The offline data collection phase is very time consuming (Brunato & Battiti, 2005) and is typically conducted in IPS that are based on location fingerprinting and consists of the following steps (Kaemarungsi & Krishnamurthy, 2004):

1. A grid space is defined over the area covered by the wireless network (e.g., a WSN or WiFi-based network). The grid spacing is usually reported in meters or feet. Some points in the area may be omitted due to inaccessibility (e.g., columns, equipment, etc.).
2. A site survey is conducted on the now discretized area to collect multiple sample values of either received signal strength indicator (RSSI) or link quality indicator (LQI) at each point in the grid from multiple beacon nodes. In this research, direct LQI values were used instead of RSSI values to conduct the site survey.
3. The RSSI or LQI values collected for each grid location are stored in a database. The database of RSSI or LQI value patterns is referred to as a *radio map* or *radio fingerprint*.

Since it was anticipated that the design characteristics of the WSN would influence the ability of the IPS to accurately estimate individual task times, a factorial designed experiment was conducted. Factorial design experiments are widely used in experiments involving several factors where it is necessary to study the joint effect of these factors on a response (Montgomery, 2008). The four specific WSN design factors investigated were:

- Number of tag nodes
- Number of site survey grid locations
- Number of tag node orientations at each grid location
- Number of sample LQI values collected per grid location and orientation.

The effect of these factors was studied using a 2^k factorial design (where k represents the number of experimental factors). Each factor was tested at two levels (i.e., low and high), as shown in Table 5.

Table 5: Experimental controlled factors.

		Factors			
		(A)	**(B)**	**(C)**	**(D)**
		Number of Tag Nodes	Number of sample LQI values collected per grid location and orientation	Number of tag node orientations at each grid location	Number of site survey grid locations
Level	+	1	2,000	4	5
	-	2	6,000	8	9

4.3.2.1 Number of Tag Nodes

As illustrated in Table 5, either one or two tag nodes were used in the offline data collection phase. The justification for selecting the number of tag nodes as a controlled factor was to investigate the effect that the coverage area of the tag node's antenna had on the ability of the WSN-based IPS to accurately estimate individual task times. Figure 31 illustrates the approximate antenna coverage areas when the operator utilized one or two tag nodes.

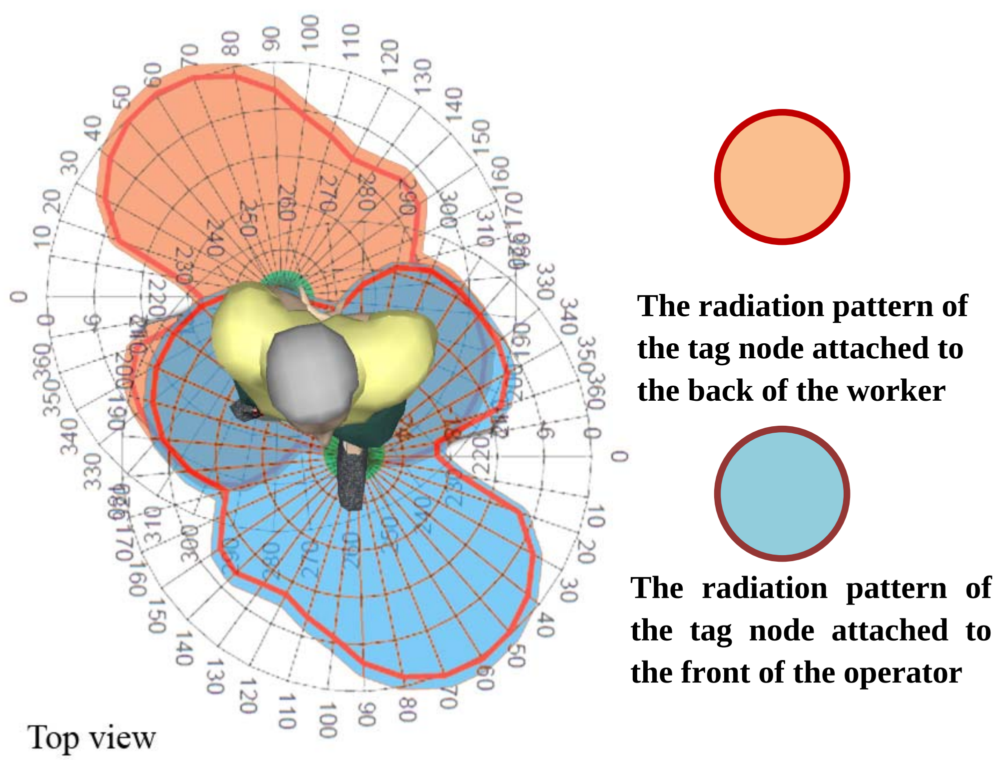


Figure 31: Approximate coverage areas for one or two tag nodes.

4.3.2.2 Number of Site Survey Grid Locations

Either five or nine grid locations were defined within the simulated assembly area to perform the site survey. The levels of this factor were selected based on the number of workstations and the area that the operator was allowed to access.

This approach was different to the common practice in location fingerprinting of using the full location grid. The justification for this is that the ultimate objective was to estimate the time an operator spent performing a task at a specific workstation within the simulated assembly area. To accomplish this, it was sufficient to know whether or not the operator's location could be associated with a few points that corresponded to a specific workstation. This is in contrast with trying to pinpoint the *exact* location of the operator anywhere within the simulated assembly area. Consequently, the space grid could be *relaxed*, less time was spent creating the fingerprint map, and a smaller (and more manageable) database of LQI values was created.

Figure 32 and Figure 33 illustrate the specific grid locations at which LQI values were collected for the five and nine grid location configurations, respectively.

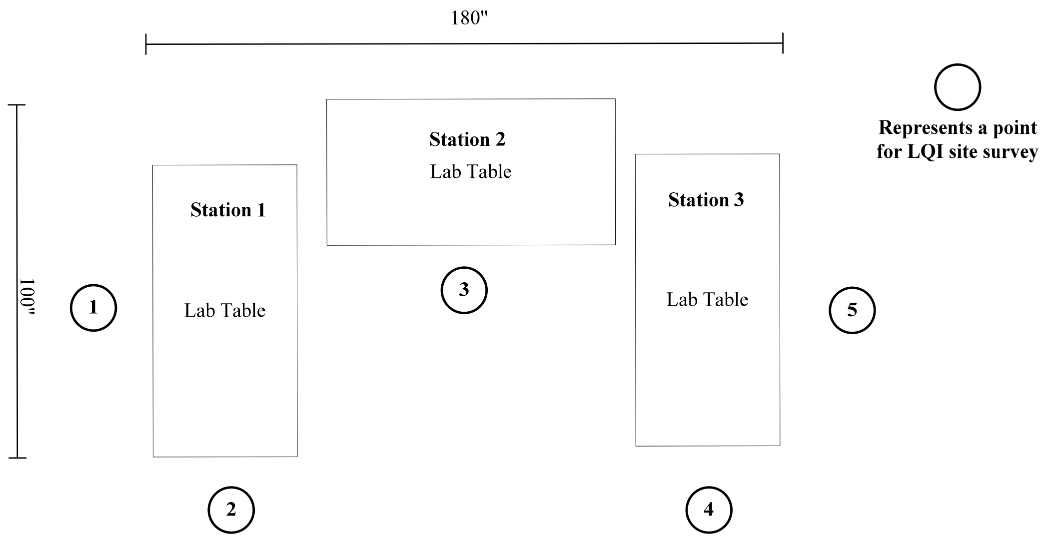


Figure 32: The layout of the five grid location configuration.

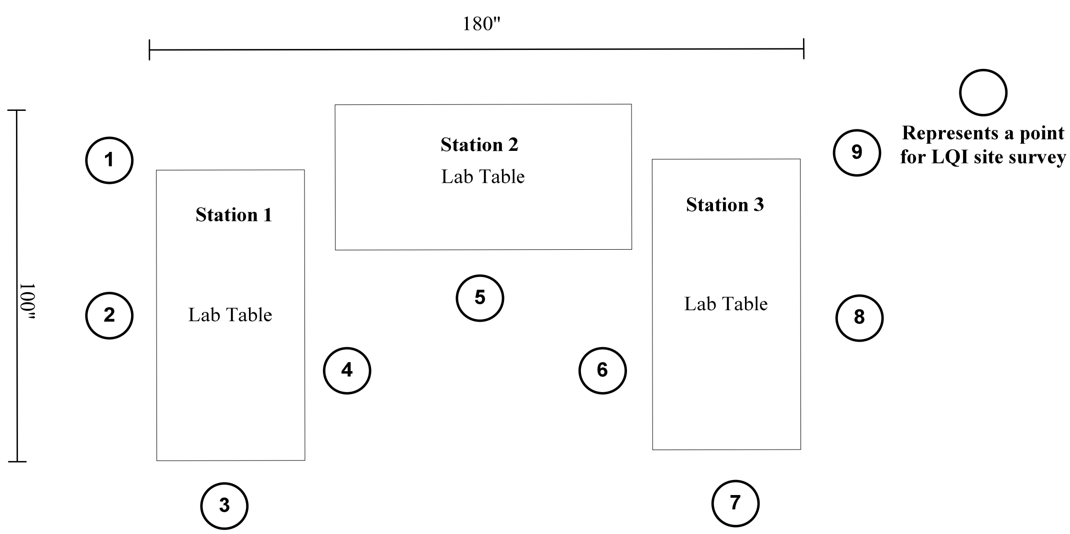


Figure 33: The layout of the nine grid location configuration.

4.3.2.3 Number of Tag Node Orientations at each Grid Location

Saxena et al. (2008) conducted an offline data collection experiment utilizing a tag node with two orientations (i.e., north and south) in a wireless network based IPS. However, they did not investigate the effect that other orientations of the tag node could have on the performance of the IPS.

In this research, two levels were used for the number of orientations at each grid location. The low level utilized four orientations, whereas the high level utilized eight orientations, as depicted in Figure 34.

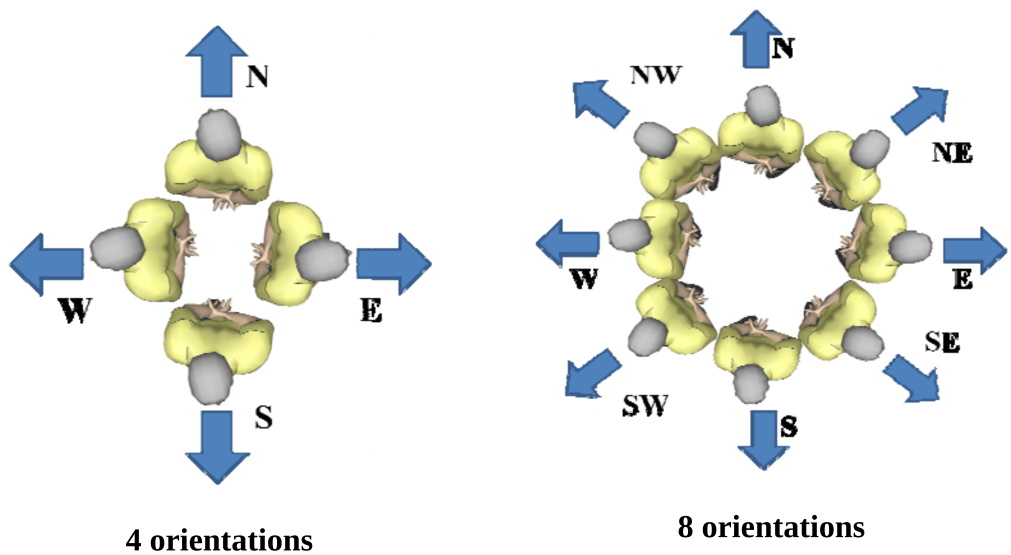


Figure 34: Tag node orientations.

4.3.2.4 Number of Sample LQI Values Collected per Orientation and Grid Location

The low and high levels for the number of sample LQI values collected per orientation and grid location were 2,000 and 6,000, respectively.

4.3.2.5 Offline Design Matrix

A total of 16 treatment combinations resulted from having four main factors, each at two levels, as shown in Table 6. Treatment combinations were randomized before conducting the offline data collection process to minimize experimental bias. A data sheet was developed for each experimental run to ensure that the offline data collection procedure was consistent. An example of the data sheet is included in Appendix E.

For the remainder of this document, the 16 treatment combinations utilized in the offline data collection phase are referred to as *offline templates*.

Table 6: Treatment combinations for the offline data collection phase.

Template Number	**Factors**			
	A	**B**	**C**	**D**
1	-	+	+	+
2	+	+	+	-
3	-	+	-	-
4	-	-	-	-
5	+	+	+	+
6	+	-	+	-
7	+	+	-	-
8	+	-	+	+
9	-	+	-	+
10	+	-	-	+
11	-	-	+	+
12	-	+	+	-
13	-	-	-	+
14	-	-	+	-
15	+	+	-	+
16	+	-	-	-

4.3.3 Online Data Collection Phase

The purpose of the online data collection phase was to generate LQI values that could be used to evaluate the effectiveness of each of the 16 offline templates in estimating the location of the operator within the simulated assembly area, so that individual task times could be calculated. To this end, the operator was equipped with a single tag node and allowed to move without restraint in the simulated assembly area to perform twenty runs of a job consisting of assembling a different Lego set at each of the three workstations. The Lego sets varied in their level of difficulty (see Appendix F).

In each online run, the operator started the job at a randomly selected workstation. Once the first Lego set assembly task was completed, he then randomly moved to the next workstation until all the Lego set assembly tasks were finished.

LQI values with time stamps were automatically collected from the three beacons and sent to the main computer via the centralization node. It is important to note that the number of LQI values collected in each of the 20 runs were not always the same due to inconsistencies in the communication speed between the nodes in the network. This problem was addressed by considering only the first ten LQI values reported by each beacon node within every second for a period of five seconds. The diagram of the online data collection process setup is depicted in Figure 35.

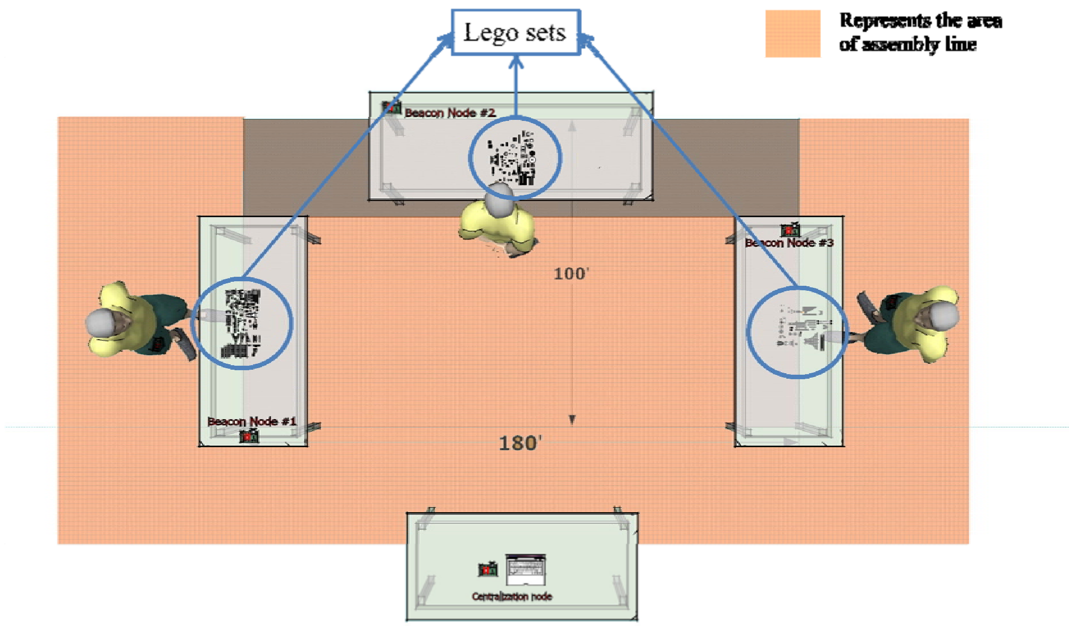


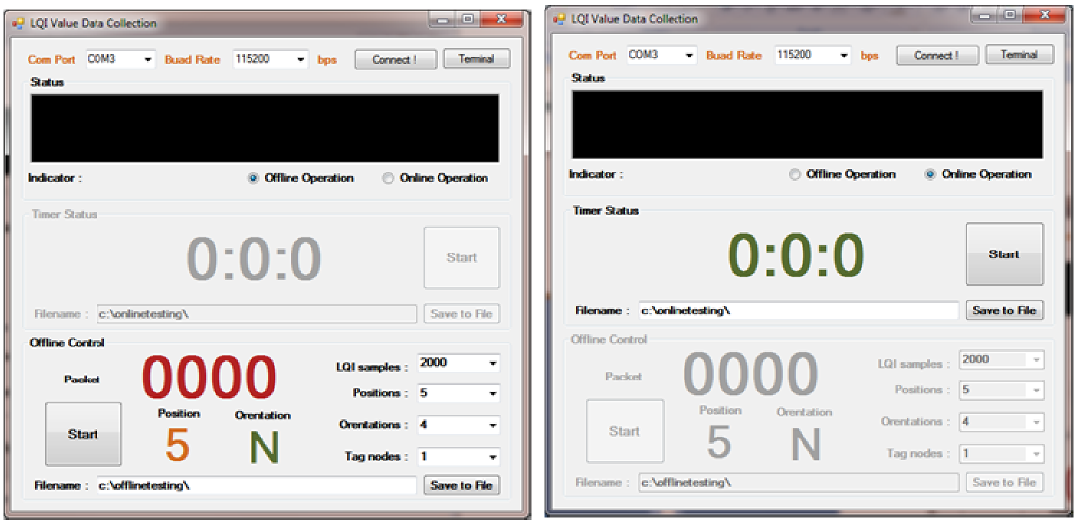
Figure 35: Online data collection process setup.

4.3.3.1 Manual task time data collection

The time the operator spent at each workstation during each of the 20 online runs was recorded manually using a stopwatch (see Appendix G). The manually recorded times were then stored in a spreadsheet and were later used as a baseline for measuring the ability of the WSN-based IPS to estimate individual task times.

4.4 LQI Value Data Collection Software Application

A data collection software application was developed in Visual Basic to collect LQI values on both the offline and online data collection phases. The graphical user interface (GUI) of the data collection software is depicted in Figure 36.



(a) (b)

Figure 36: Data collection software: (a) offline mode, (b) online mode.

During the offline data collection phase, the data collection software application utilized a packet counter feature which automatically forced the centralization node to stop receiving packets once the number required sample LQI values (i.e., 2,000 or 6,000) had been reached. The LQI values collected for each of the 16 offline templates were stored in a Microsoft® Access database according to the format shown in Table 7.

Table 7: Data format for offline data collection phase.

Packet number	Position	Orientation	Orientation (Angle)	Number of mobile nodes	LQI Station 1	LQI Station 2	LQI Station 3
1	1	North	0	1	168	108	162
2	1	North	0	1	168	108	162
3	1	North	0	1	126	108	144
4	1	East	90	1	168	102	96
5	1	East	90	1	174	138	150
6	1	East	90	1	168	102	96
7	1	South	180	1	114	54	90
8	1	South	180	1	156	60	90
9	1	South	180	1	120	54	90

In the online data collection phase, the received data packets were formatted as depicted in Figure 37. They were then stored in a comma separated text file.

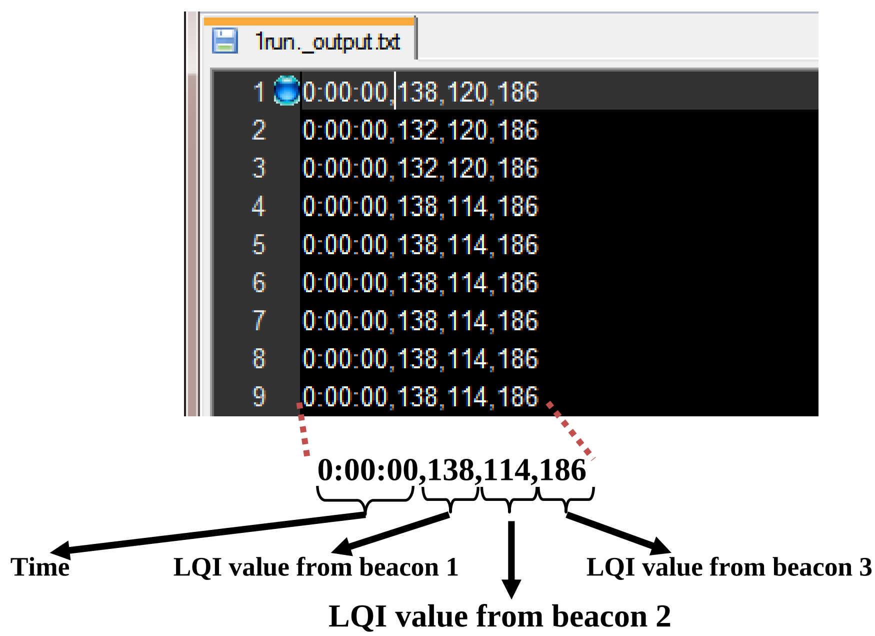


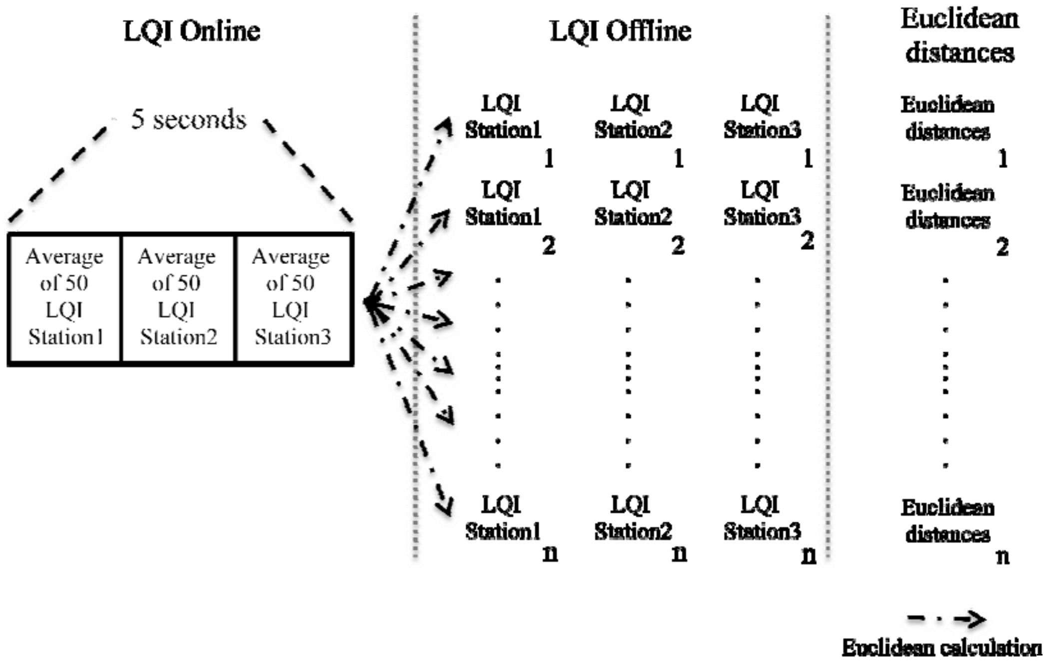
Figure 37: Data format for online data collection phase.

4.5 Estimating Operator Location Using LQI Data

The process of estimating the location of the operator relative to the workstations in the simulated assembly area was performed after both the offline and online data collection phases were completed. This was accomplished by comparing the data sets of LQI values collected in the online data collection phase against the data sets of LQI values collected in the offline data collection phase in intervals of five seconds. The specific steps in this process were as follows:

1. During an online data collection run, each of the three beacon nodes collected LQI values from the tag node(s) in intervals of five seconds. Since the beacon nodes collected an unequal number of LQI values, only the first ten LQI values reported each second by each beacon node during the five second interval were selected resulting in a total of 50 LQI values per beacon node.
2. The average of the 50 LQI values per beacon node was calculated.
3. The *k*-nearest neighbor algorithm was applied to the LQI data. As explained in the literature review section, the *k*-nearest neighbor algorithm is a *pattern recognition* algorithm. The key feature of the *k*-nearest neighbor algorithm is the ability to scope a dataset based on the value of the parameter *k* to decrease the calculation time and increase the accuracy of the algorithm depending on the pattern of the dataset (Hand et al., 2001):

a. First, the Euclidean distances between the average online LQI values per beacon and the corresponding LQI values per beacon node in each of the 16 offline templates were calculated. For example, the offline template consisting of one tag node, five site survey grid locations, four orientations per survey grid location, and 2,000 sample LQI values per grid location per orientation, contained the smallest number of LQI values per beacon node (i.e., 40,000). Therefore, a total of 40,000 Euclidean distances were calculated in this offline template for each five second interval. For the offline template consisting of two tag nodes, nine site survey grid locations, eight orientations per survey grid location, and 6,000 sample LQI values per grid location per orientation, the largest numbers of Euclidean distances were calculated at 864,000. Figure 38 graphically depicts the process of calculating Euclidean distances.
b. The values of the Euclidean distances were sorted in ascending order.
c. The locations associated with the Euclidean distance values were tallied.
d. The location with the largest tally is reported by the *k*-nearest neighbor algorithm.



*Where n = total number of tag nodes * total number of sample LQI values collected per grid location and orientation * total number of tag node orientations at each grid location * total number of site survey grid locations.*

Figure 38: Process to calculate Euclidean distances.

4. The five second interval is allocated to the workstation associated with the location with the largest tally reported by the k-nearest neighbor algorithm. As explained earlier, offline templates contained either five or nine site survey grid locations. Table 8 shows which locations were associated with each workstation in both cases. This is also shown graphically for offline templates with five and nine site survey grid locations in Figure 39 and Figure 40, respectively.
5. The process is repeated for the next five second interval.

Table 8: Relationship between site survey locations and workstations.

Number of Site Survey Grid Locations	Locations associated with Workstation #1	Locations associated with Workstation #2	Locations associated with Workstation #3
5	1, 2	3	4, 5
9	1, 2, 3	4, 5, 6	7, 8, 9

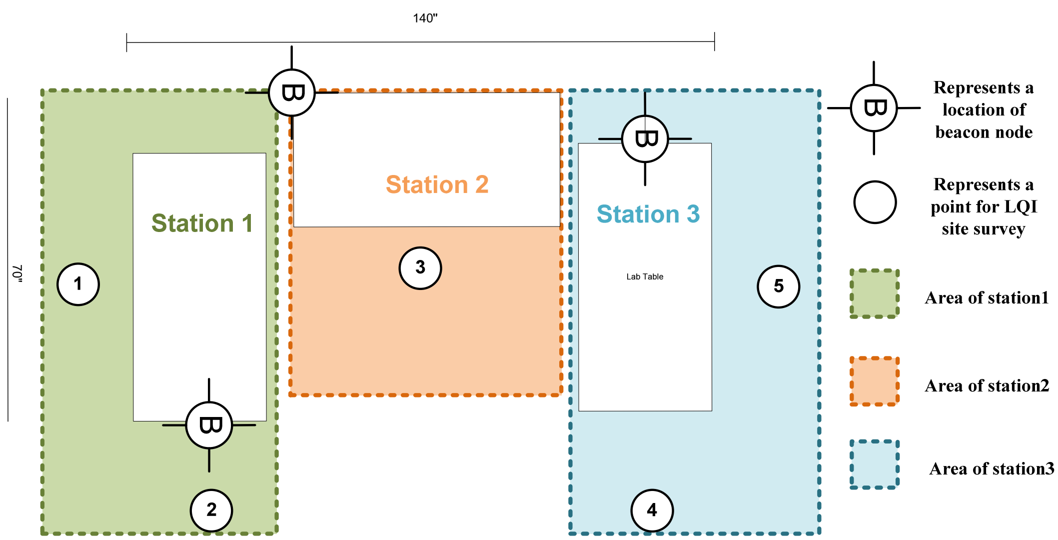


Figure 39: Locations associated with each workstation for offline templates with five site survey grid locations.

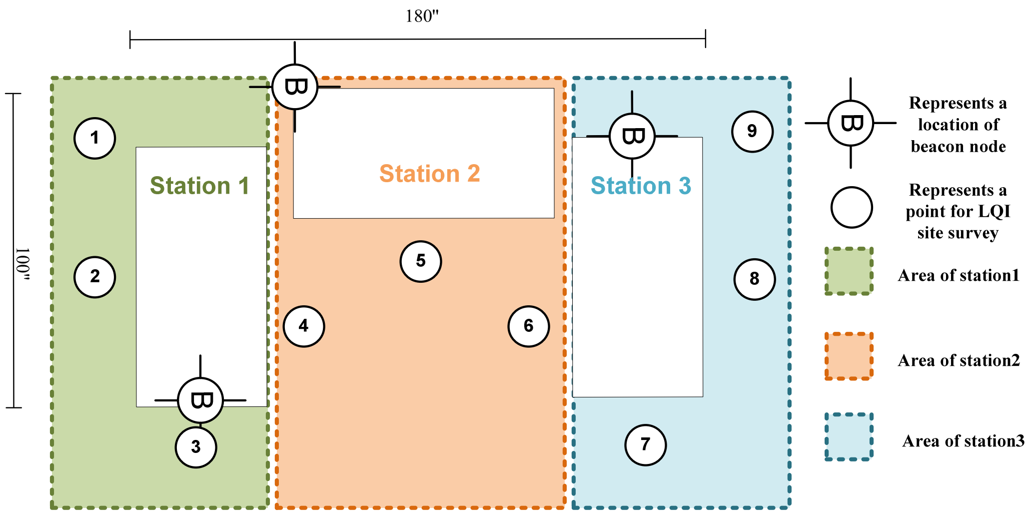


Figure 40: Locations associated with each workstation for offline templates with nine site survey grid locations.

Figure 41 depicts a flowchart of the process to estimate the location of the operator relative to the workstations in the simulated assembly area.

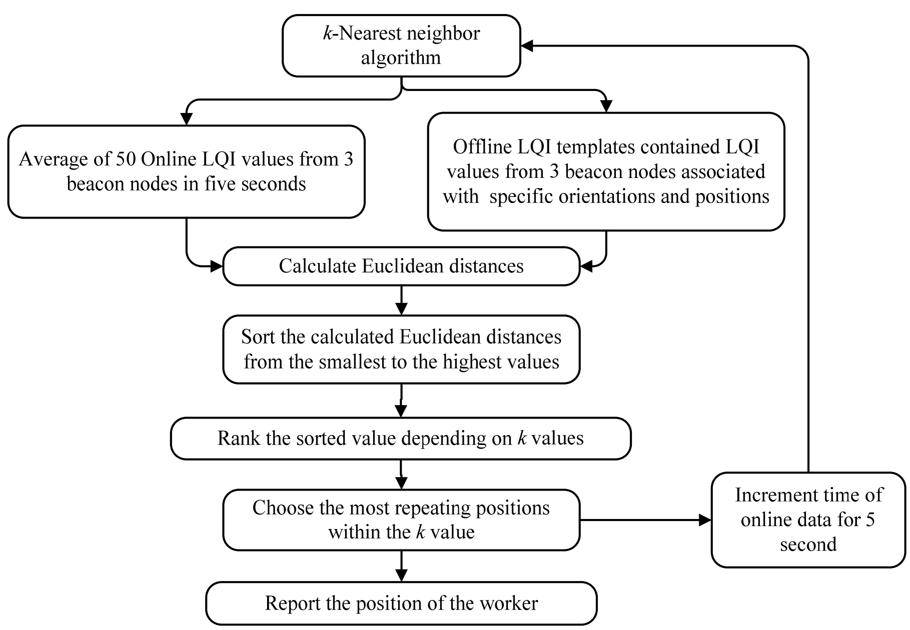


Figure 41: The steps of the *k*-nearest neighbor algorithm.

4.5.1 Task time estimation process

As explained in section 4.5, the location of the operator relative to the workstations in the simulated assembly area was updated every five seconds until all three assembly tasks were completed. The results were then graphed using Microsoft® Excel 2007.

For example, Figure 42 depicts the results of the sixth run of the online data collection phase. This online run involved five site survey grid locations, in which site survey grid locations 1 and 2 correspond to workstation 1; site survey grid location 3 corresponds to workstation 2; and site survey grid locations 4 and 5 correspond to workstation 3. The data points associated with these locations were then aggregated to generate the graph shown in Figure 43.

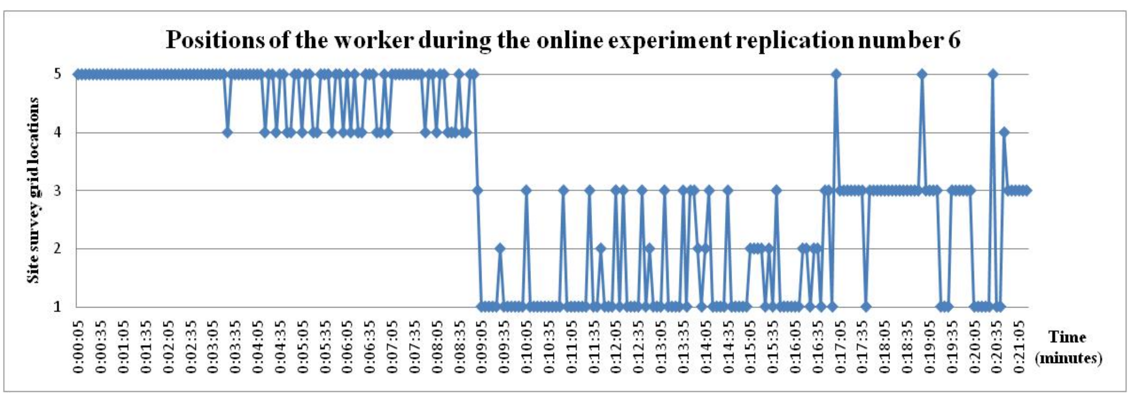


Figure 42: Operator's locations during the sixth run of the online data collection phase.

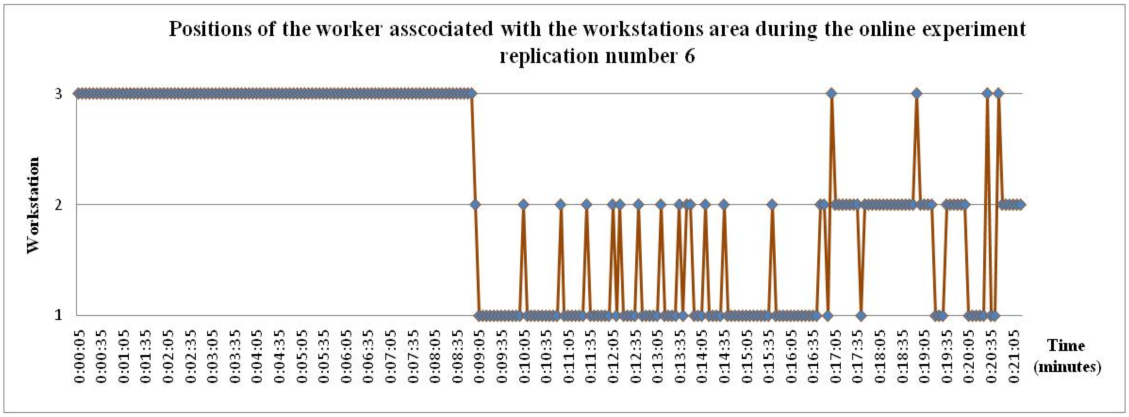


Figure 43: Data points associated with each workstation during the sixth run of the online data collection phase.

Individual task times were calculated after the number of data points associated with each workstation within the simulated assembly area was determined for each online run. To do this, the ratio of observations tallied versus total observations was calculated for each workstation. Finally, these ratios were multiplied by the total time it took to complete the online run to obtain the individual workstation's task times.

4.5.2 Levels of the k parameter

The value of the parameter *k* of the *k*-nearest neighbor algorithm can be changed to affect the performance of the algorithm depending on the quantity and the trend of the data. The main advantages of using large values of *k* are smoother decision regions and providing accuracy probabilistic information. However, using a value of *k* that is too large is detrimental because it destroys the locality of the estimation since farther data values are taken into account. In addition, the requirement in terms of computational power and time are increased (Hand et al., 2001).

Therefore, different values of *k* were used in this research to investigate their effect on the results. Three *k* value levels (i.e., low, medium, and high) were chosen for each level of sample LQI values per grid location per orientation in the offline templates and were calculated as percentages of the total number of samples, as shown in Table 9. Each *k* level produced 320 task time results, as depicted in Figure 44.

Table 9: Levels of the *k* parameter according to the offline sample sizes.

Sample LQI values per grid location per orientation	*k* low (25%)	*k* medium (50%)	*k* high (75%)
2,000	500	1,000	1,500
6,000	1,500	3,000	4,500

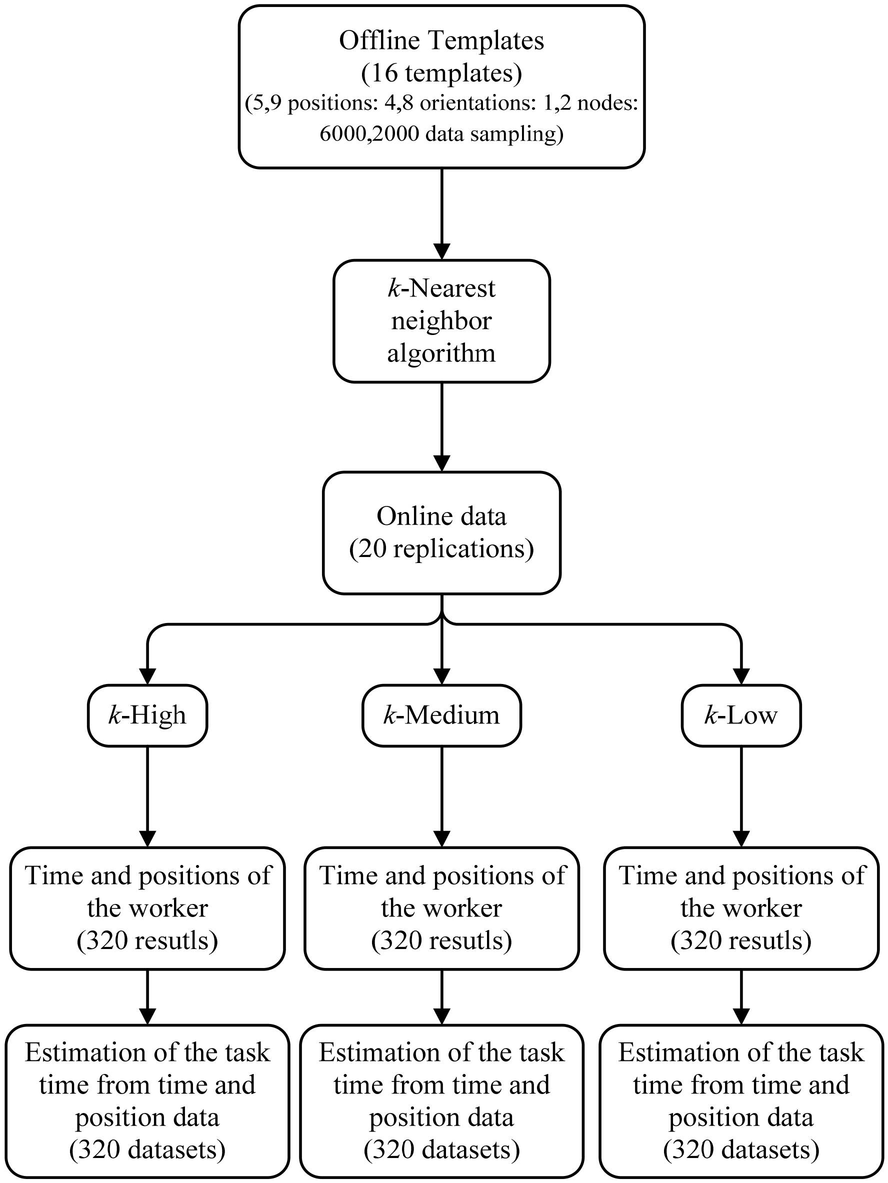


Figure 44: Numbers of task time results categorized by three levels of the *k* parameter.

4.6 LQI Data Processing and Data Management Software Application

A software application was developed in Visual Basic to automate the process described in section 4.5 to estimate the location of the operator relative to the workstations in the simulated assembly area based on LQI data. The graphical user interface of this software application is depicted in Figure 45.

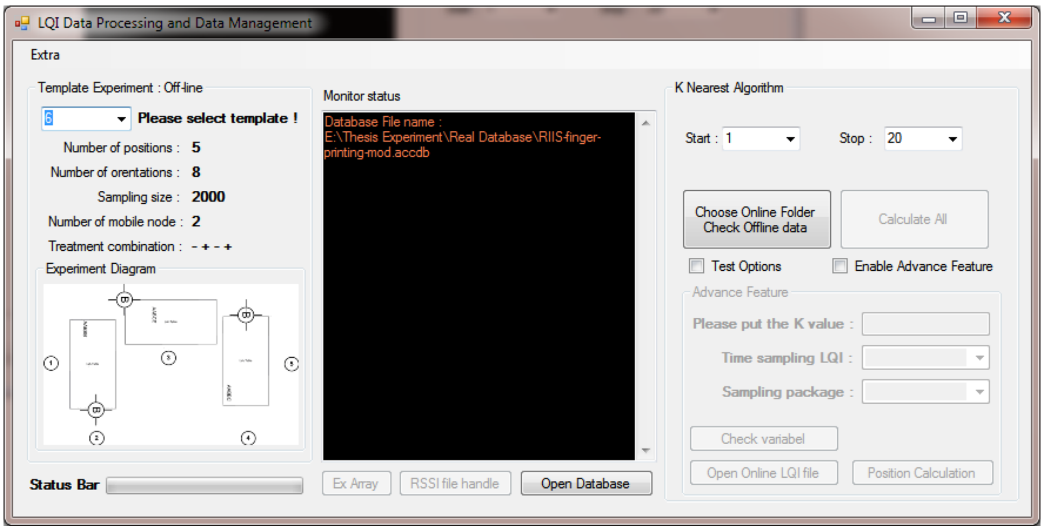


Figure 45: LQI data processing and data management program.

The main feature of this software application is its ability to automatically implement the *k*-nearest neighbor algorithm (based on a selected offline template using all three *k* levels) by only defining the subdirectory address of a folder containing a series of 20 datasets collected during the online phase. After completing this process, the software generates a text file which reports the location of the worker and the estimated task times results. An example of the text file report generated by this software is included in Appendix H.

5. RESULTS

5.1 Task Time Estimation Results

As explained in section 4.5, the k-nearest neighbor algorithm was used to calculate individual task times based on the locations of the operator within the simulated assembly area as estimated by the wireless sensor network (WSN) based indoor positioning system (IPS). Three different levels of the k parameter were used. Therefore, with 16 offline templates and 20 online runs, a total of 960 individual task times were estimated for each level of the k parameter for each workstation. The complete set of individual task times is included in Appendix I.

5.2 Percentage Error between Estimated Task Time and Observed Task Time Results

Once all the individual task times estimated from the data collected by the WSN-based IPS were obtained, the percentage error between these values and the observed task times were calculated using equation 4.

$$\%Error = \left|\frac{Observed\ task\ time_n - Estimated\ task\ time_n}{Observed\ task\ time_n}\right| \times 100 \qquad (4)$$

In equation 4, n represents the workstation number (n = 1, 2, or 3). The observed task time represents the period of time the operator spent at each workstation during each of the 20 online runs. As explained in section 4.3.3.1, observed task times were recorded manually using a stopwatch. The estimated task time is the period of time the WSN-based IPS estimated that the operator spent at each workstation during each of the 20 online runs.

Since each of the three workstations accounted for 960 individual percentage errors, a total of 2,880 percentage errors were calculated. The complete set of individual percentage errors is included in Appendix J.

For the remainder of this document, the percentage error between the observed task times and the estimated task times is referred to as the *estimated task time percentage error*.

5.3 Model Adequacy Checking

To be able to apply the analysis of variance (ANOVA) technique to statistically evaluate the results of this research, the ANOVA assumptions were validated first (Montgomery, 2008). These assumptions mainly focus on the distribution of the dependent variable and include:

- Normality of the residuals
- Independence of observations within and between samples
- Equal variance.

To check the normality assumption of the estimated task time percentage error data, a normal probability plot of the residuals was constructed (see Figure 46). The plot shows that indeed the error distribution is approximately normal.

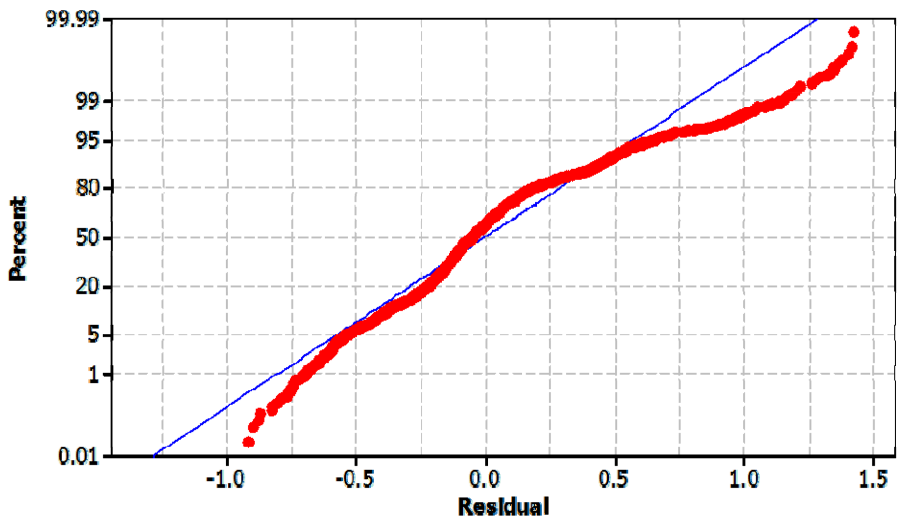


Figure 46: Normal probability plot of the residuals from the estimated task time percentage error.

The independence of observations within and between samples and the equal variance assumptions of the estimated task time percentage error data can be verified by a plot of residuals, as depicted in Figure 47. Based on the results of this plot, there is no reason to suspect any violation of the independence or constant variance assumptions becasue the residulals plot is visually structureless.

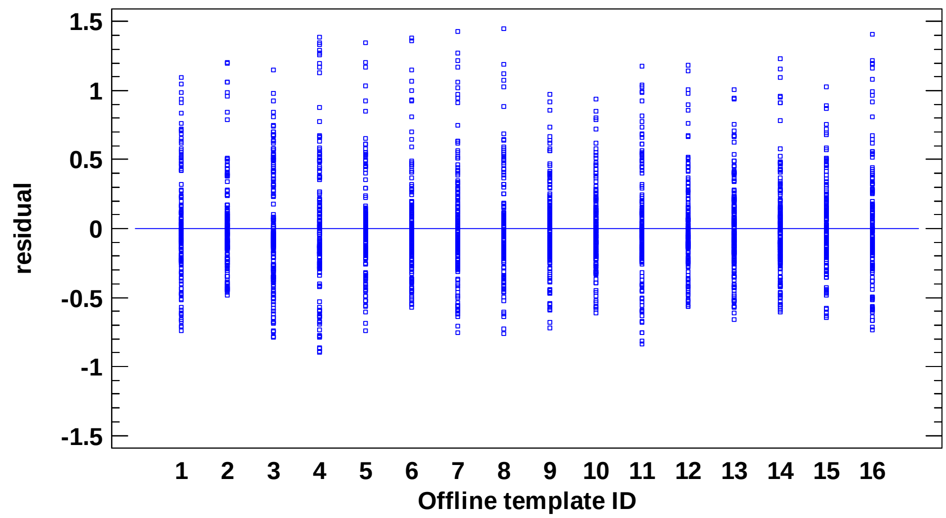


Figure 47: Residual plot of the estimated task time percentage error.

5.4 Results of the Statistical Analyses

The results of the statistical analyses conducted on the experimental data collected via the WSN-based IPS are presented in two subsections.

The first subsection details the statistical analysis performed to assess whether or not the offline templates had an effect on the quality of the individual task times estimated by the WSN-based IPS. Thus, the main objective of this analysis was to reveal differences (if any) *between* offline templates, especially whether or not an offline template (or a group of templates) resulted in a lower estimated task time percentage error.

The second subsection presents the results of the statistical analysis performed to determine whether or not the four WSN design factors considered in the construction of each individual offline template had an effect on the quality of the estimated individual task times. Table 10 presents the main WSN design factors and their corresponding levels utilized to construct each individual offline template. The main objective of this analysis was to investigate the differences (if any) that existed *within* offline templates, in particular the effects of the different levels of the main WSN design factors.

Table 10: Main WSN design factors and their corresponding levels by offline template.

Offline Template	Factors			
	(A)	(B)	(C)	(D)
	Number of Tag Nodes	Number of sample LQI values collected per grid location and orientation	Number of tag node orientations at each grid location	Number of site survey grid locations
1	1	6000	8	9
2	2	6000	8	5
3	1	6000	4	5
4	1	2000	4	5
5	2	6000	8	9
6	2	2000	8	5
7	2	6000	4	5
8	2	2000	8	9
9	1	6000	4	9
10	2	2000	4	9
11	1	2000	8	9
12	1	6000	8	5
13	1	2000	4	9
14	1	2000	8	5
15	2	6000	4	9
16	2	2000	4	5

5.4.1 Differences between Offline Templates

A multi-factor mixed model ANOVA was used to determine whether or not the offline templates had an effect on the quality of the individual task times estimated by the WSN-based IPS.

The multi-factor mixed model ANOVA was used because the *offline templates*, *levels of the k parameter*, and *workstations* were considered fixed factors, whereas the *online runs* were considered a random factor. Each online run was also considered a block in the analysis for two reasons. First, this approach reduced the amount of experimental data needed (and the time to collect it) to reveal differences between offline templates. For comparison purposes, if a completely randomized design were used with two replications per treatment combination, then 32 online runs would be needed. Second, a completely randomized design would have increased the variability of the individual task time percentage errors estimated by each offline template, thus making a true difference between offline templates more difficult to detect.

Table 11 shows the multi-factor mixed model ANOVA results. Since the estimated task time percentage errors were calculated for each workstation using three different levels for the *k* parameter, these factors were also included in the analysis to assess their significance on the accuracy of the estimated individual task time percentage errors.

Table 11: Multi-factor mixed model ANOVA results for differences between offline templates.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	F-ratios test
MAIN EFFECTS						
A: Offline template	10.1383	15	0.675887	4.53	**0.0000**	MS_{AD}
B: Level of *k* parameter	0.560257	2	0.280128	8.32	**0.0010**	MS_{BD}
C: Workstation	140.004	2	70.0021	27.04	**0.0000**	MS_{CD}
D: Online run	148.341	19	7.80741			
INTERACTIONS						
AB	0.63818	30	0.0212727	0.97	0.5179	MS_E
AC	17.7231	30	0.590769	26.84	**0.0000**	MS_E
AD	42.5003	285	0.149124	6.78	**0.0000**	MS_E
BC	0.649376	4	0.162344	7.38	**0.0000**	MS_E
BD	1.27934	38	0.0336669	1.53	**0.0204**	MS_E
CD	98.36	38	2.58842	117.62	**0.0000**	MS_E
RESIDUAL	53.1682	2416	0.0220067			
TOTAL (CORRECTED)	513.362	2879				

Main factors and two-factor interactions were considered to be statistically significant if their P-value was less than 0.05. Due to the fact that this multi-factor mixed model ANOVA has only one replication, the internal estimate of error (or "pure error") cannot be assessed. However, this problem can be solved based on the *sparsity of effects* principle. This principle assumes that a system is usually dominated by main factors and low-order interactions (Montgomery, 2008). Thus, the mean square values of three-factor interactions and higher-order interactions in this analysis were pooled into the mean square error (MS_E) term.

As shown in Table 11, the P-value of all main effects *offline template*, level of *k parameter*, and *workstations* is less than 0.05, which indicates that they all have a statistically significant effect on the accuracy of the individual task times estimated by the WSN-based IPS. The two-factor interactions in Table 11 that show a statistically significant effect are the following:

- Offline templates with workstations (AC)
- Level of the *k* parameter with workstations (BC)

Despite the fact that the two-factor interaction effects AD, BD, and CD are statistically significant based on their P-value results, they include the blocking factor (i.e., online run) and therefore are not of interest.

Since the multi-factor ANOVA null hypothesis of equal treatment means (i.e., $H_0 : \mu_1 = \mu_2 = \ldots = \mu_n$) was rejected based on the P-values shown in Table 11, Fisher's least significant difference (LSD) interval plots of the main factors *offline template* and *level of k parameter* were produced (at a 95% confidence level) to further understand how they influence the performance of the WSN in estimating individual task times. It is important to note that since the two-factor interactions *offline templates with workstations (AC)* and *level of the k parameter with workstation (BC)* are significant, separate Fisher's LSD interval plots of the main factors *offline template* and *level of the k parameter* were produced for each individual workstation.

The Fisher's LSD interval plots for the main factor *offline template* for workstation #1, workstation #2, and workstation #3 are depicted in Figure 48, Figure 49, and Figure 50, respectively. Fisher's LSD multiple comparison method (at a 95% confidence level) was used to compare all pairs of means of estimated task time percentage errors calculated from the offline templates for each workstation. The complete results of these analyses (including tables of homogeneous groups) are included in Appendix K, Appendix L and Appendix M.

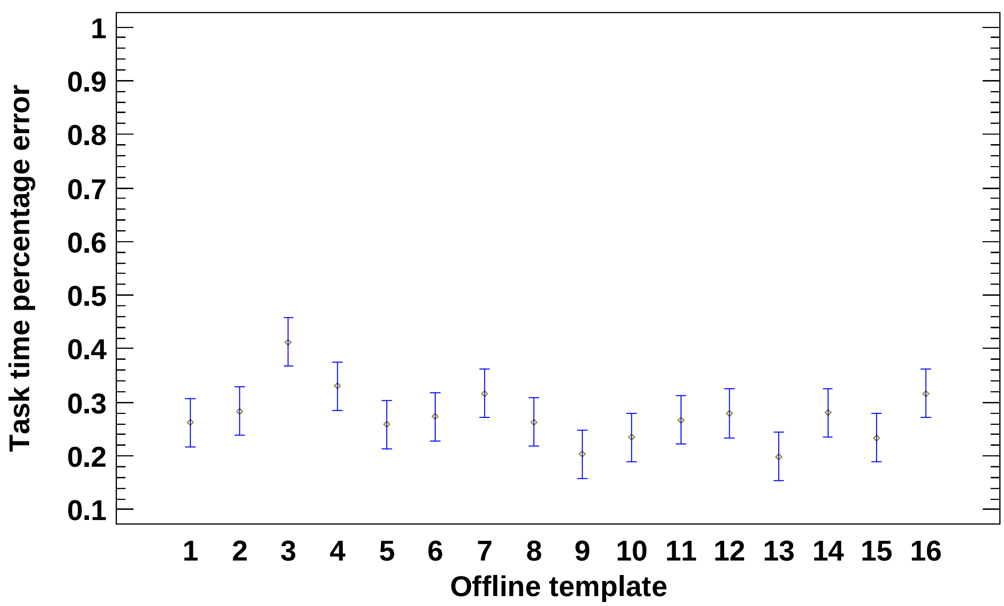


Figure 48: LSD interval plot of the main factor *offline template* based on workstation 1.

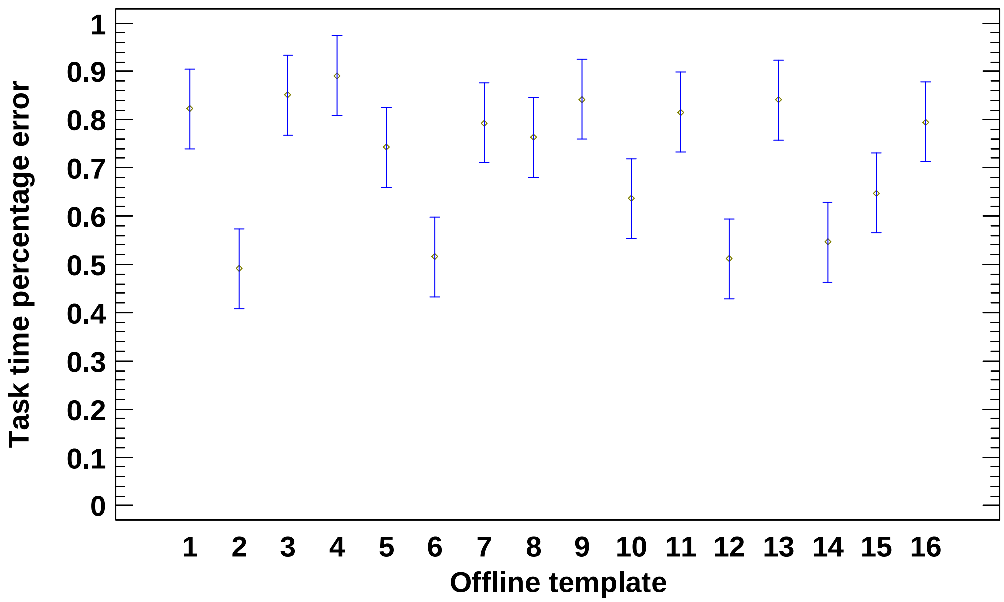


Figure 49: LSD interval plot of the main factor *offline template* based on workstation 2.

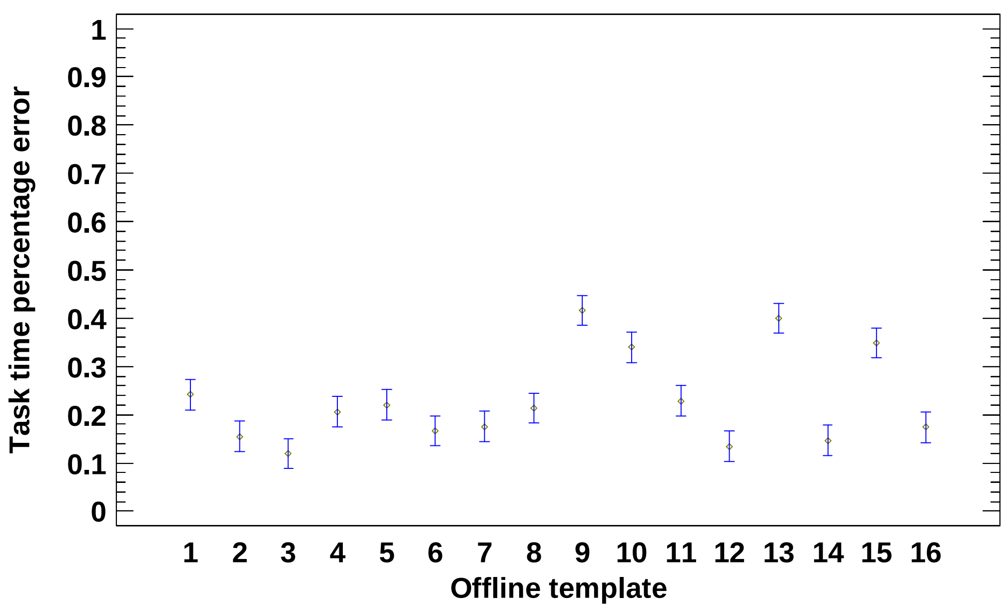


Figure 50: LSD interval plot of the main factor *offline template* based on workstation 3.

The Fisher's LSD interval plots of the main factor *level of the k parameter* for workstation #1, workstation #2 and workstation #3 are depicted in Figure 51, Figure 52, and Figure 53, respectively.

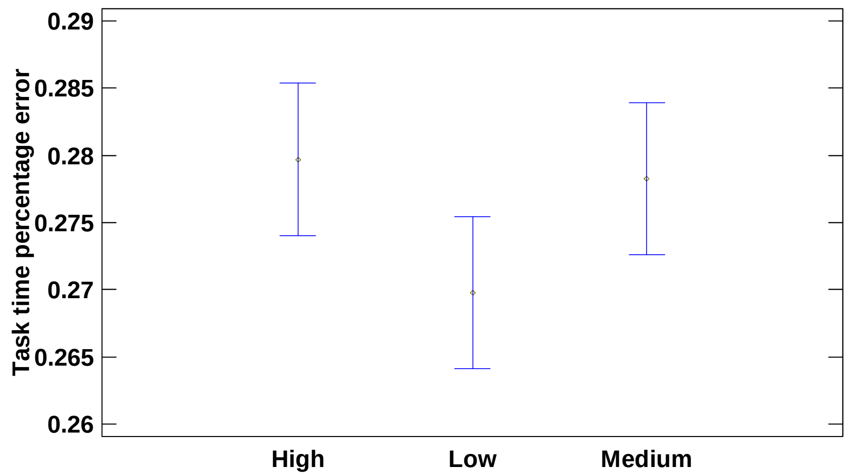


Figure 51: LSD interval plot of the main factor *level of k parameter* based on workstation 1.

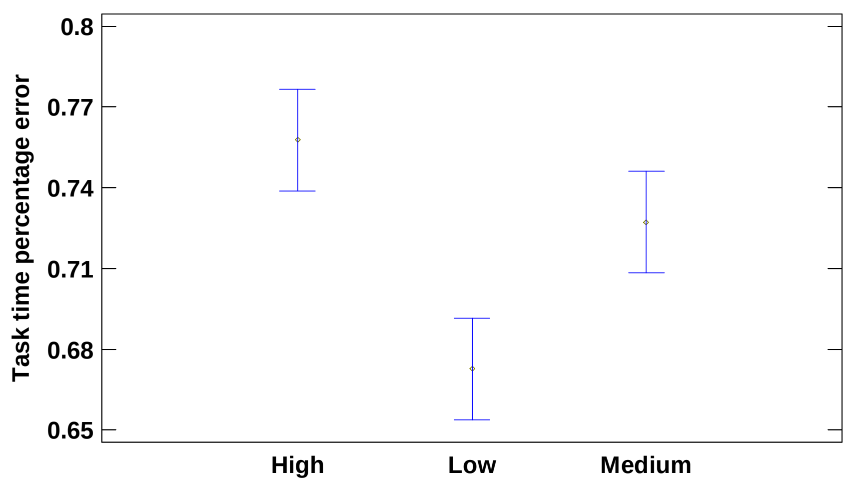


Figure 52: LSD interval plot of the main factor *level of k parameter* based on workstation 2.

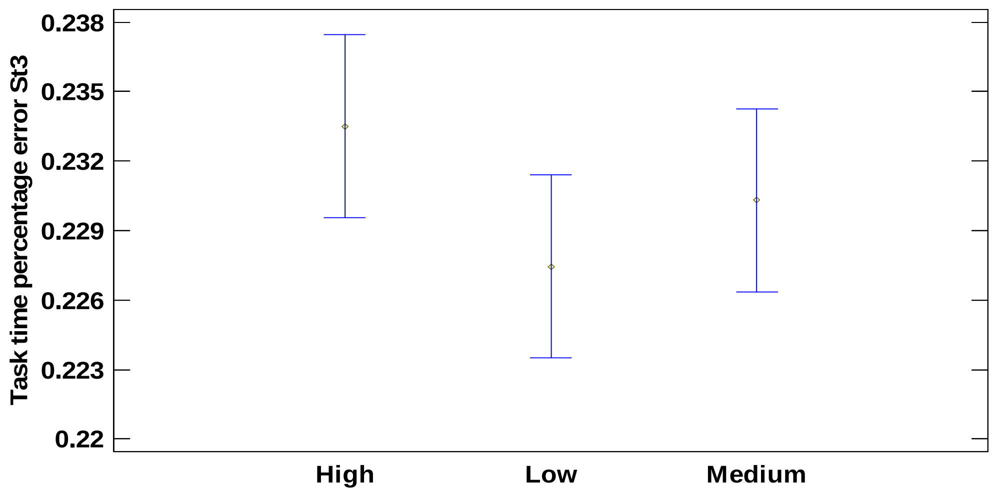


Figure 53: LSD interval plot of the main factor *level of k parameter* based on workstation 3.

For comparison purposes, interaction plots combined with Fisher's LSD interval plots of the main factor *level of k parameter* for all three workstations are depicted in Figure 54.

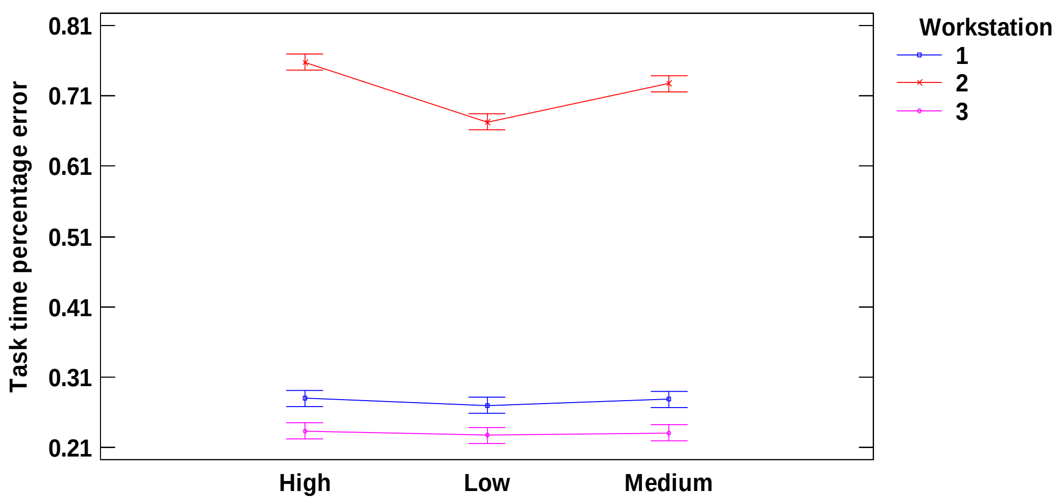


Figure 54: Interaction plots and Fisher's LSD interval plots of *level of k parameter* main factor based on the three workstations.

5.4.2 Analysis of the result based on WSN design factors

Based on the fact that the results presented in section 5.4.1 showed that the offline template main factor did have an effect on the ability of the WSN-based IPS to estimate individual task times, a multi-factor mixed model ANOVA was used to determine which of the WSN design factors were statistically significant. A multi-factor mixed model ANOVA was used at this stage for the same reasons stated in section 5.4.1.

Table 12 shows the multi-factor mixed model ANOVA results. In this analysis, *number of tag nodes*, *LQI sample size*, *orientations at each grid location*, *site survey grid locations*, *level of k parameter*, and *workstations* were considered fixed factors. As before, *online run* was considered a random factor.

Table 12: Multi-factor mixed model ANOVA results of estimated task time percentage errors obtained by all three k level parameters based on WSN design factors.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	F-ratios test
MAIN EFFECTS						
A: Number of Tag Nodes	0.995703	1	0.995703	12.07	**0.0025**	MS_{AG}
B: LQI sample size	0.0075144	1	0.0075144	0.29	0.5985	MS_{BG}
C: Orientations at each grid location	4.24364	1	4.24364	18.16	**0.0004**	MS_{CG}
D: Site survey grid locations	2.02785	1	2.02785	2.39	0.1386	MS_{DG}
E:Level of *k* parameter	0.560257	2	0.280128	8.32	**0.0010**	MS_{EG}
F: Workstation	140.004	2	70.0021	27.04	**0.0000**	MS_{FG}
G: Online run	148.341	19	7.80741			
INTERACTIONS						
AB	0.00117201	1	0.00117201	0.04	0.8449	MS_E
AC	0.325855	1	0.325855	10.64	**0.0011**	MS_E
AD	0.184672	1	0.184672	6.03	**0.0141**	MS_E
AE	0.0102424	2	0.00512122	0.17	0.8460	MS_E
AF	1.09033	2	0.545165	17.80	**0.0000**	MS_E
AG	1.56728	19	0.0824886	2.69	**0.0001**	MS_E
BC	0.00693614	1	0.00693614	0.23	0.6341	MS_E
BD	0.0307677	1	0.0307677	1.00	0.3162	MS_E
BE	0.00235053	2	0.00117526	0.04	0.9623	MS_E
BF	0.0741218	2	0.0370609	1.21	0.2983	MS_E
BG	0.497825	19	0.0262013	0.86	0.6399	MS_E
CD	2.2932	1	2.2932	74.89	**0.0000**	MS_E
CE	0.0273934	2	0.0136967	0.45	0.6394	MS_E
CF	1.93279	2	0.966393	31.56	**0.0000**	MS_E
CG	4.43993	19	0.233681	7.63	**0.0000**	MS_E
DE	0.492523	2	0.246262	8.04	**0.0003**	MS_E
DF	5.90859	2	2.95429	96.48	**0.0000**	MS_E
DG	16.1236	19	0.84861	27.71	**0.0000**	MS_E
EF	0.649376	4	0.162344	5.30	**0.0003**	MS_E
EG	1.27934	38	0.0336669	1.10	0.3117	MS_E
FG	98.36	38	2.58842	84.53	**0.0000**	MS_E
RESIDUAL	81.8839	2674	0.0306222			
TOTAL (CORRECTED)	513.362	2879				

In the P-values of the main factors *number of tag nodes*, *tag node orientations at each grid location*, *level of the k parameter* and *workstations* are less than 0.05, which indicates that they have a statistically significant effect on the accuracy of the individual task times estimated by the WSN-based IPS.

The two-factor interactions in Table 12 that show a statistically significant effect are:

- Number of tag nodes with tag node orientations at each grid location (AC)
- Number of tag nodes with site survey grid locations (AD)
- Number of tag nodes with workstations (AF)
- Orientations at each grid locations with site survey grid locations (CD)
- Orientations at each grid locations with workstations (CF)
- Site survey grid locations with level of the *k* parameter (DE)
- Site survey grid locations with workstations (DF)
- Level of the *k* parameter with workstations (EF)

Fisher's least significant difference (LSD) interval plots of all main factors (at a 95% confidence level) were produced to depict how they influence the performance of the WSN-based IPS in estimating individual task times. The LSD interval plots for the *number of tag nodes*, *LQI sample size*, *tag node orientations at each grid location*, *site survey grid locations*, *level of k parameter*, and *workstations* are depicted in Figure 55, Figure 56, Figure 57, Figure 58, Figure 59 and Figure 60, respectively.

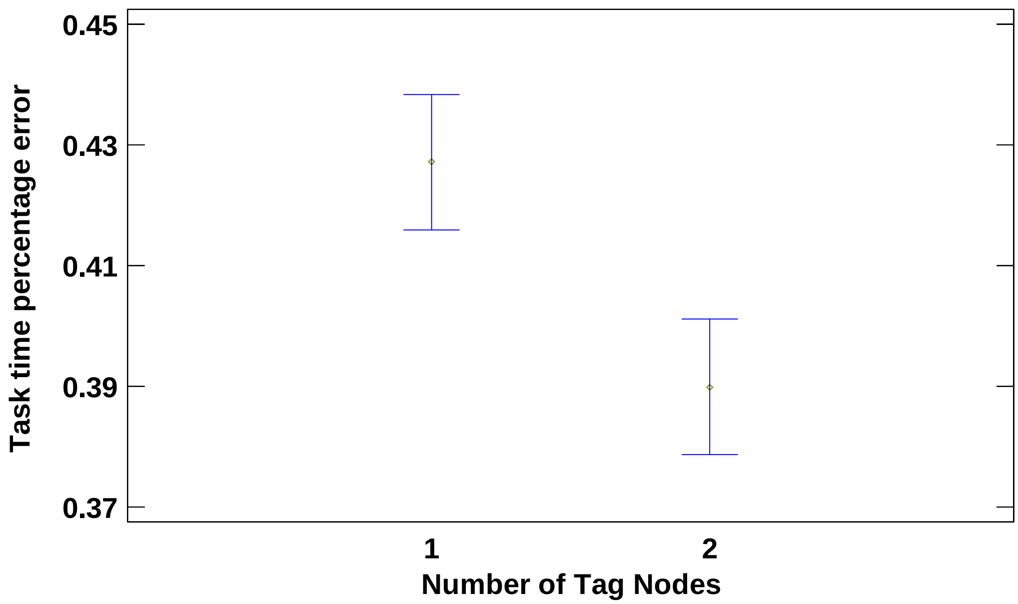


Figure 55: LSD interval plot of the tag nodes main factor.

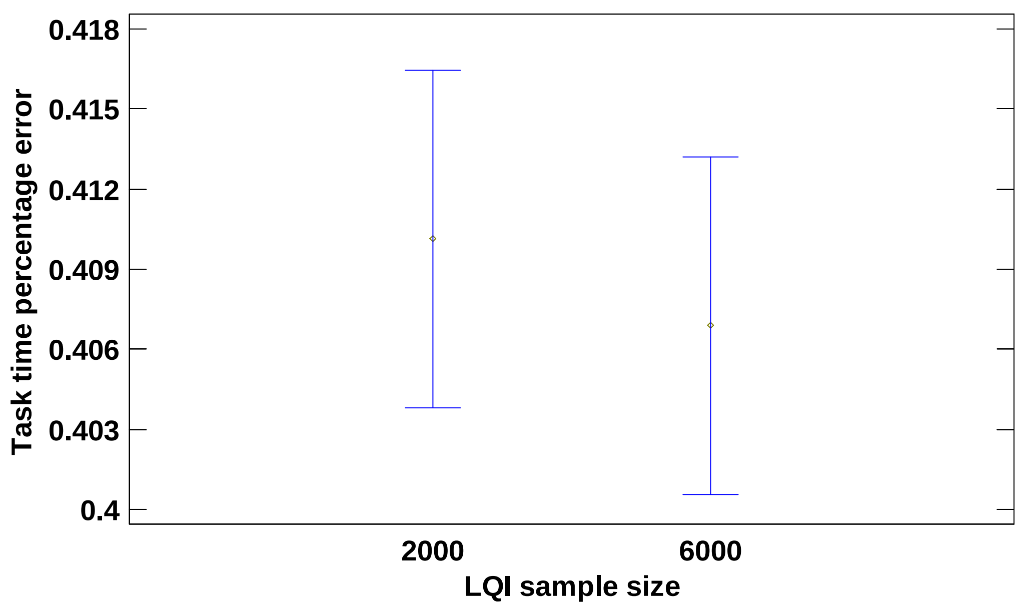


Figure 56: LSD interval plot of the LQI sample size main factor.

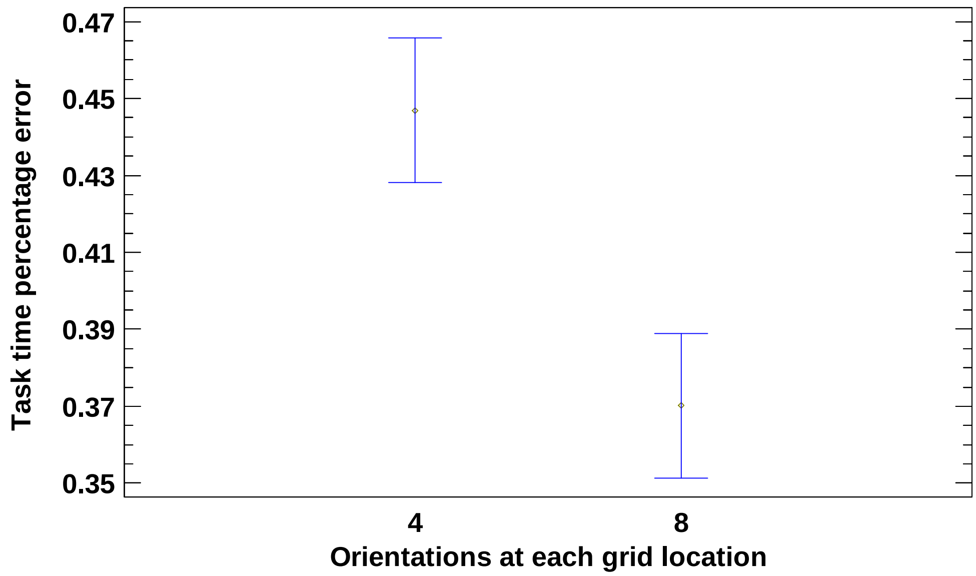


Figure 57: LSD interval plot of the tag nodes orientation at each grid location main factor.

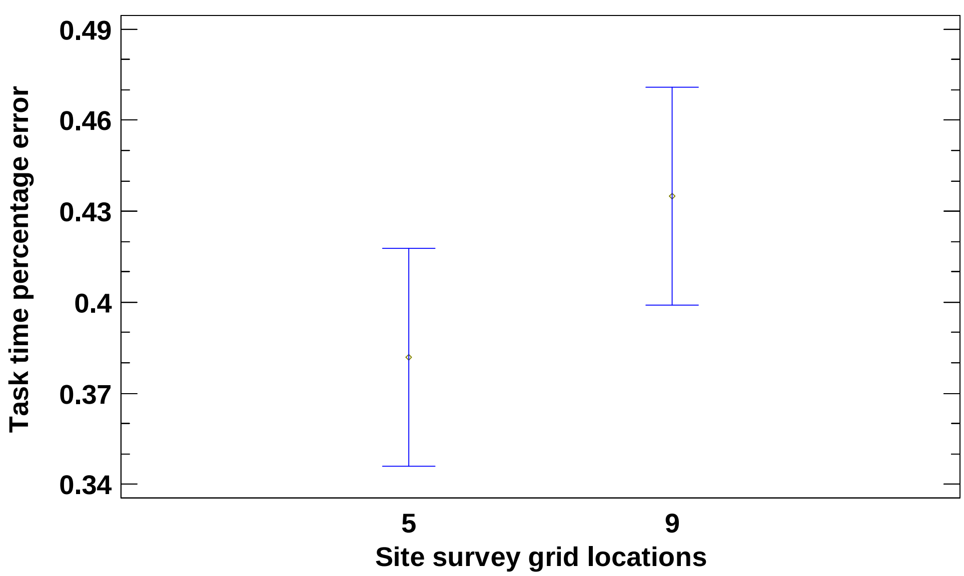


Figure 58: LSD interval plot of the site survey grid locations main factor.

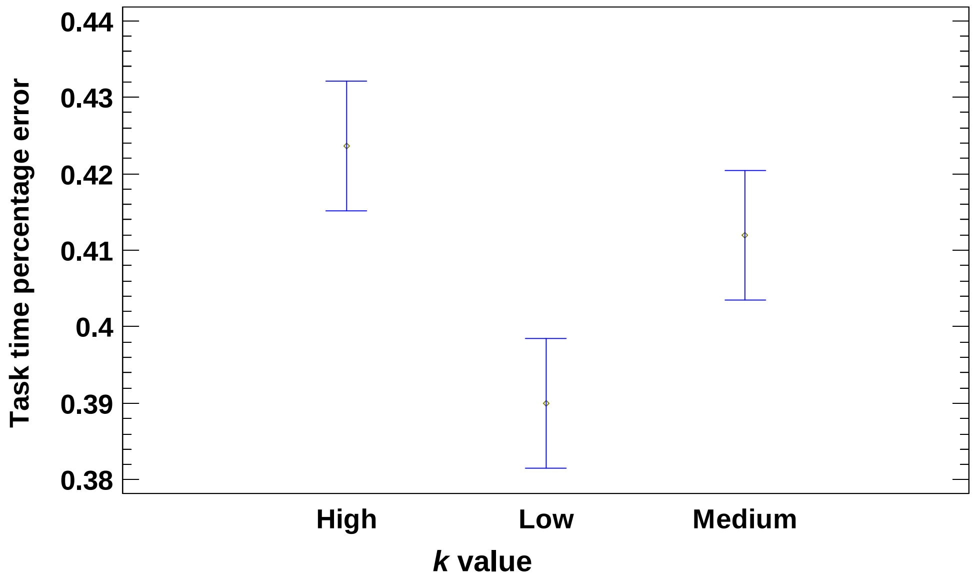


Figure 59: LSD interval plot of the level of *k* parameter main factor.

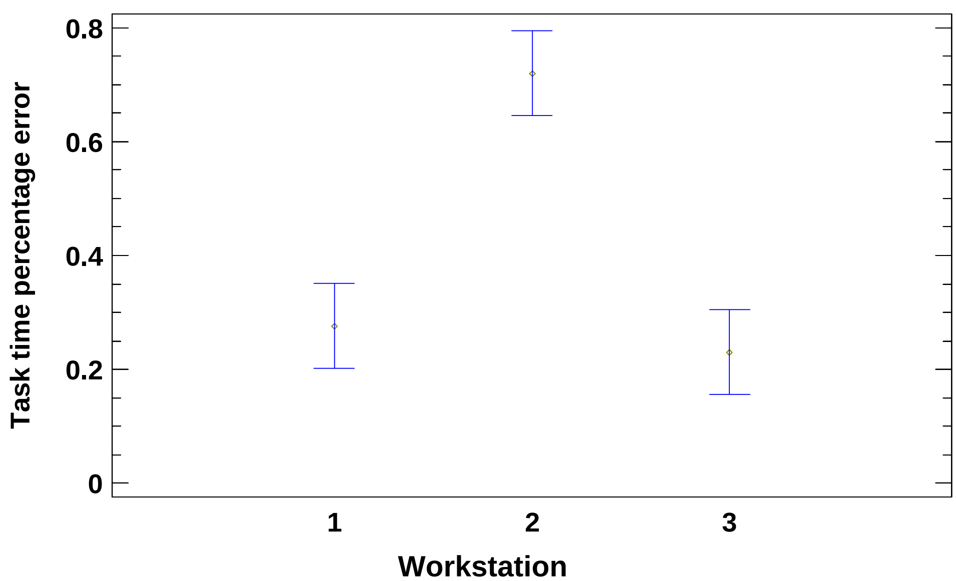


Figure 60: LSD interval plot of the workstations additional main factor.

6. DISCUSSION

In this chapter, the effects of the different experimental factors on the ability of the wireless sensor network (WSN) based indoor positioning system (IPS) to accurately estimate individual task times are discussed. In some cases, additional insight is provided to explain the results observed in the analyses of the experimental data.

The rest of the chapter is organized as follows. Section 6.1 discusses the effects of the offline templates. Section 6.2 discusses the effects of the WSN design factors. Section 6.3 discusses the effects of the *k* parameter. Finally, the effect of the workstations is discussed in Section 6.4.

6.1 Effects of the Offline Templates

The results of the multi-factor ANOVA presented in section 5.4.1 indicate that there is sufficient statistical proof that all 16 offline templates performed differently when used to estimate individual task times. Furthermore, the graphical results provided by the Fisher's LSD interval plots of the main factor *offline template* constructed for each workstation (see Figure 48, Figure 49, and Figure 50, respectively) revealed that the accuracy of the estimated task times obtained with different offline templates is different at each workstation.

Figure 61 depicts interaction plots combined with Fisher's LSD interval plots of the main factor *offline template* for all three workstations.

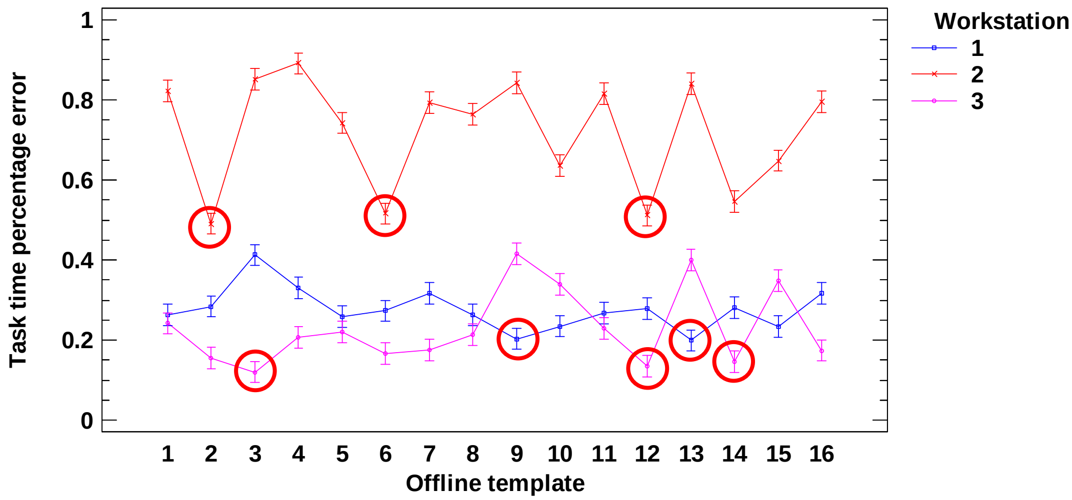


Figure 61: Interaction plots and Fisher's LSD interval plots of main factor *offline template* for all three workstations.

The red circles in Figure 61 identify those offline templates that resulted in the *lowest* mean value of the estimated task time percentage error at each workstation. In other words, these offline templates yielded the highest precision for the estimated individual task times out of the 16 offline templates evaluated. The specific offline templates selected per workstation were as follows:

- Workstation 1: offline template 13 and 9
- Workstation 2: offline template 2, 12 and 6
- Workstation 3: offline template 3, 12 and 14

Table 13 shows the levels of the main factors used to construct the eight offline templates identified above and a tally of how many times a specific level was used by these offline templates (the levels of the main factors that were the most common among these offline templates are shown in **bold**).

Table 13: WSN factors and levels used to construct the offline templates that yielded the highest precision for the estimated individual task times

	(A)		(B)		(C)		(D)	
	Number of Tag Nodes		Number of sample LQI values collected per grid location and orientation		Number of tag node orientations at each grid location		Number of site survey grid locations	
Level of factor	-	+	-	+	-	+	-	+
	1	2	2000	**6000**	4	**8**	**5**	9
Tallied level of factor	**6**	2	3	**5**	3	**5**	**6**	2

In summary, the data shown in Figure 61 and Table 13 is a clear indication that the different WSN design factors and their levels influenced the performance of the offline templates and affected the resulting mean estimated task time percentage error recorded at each workstation.

6.2 Effects of the WSN Design Factors

The results of the multi-factor ANOVA presented in section 5.4.2 show that the WSN design factors *number of tag nodes* and *number of tag node orientations at each grid location* had an effect on the ability of the WSN-based IPS to accurately estimate individual task times. Additionally, the data in Table 13 indicates that certain combinations of the levels of these WSN design factors are present in the offline templates that resulted in the lowest mean values for the estimated task time percentage error. The next three subsections elucidate why this difference in performance occurred.

6.2.1 Effects of the Number of Tag Nodes

The Fisher's LSD interval plot of the *number of tag nodes* shown in Figure 55 indicates that when two tag nodes were attached to the operator, a lower mean percentage error for the estimated task time was obtained. Intuitively, two tag nodes appear as the better option since more data would be available to determine the operator's position. Additionally, the interference effect created by the operator moving around the assembly area and possibly obstructing the line of sight between the tag node and the beacon node could be alleviated. However, Table 13 shows that six out of the eight selected offline templates yielded the lowest task time percentage error employed only one tag node.

From the aforementioned information, it is difficult to ascertain whether one or two tag nodes are better when creating radio fingerprinting maps.

6.2.2 Effects of the Number of Tag Node Orientations at Each Grid Location

The Fisher's LSD interval plot depicted in Figure 57 and the data shown in Table 13 provide enough evidence that WSN design factor *number of tag node orientations at each grid location* had an effect on the ability of the WSN-based

IPS to accurately estimate individual task times. More specifically, as the number of tag node orientations at each grid location increases so does the accuracy of the estimated individual task times.

An explanation for this effect may be that a higher number of tag node orientations at each grid location translate into a larger number of LQI values collected by the WSN-based IPS to characterize a single site survey location within the simulated assembly area. This increase in the number of LQI values available also increases the effectiveness of the *k*-nearest neighbor algorithm in estimating the location of the operator, which then translates into a more accurate task time.

6.2.3 Effects of the Number of Site Survey Grid Locations

Despite the fact that the results of the multi-factor ANOVA shown in Table 12 did not identify the *number of site survey grid locations* as a statistically significant factor, the Fisher's LSD interval plot depicted in Figure 58 shows that the mean estimated task time percentage error for offline templates that use five site survey grid locations was lower than those that used nine site survey grid locations. This is also supported by the results in Table 13, which show that six out of eight of the selected offline templates from the three workstations utilized five site survey grid locations.

An explanation for this effect may be that offline templates that utilized nine site survey grid locations experienced more signal interference and more signal overlap since the site survey grid locations were located much more closely when compared to the offline templates that used five site survey grid locations.

6.3 Effects of the Levels of the *k* Parameter

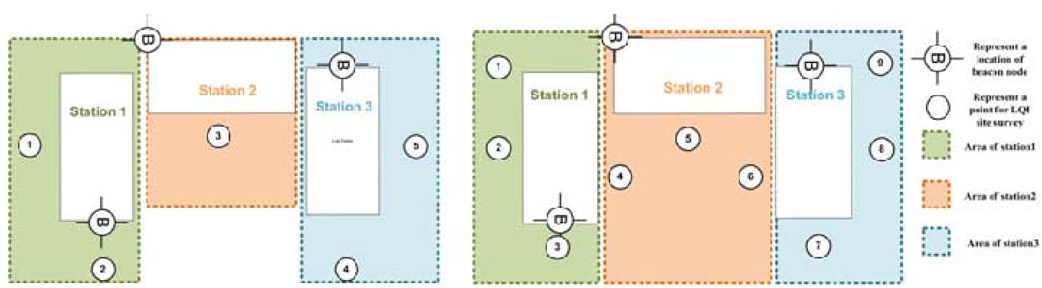
The multi-factor ANOVA results in sections 5.4.1 and 5.4.2 confirmed that the level of the *k* parameter did have an effect on the ability of the WSN-based IPS to accurately estimate task times. The Fisher's LSD interval plots for the three levels of the *k* parameter based on each workstation depicted in Figure 51, Figure 52, and Figure 53 indicate that the low level of the *k* parameter always resulted in the lower mean estimated task time percentage error.

An explanation for this effect may be that the low level of the *k* parameter provided just enough data points to estimate the locations of the operator within the simulated assembly area. Conversely, the higher mean estimated task time percentage errors that resulted from using the medium and high levels of the *k* parameter indicate that providing more LQI values to the *k*-nearest neighbor algorithm also increases the variability present in the data causing the increased level of error in estimating the locations of the operator and, consequently, the individual task times.

6.4 Effects of the Workstations

The results of multi-factor ANOVA presented in sections 5.4.1 and 5.4.2 and the Fisher's LSD interval plots depicted in Figure 60 and Figure 61 showed that workstation #2 had the highest mean estimated task time percentage error. Conversely, the mean task times percentage errors estimated for workstations #1 and #3 were very similar. This is also supported by the graphical results depicted in Figure 61, which show that the task times estimated at workstation #2 always yielded the highest percentage error compared to the other two workstations.

An explanation for this effect is both the number and location of site survey grid locations that were used to estimate task times for workstation #2. In both layouts shown in Figure 62, the site survey grid location points defined for workstation #2 are in very close proximity (due to the fixed placement of beacon nodes) to the zones within the simulated assembly area defined for workstation #1 and workstation #3, especially in the layout that used nine site survey grid locations. The close proximity of these points may have resulted in excessive signal overlap making the LQI values collected in this area more variable and thus affecting the resulting task time estimates.



Five site survey grid locations **Nine site survey grid locations**

Figure 62: Five and nine site survey grid locations.

7. CONCLUSIONS AND OPPORTUNITIES FOR FUTURE WORK

The potential of utilizing a wireless sensor network (WSN) based indoor positioning system (IPS) to estimate individual task times was investigated in this research. To accomplish this objective, two different levels of the WSN design factors *number of tag nodes*, *LQI sample size*, *orientations at each grid location*, and *site survey grid locations* were used to define a total of 16 offline templates. Link quality indicator (LQI) data was collected during the offline data collection phase to transform each individual offline template into a radio fingerprinting map. Next, a total of 20 runs were conducted during the online data collection phase to mimic a manual assembly line with one operator working on each workstation for a period of time and then traveling to other workstations until the completion of the process. The LQI data collected during the online phase was matched against each individual offline template to estimate individual task times. Finally, an estimated task time error was calculated by comparing the individual task times estimated by the WSN-based IPS against observed task times recorded with a stopwatch.

The rest of this chapter is organized as follows. Section 7.1 presents the conclusions reached in this study and section 7.2 discusses the opportunities for future work.

7.1 Research Conclusions

The results obtained in this research show that a WSN-based IPS is a viable approach to estimating individual task times.

More specifically, the analysis of the experimental data showed that the WSN design factors *number of tag nodes* and *orientations at each grid location* need to be set carefully to ensure good quality in the estimation of individual task times. Most of the prior research done in this area considered only one tag node and no more than four orientations at each site survey location when defining a radio fingerprinting map. Therefore, demonstrating that by using two tag nodes and eight orientations reasonable results can be obtained when determining the location of the operator is considered one of the main contributions of this research. An attractive feature of the WSN design factors *number of tag nodes* and *orientations at each grid location* is that they are independent of the size of the work area where task times estimates need to be calculated. The same cannot be said about the WSN design factor *number of site survey grid locations*, since the results clearly showed that the quality of the task times estimated for workstation #2 was lower due to the interference caused by the proximity of the site survey grid location points of workstation #2 to the zones associated with workstations #1 and #3.

Finally, the pattern recognition technique used to determine the position of the operator within a work area is also important. In this research, the *k*-nearest neighbor algorithm was used and the results showed that the quality of the estimated task times was sensitive to the level of the *k* parameter. Instead, determining the appropriate level of the *k* parameter is a process that needs to be done carefully through system calibration and testing. If the *k*-nearest neighbor algorithm is used as the pattern recognition technique, the level of the *k* parameter recommended is about 15% of the total number of LQI sampling points to reduce the calculation time.

7.2 Opportunities for Future Work

Following are potential research opportunities that can extend the work performed in this study to gain a better understanding of how a WSN-based IPS can be used to estimate accurate individual task times:

- The location of beacon nodes at each workstation was fixed in the experiments conducted in this study. Therefore, varying the position of the beacon nodes within the working area to assess how signal propagation, antenna coverage and interference affect the quality of the estimated locations of the operator could be explored.
- All the Jennic JN5139 wireless microcontrollers utilized the same internal-type antenna. An interesting design change could be to equip the tag used by the operator with a directional antenna so that the LQI values are directed in the most appropriate orientation.
- In the online data collection phase, the operator wore only one tag node while collecting LQI values. The effect of using two tag nodes during

the online data collection phase on the accuracy of the estimated operator locations could be explored.

- The performance of different pattern recognition techniques could also be compared in terms of their ability to estimate operator locations and their computational times.
- An increased number of online runs could be executed to better understand (particularly from a statistical point of view) their impact on the performance of the WSN-based IPS.
- Finally, the possibility of validating the performance of a WSN-based IPS for task time estimation on a larger working area or in a real production line should be investigated.

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APPENDICES

Appendix A

Glossary of wireless network technologies terms

UMTS: Universal Mobile Telecommunications System

GPRS: General packet radio service

EDGE: Enhanced Data rates for GSM Evolution

CDMA: Code division multiple access

GSM: Global System for Mobile Communications

CDPD: Cellular Digital Packet Data

HSDPA: High-Speed Downlink Packet Access

WIMAX: Worldwide Interoperability for Microwave Access

Appendix B

Coordinator node source code

```
/****************************************************************************/
/*!
 *\MODULE              Coordinator
 *
 *\COMPONENT                $HeadURL: http://svn/apps/Application_Notes/JN-AN-1085-
Jenie-Tutorial/Tags/Release_1v3-Public/Step3_Coordinator/Source/Coordinator.c $
 *
 *\VERSION                       $Revision: 5394 $
 *
 *\REVISION            $Id: Coordinator.c 5394 2010-02-15 14:15:22Z mlook $
 *
 *\DATED               $Date: 2010-02-15 14:15:22 +0000 $
 *
 *\AUTHOR              $Author: mlook $
 *
 *\DESCRIPTION         Coordinator - implementation.
 */
/****************************************************************************
 *
 * Copyright Jennic Ltd 2010. All rights reserved
 *
 ****************************************************************************/

/****************************************************************************/
/***        Include files                                                 ***/
/****************************************************************************/
#include <jendefs.h> /* Standard Jennic type definitions */
#include <Jenie.h>      /* Jenie API definitions and interface */
#include <Printf.h>     /* Basic Printf to UART0-19200-8-NP-1 {v2} */
#include "App.h"        /* Application definitions and interface */

#include <AppHardwareApi.h>
#include <JPI.h>               /* Jenie Peripheral Interface {v2} */
#include <LedControl.h>        /* Led Interface {v2} */
#include <Button.h>            /* Button Interface {v3}  */
/****************************************************************************/
/***        Macro Definitions                                             ***/
/****************************************************************************/
#define BUTTON_P_MASK (BUTTON_3_MASK << 1)  /* Mask for program button {v3}
/****************************************************************************/
/***        Type Definitions                                              ***/
/****************************************************************************/

/****************************************************************************/
/***        Local Variables                                               ***/
/****************************************************************************/
PRIVATE bool_t    bNetworkUp;   /* Network up {v2} */
PRIVATE uint8   au8Led[2];                     /* Led states {v2} */
PRIVATE uint8    u8Tick;                               /* Ticker {v2} */
PRIVATE uint8    u8Button;                /* Button state {v3} */

PRIVATE uint64  u64Parent;                    /* Parent address {v3} */
PRIVATE uint64  u64Local;            /* Local address*/
PRIVATE uint64  u64Last;                           /*  Last  address  to  send  to  us
{v3} */

/** Routing table storage */
PRIVATE tsJenieRoutingTable asRoutingTable[ROUTING_TABLE_SIZE];
```

```
/****************************************************************************
 *
 * NAME: vJenie_CbConfigureNetwork
 *
 * DESCRIPTION:
 * Entry point for application from boot loader.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbConfigureNetwork(void)
{
       /* Set up routing table */
       gJenie_RoutingEnabled    = TRUE;
       gJenie_RoutingTableSize  = ROUTING_TABLE_SIZE;
       gJenie_RoutingTableSpace = (void *) asRoutingTable;

    /* Change default network config */
    gJenie_NetworkApplicationID = APPLICATION_ID;
    gJenie_PanID                = PAN_ID;
    gJenie_Channel              = CHANNEL;
    gJenie_ScanChannels         = SCAN_CHANNELS;

    /* Extra initiate variable for Coordinator*/
    gJenie_MaxFailedPkts       =  0;
    gJenie_MaxBcastTTL    = 0;
    gJenie_RouterPingPeriod   = Ping_Period ;

       /* Open UART for printf use {v2} */
       vUART_printInit();
       /* Output function call to UART */
       vPrintf("\n Initiation variables already initiated (Cbconfigure Nw)\n");
}

/****************************************************************************
 *
 * NAME: vJenie_CbInit
 *
 * DESCRIPTION:
 * Initialisation of system.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbInit(bool_t bWarmStart)
{
       teJenieStatusCode eStatus; /* Jenie status code */

       /* Warm start - reopen UART for printf use {v2} */
       if (bWarmStart) vUART_printInit();
       /* Output function call to UART */
       vPrintf("vJenie_CbInit(%d)\n", bWarmStart);

    /* Initialise application in APP.C*/
    vApp_CbInit(bWarmStart);

       /* Start Jenie */
    eStatus = eJenie_Start(E_JENIE_COORDINATOR);
       vPrintf("Coordinator start status : %d\n", eStatus);
}

/****************************************************************************
 *
 * NAME: vJenie_CbMain
```

```
 *
 * DESCRIPTION:
 * Main user routine. This is called by the Basic Operating System (BOS)
 * at regular intervals.
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbMain(void)
{
    /* Regular watchdog reset */
    #ifdef WATCHDOG_ENABLED
       vAHI_WatchdogRestart();
    #endif

        /* Network is down ? */
        if (! bNetworkUp)
        {
                /* Flash LED0 quickly while we wait for the network to come up */
                au8Led[0] = 0x02;
        }
        /* Network up and permit join is on {v3} ? */
        else if (bJenie_GetPermitJoin())
        {
                /* Flash LED0 quickish while we are allowing joining */
                au8Led[0] = 0x04;
        }
        /* Led has been left flashing ? */
        else if (au8Led[0] != 0 && au8Led[0] != 0xFF)
        {
                /* Turn off LED */
                au8Led[0] = 0x00;
        }
}

/****************************************************************************
 *
 * NAME: vJenie_CbStackMgmtEvent
 *
 * DESCRIPTION:
 * Used to receive stack management events
 *
 * PARAMETERS:      Name                     RW  Usage
 *                                   *psStackMgmtEvent             R       Pointer
to event structure
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbStackMgmtEvent(teEventType eEventType, void *pvEventPrim)
{
teJenieStatusCode eStatus; /* Jenie status code {v3} */

        /* Which event occurred ? */
    switch (eEventType)
    {
                /* Indicates stack is up and running */
                case E_JENIE_NETWORK_UP:
                {
                        /* Get pointer to correct primitive structure {v3} */
                        tsNwkStartUp *psNwkStartUp = (tsNwkStartUp *) pvEventPrim;
                        vPrintf("NETWORK Start-up info -> MAC No: %x:%x, Net level :
%d, Net ID: %x, Net channel: %d)\n",
                                (uint32)(psNwkStartUp->u64LocalAddress >> 32),
```

```
                                (uint32)(psNwkStartUp->u64LocalAddress&  0xFFFFFFFF),
                                psNwkStartUp->u16Depth,
                                psNwkStartUp->u16PanID,
                        psNwkStartUp->u8Channel);

                        /* Network is now up */
                        bNetworkUp = TRUE;
                        /* Note our parent address {v3} */
                        u64Parent = psNwkStartUp->u64ParentAddress;

                        /* Note our local address {v3} */
                        u64Local = psNwkStartUp->u64LocalAddress;

                        /* Turn on permit joining {v3} */
                        eStatus = eJenie_SetPermitJoin(TRUE);

                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);
                } break;
                /* Indicates stack has reset */
                case E_JENIE_STACK_RESET:
                {
                        /* Output to UART */
                        vPrintf(" The stack reset: vApp_CbStackMgmtEvent\n");

                        /* Network is now down */
                        bNetworkUp = FALSE;
                        /* Clear our parent address {v3} */
                        u64Parent = 0ULL;

                        /* Turn off permit joining {v3} */
                        eStatus = eJenie_SetPermitJoin(FALSE);

                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);
                }   break;

                /* Indicates child has joined {v3} */

                case E_JENIE_CHILD_JOINED:
                {
                        /* Get pointer to correct primitive structure */
                        tsChildJoined *psChildJoined = (tsChildJoined *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("Child  joined  info:  (vApp_CbStackMgmtEvent)  ->  MAC
No: %x:%x)\n",
                                (uint32)(psChildJoined->u64SrcAddress >> 32),
                                (uint32)(psChildJoined->u64SrcAddress&  0xFFFFFFFF));

                        /* Note our latest child */
                        u64Last = psChildJoined->u64SrcAddress;

                        /* Still turn on permit joining */
                        eStatus = eJenie_SetPermitJoin(TRUE);
                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);
                }   break;

                /* Indicates child has left {v3} */
                case E_JENIE_CHILD_LEAVE:
```

```
                {
                        /* Get pointer to correct primitive structure */
                        tsChildLeave *psChildLeave = (tsChildLeave *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("Child left info: (vApp_CbStackMgmtEvent) -> MAC No:
%x:%x)\n",
                                (uint32)(psChildLeave->u64SrcAddress >> 32),
                                (uint32)(psChildLeave->u64SrcAddress &  0xFFFFFFFF));

                        /* Was that the last device to send us something ? */
                        if (u64Last == psChildLeave->u64SrcAddress)
                        {
                                /* Clear the last address */
                                u64Last = 0ULL;
                        }

                        /* Turn on permit joining */
                        eStatus = eJenie_SetPermitJoin(TRUE);
                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);
                }   break;

                default:
                {

                }   break;
    }
}
/*****************************************************************************
 *
 * NAME: vJenie_CbStackDataEvent
 *
 * DESCRIPTION:
 * Used to receive stack data events
 *
 * PARAMETERS:      Name                    RW  Usage
 *                                  *psStackDataEvent            R       Pointer
to data structure
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbStackDataEvent(teEventType eEventType, void *pvEventPrim)
{
        /* Which event occurred ? */
    switch(eEventType)
    {
                /* Incoming data {v3} */
                case E_JENIE_DATA:
                {

                        /* Get pointer to correct primitive structure */
                        tsData *psData = (tsData *) pvEventPrim;

                        /* Output to UART */

                        if (psData->pau8Data[0] != 'B' &&
                 psData->pau8Data[1] != '0')

             {
                            vPrintf("Receive From,%x:%x,%d,%d\n",
                                (uint32)(psData->u64SrcAddress >> 32),
                                (uint32)(psData->u64SrcAddress &  0xFFFFFFFF),
                                 psData->u16Length,
```

```
                              psData->pau8Data[0]);

                 /* Toggle LED0 */
                 if      (au8Led[0] == 0)    au8Led[0] = 0xFF;
                 else if (au8Led[0] == 0xFF) au8Led[0] = 0;
             }
                }  break;


                /* Incoming data ack {v3} */

                case E_JENIE_DATA_ACK:
                {
                        /* Turn on LED0 */
                        au8Led[0] = 1;

                        /* Get pointer to correct primitive structure */
                        tsDataAck *psDataAck = (tsDataAck *) pvEventPrim;
                        vPrintf("Receive ACK data from: %x:%x\n",
                                (uint32)(psDataAck->u64SrcAddress >> 32),
                                (uint32)(psDataAck->u64SrcAddress &  0xFFFFFFFF));
                        /* Turn off LED0 */
                        au8Led[0] = 0;
                }   break;

                default:
                {
                        /* Unknown event type */
                }       break;
    }
}

/****************************************************************************
 *
 * NAME: vJenie_CbHwEvent
 *
 * DESCRIPTION:
 * Adds events to the hardware event queue.
 *
 * PARAMETERS:      Name            RW  Usage
 *                    u32Device        R    Peripheral responsible for interrupt e.g
DIO
 *                                      u32ItemBitmap  R     Source  of  interrupt  e.g.
DIO bit map
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbHwEvent(uint32 u32DeviceId,uint32 u32ItemBitmap)
{
    uint8              u8Led;               /* LED loop variable */
    uint8              u8ButtonRead;        /* New button reading {v3} */
    uint64                   u64Address;    /* Address to send data to {v3} */
    teJenieStatusCode eStatus;              /* Jenie status code {v3} */

    /* Is this the tick timer ? */
        if (u32DeviceId == E_JPI_DEVICE_TICK_TIMER)
    {
        /* Increment our ticker */
        u8Tick++;

                /* Is the network up {v3} ? */
                if (bNetworkUp)
                {
                        /* Read standard buttons */
```

```
                      u8ButtonRead = u8ButtonReadRfd();
/* If the SPI bus is in use - reuse the last value from the program button */
if      (bJPI_SpiPollBusy()) u8ButtonRead |= (u8Button & BUTTON_P_MASK);

/* SPI bus not in use and program button is pressed - set mask for program button
UNDOCUMENTED */
else if ((u8JPI_PowerStatus() & 0x10) == 0) u8ButtonRead |= BUTTON_P_MASK;

/* Have the buttons changed ? */
                      if (u8ButtonRead != u8Button)
                      {
                              /* Has the program button been released ? */
                              if ((u8ButtonRead & BUTTON_P_MASK) == 0 && (u8Button
& BUTTON_P_MASK) != 0)
                              {
                    /* Turn on or off  permit joining */
                    eStatus = eJenie_SetPermitJoin(! bJenie_GetPermitJoin());
                    vPrintf("    Permition    devices    to    join    the    network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);
                              }

                              /* Has button 0 been released ? */

                      if  ((u8ButtonRead  &  BUTTON_0_MASK)  ==  0  &&  (u8Button  &
BUTTON_0_MASK) != 0)
                              {
                                      /* No errors ? */
                                      if (E_JENIE_DEFERRED == eStatus)
                                      {
                                              /* Light LED0 */
                    if      (au8Led[0] == 0)    au8Led[0] = 0xFF;
                    else if (au8Led[0] == 0xFF) au8Led[0] = 0;
                                      }
                              }

                              /* Note the current button reading */
                              u8Button = u8ButtonRead;
                      }
              }

        /* Loop through LEDs */
        for (u8Led = 0; u8Led < 2; u8Led++)
        {
            /* Set LED according to status */
            if  (au8Led[u8Led]  ==  0  ||  au8Led[u8Led]  ==  0xFF)  vLedControl(u8Led,
au8Led[u8Led]);
            else
                vLedControl(u8Led, au8Led[u8Led] & u8Tick);
        }
      }
    }
/****************************************************************************/
/***        END OF FILE                                                   ***/
/****************************************************************************/
```

Appendix C

Beacon node source code

```
/****************************************************************************/
/*!
 *\MODULE              Beacon
 *
 *\COMPONENT           $HeadURL: http://svn/apps/Application_Notes/JN-AN-1085-
Jenie-Tutorial/Tags/Release_1v3-Public/Step3_Router/Source/Router.c $
 *
 *\VERSION                      $Revision: 5394 $
 *
 *
 *\DATED               $Date: 2010-08-05 19:08:00
 *
 *\AUTHOR              $Author: Tan
 *
 *\DESCRIPTION         Beacon

 *\ Pup New Modification 7/16/2010
 */
/****************************************************************************
 *
 * Copyright Jennic Ltd 2010. All rights reserved
 *
 ****************************************************************************/

/****************************************************************************/
/***        Include files                                                 ***/
/****************************************************************************/
#include <jendefs.h> /* Standard Jennic type definitions */
#include <Jenie.h>      /* Jenie API definitions and interface */
#include <Printf.h>     /* Basic Printf to UART0-19200-8-NP-1 {v2} */
#include "App.h"        /* Application definitions and interface */

#include <AppHardwareApi.h>
#include <JPI.h>               /* Jenie Peripheral Interface {v2} */
#include <LedControl.h>        /* Led Interface {v2} */
#include <Button.h>            /* Button Interface {v3} */


/****************************************************************************/
/***        Macro Definitions                                             ***/
/****************************************************************************/
#define BUTTON_P_MASK (BUTTON_3_MASK << 1)  /* Mask for program button {v3} */
/****************************************************************************/
/***        Type Definitions                                              ***/
/****************************************************************************/

/****************************************************************************/
/***        Local Variables                                               ***/
/****************************************************************************/
PRIVATE bool_t    bNetworkUp;                                            /*
Network up {v2} */
PRIVATE uint8   au8Led[2];
/* Led states {v2} */
PRIVATE uint8    u8Tick;
/* Ticker {v2} */
PRIVATE uint8    u8Button;                                                 /*
Button state {v3} */
PRIVATE uint64  u64Parent;                                               /*
Parent address {v3} */
```

```
PRIVATE uint64  u64Local;                          /* Local address*/
PRIVATE uint64  u64Last;                            /* Last address to send to us
{v3} */

/*PRIVATE uint8 Data_couter;
PRIVATE uint8 Data_couter2;*/


/** Routing table storage */
PRIVATE tsJenieRoutingTable asRoutingTable[ROUTING_TABLE_SIZE];

/****************************************************************************
 *
 * NAME: vJenie_CbConfigureNetwork
 *
 * DESCRIPTION:
 * Entry point for application from boot loader.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbConfigureNetwork(void)
{
       /* Set up routing table */
       gJenie_RoutingEnabled    = TRUE;
       gJenie_RoutingTableSize  = ROUTING_TABLE_SIZE;
       gJenie_RoutingTableSpace = (void *) asRoutingTable;

    /* Change default network config */
    gJenie_NetworkApplicationID = APPLICATION_ID;
    /*gJenie_PanID                = PAN_ID;*/
    /*gJenie_Channel              = CHANNEL;*/  /*This two valiables are only for
Coordinator device */
    gJenie_ScanChannels         = SCAN_CHANNELS;

    /* Extra valiables setup for coordinator, router or enddevice*/
    gJenie_MaxFailedPkts       =  0;
    gJenie_MaxBcastTTL       = 0;
    gJenie_RouterPingPeriod  = Ping_Period ;

       /* Open UART for printf use */
       vUART_printInit();
       /* Output function call to UART */
       vPrintf("\n Initiation variables already initiated (Cbconfigure Nw)\n");
}

/****************************************************************************
 *
 * NAME: vJenie_CbInit
 *
 * DESCRIPTION:
 * Initialisation of system.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbInit(bool_t bWarmStart)
{
       teJenieStatusCode eStatus; /* Jenie status code */

       /* Warm start - reopen UART for printf use */
       if (bWarmStart) vUART_printInit();
       /* Output function call to UART */
       vPrintf("vJenie_CbInit(%d)\n", bWarmStart);
```

```
    /* Initialise application */
    vApp_CbInit(bWarmStart);

        /* Start Jenie */
    eStatus = eJenie_Start(E_JENIE_ROUTER);
        /* Output function call to UART */
        vPrintf("Router start status : %d\n", eStatus);
}

/****************************************************************************
 *
 * NAME: vJenie_CbMain
 *
 * DESCRIPTION:
 * Main user routine. This is called by the Basic Operating System (BOS)
 * at regular intervals.
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/

PUBLIC void vJenie_CbMain(void)
{
    /* Regular watchdog reset */
    #ifdef WATCHDOG_ENABLED
       vAHI_WatchdogRestart();
    #endif

    /* Data_couter = 0; */
    /* inisitial Data_couter*/
        /* Network is down ? */
        if (! bNetworkUp)
        {
                /* Flash LED0 quickly while we wait for the network to come up */
                au8Led[0] = 0x02;
        }
        /* Network up and permit join is on {v3} ? */
        else if (bJenie_GetPermitJoin())
        {
                /* Flash LED0 quickish while we are allowing joining */
                au8Led[0] = 0x04;
        }
        /* Led has been left flashing ? */
        else if (au8Led[0] != 0 && au8Led[0] != 0xFF)
        {
                /* Turn off LED */
                au8Led[0] = 0x00;
        }
}
/****************************************************************************
 *
 * NAME: vJenie_CbStackMgmtEvent
 *
 * DESCRIPTION:
 * Used to receive stack management events
 *
 * PARAMETERS:      Name                     RW  Usage
 *                              *psStackMgmtEvent           R       Pointer
to event structure
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/
```

```
PUBLIC void vJenie_CbStackMgmtEvent(teEventType eEventType, void *pvEventPrim)
{
teJenieStatusCode eStatus; /* Jenie status code {v3} */

       /* Which event occurred ? */
    switch (eEventType)
    {
               /* Indicates stack is up and running */
               case E_JENIE_NETWORK_UP:
               {
                      /* Get pointer to correct primitive structure {v3} */
                      tsNwkStartUp *psNwkStartUp = (tsNwkStartUp *) pvEventPrim;

                      /* Output to UART */
                      vPrintf("NETWORK Start-up info -> Root MAC No: %x:%x, Self
MAC No: %x:%x, Depth:  %d, Pan ID: %x, Ch: %d)\n",
                             (uint32)(psNwkStartUp->u64ParentAddress >> 32),
                             (uint32)(psNwkStartUp->u64ParentAddress &
0xFFFFFFFF),
                             (uint32)(psNwkStartUp->u64LocalAddress  >> 32),
                             (uint32)(psNwkStartUp->u64LocalAddress  &
0xFFFFFFFF),
                             psNwkStartUp->u16Depth,
                             psNwkStartUp->u16PanID,
                      psNwkStartUp->u8Channel);

                      /* Network is now up */
                      bNetworkUp = TRUE;
                      /* Note our parent address {v3} */
                      u64Parent = psNwkStartUp->u64ParentAddress;

                      /* Note our local address {v3} */
                      u64Local    = psNwkStartUp->u64LocalAddress;

                      /* Turn on permit joining {v3} */
                      eStatus = eJenie_SetPermitJoin(FALSE);

                      /* Output to UART */
                      vPrintf(" Permition devices to join the network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                   vPrintf(" Status report (eStatus: %d )\n",eStatus);

               }   break;

               /* Indicates stack has reset */
               case E_JENIE_STACK_RESET:
               {
                      /* Output to UART */
                      vPrintf("vApp_CbStackMgmtEvent(STACK_RESET)\n");

                      /* Network is now down */
                      bNetworkUp = FALSE;
                      /* Clear our parent address {v3} */
                      u64Parent = 0ULL;

                      /* Turn off permit joining {v3} */
                      eStatus = eJenie_SetPermitJoin(FALSE);

            /* Output to UART */
                      vPrintf(" Permition devices to join the network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                   vPrintf(" Status report (eStatus: %d )\n",eStatus);

               }   break;

               /* Indicates child has joined {v3} */
```

```
                case E_JENIE_CHILD_JOINED:
                {
                        /* Get pointer to correct primitive structure */
                        tsChildJoined *psChildJoined = (tsChildJoined *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("vApp_CbStackMgmtEvent(CHILD_JOINED, %x:%x)\n",
                                (uint32)(psChildJoined->u64SrcAddress >> 32),
                                (uint32)(psChildJoined->u64SrcAddress &
0xFFFFFFFF));

                        /* Note our latest child */
                        u64Last = psChildJoined->u64SrcAddress;

                        /* Turn off permit joining */
                        eStatus = eJenie_SetPermitJoin(FALSE);

                        /* Output to UART */
                        vPrintf(" Permition devices to join the network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                /* Indicates child has left {v3} */
                case E_JENIE_CHILD_LEAVE:
                {
                        /* Get pointer to correct primitive structure */
                        tsChildLeave *psChildLeave = (tsChildLeave *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("vApp_CbStackMgmtEvent(CHILD_LEAVE, %x:%x)\n",
                                (uint32)(psChildLeave->u64SrcAddress >> 32),
                                (uint32)(psChildLeave->u64SrcAddress &  0xFFFFFFFF));

                        /* Was that the last device to send us something ? */
                        if (u64Last == psChildLeave->u64SrcAddress)
                        {
                                /* Clear the last address */
                                u64Last = 0ULL;
                        }

                        /* Turn on permit joining */
                        eStatus = eJenie_SetPermitJoin(TRUE);

                        /* Output to UART */
                        vPrintf(" Permition devices to join the network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                default:
                {
                        /* Unknown event type */
                }   break;
    }
}

/****************************************************************************
 *
 * NAME: vJenie_CbStackDataEvent
 *
 * DESCRIPTION:
 * Used to receive stack data events
 *
 * PARAMETERS:      Name                     RW  Usage
```

```
 *                                  *psStackDataEvent             R       Pointer
to data structure
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbStackDataEvent(teEventType eEventType, void *pvEventPrim)
{
uint8 au8Data[3];
uint8 Lqitest; /* Store LQI value*/
uint64 u64Address;            /* Address to send data to {v3} */
teJenieStatusCode eStatus;            /* Jenie status code {v3} */


/* Which event occurred ? */
      switch(eEventType)
    {
               /* Incoming data {v3} */
               case E_JENIE_DATA:
               {
                      /* Get pointer to correct primitive structure */
                      tsData *psData = (tsData *) pvEventPrim;

            if (psData->pau8Data[0] == 'B' && /*Check received data info*/
                             psData->pau8Data[1] == '0')

                             {

                                 /*vDelay(500); /* Add delay function to delay
package replete to the coordinator*/

                    Lqitest = u8Api_GetLastPktLqi(); /* Get LQI value from last
received package*/

                    /* Initialise data for transmission */
                                    au8Data[0] = Lqitest;

                                 /*Indentify address for sending data*/
                                  u64Address = u64Parent;

                    /* Try to send data */
                                    eStatus = eJenie_SendData(u64Address, au8Data,
1 , TXOPTION_SILENT);

                                    /*vPrintf("u64Address : '%s')\n",
u64Address);*/
                                    /*vPrintf("LQI Last Pkg: %d, %d, %d)\n",
Lqitest, Data_couter, Data_couter2);
                    /*vPrintf("Data_counter: %d)\n", Data_couter);*/

                    /* Toggle LED0 */
                    if      (au8Led[0] == 0)    au8Led[0] = 0xFF;
                    else if (au8Led[0] == 0xFF) au8Led[0] = 0;

                             }

                      }
                       break;

               /* Incoming data ack {v3} */

               case E_JENIE_DATA_ACK:
               {
               /* Turn on LED0 */
                      au8Led[0] = 1;
```

```
                /* Get pointer to correct primitive structure */
                tsDataAck *psDataAck = (tsDataAck *) pvEventPrim;
         vPrintf("Receive ACK data from: %x:%x\n",
                        (uint32)(psDataAck->u64SrcAddress &  0xFFFFFFFF));

                /* Turn off LED0 */
                au8Led[0] = 0;
            }   break;

            default:
            {
                /* Unknown event type */
            }       break;
    }
}

/****************************************************************************
 *
 * NAME: vJenie_CbHwEvent
 *
 * DESCRIPTION:
 * Adds events to the hardware event queue.
 *
 * PARAMETERS:      Name            RW  Usage
 *                  u32Device       R   Peripheral responsible for interrupt e.g
DIO
 *                                   u32ItemBitmap  R   Source of interrupt e.g.
DIO bit map
 *
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbHwEvent(uint32 u32DeviceId,uint32 u32ItemBitmap)
{
    uint8              u8Led;              /* LED loop variable */
    uint8              u8ButtonRead;       /* New button reading {v3} */
       uint64                u64Address;            /* Address to send data to {v3}
*/
       teJenieStatusCode eStatus;          /* Jenie status code {v3} */

    /* Is this the tick timer ? */
       if (u32DeviceId == E_JPI_DEVICE_TICK_TIMER)
    {
        /* Increment our ticker */
        u8Tick++;

            /* Is the network up {v3} ? */
            if (bNetworkUp)
            {
                /* Read standard buttons */
                u8ButtonRead = u8ButtonReadRfd();
                /* If the SPI bus is in use - reuse the last value from the
program button */
                if      (bJPI_SpiPollBusy())                u8ButtonRead |=
(u8Button & BUTTON_P_MASK);
                /* SPI bus not in use and program button is pressed - set
mask for program button UNDOCUMENTED */
                else if ((u8JPI_PowerStatus() & 0x10) == 0) u8ButtonRead |=
BUTTON_P_MASK;
                /* Have the buttons changed ? */
                if (u8ButtonRead != u8Button)
                {
                    /* Has the program button been released ? */
                    if ((u8ButtonRead & BUTTON_P_MASK) == 0 && (u8Button
& BUTTON_P_MASK) != 0)
```

```
                              {
                                     /* Toggle permit join setting */
                                     eStatus = eJenie_SetPermitJoin(!
bJenie_GetPermitJoin());
                                     /* Output to UART */
                                     vPrintf("eJenie_SetPermitJoin(%d) = %d\n",
                                            bJenie_GetPermitJoin(),
                                            eStatus);
                              }

                              /* Has button 0 been released ? */
                              if ((u8ButtonRead & BUTTON_0_MASK) == 0 && (u8Button
& BUTTON_0_MASK) != 0)
                              {
               /* Clear counter for Offline Data*/
               /* Data_couter = 0;
                                 Data_couter2 =0;
                vPrintf("Data Couter clear/n");*

                    /* Initialise data for transmission */
                                     uint8 au8Data[3] = "B1";

                    /*Indentify address for sending data*/
                                   u64Address = u64Parent;

                    /* Try to send data */
                                     eStatus = eJenie_SendData(u64Address, au8Data,
1 , TXOPTION_SILENT);

/*vPrintf("LQI Last Pkg: %d, %d, %d)\n", Lqitest, Data_couter, Data_couter2);
                    /*vPrintf("Data_counter: %d)\n", Data_couter);*/

                    /* No errors ? */
                                     if (E_JENIE_DEFERRED == eStatus)
                                     {
                                            /* Light LED0 */
                    if       (au8Led[0] == 0)    au8Led[0] = 0xFF;
                    else if (au8Led[0] == 0xFF) au8Led[0] = 0;
                                     }
                              }

                              /* Note the current button reading */
                              u8Button = u8ButtonRead;
                       }
               }

        /* Loop through LEDs */
        for (u8Led = 0; u8Led < 2; u8Led++)
        {
            /* Set LED according to status */
            if (au8Led[u8Led] == 0 || au8Led[u8Led] == 0xFF) vLedControl(u8Led,
au8Led[u8Led]);
            else
                vLedControl(u8Led, au8Led[u8Led] & u8Tick);
        }
    }
}

/****************************************************************************/
/***        END OF FILE                                                   ***/
/****************************************************************************/
```

Appendix D

Tag node source code

```
/****************************************************************************/
/*!
 *\MODULE              Tag node
 *
 *\COMPONENT           $HeadURL: http://svn/apps/Application_Notes/JN-AN-1085-Jenie-
Tutorial/Tags/Release_1v3-Public/Step3_Router/Source/Router.c $
 *
 *\VERSION             $Revision: 5394 $
 *
 *
 *\DATED               $Date: 2010-03-25 10:11:12 +0000) $
 *
 *\AUTHOR              $Author: mlook $
 *
 *\DESCRIPTION         Tag node

 *\ Pup New Modification 7/15/2010
 */
/****************************************************************************
 *
 * Copyright Jennic Ltd 2010. All rights reserved
 *
 ****************************************************************************/

/****************************************************************************/
/***        Include files                                                 ***/
/****************************************************************************/
#include <jendefs.h> /* Standard Jennic type definitions */
#include <Jenie.h>      /* Jenie API definitions and interface */
#include <Printf.h>     /* Basic Printf to UART0-19200-8-NP-1 {v2} */
#include "App.h"        /* Application definitions and interface */
#include <AppHardwareApi.h>
#include <JPI.h>                /* Jenie Peripheral Interface {v2} */
#include <LedControl.h>         /* Led Interface {v2} */
#include <Button.h>             /* Button Interface {v3} */


/****************************************************************************/
/***        Macro Definitions                                             ***/
/****************************************************************************/
#define BUTTON_P_MASK (BUTTON_3_MASK << 1)  /* Mask for program button {v3} */
/****************************************************************************/
/***        Type Definitions                                              ***/
/****************************************************************************/

/****************************************************************************/
/***        Local Variables                                               ***/
/****************************************************************************/
PRIVATE bool_t    bNetworkUp;                                             /*
Network up {v2} */
PRIVATE uint8   au8Led[2];
/* Led states {v2} */
PRIVATE uint8    u8Tick;
/* Ticker {v2} */
PRIVATE uint8    u8Button;                                                  /*
Button state {v3} */
PRIVATE uint64  u64Parent;                                                /*
Parent address {v3} */
PRIVATE uint64  u64Local;                        /* Local address*/
```

```
PRIVATE uint64  u64Last;                              /* Last address to send
/** Routing table storage */
PRIVATE tsJenieRoutingTable asRoutingTable[ROUTING_TABLE_SIZE];

/****************************************************************************
 *
 * NAME: vJenie_CbConfigureNetwork
 *
 * DESCRIPTION:
 * Entry point for application from boot loader.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbConfigureNetwork(void)
{
       /* Set up routing table */
       gJenie_RoutingEnabled    = TRUE;
       gJenie_RoutingTableSize  = ROUTING_TABLE_SIZE;
       gJenie_RoutingTableSpace = (void *) asRoutingTable;

    /* Change default network config */
    gJenie_NetworkApplicationID = APPLICATION_ID;
    gJenie_ScanChannels         = SCAN_CHANNELS;

    /* Extra valiables setup for coordinator, router or enddevice*/
    gJenie_MaxFailedPkts       =  0;
    gJenie_MaxBcastTTL       = 0;
    gJenie_RouterPingPeriod  = Ping_Period ;

       /* Open UART for printf use */
       vUART_printInit();
       /* Output function call to UART */
       vPrintf("\n Initiation variables already initiated (Cbconfigure Nw)\n");
}

/****************************************************************************
 *
 * NAME: vJenie_CbInit
 *
 * DESCRIPTION:
 * Initialisation of system.
 *
 * RETURNS:
 * Nothing
 *
 ****************************************************************************/
PUBLIC void vJenie_CbInit(bool_t bWarmStart)
{
       teJenieStatusCode eStatus; /* Jenie status code */

       /* Warm start - reopen UART for printf use */
       if (bWarmStart) vUART_printInit();
       /* Output function call to UART */
       vPrintf("vJenie_CbInit(%d)\n", bWarmStart);

    /* Initialise application */
    vApp_CbInit(bWarmStart);

       /* Start Jenie */
    eStatus = eJenie_Start(E_JENIE_ROUTER);
       /* Output function call to UART */
       vPrintf("Router start status : %d\n", eStatus);
}
```

```
/************************************************************************
 *
 * NAME: vJenie_CbMain
 *
 * DESCRIPTION:
 * Main user routine. This is called by the Basic Operating System (BOS)
 * at regular intervals.
 *
 * RETURNS:
 * void
 *
 ************************************************************************/

PUBLIC void vJenie_CbMain(void)
{
    /* Regular watchdog reset */
    #ifdef WATCHDOG_ENABLED
       vAHI_WatchdogRestart();
    #endif

    /* Data_couter = 0; */
    /* inisitial Data_couter*/
       /* Network is down ? */
       if (! bNetworkUp)
       {
              au8Led[0] = 0x02;
       }
       /* Network up and permit join is on {v3} ? */
       else if (bJenie_GetPermitJoin())
       {
              /* Flash LED0 quickish while we are allowing joining */
              au8Led[0] = 0x04;
       }
       /* Led has been left flashing ? */
       else if (au8Led[0] != 0 && au8Led[0] != 0xFF)
       {
              /* Turn off LED */
              au8Led[0] = 0x00;
       }
}
/************************************************************************
 *
 * NAME: vJenie_CbStackMgmtEvent
 *
 * DESCRIPTION:
 * Used to receive stack management events
 *
 * PARAMETERS:      Name                    RW  Usage
 *                                *psStackMgmtEvent             R      Pointer
to event structure
 *
 * RETURNS:
 * void
 *
 ************************************************************************/
PUBLIC void vJenie_CbStackMgmtEvent(teEventType eEventType, void *pvEventPrim)
{
teJenieStatusCode eStatus; /* Jenie status code {v3} */

       /* Which event occurred ? */
    switch (eEventType)
    {
              /* Indicates stack is up and running */
              case E_JENIE_NETWORK_UP:
              {
                     /* Get pointer to correct primitive structure {v3} */
```

```
                        tsNwkStartUp *psNwkStartUp = (tsNwkStartUp *) pvEventPrim;

                        /* Output to UART */
                        vPrintf("NETWORK Start-up info -> Root MAC No: %x:%x, Self
MAC No: %x:%x, Depth:  %d, Pan ID: %x, Ch: %d)\n",
                                (uint32)(psNwkStartUp->u64ParentAddress >> 32),
                                (uint32)(psNwkStartUp->u64ParentAddress&  0xFFFFFFFF),
                                (uint32)(psNwkStartUp->u64LocalAddress  >> 32),
                                (uint32)(psNwkStartUp->u64LocalAddress&  0xFFFFFFFF),
                                psNwkStartUp->u16Depth,
                                psNwkStartUp->u16PanID,
                        psNwkStartUp->u8Channel);

                        /* Network is now up */
                        bNetworkUp = TRUE;
                        /* Note our parent address {v3} */
                        u64Parent = psNwkStartUp->u64ParentAddress;

                        /* Note our local address {v3} */
                        u64Local    = psNwkStartUp->u64LocalAddress;

                        /* Turn on permit joining {v3} */
                        eStatus = eJenie_SetPermitJoin(FALSE);

                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                /* Indicates stack has reset */
                case E_JENIE_STACK_RESET:
                {
                        /* Output to UART */
                        vPrintf("vApp_CbStackMgmtEvent(STACK_RESET)\n");

                        /* Network is now down */
                        bNetworkUp = FALSE;
                        /* Clear our parent address {v3} */
                        u64Parent = 0ULL;

                        /* Turn off permit joining {v3} */
                        eStatus = eJenie_SetPermitJoin(FALSE);

            /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                /* Indicates child has joined {v3} */
                case E_JENIE_CHILD_JOINED:
                {
                        /* Get pointer to correct primitive structure */
                        tsChildJoined *psChildJoined = (tsChildJoined *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("vApp_CbStackMgmtEvent(CHILD_JOINED, %x:%x)\n",
                                (uint32)(psChildJoined->u64SrcAddress >> 32),
                                (uint32)(psChildJoined->u64SrcAddress&  0xFFFFFFFF));

                        /* Note our latest child */
                        u64Last = psChildJoined->u64SrcAddress;

                        /* Turn off permit joining */
```

```
                        eStatus = eJenie_SetPermitJoin(FALSE);

                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                /* Indicates child has left {v3} */
                case E_JENIE_CHILD_LEAVE:
                {
                        /* Get pointer to correct primitive structure */
                        tsChildLeave *psChildLeave = (tsChildLeave *) pvEventPrim;
                        /* Output to UART */
                        vPrintf("vApp_CbStackMgmtEvent(CHILD_LEAVE, %x:%x)\n",
                                (uint32)(psChildLeave->u64SrcAddress >> 32),
                                (uint32)(psChildLeave->u64SrcAddress &  0xFFFFFFFF));

                        /* Was that the last device to send us something ? */
                        if (u64Last == psChildLeave->u64SrcAddress)
                        {
                                /* Clear the last address */
                                u64Last = 0ULL;
                        }

                        /* Turn on permit joining */
                        eStatus = eJenie_SetPermitJoin(TRUE);

                        /* Output to UART */
                        vPrintf("   Permition   devices   to   join   the   network
(eJenie_SetPermitJoin: %d )\n",bJenie_GetPermitJoin());
                    vPrintf(" Status report (eStatus: %d )\n",eStatus);

                }   break;

                default:
                {
                        /* Unknown event type */
                }   break;
    }
}

/****************************************************************************
 *
 * NAME: vJenie_CbStackDataEvent
 *
 * DESCRIPTION:
 * Used to receive stack data events
 *
 * PARAMETERS:      Name                     RW  Usage
 *                        *psStackDataEvent             R      Pointer  to  data
structure
 * RETURNS:
 * void
 *
 ****************************************************************************/
PUBLIC void vJenie_CbStackDataEvent(teEventType eEventType, void *pvEventPrim)
{
/*uint8 Lqitest; /* Store LQI value*/
uint64 u64Address;            /* Address to send data to {v3} */
teJenieStatusCode eStatus;            /* Jenie status code {v3} */
/* Which event occurred ? */
      switch(eEventType)

 {
```

```
               /* Incoming data {v3} */
               case E_JENIE_DATA:
               {
                       /* Get pointer to correct primitive structure */
                       tsData *psData = (tsData *) pvEventPrim;
                       }

                        break;

               /* Incoming data ack {v3} */

               case E_JENIE_DATA_ACK:
               {
               /* Turn on LED0 */
                       au8Led[0] = 1;

                       /* Get pointer to correct primitive structure */
                       tsDataAck *psDataAck = (tsDataAck *) pvEventPrim;
                vPrintf("Receive ACK data from: %x:%x\n",
                               (uint32)(psDataAck->u64SrcAddress &  0xFFFFFFFF));

                       /* Turn off LED0 */
                       au8Led[0] = 0;
               }   break;

               default:
               {
                       /* Unknown event type */
               }       break;
    }
}

/****************************************************************************
 *
 * NAME: vJenie_CbHwEvent
 *
 * DESCRIPTION:
 * Adds events to the hardware event queue.
 *
 * PARAMETERS:      Name            RW  Usage
 *                  u32Device       R   Peripheral responsible for interrupt e.g
 *
 ****************************************************************************/
PUBLIC void vJenie_CbHwEvent(uint32 u32DeviceId,uint32 u32ItemBitmap)
{
    uint8              u8Led;                /* LED loop variable */
    uint8              u8ButtonRead;         /* New button reading {v3} */
       uint64                u64Address;           /* Address to send data to {v3}
*/
       teJenieStatusCode eStatus;            /* Jenie status code {v3} */

    /* Is this the tick timer ? */
       if (u32DeviceId == E_JPI_DEVICE_TICK_TIMER)
    {
        /* Increment our ticker */
        u8Tick++;

               /* Is the network up {v3} ? */
               if (bNetworkUp)
               {
                       /* Read standard buttons */
                       u8ButtonRead = u8ButtonReadRfd();
                       /* If the SPI bus is in use - reuse the last value from the
program button*
               if(bJPI_SpiPollBusy())u8ButtonRead|=(u8Button & BUTTON_P_MASK);
                       /* SPI bus not in use and program button is pressed - set
```

```
mask for program button UNDOCUMENTED */
               else if((u8JPI_PowerStatus()&0x10)==0) u8ButtonRead |= BUTTON_P_MASK
                       /* Have the buttons changed ? */
                       if (u8ButtonRead != u8Button)
                       {
                               /* Has the program button been released ? */
                               if ((u8ButtonRead & BUTTON_P_MASK) == 0 && (u8Button
& BUTTON_P_MASK) != 0)
                               {
                       /* Toggle permit join setting */
                       eStatus = eJenie_SetPermitJoin(! bJenie_GetPermitJoin());
                                       /* Output to UART */
                                       vPrintf("eJenie_SetPermitJoin(%d) = %d\n",
                                               bJenie_GetPermitJoin(),
                                               eStatus);
                               }

                               /* Has button 0 been released ? */
            if ((u8ButtonRead & BUTTON_0_MASK) == 0 && (u8Button & BUTTON_0_MASK)
!= 0)
                       {
               /* Clear counter for Offline Data*/
                for(;;) /* Infinite loop*/
                {
                    vDelay(500); /* Delay function waitting for other nodes to
operate

                    /* Initialise data for transmission */
                                     uint8 au8Data[3] = "B0";

                    /*Indentify address for sending data*/
                                   u64Address = u64Parent;

                    /* Try to send data as a boardcast package */
                                     eStatus = eJenie_SendData(0, au8Data, 3,
TXOPTION_BDCAST);
                                     if (E_JENIE_DEFERRED == eStatus)
                                     {
                                             /* Light LED0 */
                    if      (au8Led[0] == 0)    au8Led[0] = 0xFF;
                    else if (au8Led[0] == 0xFF) au8Led[0] = 0;
                                     }

                               }
                       }

                               /* Note the current button reading */
                               u8Button = u8ButtonRead;
                       }
               }

        /* Loop through LEDs */
        for (u8Led = 0; u8Led < 2; u8Led++)
        {
            /* Set LED according to status */
            if (au8Led[u8Led] == 0 || au8Led[u8Led] == 0xFF) vLedControl(u8Led,
au8Led[u8Led]);
            else
                vLedControl(u8Led, au8Led[u8Led] & u8Tick);
        }
    }
}

/****************************************************************************/
/***        END OF FILE                                                   ***/
/****************************************************************************/
```

Appendix E

Offline data sheet form

Date ____________________ Time ____________________ Comment ____________________

Experiment #1

Treatment Combinations: − + + +

Run No.	Number of Mobile or Tag Nodes	Sampling size	Orientations of mobile nodes	Number of mapped positions
1	1	6000	8	9

Experimental Procedure

Check list

- ☐ Record Date and Time
- ☐ Check all factors (Treatment combinations)
  - o # of mobile node
  - o Sampling size ________
  - o Orientation of mobile nodes ________
  - o # of Mapped position (Check figure)
- ☐ Workstation Size
  - o 180" Long
  - o 100" Wide
- ☐ Location of Beacon nodes (Same)
- ☐ VDO camera
- ☐ New batteries installation
  - ☐ Beacon node 1
  - ☐ Beacon node 2
  - ☐ Beacon node 3
  - ☐ Mobile node 1
  - ☐ Mobile node 2
  - ☐ Coordinator Node
- ☐ **Mapped location order**
  - ☐**1** ☐**2** ☐**3** ☐**4** ☐ **5** ☐**6** ☐**7** ☐**8**

Procedures

- ☐ **Start all Beacon nodes**
- ☐ **Start mobile nodes**
  - ☐ **1** ☐ **2**
- ☐ **Connect serial port between co-node to computer**
  - o **Port Speed 115,200 bps**
- ☐ **Start Coordinator node**
- ☐ **Start computer coordinator program**
- ☐ **Start data collection program**
- ☐ ***Save data file***

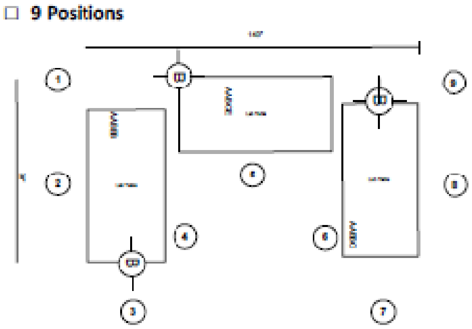
☐ **Repeat on every orientation**

☐ **0°** ☐ **45°** ☐ **90°** ☐ **135°** ☐ **180°**
☐ **225°** ☐ **270°** ☐ **315°** ☐ **360°**

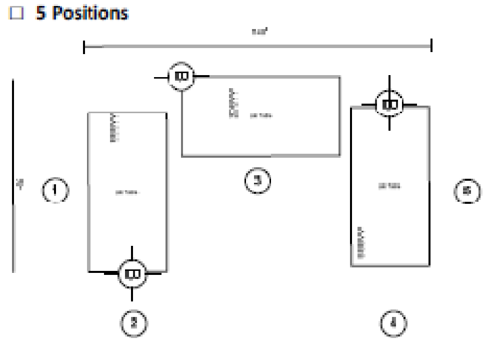
☐ **Repeat on every mapped position**

☐**1** ☐**2** ☐**3** ☐**4** ☐ **5** ☐**6** ☐**7** ☐**8**

☐ **9 Positions**



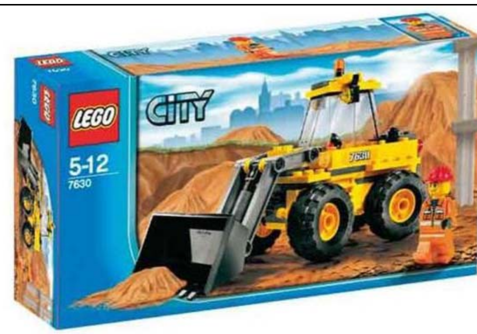
☐ **5 Positions**



Comments: ____

Appendix F

Lego descriptions at each workstation

Lego description	Picture
Lego at workstation 1 **Lego part number: LE3178**	
Lego at workstation 2 **Lego part number: LE8402**	
Lego at workstation 3 **Lego part number: LE7630**	

Appendix G

Observed individual task times of each workstation during the online runs

Online run	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Overall time (sec)	Overall time (min)
1	480	255	615	1350	22:30:00
2	420	245	475	1140	19:00:00
3	509	304	788	1601	26:41:00
4	422	241	519	1182	19:42:00
5	390	191	531	1112	18:32:00
6	466	252	519	1237	20:37:00
7	374	160	472	1006	16:46:00
8	408	241	502	1151	19:11:00
9	355	206	473	1034	17:14:00
10	320	258	462	1040	17:20:00
11	310	261	526	1097	18:17:00
12	353	244	559	1156	19:16:00
13	453	227	495	1175	19:35:00
14	339	210	559	1108	18:28:00
15	371	248	574	1193	19:53:00
16	342	220	517	1079	17:59:00
17	356	224	485	1065	17:45:00
18	319	205	531	1055	17:35:00
19	330	249	582	1161	19:21:00
20	356	216	497	1069	17:49:00

Appendix H

Examples of a text file result generated by the data management program

```
Timimg at: 0:00:05 Location: 1 at orentation 45 degree
Timimg at: 0:00:10 Location: 8 at orentation 90 degree
Timimg at: 0:00:15 Location: 8 at orentation 90 degree
Timimg at: 0:00:20 Location: 8 at orentation 90 degree
Timimg at: 0:00:25 Location: 7 at orentation 270 degree
Timimg at: 0:00:30 Location: 1 at orentation 45 degree
Timimg at: 0:00:35 Location: 1 at orentation 0 degree
Timimg at: 0:00:40 Location: 6 at orentation 225 degree
Timimg at: 0:00:45 Location: 6 at orentation 225 degree
Timimg at: 0:00:50 Location: 1 at orentation 0 degree
Timimg at: 0:00:55 Location: 8 at orentation 90 degree
Timimg at: 0:01:00 Location: 6 at orentation 225 degree
Timimg at: 0:01:05 Location: 8 at orentation 90 degree
Timimg at: 0:01:10 Location: 8 at orentation 315 degree
Timimg at: 0:01:15 Location: 8 at orentation 90 degree
Timimg at: 0:01:20 Location: 7 at orentation 270 degree
Timimg at: 0:01:25 Location: 8 at orentation 315 degree
Timimg at: 0:01:30 Location: 8 at orentation 90 degree
Timimg at: 0:01:35 Location: 8 at orentation 90 degree
Timimg at: 0:01:40 Location: 7 at orentation 270 degree
Timimg at: 0:01:45 Location: 8 at orentation 90 degree
Timimg at: 0:01:50 Location: 7 at orentation 270 degree
Timimg at: 0:01:55 Location: 1 at orentation 45 degree
Timimg at: 0:02:00 Location: 8 at orentation 90 degree
Timimg at: 0:02:05 Location: 8 at orentation 90 degree
Timimg at: 0:02:10 Location: 8 at orentation 90 degree
Timimg at: 0:02:15 Location: 8 at orentation 90 degree
Timimg at: 0:02:20 Location: 6 at orentation 45 degree
Timimg at: 0:02:25 Location: 8 at orentation 90 degree
Timimg at: 0:02:30 Location: 8 at orentation 315 degree
Timimg at: 0:02:35 Location: 7 at orentation 270 degree
.      .      .      .      .      .
.      .      .      .      .      .
.      .      .      .      .      .
Timimg at: 0:04:15 Location: 7 at orentation 270 degree
Timimg at: 0:19:25 Location: 1 at orentation 315 degree
Timimg at: 0:19:30 Location: 2 at orentation 0 degree
Timimg at: 0:19:35 Location: 2 at orentation 0 degree
Timimg at: 0:19:40 Location: 3 at orentation 315 degree
Timimg at: 0:19:45 Location: 3 at orentation 315 degree
Timimg at: 0:19:50 Location: 6 at orentation 225 degree
Timimg at: 0:19:55 Location: 6 at orentation 225 degree

Time spent on station1 (sec) = 255
Time spent on station2 (sec)= 325
Time spent on station3 (sec)= 615

Time spent on station1 (min) = 4:15
Time spent on station2 (min) = 5:25
Time spent on station3 (min) = 10:15
```

Appendix I

Estimated individual task times results

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
1	4	- - - -	1	2000	4	5	100	435	735	85	450	735	75	425	770
1	13	- - - +	1	2000	4	9	295	480	495	345	445	480	420	365	485
1	14	- - + -	1	2000	8	5	140	350	780	120	345	805	105	380	785
1	11	- - + +	1	2000	8	9	280	610	380	295	600	375	305	550	415
1	3	- + - -	1	6000	4	5	90	635	545	75	650	545	70	660	540
1	9	- + - +	1	6000	4	9	345	475	450	325	475	470	415	360	495
1	12	- + + -	1	6000	8	5	160	335	775	115	355	800	90	400	780
1	1	- + + +	1	6000	8	9	320	585	365	300	575	395	300	545	425
1	16	+ - - -	2	2000	4	5	155	420	695	115	430	725	120	420	730
1	10	+ - - +	2	2000	4	9	380	435	455	315	475	480	350	435	485
1	6	+ - + -	2	2000	8	5	280	245	745	225	270	775	220	305	745
1	8	+ - + +	2	2000	8	9	375	525	370	410	465	395	370	520	380
1	7	+ + - -	2	6000	4	5	150	410	710	110	430	730	120	405	745
1	15	+ + - +	2	6000	4	9	390	415	465	335	470	465	365	400	505
1	2	+ + + -	2	6000	8	5	235	290	745	215	300	755	220	280	770
1	5	+ + + +	2	6000	8	9	365	510	395	340	520	410	380	475	415
2	4	- - - -	1	2000	4	5	135	460	495	125	470	495	115	470	505
2	13	- - - +	1	2000	4	9	315	425	350	355	390	345	400	355	335
2	14	- - + -	1	2000	8	5	275	250	565	265	265	560	290	255	545
2	11	- - + +	1	2000	8	9	260	400	430	225	410	455	205	440	445
2	3	- + - -	1	6000	4	5	40	605	445	50	605	435	40	610	440
2	9	- + - +	1	6000	4	9	315	420	355	330	435	325	410	360	320
2	12	- + + -	1	6000	8	5	270	260	560	290	255	545	305	245	540
2	1	- + + +	1	6000	8	9	215	415	460	225	415	450	210	430	450
2	16	+ - - -	2	2000	4	5	180	410	500	140	440	510	145	425	520
2	10	+ - - +	2	2000	4	9	305	395	390	330	400	360	360	360	370
2	6	+ - + -	2	2000	8	5	265	240	585	290	240	560	285	245	560
2	8	+ - + +	2	2000	8	9	260	375	455	250	380	460	240	420	430

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
2	7	+ + - -	2	6000	4	5	180	395	515	135	450	505	140	435	515
2	15	+ + - +	2	6000	4	9	325	380	385	315	395	380	350	350	390
2	2	+ + + -	2	6000	8	5	265	245	580	290	260	540	285	275	530
2	5	+ + + +	2	6000	8	9	280	365	445	250	385	455	255	400	435
3	4	- - - -	1	2000	4	5	645	290	665	600	355	645	540	385	675
3	13	- - - +	1	2000	4	9	600	390	610	600	390	610	585	390	625
3	14	- - + -	1	2000	8	5	580	255	765	555	250	795	560	240	800
3	11	- - + +	1	2000	8	9	615	335	650	640	305	655	655	300	645
3	3	- + - -	1	6000	4	5	550	390	660	560	395	645	555	435	610
3	9	- + - +	1	6000	4	9	605	410	585	580	425	595	575	420	605
3	12	- + + -	1	6000	8	5	580	250	770	565	255	780	535	260	805
3	1	- + + +	1	6000	8	9	625	340	635	660	340	600	610	350	640
3	16	+ - - -	2	2000	4	5	685	210	705	635	260	705	625	270	705
3	10	+ - - +	2	2000	4	9	610	390	600	580	380	640	600	325	675
3	6	+ - + -	2	2000	8	5	545	265	790	585	225	790	560	240	800
3	8	+ - + +	2	2000	8	9	630	335	635	595	315	690	620	295	685
3	7	+ + - -	2	6000	4	5	685	225	690	635	245	720	625	275	700
3	15	+ + - +	2	6000	4	9	615	385	600	595	370	635	585	370	645
3	2	+ + + -	2	6000	8	5	580	245	775	590	240	770	570	215	815
3	5	+ + + +	2	6000	8	9	615	360	625	650	305	645	615	330	655
4	4	- - - -	1	2000	4	5	270	570	420	215	645	400	185	680	395
4	13	- - - +	1	2000	4	9	330	500	430	330	495	435	330	515	415
4	14	- - + -	1	2000	8	5	205	390	665	185	440	635	175	485	600
4	11	- - + +	1	2000	8	9	225	575	460	220	570	470	175	605	480
4	3	- + - -	1	6000	4	5	45	525	690	60	600	600	65	640	555
4	9	- + - +	1	6000	4	9	370	475	415	330	525	405	335	535	390
4	12	- + + -	1	6000	8	5	215	385	660	170	435	655	160	465	635
4	1	- + + +	1	6000	8	9	220	580	460	195	625	440	175	620	465
4	16	+ - - -	2	2000	4	5	250	505	505	225	600	435	200	640	420
4	10	+ - - +	2	2000	4	9	360	450	450	345	445	470	350	415	495
4	6	+ - + -	2	2000	8	5	230	345	685	245	355	660	230	395	635
4	8	+ - + +	2	2000	8	9	225	585	450	180	580	500	210	560	490
4	7	+ + - -	2	6000	4	5	260	495	505	230	585	445	195	625	440
4	15	+ + - +	2	6000	4	9	370	420	470	375	405	480	365	405	490

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
4	2	+ + + -	2	6000	8	5	250	355	655	240	365	655	225	375	660
4	5	+ + + +	2	6000	8	9	250	545	465	220	560	480	215	575	470
5	4	- - - -	1	2000	4	5	240	380	510	185	475	470	150	500	480
5	13	- - - +	1	2000	4	9	225	475	430	255	440	435	290	420	420
5	14	- - + -	1	2000	8	5	280	290	560	250	325	555	235	335	560
5	11	- - + +	1	2000	8	9	240	480	410	210	495	425	195	510	425
5	3	- + - -	1	6000	4	5	115	485	530	125	515	490	125	520	485
5	9	- + - +	1	6000	4	9	260	455	415	270	420	440	290	420	420
5	12	- + + -	1	6000	8	5	290	270	570	250	305	575	245	310	575
5	1	- + + +	1	6000	8	9	260	475	395	240	445	445	200	480	450
5	16	+ - - -	2	2000	4	5	240	360	530	245	360	525	230	405	495
5	10	+ - - +	2	2000	4	9	250	445	435	255	425	450	245	420	465
5	6	+ - + -	2	2000	8	5	285	270	575	290	255	585	275	280	575
5	8	+ - + +	2	2000	8	9	275	455	400	245	450	435	250	450	430
5	7	+ + - -	2	6000	4	5	250	370	510	230	395	505	230	415	485
5	15	+ + - +	2	6000	4	9	250	440	440	255	425	450	245	415	470
5	2	+ + + -	2	6000	8	5	280	260	590	295	270	565	255	310	565
5	5	+ + + +	2	6000	8	9	285	420	425	275	410	445	260	455	415
6	4	- - - -	1	2000	4	5	540	205	530	505	255	515	470	295	510
6	13	- - - +	1	2000	4	9	425	370	480	450	335	490	430	365	480
6	14	- - + -	1	2000	8	5	495	275	505	515	240	520	505	255	515
6	11	- - + +	1	2000	8	9	560	205	510	580	180	515	575	190	510
6	3	- + - -	1	6000	4	5	455	265	555	450	295	530	395	355	525
6	9	- + - +	1	6000	4	9	420	410	445	435	355	485	435	350	490
6	12	- + + -	1	6000	8	5	505	255	515	535	225	515	490	250	535
6	1	- + + +	1	6000	8	9	595	165	515	560	200	515	570	185	520
6	16	+ - - -	2	2000	4	5	575	165	535	565	175	535	560	185	530
6	10	+ - - +	2	2000	4	9	445	355	475	445	335	495	460	300	515
6	6	+ - + -	2	2000	8	5	485	250	540	490	250	535	515	220	540
6	8	+ - + +	2	2000	8	9	600	155	520	620	150	505	610	150	515
6	7	+ + - -	2	6000	4	5	575	165	535	550	195	530	560	180	535
6	15	+ + - +	2	6000	4	9	445	345	485	435	340	500	440	330	505
6	2	+ + + -	2	6000	8	5	490	245	540	495	235	545	535	205	535
6	5	+ + + +	2	6000	8	9	600	175	500	615	145	515	625	140	510

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
7	4	- - - -	1	2000	4	5	370	190	480	345	210	485	335	215	490
7	13	- - - +	1	2000	4	9	465	135	440	480	100	460	500	95	445
7	14	- - + -	1	2000	8	5	425	150	465	400	160	480	405	155	480
7	11	- - + +	1	2000	8	9	385	175	480	440	130	470	430	145	465
7	3	- + - -	1	6000	4	5	325	230	485	335	220	485	320	235	485
7	9	- + - +	1	6000	4	9	445	175	420	475	110	455	495	95	450
7	12	- + + -	1	6000	8	5	420	160	460	435	130	475	405	155	480
7	1	- + + +	1	6000	8	9	425	135	480	445	125	470	445	130	465
7	16	+ - - -	2	2000	4	5	375	180	485	345	210	485	350	205	485
7	10	+ - - +	2	2000	4	9	460	125	455	450	115	475	465	100	475
7	6	+ - + -	2	2000	8	5	480	90	470	490	90	460	450	105	485
7	8	+ - + +	2	2000	8	9	465	125	450	440	135	465	470	95	475
7	7	+ + - -	2	6000	4	5	375	185	480	335	220	485	340	215	485
7	15	+ + - +	2	6000	4	9	450	135	455	455	105	480	480	75	485
7	2	+ + + -	2	6000	8	5	470	105	465	430	145	465	430	130	480
7	5	+ + + +	2	6000	8	9	455	130	455	435	130	475	455	105	480
8	4	- - - -	1	2000	4	5	335	475	315	330	500	295	320	495	310
8	13	- - - +	1	2000	4	9	525	290	310	520	320	285	520	330	275
8	14	- - + -	1	2000	8	5	280	445	400	265	490	370	275	490	360
8	11	- - + +	1	2000	8	9	320	375	430	325	410	390	320	410	395
8	3	- + - -	1	6000	4	5	275	365	485	285	375	465	300	410	415
8	9	- + - +	1	6000	4	9	535	300	290	525	315	285	520	315	290
8	12	- + + -	1	6000	8	5	300	400	425	265	475	385	290	450	385
8	1	- + + +	1	6000	8	9	345	395	385	335	420	370	330	410	385
8	16	+ - - -	2	2000	4	5	330	455	340	315	470	340	320	480	325
8	10	+ - - +	2	2000	4	9	540	270	315	535	260	330	545	260	320
8	6	+ - + -	2	2000	8	5	260	390	475	275	405	445	270	415	440
8	8	+ - + +	2	2000	8	9	340	370	415	310	410	405	325	395	405
8	7	+ + - -	2	6000	4	5	340	440	345	325	450	350	330	465	330
8	15	+ + - +	2	6000	4	9	535	275	315	540	260	325	540	260	325
8	2	+ + + -	2	6000	8	5	270	365	490	265	365	495	250	400	475
8	5	+ + + +	2	6000	8	9	345	360	420	345	405	375	335	395	395
9	4	- - - -	1	2000	4	5	75	635	325	40	670	325	55	675	305
9	13	- - - +	1	2000	4	9	300	485	250	345	465	225	330	475	230

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
9	14	- - + -	1	2000	8	5	95	425	515	85	545	405	80	585	370
9	11	- - + +	1	2000	8	9	110	570	355	105	565	365	85	585	365
9	3	- + - -	1	6000	4	5	10	420	605	5	455	575	10	535	490
9	9	- + - +	1	6000	4	9	350	435	250	340	465	230	335	475	225
9	12	- + + -	1	6000	8	5	105	455	475	75	550	410	70	565	400
9	1	- + + +	1	6000	8	9	110	560	365	110	565	360	100	555	380
9	16	+ - - -	2	2000	4	5	125	560	350	80	620	335	40	670	325
9	10	+ - - +	2	2000	4	9	415	330	290	385	365	285	385	360	290
9	6	+ - + -	2	2000	8	5	95	445	495	130	505	400	100	605	330
9	8	+ - + +	2	2000	8	9	90	580	365	80	575	380	90	550	395
9	7	+ + - -	2	6000	4	5	150	555	330	75	635	325	35	675	325
9	15	+ + - +	2	6000	4	9	405	365	265	370	390	275	395	335	305
9	2	+ + + -	2	6000	8	5	105	380	550	100	470	465	115	535	385
9	5	+ + + +	2	6000	8	9	95	565	375	105	550	380	105	540	390
10	4	- - - -	1	2000	4	5	110	780	85	90	825	60	65	860	50
10	13	- - - +	1	2000	4	9	375	510	90	395	490	90	370	510	95
10	14	- - + -	1	2000	8	5	70	630	275	95	635	245	85	650	240
10	11	- - + +	1	2000	8	9	230	575	170	200	645	130	200	655	120
10	3	- + - -	1	6000	4	5	35	700	240	25	730	220	20	790	165
10	9	- + - +	1	6000	4	9	400	495	80	420	475	80	370	515	90
10	12	- + + -	1	6000	8	5	85	605	285	85	615	275	90	655	230
10	1	- + + +	1	6000	8	9	240	580	155	210	650	115	220	665	90
10	16	+ - - -	2	2000	4	5	140	695	140	110	775	90	110	790	75
10	10	+ - - +	2	2000	4	9	395	470	110	390	495	90	380	500	95
10	6	+ - + -	2	2000	8	5	90	585	300	85	650	240	95	645	235
10	8	+ - + +	2	2000	8	9	250	560	165	220	585	170	215	610	150
10	7	+ + - -	2	6000	4	5	155	680	140	120	770	85	105	790	80
10	15	+ + - +	2	6000	4	9	380	495	100	405	480	90	410	480	85
10	2	+ + + -	2	6000	8	5	75	620	280	70	640	265	95	670	210
10	5	+ + + +	2	6000	8	9	255	575	145	230	590	155	215	625	135
11	4	- - - -	1	2000	4	5	300	410	405	285	420	410	280	445	390
11	13	- - - +	1	2000	4	9	410	465	240	390	520	205	385	525	205
11	14	- - + -	1	2000	8	5	260	420	435	285	410	420	265	465	385
11	11	- - + +	1	2000	8	9	415	355	345	405	370	340	390	385	340

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
11	3	- + - -	1	6000	4	5	270	305	540	280	315	520	285	320	510
11	9	- + - +	1	6000	4	9	395	485	235	390	525	200	385	535	195
11	12	- + + -	1	6000	8	5	270	410	435	295	435	385	285	415	415
11	1	- + + +	1	6000	8	9	410	370	335	410	365	340	400	385	330
11	16	+ - - -	2	2000	4	5	310	370	435	290	390	435	290	390	435
11	10	+ - - +	2	2000	4	9	440	380	295	430	405	280	400	415	300
11	6	+ - + -	2	2000	8	5	225	405	485	245	445	425	245	460	410
11	8	+ - + +	2	2000	8	9	365	365	385	380	365	370	370	365	380
11	7	+ + - -	2	6000	4	5	305	385	425	290	395	430	290	405	420
11	15	+ + - +	2	6000	4	9	425	425	265	435	415	265	405	435	275
11	2	+ + + -	2	6000	8	5	225	420	470	250	435	430	250	440	425
11	5	+ + + +	2	6000	8	9	370	405	340	400	360	355	390	345	380
12	4	- - - -	1	2000	4	5	345	300	530	325	335	515	325	320	530
12	13	- - - +	1	2000	4	9	350	430	395	375	415	385	370	430	375
12	14	- - + -	1	2000	8	5	325	275	575	340	260	575	330	290	555
12	11	- - + +	1	2000	8	9	440	200	535	440	180	555	410	220	545
12	3	- + - -	1	6000	4	5	260	325	590	260	365	550	240	385	550
12	9	- + - +	1	6000	4	9	350	440	385	375	430	370	390	410	375
12	12	- + + -	1	6000	8	5	330	255	590	330	270	575	330	265	580
12	1	- + + +	1	6000	8	9	430	235	510	445	165	565	440	195	540
12	16	+ - - -	2	2000	4	5	330	300	545	335	300	540	330	305	540
12	10	+ - - +	2	2000	4	9	365	395	415	365	355	455	375	340	460
12	6	+ - + -	2	2000	8	5	305	280	590	335	275	565	345	250	580
12	8	+ - + +	2	2000	8	9	485	185	505	455	170	550	480	160	535
12	7	+ + - -	2	6000	4	5	325	300	550	330	300	545	335	305	535
12	15	+ + - +	2	6000	4	9	380	370	425	365	355	455	390	325	460
12	2	+ + + -	2	6000	8	5	305	280	590	320	270	585	325	265	585
12	5	+ + + +	2	6000	8	9	480	190	505	480	170	525	500	135	540
13	4	- - - -	1	2000	4	5	485	185	495	475	235	455	465	245	455
13	13	- - - +	1	2000	4	9	505	385	275	495	400	270	500	375	290
13	14	- - + -	1	2000	8	5	450	175	540	455	215	495	460	240	465
13	11	- - + +	1	2000	8	9	490	385	290	500	320	345	495	285	385
13	3	- + - -	1	6000	4	5	455	225	485	445	250	470	445	255	465
13	9	- + - +	1	6000	4	9	515	380	270	500	400	265	500	390	275

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
13	12	- + + -	1	6000	8	5	455	175	535	440	190	535	460	205	500
13	1	- + + +	1	6000	8	9	470	400	295	500	345	320	505	305	355
13	16	+ - - -	2	2000	4	5	470	180	515	475	175	515	480	180	505
13	10	+ - - +	2	2000	4	9	540	325	300	515	315	335	520	325	320
13	6	+ - + -	2	2000	8	5	455	165	545	445	215	505	465	215	485
13	8	+ - + +	2	2000	8	9	455	350	360	500	310	355	510	265	390
13	7	+ + - -	2	6000	4	5	470	175	520	475	170	520	475	170	520
13	15	+ + - +	2	6000	4	9	560	325	280	520	325	320	535	340	290
13	2	+ + + -	2	6000	8	5	465	175	525	470	165	530	465	215	485
13	5	+ + + +	2	6000	8	9	450	370	345	505	300	360	505	265	395
14	4	- - - -	1	2000	4	5	315	620	135	285	645	140	250	675	145
14	13	- - - +	1	2000	4	9	455	485	130	445	520	105	415	530	125
14	14	- - + -	1	2000	8	5	285	475	310	255	525	290	255	580	235
14	11	- - + +	1	2000	8	9	330	620	120	350	600	120	330	605	135
14	3	- + - -	1	6000	4	5	240	495	335	240	530	300	235	535	300
14	9	- + - +	1	6000	4	9	470	500	100	430	530	110	445	510	115
14	12	- + + -	1	6000	8	5	285	445	340	275	460	335	240	540	290
14	1	- + + +	1	6000	8	9	340	580	150	340	605	125	335	620	115
14	16	+ - - -	2	2000	4	5	340	555	175	300	625	145	290	615	165
14	10	+ - - +	2	2000	4	9	485	450	135	465	475	130	450	525	95
14	6	+ - + -	2	2000	8	5	295	530	245	305	560	205	270	620	180
14	8	+ - + +	2	2000	8	9	280	670	120	300	605	165	300	625	145
14	7	+ + - -	2	6000	4	5	325	560	185	305	595	170	295	610	165
14	15	+ + - +	2	6000	4	9	465	500	105	465	500	105	460	495	115
14	2	+ + + -	2	6000	8	5	335	480	255	290	565	215	315	575	180
14	5	+ + + +	2	6000	8	9	335	605	130	310	620	140	285	655	130
15	4	- - - -	1	2000	4	5	430	280	470	390	330	460	395	315	470
15	13	- - - +	1	2000	4	9	460	310	410	465	330	385	455	335	390
15	14	- - + -	1	2000	8	5	415	230	535	400	280	500	400	310	470
15	11	- - + +	1	2000	8	9	415	355	410	420	340	420	420	335	425
15	3	- + - -	1	6000	4	5	315	295	570	320	315	545	305	350	525
15	9	- + - +	1	6000	4	9	490	305	385	465	315	400	475	290	415
15	12	- + + -	1	6000	8	5	435	215	530	415	250	515	405	295	480
15	1	- + + +	1	6000	8	9	415	370	395	430	335	415	430	320	430

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
15	16	+ - - -	2	2000	4	5	450	245	485	420	285	475	395	310	475
15	10	+ - - +	2	2000	4	9	485	270	425	505	240	435	510	220	450
15	6	+ - + -	2	2000	8	5	405	195	580	435	240	505	435	255	490
15	8	+ - + +	2	2000	8	9	445	345	390	420	345	415	415	335	430
15	7	+ + - -	2	6000	4	5	445	245	490	410	290	480	390	320	470
15	15	+ + - +	2	6000	4	9	510	250	420	500	245	435	485	255	440
15	2	+ + + -	2	6000	8	5	445	170	565	440	235	505	440	230	510
15	5	+ + + +	2	6000	8	9	435	340	405	435	320	425	430	300	450
16	4	- - - -	1	2000	4	5	405	175	515	395	195	505	375	230	490
16	13	- - - +	1	2000	4	9	415	345	335	425	345	325	440	340	315
16	14	- - + -	1	2000	8	5	330	235	530	360	225	510	350	220	525
16	11	- - + +	1	2000	8	9	330	350	415	340	330	425	350	295	450
16	3	- + - -	1	6000	4	5	335	245	515	325	265	505	310	305	480
16	9	- + - +	1	6000	4	9	420	350	325	435	355	305	445	345	305
16	12	- + + -	1	6000	8	5	345	215	535	365	220	510	360	220	515
16	1	- + + +	1	6000	8	9	365	320	410	355	315	425	355	305	435
16	16	+ - - -	2	2000	4	5	455	125	515	420	150	525	425	160	510
16	10	+ - - +	2	2000	4	9	430	305	360	435	290	370	440	265	390
16	6	+ - + -	2	2000	8	5	315	200	580	325	200	570	345	175	575
16	8	+ - + +	2	2000	8	9	390	290	415	355	325	415	345	325	425
16	7	+ + - -	2	6000	4	5	440	130	525	425	160	510	415	170	510
16	15	+ + - +	2	6000	4	9	450	280	365	445	270	380	440	265	390
16	2	+ + + -	2	6000	8	5	310	210	575	330	205	560	335	200	560
16	5	+ + + +	2	6000	8	9	405	300	390	380	300	415	385	275	435
17	4	- - - -	1	2000	4	5	210	465	415	185	475	430	185	495	410
17	13	- - - +	1	2000	4	9	380	345	365	400	320	370	390	320	380
17	14	- - + -	1	2000	8	5	225	300	565	245	320	525	230	360	500
17	11	- - + +	1	2000	8	9	265	355	470	285	355	450	245	410	435
17	3	- + - -	1	6000	4	5	95	515	480	100	535	455	100	550	440
17	9	- + - +	1	6000	4	9	390	370	330	385	335	370	395	315	380
17	12	- + + -	1	6000	8	5	230	300	560	240	320	530	230	355	505
17	1	- + + +	1	6000	8	9	300	325	465	315	360	415	270	400	420
17	16	+ - - -	2	2000	4	5	190	445	455	180	465	445	175	470	445
17	10	+ - - +	2	2000	4	9	400	325	365	390	320	380	405	300	385

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
17	6	+ - + -	2	2000	8	5	215	240	635	230	255	605	245	270	575
17	8	+ - + +	2	2000	8	9	295	335	460	285	315	490	280	320	490
17	7	+ + - -	2	6000	4	5	200	445	445	175	475	440	170	470	450
17	15	+ + - +	2	6000	4	9	375	335	380	385	310	395	400	300	390
17	2	+ + + -	2	6000	8	5	220	245	625	240	245	605	250	260	580
17	5	+ + + +	2	6000	8	9	320	325	445	285	310	495	275	305	510
18	4	- - - -	1	2000	4	5	195	350	545	195	365	530	190	390	510
18	13	- - - +	1	2000	4	9	305	565	220	330	585	175	340	525	225
18	14	- - + -	1	2000	8	5	245	290	555	230	360	500	230	370	490
18	11	- - + +	1	2000	8	9	290	355	445	290	370	430	220	440	430
18	3	- + - -	1	6000	4	5	190	340	560	190	365	535	190	390	510
18	9	- + - +	1	6000	4	9	325	560	205	340	580	170	340	530	220
18	12	- + + -	1	6000	8	5	225	315	550	235	325	530	240	355	495
18	1	- + + +	1	6000	8	9	310	360	420	270	385	435	250	415	425
18	16	+ - - -	2	2000	4	5	210	335	545	210	335	545	220	345	525
18	10	+ - - +	2	2000	4	9	335	495	260	330	530	230	375	500	215
18	6	+ - + -	2	2000	8	5	205	305	580	240	370	480	240	415	435
18	8	+ - + +	2	2000	8	9	270	365	455	285	370	435	280	380	430
18	7	+ + - -	2	6000	4	5	205	340	545	200	335	555	205	355	530
18	15	+ + - +	2	6000	4	9	340	515	235	330	550	210	385	520	185
18	2	+ + + -	2	6000	8	5	200	310	580	215	400	475	235	385	470
18	5	+ + + +	2	6000	8	9	280	365	445	285	370	435	270	385	435
19	4	- - - -	1	2000	4	5	265	355	575	260	370	565	240	380	575
19	13	- - - +	1	2000	4	9	465	510	220	470	510	215	445	515	235
19	14	- - + -	1	2000	8	5	255	305	635	285	355	555	290	390	515
19	11	- - + +	1	2000	8	9	260	330	605	275	340	580	265	360	570
19	3	- + - -	1	6000	4	5	255	360	580	250	360	585	245	360	590
19	9	- + - +	1	6000	4	9	465	525	205	480	505	210	455	515	225
19	12	- + + -	1	6000	8	5	270	335	590	285	350	560	290	375	530
19	1	- + + +	1	6000	8	9	255	325	615	260	340	595	270	375	550

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	K low			K medium			K high		
							Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)	Station 1 (sec)	Station 2 (sec)	Station 3 (sec)
19	16	+ - - -	2	2000	4	5	255	320	620	245	385	565	275	365	555
19	10	+ - - +	2	2000	4	9	490	405	300	480	460	255	485	460	250
19	6	+ - + -	2	2000	8	5	255	265	675	275	305	615	260	365	570
19	8	+ - + +	2	2000	8	9	230	330	635	235	340	620	265	330	600
19	7	+ + - -	2	6000	4	5	250	325	620	245	360	590	265	360	570
19	15	+ + - +	2	6000	4	9	485	430	280	495	465	235	470	490	235
19	2	+ + + -	2	6000	8	5	230	250	715	240	335	620	245	355	595
19	5	+ + + +	2	6000	8	9	260	340	595	240	345	610	265	320	610
20	4	- - - -	1	2000	4	5	225	505	355	230	505	350	220	510	355
20	13	- - - +	1	2000	4	9	420	555	110	440	545	100	415	605	65
20	14	- - + -	1	2000	8	5	275	300	510	275	380	430	315	400	370
20	11	- - + +	1	2000	8	9	255	485	345	260	490	335	265	505	315
20	3	- + - -	1	6000	4	5	280	400	405	285	395	405	275	400	410
20	9	- + - +	1	6000	4	9	445	530	110	460	535	90	430	585	70
20	12	- + + -	1	6000	8	5	285	300	500	275	370	440	290	385	410
20	1	- + + +	1	6000	8	9	255	485	345	250	520	315	250	535	300
20	16	+ - - -	2	2000	4	5	275	435	375	240	475	370	240	485	360
20	10	+ - - +	2	2000	4	9	480	440	165	490	435	160	480	455	150
20	6	+ - + -	2	2000	8	5	270	375	440	275	455	355	275	480	330
20	8	+ - + +	2	2000	8	9	270	440	375	270	460	355	250	470	365
20	7	+ + - -	2	6000	4	5	265	420	400	235	475	375	230	490	365
20	15	+ + - +	2	6000	4	9	480	460	145	475	465	145	460	485	140
20	2	+ + + -	2	6000	8	5	265	395	425	265	405	415	260	440	385
20	5	+ + + +	2	6000	8	9	270	445	370	270	475	340	245	475	365

Appendix J

Estimated individual task times percentage error results

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
1	4	- - - -	1	2000	4	5	79%	71%	20%	82%	76%	20%	84%	67%	25%
1	13	- - - +	1	2000	4	9	39%	88%	20%	28%	75%	22%	13%	43%	21%
1	14	- - + -	1	2000	8	5	71%	37%	27%	75%	35%	31%	78%	49%	28%
1	11	- - + +	1	2000	8	9	42%	139%	38%	39%	135%	39%	36%	116%	33%
1	3	- + - -	1	6000	4	5	81%	149%	11%	84%	155%	11%	85%	159%	12%
1	9	- + - +	1	6000	4	9	28%	86%	27%	32%	86%	24%	14%	41%	20%
1	12	- + + -	1	6000	8	5	67%	31%	26%	76%	39%	30%	81%	57%	27%
1	1	- + + +	1	6000	8	9	33%	129%	41%	38%	125%	36%	38%	114%	31%
1	16	+ - - -	2	2000	4	5	68%	65%	13%	76%	69%	18%	75%	65%	19%
1	10	+ - - +	2	2000	4	9	21%	71%	26%	34%	86%	22%	27%	71%	21%
1	6	+ - + -	2	2000	8	5	42%	4%	21%	53%	6%	26%	54%	20%	21%
1	8	+ - + +	2	2000	8	9	22%	106%	40%	15%	82%	36%	23%	104%	38%
1	7	+ + - -	2	6000	4	5	69%	61%	15%	77%	69%	19%	75%	59%	21%
1	15	+ + - +	2	6000	4	9	19%	63%	24%	30%	84%	24%	24%	57%	18%
1	2	+ + + -	2	6000	8	5	51%	14%	21%	55%	18%	23%	54%	10%	25%
1	5	+ + + +	2	6000	8	9	24%	100%	36%	29%	104%	33%	21%	86%	33%
2	4	- - - -	1	2000	4	5	68%	88%	4%	70%	92%	4%	73%	92%	6%
2	13	- - - +	1	2000	4	9	25%	73%	26%	15%	59%	27%	5%	45%	29%
2	14	- - + -	1	2000	8	5	35%	2%	19%	37%	8%	18%	31%	4%	15%
2	11	- - + +	1	2000	8	9	38%	63%	9%	46%	67%	4%	51%	80%	6%
2	3	- + - -	1	6000	4	5	90%	147%	6%	88%	147%	8%	90%	149%	7%
2	9	- + - +	1	6000	4	9	25%	71%	25%	21%	78%	32%	2%	47%	33%
2	12	- + + -	1	6000	8	5	36%	6%	18%	31%	4%	15%	27%	0%	14%
2	1	- + + +	1	6000	8	9	49%	69%	3%	46%	69%	5%	50%	76%	5%
2	16	+ - - -	2	2000	4	5	57%	67%	5%	67%	80%	7%	65%	73%	9%
2	10	+ - - +	2	2000	4	9	27%	61%	18%	21%	63%	24%	14%	47%	22%
2	6	+ - + -	2	2000	8	5	37%	2%	23%	31%	2%	18%	32%	0%	18%
2	8	+ - + +	2	2000	8	9	38%	53%	4%	40%	55%	3%	43%	71%	9%
2	7	+ + - -	2	6000	4	5	57%	61%	8%	68%	84%	6%	67%	78%	8%
2	15	+ + - +	2	6000	4	9	23%	55%	19%	25%	61%	20%	17%	43%	18%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
2	2	+ + + -	2	6000	8	5	37%	0%	22%	31%	6%	14%	32%	12%	12%
2	5	+ + + +	2	6000	8	9	33%	49%	6%	40%	57%	4%	39%	63%	8%
3	4	- - - -	1	2000	4	5	27%	5%	16%	18%	17%	18%	6%	27%	14%
3	13	- - - +	1	2000	4	9	18%	28%	23%	18%	28%	23%	15%	28%	21%
3	14	- - + -	1	2000	8	5	14%	16%	3%	9%	18%	1%	10%	21%	2%
3	11	- - + +	1	2000	8	9	21%	10%	18%	26%	0%	17%	29%	1%	18%
3	3	- + - -	1	6000	4	5	8%	28%	16%	10%	30%	18%	9%	43%	23%
3	9	- + - +	1	6000	4	9	19%	35%	26%	14%	40%	24%	13%	38%	23%
3	12	- + + -	1	6000	8	5	14%	18%	2%	11%	16%	1%	5%	14%	2%
3	1	- + + +	1	6000	8	9	23%	12%	19%	30%	12%	24%	20%	15%	19%
3	16	+ - - -	2	2000	4	5	35%	31%	11%	25%	14%	11%	23%	11%	11%
3	10	+ - - +	2	2000	4	9	20%	28%	24%	14%	25%	19%	18%	7%	14%
3	6	+ - + -	2	2000	8	5	7%	13%	0%	15%	26%	0%	10%	21%	2%
3	8	+ - + +	2	2000	8	9	24%	10%	19%	17%	4%	12%	22%	3%	13%
3	7	+ + - -	2	6000	4	5	35%	26%	12%	25%	19%	9%	23%	10%	11%
3	15	+ + - +	2	6000	4	9	21%	27%	24%	17%	22%	19%	15%	22%	18%
3	2	+ + + -	2	6000	8	5	14%	19%	2%	16%	21%	2%	12%	29%	3%
3	5	+ + + +	2	6000	8	9	21%	18%	21%	28%	0%	18%	21%	9%	17%
4	4	- - - -	1	2000	4	5	36%	137%	19%	49%	168%	23%	56%	182%	24%
4	13	- - - +	1	2000	4	9	22%	107%	17%	22%	105%	16%	22%	114%	20%
4	14	- - + -	1	2000	8	5	51%	62%	28%	56%	83%	22%	59%	101%	16%
4	11	- - + +	1	2000	8	9	47%	139%	11%	48%	137%	9%	59%	151%	8%
4	3	- + - -	1	6000	4	5	89%	118%	33%	86%	149%	16%	85%	166%	7%
4	9	- + - +	1	6000	4	9	12%	97%	20%	22%	118%	22%	21%	122%	25%
4	12	- + + -	1	6000	8	5	49%	60%	27%	60%	80%	26%	62%	93%	22%
4	1	- + + +	1	6000	8	9	48%	141%	11%	54%	159%	15%	59%	157%	10%
4	16	+ - - -	2	2000	4	5	41%	110%	3%	47%	149%	16%	53%	166%	19%
4	10	+ - - +	2	2000	4	9	15%	87%	13%	18%	85%	9%	17%	72%	5%
4	6	+ - + -	2	2000	8	5	45%	43%	32%	42%	47%	27%	45%	64%	22%
4	8	+ - + +	2	2000	8	9	47%	143%	13%	57%	141%	4%	50%	132%	6%
4	7	+ + - -	2	6000	4	5	38%	105%	3%	45%	143%	14%	54%	159%	15%
4	15	+ + - +	2	6000	4	9	12%	74%	9%	11%	68%	8%	14%	68%	6%
4	2	+ + + -	2	6000	8	5	41%	47%	26%	43%	51%	26%	47%	56%	27%
4	5	+ + + +	2	6000	8	9	41%	126%	10%	48%	132%	8%	49%	139%	9%
5	4	- - - -	1	2000	4	5	38%	99%	4%	53%	149%	11%	62%	162%	10%
5	13	- - - +	1	2000	4	9	42%	149%	19%	35%	130%	18%	26%	120%	21%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
5	14	- - + -	1	2000	8	5	28%	52%	5%	36%	70%	5%	40%	75%	5%
5	11	- - + +	1	2000	8	9	38%	151%	23%	46%	159%	20%	50%	167%	20%
5	3	- + - -	1	6000	4	5	71%	154%	0%	68%	170%	8%	68%	172%	9%
5	9	- + - +	1	6000	4	9	33%	138%	22%	31%	120%	17%	26%	120%	21%
5	12	- + + -	1	6000	8	5	26%	41%	7%	36%	60%	8%	37%	62%	8%
5	1	- + + +	1	6000	8	9	33%	149%	26%	38%	133%	16%	49%	151%	15%
5	16	+ - - -	2	2000	4	5	38%	88%	0%	37%	88%	1%	41%	112%	7%
5	10	+ - - +	2	2000	4	9	36%	133%	18%	35%	123%	15%	37%	120%	12%
5	6	+ - + -	2	2000	8	5	27%	41%	8%	26%	34%	10%	29%	47%	8%
5	8	+ - + +	2	2000	8	9	29%	138%	25%	37%	136%	18%	36%	136%	19%
5	7	+ + - -	2	6000	4	5	36%	94%	4%	41%	107%	5%	41%	117%	9%
5	15	+ + - +	2	6000	4	9	36%	130%	17%	35%	123%	15%	37%	117%	11%
5	2	+ + + -	2	6000	8	5	28%	36%	11%	24%	41%	6%	35%	62%	6%
5	5	+ + + +	2	6000	8	9	27%	120%	20%	29%	115%	16%	33%	138%	22%
6	4	- - - -	1	2000	4	5	16%	19%	2%	8%	1%	1%	1%	17%	2%
6	13	- - - +	1	2000	4	9	9%	47%	8%	3%	33%	6%	8%	45%	8%
6	14	- - + -	1	2000	8	5	6%	9%	3%	11%	5%	0%	8%	1%	1%
6	11	- - + +	1	2000	8	9	20%	19%	2%	24%	29%	1%	23%	25%	2%
6	3	- + - -	1	6000	4	5	2%	5%	7%	3%	17%	2%	15%	41%	1%
6	9	- + - +	1	6000	4	9	10%	63%	14%	7%	41%	7%	7%	39%	6%
6	12	- + + -	1	6000	8	5	8%	1%	1%	15%	11%	1%	5%	1%	3%
6	1	- + + +	1	6000	8	9	28%	35%	1%	20%	21%	1%	22%	27%	0%
6	16	+ - - -	2	2000	4	5	23%	35%	3%	21%	31%	3%	20%	27%	2%
6	10	+ - - +	2	2000	4	9	5%	41%	8%	5%	33%	5%	1%	19%	1%
6	6	+ - + -	2	2000	8	5	4%	1%	4%	5%	1%	3%	11%	13%	4%
6	8	+ - + +	2	2000	8	9	29%	38%	0%	33%	40%	3%	31%	40%	1%
6	7	+ + - -	2	6000	4	5	23%	35%	3%	18%	23%	2%	20%	29%	3%
6	15	+ + - +	2	6000	4	9	5%	37%	7%	7%	35%	4%	6%	31%	3%
6	2	+ + + -	2	6000	8	5	5%	3%	4%	6%	7%	5%	15%	19%	3%
6	5	+ + + +	2	6000	8	9	29%	31%	4%	32%	42%	1%	34%	44%	2%
7	4	- - - -	1	2000	4	5	1%	19%	2%	8%	31%	3%	10%	34%	4%
7	13	- - - +	1	2000	4	9	24%	16%	7%	28%	38%	3%	34%	41%	6%
7	14	- - + -	1	2000	8	5	14%	6%	1%	7%	0%	2%	8%	3%	2%
7	11	- - + +	1	2000	8	9	3%	9%	2%	18%	19%	0%	15%	9%	1%
7	3	- + - -	1	6000	4	5	13%	44%	3%	10%	38%	3%	14%	47%	3%
7	9	- + - +	1	6000	4	9	19%	9%	11%	27%	31%	4%	32%	41%	5%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
7	12	- + + -	1	6000	8	5	12%	0%	3%	16%	19%	1%	8%	3%	2%
7	1	- + + +	1	6000	8	9	14%	16%	2%	19%	22%	0%	19%	19%	1%
7	16	+ - - -	2	2000	4	5	0%	13%	3%	8%	31%	3%	6%	28%	3%
7	10	+ - - +	2	2000	4	9	23%	22%	4%	20%	28%	1%	24%	38%	1%
7	6	+ - + -	2	2000	8	5	28%	44%	0%	31%	44%	3%	20%	34%	3%
7	8	+ - + +	2	2000	8	9	24%	22%	5%	18%	16%	1%	26%	41%	1%
7	7	+ + - -	2	6000	4	5	0%	16%	2%	10%	38%	3%	9%	34%	3%
7	15	+ + - +	2	6000	4	9	20%	16%	4%	22%	34%	2%	28%	53%	3%
7	2	+ + + -	2	6000	8	5	26%	34%	1%	15%	9%	1%	15%	19%	2%
7	5	+ + + +	2	6000	8	9	22%	19%	4%	16%	19%	1%	22%	34%	2%
8	4	- - - -	1	2000	4	5	18%	97%	37%	19%	107%	41%	22%	105%	38%
8	13	- - - +	1	2000	4	9	29%	20%	38%	27%	33%	43%	27%	37%	45%
8	14	- - + -	1	2000	8	5	31%	85%	20%	35%	103%	26%	33%	103%	28%
8	11	- - + +	1	2000	8	9	22%	56%	14%	20%	70%	22%	22%	70%	21%
8	3	- + - -	1	6000	4	5	33%	51%	3%	30%	56%	7%	26%	70%	17%
8	9	- + - +	1	6000	4	9	31%	24%	42%	29%	31%	43%	27%	31%	42%
8	12	- + + -	1	6000	8	5	26%	66%	15%	35%	97%	23%	29%	87%	23%
8	1	- + + +	1	6000	8	9	15%	64%	23%	18%	74%	26%	19%	70%	23%
8	16	+ - - -	2	2000	4	5	19%	89%	32%	23%	95%	32%	22%	99%	35%
8	10	+ - - +	2	2000	4	9	32%	12%	37%	31%	8%	34%	34%	8%	36%
8	6	+ - + -	2	2000	8	5	36%	62%	5%	33%	68%	11%	34%	72%	12%
8	8	+ - + +	2	2000	8	9	17%	54%	17%	24%	70%	19%	20%	64%	19%
8	7	+ + - -	2	6000	4	5	17%	83%	31%	20%	87%	30%	19%	93%	34%
8	15	+ + - +	2	6000	4	9	31%	14%	37%	32%	8%	35%	32%	8%	35%
8	2	+ + + -	2	6000	8	5	34%	51%	2%	35%	51%	1%	39%	66%	5%
8	5	+ + + +	2	6000	8	9	15%	49%	16%	15%	68%	25%	18%	64%	21%
9	4	- - - -	1	2000	4	5	79%	208%	31%	89%	225%	31%	85%	228%	36%
9	13	- - - +	1	2000	4	9	15%	135%	47%	3%	126%	52%	7%	131%	51%
9	14	- - + -	1	2000	8	5	73%	106%	9%	76%	165%	14%	77%	184%	22%
9	11	- - + +	1	2000	8	9	69%	177%	25%	70%	174%	23%	76%	184%	23%
9	3	- + - -	1	6000	4	5	97%	104%	28%	99%	121%	22%	97%	160%	4%
9	9	- + - +	1	6000	4	9	1%	111%	47%	4%	126%	51%	6%	131%	52%
9	12	- + + -	1	6000	8	5	70%	121%	0%	79%	167%	13%	80%	174%	15%
9	1	- + + +	1	6000	8	9	69%	172%	23%	69%	174%	24%	72%	169%	20%
9	16	+ - - -	2	2000	4	5	65%	172%	26%	77%	201%	29%	89%	225%	31%
9	10	+ - - +	2	2000	4	9	17%	60%	39%	8%	77%	40%	8%	75%	39%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
9	6	+ - + -	2	2000	8	5	73%	116%	5%	63%	145%	15%	72%	194%	30%
9	8	+ - + +	2	2000	8	9	75%	182%	23%	77%	179%	20%	75%	167%	16%
9	7	+ + - -	2	6000	4	5	58%	169%	30%	79%	208%	31%	90%	228%	31%
9	15	+ + - +	2	6000	4	9	14%	77%	44%	4%	89%	42%	11%	63%	36%
9	2	+ + + -	2	6000	8	5	70%	84%	16%	72%	128%	2%	68%	160%	19%
9	5	+ + + +	2	6000	8	9	73%	174%	21%	70%	167%	20%	70%	162%	18%
10	4	- - - -	1	2000	4	5	66%	202%	82%	72%	220%	87%	80%	233%	89%
10	13	- - - +	1	2000	4	9	17%	98%	81%	23%	90%	81%	16%	98%	79%
10	14	- - + -	1	2000	8	5	78%	144%	40%	70%	146%	47%	73%	152%	48%
10	11	- - + +	1	2000	8	9	28%	123%	63%	38%	150%	72%	38%	154%	74%
10	3	- + - -	1	6000	4	5	89%	171%	48%	92%	183%	52%	94%	206%	64%
10	9	- + - +	1	6000	4	9	25%	92%	83%	31%	84%	83%	16%	100%	81%
10	12	- + + -	1	6000	8	5	73%	134%	38%	73%	138%	40%	72%	154%	50%
10	1	- + + +	1	6000	8	9	25%	125%	66%	34%	152%	75%	31%	158%	81%
10	16	+ - - -	2	2000	4	5	56%	169%	70%	66%	200%	81%	66%	206%	84%
10	10	+ - - +	2	2000	4	9	23%	82%	76%	22%	92%	81%	19%	94%	79%
10	6	+ - + -	2	2000	8	5	72%	127%	35%	73%	152%	48%	70%	150%	49%
10	8	+ - + +	2	2000	8	9	22%	117%	64%	31%	127%	63%	33%	136%	68%
10	7	+ + - -	2	6000	4	5	52%	164%	70%	63%	198%	82%	67%	206%	83%
10	15	+ + - +	2	6000	4	9	19%	92%	78%	27%	86%	81%	28%	86%	82%
10	2	+ + + -	2	6000	8	5	77%	140%	39%	78%	148%	43%	70%	160%	55%
10	5	+ + + +	2	6000	8	9	20%	123%	69%	28%	129%	66%	33%	142%	71%
11	4	- - - -	1	2000	4	5	3%	57%	23%	8%	61%	22%	10%	70%	26%
11	13	- - - +	1	2000	4	9	32%	78%	54%	26%	99%	61%	24%	101%	61%
11	14	- - + -	1	2000	8	5	16%	61%	17%	8%	57%	20%	15%	78%	27%
11	11	- - + +	1	2000	8	9	34%	36%	34%	31%	42%	35%	26%	48%	35%
11	3	- + - -	1	6000	4	5	13%	17%	3%	10%	21%	1%	8%	23%	3%
11	9	- + - +	1	6000	4	9	27%	86%	55%	26%	101%	62%	24%	105%	63%
11	12	- + + -	1	6000	8	5	13%	57%	17%	5%	67%	27%	8%	59%	21%
11	1	- + + +	1	6000	8	9	32%	42%	36%	32%	40%	35%	29%	48%	37%
11	16	+ - - -	2	2000	4	5	0%	42%	17%	6%	49%	17%	6%	49%	17%
11	10	+ - - +	2	2000	4	9	42%	46%	44%	39%	55%	47%	29%	59%	43%
11	6	+ - + -	2	2000	8	5	27%	55%	8%	21%	70%	19%	21%	76%	22%
11	8	+ - + +	2	2000	8	9	18%	40%	27%	23%	40%	30%	19%	40%	28%
11	7	+ + - -	2	6000	4	5	2%	48%	19%	6%	51%	18%	6%	55%	20%
11	15	+ + - +	2	6000	4	9	37%	63%	50%	40%	59%	50%	31%	67%	48%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
11	2	+ + + -	2	6000	8	5	27%	61%	11%	19%	67%	18%	19%	69%	19%
11	5	+ + + +	2	6000	8	9	19%	55%	35%	29%	38%	33%	26%	32%	28%
12	4	- - - -	1	2000	4	5	2%	23%	5%	8%	37%	8%	8%	31%	5%
12	13	- - - +	1	2000	4	9	1%	76%	29%	6%	70%	31%	5%	76%	33%
12	14	- - + -	1	2000	8	5	8%	13%	3%	4%	7%	3%	7%	19%	1%
12	11	- - + +	1	2000	8	9	25%	18%	4%	25%	26%	1%	16%	10%	3%
12	3	- + - -	1	6000	4	5	26%	33%	6%	26%	50%	2%	32%	58%	2%
12	9	- + - +	1	6000	4	9	1%	80%	31%	6%	76%	34%	10%	68%	33%
12	12	- + + -	1	6000	8	5	7%	5%	6%	7%	11%	3%	7%	9%	4%
12	1	- + + +	1	6000	8	9	22%	4%	9%	26%	32%	1%	25%	20%	3%
12	16	+ - - -	2	2000	4	5	7%	23%	3%	5%	23%	3%	7%	25%	3%
12	10	+ - - +	2	2000	4	9	3%	62%	26%	3%	45%	19%	6%	39%	18%
12	6	+ - + -	2	2000	8	5	14%	15%	6%	5%	13%	1%	2%	2%	4%
12	8	+ - + +	2	2000	8	9	37%	24%	10%	29%	30%	2%	36%	34%	4%
12	7	+ + - -	2	6000	4	5	8%	23%	2%	7%	23%	3%	5%	25%	4%
12	15	+ + - +	2	6000	4	9	8%	52%	24%	3%	45%	19%	10%	33%	18%
12	2	+ + + -	2	6000	8	5	14%	15%	6%	9%	11%	5%	8%	9%	5%
12	5	+ + + +	2	6000	8	9	36%	22%	10%	36%	30%	6%	42%	45%	3%
13	4	- - - -	1	2000	4	5	7%	19%	0%	5%	4%	8%	3%	8%	8%
13	13	- - - +	1	2000	4	9	11%	70%	44%	9%	76%	45%	10%	65%	41%
13	14	- - + -	1	2000	8	5	1%	23%	9%	0%	5%	0%	2%	6%	6%
13	11	- - + +	1	2000	8	9	8%	70%	41%	10%	41%	30%	9%	26%	22%
13	3	- + - -	1	6000	4	5	0%	1%	2%	2%	10%	5%	2%	12%	6%
13	9	- + - +	1	6000	4	9	14%	67%	45%	10%	76%	46%	10%	72%	44%
13	12	- + + -	1	6000	8	5	0%	23%	8%	3%	16%	8%	2%	10%	1%
13	1	- + + +	1	6000	8	9	4%	76%	40%	10%	52%	35%	11%	34%	28%
13	16	+ - - -	2	2000	4	5	4%	21%	4%	5%	23%	4%	6%	21%	2%
13	10	+ - - +	2	2000	4	9	19%	43%	39%	14%	39%	32%	15%	43%	35%
13	6	+ - + -	2	2000	8	5	0%	27%	10%	2%	5%	2%	3%	5%	2%
13	8	+ - + +	2	2000	8	9	0%	54%	27%	10%	37%	28%	13%	17%	21%
13	7	+ + - -	2	6000	4	5	4%	23%	5%	5%	25%	5%	5%	25%	5%
13	15	+ + - +	2	6000	4	9	24%	43%	43%	15%	43%	35%	18%	50%	41%
13	2	+ + + -	2	6000	8	5	3%	23%	6%	4%	27%	7%	3%	5%	2%
13	5	+ + + +	2	6000	8	9	1%	63%	30%	11%	32%	27%	11%	17%	20%
14	4	- - - -	1	2000	4	5	7%	195%	76%	16%	207%	75%	26%	221%	74%
14	13	- - - +	1	2000	4	9	34%	131%	77%	31%	148%	81%	22%	152%	78%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
14	14	- - + -	1	2000	8	5	16%	126%	45%	25%	150%	48%	25%	176%	58%
14	11	- - + +	1	2000	8	9	3%	195%	79%	3%	186%	79%	3%	188%	76%
14	3	- + - -	1	6000	4	5	29%	136%	40%	29%	152%	46%	31%	155%	46%
14	9	- + - +	1	6000	4	9	39%	138%	82%	27%	152%	80%	31%	143%	79%
14	12	- + + -	1	6000	8	5	16%	112%	39%	19%	119%	40%	29%	157%	48%
14	1	- + + +	1	6000	8	9	0%	176%	73%	0%	188%	78%	1%	195%	79%
14	16	+ - - -	2	2000	4	5	0%	164%	69%	12%	198%	74%	14%	193%	70%
14	10	+ - - +	2	2000	4	9	43%	114%	76%	37%	126%	77%	33%	150%	83%
14	6	+ - + -	2	2000	8	5	13%	152%	56%	10%	167%	63%	20%	195%	68%
14	8	+ - + +	2	2000	8	9	17%	219%	79%	12%	188%	70%	12%	198%	74%
14	7	+ + - -	2	6000	4	5	4%	167%	67%	10%	183%	70%	13%	190%	70%
14	15	+ + - +	2	6000	4	9	37%	138%	81%	37%	138%	81%	36%	136%	79%
14	2	+ + + -	2	6000	8	5	1%	129%	54%	14%	169%	62%	7%	174%	68%
14	5	+ + + +	2	6000	8	9	1%	188%	77%	9%	195%	75%	16%	212%	77%
15	4	- - - -	1	2000	4	5	16%	13%	18%	5%	33%	20%	6%	27%	18%
15	13	- - - +	1	2000	4	9	24%	25%	29%	25%	33%	33%	23%	35%	32%
15	14	- - + -	1	2000	8	5	12%	7%	7%	8%	13%	13%	8%	25%	18%
15	11	- - + +	1	2000	8	9	12%	43%	29%	13%	37%	27%	13%	35%	26%
15	3	- + - -	1	6000	4	5	15%	19%	1%	14%	27%	5%	18%	41%	9%
15	9	- + - +	1	6000	4	9	32%	23%	33%	25%	27%	30%	28%	17%	28%
15	12	- + + -	1	6000	8	5	17%	13%	8%	12%	1%	10%	9%	19%	16%
15	1	- + + +	1	6000	8	9	12%	49%	31%	16%	35%	28%	16%	29%	25%
15	16	+ - - -	2	2000	4	5	21%	1%	16%	13%	15%	17%	6%	25%	17%
15	10	+ - - +	2	2000	4	9	31%	9%	26%	36%	3%	24%	37%	11%	22%
15	6	+ - + -	2	2000	8	5	9%	21%	1%	17%	3%	12%	17%	3%	15%
15	8	+ - + +	2	2000	8	9	20%	39%	32%	13%	39%	28%	12%	35%	25%
15	7	+ + - -	2	6000	4	5	20%	1%	15%	11%	17%	16%	5%	29%	18%
15	15	+ + - +	2	6000	4	9	37%	1%	27%	35%	1%	24%	31%	3%	23%
15	2	+ + + -	2	6000	8	5	20%	31%	2%	19%	5%	12%	19%	7%	11%
15	5	+ + + +	2	6000	8	9	17%	37%	29%	17%	29%	26%	16%	21%	22%
16	4	- - - -	1	2000	4	5	18%	20%	0%	15%	11%	2%	10%	5%	5%
16	13	- - - +	1	2000	4	9	21%	57%	35%	24%	57%	37%	29%	55%	39%
16	14	- - + -	1	2000	8	5	4%	7%	3%	5%	2%	1%	2%	0%	2%
16	11	- - + +	1	2000	8	9	4%	59%	20%	1%	50%	18%	2%	34%	13%
16	3	- + - -	1	6000	4	5	2%	11%	0%	5%	20%	2%	9%	39%	7%
16	9	- + - +	1	6000	4	9	23%	59%	37%	27%	61%	41%	30%	57%	41%

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
16	12	- + + -	1	6000	8	5	1%	2%	3%	7%	0%	1%	5%	0%	0%
16	1	- + + +	1	6000	8	9	7%	45%	21%	4%	43%	18%	4%	39%	16%
16	16	+ - - -	2	2000	4	5	33%	43%	0%	23%	32%	2%	24%	27%	1%
16	10	+ - - +	2	2000	4	9	26%	39%	30%	27%	32%	28%	29%	20%	25%
16	6	+ - + -	2	2000	8	5	8%	9%	12%	5%	9%	10%	1%	20%	11%
16	8	+ - + +	2	2000	8	9	14%	32%	20%	4%	48%	20%	1%	48%	18%
16	7	+ + - -	2	6000	4	5	29%	41%	2%	24%	27%	1%	21%	23%	1%
16	15	+ + - +	2	6000	4	9	32%	27%	29%	30%	23%	26%	29%	20%	25%
16	2	+ + + -	2	6000	8	5	9%	5%	11%	4%	7%	8%	2%	9%	8%
16	5	+ + + +	2	6000	8	9	18%	36%	25%	11%	36%	20%	13%	25%	16%
17	4	- - - -	1	2000	4	5	41%	108%	14%	48%	112%	11%	48%	121%	15%
17	13	- - - +	1	2000	4	9	7%	54%	25%	12%	43%	24%	10%	43%	22%
17	14	- - + -	1	2000	8	5	37%	34%	16%	31%	43%	8%	35%	61%	3%
17	11	- - + +	1	2000	8	9	26%	58%	3%	20%	58%	7%	31%	83%	10%
17	3	- + - -	1	6000	4	5	73%	130%	1%	72%	139%	6%	72%	146%	9%
17	9	- + - +	1	6000	4	9	10%	65%	32%	8%	50%	24%	11%	41%	22%
17	12	- + + -	1	6000	8	5	35%	34%	15%	33%	43%	9%	35%	58%	4%
17	1	- + + +	1	6000	8	9	16%	45%	4%	12%	61%	14%	24%	79%	13%
17	16	+ - - -	2	2000	4	5	47%	99%	6%	49%	108%	8%	51%	110%	8%
17	10	+ - - +	2	2000	4	9	12%	45%	25%	10%	43%	22%	14%	34%	21%
17	6	+ - + -	2	2000	8	5	40%	7%	31%	35%	14%	25%	31%	21%	19%
17	8	+ - + +	2	2000	8	9	17%	50%	5%	20%	41%	1%	21%	43%	1%
17	7	+ + - -	2	6000	4	5	44%	99%	8%	51%	112%	9%	52%	110%	7%
17	15	+ + - +	2	6000	4	9	5%	50%	22%	8%	38%	19%	12%	34%	20%
17	2	+ + + -	2	6000	8	5	38%	9%	29%	33%	9%	25%	30%	16%	20%
17	5	+ + + +	2	6000	8	9	10%	45%	8%	20%	38%	2%	23%	36%	5%
18	4	- - - -	1	2000	4	5	39%	71%	3%	39%	78%	0%	40%	90%	4%
18	13	- - - +	1	2000	4	9	4%	176%	59%	3%	185%	67%	7%	156%	58%
18	14	- - + -	1	2000	8	5	23%	41%	5%	28%	76%	6%	28%	80%	8%
18	11	- - + +	1	2000	8	9	9%	73%	16%	9%	80%	19%	31%	115%	19%
18	3	- + - -	1	6000	4	5	40%	66%	5%	40%	78%	1%	40%	90%	4%
18	9	- + - +	1	6000	4	9	2%	173%	61%	7%	183%	68%	7%	159%	59%
18	12	- + + -	1	6000	8	5	29%	54%	4%	26%	59%	0%	25%	73%	7%
18	1	- + + +	1	6000	8	9	3%	76%	21%	15%	88%	18%	22%	102%	20%
18	16	+ - - -	2	2000	4	5	34%	63%	3%	34%	63%	3%	31%	68%	1%
18	10	+ - - +	2	2000	4	9	5%	141%	51%	3%	159%	57%	18%	144%	60%

Continue on next page

Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
18	6	+ - + -	2	2000	8	5	36%	49%	9%	25%	80%	10%	25%	102%	18%
18	8	+ - + +	2	2000	8	9	15%	78%	14%	11%	80%	18%	12%	85%	19%
18	7	+ + - -	2	6000	4	5	36%	66%	3%	37%	63%	5%	36%	73%	0%
18	15	+ + - +	2	6000	4	9	7%	151%	56%	3%	168%	60%	21%	154%	65%
18	2	+ + + -	2	6000	8	5	37%	51%	9%	33%	95%	11%	26%	88%	11%
18	5	+ + + +	2	6000	8	9	12%	78%	16%	11%	80%	18%	15%	88%	18%
19	4	- - - -	1	2000	4	5	20%	43%	1%	21%	49%	3%	27%	53%	1%
19	13	- - - +	1	2000	4	9	41%	105%	62%	42%	105%	63%	35%	107%	60%
19	14	- - + -	1	2000	8	5	23%	22%	9%	14%	43%	5%	12%	57%	12%
19	11	- - + +	1	2000	8	9	21%	33%	4%	17%	37%	0%	20%	45%	2%
19	3	- + - -	1	6000	4	5	23%	45%	0%	24%	45%	1%	26%	45%	1%
19	9	- + - +	1	6000	4	9	41%	111%	65%	45%	103%	64%	38%	107%	61%
19	12	- + + -	1	6000	8	5	18%	35%	1%	14%	41%	4%	12%	51%	9%
19	16	+ - - -	2	2000	4	5	23%	29%	7%	26%	55%	3%	17%	47%	5%
19	10	+ - - +	2	2000	4	9	48%	63%	48%	45%	85%	56%	47%	85%	57%
19	6	+ - + -	2	2000	8	5	23%	6%	16%	17%	22%	6%	21%	47%	2%
19	8	+ - + +	2	2000	8	9	30%	33%	9%	29%	37%	7%	20%	33%	3%
19	7	+ + - -	2	6000	4	5	24%	31%	7%	26%	45%	1%	20%	45%	2%
19	15	+ + - +	2	6000	4	9	47%	73%	52%	50%	87%	60%	42%	97%	60%
19	2	+ + + -	2	6000	8	5	30%	0%	23%	27%	35%	7%	26%	43%	2%
19	5	+ + + +	2	6000	8	9	21%	37%	2%	27%	39%	5%	20%	29%	5%
20	4	- - - -	1	2000	4	5	37%	134%	29%	35%	134%	30%	38%	136%	29%
20	13	- - - +	1	2000	4	9	18%	157%	78%	24%	152%	80%	17%	180%	87%
20	14	- - + -	1	2000	8	5	23%	39%	3%	23%	76%	13%	12%	85%	26%
20	11	- - + +	1	2000	8	9	28%	125%	31%	27%	127%	33%	26%	134%	37%
20	3	- + - -	1	6000	4	5	21%	85%	19%	20%	83%	19%	23%	85%	18%
20	9	- + - +	1	6000	4	9	25%	145%	78%	29%	148%	82%	21%	171%	86%
20	12	- + + -	1	6000	8	5	20%	39%	1%	23%	71%	11%	19%	78%	18%
20	1	- + + +	1	6000	8	9	28%	125%	31%	30%	141%	37%	30%	148%	40%
20	16	+ - - -	2	2000	4	5	23%	101%	25%	33%	120%	26%	33%	125%	28%
20	10	+ - - +	2	2000	4	9	35%	104%	67%	38%	101%	68%	35%	111%	70%
20	6	+ - + -	2	2000	8	5	24%	74%	11%	23%	111%	29%	23%	122%	34%
20	8	+ - + +	2	2000	8	9	24%	104%	25%	24%	113%	29%	30%	118%	27%

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Online run	Offline template ID	Treatment combinations	Number of Tag Nodes	LQI sample size	Orientations at each grid location	Site survey grid locations	Individual Task Time Percentage Error								
							K low			K medium			K high		
							Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
20	7	+ + - -	2	6000	4	5	26%	94%	20%	34%	120%	25%	35%	127%	27%
20	15	+ + - +	2	6000	4	9	35%	113%	71%	33%	115%	71%	29%	125%	72%
20	2	+ + + -	2	6000	8	5	26%	83%	14%	26%	88%	16%	27%	104%	23%
20	5	+ + + +	2	6000	8	9	24%	106%	26%	24%	120%	32%	31%	120%	27%

Appendix K

LSD multiple comparisons of the offline templates based on workstation #1

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.0215555	0.0902963
1 - 3	*	**-0.15036**	0.0902963
1 - 4		-0.0678523	0.0902963
1 - 5		0.00387633	0.0902963
1 - 6		-0.0109747	0.0902963
1 - 7		-0.054438	0.0902963
1 - 8		-0.000539333	0.0902963
1 - 9		0.0590603	0.0902963
1 - 10		0.0278658	0.0902963
1 - 11		-0.00470767	0.0902963
1 - 12		-0.0170203	0.0902963
1 - 13		0.0634327	0.0902963
1 - 14		-0.0180702	0.0902963
1 - 15		0.028447	0.0902963
1 - 16		-0.0544008	0.0902963
2 - 3	*	**-0.128804**	0.0902963
2 - 4		-0.0462968	0.0902963
2 - 5		0.0254318	0.0902963
2 - 6		0.0105808	0.0902963
2 - 7		-0.0328825	0.0902963
2 - 8		0.0210162	0.0902963
2 - 9		0.0806158	0.0902963
2 - 10		0.0494213	0.0902963
2 - 11		0.0168478	0.0902963
2 - 12		0.00453517	0.0902963
2 - 13		0.0849882	0.0902963
2 - 14		0.00348533	0.0902963
2 - 15		0.0500025	0.0902963
2 - 16		-0.0328453	0.0902963
3 - 4		0.0825073	0.0902963
3 - 5	*	**0.154236**	0.0902963
3 - 6	*	**0.139385**	0.0902963
3 - 7	*	**0.0959217**	0.0902963
3 - 8	*	**0.14982**	0.0902963
3 - 9	*	**0.20942**	0.0902963
3 - 10	*	**0.178225**	0.0902963
3 - 11	*	**0.145652**	0.0902963
3 - 12	*	**0.133339**	0.0902963
3 - 13	*	**0.213792**	0.0902963
3 - 14	*	**0.13229**	0.0902963
3 - 15	*	**0.178807**	0.0902963
3 - 16	*	**0.0959588**	0.0902963
4 - 5		0.0717287	0.0902963
4 - 6		0.0568777	0.0902963
4 - 7		0.0134143	0.0902963
4 - 8		0.067313	0.0902963
4 - 9	*	**0.126913**	0.0902963

Contrast	*Sig.*	*Difference*	*+/- Limits*
4 - 10	*	**0.0957182**	0.0902963
4 - 11		0.0631447	0.0902963
4 - 12		0.050832	0.0902963
4 - 13	*	**0.131285**	0.0902963
4 - 14		0.0497822	0.0902963
4 - 15	*	**0.0962993**	0.0902963
4 - 16		0.0134515	0.0902963
5 - 6		-0.014851	0.0902963
5 - 7		-0.0583143	0.0902963
5 - 8		-0.00441567	0.0902963
5 - 9		0.055184	0.0902963
5 - 10		0.0239895	0.0902963
5 - 11		-0.008584	0.0902963
5 - 12		-0.0208967	0.0902963
5 - 13		0.0595563	0.0902963
5 - 14		-0.0219465	0.0902963
5 - 15		0.0245707	0.0902963
5 - 16		-0.0582772	0.0902963
6 - 7		-0.0434633	0.0902963
6 - 8		0.0104353	0.0902963
6 - 9		0.070035	0.0902963
6 - 10		0.0388405	0.0902963
6 - 11		0.006267	0.0902963
6 - 12		-0.00604567	0.0902963
6 - 13		0.0744073	0.0902963
6 - 14		-0.0070955	0.0902963
6 - 15		0.0394217	0.0902963
6 - 16		-0.0434262	0.0902963
7 - 8		0.0538987	0.0902963
7 - 9	*	**0.113498**	0.0902963
7 - 10		0.0823038	0.0902963
7 - 11		0.0497303	0.0902963
7 - 12		0.0374177	0.0902963
7 - 13	*	**0.117871**	0.0902963
7 - 14		0.0363678	0.0902963
7 - 15		0.082885	0.0902963
7 - 16		0.0000371667	0.0902963
8 - 9		0.0595997	0.0902963
8 - 10		0.0284052	0.0902963
8 - 11		-0.00416833	0.0902963
8 - 12		-0.016481	0.0902963
8 - 13		0.063972	0.0902963
8 - 14		-0.0175308	0.0902963
8 - 15		0.0289863	0.0902963
8 - 16		-0.0538615	0.0902963
9 - 10		-0.0311945	0.0902963
9 - 11		-0.063768	0.0902963

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Contrast	*Sig.*	*Difference*	*+/- Limits*
9 - 12		-0.0760807	0.0902963
9 - 13		0.00437233	0.0902963
9 - 14		-0.0771305	0.0902963
9 - 15		-0.0306133	0.0902963
9 - 16	*	**-0.113461**	0.0902963
10 - 11		-0.0325735	0.0902963
10 - 12		-0.0448862	0.0902963
10 - 13		0.0355668	0.0902963
10 - 14		-0.045936	0.0902963
10 - 15		0.000581167	0.0902963
10 - 16		-0.0822667	0.0902963
11 - 12		-0.0123127	0.0902963
11 - 13		0.0681403	0.0902963
11 - 14		-0.0133625	0.0902963

Contrast	*Sig.*	*Difference*	*+/- Limits*
11 - 15		0.0331547	0.0902963
11 - 16		-0.0496932	0.0902963
12 - 13		0.080453	0.0902963
12 - 14		-0.00104983	0.0902963
12 - 15		0.0454673	0.0902963
12 - 16		-0.0373805	0.0902963
13 - 14		-0.0815028	0.0902963
13 - 15		-0.0349857	0.0902963
13 - 16	*	**-0.117833**	0.0902963
14 - 15		0.0465172	0.0902963
14 - 16		-0.0363307	0.0902963
15 - 16		-0.0828478	0.0902963

* denotes a statistically significant difference

Homogeneous groups derived from the LSD multiple comparisons

Method: 95.0 percent LSD

Offline template VS. Station1	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
13	60	0.198898	0.0324383	X
9	60	0.20327	0.0324383	X
15	60	0.233883	0.0324383	XX
10	60	0.234464	0.0324383	XX
5	60	0.258454	0.0324383	XXX
1	60	0.26233	0.0324383	XXX
8	60	0.26287	0.0324383	XXX
11	60	0.267038	0.0324383	XXX
6	60	0.273305	0.0324383	XXX
12	60	0.279351	0.0324383	XXX
14	60	0.2804	0.0324383	XXX
2	60	0.283886	0.0324383	XXX
16	60	0.316731	0.0324383	XX
7	60	0.316768	0.0324383	XX
4	60	0.330182	0.0324383	XX
3	60	0.41269	0.0324383	X

Appendix L

LSD multiple comparisons of the offline templates based on workstation #2

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	*	**0.331938**	0.165766
1 - 3		-0.028539	0.165766
1 - 4		-0.0682998	0.165766
1 - 5		0.080443	0.165766
1 - 6	*	**0.306809**	0.165766
1 - 7		0.0294523	0.165766
1 - 8		0.0593725	0.165766
1 - 9		-0.0194757	0.165766
1 - 10	*	**0.186817**	0.165766
1 - 11		0.007358	0.165766
1 - 12	*	**0.311276**	0.165766
1 - 13		-0.0181897	0.165766
1 - 14	*	**0.276474**	0.165766
1 - 15	*	**0.174719**	0.165766
1 - 16		0.0279475	0.165766
2 - 3	*	**-0.360477**	0.165766
2 - 4	*	**-0.400238**	0.165766
2 - 5	*	**-0.251495**	0.165766
2 - 6		-0.025129	0.165766
2 - 7	*	**-0.302486**	0.165766
2 - 8	*	**-0.272566**	0.165766
2 - 9	*	**-0.351414**	0.165766
2 - 10		-0.145121	0.165766
2 - 11	*	**-0.32458**	0.165766
2 - 12		-0.0206623	0.165766
2 - 13	*	**-0.350128**	0.165766
2 - 14		-0.0554648	0.165766
2 - 15		-0.157219	0.165766
2 - 16	*	**-0.303991**	0.165766
3 - 4		-0.0397608	0.165766
3 - 5		0.108982	0.165766
3 - 6	*	**0.335348**	0.165766
3 - 7		0.0579913	0.165766
3 - 8		0.0879115	0.165766
3 - 9		0.00906333	0.165766
3 - 10	*	**0.215356**	0.165766
3 - 11		0.035897	0.165766
3 - 12	*	**0.339815**	0.165766
3 - 13		0.0103493	0.165766
3 - 14	*	**0.305013**	0.165766
3 - 15	*	**0.203258**	0.165766
3 - 16		0.0564865	0.165766
4 - 5		0.148743	0.165766
4 - 6	*	**0.375109**	0.165766
4 - 7		0.0977522	0.165766
4 - 8		0.127672	0.165766
4 - 9		0.0488242	0.165766
4 - 10	*	**0.255117**	0.165766
4 - 11		0.0756578	0.165766
4 - 12	*	**0.379576**	0.165766
4 - 13		0.0501102	0.165766
4 - 14	*	**0.344773**	0.165766
4 - 15	*	**0.243019**	0.165766
4 - 16		0.0962473	0.165766
5 - 6	*	**0.226366**	0.165766
5 - 7		-0.0509907	0.165766
5 - 8		-0.0210705	0.165766
5 - 9		-0.0999187	0.165766
5 - 10		0.106374	0.165766
5 - 11		-0.073085	0.165766
5 - 12	*	**0.230833**	0.165766
5 - 13		-0.0986327	0.165766
5 - 14	*	**0.196031**	0.165766
5 - 15		0.0942763	0.165766
5 - 16		-0.0524955	0.165766
6 - 7	*	**-0.277357**	0.165766
6 - 8	*	**-0.247437**	0.165766
6 - 9	*	**-0.326285**	0.165766
6 - 10		-0.119992	0.165766
6 - 11	*	**-0.299451**	0.165766
6 - 12		0.00446667	0.165766
6 - 13	*	**-0.324999**	0.165766
6 - 14		-0.0303358	0.165766
6 - 15		-0.13209	0.165766
6 - 16	*	**-0.278862**	0.165766
7 - 8		0.0299202	0.165766
7 - 9		-0.048928	0.165766
7 - 10		0.157365	0.165766
7 - 11		-0.0220943	0.165766
7 - 12	*	**0.281824**	0.165766
7 - 13		-0.047642	0.165766
7 - 14	*	**0.247021**	0.165766
7 - 15		0.145267	0.165766
7 - 16		-0.00150483	0.165766
8 - 9		-0.0788482	0.165766
8 - 10		0.127445	0.165766
8 - 11		-0.0520145	0.165766
8 - 12	*	**0.251904**	0.165766
8 - 13		-0.0775622	0.165766
8 - 14	*	**0.217101**	0.165766
8 - 15		0.115347	0.165766
8 - 16		-0.031425	0.165766
9 - 10	*	**0.206293**	0.165766
9 - 11		0.0268337	0.165766

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Contrast	*Sig.*	*Difference*	*+/- Limits*
9 - 12	*	**0.330752**	0.165766
9 - 13		0.001286	0.165766
9 - 14	*	**0.295949**	0.165766
9 - 15	*	**0.194195**	0.165766
9 - 16		0.0474232	0.165766
10 - 11	*	**-0.179459**	0.165766
10 - 12		0.124459	0.165766
10 - 13	*	**-0.205007**	0.165766
10 - 14		0.0896563	0.165766
10 - 15		-0.0120978	0.165766
10 - 16		-0.15887	0.165766
11 - 12	*	**0.303918**	0.165766
11 - 13		-0.0255477	0.165766
11 - 14	*	**0.269116**	0.165766

Contrast	*Sig.*	*Difference*	*+/- Limits*
11 - 15	*	**0.167361**	0.165766
11 - 16		0.0205895	0.165766
12 - 13	*	**-0.329466**	0.165766
12 - 14		-0.0348025	0.165766
12 - 15		-0.136557	0.165766
12 - 16	*	**-0.283329**	0.165766
13 - 14	*	**0.294663**	0.165766
13 - 15	*	**0.192909**	0.165766
13 - 16		0.0461372	0.165766
14 - 15		-0.101754	0.165766
14 - 16	*	**-0.248526**	0.165766
15 - 16		-0.146772	0.165766

* denotes a statistically significant difference

Homogeneous groups derived from the LSD multiple comparisons

Method: 95.0 percent LSD

Offline template VS. Station1	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
2	60	0.490909	0.0595501	X
12	60	0.511571	0.0595501	X
6	60	0.516038	0.0595501	X
14	60	0.546374	0.0595501	X
10	60	0.63603	0.0595501	XX
15	60	0.648128	0.0595501	XX
5	60	0.742404	0.0595501	XX
8	60	0.763475	0.0595501	XX
7	60	0.793395	0.0595501	XX
16	60	0.7949	0.0595501	XX
11	60	0.815489	0.0595501	X
1	60	0.822847	0.0595501	X
13	60	0.841037	0.0595501	X
9	60	0.842323	0.0595501	X
3	60	0.851386	0.0595501	X
4	60	0.891147	0.0595501	X

Appendix M

LSD multiple comparisons of the offline templates based on workstation #3

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	*	**0.0865485**	0.0623115
1 - 3	*	**0.121705**	0.0623115
1 - 4		0.0353245	0.0623115
1 - 5		0.0212912	0.0623115
1 - 6	*	**0.0754938**	0.0623115
1 - 7	*	**0.0661787**	0.0623115
1 - 8		0.0284423	0.0623115
1 - 9	*	**-0.174575**	0.0623115
1 - 10	*	**-0.0978925**	0.0623115
1 - 11		0.0130905	0.0623115
1 - 12	*	**0.106872**	0.0623115
1 - 13	*	**-0.158601**	0.0623115
1 - 14	*	**0.0949087**	0.0623115
1 - 15	*	**-0.107016**	0.0623115
1 - 16	*	**0.0674873**	0.0623115
2 - 3		0.0351567	0.0623115
2 - 4		-0.051224	0.0623115
2 - 5	*	**-0.0652573**	0.0623115
2 - 6		-0.0110547	0.0623115
2 - 7		-0.0203698	0.0623115
2 - 8		-0.0581062	0.0623115
2 - 9	*	**-0.261123**	0.0623115
2 - 10	*	**-0.184441**	0.0623115
2 - 11	*	**-0.073458**	0.0623115
2 - 12		0.0203233	0.0623115
2 - 13	*	**-0.24515**	0.0623115
2 - 14		0.00836017	0.0623115
2 - 15	*	**-0.193564**	0.0623115
2 - 16		-0.0190612	0.0623115
3 - 4	*	**-0.0863807**	0.0623115
3 - 5	*	**-0.100414**	0.0623115
3 - 6		-0.0462113	0.0623115
3 - 7		-0.0555265	0.0623115
3 - 8	*	**-0.0932628**	0.0623115
3 - 9	*	**-0.29628**	0.0623115
3 - 10	*	**-0.219598**	0.0623115
3 - 11	*	**-0.108615**	0.0623115
3 - 12		-0.0148333	0.0623115
3 - 13	*	**-0.280307**	0.0623115
3 - 14		-0.0267965	0.0623115
3 - 15	*	**-0.228721**	0.0623115
3 - 16		-0.0542178	0.0623115
4 - 5		-0.0140333	0.0623115
4 - 6		0.0401693	0.0623115
4 - 7		0.0308542	0.0623115
4 - 8		-0.00688217	0.0623115
4 - 9	*	**-0.209899**	0.0623115
4 - 10	*	**-0.133217**	0.0623115
4 - 11		-0.022234	0.0623115
4 - 12	*	**0.0715473**	0.0623115
4 - 13	*	**-0.193926**	0.0623115
4 - 14		0.0595842	0.0623115
4 - 15	*	**-0.14234**	0.0623115
4 - 16		0.0321628	0.0623115
5 - 6		0.0542027	0.0623115
5 - 7		0.0448875	0.0623115
5 - 8		0.00715117	0.0623115
5 - 9	*	**-0.195866**	0.0623115
5 - 10	*	**-0.119184**	0.0623115
5 - 11		-0.00820067	0.0623115
5 - 12	*	**0.0855807**	0.0623115
5 - 13	*	**-0.179893**	0.0623115
5 - 14	*	**0.0736175**	0.0623115
5 - 15	*	**-0.128307**	0.0623115
5 - 16		0.0461962	0.0623115
6 - 7		-0.00931517	0.0623115
6 - 8		-0.0470515	0.0623115
6 - 9	*	**-0.250069**	0.0623115
6 - 10	*	**-0.173386**	0.0623115
6 - 11	*	**-0.0624033**	0.0623115
6 - 12		0.031378	0.0623115
6 - 13	*	**-0.234095**	0.0623115
6 - 14		0.0194148	0.0623115
6 - 15	*	**-0.18251**	0.0623115
6 - 16		-0.0080065	0.0623115
7 - 8		-0.0377363	0.0623115
7 - 9	*	**-0.240754**	0.0623115
7 - 10	*	**-0.164071**	0.0623115
7 - 11		-0.0530882	0.0623115
7 - 12		0.0406932	0.0623115
7 - 13	*	**-0.22478**	0.0623115
7 - 14		0.02873	0.0623115
7 - 15	*	**-0.173194**	0.0623115
7 - 16		0.00130867	0.0623115
8 - 9	*	**-0.203017**	0.0623115
8 - 10	*	**-0.126335**	0.0623115
8 - 11		-0.0153518	0.0623115
8 - 12	*	**0.0784295**	0.0623115
8 - 13	*	**-0.187044**	0.0623115
8 - 14	*	**0.0664663**	0.0623115
8 - 15	*	**-0.135458**	0.0623115
8 - 16		0.039045	0.0623115
9 - 10	*	**0.0766823**	0.0623115
9 - 11	*	**0.187665**	0.0623115

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Contrast	*Sig.*	*Difference*	*+/- Limits*
9 - 12	*	**0.281447**	0.0623115
9 - 13		0.0159733	0.0623115
9 - 14	*	**0.269484**	0.0623115
9 - 15	*	**0.067559**	0.0623115
9 - 16	*	**0.242062**	0.0623115
10 - 11	*	**0.110983**	0.0623115
10 - 12	*	**0.204764**	0.0623115
10 - 13		-0.060709	0.0623115
10 - 14	*	**0.192801**	0.0623115
10 - 15		-0.00912333	0.0623115
10 - 16	*	**0.16538**	0.0623115
11 - 12	*	**0.0937813**	0.0623115
11 - 13	*	**-0.171692**	0.0623115
11 - 14	*	**0.0818182**	0.0623115

Contrast	*Sig.*	*Difference*	*+/- Limits*
11 - 15	*	**-0.120106**	0.0623115
11 - 16		0.0543968	0.0623115
12 - 13	*	**-0.265473**	0.0623115
12 - 14		-0.0119632	0.0623115
12 - 15	*	**-0.213888**	0.0623115
12 - 16		-0.0393845	0.0623115
13 - 14	*	**0.25351**	0.0623115
13 - 15		0.0515857	0.0623115
13 - 16	*	**0.226089**	0.0623115
14 - 15	*	**-0.201924**	0.0623115
14 - 16		-0.0274213	0.0623115
15 - 16	*	**0.174503**	0.0623115

* denotes a statistically significant difference

Homogeneous groups derived from the LSD multiple comparisons

Method: 95.0 percent LSD

Offline template VS. Station1	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
3	60	0.119918	0.0223849	X
12	60	0.134752	0.0223849	X
14	60	0.146715	0.0223849	XX
2	60	0.155075	0.0223849	XXX
6	60	0.166129	0.0223849	XXXX
16	60	0.174136	0.0223849	XXXXX
7	60	0.175445	0.0223849	XXXXX
4	60	0.206299	0.0223849	XXXXX
8	60	0.213181	0.0223849	XXXX
5	60	0.220332	0.0223849	XXX
11	60	0.228533	0.0223849	XX
1	60	0.241623	0.0223849	X
10	60	0.339516	0.0223849	X
15	60	0.348639	0.0223849	X
13	60	0.400225	0.0223849	XX
9	60	0.416198	0.0223849	X