Enabling location awareness with automatic reprogrammable context-sensitive bio-bridge middleware for smart bio-laboratories

For, Wei Khing

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**Enabling Location Awareness with
Automatic-Reprogrammable
Context-Sensitive Bio-Bridge Middleware for
Smart Bio-Laboratories**

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Master of Engineering

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Acknowledgments

In retrospect of the past 18 months over which this project was carried out, it would be difficult to envisage the success of this project without the support and encouragement of several people.

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Summary

With the recent advances in genomic research and biotechnology, ubiquitous smart services are required in a bio-laboratory to simplify complex experiments that are now routine. In this thesis, we show that with our custom-designed Bio-Bridge (BB) device — a smart middleware that possesses: (a) a common interface platform for communication between multi-vendor bio-instruments and mobile devices; (b) next-generation middleware characteristics such as transparent computing and awareness functionalities; and (c) low-cost scalability and easy reprogrammable. We can provide a *scalable unwired* Smart Lab platform with *location awareness* feature for operation in the common IEEE 802.11b wireless network environment. We propose novel solutions to investigate two of the challenging research issues on BB device, namely: reprogrammable and context-sensitive computing. In addition, we also describe a novel Stochastic Positioning by Interpolated Radial Mapping (SPIRM) method devised for enabling a low-cost small-scale relative positioning engine operating in smart laboratory platform. Our results show that SPIRM method can provide accurate relative positioning for the virtual linking of man and machine in the smart laboratory.

Contents

1	Introduction	1
1.1	Motivation	6
1.2	Objectives	7
1.3	Major contribution of the Thesis	8
1.3.1	BB Devices	9
1.3.2	Location Awareness	11
1.3.3	Other Smart Applications	12
1.4	Organization of the Thesis	13
2	Smart Laboratory Project	15
2.1	Introduction	15
2.2	System Architecture	17
2.3	Smart lab Components	19
2.3.1	Bio-Bridge (BB) Device	19
2.3.2	Service Gateway	19

2.3.3	Bio-instrumnet	21
2.3.4	Lab Users	22
2.4	Ubiquitous Multi-Modal Access to Bio-instrument (Scenarios)	23
2.5	Conclusion	25
3	Related Work	27
3.1	Introduction	27
3.2	Labscape	28
3.3	Indoor Positioning Systems	28
3.3.1	RADAR	30
3.3.2	Ekahau	31
3.3.3	Hitachi AirLocation	33
3.3.4	Ubisense	34
3.4	Our Approach's Novelty	35
3.5	Conclusion	36
4	Our Work: Novel BioBridge (BB) Device Design	37
4.1	Introduction	37
4.2	Applications of BB Device in Smart Lab	43
4.2.1	Unwired Lab Equipment Access	43
4.2.2	Smart e-Post-It-Note	44
4.3	Automatic Reprogrammable	45

4.4	Context Sensitivity	47
4.5	Limitations	49
4.6	Conclusion	50
5	Our Work: Novel Proximity-Awareness Method	51
5.1	Introduction	51
5.2	Small-Scale Proximity Problem	52
5.3	Evaluation	54
5.3.1	Methodology	54
5.3.2	Direct Comparison Method	60
5.3.3	K-Nearest Neighbor (K-NN)	62
5.3.4	SPIRM	65
5.4	Results	70
5.5	Conclusion	74
6	Conclusions and Discussions	75
6.1	Conclusions	75
6.2	Recommendations for further research	77
7	Author's Publication	80

List of Figures

1.1	Physical wired link is removed and replaced by BB device to provide a common platform for unwired remote monitoring and controlling of bio-instruments	10
2.1	Smart Lab architecture	18
2.2	Service Gateway Block Diagram	20
2.3	3 Scenarios for Smart Lab Platform	23
2.4	Multi-modal remote access on a user’s laptop and PDA	24
3.1	Ekahau Positioning Engine System (quote from [5])	32
3.2	Ekahau Wi-fi Tag (quote from [5])	32
3.3	Hitachi AirLocation System (quote from [3])	33
3.4	Ubisense Tag (quote from [12])	34
4.1	BB Device’s Technical Block Diagram	38
4.2	Software architecture of BB device	39

4.3 User friendly GUI for configurations of BB device 40

4.4 A bio-instrument (a thermal cyclers for polymerase chain reaction) connected to a prototype BB device. 42

4.5 Listener Hardware 47

4.6 Hardware setup for reprogramming of command set in BB device 48

5.1 Relative Proximity is needed for intelligent virtual linking . . . 53

5.2 Experiment Setup: Data Collection 55

5.3 Locations of SS Data Collection 57

5.4 Radiation Pattern of Single BB Device 58

5.5 Radiation Patterns of 2 BB Devices 58

5.6 Radiation Patterns for the Same BB Device at Different Times 59

5.7 Shaded area shows a problematic region. 59

5.8 (a) Distribution of SS in Non-shaded Area of Figure 5.3; (b) Distribution in Shaded Region of Figure 5.3 62

5.9 Poor Estimations by Direct Comparison Method. The 5 marked locations experienced worst performance. 72

List of Tables

5.1 Comparative performance between SPIRM, K-NN and Direct
Comparison. (The numbered locations refer to those labeled
in Figure 5.9.) 73

Chapter 1

Introduction

The proliferation of low power consumption wireless access mobile devices together with the emergence of advances in technologies for embedding computing power in virtually every device, appliance, and piece of equipment, have led to the dawn of the so-called post-PC era of pervasive computing. There are already numerous pervasive computing implementations of smart spaces in terms of smart homes[44, 57], smart museums[24], smart tour guide[28, 29], smart towns[18, 55, 62], smart offices[13, 69], smart healthcare environment[21, 33, 38] and so on. These smart spaces embed human living and work spaces with computers, information appliances, and multi-modal sensors in such a way that they employ pervasive computing to make computers “disappear”—by moving computation beyond desktop PCs onto large numbers of dispersed heterogeneous information and communication devices,

seamlessly coordinated to deliver powerful information services to people.

At the same time, biology is no longer a cottage industry to be carried out by bench scientists in humble petri-dishes in the so-called post-genome era marked by the recent completion of the sequencing of the human genome. With the recent successful completion of the Human Genome Project[47, 65], technologies for large-scale, genome-level experimental investigations of biology, together with the advent of new computationally-based cross-disciplines such as bioinformatics, have led to an evident increase in the level of technological sophistication in today's biology laboratories. Continued innovation in lab processes and instrumentation has yielded new bio-technologies, enhancing laboratory productivity in such areas as high-throughput syntheses and screening, but, simultaneously, has brought about a vast increase in the numbers of samples and experiments to be processed in much less time, putting unprecedented pressure on lab personnels. Complex experiments are now routinely carried out in the labs on high-tech computer-controlled biotech equipment, requiring lab scientists not only to be experts in their respective biological domains, but they must also be technologically and computationally savvy at the same time. Moreover, to conduct a biological experiment, a lab scientist needs to move about in the laboratory from one work station to another to carry out different subtasks as the lab-instruments are often shared and stationed in different parts of the laboratory. As such, the bio-

laboratory, with its dispersed heterogeneous experimentation devices and its increasing needs for bio-computation, makes it a perfect candidate for smart technology deployment.

There are several specific characteristics and requirements of the modern biology laboratory that make it particularly amenable to implementation of smart technologies:

- *Computerization of the wet lab.* Biology is following in the footsteps of physics and chemistry and becoming highly computerized in response to the significant volume of data being generated and the computational grand challenges of managing and analyzing the experimental data. Because of the increasingly sophisticated experimental steps being performed in the laboratory, computers have now become a common fixture in a modern bio-laboratory as most of the lab equipment now require a dedicated desktop computer connected to each of them for user control and monitoring. Technologies for smart environments will be applicable to address the evidently increasing computational needs in the wet lab.
- *Meticulous record keeping and data capture in the lab.* The primary objective of a biology laboratory is to generate new intellectual property from the information gathered through performing experiments.

The process by which the information are generated must therefore be meticulously recorded and the data faithfully captured by the scientists. In this respect, the bio-lab is a space whereby the physical and information aspects are highly entwined. As such, it provides an excellent domain for deploying smart technologies designated to seamlessly integrate the disparate physical and information aspects of the laboratory environment.

- *High degree of personal mobility and device heterogeneity in the lab.* It is common for a biological experiment to involve multiple lengthy operations performed on different lab instruments that are often shared and stationed at different areas in the laboratory. This results in frequent physical movements of the scientists in the laboratory for the coordination and progress monitoring of multiple heterogeneous laboratory devices. This inherently dynamic and heterogeneous environment is well-suited for smart technology deployments.
- *Semi-structured work flow in the lab.* Unlike other less well-defined environments like smart homes or smart offices, biology laboratories house specially-trained people engaged in complex but well-structured goal-oriented activities. The highly procedural work processes in the lab are therefore more predictable as there are specific protocols that

have to be followed—in a semi-strict fashion at the very least—when performing a biology experiment. Since the work processes also require constant monitoring by default, the laboratory is therefore an excellent candidate for becoming a smart space.

In this project, we focus on providing a common platform for integrating the heterogeneous lab instruments in the Smart Lab with the necessary intelligence to detect and establish the communication links with a user automatically and wirelessly. This allows the lab scientist to move about freely from one work station to another in the lab, using his personal computing device - such as a laptop, PDA or even a mobile phone - to perform experimental procedures on various lab equipment in a truly mobile fashion. As such, we have designed and implemented Smart Lab to provide a *scalable smart unwired access infrastructure* with *location awareness* feature operating in the common IEEE 802.11b wireless network. As a result, the smart bio-laboratory is not only an integrated ubiquitous unwired access platform for multi-vendor computer controlled biotech equipment, it is also a location-aware platform for on-the-move unwired access of lab equipment to address the unique need for frequent physical movements of the scientists operating in the heterogeneous bio-instruments lab environment.

1.1 Motivation

In current “wet lab”¹ environment, scientist required frequent physical movement to work in different laboratories to carry out an experiment. For example, a typical proteomics laboratory includes lab instruments for protein separation, imaging, and robotics sample preparation, and mass spectrometers, computers, and advanced software. To conduct a biological experiment, a lab scientist would need to move about in the laboratory from one workstation to another to carry out different subtasks. In fact, a busy biologist can change locations as high as a total of 76 times in the span of 60 minutes (i.e. more than once per minute) as reported in [15]. In addition, because of the increasing complexity of bio-equipments, most of the equipments in a post-genome laboratory require dedicated desktop computers to control the sophisticated experimental steps being performed. This is not only takes up the valuable bench space in the laboratory but also constrains the scientist to a static place for a lengthy experiment to monitor progress

¹The “wet laboratories” in this thesis refer to the traditional bio-laboratories where biological (“wet”) experiments are carried at the lab benches. The “dry laboratories”, on the other hand, are a new kind of bio-laboratories in the form of computer labs - intelligent and paperless laboratory, where *bioinformatics*—a new computationally-based cross-discipline between computer science and biology—is the primary tool used to analyze the massive biological data generated in the wet laboratories.

and control adjustment due to the conventional wired setup. Hence, there is a need in integrating heterogeneous equipment for remote monitoring and controlling in order to improve the quality and productivity of scientists' experimentations. As such, we envision to create Smart Bio-Laboratories of the Future[51], where computing technologies are deployed pervasively and unobtrusively within the wet laboratories to create an intelligent and paperless laboratory environment for better biological research at the bench.

1.2 Objectives

To deal with the above deficiency in current lab environment, we developed a Smart Lab platform in an IEEE 802.11b wireless networks that is able to provide *scalable smart unwired access infrastructure* with a *location awareness* feature that enables seamless communication between *man, machine and computer* to address:

1. *Heterogeneous lab instruments.* - custom designed embedded system - BioBridge (BB) devices provide a common interface platform for the multi-vendor bio-instruments by replacing the dedicated wired connection. Each of our BB device has a programmable controller so that the command sets of a bio-equipment can be easily programmed into the device for controlling the specific bio-equipment. This provides for easy

reprogramming that is necessary for the integration of heterogeneous bio-equipment integration in the lab where each bio-equipment is fitted with a BB device as the common platform for integrated communication and control.

2. *Mobile lab scientists.* - through small-scale relative positioning of our custom-designed embedded devices (“BioBridge (BB) devices”) attached to bio-equipment in the lab, we can provide the essential location awareness feature for intelligent on-the-move access of lab equipment in a smart bio-laboratory. A novel Stochastic Positioning by Interpolated Radial Mapping (SPIRM) method is devised for implementing a low-cost small-scale relative positioning engine in a smart laboratory operating in the popular IEEE 802.11b based wireless network environment.

1.3 Major contribution of the Thesis

We have designed and implemented a Smart Lab platform in an IEEE 802.11b ad hoc network that is able to provide integrated ubiquitous unwired access platform for multi-vendor computer controlled biotech equipments so that lab user is able to remotely monitoring and accessing of heterogeneous lab instruments. In addition, we have also provided on-the-move unwired access of lab equipment to address the need for frequent physical movements of the

scientists operating in the lab environment. With this implementation, we have converted the “pen and paper” based “wet-lab” to an intelligent and paperless laboratory environment for better biological research at the bench.

1.3.1 BB Devices

BB device is an embedded system that possesses: (a) a common interface platform for communication between multi-vendor bio-instruments and mobile devices; (b) next-generation middleware characteristics such as transparent computing and awareness functionalities[25]; and (c) low-cost scalability and easy reprogrammable, attached to every bio-instrument to form an unwired virtual link between lab user and bio-instrument. In Smart Lab, BB device has replaced the bulky PC and the dedicated wired connection between the PC and the bio-instrument (Figure 1.1). With the BB device, user with his laptop, PDA or even hand phone in the near future can connect to the BB device directly and access the bio-instrument when they are in the lab. When they are not in the lab, the user can access the bio-instrument through the service gateway which is configured to connect to the BB device in an IEEE 802.11b ad hoc network.

Figure 1.1: Physical wired link is removed and replaced by BB device to provide a common platform for unwired remote monitoring and controlling of bio-instruments

The BB device has a programmable controller so that remote command set of the bio-instrument can be programmed into the device for controlling the bio-instruments. We have programmed the BB device to control the Polymerase Chain Reaction (PCR) bio-instrument. Besides, we have also configured the BB device to broadcast a beacon which consists of Service Set Identifier (SSID) periodically to support for location-aware computing in smart laboratory. In this thesis, we also propose novel solutions to address

two challenging research issues on our BB devices, namely: reprogramming of BB device and the role of BB device in context-sensitive computing.

1.3.2 Location Awareness

We have implemented location awareness feature to Smart Lab platform. With the BB devices attached to every bio-instruments, user with his laptop or PDA can connect to nearest bio-instrument without any explicit input from the user. This can be achieved by computing the Received Signal Strength Indication (RSSI) from the BB devices. However, in a small scale and congested lab environment, bio-instruments normally are close to each other. Therefore, the key challenge in the confined lab environment is a close-range *relative proximity* detection problem. Due to the distribution of the signal strength of BB devices are often overlapped in the lab and therefore we can get a stronger signal strength from the further BB device as compared to the nearer one. To address this difficulty, we have devised a new algorithm - Stochastic Positioning by Interpolated Radial Mapping (SPIRM) that takes the radiation pattern of the BB device into consideration. This low-cost and small scale relative positioning engine implemented in Smart Lab is able to provide location awareness in a smart laboratory for intelligent on-the-move unwired access of lab equipment. In addition, we have also

shown that SPIRM is robust and accurate in assigning user to the nearest BB-equipped lab instrument in a confined area as compared to conventional methods.

1.3.3 Other Smart Applications

Besides Smart Lab, our smart unwired system is also applicable to smart museum, smart exhibition such as painting exhibition and so on. Here, we give three brief scenarios:

1. *Painting exhibition* - A visitor is visiting a painting exhibition[32].

When the visitor is entering the hall of a painting exhibition with his PDA, the server sends the layout of the booths to the visitor's PDA. During his visit, whenever he is approaching to a painting. The server will download the relevant painting information to his PDA automatically. Moreover, map of the exhibition will be also shown in his PDA to guide the visitor throughout his visit.

2. *Photo printing machine* - A user wants to develop his photo. When he is approaching to a photo printing machine, his photos in his mobile phone are downloaded to the printing machine automatically without taking out his memory card in his mobile phone by turning off his mobile devices. Once the printing finished, the machine will send a

charge summary to his mobile devices through SMS and the charges will be included in the monthly hand phone invoice. This neither requires a user to pay by cash on the spot nor a cashier to station in the shop to collect the amount from user.

3. *Smart Seminar* - A researcher attends a technical seminar[30, 43]. The seminar is a multi tracks seminar that is held simultaneously. When he is entering one of the presentation room with his PDA, the PDA will automatically download the relevant information about the presentation such as biographies of the presenter, presentation topic and presentation paper that is about to begin in that room. During the seminar, the researcher can take notes the important points of the presentation to his PDA. In addition, the PDA is able to download the real-time video conferencing from the server about the on-going presentation in the other presentation room.

1.4 Organization of the Thesis

A brief introduction of current lab environment is presented in Chapter 1. We also present our motivations and objectives in providing a better research environment for bio-scientists. Our contributions toward current smart and ubiquitous environments are also discussed in details. In Chapter 2, we

provide further details on our Smart Lab project. Architecture of our system and the functionalities of each Smart Lab's components is presented in detail. Most importantly, various scenarios of Smart Lab are discussed in details in this chapter.

We then describe several related works in Chapter 3. Details of popular research works done in indoor positioning system are presented. The main drawback of the previous research works and our approaches' novelty is furnished in this chapter. In Chapter 4, we discussed the smart functionalities and software architecture of BB devices in details. We also propose novel solutions based on BB devices to address two challenging research issues on BB device: namely, reprogrammable and context-sensitive computing.

In Chapter 5, we describe the challenging issues in providing relative proximity in small-scale bio-laboratory and how these issues affect the accuracy of conventional method. We present our approach for relative positioning in a lab environment, including our SPIRM algorithm. We show positive evaluation results using SPIRM as compared to conventional methods. Finally, we conclude in Chapter 6 with some discussions on possible further work.

Chapter 2

Smart Laboratory Project

2.1 Introduction

Our Smart Laboratory project aims to convert the biology laboratory into an intelligent and productive work place for the scientists. The grand objective of our Smart Laboratory project is to develop *pervasive LIMS*—a smart laboratory information management system (LIMS) that uses novel applications of pervasive computing technologies to seamlessly integrate the physical and information aspects of the biology laboratory environment. The pervasive LIMS will provide ubiquitous online accessing, monitoring, controlling, and capturing of experiments which allows maximal freedom of mobility for the laboratory scientists and requires minimal manual computing efforts from them. To do so, we created Virtual Lab Dashboard (VLD)’s to be our Smart

Lab platform that provides for borderless man-machine interface both in and out of the bio-laboratory – a platform that provides for both ubiquitous monitoring and control services *remotely* over internet or other public network and *locally* within the bio-laboratory. Our Smart Lab platform address two key issues specific to a biology laboratory environment:

1. *Heterogeneous lab instruments.* It is typical for a biology laboratory to house multiple lab instruments from different vendors for similar or different experimental procedures. A common platform for integrating this heterogeneous environment has to be provided.
2. *Mobile lab scientists.* As mentioned previously, frequent physical movements of the scientists in the laboratory are necessary for the coordination and progress monitoring of multiple heterogeneous laboratory devices. Intelligent on-the-move access of the equipment must be provided in a smart laboratory.

In the next section, we describe our Smart Lab platform together with the functionalities of its components in addressing the above issues.

2.2 System Architecture

To make our Smart Lab feasible, Smart Lab platform must provide an integrated unwired platform that links multi-vendor lab instruments together wirelessly and makes them remotely accessible by lab user. However, as mentioned previously, a bio-laboratory usually houses multiple lab instruments from different vendors for similar or different experimental procedures. These lab instruments have different vendor-specific communication protocols for remote monitoring and control purpose, creating a big challenge for effective system integration. Although there are some well-known enterprise middlewares like CORBA[4], JINI[9] that were developed for supporting application software on different platforms to communicate with each other over the network, these technologies are not applicable in the smart bio-laboratory because the firmware in the various lab instruments are fixed and not re-programmable. As a result, to deal with the heterogeneity issue, we introduce a custom designed embedded system - BioBridge (BB) Device. BB device integrates heterogeneous lab instruments to the Smart Lab platform and links them to the network in a plug-and-play fashion while providing a unified communication interface for remote access to the lab instruments.

Figure 2.1 shows the system architecture of our Smart Lab implemented in an IEEE 802.11b Wireless LAN ad-hoc network. We have adopted IEEE

802.11b as our wireless communication protocol in our current work because high data transmission rate is necessary for Smart Lab real-time applications. IEEE 802.11b[53] can provide up to 11 Mbps data transmission rate in a distance of up to 100 meters. In comparison, Bluetooth[35, 36] allows only up to 720 Kbps within a distance of 50 meters, while Infra Red[8] yields a limited 115 Kbps transmission rate and requires line of sight. Moreover, IEEE 802.11b is relatively mature and more widely accepted, and we can also look forward to the future integration between Third Generation (3G) systems[6] and wireless LAN. With the potential availability of Wi-Fi mobile phones[10], monitoring an ongoing bio-experiment with a mobile phone will also be realized in the near future.

Figure 2.1: Smart Lab architecture

2.3 Smart lab Components

Smart Lab platform consists of four important components, namely Bio-Bridge(BB) Device, Service Gateway, Bio-instrument and lab users.

2.3.1 Bio-Bridge (BB) Device

BB device is a low cost, small form-factored embedded system that acts as a bridge to form an unwired virtual link between lab user and bio-instrument. The BB devices can receive remote commands from the user and thus control the bio-equipment. In addition, it can also retrieve the real-time data from the bio-instrument and send to the server. All the remote commands have been hard coded inside the BB device. To support for location aware computing, Bio-Bridge is configured to broadcast beacon periodically. More details on the BB devices are discussed in Chapter 4.

2.3.2 Service Gateway

A Java based server which links to MySQL database in real-time has been implemented. In our current prototype system, it physically consists of a LinkSys WUSB11 IEEE 802.11b adapter, a WaveCom FastTrack GSM Modem and a Dell Desktop PC. Figure 2.2 shows the architectural block diagram of the service gateway.

Figure 2.2: Service Gateway Block Diagram

The Apache web server provides client with access to dynamic web pages that are made up of PHP scripts and Java applets. Two different levels of access are provided in our current system: Administrative access and User access. The core program is depicted as the Virtual Lab Dashboard (VLD) Engine; it keeps track of active user status and active BB Device (lab-equipment) status, controls the access to database, schedules the peer-to-peer wireless communication between the Service Gateway and the BB Devices. A specific communication protocol is designed for inter PHP-VLD communication.

The VLD platform stores its system information and experimental data in a MySQL DBMS server. All VLD databases are updated through the core VLD Engine. While the system supports multiple connections to the DBMS server by different PHP scripts for database queries, the granting of

permission by VLD Engine is always required before the direct connection can be created. This is essential in the case of multiple users accessing multiple lab equipment through the web server.

Our current system design also includes Java SMSA (SMS Alerting) which is an independent Java program running on the Service Gateway. It listens for incoming SMS from the GSM Modem, parses the SMS command and sender information, performs both the sender and the command authentication, and once authenticated, queries the database and sends the appropriate SMS about (say) lab-equipment status to the user in the way that is specified in the user's SMS request commands.

2.3.3 Bio-instrumnet

In this project, PCR (Polymerase Chain Reaction) machine[7] has been used as the Bio-instrument. It is a DNA duplication machine. It has an on-board processor which is physically connected to a dedicated PC. However, in Smart Lab, we have replaced this physical link with our BB device, and hence the bio-instrument is able to communicate with the BB device through UART and perform users' intended task.

2.3.4 Lab Users

User mobile devices such as laptop, PDA or even mobile phone can connect to the service gateway for remote monitoring and controlling when they are not in the lab. For the user in the lab, with notebooks that are equipped with Wireless LAN 802.11b network interface card (NIC), they can connect to the nearest equipment automatically without any explicit input from the users. This can be achieved by location-aware computing algorithm which is pre-installed in users' notebooks.

In our current implementation, BB Devices are configured together with the Service Gateway in an “on-the-fly” IEEE 802.11b ad hoc network due to its flexibility in controlling and scheduling wireless bandwidth for critical peer-to-peer communication. With this architecture, our Smart Lab platform not only can provide ubiquitous local and remote control and access to multi-modal bio-instruments through web-based services via Virtual Lab Dashboard on another remote computer, PDA or even mobile phone, but is also able to provide intelligent on-the-move access of lab-instrument for the user in the lab with the custom designed BioBridge Devices attached to the bio-instrument (more details on this in Chapter 5).

2.4 Ubiquitous Multi-Modal Access to Bio-instrument (Scenarios)

We have designed a VLD platform to support ubiquitous remote and local access to bio-instrument in a smart bio-laboratory. Three scenarios (Figure 2.3) are shown in below:

Figure 2.3: 3 Scenarios for Smart Lab Platform

1. *Smart on-the-go access within the lab.* Bio-scientists frequently need to move from one work station to another in the laboratory to perform various experimental procedures. It is thus desirable that the linking of a bio-instrument to a scientist can be automatically done when they

approach an equipment. With the help of BB Devices and a novel relative positioning algorithm - SPIRM, running on the mobile computing device (e.g. a laptop or a palmtop) carried by the scientist, a wireless communication link is dynamically established and maintained between the scientist and the nearest lab equipment.

2. *Internet access through a web browser.* As most of the biological experiments are time consuming, lab scientists would rather not be tethered within the lab for hours before the completion of their experiments. Thus, the Smart Lab platform provides a web based services for remote monitoring and controlling services so that scientists can go back to their offices to work on other productive tasks while logging into the VLD Service Gateway via a web browser for monitoring their experiments remotely (Figure 2.4).

Figure 2.4: Multi-modal remote access on a user's laptop and PDA

3. *Mobile access through public network.* In the event when the lab scientist is not within the reach of internet (e.g., during commute), the VLD system provides an alternate way to access the lab equipment through mobile phones. The GSM SMS alerting service is developed for this purpose. While service content adaptation to the mobile user remains a research issue, we focus here on simple text alerting services that would be helpful to the scientist in efficient time management for monitoring lengthy (oftentimes overnight) experiments.

2.5 Conclusion

In this chapter, we have presented the Smart Lab Architecture, a *scalable unwired platform* that enables seamless communication between *man, machine and computer* to address two specific issues namely: (a) heterogeneous lab instruments; and (b) mobile lab scientists. Smart Lab platform not only can provide ubiquitous remote monitoring and control services over the public network (internet and GSM network), but also can provide intelligent on-the-move access of lab-instrument within the lab. In addition, we have also presented the functionalities of each Smart Lab's components. Moreover, various Smart Lab scenarios have been discussed in detail. We believe that our Smart Lab platform is able to create an intelligent and paperless

laboratory environment for better research at the bench [51].

Chapter 3

Related Work

3.1 Introduction

Prior to the design of our system, we have surveyed the representative works that were carried out in smart environment and indoor positioning system. It is important that we have investigated the current state-of-art in the smart environment and indoor positioning system so that it can give us a guidance to design and implement our method in order to improve the limitations of the previous works. In the following section, we describe the Labscape project in detail. In addition, various indoor positioning techniques and systems will also be discussed. Last but not least, we will present the novelty of our project as compared to the previous works.

3.2 Labscape

Interestingly, while the biology lab—with its many high tech equipment and dynamic mobile experimental work-flow—makes it a good candidate for deploying smart technologies, most current work on smart spaces have focused on more generic domains such as smart homes, classrooms, and offices. As far as we know, the only related project is Labscape[15, 48] which focused on the server-side capturing of meta-data of lab scientists carrying out their experiments in the laboratory in order to produce more complete record of their work. In our user-oriented work, we focus on *user-oriented applications* of smart technologies such as remote monitoring and on-the-go access and control of the lab equipment to help simplifying laboratory works and hence improve the productivity of the experimentation activities.

3.3 Indoor Positioning Systems

In terms of location-aware computing in a similar indoor setting, various wireless technologies such as infra red, ultrasonic and radio frequency, have been utilized for indoor positioning. Before we discuss some of the previous popular research work carried in indoor positioning area, let us look at the common techniques[63] that can be used to compute a user's location:

- *Time-of-Flight (ToF)*. ToF is the round trip time between a transmitter and a receiver. The distance is translated using ToF. The main drawback of this technique is a precise and expensive synchronizing clock is needed. Slight difference in synchronization can give poor estimation.
- *TDoA (Time Difference of Arrival)*. TDoA is used for a device that consists of 2 wireless technologies such as combination of RF signal and ultrasonic pulses. With the different propagation speed of the wireless technologies, the receiver of these 2 wireless technologies can estimate a location using their TDoA.
- *Angle of Arrival (AOA)*. Normally, AOA[52] is implemented in sensor array or directional antenna that has the capability to determine from which direction the signal is originated.
- *Received Signal Strength Indication (RSSI)*. Due to the nature of wireless signal, they suffer attenuation when they propagate. Hence, the difference between the transmitter signal strength and the RSSI can be translated to distance.

3.3.1 RADAR

In recent years, location estimation in IEEE 802.11 Wireless LAN[17, 19, 26, 31, 58, 61, 71, 72] has also become a hot research topic in location-aware computing. A representative work is the RADAR[17, 16] system developed by Microsoft Research group that uses RSSI (Received Signal Strength Indication) from multiple access points to triangulate users' location. To estimate user location, a set of comprehensive signal strength measurements from multiple access points was taken during an off-line phase for a known location. The map is then stored in a central server database and used as a reference for matching with the real time signal strength in the on-line phase. By using K-Nearest Neighbor (KNN) algorithm - smallest deviation between the on-line signal strength and the off-line signal strength, user location can be estimated. RADAR can provide an accuracy of 3 meters with a confident interval of 50%. In addition, RADAR also developed a propagation model that uses Wall Attenuation Factor (WAF) to estimate the distance based on path loss theory. The number of walls between the transmitters and receivers are taken into consideration in estimating the propagation loss of the signal. With this model, RADAR can furnish an accuracy of 4.3 meters. RADAR uses off-the-shelf network interface card (NIC), and hence achieve a low setup cost. However, it relies on central server to compute the user location based

on the RSSI.

3.3.2 Ekahau

Ekahau was developed by a research group from University of Helsinki, Complex System Computation Group[5]. It is a software based positioning engine that uses IEEE 802.11 wireless network to locate users who carry mobile devices. Ekahau Positioning Engine (Figure 3.1) comprises of three components: Ekahau Client, Ekahau Manager and Positioning Engine. Ekahau Client is software that can be installed in mobile devices and perform continuous RSSI collection from the network access point and send it to Positioning Engine. While for Ekahau Manager, it is used to create and calibrate a model based on the pre-collected RSSI. With this model, Positioning Engine which can receive real time signal strength data from the mobile devices will compute user location and send this information back to the mobile devices.

Ekahau does not apply propagation method thus does not suffer from RF multipaths, scattering and attenuation effects. Hence, it can provide accuracy up to 1 meter in average. In addition, Ekahau has also developed a T101 Wi-Fi Tag as shown in Figure 3.2. It is a small and light weight hardware that carried by users or attached to asset. This hardware can be incorporated to Ekahau Positioning Engine so that continuous movement of user and asset

Figure 3.1: Ekahau Positioning Engine System (quote from [5])

is kept tracked by the system. However, similar to RADAR system, Ekahau system relies on the central server to compute the user location based on the RSSI.

Figure 3.2: Ekahau Wi-fi Tag (quote from [5])

3.3.3 Hitachi AirLocation

Hitachi AirLocation (Figure 3.3) is a commercial product that utilizes IEEE 802.11b wireless LAN to perform ranging applications[3]. The system consists of a location detection server, a management server, five base station (one master and four slaves) and wireless LAN devices. The master of the base station will broadcast synchronized signal, which received by the wireless LAN devices. The devices will respond to the base stations by sending another signal. The system works by detecting and measuring the slight difference of time arrival of radio wave from the devices. Although this system provides an error range of 1 to 3 meters, it is an expensive system since it consists of servers and base stations.

Figure 3.3: Hitachi AirLocation System (quote from [3])

3.3.4 Ubisense

Ubisense[12] is an ultra-wideband (UWB) sensor technology to locate people and mobile objects[22]. This system consists of Ubitags, Ubisense Sensor and Ubisense Control System. Ubitags (Figure 3.4) is a small, light weight hardware carried by users or attached to the moving objects that transmit UWB radio signal periodically so that the network sensor, mounted throughout the area of interest can pick up the signals. The Ubisense Sensor which is equipped with an Ethernet cable can connect to the buildings' existing network infrastructure and link to the Ubisense Control System, a server that can manage up to 15 sensors. This ultra wideband technology can furnish an accuracy of 15 centimeters which is much higher than RF signal technology. Although this system furnish a high accuracy for the user, it requires user to carry a tag which is an extra hardware for performing ranging and estimation.

Figure 3.4: Ubisense Tag (quote from [12])

3.4 Our Approach's Novelty

Stochastic positioning approaches have also been reported recently. In [26, 58, 72], probability distributions were used for estimating user location. In these works, the probability distributions of signal strength in all the data collection locations were computed and stored in a database. The systems then estimate a user's location using maximum likelihood. Machine learning approaches such as the neural network[19] have also been proposed to improve the accuracy of position detection. Thus far, probabilistic based methods offered better accuracies as compared to modal based methods. Hence, in this project, we take advantage of the probabilistic based method and deploy a relative positioning engine operating in our Smart Lab.

Most of these previous research such as RADAR, Ekahau have focused on physical location estimation in large areas. Positioning using RSSI in a *small-scale area* such as a room-sized laboratory has not been attempted so far. As such, we investigate the relative proximity problem in a biology laboratory by using RSSI as our primary computational parameter. To maintain low cost for our system, we avoid additional hardware such as camera[14], magnetometers[34] and tag[12] (i.e Active Badges System[66, 67], Active Bats[68], Cricket[56] and Ubisense) and instead we attempt to exploit the inexpensive off-the-shelf NIC that the scientists would own as long as their

lab's wireless computing environment is the common IEEE 802.11b. As such, we have devised a new algorithm for performing relative localization in a small-scale, confined environment by considering *radiation patterns* of NIC. With our novel Stochastic Positioning by Interpolated Radial Mapping (SPIRM) method, a Smart Lab can then intelligently connect a user to the nearest bio-equipment without any explicit input from the user.

3.5 Conclusion

In this chapter, we have first presented the only related work, Labscape project that was carried out to develop a smart lab. After that, we then surveyed the indoor positioning techniques and representative indoor positioning systems such as RADAR, Ekahau and so on. The pros and cons of each of the techniques and systems are discussed in detail. Finally, we discussed our project's novelty where we exploit the *radiation pattern* of NIC in investigating the *relative proximity* detection problem in a *small-scale area* such as a laboratory environment.

Chapter 4

Our Work: Novel BioBridge (BB) Device Design

4.1 Introduction

Due to the sophisticated experimental steps being performed, most of the equipments in a post-genome laboratory require dedicated desktop computers to control. Nearly every analytical instrument in the lab requires at least one on-board processor, with most having the capability of interfacing with a computer via RS232/485 for command and control. This requirement for a dedicated PC for equipment command and control not only introduces extra equipment costs but also takes up the valuable bench space in the laboratory. In addition, it also requires the scientist to be familiar with different

operating systems for different PCs connected to the various instruments. For experimental procedures that require constant monitoring, the dedicated wired connection also constrain a user in a static place for a lengthy experiment. In our Smart Laboratory, we have replaced this physical wired link with our custom designed programmable BioBridge (BB) devices as shown in Figure 4.1. In addition to freeing up valuable bench space in the lab, the BB device also allows us to address the issue of equipment heterogeneity at the middleware level. It provides a unified platform for us to embed necessary smart features for addressing the specific needs of a biology laboratory, such as the provision of context-aware computing for addressing the specific needs of a biology laboratory.

Figure 4.1: BB Device's Technical Block Diagram

A BB device is a embedded system that acts as a bridge to form an un-wired virtual link between end user and bio-instrument. Figure 4.2 shows the software architecture of the BB device. Functionally, it acts as a low cost computer which consists of its own Internet Protocol (IP) address, Service Set IDentifier (SSID) as well as other wireless configurations such as Wired Equivalent Privacy (WEP). All these wireless configurations can be configured through a user friendly GUI as shown in Figure 4.3 which does not require the non-programmer user such as bio-scientists to get involved with programming the BB device.

Figure 4.2: Software architecture of BB device

Our current prototype for BB device is implemented in the Ubicom IP2022 Processor[11]. IP2022 is a high speed (up to 120 MIPS) *wireless network* processor that is able to deliver Software I/O solutions using pre-built

APIs to create single-chip solutions for a wide range of prevalent communication protocols such as IEEE 802.11a/b/g, UART, and so on. In addition, IP2022 has a self-programming feature that is useful for implementing smart (e.g. context-aware) adaptive applications. For this work, we have reprogrammed the IP2022 to be a scalable unwired middleware in an IEEE 802.11b wireless network as shown in Figure 2.1.

Figure 4.3: User friendly GUI for configurations of BB device

Through the use of BB devices, the two issues specific to a biology laboratory environment that we have mentioned earlier can now be addressed at the middleware level:

1. *Heterogeneous lab instruments.* The BB devices provide a common interface platform for the multi-vendor bio-instruments that is common in today's bio-laboratories. This is feasible because nearly every analytical instrument in the lab requires at least one on-board processor, with most having the capability of interfacing with a computer via RS232 or GPIB port for command and control. In Smart Lab, we replace the physical RS232 computer connection with BB device (see Figure 4.4). For ease of command and controlling a bio-instrument, the command sets of the specific bio-instrument is programmed into the BB device's programmable controller. This easy reprogramming (more on this will be discussed in Section 4.3) is necessary for the integration of heterogeneous bio-equipment in the lab where BB devices serve as a common platform for communication and control.
2. *Mobile lab scientists.* In addition, the BB device can now be deployed for providing unwired local and remote equipment access for the mobile lab scientists. Together with the context-sensitive smart features that can be built into the BB devices (see Chapter 4.4), intelligent on-the-move access of equipment becomes possible. As a user moves about in the lab from one workstation to another to perform experimental tasks, the BB device attached to the bio-equipment at each worksta-

tion can communicate directly to the user's information appliance (a laptop, PDA, mobile phone or any Wi-Fi enabled wearable computing devices) to automatically establish a virtual link between the user and the lab equipment via location-aware computing. When the user is away from the lab, he can also monitor remotely by retrieving real-time data from the Smart Lab server which communicates to the BB devices and captures the data ubiquitously.

Figure 4.4: A bio-instrument (a thermal cycler for polymerase chain reaction) connected to a prototype BB device.

4.2 Applications of BB Device in Smart Lab

4.2.1 Unwired Lab Equipment Access

The BB device is also a multi-communication protocol middleware that supports various communication protocols such as IEEE 802.11b, Bluetooth, Universal Serial Bus (USB), Ethernet and so on. It contains two Serializer/Deserializer (SERDES) units (See Figure 4.1) which allows for two different communication protocols to be implemented in a device. SERDES is a special hardware feature of IP2022 that supports a variety of serial communication protocols including General Purpose Serial Interface (GPSI), Universal Asynchronous Receiver Transmitter (UART), USB, 10-Base-T-Ethernet and so on. Most importantly, SERDES is able to perform efficient data serialization and deserialization in reducing the CPU bandwidth so as to support the high baud rate serial communication necessary for the wet labs. Through SERDES, the wired communication protocol such as UART can be converted to the wireless communication protocol such as IEEE 802.11b. In this way, BB device provides the necessary unwired equipment access in a smart bio-lab.

4.2.2 Smart e-Post-It-Note

With the BB device as a common middleware platform, many smart lab applications can be implemented across the various multi-vendor equipment that exist in the wet lab. For example, we can now provide a user friendly “intelligent e-Post-It-Note” service (see Figure 4.2) for the lab scientists through the BB devices. Post-it notes are commonly used by lab scientists to leave important messages to other lab users (for example, “Please Do Not Touch”) when they are not in the lab, or reminders[41] to themselves when they return after leaving their lengthy experiments to run overnight. In a Smart Lab where the instruments are equipped with BB devices, lab scientists can store their messages into the respective BB devices associated with the lab instruments. The BB devices will record down the messages and activate them whenever a virtual link is established with a relevant user. Intelligent e-Post-It-Note is a context-aware smart lab application — the BB devices have to be aware of the correct context in order to send the right message to the relevant user. Through the use of BB devices as the common middleware platform, this and many other Smart Lab features can thus be easily implemented across the various multi-vendor equipment in the wet lab.

4.3 Automatic Reprogrammable

Reprogramming is an important issue for heterogeneous environment , and this is especially so in a biology laboratory where the environment is highly heterogeneous. In our current Smart Lab set-up, every bio-instrument in the lab is equipped with a BB device that acts as a smart bridge to form an unwired communication link between a lab user and the bio-instrument. Each of the BB devices must therefore be easily programmable to support the corresponding bio-instrument's command set. Currently, the bio-equipment's command sets are manually programmed into our BB device prototypes. To avoid this manual re-programming, we propose a novel "listener" method for automatic reprogramming.

As mentioned before, most of the bio-equipment are high-tech computer-controlled equipment. These equipment come with vendor command and control programs that send commands from the computer through the RS232 port or GPIB port to the bio-instrument to instruct the bio-instrument to perform an intended task once it receives the command from the vendor program. These commands that pass through the RS232 or GPIB are normally ended with a special symbol such as *new line* symbol, 0x0A in ASCII, so as to distinguish a complete command with one another.

For automatic reprogramming of a BB device, we insert a "listener" hard-

ware (Figure 4.5) that simply listens for the command stream transmitted from the PC. The listener is to be inserted between the bio-instrument and the computer that runs the vendor command and control application program, as shown in Figure 4.6, and it is connected to the BB device through serial port. As the vendor application software is invoked on the PC, the command stream transmitted from the PC to the bio-instrument are captured by the listener and sent to the BB device. The BB device then splits the captured command stream by recognizing the special terminating characters or symbols and discarding any repeated commands. By triggering the self-programming function, it will store the set of captured commands in its flash memory. This automatic reprogramming method can also be applied to multiple BB devices so that they can be reconfigured with a new bio-equipment simultaneously. In this way, the BB devices can be reprogrammed easily for new bio-instruments, especially those that do not provide open command sets.

Figure 4.5: Listener Hardware

4.4 Context Sensitivity

Context-aware computing[42, 59, 60] is necessary for a biology laboratory to be a smart work place. Since the mobility of lab scientists (within and away from) the lab is an important issue for smart bio-laboratories, location is the key context to enable smart computing in the lab. The BB device must therefore be equipped with features to support such context sensitive computing.

In this case, the BB devices are configured to broadcast a beacon which consists of Service Set IDentity (SSID) periodically with the IEEE 802.11b wireless LAN API provided in BB device software stack. This allows the users' mobile devices such as laptop, PDA which are within its purview to

Figure 4.6: Hardware setup for reprogramming of command set in BB device

detect its beacon so that relative proximity amongst multiple BB-device enabled bio-instruments can be determine using the relative Received Signal Strength Indications (RSSIs) (More on this location awareness is discussed in Chapter 5). Similarly, the BB devices can be used to determine whether a user is in the lab or outside the lab by comparing the RSSI with a pre-set threshold value (The threshold value is pre-set as the pre-calibrated minimum RSSI of a user's mobile device when he is in the lab). The BB device can then use this information to detect that a user has exited the lab when the RSSI is smaller than this pre-set threshold. This allows the the BB device to intelligently switch from the local wireless virtual link between man and machine to the remote communication mode between server and machine where the data are transmitted to the server for the user to retrieve remotely. Such

smart features are made feasible by exploiting the BB device as a common middleware platform that supports context sensitive features in the lab.

4.5 Limitations

At the current stage, BB device is configured only to support RS232 connection from bio-instrument. This is because nearly every analytical bio-instrument consists of RS232 interface. However, BB device also supports USB, parallel and 10-base Ethernet internet protocols as it contains two SERDES units and parallel port. As a result, bio-instruments which have such interfaces can be connected to a BB device for command and control.

On the other hand, user's mobile devices such as laptop, PDA can only connect to a bio-instrument once at a time. Multiple connections are not supported at this moment as each of the NIC in a mobile device can only configured to connect to an ad-hoc network. Besides, in order to support for location-aware computing, BB devices are fitted statically to a bio-instrument. As a result, pre-calibrated data (more on this will be discussed in Section 5.3.4) can be used as a reference to estimate a user's relative proximity with respect to the BB devices.

4.6 Conclusion

In this chapter, we have discussed the important roles of a BB device in our Smart Lab. BB device is an embedded system that acts as a common interface platform for communication between user and bio-instrument. In addition, we have presented the software architecture and block diagram of a BB device in detail. Smart Applications such as unwired lab equipment access and smart e-Post-It-Note can now be deployed with the existing of BB device. In addition, we also proposed two challenging research issues namely automatic reprogrammable and context sensitive based on the design of our BB device. However, there are some limitations of a BB device such as interface between BB device and bio-instrument, access of multiple bio-instruments simultaneously in the lab and unmovable of BB device after fitted to a bio-instrument. We plan to further study these limitations so that we can provide a more user friendly solutions to the lab user.

Chapter 5

Our Work: Novel

Proximity-Awareness Method

5.1 Introduction

In a traditional laboratory set-up, when a scientist arrives at a work station to carry out an experimental procedure, he can use the dedicated computer to access and operate the equipment. In our Smart Lab, we have replaced the lab equipment's dedicated PCs with BB devices. When a scientist arrives at the PC-less workstation, he parks his mobile computing equipment (a laptop in our current implementation, but it can be a PDA, mobile phone or even a wearable computer) near the equipment and expects to work on the equipment of his interest. This requires that a virtual link be set up auto-

matically (and wirelessly of course) between his personal computer with the lab instrument of his interest. For a Smart Lab to achieve this intelligently, the key contextual information to establish the virtual link are the relative locations of the lab equipment and the user's laptop. The specific context-aware computing that have to be at work here is location-awareness, or more specifically, proximity-awareness, since the knowledge of absolute positions is not necessary in this case. However, as mentioned earlier, the bio-laboratory often have limited bench space; thus, it is not uncommon in the lab that one apparatus is closely stationed with another. As such, the key challenge here is a close-range *relative proximity* detection problem (Figure 5.1). When a user parks his laptop near a lab equipment, the Smart Lab must be able to determine that this lab equipment is the nearest to the user's laptop even though there may be other equipment in close vicinity. For the rest of this chapter, we focus on describing our work on this relative proximity problem in a biology laboratory setting.

5.2 Small-Scale Proximity Problem

To localize the nearest equipment in a lab, a straight-forward method is to directly utilize the RSSI emitting from the BB devices (i.e. the bio-equipment in the Smart Lab). A nearer BB device should in principle provide

Figure 5.1: Relative Proximity is needed for intelligent virtual linking a stronger signal strength than a more distant one. This is true only when the bio-equipment are placed sparsely in a large area. This is not applicable in a laboratory setting as a typical bio-laboratory is a small and confined environment where equipment are often placed close to one another.

In an ideal case, the radiation pattern of an omni-directional antenna is perfectly circular. In other words, one should get the same signal strength around the antenna at a constant distance from the antenna. Unfortunately, this is not the case in real life. We have found that the radiation patterns of the NICs' antenna in the BB devices are indeed not perfectly circular. This means that a lab user who is nearer to a BB device might get a weaker signal than the signal from a more distant BB device.

To solve this problem, we construct RSSI histogram-based radial maps of the BB devices. The relative locations of the user can then be estimated

and assigned to the nearest bio-equipment using Stochastic Positioning by Interpolated Radial Mapping (SPIRM). Before we go into the details of our algorithm, let us describe how data can be collected for constructing the radial maps of BB devices for SPIRM as discussed in next section.

5.3 Evaluation

5.3.1 Methodology

Experimental Test-bed and Tools

We set up our experimental test-bed in a room with a dimension of 5 meters by 7 meters to represent a typical indoor and confined environment like a small biology laboratory. For our current experimentation, we have placed two BB devices in the center of the room and at the same height. The BB devices are equipped with Linksys wireless LAN card. They have been configured to broadcast beacon which consists of Service Set Identifier (SSID) periodically. Any devices which are within their purview can detect their beacons.

In our current set-up, the mobile device carried by our lab user is a Fujitsu Laptop running Windows XP Operating System. The laptop is equipped with an Orinoco Gold wireless network card and installed with the Wireless

Research API (WRAPI) software library[2] running in Visual C++ environment. WRAPI is a hardware-independent software library built for windows XP based system. It can be used to monitor, control, and query about the IEEE 802.11b wireless networks that are within its range. WRAPI obtains the data through the Network Driver Interface Specification User Mode I/O (NDISUIO) protocol. Details of NDISUIO can be found in [1].

Data Collection

We implemented a GUI application program to collect RSSI from our BB devices using WRAPI. The user laptop running the GUI application program was placed in the same height with the BB devices for data collection (Figure 5.2).

Figure 5.2: Experiment Setup: Data Collection

First, we collected signal strength (SS) data from individual BB devices. Each of the BB devices was placed in the same location, and 500 SS samples were collected in 8 different directions around the BB device at distances of 0.25 meter, 0.5 meter, 1.0 meter and 1.5 meters. The SS data were collected at an interval of 200 milliseconds (ms). The purpose of this measurement was to find out the variation of the NIC in the BB devices by verifying whether the transmission power of the two NICs are the same.

Next, we collected the SS data from two BB devices placed as shown in Figure 5.3. Measurements were again taken from the two BB devices in 8 different directions around them at distances of 0.25 meter, 0.5 meter, 1.0 meter and 1.5 meters. In other words, SS data were collected at a total of 64 locations. At each location, 500 SS samples were again collected at 200 ms intervals. We also collected multiple sets of SS data at the same locations but at different times. Based on these data, a histogram-based radial map is constructed for our SPIRM algorithm.

Data Analysis

For analysis, the signal strength of each of the BB devices was collected at a same location but at different times in order to find out their transmission power and radiation patterns. We computed the averages and standard deviations of the collected signal strength for comparison. Our results verified

Figure 5.3: Locations of SS Data Collection

that the radiation patterns of NICs were not perfectly circular. As shown in Figure 5.4, some directions resulted in stronger signals than others. We therefore conclude that there are no single relationships between the received signal strength and the distance. As such, we will have to take the directional information into consideration for deriving the relationship between distance and received signal strength.

Figure 5.5 shows the radiation patterns of 2 BB devices. The maximum standard deviation between these two NICs at similar distances and directions is only around 2 dBm while over 90% of the results show that the standard deviation is within a mere 1 dBm. The maximum difference is around 1.9 dBm, and around 50% of the average differences fall within

Figure 5.4: Radiation Pattern of Single BB Device

1 dBm. Figure 5.6 shows the radiation patterns for the same BB device collected at different times. The maximum average difference between the signal strength data from the same BB device collected at different times is 2.8 dBm, while over 65% of the average differences fall within 1 dBm. From these measurements, we conclude that the two NICs were transmitting at the same power even at different times. Moreover, we can also conclude that the radiation patterns of the NICs were similar, though not perfectly circular.

Figure 5.5: Radiation Patterns of 2 BB Devices

Figure 5.6: Radiation Patterns for the Same BB Device at Different Times

On the other hand, Figure 5.7(shaded area) illustrates that it is possible for a user to receive a weaker SS from a closer BB device. However, our above results have shown that this irregularity in SS is not caused by the difference of transmission power in NICs. This means that the specific radiation pattern for each NIC must be taken into account when using the SS data for positioning.

Figure 5.7: Shaded area shows a problematic region.

5.3.2 Direct Comparison Method

A baseline method for detecting relative proximity is by direct comparison. This method is based on the received signal strength values $SS1$ and $SS2$ from two BB devices BB1 and BB2, respectively. A user is assigned to the BB device having the stronger SS value. More formally, given two sets of signal strength data $\{SS1_i\}$, $\{SS2_j\}$, where $i, j \in \text{sample numbers}, N$. $\{SS1_i\}$ and $\{SS2_j\}$ are treated as *random independent variables*. If $SS1_i > SS2_j$, user is assigned to BB1 and vice versa. The error rate of this baseline algorithm (assume user is actually closer to BB1) is defined as:

$$\text{Error rate} = \frac{\text{Number of times } (\{SS1_i\} \leq \{SS2_j\})}{N^2} \quad \text{where } (i \in N, j \in N) \quad (5.1)$$

In an attempt to make the direct comparison method more robust, we take the average of $\{SS1_i\}$ and $\{SS2_j\}$ in a window for determining user location. In other words, instead of using individual $\{SS1_i\}$ and $\{SS2_j\}$ values, we use the averages in sets of $\{SS1_i\}$ and $\{SS2_j\}$ defined as $\{\overline{SS1_q}\}$ and $\{\overline{SS2_r}\}$ where $q, r \in \text{sample number}, M$, where $M = N/W$ and W is the window size. The modified error rate (again, assuming the user is nearer to BB1) is thus:

$$Error\ rate = \frac{\text{Number of times } (\{\overline{SS1_q}\} \leq \{\overline{SS2_r}\})}{M^2} \quad \text{where } (q \in M, r \in M) \quad (5.2)$$

One observation from the histogram-based distribution plotted for the 64 locations around the two BB devices is that the distribution of the signal strength of both BB devices do not overlap in the unshaded area shown in Figure 5.3. A relative positioning engine can therefore make accurate decisions in this area using the simple direct comparison method. However, the distributions of the two BB devices cross-talk in the shaded area in Figure 5.3. This means that at these locations, even with robust window averaging, the direct comparison method will not be able to provide adequate reliability for determining user relative proximity. Figure 5.8(a) shows the distribution of SS data in non-shaded area while Figure 5.8(b) shows the distribution of SS data in the shaded area. We must therefore devise an algorithm to solve the SS overlapping problem for small-scale relative positioning in these problematic locations. For this, we introduce our SPIRM algorithm.

Figure 5.8: (a) Distribution of SS in Non-shaded Area of Figure 5.3; (b) Distribution in Shaded Region of Figure 5.3

5.3.3 K-Nearest Neighbor (K-NN)

Before we discuss our novel algorithm, let us investigate the provision of location-aware computing in a smart bio-laboratory through K-Nearest Neighbor (K-NN)[17] relative proximity estimation. K-Nearest Neighbor is a decision algorithm that searches for the K nearest data entries (in terms of Euclidean distances) in a real-time measurement and uses the information for making a decision. In this case, the system decides which is the nearer BB device by checking whether the K nearest neighbors come mostly from a particular BB device (which can then be predicted to be the nearer one in deciding relative proximity).

There are two phases in K-NN location estimation method. First, a set of pre-calibrated data or radio map has to be constructed and stored in a database in the off-line training phase. Then, during the on-line phase, given real-time SS, we compute the difference between the real-time SS and

the pre-calibrated data from the radio maps in each of the data collection locations using Euclidean distance measures. We select K number of the closest data points from the computed result and calculate the percentage of the corresponding origins of the K data points in terms of the BB devices, assigning the user to the BB device which has the highest percentage of data points in the set of K nearest neighbors. We show the details of K-NN implemented in our Smart Lab for the case of two BB devices (BB1 and BB2) in 64 data points as below:

- **Step 1: Compute the Euclidean distances**

We denote pre-calibrated means of SS as $\overline{SS1}$, $\overline{SS2}$ with respect to BB1 and BB2 respectively. Each of the data collection locations contribute one pair of means, resulting in a total of 64 pairs of means of signal strengths in the pre-calibrated radio map. Then, during the on-line (real-time) phase, we compute a mean from 5 real-time SS from each of the 2 BB devices, denoted as $\ast\overline{SS1}$, $\ast\overline{SS2}$. We then compute the difference between real-time mean and the pre-calibrated means using Euclidean distance as follows:

$$\sqrt{(\ast\overline{SS1} - \overline{SS1})^2 + (\ast\overline{SS2} - \overline{SS2})^2}. \quad (5.3)$$

As a result, we have a total of 64 differences. The smaller the difference between the real-time data and the pre-calibrated data, the higher

similarities between these 2 set of data.

- **Step 2: Select the K number of closest data**

From the 64 differences, we select K number of closest data. This is because given a real-time SS which is inherent variability in nature at a location. Intuitively, it is not reasonable to select only the nearest neighbor point (in this case, $k=1$) and reject the rest of the points which are in close proximity to the true location. On the other hand, for larger K value, the accuracy decreases as the locations that are far from the true location is taken into consideration in *Step 3*. We have tested the system when $K = 5$, it does not give us a better accuracy as compared to the accuracy of $K = 3$. Thus, in our case, we select $K = 3$.

- **Step 3: Locate user to the BB device that posses the highest percentage from the K results**

Instead of computing the physical distance with respect to a BB device, we modify the K-NN method as proposed in the RADAR project as we are determining only relative proximity in this case. From the K nearest neighbors, we compute the percentage of the K results with respect to the BB devices and assign the user to the BB device that has the highest percentage of nearest neighbors.

5.3.4 SPIRM

To solve the SS overlapping problem for small-scale relative positioning in Smart Lab, we have designed and implemented the SPIRM algorithm. Our area of interest includes the 30 locations marked in the shaded area where the SS distribution overlaps (see shaded area in Figure 5.3), and the direct comparison method will not work. As mentioned earlier, the directional information must be taken into account since the radiation patterns of the BB devices are not perfectly circular. However, the directional information cannot be obtained in real time in our current lab set-up. As such, our positioning algorithm must hypothesize about a user's direction relative to a BB device. With each hypothesized direction, we then use the corresponding pre-calibrated radial maps to interpolate the user's distance d relative to the BB devices. In other words, for each direction θ , we derive a third-order interpolation equation $SS = f(d, \theta)$ using the received signal strength, SS and the hypothesized direction, θ . We then make a maximum likelihood estimation of the relative proximity of a user against two BB devices using the probability distribution of each data collection location computed and pre-stored for each BB device.

The third-order interpolation equations (See Figure 5.3) are shown below:

$$\begin{aligned}
SS1_{\theta_1=\pi/2} &= 1.457d^3 + 10.52d^2 - 35.68d - 14.18 \\
SS1_{\theta_1=\pi/4} &= 18.72d^3 - 47.87d^2 + 28.33d - 34.94 \\
SS1_{\theta_1=0} &= -8.15d^3 + 46.2d^2 - 73d - 11.82 \\
SS1_{\theta_1=-\pi/4} &= -19.58d^3 + 70.72d^2 - 79.98d - 11.89 \\
SS1_{\theta_1=-\pi/2} &= 5.033d^3 - 16.82d^2 + 6.723d - 28.01 \\
SS2_{\theta_2=-\pi/2} &= 3.51d^3 - 4.207d^2 - 11.71d - 30.07 \\
SS2_{\theta_2=-3\pi/4} &= 19.55d^3 - 37.84d^2 + 9.067d - 31.08 \\
SS2_{\theta_2=\pi} &= -46.03d^3 + 126.07d^2 - 107.8d - 10.85 \\
SS2_{\theta_2=3\pi/4} &= -47.13d^3 + 136.2d^2 - 110.34d - 18.62 \\
SS2_{\theta_2=\pi/2} &= -4.453d^3 + 20.44d^2 - 29.47d - 25.39
\end{aligned} \tag{5.4}$$

For ease of understanding, we show the details of our SPIRM algorithm for the case of two BB devices below.

- **Step 1: Estimate distances at all directions**

With the signal strength data $\{SS1\}$, $\{SS2\}$ from the two BB devices BB1 and BB2, the user distance d relative to each of the BB devices is computed for every possible user direction θ by solving the corresponding interpolation functions $f(d_1, \theta_1)$ and $f(d_2, \theta_2)$ in the area of interest shown in Figure 5.3, where $\theta_1 \in \{\pi/2, \pi/4, 0, -\pi/2, -\pi/4\}$ and $\theta_2 \in \{\pi/2, 3\pi/4, \pi, -3\pi/4, -\pi/2\}$.

- **Step 2: Exclude outlier distances**

For the area of interest in our current laboratory setting, only distances that satisfied the boundary of $0.49 < d < 1.51$ are valid. Those distances that do not satisfy this boundary condition are discarded.

- **Step 3: Locate user using maximum likelihood estimation**

We map each of the computed distances in $\{d1_{\theta_1}\}$ and $\{d2_{\theta_2}\}$ into its nearest SS data collection locations out of the 3 possible locations along each direction. Let us use the random variables $W1_{\theta_1}$ and $W2_{\theta_2}$ where $W1_{\theta_1} = \{d1, \theta_1\}$ and $W2_{\theta_2} = \{d2, \theta_2\}$ to denote the respective locations relative to BB1 and BB2 in each corresponding direction, θ_1 and θ_2 . We assign relative proximity to BB1 if given a $SS2$, the probability of the occurrence of $W1_{\theta_1}$ is greater than the probability of the occurrence

of $W2_{\theta_2}$, given a $SS1$.

$$\max P(W1_{\theta_1}|SS2) > \max P(W2_{\theta_2}|SS1) \quad (5.5)$$

Otherwise, we assign relative proximity to BB2.

We use Bayes' Theorem to compute the posterior probabilities of the user location relative to one BB device based on the observed SS from another BB device:

$$P(W1_{\theta_1}|SS2) = \frac{P(SS2|W1_{\theta_1})P(W1_{\theta_1})}{P(SS2)} \text{ for BB1} \quad (5.6)$$

$$P(W2_{\theta_2}|SS1) = \frac{P(SS1|W2_{\theta_2})P(W2_{\theta_2})}{P(SS1)} \text{ for BB2} \quad (5.7)$$

Assuming that any of the bio-equipment can be used with equal likelihood, $P(SS2) = P(SS1)$ and the user can also be anywhere in the laboratory. Thus, $P(W1_{\theta_1})$ and $P(W2_{\theta_2})$ are the same for all θ_1 and θ_2 . Our problem is then reduced to maximizing the likelihoods $P(SS2|W1_{\theta_1})$ and $P(SS1|W2_{\theta_2})$. As in the case for the Direct Comparison method and K-NN method, for increased robustness, we use multiple vectors of $\overline{SS1}$ and $\overline{SS2}$ instead of single $SS1$ and $SS2$ values, where $\overline{SS} = \{SS_1, SS_2, \dots, SS_n\}$ and n is the number of vectors. Thus, the likelihood equations in Equations (5.6) and (5.7) become:

$$P(\overline{SS2}|W1_{\theta_1}) = \prod_{i=1}^n P_i(SS2|W1_{\theta_1}) \quad \text{for BB1} \quad (5.8)$$

$$P(\overline{SS1}|W2_{\theta_2}) = \prod_{i=1}^n P_i(SS1|W2_{\theta_2}) \quad \text{for BB2} \quad (5.9)$$

Finally, instead of the decision rule labeled 5.5 in Step 3 of our SPIRM method above, we use the following rule:

$$\max P(\overline{SS2}|W1_{\theta_1}) > \max P(\overline{SS1}|W2_{\theta_2}) \quad (5.10)$$

The discrete probability in Equation (5.10) can be computed from the pre-calibrated data or radial map. Given $W1_{\theta_1}$ and $W2_{\theta_2}$, we assign relative proximity to BB1 if the product of the discrete probability of $SS2$ in $W1_{\theta_1}$ (Equation (5.8)) is the greater than the discrete probability of $SS1$ in $W2_{\theta_2}$ (Equation (5.9)) which means that the rule in (5.10) is satisfied. Otherwise, we deduce that the user is nearer to BB2 instead.

When more than two bio-instruments are present in a lab, the relative positioning engine selects the strongest two signal strengths from the multiple NICs available and then apply the SPIRM algorithm to compute a user's relative location.

5.4 Results

We compare the accuracy of the commonly used approaches such as Direct Comparison method and K-NN method versus our SPIRM method for relative proximity assignment using the collected data set described in Section 5.3.1. Figure 5.9 shows the poor estimations of the Direct Comparison method. The Direct comparison method cannot furnish high accuracy in these problematic spots since the user receive a weaker SS from a nearer BB device as compared to the further BB device.

In comparison, our SPIRM method delivered much better accuracy for relative proximity detection. Table 5.1 shows the comparative performance of SPIRM and K-NN in the 5 problematic locations of the Direct Comparison method. The Direct Comparison method was able to provide only around 10% of accuracy on average in these locations. In the worst location (marked “5” in Figure 5.9), only around 3% of accuracy was achieved. Even with the help of window averaging for added robustness, the accuracy of Direct Comparison can only be improved to above 7% on average and a mere 1% for the worst location, indicating that the data samples do not deviate much from the mean value. For K-NN method, it was able to provide around 52% of accuracy on average in the problematic spots. However, 2 out of 5 locations, the K-NN method did not perform significantly better than the

Direct Comparison method (with window averaging).

With our SPIRM approach, the accuracy for relative proximity estimation was improved by about 65% in average. In the best case, our algorithm provided 98% of accuracy as compared to the low accuracy achieved by the direct comparison methods (16% for Direct Comparison only, and 28% for Direct Comparison with Window Averaging). As compared to K-NN method, SPIRM achieved a better accuracy 3 out of 5 problematic spots. For the other 2 problematic spots, SPIRM furnished a comparable accuracy as compared to K-NN method. This shows that the interpolative stochastic models employed in our SPIRM method are more informative and robust than simple window averaging models and K-NN method. In fact, the SPIRM method can also provide the physical location of the user, including the direction from the BB devices, for up to 50% of accuracy.

Figure 5.9: Poor Estimations by Direct Comparison Method. The 5 marked locations experienced worst performance.

Table 5.1: Comparative performance between SPIRM, K-NN and Direct Comparison. (The numbered locations refer to those labeled in Figure 5.9.)

Locations	Direct Comparison Method (Single Value)	Direct Comparison Method + Window Averaging	K-NN	SPIRM
1	8%	17%	18%	70%
2	16%	28%	100%	98%
3	5%	5%	35%	60%
4	16%	31%	100%	97%
5	3%	4%	5%	51%
Average	10%	17%	52%	75%

5.5 Conclusion

In this chapter, we have first defined the *small-scale relative proximity* detection problems, where the user can get a stronger signal from a more distant BB device as compared to the closer BB device. This is due to the radiation pattern of the NIC's antenna is not perfectly circular in real life. We then describe our methodology which includes experimental setup, data collection and data analysis. After that, we present a baseline method, Direct Comparison method; a conventional method, K-NN and our novel method, SPIRM in detail. Finally, we evaluate these three methods and our result shows that the SPIRM method delivers much better accuracy than the Direct Comparison and K-NN method.

Chapter 6

Conclusions and Discussions

6.1 Conclusions

The primary objective of smart spaces is to allow people to work together or individually, efficiently. In the Smart Lab, we have utilized current advances in wireless and embedded technologies to create a unique smart work space for scientific experimentation and research in the wet laboratories. We have designed and implemented a Smart Lab platform that operates in the common IEEE 802.11b wireless network. We have designed a smart middleware called BioBridge (BB) device to provide a common interface platform between multi-vendor bio-instrument and mobile devices. We have also showed how the BB devices can be easily reprogrammed to address the inherent heterogeneity of the bio-instruments in the wet lab. To address the frequent

mobility of lab scientists in carrying out their tasks, we have also showed that our BB device supports next-generation middleware characteristics such as transparent computing and awareness functionality to be embedded into the lab environment.

In addition, we showed that the location-awareness necessary for accurate relative positioning for the virtual linking of man and machine in the smart laboratory can be provided through small-scale relative positioning of our custom-designed embedded BB devices attached to bio-equipment. We showed that our Stochastic Positioning by Interpolated Radial Mapping (SPIRM) method provide accurate relative proximity estimations for a small-scale confined environment in a biology laboratory. To maintain a low-cost implementation, we have shown that our method operates well in the popular IEEE 802.11b based wireless network environment. We have chosen not to use Bluetooth[20, 37, 64] because Bluetooth protocol caters for only limited numbers of slave devices in a piconet, and it provides only up to 1 Mbps of data transmission rate which is 11 times lower as compared to IEEE 802.11b. We have also decided against using Ultra Wide Band (UWB) wireless technology in our current implementation as UWB still does not have an international standard as required by our service platform. Nevertheless, our SPIRM approach is also applicable in an UWB environment.

Moreover, our Smart Lab platform is not only applicable to bio-laboratory

but also to other smart spaces such as smart museum tour, smart exhibition or even smart printing services. This is due to its automatic-reprogrammable middleware and location-awareness features. We are interested in integrating more smart services to our platform to provide a better quality of services to human's daily activities.

6.2 Recommendations for further research

In our current implementation, we have designed and developed two types of web pages for the user who access our service gateway using different mobile devices as the service content adaptation to the user mobile devices remains a research issue. Smart Lab VLD provides graphical web pages for the user who access our Smart Lab service gateway using their laptop while for the user who access our gateway using their PDA, Smart Lab VLD provides them text-based web pages for remote monitoring and accessing. Therefore, as our next step, we would like to implement web based services which can adapt their web-content[22, 23, 46, 50] either based on the user's location[40, 49] or user's mobile devices.

In addition, scalability is frequently a limiting issue in many smart space systems. Many systems cannot scale up gracefully because of major additional hardware and maintenance costs, making these smart systems infeasible.

ble for practical use. In our Smart Lab, no major hardware and maintenance cost will be incurred when the system scales up, since only a BB device is required for each additional bio-instrument. In theory, we can add as many BB devices to the system as we wish, given that the BB devices are implemented as decentralized objects (in an ad-hoc network) in our Smart Lab. However, due to the limitations of IEEE 802.11b Medium Access Control (MAC) protocol[54] in supporting time-bounded real-time data, there is a limitation on the number of BB devices that can be supported in a single ad-hoc network. We can resolve this limitation by deploying multiple ad-hoc networks with different SSIDs in a large-scale Smart Lab — each of these networks will support a different set of bio-instruments equipped with BB devices in the lab. As for further work, hierarchical ad-hoc network model should be explored so that current Smart Lab platform can support unlimited numbers of bio-equipment in the lab.

On the other hand, our relative positioning engine can handle multiple bio-instruments in a lab by applying SPIRM on the signal strengths from the two strongest NICs. However, our current set-up depends on a static arrangement of bio-instruments in the laboratory – the introduction of new bio-instruments into the laboratory may affect the previously calibrated radial maps of existing bio-instruments and re-calibration may be required. In order to minimize such additional calibration requirement[27, 45, 70], practi-

cal methods for incremental or adaptive calibration to pre-configured radial maps of the BB devices should be investigated for further research.

Chapter 7

Author's Publication

1. **W.K.FOR**, X.BAO, W.S.GAN, S.K.NG, "Location Awareness for On-the-Go Equipment Access in a Smart Bio-Laboratory," *Proceeding of IEEE Wireless and Optical Communications Networks (WOCN 2005)*, March 6-8, 2005.
2. **W.K.FOR**, X.BAO, W.S.GAN, S.K.NG, "Reconfigurable Context-Sensitive Bio-Bridge Middleware for Smart Bio-Laboratories," *Proceeding of the First International Workshop on Ubiquitous Smart Worlds (USW2005) conjunction with 19th IEEE International Conference on Advanced Information Networking and Applications (AINA 2005)*, March 28-29, 2005.

3. X.BAO, S-K.NG, E-H.CHUA, **W-K.FOR**, "Virtual Lab Dashboard - Ubiquitous Monitoring and Control in a Smart Bio-Laboratory", *Ubiquitous Web Systems and Intelligences Workshop*, May 9-12, 2005.
4. **W.K.FOR**, S.K.NG, X.BAO, W.S.GAN, "Relative Proximity Estimation in a Confined Small-Scale Environment," *International Workshop on Wireless Ad-hoc Networks 2005 (IWWAN 2005)*, May 23-26 2005.
5. X.BAO, S-K.NG, **W-K.FOR**, "Reconfigurable Virtual Lab Dashboard for Ubiquitous Remote Monitoring and Control in a Smart Bio-Laboratory", *Invited Journal for Ubiquitous Web Systems and Intelligences Workshop 2005 Special Issue*, May 9-12, 2005. (Submitted)

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