An Indoor Positioning Service for Bluetooth Ad Hoc Networks

Kiran Thapa
Department of Computer & Information Sciences
Minnesota State University, Mankato
kiran.thapa@mnsu.edu
(507) 385-1648

Steven Case
Department of Computer & Information Sciences
Minnesota State University, Mankato
steven.case@mnsu.edu
(507) 389-5310

Abstract

Mobility has been one of the key features behind the success of wireless technology. A wide variety of additional applications are possible once this mobility is combined with location awareness. Critical for location awareness is an accurate assessment of the mobile user's local position.

Local Positioning refers to a technology used to determine the position of any device with respect to the other devices whose positions are already known. There are already several positioning technologies such Global Positioning System (GPS), Wave LAN, Loran, Decca and Omega ranging from satellite-based to terrestrial-based, military-owned to fully commercial and with varying frequencies of operations. These positioning technologies are, generally, unsuitable for indoor positioning.

This paper discusses the development of a local positioning service based on the Bluetooth ad-hoc wireless network standard. Originally conceived as a cable replacement, Bluetooth is a promising new technology of low power, short range, wireless radio system that can be used to create a wide range of wireless services.

Position information can be obtained by using any generic wireless infrastructure by using various communication metrics to triangulate from known positions. Typical metrics include the use of signal strength, bit error rate (BER), or time delay. The original Bluetooth specification does not provide inherent support for access to such communication metrics. Thus, utilization of Bluetooth for local positioning applications still remains an emerging research area and offers a variety of challenges that must be addressed in order to provide accurate positioning information.

This paper begins with a discussion of the various theoretical and practical aspects associated with indoor positioning based on Bluetooth communication. The paper then presents a proposed solution based on the exchange of positioning information between master and slave devices within a Bluetooth piconet. The paper closes with a presentation of preliminary results based on an initial implementation of the proposed service.

Introduction

Information such as location, group, objects that are directly related to an application's operating environment are often referred to as context of that application and the application which can detect the context and modify its behavior based on dynamic context is called a context-aware application [13]. Location is one such context that can be of great significance for wireless applications.

The wireless location market has been growing tremendously over the last few years. According to the findings of the Strategis Group [1], within the global market opportunity for wireless location solutions the U.S. wireless market has been the frontrunner while the Japanese market has been very keen to adopt the technology. The U.S. carriers have accepted, rather unwillingly, the regulatory Enhanced 911(E911) mandatory from FCC (Telecommunication Act 1996) that forces them to deploy high-accuracy location technologies in their services [1]. While the E911 requirement and the Global Positioning System (GPS) satellite positioning system have heralded a new beginning in outdoor wireless positioning, these solutions are not appropriate for indoor positioning. Small range technologies like Bluetooth, HomeRF and IrDA offer promising solutions for indoor applications.

The Bluetooth Specification [3,4] provides no specific support for positioning service. In the absence of such support, various research efforts have been made in this area with alternating conclusions. Bahl and Padmanabhan used Bluetooth signal strength information to create a system for locating and tracking users inside buildings [2]. Patil introduces the concept of reference tags and readers that work with both the possibilities of Bluetooth supporting and not supporting the signal strength parameter [18]. On the other hand, work by Hallberg, Nilsson, and Synnes suggests an unreliable relationship between the positioning and the signal strength and hence avoids this parameter for positioning with Bluetooth [11].

In this paper, we will investigate the Bluetooth adhoc network and its ability to be used for more accurate and low cost indoor positioning as compared to other methods. Specifically, we will focus primarily on signal strength measurement for the positioning service, but will consider other available Bluetooth metrics such as link quality and bit-error rate. We base our early discussions of various location techniques and technologies on the foundation work performed by Tahvildari at the University of Waterloo [22].

Location Techniques

It is necessary to create a distinction between *position* and *location*. For our purposes, position refers to the exact position of the device whereas location refers to the secondary information derived from the position of that device. For instance, the position of a device may be provided as 44.154º latitude and -94.0235º longitude, whereas the location of the device may be provided as two blocks south and three blocks west of the high school. This paper makes a very loose distinction between the two though.

Determining location is a science in itself and is often associated with the general topic area of navigation. Historically, navigational techniques like Celestial navigation, dead reckoning, proximity system and radiolocation have been employed at different times.

Once used by Chinese sailors, celestial navigation involved determining one's position based on the position of the stars. Dead reckoning is one of the simplest and primitive location techniques that makes use of the initial position of the mobile device and other information such as speed, acceleration and the direction of travel. This type of navigational system can be expressed by the mathematical expression [22] given as

$$X_n = X_0 + \sum_{i=0}^{n-1} D_i$$

where D_i is the displacement vector at a certain time. The displacement vector, in turn, is represented in terms of distance (d) and direction (α) and is provided below:

$$D_i = \left[d_i \cos(\alpha), d_i \sin(\alpha)\right]$$

Piloting (often known by other names like proximity system, signpost and beaconing) works by steering a mobile device from fixed reference points. Each reference point is usually a fixed detection device like a radio transmitter or a receiver [21]. The cellular radio system can be based on this type of navigation.

A modern approach for navigation systems is the technique of radiolocation. In this system, the location of a mobile device is found by measuring various parameters of the electromagnetic signal traveling between a mobile device and a set of fixed base stations. Radiolocation can be implemented either in a direct or an indirect way depending on whether the position determination is done at the mobile device or the base stations.

Depending on the electromagnetic signal parameter chosen for the position determination, Caffery and Stüber [6] and Tahvildari [22] identify three fundamental approaches to radiolocation system.

1. Received Signal Strength Indication (RSSI) measurement: This approach of radiolocation system makes use of the relationship the received signal strength and the distance [10]. Theoretically, there exists an inverse proportional relationship between the received signal and the distance from the receiving station that can be represented linearly. Unfortunately, various phenomena like multipath fading and shadowing make it impossible to establish a precise relationship. For practical purposes, this technique involves determining the path loss function based on statistical analysis.

2. Angle of Arrival (AOA) This technique computes the angle of arrival of the signals from the mobile device to more than one base station making use of directional antennas and using simple geometric rules to calculate the distance from the angle measurements. The performance of this system highly depends on the accuracy of the antennas used for the angle measurement. Also, changing scattering characteristics and multipath signals hinder the performance of AOA navigation techniques. One way of reducing the scattering characteristic and the multipath issues is to elevate the antenna to a height well above the terrain [12]. This system is almost impractical for micro cell based networks like Bluetooth because of this need for a high antenna elevation.

3. Time based Systems: This navigation technique is based on estimating the time of arrival of a signal transmitted by the mobile device and received at the minimum of three base stations. Sometimes it is also based on the time difference of arrival of a signal received at multiple pairs of base stations [6]. The major concern with this type of navigation technique is the preciseness of time measurement and unlike other navigational technique, the error factor decreases as the distance between the mobile device and the base station increases. Since the time delay to be measured in microcellular technologies is very small, technologies like Bluetooth do not easily support this technique of positioning.

There are other variations to the time measurements like phase estimation through synchronized phase detection, pulse transmission through different correlation techniques and different spread spectrum techniques [23].

Besides the navigational techniques we have seen above, the bit error rate involved in the actual signal transmission can be a good indicator of the distance between two devices. Like RSSI, BER is directly proportional to the distance between the mobile device and the base station.

Existing Technologies

Tahvildari provides an overview of early technologies developed for large scale positioning systems [22], specifically identifying Loran, Omega, and the Decca System. Long Range Navigation (Loran) positioning system, initially proposed as Loran A has been present since World War II and is used for the aircraft and marine navigation [9]. Loran A was upgraded to Loran C for better range and accuracy. The Omega navigation system is another outdoor, long-range system initially designed by the U.S. Navy and is used for maritime and aeronautical purpose. Its range can go up to several thousand kilometers but with accuracy ob the order of 1-3 km [22]. The Decca System is a low frequency navigation system that makes use of phase difference to calculate position information [20]. Besides these terrestrial systems, the most popular satellite based navigation system is the Global Positioning System (GPS). A modified form of GPS known as Differential GPS is used for precise positioning purpose.

The technologies mentioned above are large scale positioning technologies and are used for long range outdoor positioning. With the huge success of these technologies, in one hand, it is natural for these technologies to be extended to the indoor applications and on the other hand, indoor positioning in itself promises a huge full-fledged market in the future.

One popular indoor wireless technology is Infrared Data Association (IrDA) which is a direct line of sight narrow angle communication system working at infrared frequency spectrum. IrDA has classified its products in two different standards, IrDA Data and IrDA control. IrDA data standard is usually used for high speed short range applications whereas IrDA control is usually recommended for low speed applications like keyboard, joystick and mouse controls. IrDA has its own set of protocols covering all layers of data transfer and some optional protocols for handling network management. The working range for IrDA is 1 to 2 meters and supports bi-directional communication with data transfer rates of 9600 bps to 4 Mbps.

Another popular indoor wireless technology that can be used for the positioning is Home RF system. Home RF supports both an ad-hoc and infrastructure network technologies. It is a simple home networking technology aiming to make use of the existing home PC industry infrastructure. Working in the frequency range of 2.45 GHz and covering up to 150 ft., Home RF supports the equivalent maximum of 6 full duplex voice connections.

Yet another technology which directly competes with Bluetooth is the IEEE 802.11 set of wireless local area network standards. The IEEE 802.11 standards can also support both ad-hoc networks and infrastructure networks. HIPERLAN, available in Type 1 and Type 2 modes, is another related indoor wireless technology and shares many similarities to IEEE 802.11.

Positioning with Bluetooth

Bluetooth is an open specification for a technology that enables low power, short range wireless data and voice connections [17]. Initially conceived by Ericsson Mobile Communication in the mid 90's as a cable replacement technology, Bluetooth has gained a huge popularity within a short span of time. Ericsson was joined by IBM, Microsoft, Nokia and Toshiba to form the Bluetooth Special Interest Group (SIG) in order to standardize the Bluetooth specification. Besides regulating the protocols from the top level to the bottom level of the protocol stack, the Bluetooth SIG has also been created different working groups to focus on a specific application and service area. Each working group concentrates on the standardization of a Bluetooth profile. Bluetooth profiles create a vertical slice through the protocol layers in order to define an appropriate subset of the standard to support a particular service.

Bluetooth offers a promising solution to indoor positioning. A separate working group called the Local Positioning Working Group has been created with an aim to develop a Bluetooth profile which describes the type and format of messages allowing Bluetooth devices to exchange position information and also the algorithm to compute the position. While it is going to take some time before the group comes up with a profile, the authors are currently involved in a project to investigate the Bluetooth performance for local positioning.

The Mobile Ad-hoc Network (MANET) working group defines an ad hoc network as an autonomous system of individual routers which are free to move randomly. Such a network is often characterized by rapidly changing and unpredictable wireless topology [8]. Because the multiple nodes in such a system can enter and leave the system at any time, this system requires some sensing of the location and hence offers a very attractive environment to support context aware applications. The ad-hoc network provides limited automation needed in the position calculation and is an ideal and cheap alternative in the environment where the infrastructure is not developed yet. . Bluetooth is one such emerging technology that provides ad-hoc networking.

With different competing technologies existing, it is important to analyze theoretical performance of Bluetooth in order to understand its viability as a technology for indoor positioning. Accuracy is the key feature of any technology. Like many other wireless technologies based on radiolocation navigation, the accuracy of Bluetooth is directly proportional to the range of the system. Because Bluetooth works in a relatively short range of 10 meters to 100 meters, the system is relatively limited in accuracy. Fortunately, more than one metric is available for positioning calculation and it is expected that these metrics can be combined in order to improve accuracy.

When a new service is integrated, it is very important that the existing system is unaffected. . With the automatic service discovery in Bluetooth, the network can automatically check for the new service in the entering device and then provide appropriate support for the positioning service. In addition, security is a major issue attached to any wireless technology. Inherent authentication and encryption present in Bluetooth makes it a better technology than others that rely on external means of achieving the security.

Theoretical Model for Position Determination

Our work is based on a very popular radio propagation model that describes the relationship between the signal strength and the distance. This model indicates that the received signal power decreases logarithmically with distance. This relationship exists for both outdoor and indoor conditions. It can be represented by the expression

$$P(d) = P(d_0) - 10\gamma \log(d/d_0)$$

where $P(d)$ is the signal strength at a distance d and $P(d_0)$ is the signal strength at some reference distance. The factor γ represents the path loss exponent and is affected by the external factors like multi-path fading, absorption, air temperature etc.

With this model we can determine the position using a standard triangulation algorithm. For every location, we have a set of individual readings of signal strengths gathered from a group of access points located at different physical positions. The location given by a single access point generally tends to be highly erroneous because of various factors obstructing the relationship between the signal strength and the distance. More importantly, the theoretical signal strength contours of a single omni-directional antenna around a base station are a circle and we can only have a radial distance measurement. We are lacking directional information and, in practice, the actual contour lines will rarely retain the ideal circular pattern.

If signal levels from three different base stations are known, the location of the mobile device can be approximated as the unique intersection point of the three circles. With the addition of more access points, we can relate all of them to infer the distance with increasing accuracy. Assuming that the mobile device and the access points are all located on the same geometric plane (i.e. on the same floor of the building), the triangulation algorithm specifies that a minimum of three base stations are required in order to calculate a unique intersection point of the three circles. This can be represented by a figure 1 as shown below.

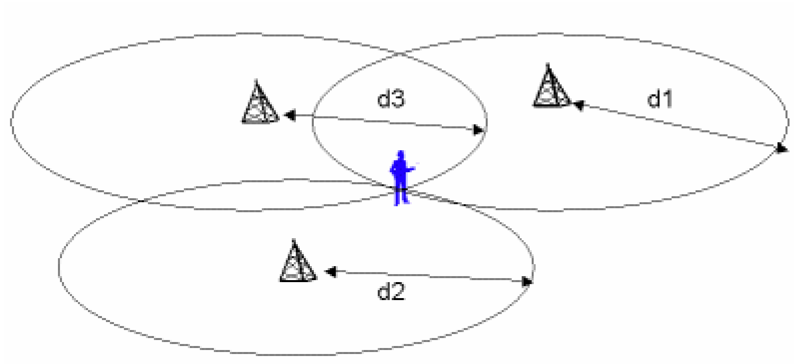

Fig. 1 Triangulation to locate a position [14]

Proposed Positioning Solution

A desired goal of the authors' research is to develop a Bluetooth service, supported by the Bluetooth Service Discovery Protocol, that can be readily ported to a variety of manufacturer's Bluetooth modules. As such, the positioning service will rely on the Host Controller Interface (HCI) and will limit itself to HCI commands that are not manufacturer specific. (The Bluetooth Specification allows for manufacturers to add their own proprietary extensions to the HCI layer.)

The HCI layer provides several HCI services that have potential value in supporting a positioning service. Specifically, the following HCI services are of interest:

- Get_Link_Quality. This HCI command returns measure of the quality of a link between the local module and a remote Bluetooth device. The link quality is scaled to a value of 0-255. Unfortunately, the link quality metric is manufacturer specific.

- Read_RSSI. This HCI command returns a measure of the received signal strength indication of a link between the local module and a remote Bluetooth device. The returned value provides a relative measure of the RSSI and the "Golden Receive Power Range." The golden receive power range is the range of desired received signal power resulting in minimal error and is usually a range of approximately 20 dB). A received signal with too little or too much power results in an inability to accurately decode the transmitted signal. This command returns a negative measure if the RSSI is too low, zero if the RSSI is within the golden range, and a positive measure if the RSSI is too high.

- Read_Transmit_Power_Level. This HCI command returns the current transmit power level of a link between the local module and a remote Bluetooth device.

In addition, the L2CAP layer provides support for an echo command. The echo command allows an arbitrary packet to be sent to a remote device and the remote device is expected to send back a reply packet containing the same bit sequence received in the echo request. The L2CAP and lower level layers are assumed to perform no error detection and recovery on echo packets and responses. The echo command can be used to perform a limited measure of bit errors by comparing the transmitted data to the received data and identifying any errors between the two.

The expectation is that a set of heuristics can be created to allow the Get_Link_Quality and Read_RSSI commands to be used to perform relative distance calculations between two Bluetooth devices. The Bluetooth protocol allows two devices to dynamically adjust their transmit power in order to maintain a reasonable quality of service. Thus, the Read_Transmit_Power_Level command must be used to allow the positioning service to dynamically adjust its calculations based on the current transmit power level.

In general, the assumption is that a remote device will establish a connection to the proposed positioning service. A Bluetooth device offering a positioning service is a Bluetooth device that knows its own position and supports the positioning protocol. Once a connection to the service is established, the device offering the service will periodically poll its local HCI layer to determine the current transmit power level for the connection with the remote device. This information and the current known position will be shared with the remote device. The remote device can dynamically adjust its distance calculations (whether using link quality or RSSI as a metric) in order to determine the relative distance from each other and, hence, its relative distance from a known position.

It should be noted that the standard HCI services provide very rough measurements for link quality and RSSI. The vagueness of these metrics suggests that a significant amount of error will result when determining position based on this data. For example, if the Read_RSSI command returns a value of 0 then the device has only limited information pertaining to signal strength. However, this information will still provide useful localization information. Perhaps the value indicates that the device is between 1 and 10 meters from the transmitting device. This single point of information can be combined with similar data from another Bluetooth device to help eliminate the inherent error. Even if the second device results in another Read_RSSI value of 0, the position is now known to be within the intersection of two regions, each bounded by a minimum radius of 1 meter and a maximum radius of 10 meter. Assuming the base stations offering the positioning service are strategically located within the building, the user's known position can likely be narrowed down to a square meter by triangulating position from three base stations. This should certainly be sufficient to accurately indicate the user's location to a specific room or hallway within the building.

Progress Toward the Proposed Positioning Solution

The research documented in this paper is nearing the actual experiment stage. We will begin by investigating the limitations of local position determination using Bluetooth's supported RSSI service. This is based on a simple relationship that the RSSI increases with decreasing distance and vice versa.

The experiments will utilize hardware and software currently available in the wireless lab at Minnesota State University Mankato. The test hardware will consist primarily of TINI boards communicating over an HCI interface to Bluetooth modules using the CSR Bluetooth chipset.

This experiment is conducted over Tiny InterNet Interface (TINI) environment developed by Dallas Semiconductor. The TINI platform provides simple and cost effective processing, control, and device-level communication and networking capabilities [16].

The protocol stack used in the experiments is written in Java and has been developed at the University. This configuration provides full access to the capabilities of Bluetooth and offers the opportunity to extend the protocol stack, as necessary, to affect better performance. In addition, the protocol stack is portable to any device compliant with the J2SE, J2EE, and J2ME specification.

Future Work and Conclusion

Positioning based on Bluetooth technology is a very promising technology. Current technology offers the potential for calculating location with an assumed accuracy of several feet. Although this is considered only moderately accurate, particularly when compared to more predominate positioning systems such as GPS, this should be sufficiently accurate to support a wide variety of context-aware applications.

Effort was made to study the potential limitations within Bluetooth for determining accurate position. In our analysis, we assumed the distance to be the only factor that affects the signal strength but in reality factors like wall attenuation, obstruction, and temperature cannot be neglected. The affect is even more prominent in the indoor environment where there are more factors to reflect, attenuate and obstruct the radio signals.

Although the Bluetooth SIG's Positioning Working Group is developing a profile for the positioning, in the mean time efforts need to be taken to establish practical models that best fit the available Bluetooth components and heuristics to make reasonable inference of relative distance based on the limited capabilities of the HCI layer.

Future work will focus on establish the above mentioned models. The initial work will likely be based on very discrete distances inferred from relatively inaccurate measurements provided by the HCI services. Additional future work is expected to provide improved accuracy by applying a statistical approach as suggested by Figel *et al.* [10]. We also intend to extend the positioning service to dynamically adjust the period of reporting in order to support mobile users traveling at a wide range of speed.

References

1. Allison, C., Moss, J., & Jaffery, N. (2001). *Wireless Location Technologies: Options for E-911 and Beyond*. The Stategis Group. Retrieved from http://www.wow-com.com/market_research/documents/1270-01_ExSum.pdf

2. Bahl, P. & Padmanabhan, V. (2000). *Radar: An in-building RF_based user location and tracking system*. Proceedings of the IEEE Infocom 2000, Tel-Aviv, Israel, vol. 2, Mar. 2000, pp. 775-784.

3. Bluetooth Special Interest Group (2001). *Specification Volume 1, Specification of the Bluetooth System, Core*. Version 1.1, February 22, 2001.

4. Bluetooth Special Interest Group (2001). *Specification Volume 2, Specification of the Bluetooth System, Profiles*. Version 1.1, February 22, 2001.

5. Bray, J., & Sturman, C. (2002). *Bluetooth 1.1: Connect without Cables*. Upper Saddle River, NJ: Prentice-Hall, Inc.

6. Caffery, J. & Stüber, G. (1998). *Overview of Radiolocation in CDMA Cellular Systems*. IEEE Communications Magazine. pp 38-45. April 1998.

7. Chen, Y. & Kobayashi, H. (2002). *Signal Strength Based Indoor Geolocation*. Proceedings of the IEEE International Conference on Communications. pp 436-439. 28 April – 2 May 2002. New York.

8. Corson, S. & Macker, J. (1999). Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations. IETF RFC-2501. Retrieved from http://www.ietf.org/rfc/rfc2501.txt

9. Etten, J. (1970). *Navigation Systems: Fundamentals of low and very low frequency Hyperbolic Techniques*. Electrical Communication. vol. 45, pp192-212. March 1970.

10. Figel, W., Shepherd, N., & Trammel W. (1969). *Vehicle Location by a Signal Attenuation Method*. IEEE Transactions on Vehicular Technology. 18(3). pp. 105-109.

11. Hallberg, J., Nilsson, M., & Synnes, K. (2003). *Positioning with Bluetooth*. Proceedings of the 10th International Conference on Telecommunications (ICT 2003). February 23 – March 1, 2003. Tahiti.

12. Jakes, W. (1994). *Microwave Mobile Communications*. USA: Wiley-IEEE Press.

13. Klemmer, S., Waterson, S., & Whitehouse, K. (n.d.). *An Empirical Analysis of TinyOS RF Networking (and Beyond…)*. University of California at Berkley. Retrieved from http://guir.berkeley.edu/projects/location/.

14. Lähteenmäki, J., Laitinen, H., & Nordström, T. (2001). *Location Methods*. VTT Information Technology. Retrieved from http://location.vtt.fi/source/technologies.html

15. Li, S., Zhao, G., & Liao, L. (n.d.) *User Location Service Over an 802.11 Ad-Hoc Network*. Retrieved from http://www.cs.washington.edu/homes/liaolin/Courses/networks02.pdf.

16. Loomis, D. (2001). *The TINI Specification and Developer's Guide*. Upper Saddle River, NJ: Addison-Wesley.

17. Muller, N. (2001). *Bluetooth Demystified*. New York: McGraw-Hill.

18. Patil, A. (2002). *Performance Of Bluetooth Technologies And Their Applications To Location Sensing*. Michigan State University Master's Thesis. Retrieved from http://www.egr.msu.edu/~patilabh/Thesis_Report.pdf

19. Pierce, J. (1989). *Omega.* IEEE Aerospace and Electronics Systems Magazine. 4(7). pp. 4-13.

20. Powell, C. (1958). *The Decca Navigator system for Ship and Aircraft use.* Proceedings of Institution of Electrical Engineers, Vol. 105. pp. 225-234. March 1958.

21. Riter, S. & McCoy, J. (1977). *Automatic Vehicle Location-An Overview*. IEEE Transactions on Vehicular Technology. pp 7-11. February 1977.

22. Tahvildari, L. (2001). *Local Positioning Techniques with Emphasis on Bluetooth*. E&CE750: Topic 4 – Final Project Report. November 15, 2001. Retrieved from http://www.swen.uwaterloo.ca/~ltahvild/Publications/ECE750-4.pdf

23. Turin, G., Jewell, S., & Johnston, T. (1972). *Simulation of Urban Vehicle Monitoring Systems*. IEEE Transactions on Vehicular Technology. pp 9-16. February 1972.