社団法人 情報処理学会　研究報告
IPSJ SIG Technical Report

2004－UBI－3　(2)
2004／1／20

Bluetooth を用いた室内位置検出システムの設計と実装

バンダーラ ウダーナ[1,2]　長谷川幹雄[1]　井上真杉[1]　森川博之[1,3]　青山友紀[3]

1 独立行政法人 通信総合研究所 新世代モバイル研究開発プロジェクト

2 東京大学大学院 情報理工学系研究科

3 東京大学大学院 新領域創成科学研究科

近年、ユビキタスコンピューティング環境実現のための研究が注目を集めている。ユーザの周りに遍在する様々なデバイスを自在に利用するには、それらのデバイスの位置やユーザの位置が同定可能となる必要がある。本研究では、近年様々なデバイスに組み込まれるようになってきた Bluetooth を用いた位置検出システムについて検討する。既存の無線モジュールを利用出来るようにするために、基本的には RSSI 値を用いた位置検出を行う。しかしながら、Bluetooth の場合、Golden Received Power Range の存在などのために、細かい電界強度値をＲＳＳＩ値のみから算出することが出来ない。このような問題点を解決するために、本研究では、可変アッテネータを搭載したアクセスポイントを利用し、ソフト的に値を制御することで、より詳細な電界強度の測定を可能とした。更に、各地点での RSSI 値を学習させるアルゴリズムを導入することで、位置検出精度の向上を行った。可変アッテネータを用いない場合と比較した結果、エラー率を約３分の１にまで減少させることが可能となった。

Design and Implementation of Bluetooth based Indoor Location-sensing System

Udana Bandara[1,2]　Mikio Hasegawa[1]　Masugi Inoue[1]　Hiroyuki Morikawa[1,3]　Tomonori Aoyama[2]

1 New Generation Mobile Network Project, Communications Research Laboratory

2 Graduate School of Information Science and Technology, The University of Tokyo

3 Graduate School of Frontier Science, The University of Tokyo

In a ubiquitous computing environment, location awareness is a basic necessity. There are various research projects, which discuss the problem of indoor location sensing. We have recognized acceptability, low power consumption, user privacy, and cost as the key design factors for developing widely deployable location sensing system. Here we have considered developing such a system, based on the widely available Bluetooth medium, as a good candidate to satisfy those needs. We use Bluetooth signal strength with a reference model based approach for evaluating the location. We discuss the problems, which arise when Bluetooth RSSI (received signal strength indicator) is used as a signal strength indicator, and introduce a novel access point that supports variable attenuators to overcome this problem. The access point allows reading wider areas of signal strength using RSSI. We showed that our approach to the location sensing system has reduced the error rate about threefold compared to a system which does not use variable attenuator supported access points.

1. Introduction

Writing in Scientific American (1991), Mark Wiser commented that, "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."[1]. In recent years, we have seen an increase in the number of research projects incorporating this idea. Indeed, Project Oxygen at MIT[5], Project STONE[7] at The University of Tokyo, and Project Cooltown[6] at Hewlett-Packard, could, among others, be given as examples of some of these efforts. We have also seen the proliferation of various computing devices with varying degrees of computational power [4], ranging from powerful server systems to tiny sensor nodes. A natural progression of these trends is moving towards an era where computers will be widely available and embedded in our environments, i.e. where they will be "ubiquitous"[1] or "pervasive"[3].

In the future, a ubiquitous computing environment's "context awareness" will be indispensable. For example, the user should be able to establish distress free communication between both system and users. Let us consider a simple ubiquitous computing scenario. Alice enters a room while communicating with a colleague by cellular phone. The colleague (Bob) is sitting in the lab in front of a fully equipped video conferencing system, using voice over IP to reach Alice's cellular phone. When Alice enters the room, she is faced with a network television system with greater communication abilities. The system thus automatically, in accordance with Alice's selected preferences, changes her communication session to the TV display system, and launches video conferencing. Among many other technologies, location sensing is one of the basic technologies needed to realize this scenario.

There are many location-sensing systems proposed within the past few years. MIT's Cricket[8], Microsoft Research's RADAR[3], AT&T Cambridge's Active Badge[10], and Active Bat[9] are just a few of the well known systems in this field, each of which have their own merits and shortages.

With regards to service provision, location sensing can be categorized by the following stages:

1. A user's terminal recognizes the existence of nearby devices;
2. The terminal recognizes the location and the relative distance of nearby devices;
3. The system knows the location information of the user's device and of other nearby devices as points in a predefined coordinate system;
4. The system knows the orientation of the user and of the nearby devices.

The quality of service provided at each stage of the location sensing varies. With our experience of designing a ubiquitous computing environment (see[13]), category 3 offers the best choice with regards to the location service within a ubiquitous computing environment. Our experiences show that it is not always necessary to have highly precise location data for context aware applications. Usually applications need a higher abstraction of the logical position of the user than the exact coordinate of that point. Thus, we argue that in order for a system to be useful, accuracy about 2 meters is enough, since within this range a user maintains full awareness of all available devices.

In the next section, we survey the related works and design goals in the field of indoor locating. Section 3 explains the challenges we faced dealing with Bluetooth as a location-sensing technology. Section 4 presents a novel Bluetooth based location sensing system. An evaluation of the proposed system is given in section 5. Finally in section 6 conclusions are given.

2. Design goal

Even though many indoor locating systems have been proposed, none of them have gained wide acceptance for real world deployment. A few of them have been industrialized and introduced into the market, but of these, most address special cases in location sensing such as high precision location sensing for industrial environments etc. It is thus our research goal to design a widely deployable location sensing system. We identify the following criteria as being necessary in designing such a system.

- *Acceptability*: Ability to integrate smoothly with existing infrastructure. i.e. Providing location sensing to user terminals should not require additional oversized hardware installation using existing technologies to provide the service.
- *Low Power Consumption*: Power consumption of the mobile terminal is a critical factor. A widely deployable location sensing technology should not consume too much energy from the mobile terminal.
- *User Privacy:* In context aware systems, privacy is a major concern. The user should be given the choice to choose whether he or she wants to be tracked by the location sensing system and make this known to other users.
- *Cost:* The infrastructure required to realize the location system should not be too expensive.

Among existing systems, CRICKET is one of the highly accurate, decentralized systems which satisfies most of the criteria except acceptability. It needs an ultrasonic receiver to be installed on the user terminal side. And on the other hand Active Bat is a centralized high priced system but it needs expensive wiring and a grid of ultrasonic receivers to be installed in the ceiling of the indoor environment, which make it less acceptable and more expensive. RADAR satisfies almost all the criteria given above. However, it has relatively high power consumption because of the use of an 802.11b wireless link.

In future ubiquitous computing environments, the devices must be able to interact with each other so as to continuously be aware of available resources which other devices may provide. For this reason, high bandwidth is not necessary. A low power consuming, always connected, wireless link would be the best candidate for the job. We consider then if we could provide location-sensing abilities to the mobile terminal using such a low power wireless link, satisfying the above criteria. Bluetooth[11] and Zigbee[12] are technologies which are currently the closest to satisfying these requirements. Bluetooth has already gained wide acceptance and many mobile devices have Bluetooth modules preinstalled. Zigbee is also a promising technology, but is yet to be released. Hence we chose Bluetooth as the low power wireless link for providing location sensing for the mobile device.

We consider it easy for a Bluetooth location sensing system to gain acceptance, since many mobile devices have Bluetooth preinstalled and many of the devices support Bluetooth as a low power communication system. Secondly, when we discuss RF based location sensing systems, RADAR is one of the well-known technologies. RADAR has many merits such as the fact that the system is totally software based, with no additional hardware being necessary. But in the case of RADAR, the user is expected to have his 802.11b link on all the time, so the system is relatively high in power consumption. If Bluetooth were used instead of 802.11b, power consumption would not be such a big problem. Thirdly, when the number of 802.11b devices operating over the same channel increases, interference between them increases as well. On the other hand, because of frequency hopping, there is very little interference between two devices placed in close proximity to one another.

3. Location sensing with Bluetooth

Most ubiquitous computing applications do not demand highly precise location data. A Bluetooth signal strength based location evaluation system was one of the best candidates for our needs since it satisfies the design goals as mentioned in the previous section. It is well known that, in indoor environments, signal-strength is affected by many factors (multi-path effects, reflection effects, etc.). Hence, it is difficult to rely purely on signal strength as an indicator of distance that the signal has traveled. Additionally, in our preliminary tests, we observed that Bluetooth RSSI (Radio Signal Strength Indicator) varies according to signal strength as shown in figure 1. Here each Bluetooth tag was connected to an Agilent Bluetooth Tester (E1852A), and while changing RF level using the tester the RSSI of the tag was recorded. With wire loss subtracted, the variation of RSSI according to the signal strength is shown in the graph. As it can be seen, RSSI does not vary uniformly with signal strength. According to the Bluetooth specification when the signal strength is within the "Golden received power range", a variant of the signal strength is not indicated by RSSI. Thus, the readable RF level range is limited from -70[dBm] to -65[dBm]. When RSSI is -10 or 0 it does not indicate the RF level variation. The upper part of the graph, from -42 [dBm] upwards; cannot be used in location sensing since RSSI values over 0 occur when the tags are few centimeters away from the antenna in real life situations. Thus, it is necessary to introduce new approaches to make the readable signal strength range wider with RSSI.

Also, we have evaluated the Bluetooth signal distribution in an anechoic chamber. The antenna was placed 2 meters above an xy-plane, at point (0,0) and the Bluetooth tag was moved around the horizontal xy-plane and RF level was recorded. The results obtained are given in Figure 2.

The graph (Figure 2) shows that the RF level decreases according to distance traveled. -45[dBm] to -60[bBm] within 3.5 [m]. Thus,

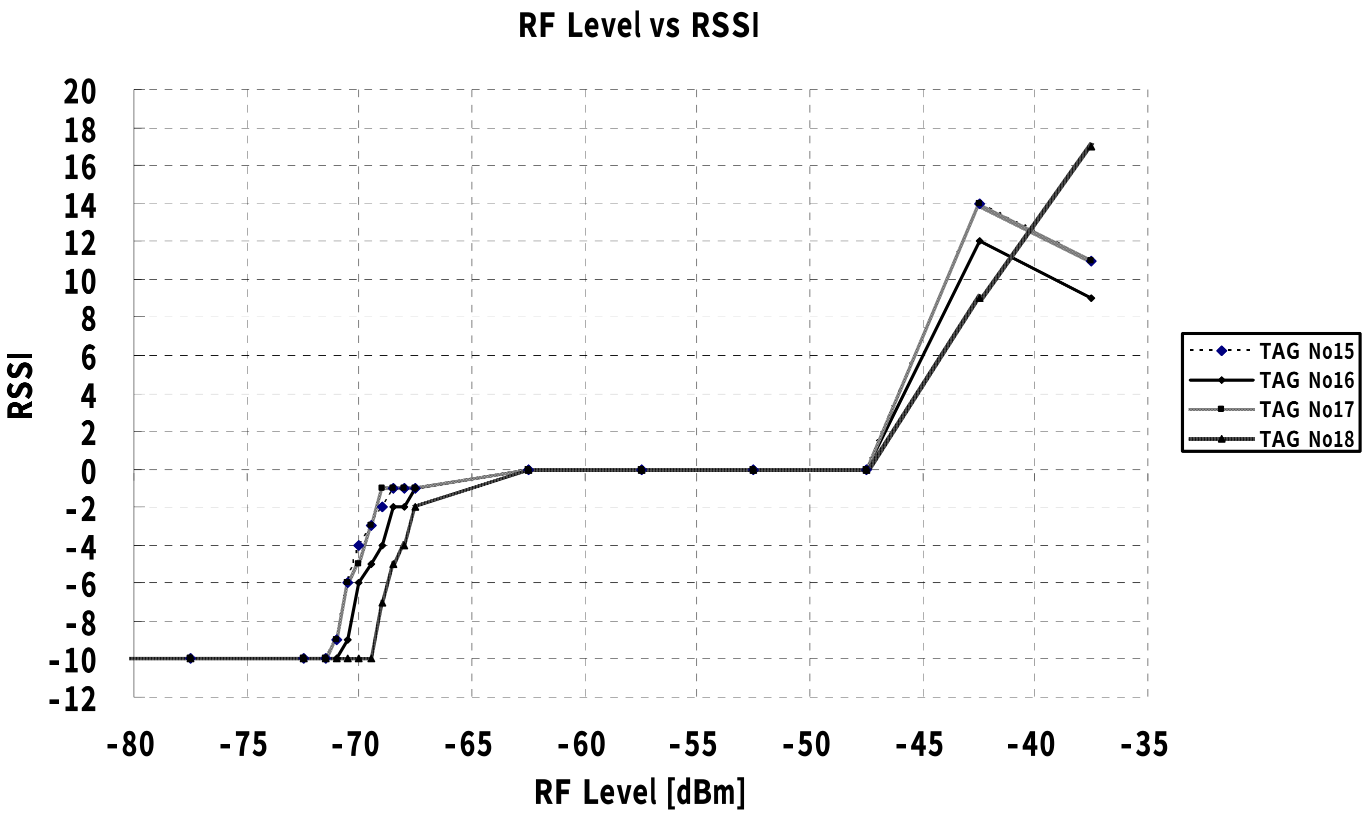

Figure 1: RSSI vs. Signal Strength

comparing with the data in graph 1 (Figure 1) shows that RSSI varies from 0 to -10 approximately within a 10[dBm] range. We can see that RSSI could not be used as a representation of distance even in an ideal environment. Thus, we adopted the variable attenuator supported multi-antenna approach given in section 4.

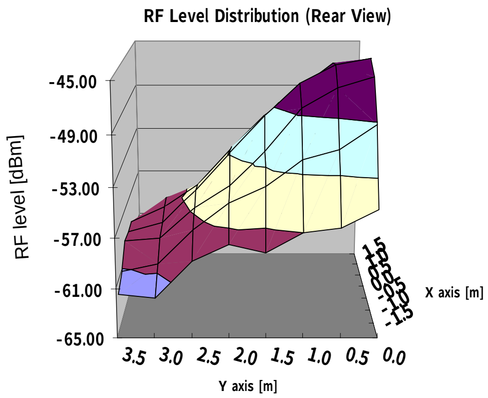

Figure 2: RF level distribution

4. Proposed System

We have developed a variable attenuator supported multi-antenna Bluetooth access point (AP) for location estimation.

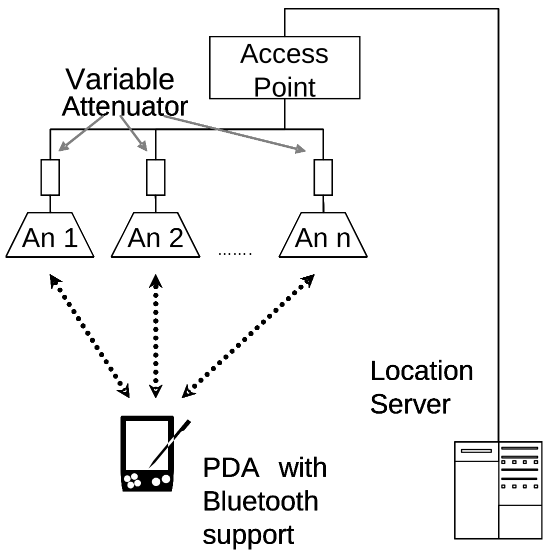

Figure 3: System architecture

The system is illustrated in figure 3. The AP could be used for evaluating the location of any Bluetooth supported device. In this system each antenna is connected to a Bluetooth access point. Every antenna connected to the AP has an attenuator. The strength of the attenuator can be controlled by the location data server. In this environment we consider that all the relevant devices support Bluetooth or that there is a Bluetooth tag attached to them. In case we are interested in locating non-communication device like tables or chairs, we assume that Bluetooth tags are connected to all such items. When a Bluetooth based device is presented to the environment, the AP

Figure 4: Bluetooth access point

establishes a connection with the device using an antenna, then for each value of the actuator the RSSI is recorded. While preserving the connection the AP changes antennas and records RSSI for each attenuator. Here attenuators are used for making the readable signal strength range wider with RSSI and the multi-antenna approach with one access point is used for reducing the number of connections established. The ability to preserve the connection is quite an important factor since it saves on the connection time. Otherwise the device has to connect to a different AP's and it will take n x (connection establishment time) to finish connecting to all the n APs.

Figure 5: Bluetooth tags

We developed a Bluetooth based location

sensing system and deployed it in a "Smart Space" room(4.5[m] x 5.5[m]) in our laboratory. The current system has 4 antennae placed in the ceiling and each actuator connected to them could be varied between 0dB, 3dB, 6dB and 9dB. The system contains the following component Bluetooth tags (Figure 5), a multi-antenna AP(Figure 4) and a location server. As mentioned in section 3, according to figure 1 the RSSI value rapidly changes from -10 to 0 when Signal strength change from -70[dBm] to -65[dBm]. Thus, most of the data received indicate RSSI level 0 or -10. In such a situation, we have to use an approximation algorithm to evaluate signal strength from the received RSSI. Here we adopt the following method to approximate the RF level from received RSSI.

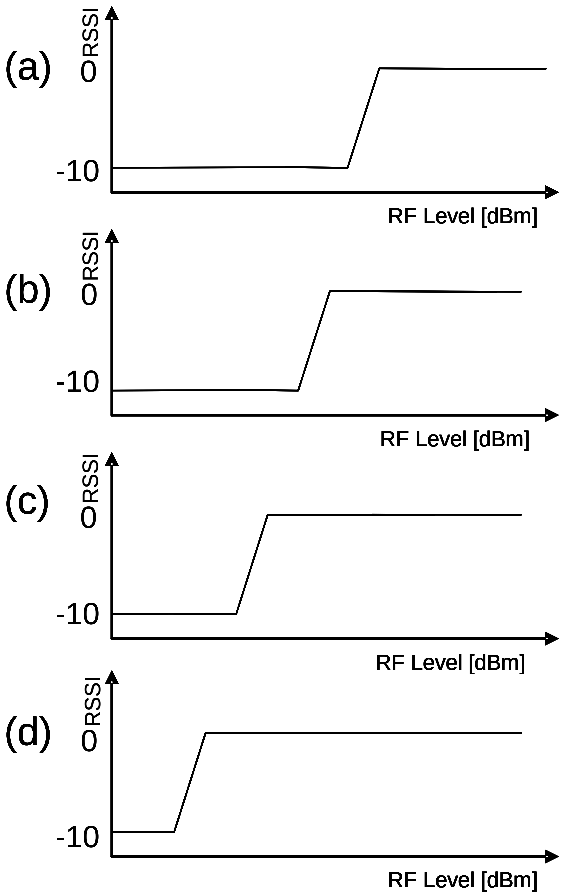

Figure 6: RF level shift

We can represent the RSSI vs. RF level graph in an abstract way as in figure 6. Figure 6 (from (a) to (b)) shows the RF level shift with the addition of attenuator value 0,-3,-6,-9 [dB]. By using the attenuator in such a way, we have widened the readable RF range. Thus, RSSI actually could be used as an indicator of signal strength. We use a non-triangulation, reference model based approach for location sensing. First we create a radio signal strength reference map by using 9 areas in the Smart Room. Approximately 2 [m] separate each area's mid-point from the adjacent areas. The signal strength reference map was created during the set up phase. The map contains 16 element signal strength vectors related to each (x,y) mid-point according to the coordinate system in the Smart space. In the present implementation, the map holds 9 reference points and the related signal strength vector of each point. The signal strength vector contains the RSSI value of each antenna with attenuator value changing from 0, 3, 6,9 [dB]. The mapping vector $v_{(x,y)}$ could be represented as follows:

$v_{(x,y)} =< s_{1,0}, s_{1,3}, s_{1,6}, s_{1,9}, s_{2,0}, s_{2,3}, ..., s_{4,9} >$

where $s_{a,b}$ represent RSSI of the a^{th} antenna while the attenuator set to b [dB]. When the median of measured RSSI values varies rapidly, $s_{a,b}$ represent a range of RSSI values.

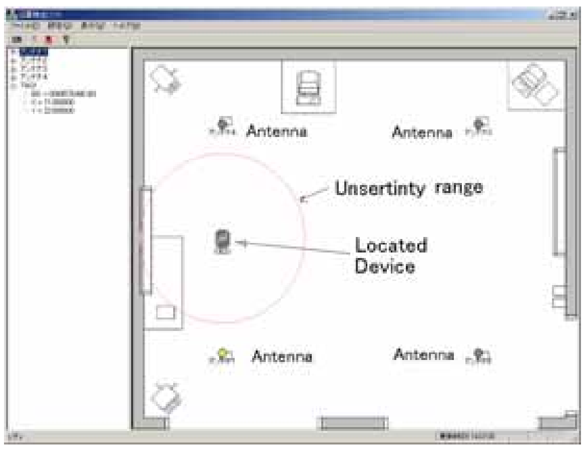

Figure 7: Location monitor on the location server

The location of a Bluetooth tag or a Bluetooth based device is evaluated as follows. The location server calculates the vector $v_{(x,y)}$ for each device in a time point *t.* Then the Euclidean distance is calculated for each reference point (the median of the RSSI is used when $s_{a,b}$ is represented as a range.) The closest vector is chosen as the related point and is given as the location.

Finally, the location server represents the located object as in Figure 7. The located Bluetooth devices are represented as a tag on the map, and the uncertainty is shown as a circle around the tag.

5. Evaluation

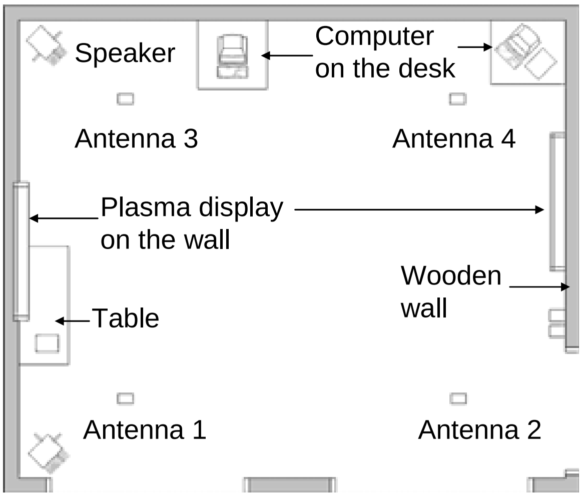

Figure 7: System settings

The system setting can be shown as in Figure 7, with the 4 antennae are placed on the ceiling, two meters above the floor. The smart room is equipped with computers, speakers, plasma displays. The boundary of the smart space is defined with wooden wall.

A Bluetooth tag was placed in the Smart space and the location of the tag was evaluated using the proposed system. As a comparison to our proposed method, we have also evaluated the location estimation ability with the attenuators locked into a certain value. In the experiment, the smart space was separated into 9 areas (1.75[m] x 1.75[m]), and we evaluated the location sensing system's ability to find the correct area where the tag was placed. The data was sampled 10 times for each area. When we used the locating system as explained in section 3, we obtained 92% precision[14] to within 2[m] accuracy[14]. When the attenuators were set to a fixed value then the error rates within 2 [m]s were as follows:

Table 1: Precision Comparison

Att level [dB]	Precision
0	38%
3	39%
6	72%
9	22%
Proposed System	92%

As shown in the table 1, the reliability of the date when the attenuator is fixed is not very high. The results show that the readable signal strength range has widened with our proposed methods. By the proposed method, the error rate becomes almost 1/3 compared to the best case with fixed valued attenuator.

In this implementation, our main focus was on making the readable RF level range wider with RSSI. It is possible to implement more complex learning (database) and attenuator switching algorithms in order to realize much better location evaluation with this system. We are planning to implement advanced location sensing algorithms on the system in the future.

6. Conclusion

Even though presetting the reference points is a cumbersome procedure, this system, like RADAR is highly acceptable, i.e. no special hardware is needed and the whole system could be implemented in software. Bluetooth has been widely supported in mobile devices. It will be quite useful if we can build a RADAR like location sensing system using Bluetooth. Bluetooth has the following merits as a location sensing technology instead of 802.11b in a RADAR like system: Namely, 1. Lower power consumption compared to 802.11b so that it is possible to use it as an always-on wireless connection. 2. High proliferation of Bluetooth. 3. Less interference when the number of device is high compared to 802.11b.

However, Bluetooth has its own problems as a location sensing medium. The RSSI does not vary homogeneously according to the signal strength because of the “Golden receiving power range” problem. We have proposed an AP architecture that can overcome this problem. We have implemented a prototype system using these ideas. Functionality evaluation with the prototype system shows that the proposed system obtained better results calculating signal strength. Also, by assigning multiple antennae to the same AP we have reduced the connection establishing time.

Reference

[1] M. Weiser. The computer of 21st century. Scientific American, September 1991

[2] P. Bahal and V. Padmanabhan. RADAR: An In-Building RF-based User Location and Tracking System. In Proc. IEEE INFOCOM, Tel-Aviv, Israel, March 2000.

[3] G. Banavar, J. Beck, E. Gluzeberg, J. Munson, J. Sussman, and D. Zukowski. An Application model for Pervasive Computing. In Proc. ACM MOBICOM, Boston, MA, August 2000.

[4] N. Bulusu, J. Heidemann, and D. Estin. GPS-less Low Cost Outdoor Location For Very Small Devices. Technical Report 00-729, Computer Science Department, University of Southern California, April 2000

[5] Oxygen Homepage, http://oxygen.lcs.mit.com.

[6] HP Cooltown Homepage, http://www.cooltown.hp.com

[7] STONE, http://www.mlab.t.u-tokyo.ac.jp/research

[8] Nissanka B. Priyantha, Anit Chakraboorty, and Hari Balakrishnan. The Cricket location-supporting system. In proceedings of MOBICOM 2000, pages 32-43,Boston,MA, August 2000 . ACM

[9] Andy Hatter, Andy Hopper, Peter Steggler, at el. The anatomy of context aware applications. In proceedings of the 5th Annual ACM/IEEE conference on mobile computing and Networking(Mobicom 1999) pages 59-68, Seattle, WA, August 1999. ACM press.

[10] Roy Want, Andy Hopper, at el. The active badge location system. ACM transaction on Information system, 10(1):91-102, January 1992

[11] Bluetooth, http://www.bluetooth.org/

[12] Zigbee, http:// www.zigbee.org/

[13] Mikio Hasegawa, Hiroyuki Morikawa, Masugi Inoue, Udana Bandara, Homare Murakami and Khaled Mahmud, Cross-Device Handover using Service Mobility Proxy, Proc. of International Symposium on Wireless Personal Multimedia Communications(WPMC), Vol. 2, pp. 357-361, 2003.

[14] Jeffrey Hightower and Gaetano Borriello. August 2001. A Survey and Taxonomy of Location Systems for Ubiquitous Computing. Extended paper from Computer, 34(8) p57-66, August 2001