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A study of frequency interference and indoor location sensing with 802.11b and Bluetooth technologies

Abhishek P. Patil*

Kiyon, Inc.
4225 Executive Sq. Ste 290
La Jolla, CA 92037, USA
E-mail: abhishek@kiyon.com
*Corresponding author

Dan J. Kim

Telecommunication, Information Studies, and Media
Michigan State University
East Lansing, MI 48824, USA
E-mail: dankim@msu.edu

Lionel M. Ni

Computer Science
Hong Kong University of Science and Technology
Kowloon, Hong Kong
E-mail: ni@cs.ust.hk

Abstract: Location-aware computing is regarded as a key feature of many future mobile applications. Recently there has been an increase in the use of commodity wireless technologies like 802.11 or Bluetooth for indoor location positioning. Since Bluetooth and Wi-Fi use the same frequency band, this paper presents the experimental results of the interference effect of one technology on the other. These results help in determining which of the two technologies is more suited for location sensing applications. The paper presents two techniques for location sensing using Bluetooth and concludes by suggesting some changes to the Bluetooth architecture to improve its capabilities for location positioning.

Keywords: Bluetooth; 802.11; location sensing; Wi-Fi; interference; co-existence; indoor location positioning.

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Biographical notes: Abhishek Patil is a member of technical staff at Kiyon, Inc. located in La Jolla, California. He received his PhD from the Department of Computer Science and Engineering at Michigan State University. He received his BE degree in Electronics and Telecommunications Engineering from University of Mumbai (India) in 1999 and an MS in Electrical and Computer Engineering from Michigan State University in 2002. His research

interests include wireless technologies, mobile *ad hoc* networks (MANETs), location-aware computing, RFIDs, and pervasive computing. He is a member of the IEEE Computer Society.

Dan J. Kim is an Assistant Professor of Telecommunication at Michigan State University. He earned his PhD in MIS from SUNY at Buffalo. He also holds an MS in Computer Science and an MBA in Management Science. His research interests are in multi-disciplinary areas such as electronic commerce, mobile commerce, information security and assurance. His research work has been published in refereed journals and conferences including *Communications of ACM*, *Decision Support Systems*, *Electronic Market*, *Journal of Global Information Management*, *ICIS*, *HICSS*, *etc*. Recently, one of his papers was nominated and received a best paper runner-up award at the ICIS 2003.

Lionel M. Ni earned his PhD degree in Electrical and Computer Engineering from Purdue University, in 1980. He is Professor and Head of Computer Science Department of Hong Kong University of Science and Technology. Dr. Ni was a Professor of Computer Science and Engineering at Michigan State University from 1981 to 2003, where he received the Distinguished Faculty Award in 1994. His research interests include location-aware computing, wireless networks, parallel architectures, distributed systems, high-speed networks, and network security. A fellow of IEEE, Dr. Ni has chaired many professional conferences and has received a number of awards for authoring outstanding papers.

1 Introduction

The location of people and objects relative to their environment is a crucial piece of information. Indoor location sensing has already found many applications other than asset tracking and security. The more traditional applications might be as simple as tracking a valuable shipping carton or detecting the theft of a laptop computer, or as complex as helping someone to find his or her way around an unfamiliar building (*e.g.*, museums or art galleries). Hospitals and day care centres have started using positioning technologies to locate personnel or the nearest doctor (or medical equipment) in case of an emergency.[1] Several researchers (Chen and Nahrstedt, 2002; Mauve *et al.*, 2003; Patil *et al.*, 2004; Stojmenovic, 2002; Xue and Li, 2001) in the area of *ad hoc* wireless networks have proposed to improve the efficiency of MANET routing algorithms by using location information of member nodes. Global Positioning System (GPS) (Kumar and Stokkeland, 2003), can help locate people or objects as long as they are outdoors, where the signals from the 24 orbiting GPS satellites may be received. However, there is a need for a similar system that works indoors, where the physics of radio propagation rules out the reception of GPS's weak microwave signals. In order to achieve location tracking in indoor environments, researchers and industry have proposed several systems, which differ with respect to the technology used, accuracy, coverage, frequency of updates and the cost of installation and maintenance (Ni *et al.*, 2003; Roussos, 2002). Some of the older technologies use costlier equipment. In other cases, the equipment is difficult to install or the system requires a person to carry or wear a device (tag) that is part of the sensory network. Steggles and Cadman (2004) provide a good comparison of various RF-tag-based location sensing technologies. Varshney (2003) gives a qualitative analysis of several location management schemes, points out performance issues, and suggests several interesting ways to design location management schemes for wireless networks.

The last few years have seen an increase in the use of commodity wireless technologies like WLAN[2] (Bahl and Padmanabhan, 2000; Battiti *et al*., 2002; Haeberlen *et al*., 2004; Niculescu and Nath, 2004; Small *et al*., 2000; Youssef *et al*., 2003) and Bluetooth (*e.g.*, Bluetags Corporation[3] and AeroScout, formally known as Bluesoft[4]) for indoor location sensing. It is interesting to note that both these technologies were designed without location sensing in mind. These two technologies are fast becoming ubiquitous in office and home environments; thus, requiring no additional infrastructure to be in place for indoor location sensing. The Bluetooth SIG is also working on a new Local Positioning (LP) Profile (version 0.95 as of this writing)[5] which specifies a mechanism and a format for the transfer of position-related data over Bluetooth. The profile also supports position determination and location awareness. Bluetooth and 802.11b use the same 2.4 GHz unlicensed frequency band; as a result, there has been a lot of concerns about interference between them (Chiasserini and Rao, 2002; Golmie *et al*., 2003; Lansford, 2000; Shoemake, 2001). In case of indoor location positioning, it is estimated that on an average, the probability of a Wi-Fi transmission colliding with a simultaneous Bluetooth transmission is around 55% (Lansford *et al*., 2001). Therefore, it is important to examine the frequency conflict between two technologies in door environments. This paper presents experimental results of the performance of two technologies (*i.e.*, Bluetooth and 802.11b) in the presence of interference from the other technology in order to examine which technology is better suited for doing indoor location sensing. The results will show a good candidate technology (that is more immune to interference) for location sensing in indoor environment.

Section 2 briefly describes some of the location sensing systems proposed in the past by various research groups from both academia and industry. The section also gives a quick review of some techniques suggested for avoiding interference between 802.11b and Bluetooth technologies. Section 3 gives a detailed description of the experiments (with their results) carried out in our eLANS lab at Michigan State University to examine the interference between the two wireless technologies. Section 4 describes two techniques of how Bluetooth can be used for location sensing. Section 5 presents the managerial implications of this research and Section 6 looks at some directions for future research. Finally, Section 7 concludes the paper with the major contributions of the study.

2 Related work

A variety of indoor location sensing systems has been proposed by different research groups in academia and industry. AT&T Olivetti Research Laboratory's Active Badge (Wang and Wang, 2005) is the pioneering work on this area based on infrared technology. However, due to the line-of-sight requirement and short-range signal transmission, researchers realised that infrared technology is not a very good solution for this problem. Other projects include Active Bats system by AT&T Research Laboratory using ultrasonic technology,[6] the Cricket Indoor Location System[7] at MIT with a combination of ultrasonic and RF technologies, TinyOS RF motes by UC Berkeley (Klemmer *et al*., 2000) and the Cooltown project by Hewlett Packard.[8] In recent years, most of the researches have been adopting the radio frequency (RF) technology for this purpose instead (*e.g.*, RADAR project by Microsoft Research – Bahl and Padmanabhan, 2000 – and SpotON done at University of Washington – Hightower *et al.*, 2000). Like the RADAR project, Project Aura done at Carnegie Mellon University also tries to utilise the IEEE 802.11 wireless technology for location sensing in addition to its use as a network infrastructure (Small *et al.*, 2000). Several other papers (Lu *et al.*, 2005; Luo *et al.*, 2004; Olla and Patel, 2003; Shih *et al.*, 2005; Siau and Shen, 2003; Wang and Wang, 2005) address the issues of location management, mobile services and security. For example, Lu *et al.* (2005) present a new approach for location management in IP-based cellular networks, while Olla and Patel (2003) developed a framework for delivering secure mobile location information.

Several groups, including the IEEE 802.15 work group,[9] have addressed the issue of co-existence between the two technologies. In general, two classes of co-existence mechanisms have been proposed: collaborative (where the Bluetooth and 802.11 exchange information) and non-collaborative (where the two technologies operate independently and cannot coordinate their transmissions). MAC EnHanced Temporal Algorithm (MEHTA), proposed by Lansford (2000), is a collaborative technique that uses a central controller that in turn, monitors Bluetooth and Wi-Fi traffic and coordinates their transmission to avoid interference. The Time Division Multiple Access (TDMA) (Shellhammer, 2001) scheme uses a similar approach where Bluetooth and Wi-Fi traffic do not overlap in time. Collaborative algorithms have a distinct shortcoming – they cannot eliminate interference in devices that are not collocated. Some non-collaborative mechanisms suggest techniques, like Adaptive Frequency Hopping (Gan and Treister, 2000; Treister *et al.*, 2001), where the Bluetooth (BT) device is given a limited choice of hop frequencies. These frequencies correspond to the frequencies not used by a nearby WLAN device. However, implementing such a mechanism would require a major change in the BT architecture. Chiasserini and Rao (2002) suggested that an OverLap Avoidance (OLA) scheme can work with or without collaboration among the devices.

3 Experiments

Several experiments were carried out at the eLANS lab to study the interplay between Bluetooth and 802.11. The experiments closely examined the interference between the two technologies and measured throughput during interference.

3.1 Experimental setup

Figure 1 shows the layout of the eLANS lab and the positions of various 802.11b devices used in the experiments. After several trial runs, it was observed that for most experiments, a signal strength log of two minutes (120 seconds) was enough to show any peculiar pattern. We therefore carried out all the experiments for three minutes (180 seconds). We then ignored the first and the last 15 seconds of the log file (to eliminate startup latencies or ending errors) and examined the rest of the 150 seconds. All the signal strength plots in this paper are shown for 150 seconds (2.5 minutes). The experiments can be divided into four sets:

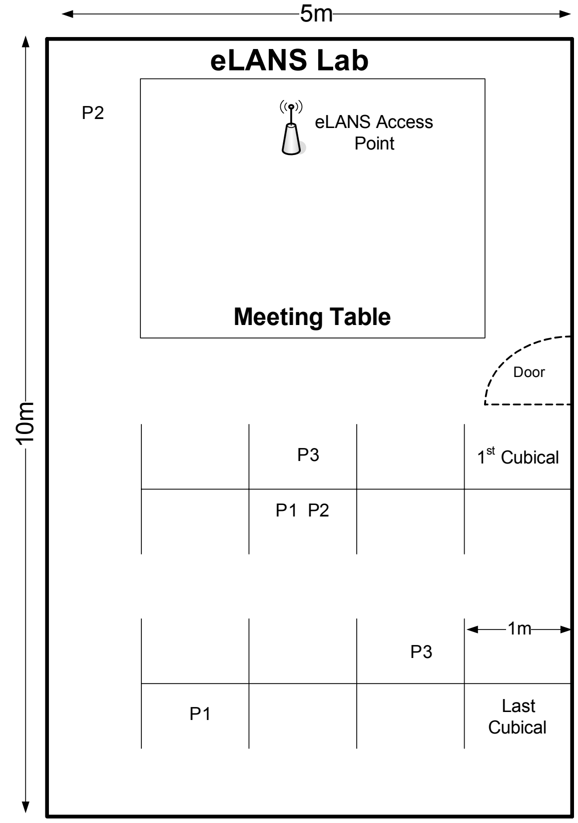
1. influence of 802.11b devices on other 802.11b devices
2. the effect of Bluetooth on 802.11b

3 the effect of 802.11b on Bluetooth

4 the effect of Bluetooth on Bluetooth.

The following four subsections give a detailed description of the setup and performance results for each of the experiment sets.

Figure 1 Layout of eLANS lab



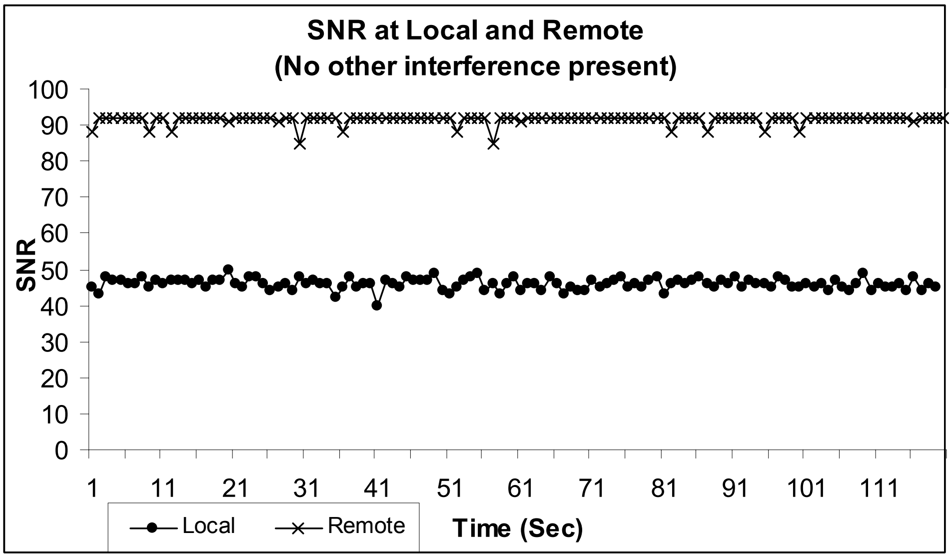
P1 – Position of first Pair (case A-1, A-2 & A-3)
P2 – Position of second Pair (case A-2 & A-3)
P3 – Position of third Pair (case A-3)

3.2 Influence of 802.11b devices on other 802.11b devices

Case A-1 Single pair of 802.11b devices present in the environment – No Interference

An iPAQ with D-Link card and a laptop with Orinoco card were configured to ping each other over the same channel (Channel 6). The activities of a particular link were monitored and logged by the Orinoco client manager software. This set-up represented the case where there was no interference. Figure 2 shows signal-to-noise ratio (SNR)[10] values at Laptop (local device) and iPAQ (remote) for the set-up when no interfering devices were present.

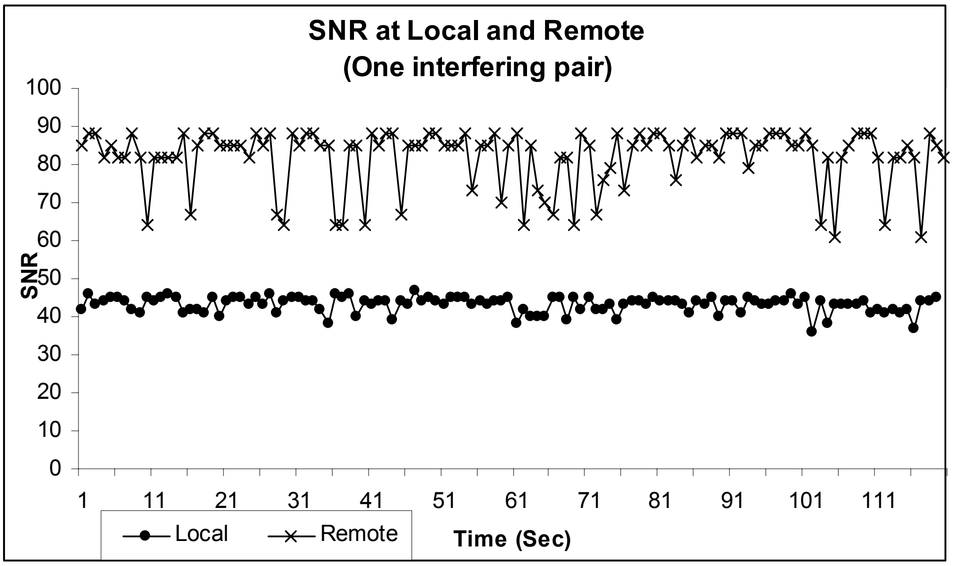
Figure 2 SNR values of Case A-1



Case A-2 Single interfering pair of 802.11b devices in the environment

Another iPAQ with D-Link card and an Orinoco USB client on a PC were added to the setting in Case A-1. They were configured so that they would communicate over the same channel as the earlier configuration. This change added another pair of 802.11b devices over the same wireless network. Figure 3 shows the new SNR values when another pair of 802.11b devices was present in the same network.

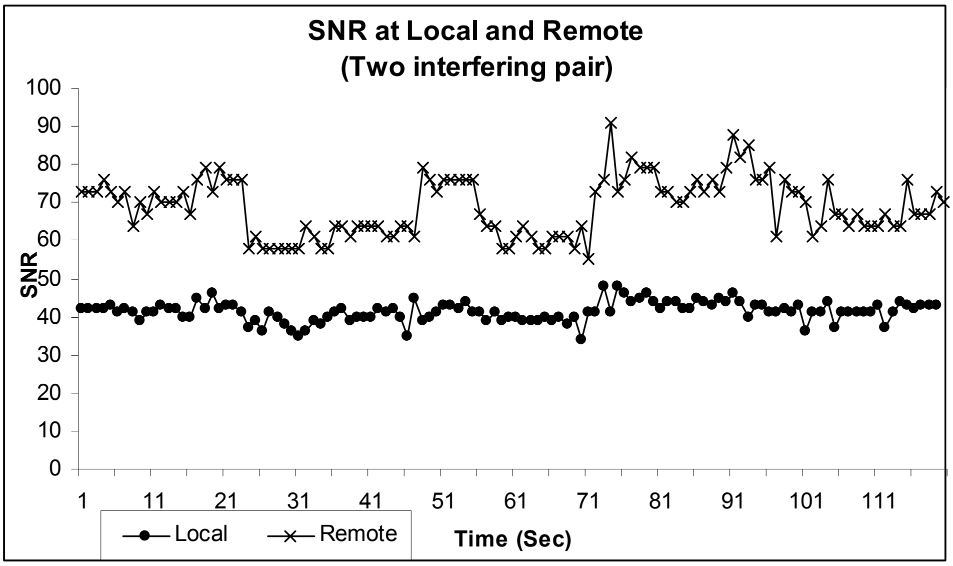
Figure 3 SNR values of Case A-2



Case A-3 Two pairs of interfering 802.11b devices are in the environment

In this set-up, the experiment was repeated with two interfering pairs. Each of these pairs consists of an iPAQ with D-Link card and an Orinoco USB client connected as well. All the devices were configured so that they communicate over the same channel as the earlier configuration. Figure 4 shows the SNR values when two other interfering pairs of 802.11b devices were present in the same environment.

Figure 4 SNR values of Case A-3



Observation

It was observed that when no interference was present, the signal strength stays stable during the experiment. When a single pair is introduced in the same network, there is interference between the two, causing the signal to fluctuate. The SNR showed a sharp drop at the point where there was collision between the two pairs. With two pairs, the interference greatly increases. Unlike in the case of single pair interference, which had interference spikes in the SNR graph, in the case of interference from two pairs, there were times when the SNR dropped and stayed flat for a long time.

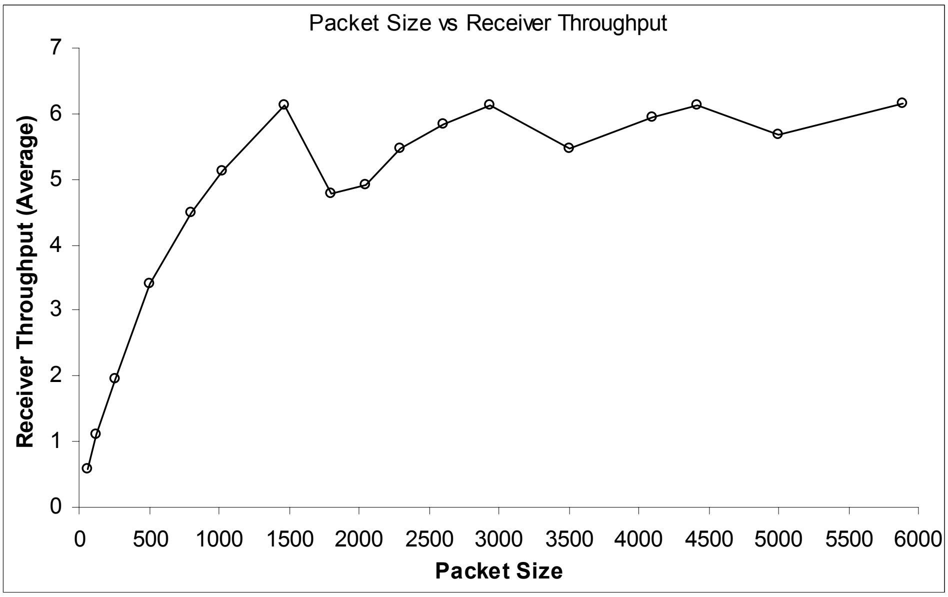
3.2.1 Effect on throughput

In theory, an 802.11b link should have an effective bandwidth of 11 Mbps. However, because of several factors – processing overhead, signalling information, stray interference, *etc.* – the bandwidth is reduced to a lower value. The interference factor increases when more devices operating over the same channel are added. The sharp drops in the SNR values on the graph show this. Collisions mean retransmission. Thus, it can be said that as the number of devices is increased in the same network, the effective bandwidth for a particular link drops.

We evaluated the performance of one 802.11b device on another by using HP's Netperf benchmarking software[11] running on a PIII-750MHz PC, which runs RedHat Linux 7.3. The client system ran on a PII-366MHz Dell Latitude Laptop running RedHat Linux 7.1. During our initial trial runs of the experiment, we found that the system reported lower throughput values when the laptop was used as the server. This might be due to the OS overhead and the laptop's slower CPU speed. As a result, for all experiments, we used the laptop as our Netperf client device. We used the Orinoco Silver wireless card for wireless access on both the host machines.

The experiment started by sending a 64-byte UDP packet from the Netperf server (pc) to the client (laptop). TCP packets are not used for throughput measurement as they try to retransmit lost packets because of connection-oriented property. In subsequent steps, we tested the performance in increments of packet size from 64 bytes up to 5888 (64 × 92) bytes. Figure 5 shows the throughput curve. We found that the throughput was high when the UDP packet size was 1472 bytes (or its multiples). This is because 1472 bytes is close to the maximum payload value for an Ethernet packet size (1518 bytes with headers). Packet sizes higher than 1472 bytes result in fragmentation; while packets smaller than 1472 bytes are not enough to keep the channel busy. This caused periods of silence between successive ping packets, thus resulting in lower throughput values. We believe, when packet size was a multiple of 1472 bytes, the fragments were equally divided resulting in local maxima. The later experiments used packet size of 1472 bytes.

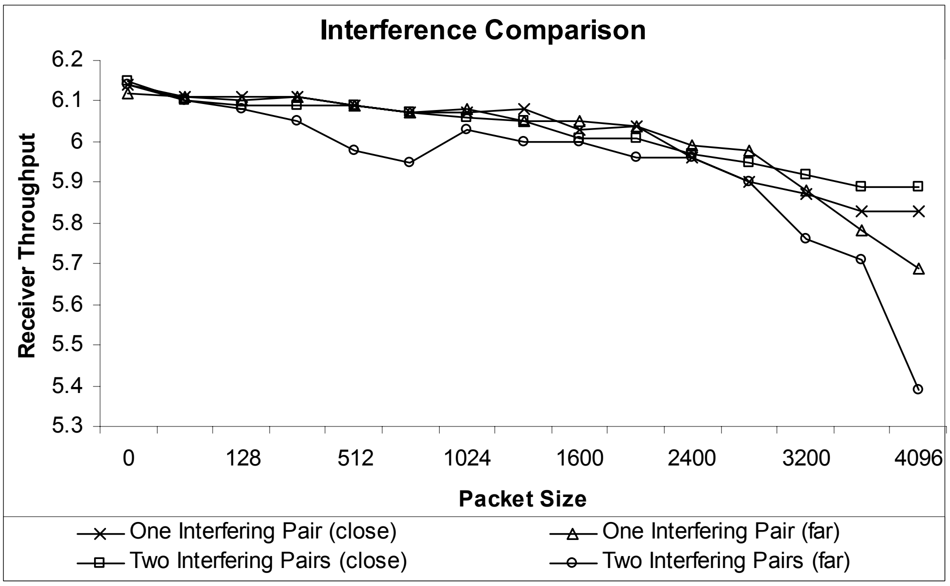
Figure 5 UDP packet size versus throughput



To test the (interference) effect of other 802.11b pairs, we introduced two pairs of wireless devices (two iPAQs and two PCs) in the same environment. Figure 6 shows the throughput for different scenarios. There were two sets of experiments that were conducted for each pair – one with the interfering pair very close to the test pair and the other with the interfering pair at a distance of 7 m with a cubicle partition in the middle.

We noticed that the throughput was not affected (by the new pairs) for smaller (ping) packet sizes. However, as the ping packet size between the new pair increased, the effect of interference was more visible (Figure 6). The receiver throughput values are the average of three trials.

Figure 6 Throughput of 802.11b



3.2.2 Location sensing with 802.11b

The 802.11b standard defines 11 possible channels that may be used. Each channel is defined by its centre frequency. These centre frequencies are located at a distance of 5 MHz from each other. Since the 20db bandwidth can be as wide as 16 MHz (Chiasserini and Rao, 2002; Golmie *et al.*, 2003; Lansford *et al.*, 2001; Shoemake, 2001), multiple co-located channels have to be spaced out from each other. Thus, one 802.11b network could operate at any channel, but two co-located networks would have to have enough spacing, say, channel 2 and channel 10, giving a minimum of 24 MHz in between them. Similarly, three co-located networks would have to choose from something like channels 1, 6 and 11, to ensure enough spacing. In our experiment, since all three pairs were using the same channel and actively involved in a file transfer operation, there was heavy interference among them. In case of real-time location sensing applications, there would be several 'sensor' 802.11b devices collaborating to detect the location of 'unknown' 802.11b devices. However, in order to avoid interference between the signals from different Wi-Fi sensors, one would have to impose a limit on the number of sensors that can exist in a given area or on the number of Wi-Fi device that could be tracked.

3.3 Effect of Bluetooth on 802.11b devices

Case B-1 Interference with a single pair of Bluetooth device

We examined two scenarios in this case:

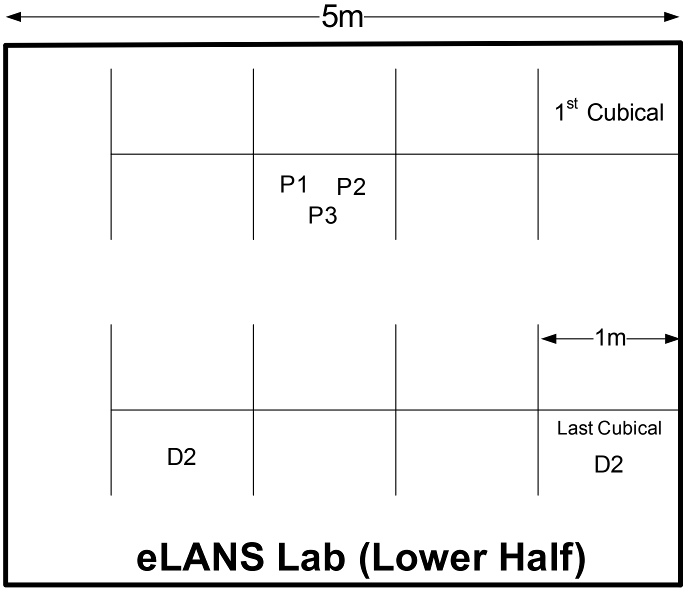
1 Interference from nearby BT devices

In this case, a pair of 802.11b devices were placed in the same cubicle (within 1m) as a pair of (interfering) Bluetooth devices (see case B-1(i) in Figure 7). The Bluetooth devices were set to exchange a large file between them. The Orinoco client manager running on the laptop logged the SNR for the two cases. Similar to the earlier set of experiments, the data was logged for 180 seconds but only the 150 seconds was considered. Figure 8 shows the SNR with and without any interference from the Bluetooth devices. Sharp negative spikes were observed when Bluetooth devices were present in the environment, clearly indicating that there is strong interference between the two technologies.

2 Interference from far away BT devices

Figure 7 case B-(ii) shows the set-up for the far scenario. The laptop running Orinoco client manager (and logging SNR) was placed in the last cubicle. Figure 9 shows the result for this set-up. Again, like the earlier case, sharp spikes are observed in the presence of Bluetooth. However, the frequency is much less, compared to the earlier case.

Figure 7 BT and 802.11b positions in various scenarios



P1 – Position of BT Pair (case B-1(i), B-1(ii) and B-2)
P2 – Position of 802.11b pair (case B-1(i))
P3 – Position of two 802.11b pairs (case B-2)
D2 – Position of 802.11b device (case B-1(ii))

Figure 8 Local SNR values for Case B-1(i)

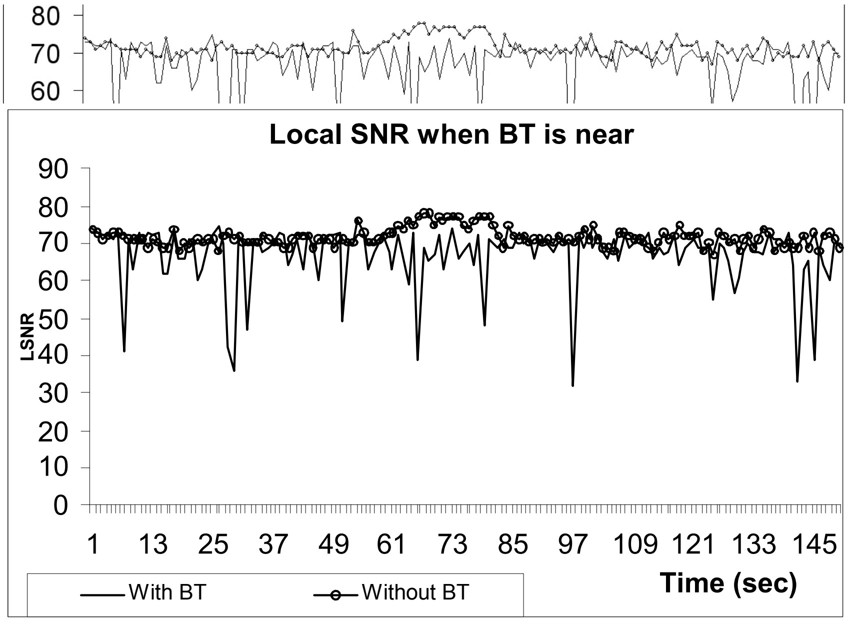
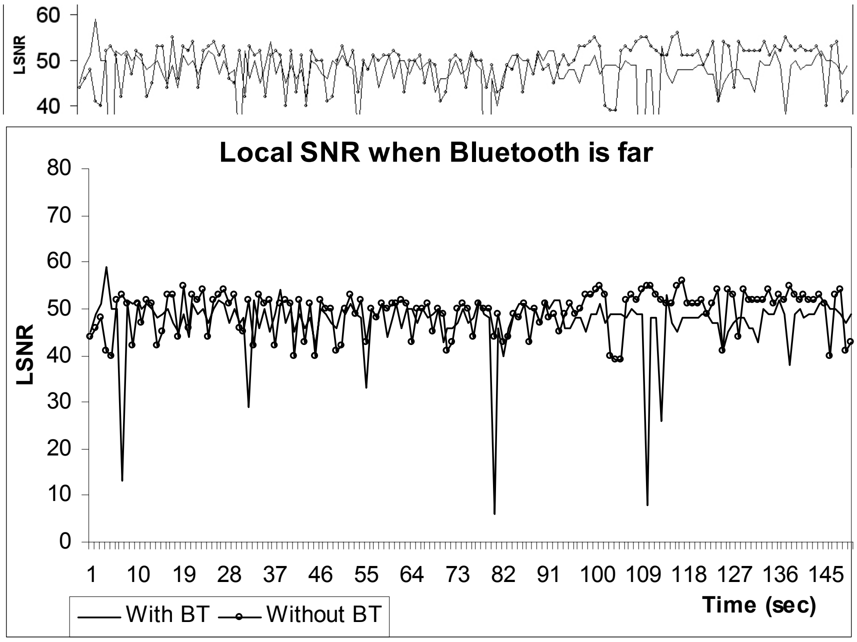


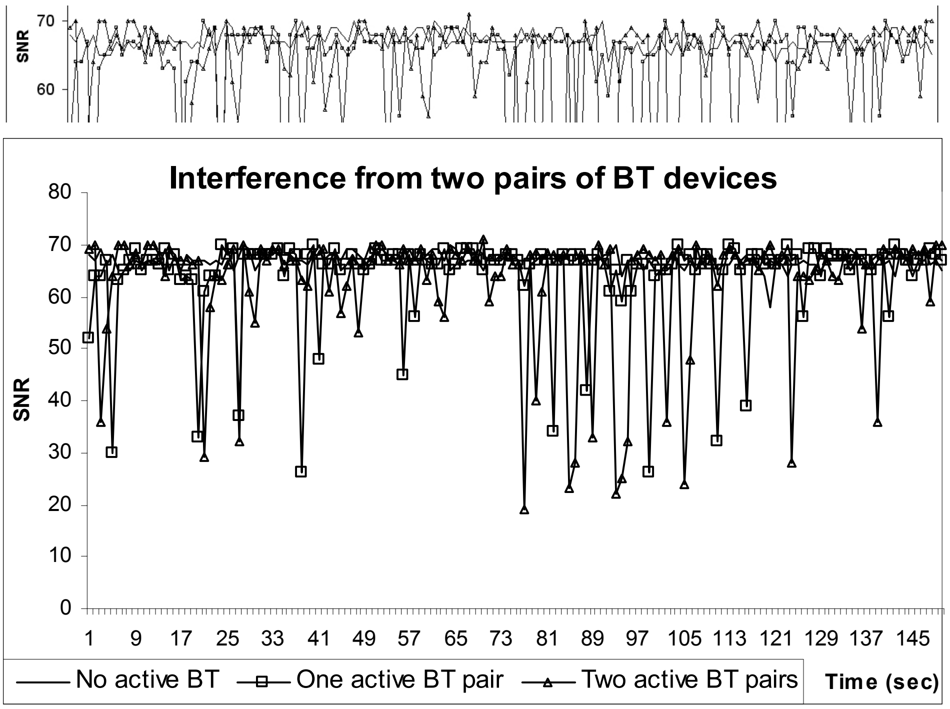
Figure 9 SNR values on the laptop for B-1(ii)



Case B-2 Interference between a pair of 802.11b and two pairs of Bluetooth devices

In this set, all the devices were placed in the same cubicle. Figure 10 shows the result for this set-up. In the presence of more devices, the frequency of the negative spikes was higher. However, as we observe, there is little increase in the magnitude of the (negative) spikes.

Figure 10 Local SNR values for Case B-2



3.4 Effect of 802.11b on Bluetooth

The Bluetooth specification makes it optional for the manufacturers to give signal strength information for a particular link. Since the Bluetooth products that were used in this study did not give signal strength information, the Bluetooth performance was measured in terms of file transfer time, which points to the effective bandwidth for a Bluetooth link. Three sets of experiments were carried out. In each case, a file of size 4437KB was transferred between two Bluetooth devices with increasing number of (interfering) 802.11b pairs. Table 1 shows the result.

Table 1 Effect of 802.11b on Bluetooth

Number of 802.11b pairs	*File transfer time*
1	6 min 4 sec
2	6 min 5 sec
3	6 min 7 sec

Observation

It was observed that there was a marginal decrease in the file transfer time as the numbers of 802.11b devices were increased. This implies that 802.11b had very little effect on the Bluetooth bandwidth. As of this writing, there is no Bluetooth API to carry out throughput measurements. In the future, we plan to take a closer look at bandwidth performance for Bluetooth in the presence of interference.

Explanation

By their nature, when both Bluetooth and 802.11b devices occasionally operate on the same frequency, packets will be lost and throughput will be reduced. In the course of the experiments, it was seen that in extreme conditions, where a Bluetooth or 802.11b interferer is positioned right beside a receiver of the opposite technology, throughput is significantly reduced. However, as the interferer was positioned further away, the interference was reduced. If the distance between the two is more than 10 m, then the throughput is only minimally reduced compared to normal. Bluetooth will cause more interference with 802.11 (or 802.11b/g), than the other way around because of Bluetooth's much faster hop rate. While a WLAN device is transmitting on a particular frequency, a Bluetooth device might hop to this frequency several times. Bluetooth hops about 600 times faster than 802.11[12] (Oraskari, 2001), which hops at the rate of 2.5 hops per second. The situation is much worse in the case of 802.11b/g, which uses Direct Sequence Spread Spectrum (DSSS) – meaning there is no change in frequency.

3.4.1 Effect on throughput

Although both technologies drop packets, Wi-Fi packets are bigger compared to Bluetooth packets. As a result, more information has to be retransmitted when 802.11b incurs retransmission. Thus, the effect of interference is more adverse on 802.11b. To study the effect of Bluetooth on the throughput of 802.11b, we collected throughput data using Netperf and carried out t-Test comparisons. Table 2 shows the results. It was observed that the throughput of 802.11b was greatly affected by the presence of Bluetooth. The throughput depended on the number of interfering devices and the distance between the interferer and the Wi-Fi pair. The throughput worsened with more devices and shorter distance.

Table 2 Performance of 802.11b in presence of BT

Condition	*Receiver Throughput (10^6 bits/sec)*			*t-Test Results*	
	Low	*Mean*[+]	*High*	*Paired*	*p-value*
C1: No Bluetooth device present	6.11	6.12	6.15	C1-C2	0.000
C2: One Bluetooth pair in close vicinity	4.37	5.33	5.91	C2-C3	0.002
C3: One Bluetooth pair in middle cubicle[++]	5.64	5.88	6.11	C3-C4	0.003
C4: One Bluetooth pair in last cubicle[+++]	6.10	6.12	6.14	C1-C4	0.096
C5: Two Bluetooth pairs in close vicinity	3.60	3.94	5.08	C1-C5	0.000

Notes: [+] Interference from Bluetooth is not constant but in the form of spikes. Hence, values in this column are average of ten trials

[++] Middle Cubicle is about 7 m away from the test pair with a wooden partition in between.

[+++] Last Cubicle was about 10 m away from the test pair with two wooden partitions in between.

3.5 Interference between Bluetooth devices

As of this writing, Bluetooth products available in the market have not supported signal strength measurement. Therefore, the average time required for a file transfer was used as a measure to study the effects of Bluetooth on other Bluetooth devices. Table 3 shows the results for a file size of 4437KB. It was observed that there was not much difference between the (mean) times it took to complete the file transfer in each case.

Table 3 Effect of Bluetooth on Bluetooth

Number of Bluetooth pairs	*Effective bandwidth*
1	6 min 7 sec
2	6 min 9 sec
3	6 min 11 sec
4	6 min 12 sec

Explanation

Since Bluetooth jumps frequencies at 1600 hops per second, the chances of collision while at a particular frequency are low. Besides, a Bluetooth packet is smaller compared to WLAN packets (Oraskari, 2001) and hence, retransmissions (due to collision) are not expensive. Thus, the effective bandwidth is not greatly affected when there is interference between Bluetooth devices only.

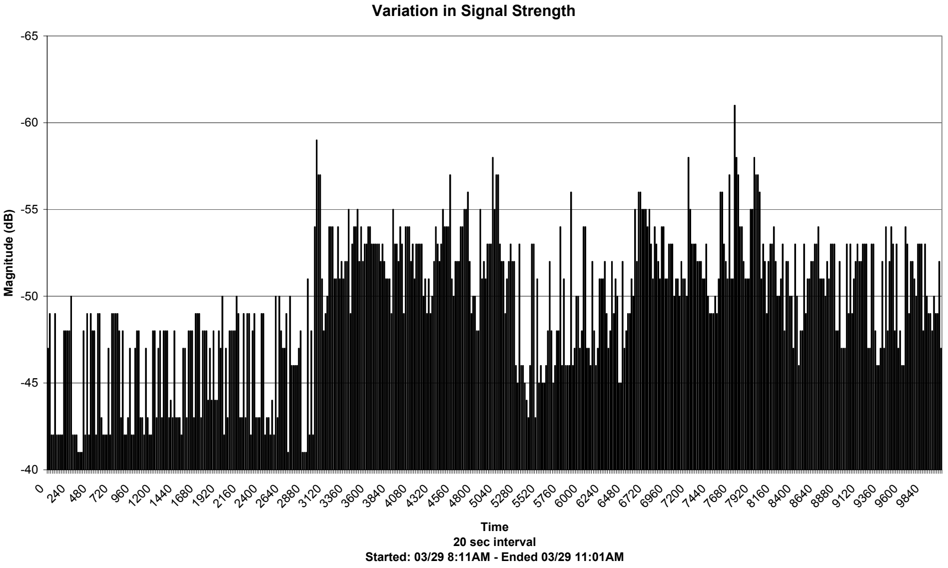
3.6 Signal variation in an indoor environment

Along with the interference comparisons, another experiment was conducted to study the signal variations of wireless devices used in indoor environments like offices, hospitals *etc*. A laptop was placed in the first cubicle in eLANS (see Figure 1) with Orinoco software to monitor and log the link status of its connection with the access point placed on the far side of the eLANS meeting table. The experiment was started at approximately 8:10 a.m. and was left running (logging data every 20 seconds) for about three hours. Some facts about the day when the experiment ran: The lab was empty between 8 a.m. to 9 a.m.; a team meeting started at 9 a.m. and went on little over 10 a.m.; many eLANS members attended a presentation in another room between 10 to 10:30 a.m.; and at 10:30 onwards, the lab was almost full with all its members present in their respective cubicles.

Observation

The results of the experiment are shown in Figure 11. Note that the values on y-axis are negative db, which means that higher values on the graph correspond to lower signal strength. From the graph, it can be seen that the signal strength was strong from 8 a.m. to 9 a.m. when the lab was empty. During the team meeting (9 a.m. – 10 a.m.), there was a strong degradation in the signal strength, which showed little improvement when some of the lab members attended the seminar in another room. However, as the number of people in the lab started increasing, (10:30 a.m. onwards), the signal strength slowly degraded. This shows that the human element had a strong influence on the RF signal strength in the lab. The environment in our lab simulated the conditions in most offices.

Figure 11 Signal variations in a busy room



Explanation

Signal propagation is greatly affected by placement of furniture, movement of people, walls, *etc*. Signal strength alone cannot be used for estimating distance. Almost all of the RF-based location sensing systems use signal strength in combination with some other techniques for improving their accuracy.

4 Location sensing with Bluetooth

From the experiments described in the previous section, we can conclude:

- As the number of 802.11b devices operating over the same channel increases, the interference among them increases.
- There is significant interference between Bluetooth and 802.11b devices. The interference is higher when the devices are close to each other. It shows a sharp drop beyond the range of Bluetooth. In addition, the effect of Bluetooth is more on 802.11b than the reverse case.
- There is very little interference between two Bluetooth devices placed in close proximity.

In a location-sensing environment, we would need to have several devices of the same type operating on the same network. Hence, it would be important that these devices have very little interference among them. With the above results, it can be seen that Bluetooth can satisfy these requirements and hence, can be a good candidate for use in indoor location sensing. Since Bluetooth is becoming a standard feature in most handheld devices, it would eliminate the need for the user to carry additional sensory devices, as needed by several location-sensing technologies of earlier times. A Bluetooth piconet can have seven active slaves and up to 200 inactive devices in parked mode. For location sensing applications, it is enough to 'see' another Bluetooth device. In addition, it does not matter if the other device is a master or a slave. The device should be within the range to be detected. This implies that a Bluetooth sensor would be able to detect up to 200 other Bluetooth devices.

Earlier, in Section 3.4.1, we saw that signal strength varies randomly with time. By using the concept of reference tags, a real-time system can be designed (Ni *et al.*, 2003). The signal strength variation in such a system will affect the tracking (unknown) and the reference (known) tags in the same manner. With the advent of Bluetooth ASIC chips, the price of Bluetooth devices is expected to drop significantly in the near future and the size of a Bluetooth sensor would be very small. Thus, using Bluetooth reference tags would be a feasible idea. Two possibilities will be considered, *i.e.*, location sensing when signal strength information is not made available, and location sensing when that information is available. As of this writing, Bluetooth devices available in the market have not made signal strength information available since it is optional, according to the Bluetooth specification.

4.1 Without signal strength information

Similar to RFIDs (Steggles and Cadman, 2004), every Bluetooth device has a 48-bit address. We can use Bluetooth tags as reference tags, which can be uniformly spread in the area of interest. The Bluetooth sensors can be placed at 5 m each so that they overlap in their range. Since the reference tags are positioned in between the sensors and the sensor range overlap, each reference tag would be seen by more than one sensor. Figure 12 shows such a set-up. We define a table whose rows represent individual tags and the columns represent every reader. We can follow this approach for an unknown device whose location is to be determined. By comparing the row of unknown devices with those for known devices, we can predict where the device might be present. Table 4 shows an example.

Figure 12 Bluetooth location sensing using the concept of reference tags

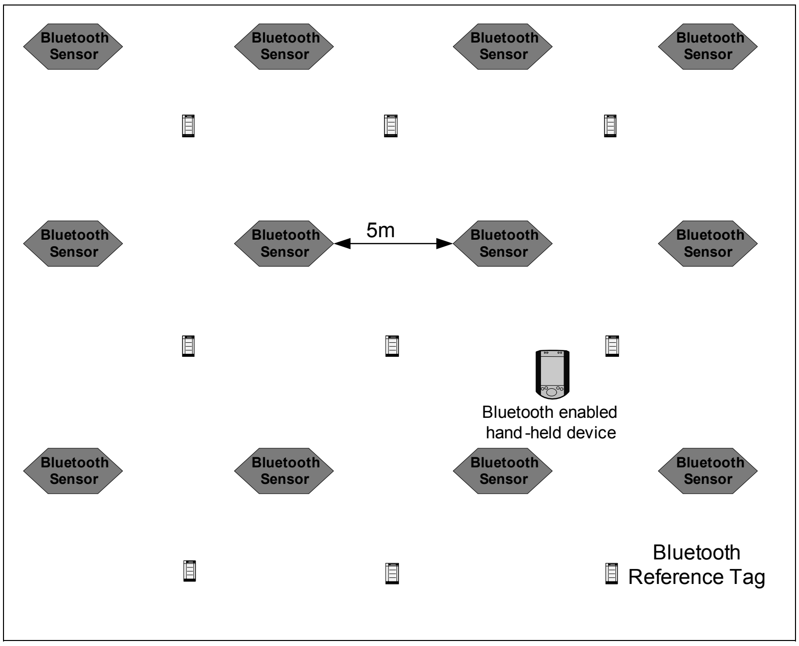


Table 4 Locating unknown tag using reference tag

Reader	*1*	*2*	*3*	*4*
Tag – 1	0	1	1	0
Tag – 2	1	1	1	0
Tag – 3	0	0	1	1
Unknown – 1	0	0	1	1
Unknown – 2	1	0	1	0

We can see from the table that the Unknown-1 device's row information matches with that of Tag 3, which means that they are very close to each other (if not at the same place). The row information for Unknown-2 closely matches with that for Reference Tag 2. Hence, it must be located somewhere in the vicinity of Ref Tag 2. The accuracy of this approach depends on how tight the reference tags are placed, the geometric placement of readers and reference tags and the amount of overlap between neighbouring readers.

4.2 Signal strength information is available

If in the future, Bluetooth products could give signal strength information, a real-time system could then be implemented. Referring to Figure 13, we do the following analysis. Assume there are 'n' Bluetooth readers and 'm' reference tags. We define the Range Vector of an unknown tag as:

$$u = (u_1, u_2, ..., u_n)$$

where *ri* denotes the signal strength value of the unknown tag perceived on Bluetooth reader *i*, $i \in (1, n)$. For the reference tags, each one also has its range vector as:

$$r_i = (r_{i,1}, r_{i,2} ...... r_{i,n}) \text{ where } i \in (1, m) .$$

Because of the instability of the signals (Section 3.4.1), we cannot obtain the physical distance between the reader and a tag (reference tag or unknown tag) directly from the signal strength. However, with the known coordinates of all the reference tags, we are able to physically locate an unknown tag based on the reference cell of the unknown tag. We can introduce the Euclidian distance in signal strength. For each individual unknown tag, we define:

$$E_i = \sqrt{\sum_{k=1}^{n} (r_{i,k} - u_k)^2}$$

as the Euclidian distance in signal strength between an unknown tag and a reference tag r_i. To simplify the description of our approach, let us assume there are four RF readers and 16 reference tags in the experimental environment. Our approach can be easily extended to an environment that has more than four RF readers and 16 reference tags. The signal strength vector of the reference tag and the unknown tag is $s = (s_1, s_2, s_3, s_4)$. When we consider one individual unknown tag, its vectors Ei (for each of the *i*-th reference tag) are given by:

$$E_1 = \sqrt{\sum_{k=1}^{4} (r_{1,k} - u_k)^2} \ldots E_2 = \sqrt{\sum_{k=1}^{4} (r_{2,k} - u_k)^2} \ldots\ldots E_{16} = \sqrt{\sum_{k=1}^{4} (r_{16k} - u_k)^2} .$$

Let *E* denote the location relationship between the reference tags and this unknown one. There are three key issues that we examine through the process of locating the unknown tag. The first issue is the placement of the reference tags. Since the unknown tag is ultimately located in a reference tag cell, the layout of reference tags may significantly affect the location accuracy of an algorithm.

The second issue is to determine the number of reference tags in a reference cell that are used in obtaining the most approximate coordinate of the unknown tags. This may also be termed as selecting ‘k’-nearest neighbours. For example, we may use the coordinate of the reference tag with the smallest *E* value to the tracking tag as this unknown tag’s coordinate (k = 1), or we can choose the two-nearest tags (k = 2) and the unknown tag’s coordinates can be simply determined by the arithmetic means of the coordinates of those two-nearest tags as:

$$x_{unknown} = \frac{1}{2}(x_{nearest1} + x_{nearest2})$$

$$y_{unknown} = \frac{1}{2}(y_{nearest1} + y_{nearest2}) .$$

When we use k-nearest reference tags' coordinate to locate one unknown tag, the following equation could be introduced:

$$(x, y) = \frac{1}{k}\sum_{i=1}^{k}(x_{ri}, y_{ri}) .$$

However, since the nearest neighbours are not at the same distance from the unknown tag, do we need to assign weight so that the nearest tag gets more importance than the one further? This becomes the third issue in this approach. Thus, the unknown's coordinate can be obtained as:

$$(x, y) = \sum_{i=1}^{k} w_i (x_{ri}, y_{ri}) .$$

Intuitively, this must be done based on the *E* value of each reference tag in the cell. Instead of giving same average weight to all k-nearest neighbours, w_i is introduced and it is a function of the *E* of all k-nearest neighbours. Our approach of the weight depends on the *E* as:

$$w_j = \frac{\frac{1}{E_i}}{\sum_{i=1}^{k}\frac{1}{E_i}} .$$

In this approach, the reference tag with the smallest *E* value has the largest weight.

Thus, a sound Bluetooth location sensing system can be designed based on the availability or unavailability of signal strength information from the Bluetooth (sensor) device.

Figure 13 Signal strength of Ref Tag 5 as perceived by Bluetooth readers

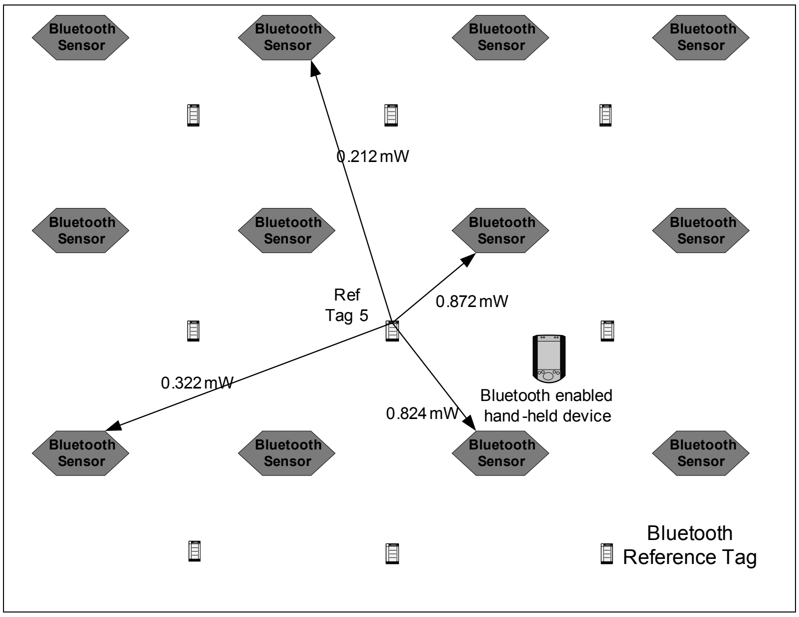
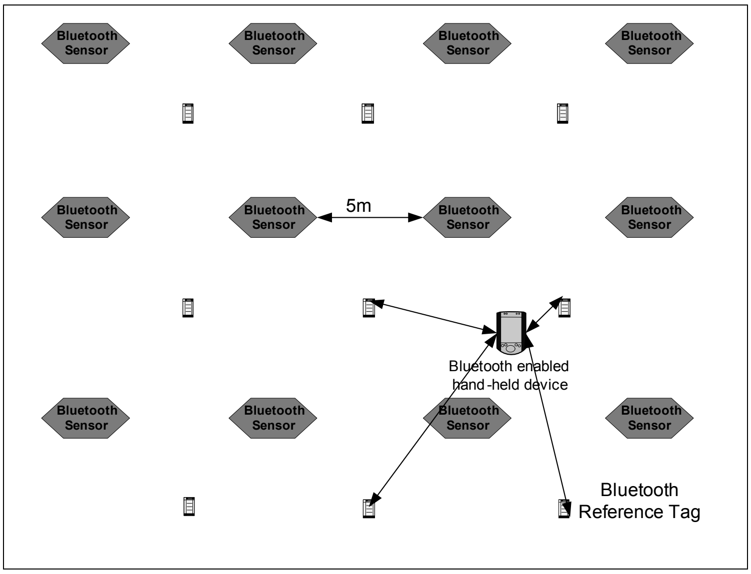


Figure 14 Case of 4-nearest neighbours



5 Managerial implications

Bluetooth was not designed for location sensing and hence, there are several problems that need closer attention. This section takes a brief look at some of the managerial issues and modifications required to make Bluetooth suitable for location sensing. An important concern is the time taken by a Bluetooth device to detect other Bluetooth devices in its vicinity. This is important in location sensing since a sensor device should be able to detect items with minimal delay. Fast moving items have very low detection window. In case of Bluetooth, the scan rate has to be very small. Current Bluetooth devices are not well adapted to meet this requirement. For example, the 3COM USB adapter that we used in our experiments had a (lowest) refresh time of five minutes.

The other concern is the availability of signal strength information from a Bluetooth sensor (or tracked device). As of this writing, the Bluetooth core specifications have not required that signal strength (RSSI) values be available to higher-level software. In the future, if this information is made available, it can greatly aid in accurate location sensing. With signal strength information, the nearest neighbour concept developed in Section 4.2 can be applied. The Bluetooth specification specifies only three power levels at which Bluetooth devices can operate. When a Bluetooth device is operated at minimum power level (1 mW in class 3), it gives a coverage range of roughly 10 m. If future implementations could give a shorter range, then location sensing (with Bluetooth) could be made more accurate. Since Bluetooth devices are expected to be cheaper in the future, we can use more sensors (operating at minimum power level) covering very small area. This configuration of closely spaced sensors would give a high accuracy. It would also help to have more options in terms of power range levels. This would increase the number of configurations in which Bluetooth sensors can be positioned in the environment.

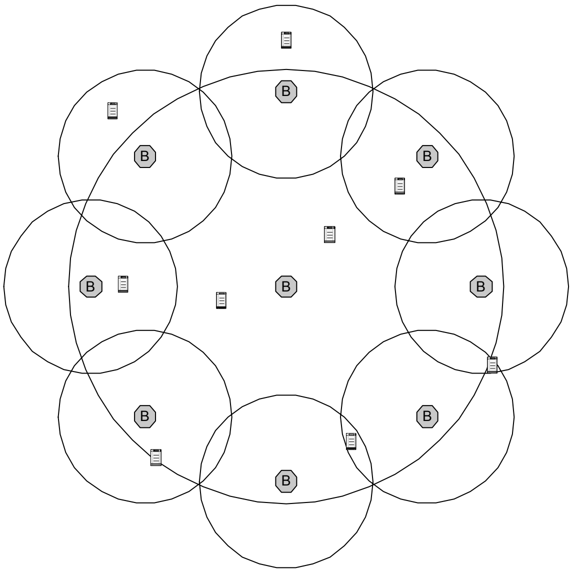
6 Future work

Moving to future work, we plan to look at other commodity wireless technologies that can be used in conjunction with Bluetooth so that we can set up a system similar to Cricket. Another item in the list of future works is the throughput measurement for Bluetooth in the presence of interference. Currently, we do not have any Bluetooth API to do bandwidth measurements and hence, we could not do effective bandwidth calculation in the presence of interference of other Bluetooth devices or other wireless technologies operating in the same frequency range.

Since we did not have many Bluetooth devices, in our current set-up, we did not test a prototype location system. Although the price of Bluetooth devices is dropping, the current price is not encouraging enough to buy Bluetooth devices in large numbers (required for implementing a prototype system in our lab). Once we get enough equipment, we plan to test the different configurations to find the one that gives the greatest accuracy.

The place of readers is an open issue. Figure 15 shows an example configuration for reader placement. With Bluetooth readers operating at different power levels, the overall accuracy of the system can be greatly improved. In the above example, the central reader is configured to operate at power level class 1 or class 2, thus allowing it to scan a large area. Several other readers are placed along the circumference range of this reader. These readers operate at a lower power level (*e.g.*, class 3). The advantage of using this approach is that the region is divided into several smaller regions that can be uniquely identified. A tag that is sensed by one of the readers along the circumference and the central reader is in the intersection of the central reader and the outer circle. A tag that is read only by an outer circle is located outside the bigger circle but within the outer circle and so on. Besides, the system is more flexible and easier to deploy because of its modularity.

Figure 15 Bluetooth sensors placed to form a ring of circles



7 Conclusion

This paper presented the experimental results of interference between 802.11b (Wi-Fi) and Bluetooth device. Since Bluetooth and 802.11 have become common technologies in most indoor (office-like) environments, it is important to study the interaction between the two technologies. In this paper, our examination of the interplay between the two technologies was purely from the point of view of identifying the one that is best suited for location positioning applications. Our experimental results showed that Bluetooth is more immune to interference both from 802.11 and itself (other Bluetooth devices), making it a good candidate technology for location sensing in indoor environment.

In the latter half of the paper, we examine location sensing closely and presented two techniques for location positioning using Bluetooth. We conclude that a sound Bluetooth location sensing system can be designed based on the availability or unavailability of signal strength information from (sensor) devices. The cost of Bluetooth chips is expected to greatly reduce, making it possible to have Bluetooth devices that cost less than a dollar. This will make location sensing with Bluetooth very inexpensive. We propose to test various configurations of reader placement to find the one that gives the best accuracy.

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Notes

1 http://www.radianse.com/ and http://www.versustech.com/

2 http://www.ekahau.com

3 http://www.bluetags.com/

4 http://www.aeroscout.com/

5 http://www.bluetooth.org/

6 http://www.uk.research.att.com/bat/

7 http://nms.lcs.mit.edu/projects/cricket/

8 http://www.hpl.hp.com/archive/cooltown/

9 http://www.ieee802.org/15/pub/TG2-Coexistence-Mechanisms.html

10 SNR is a measure (dB) of signal strength relative to background noise. In this paper, we investigate signal strength using SNR.

11 http://www.netperf.org/netperf/NetperfPage.html

12 http://www.tech.plym.ac.uk/dcee/postgrad/reference/BlueTooth/bluetooth.html