Place Lab: Device Positioning Using Radio Beacons in the Wild

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Abstract. Location awareness is an important capability for mobile computing. Yet inexpensive, pervasive positioning—a requirement for wide-scale adoption of location-aware computing—has been elusive. We demonstrate a radio beacon-based approach to location, called Place Lab, that can overcome the lack of ubiquity and high-cost found in existing location sensing approaches. Using Place Lab, commodity laptops, PDAs and cell phones estimate their position by listening for the cell IDs of fixed radio beacons, such as wireless access points, and referencing the beacons' positions in a cached database. We present experimental results showing that 802.11 and GSM beacons are sufficiently pervasive in the greater Seattle area to achieve 20-30 meter median accuracy with nearly 100% coverage measured by availability in people's daily lives.

1 Introduction

Allowing users to discover and communicate their positions in the physical world has long been identified as a key component in emerging mobile computing applications [13]. Dozens of research and commercial location systems have been built using sensing technologies including ultrasonic time-of-flight, infrared proximity, radio signal strength and time-of-flight, optical vision, and electro-magnetic field strength. There have been many research and commercial efforts to improve accuracy and precision, shrink the size of the sensing hardware, simplify deployment and calibration of sensors, and provide more convenient middleware.

Despite these efforts, building and deploying location-aware applications that are usable by a wide variety of people in everyday situations is arguably no easier now than it was ten years ago. First and foremost, current location systems do not work where people spend most of their time; coverage in current systems is either constrained to outdoor environments or limited to a particular building or campus with installed sensing infrastructure. Applications like location-aware instant messaging fall flat if they only work for a fraction of users or only during a fraction of a user's day.

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Second, existing location technologies have a high cost of entry to both users and application developers. Many location systems require expensive infrastructure, time-consuming calibration, or special tags, beacons, and sensors. The privacy cost to the many stakeholders is also typically ignored or considered only after deployment. These barriers leave location-aware computing in an unfortunate cycle: There are very few users due to a dearth of applications; developers are not interested in writing applications for nonexistent infrastructure; infrastructure investments are based on user demand, of which there is little. This cycle has not prevented researchers from prototyping and innovating in the application space. It has, however, prevented the widespread experimentation and adoption of these applications by real users. The result is that while we can give compelling demonstrations of location-based applications, few can be used in the places they are most useful: where we live, where we socialize, where we shop.

Place Lab addresses both the lack of ubiquity and the high-cost of entry of existing approaches to location. Place Lab is a fundamentally different philosophy compared to previous work because we focus on A) maximizing coverage as measured by the percent of time location fixes are available in people's daily lives and B) providing a low barrier to entry for users and developers. The Place Lab approach is to allow commodity hardware *clients* like notebooks, PDAs and cell phones to locate themselves by listening for radio *beacons* such as 802.11 access points (APs), GSM cell phone towers, and fixed Bluetooth devices that already exist in the environment. These beacons all have unique or semi-unique IDs, for example, a MAC address. Clients compute their own location by hearing one or more IDs, looking up the associated beacons' positions in a locally cached map, and estimating their own position referenced to the beacons' positions.

In this paper we show that existing radio beacon sources are sufficiently pervasive and can be mapped appropriately to meet Place Lab's goal of maximizing coverage in most people's daily lives. For example, Place Lab clients already have access to over 2.2 million mapped beacons situated in numerous cities and mechanisms are in place to scale well beyond this number. This paper will also show how Place Lab's use of commodity hardware and commitment to user's privacy lowers the cost of entry to users and how the high beacon coverage combined with flexible programming interfaces lowers the cost of entry for developers.

Precision of the location estimates, while important, is secondary to coverage, privacy, and cost in Place Lab. That is, we believe it is important to model location uncertainty and minimize it to the extent possible without requiring custom hardware or limiting the operation to controlled environments. This philosophy is similar to how ubiquitous wireless infrastructure remade telephony into an indispensable everyday tool. A cell phone with tremendous voice quality that only works in only one building has quite different affordances than one with passable voice quality that works almost everywhere. The former tends to lend itself to more niche problems like office automation while the latter finds a home in the hands of anyone who wants to socialize and conduct business throughout their daily activities. Although accuracy is not the primary concern in the Place Lab philosophy, it is clearly important to evaluate and understand the accuracy of a beacon-based approach to location. Therefore, this paper also presents experiments characterizing the accuracy of the

Place Lab approach as it relates to the types and densities of beacons in the environment.

Place Lab is released under an open source license. Binary and source releases for many platforms, as well as sample radio traces can be downloaded from http://www.placelab.org/. Adoption of Place Lab has been encouraging; as of October 2004 our system has seen around 500 downloads per month and a number of researchers are using Place Lab as a component of their projects.

This paper has three parts. First, we introduce the Place Lab architecture and show how it achieves the coverage and ease-of-use goals. Second, we present several experimental results quantifying the important relationships between beacon types, coverage, density, and accuracy. Finally, we discuss the future research problems and opportunities. This paper reports on the research contributions following the course laid out in our challenge paper which proposed using 802.11 beacons to create a global location system [11]. Specifically, we have designed a software architecture to make general beacon-based location a reality, implemented a system supporting multiple platforms and multiple beacon technologies, released the software through the open source community, and conducted coverage and accuracy experiments in the real world.

2 Related Work

Noticing the benefits afforded by high coverage and availability of a mobile service is not a new observation. Modern cellular telephone service providers stake their business on it. Moreover, many cellular providers are even starting to compute and offer the locations of the devices on their network as part of a push to branch out beyond basic telephony services. Separately, the Global Positioning System (GPS) is a location system which was designed to maximize coverage. Unfortunately neither cellular phone location nor GPS (nor any of the existing research location systems) provide both maximal coverage measured by percent of time that location fixes are available in people's daily lives and an extremely low-barrier to entry for users and developers.

GPS works world-wide and GPS capability can be added to existing devices using a variety of external dongles, cards, and corded accessories. The basic GPS scheme provides median accuracy of 10 meters, and various augmentation schemes have been added to improve this. GPS could be said to meet goal B of Place Lab in that it provides a relatively low barrier to entry (although an external card and antenna is still an additional cost over current commodity hardware). However, GPS fails to meet Place Lab's coverage goal because GPS receivers, while having high availability as measured by the percent of the earth's surface covered, have poor coverage measured by the percent of time they work where most people spend most of their time. GPS receivers require a clear view of the sky and thus they do not work indoors or under cover. They also work poorly in many cities where the so called "urban canyons" formed by tall buildings prevent them from seeing enough satellites to get a position lock. This limited availability severely constrains the class of applications for which GPS is an appropriate location technology. GPS is appropriate for and has been used successfully in navigation, tourism and search and rescue applications which primarily happen outdoors. Most individuals, however, spend the vast majority of their day indoors so day-to-day applications that rely on GPS location alone would have stretches lasting hours in which no changes in location would be reported. We present experimental results to verify this claim in Section 5.

Cell-phone companies have long been able to track phone users with network techniques like time-of-arrival or signal strength and handset techniques like assisted GPS that combine handset GPS receivers with network servers to assist in location calculation. E911 Phase II legislation in the US requires cell phone companies to be able to locate handsets within 150 meters by Dec 31, 2005. E112 initiatives in Europe are similar. Some cellular service providers have begun using the knowledge of handset location to offer users location-based services and applications. An example is AT&T Wireless' Friend Finder that is part of their mMode services. E911-like location services meet Place Lab's goal of high coverage since they work wherever normal cell phones do, but their success in providing a low barrier to entry is less encouraging. While Place Lab clients compute their own location, cellular carriers estimate a phone's location in the network and sell that information back to the user for a fee. The current fees of around $1 US per query substantially limit the application domains for which users will be willing to access these services. Furthermore, provider-driven location works only on cell phones whereas Place Lab can present the same location programming interfaces on phones, notebooks, and PDAs using any radio beacon technology.

A variety of previous device positioning systems use 802.11 access points as beacons from which to estimate location. The RADAR system showed that 1.5 meter accuracy could be obtained by constructing a detailed "radio fingerprint" of the available 802.11 access points and how strongly they could be heard along a one foot by one foot grid within an office building [3]. Ekahau (ekahau.com) sells a commercial software product that does very much the same thing with similar accuracies. These systems differ from Place Lab in two ways. First, products like Ekahau do not ship with any radio maps and require that the user collect this data himself. This violates our barrier-to-entry goal that a system can estimate location right out of the box. Second, deployment of these systems is only feasible in small environments (places measured in square meters, not square kilometers) due to the large amount of calibration data that needs to be collected and maintained. In contrast, Place Lab uses sparser calibration data that can be collected while walking or driving and is contributed by a community of users (and for this coverage and ease of mapping, Place Lab concedes an order of magnitude loss in accuracy as later experimental results will show).

Other similar systems that use specific radio sources in the environment include RightSpot and Laasonen et al's GSM based system. RightSpot showed that 15 kilometer accuracy could be obtained by using FM radio station strengths to predict location on a smart wrist watch device [6]. Laasonen et al. use changes in the set of nearby GSM cell towers to construct an abstract graph of places where the user goes [7].

Finally, there are numerous indoor location system that make use of ultrasonic [10, 15], infrared [12], ultra-wideband radio (ubisense.com). These systems all require that hardware infrastructure be installed in the environment to be monitored. These systems are generally expensive, costing thousands to tens of thousands of US dollars for a 1000 m^2 installation. These systems primarily focus on optimizing accuracy rather than wide-scale deployment and have accuracies in the 5-50 centimeter range. They have coverage constrained to a room, building, or campus environment. While this availability is sufficient for many home or office scenarios, limited coverage rules out many personal and social applications targeted at people's daily lives.

A wide variety of applications have been developed that utilize location-based technologies. Without having to disclose their location to others, users can run navigation-oriented applications that display their location on a map, highlight local points of interest, or plot a route to a destination based on current location (mappoint.com, streetatlasusa.com). Users that are comfortable disclosing their location to their social network have access to applications like dodgeball.com and mMode's Friend Finder (attwireless.com/mmode) that facilitate social interactions in the physical world. Finally, for users willing to disclose location information to institutions, useful day-to-day services like Yahoo Yellow Pages (yp.yahoo.com) and Google's Local Search (local.google.com) are available to anyone with a network connection.

3 The Place Lab Architecture

The Place Lab architecture consists of three key elements: Radio beacons in the environment, databases that hold information about beacons' locations, and the Place Lab clients that use this data to estimate their current location (See Figure 1). In the following subsections, we describe each of these elements and how they are designed to help meet Place Lab's goals of maximal coverage of daily life and low barrier to entry for users and developers.

3.1 Radio Beacons

Place Lab works by listening for the transmissions of wireless networking sources like 802.11 access points, fixed Bluetooth devices, and GSM cell towers. We collectively call these radio sources *beacons.* They all employ protocols which assign beacons a unique or semi-unique ID. Hearing this ID greatly simplifies the client's task of calculating their position. As we will show in Section 5, the coverage and accuracy of Place Lab is dependent on the number and type of beacons in range of the client device. Fortunately, wireless networking infrastructure is being deployed at a rapid pace in places that users spend their time. Most developed areas of the world have GSM coverage and cities and towns are becoming blanketed with 802.11 access points[1].

Place Lab devices need only interact with radio beacons to the extent required to learn their IDs. Place Lab clients do not need to transmit data to determine location, nor do they listen to other user's data transmissions. In the case of 802.11, receiving beacons can be done entirely passive by listening for the beacon frames periodically sent by access points. These beacon frames are sent in the clear, and are not affected by either WEP or MAC address authentication. Other technologies like Bluetooth

[1] Our measurements in downtown Seattle, for example, show an 802.11b density of 1200 access points per km^2.

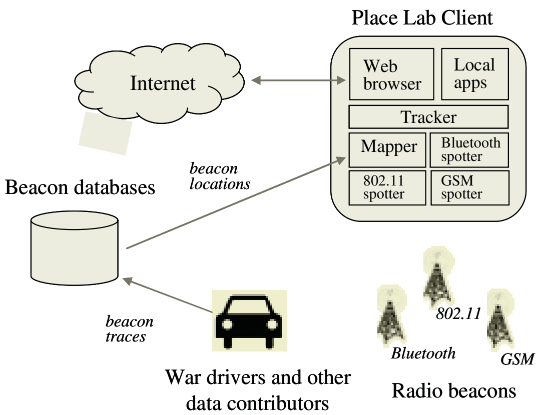

Fig. 1. Key components in the Place Lab architecture

require clients to initiate a scan in order to find nearby beacons. Due to restricted programming interfaces, detecting GSM cell IDs requires handsets to associate with nearby cell towers as they normally do when carried around and not on a phone call.

3.2 Beacon Databases

Place Lab has a critical dependence on the availability of beacon locations; if Place Lab knows nothing about a beacon, being in range does not improve our location estimates. In our architecture, the *beacon database* plays the important role of serving this beacon location information to client devices. We allow there to be multiple beacon databases and we do not specify whether beacon databases are private or public, how clients authenticate with a database or how many databases a client should load data from.

Many of these beacon databases come from institutions that own a large number of wireless networking beacons. Organizations like companies, universities and departments often know the locations of their 802.11 access points since this information is commonly recorded as part of a deployment and maintenance strategy. These data sets tend to be on the order of tens or hundreds of access points, and the maps are typically quite accurate. While these data sets were not originally built for doing beacon-based location estimation, it only requires a format-translation step to add this data to Place Lab and location-enable the institution's building or campus.

Other sources of Place Lab mapping data are the large databases produced by the *war-driving* community. War-driving is the act of driving around with a mobile computer equipped with a GPS device and a radio (typically an 802.11 card but sometimes a GSM phone or Bluetooth device) in order to collect a trace of network availability[2]. War-driving has become hobby for many radio enthusiasts and groups of

[2] The term *war-driving* is an allusion to the 1983 movie "WarGames" where Matthew Broderick's character David engaged in *war-dialing* by sequentially dialing blocks of phone numbers in an attempt to discover and establish a modem connection with interesting computers.

war-drivers have formed online and offline clubs to share and pool their trace data. Each war-driving trace is a time-coded sequence of records containing the latitude and longitude of where the record was taken, as well as the list of radio sources and associates signal strengths that could be heard at that time. By pooling their war drives together and applying some simple averaging, these groups have produced estimated locations for millions of beacons. Public domain war-driving software has been developed for most computing platforms, and there are many aggregation websites to which war-drives can be submitted. While war-driving has traditionally been performed in order to provide information about where nearby network access can be obtained, Place Lab uses these maps in reverse to infer where we are given a particular beacon is nearby.

Since the positions of beacons are being inferred from observations tied to GPS estimates, war-driving databases only contain *estimates* of beacons' positions. The error in these estimates translates into a decrease in the accuracy of location estimates made by Place Lab. However, what these databases lack in accuracy they make up for in coverage making them highly useful for Place Lab. As an example, wigle.net is the largest of the 802.11 war-driving repositories, and contains over 2 million known AP positions, and the recent "World Wide War-drive" added 275,000 new access points over an 8 day period (worldwidewardrive.org).

At this time, Place Lab clients have access to location information for approximately 2.2 million radio beacons, primarily 802.11 access points. These mostly come from wigle.net, but we have more accurate databases for UC San Diego and the University of Washington as well as some GSM tower locations imported from the FCC's database. To allow us to experiment with beacon placement algorithms, we also maintain our own database that currently has location estimates for around 40,000 GSM, 802.11, and Bluetooth beacons.

3.3 Place Lab Clients

The Place Lab clients use live radio observations and cached beacon locations to form an estimate of their location. To make client both extensible and portable, client functionality is broken into three logical pieces: spotters, mappers and trackers.

Spotters are the eyes and ears of the client and are responsible for the observing phenomenon in the physical world. Place Lab clients typically instantiate one spotter per radio protocol supported by the device. As an example, a laptop running Place Lab might have a Bluetooth and an 802.11 spotter, while a cell phone might run a Bluetooth and a GSM spotter. The spotter's task is to monitor the radio interface and share the IDs of the observed radio beacons with other system components.

An observation returned by a spotter is of little use if nothing is known about the radio beacons. The job of the *mapper* is to provide the location of known beacons. This information always includes a latitude and longitude, but may also contain other useful information like the antenna altitude, the age of the data, a learned propagation model, or the power of the transmitter. Mappers may obtain this data directly from a mapping database, or from a previously cached portion of a database. This cache can contain beacons for a large area, say the entire United States and Europe, or may, due to capacity concerns, just contain information for a single city.

The *tracker* is the Place Lab client component that uses the streams of spotter observations and associated mapper data to produce estimates of the user's position. The trackers encapsulate the system's understanding of how various types of radio signal propagate and how propagation relates to distance, the physical environment and location. Trackers may use only the data provided to them by the spotter and mapper, or may use extra data like road paths and building locations to produce more accurate estimates. As an example, Place Lab includes a simple tracker that computes a Venn diagram-like intersection of the observed beacons. This tracker uses very few resources making it appropriate for devices like cell phones. Place Lab also includes a Bayesian particle filter [1] tracker that can utilize beacon-specific range and propagation information. While computationally more expensive, the Bayesian tracker provides about a 25% improvement in accuracy and allows Place Lab to infer richer information like direction, velocity and even higher level concepts like mode of transportation (walking, driving, etc.). For more information on the intricacies and advantages of using probabilistic Bayesian filters in location systems, see Hightower et al. [5] and Patterson et al. [9].

3.4 Privacy

Privacy issues have had a strong influence on the design, implementation and use of Place Lab. Place Lab's key privacy principle is that devices should be able to position themselves based on passive monitoring of the environment. This principle gives the user control over when their location is disclosed, laying the foundation for privacy-observant location-based applications. Unfortunately, while it is theoretically possible to construct a device that senses GSM, 802.11, and Bluetooth passively, current devices are not as passive as we would like. For example, some 802.11 device drivers broadcast their existence to the infrastructure regularly. Similarly, we are not aware of any GSM cell phone that does not report itself to the infrastructure. Although the Bluetooth standard does not require that a device transmit its MAC address to neighboring devices when scanning, many of today's Bluetooth devices do so anyway.

Apart from passive scanning issues, another privacy trade-off is the manner in which mapping data is downloaded to clients from the mapping databases. Due to capacity issues, impoverished devices may only be able to load a small portion of the mapping database. However, if mapping data is downloaded for a small region, say a neighborhood, the operator of a mapping database has a reasonably fine-grained estimate of a user's location or potential location. Loading (and possibly discarding most of) a country or continent's worth of beacon locations gives the mapping servers less information about a user's location.

The war-drivers submitting their traces also have privacy considerations. War-drivers who submit their logs may not want a permanent record kept of the path they take while collecting a log. An approach to mitigating this problem is to have trusted entities anonymize and aggregate logs. For example, Place Lab has a design for a distributed backend database that slices up logs on a per-beacon basis and randomly distributes information about each beacon to a different node. Using this scheme, a contributor's war-driving path cannot easily be reconstructed yet the log is still useful for mapping. Of course any approach involving a trusted-entity still relies upon users trusting that entity.

Finally, we consider the privacy issues that affect the owners of the beacons used by Place Lab. Cell phone providers, coffee shops, and hotels probably do not mind if the existence and location of their network beacons are known. Individuals and corporations, however, may be wary in some cases of having information about their access points listed in a public database. They may be concerned about people attempting to steal network access or about revealing that they have computer equipment at a particular location. There are a variety of potential ways to mitigate these concerns. 802.11 and Bluetooth beaconing can be manually turned off, making them invisible to Place Lab. As stronger authentication becomes available for wireless networks, some concern about beacon visibility may simply disappear. Finally, there are possibly technical solutions to protecting beacon owners privacy in Place Lab such as using an encrypted hash of beacon identifiers so that clients must actually hear a beacon to resolve the true ID.

4 Implementation and Applications

With the exception of the small amount of native code that is written for each spotter, Place Lab is written entirely in Java 2 Micro Edition (J2ME). Place Lab currently runs on the following platforms and provides support for spotting the following beacon types. In addition, all platforms can access GPS devices for location and war-driving.

Operating Systems	Architectures	802.11abg Beacons	GSM Beacons	Bluetooth Beacons
Windows XP	x86	●	●[3]	●
Linux	x86, ARM, XScale	●		
Os X	Power PC	●		
Pocket PC 2003	ARM, XScale	●	●[3]	●
Symbian	Series 60 cell phones		●	●

The Place Lab APIs for spotters, mappers, and trackers are consistent across all platforms assisting developers in porting their applications to different platforms, *e.g.* from a full-featured laptop to a cell phone. To further facilitate low-effort development, Place Lab supports five ways of communicating location information to applications:

1. **Direct Linking.** Applications may link against the Place Lab Java library and invoke a single method to start the location tracking service.
2. **Daemon.** For lighter-weight interactions, Place Lab can be run in daemon mode and applications can query Place Lab via HTTP. This HTTP interface allows programs written in most languages and styles to use Place Lab.

[3] Place Lab supports GSM beacons on these platforms using a Bluetooth data connection to a paired Series 60 phone which actually receives the GSM beacons and forwards them to the master device.

3. **Web Proxy.** Place Lab supports location-enhanced web services by augmenting outgoing HTTP requests with extension headers that denote the user's location. By setting their web browser to use the Place Lab daemon's web proxy (in the same way one uses a corporate firewall's proxy), web services that understand our HTTP headers can provide location-based service to the user.
4. **JSR 179.** To support existing Java location-based applications Place Lab supports the JSR 179 Java location API [2].
5. **NMEA 0183.** Place Lab provides a virtual serial-port interface that can mimic an external GPS unit by emitting NMEA 0183 navigation sentences in the same format generated by real GPS hardware.

Several applications have been developed by both us and the Place Lab user community; we describe four of them below to illustrate the varied ways in which applications can interact with Place Lab.

- **Topiary.** Topiary is a rapid prototyping tool developed at UC Berkeley for designing location-enhanced applications [8]. A Topiary prototype can be run on one mobile device while the designer monitors the user's interactions from a second mobile device (Figure 2 is a screenshot of Topiary). In this mode, the user's location is determined Wizard-of-Oz-style by having the designer click the user's current location on a map. Topiary has been augmented to allow the designer to replace these Wizard-of-Oz estimates with live estimates from Place Lab running on the user's device. Topiary is using Place Lab as a GPS replacement, with the advantage that unlike GPS, Place Lab works both indoors and out.

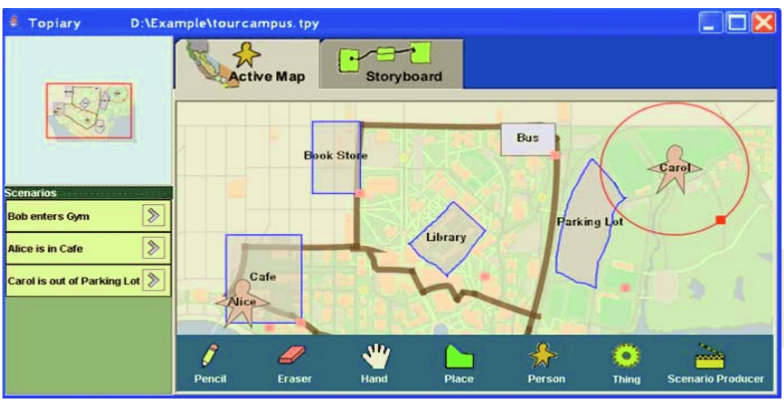

Fig. 2. A screenshot of *Topiary*, a prototyping tool for location-aware applications. Topiary uses Place Lab to allow the prototypes to use live location estimates

- **The PlaceBar.** We have developed a demonstration application called the *PlaceBar* that uses a browser toolbar to manage a user's interactions with Google's location-based search: http://local.google.com/. In addition to the query terms, Google Local accepts an address, or latitude and longitude and the results are filtered to return pages relevant to nearby places. Google determines page location by extracting information like addresses and phone numbers from the page content. When a query is performed in the PlaceBar, the user's location is obtained from Place Lab and is automatically used as the location for the query.

- **A2B.** A2B is an online catalog of web pages that allows users to add new geo-coded pages or query for nearby relevant pages (http://a2b.cc/). A2B can be queried by either manually entering a location or using a custom client that talks to a GPS unit. A2B extended their interface to support HTTP requests from by clients running the Place Lab web proxy. Devices running the Place Lab proxy can now talk directly to A2B in any web browser and automatically use their location-based lookup service.
- **Active Campus.** The Active Campus project is one of the most widely used 802.11-based location-enhanced systems [4]. Active Campus offers a suite of socially-oriented applications to students and classmates on the UC San Diego campus. The Active Campus project is currently porting their application suite to run on top Place Lab. The portability of Place Lab offers them more platforms than the small number that are currently supported. The large beacon database also offers them expanded coverage off campus in the surrounding cities.

5 Experimental Results

The coverage and accuracy of Place Lab depend on the number and mix of beacons in the environment, making it difficult to make absolute statements about the system's performance. However, certain high-level statements about the Place Lab approach are appropriate. First, due to the correlation of 802.11 and GSM beacon density with population density, Place Lab works better in urban centers than in less populated or rural areas. Second, Place Lab has better coverage in areas with ubiquitous GSM like Europe compared to partially covered areas like the United States. To quantify both the coverage and accuracy of Place Lab and how they vary by area we ran two experiments. First, to test our hypotheses about daily-life coverage of the different beacon technologies we outfitted users with an ensemble of small devices capable of monitoring GPS, GSM and 802.11 signals and had them carry the devices during their regular day. Second, we measured both 802.11 beacon density and corresponding Place Lab accuracy in an urban, a residential and a suburban area. Our coverage results were not surprising: both our user-time experiment as well as our density experiment show nearly ubiquitous GSM and 802.11 coverage whose density correlates with population density. Our accuracy results show that with sufficient density, 802.11 beacons alone can provide median accuracy of around 15-20 meters while GSM beacons alone provide accuracy of 100-200 meters.

5.1 Experimental Setups

We define the coverage of a location-tracking technology to be the percentage of time that the technology can produce a new estimate of the user's position based on what it senses from the physical world. If a GPS device, for example, has a satellite lock for 15 minutes and then loses its lock for the next 30 minutes and gets it back for 15 minutes, the coverage for that period would be 50% with an average gap of 30 minutes. Note that, consistent with the Place Lab philosophy, our formal definition of coverage is based on the user's time, not on geographic area.

To compare the coverage of GPS and the beacon technologies used in Place Lab, we outfit three users with a set of three mobile devices each and asked them to carry the devices throughout portions of a typical day. The devices included a Belkin wireless GPS, a Nokia 6600 and an Intel Stargate [14]. We logged, once per minute, the availability of GPS, 802.11 and GSM. All three devices were small enough to fit in a purse or backpack and had enough battery life to run for several hours. For our users we chose people from the authors' social network. None were computer scientists or students and the user's jobs included retail clerk, immunologist and a home maker. Between the three users we collected more than 30 hours of logs (10 for each of GSM, GPS and 802.11) that included work days as well as non-work days. Based on these logs, computing the coverage and coverage gaps of the various technologies was a straightforward task.

For the second experiment measuring beacon density its effect on accuracy, we gathered GPS, 802.11 and GSM trace data from three diverse areas:

- Downtown Seattle – a mix of commercial and residential urban high-rises
- Seattle's Ravenna neighborhood – a medium-density residential neighborhood
- Kirkland, Washington – a sparse suburb of single-family homes

For each locale, we drove around the areas for sixty minutes with a laptop, a GPS unit, and a Nokia 6600 cell phone. 802.11 scans were performed at 4Hz using an Orinoco 802.11 interface in the laptop. GPS readings were taken at approximately 1Hz using an external serial GPS unit. Finally, the GSM measurements were taken at 1Hz by the Nokia 6600 and relayed to the laptop via Bluetooth[4]. At all times we tried to navigate within areas in which GPS lock would not be lost as GPS forms the "ground truth" location to be used to estimate beacon positions and Place Lab's accuracy.

5.2 Coverage Results

The results of our user-time coverage experiment are shown in the following table:

Test Subject	**GPS**		**GSM**		**802.11**	
	coverage	avg. gap	coverage	avg. gap	coverage	avg. gap
Immunologist	12.8%	68 min	100%	-	87.7%	1.6 min
Home maker	0.6%	78 min	98.7%	2 min	95.8%	1 min
Retail clerk	0%	171 min	100%	-	100%	-
Average	**4.5%**	105 min	**99.6%**	1 min	**94.5%**	1.3 min

[4] Unfortunately, our Nokia cell phones only allow us to know the ID of the current cell tower with which the phone is associated, making it impossible to learn the full set of towers in range. While this allows us to know if coverage is available, it does not let us learn about density or Place Lab's accuracy if all towers in range were known. Thus all GSM-based Place Lab results are calculated using the *single* available cell ID.

In a real application, depending on the gap size it is often possible to apply smoothing, dead-reckoning, or various heuristics to try to fill in the gaps sensibly. This experiment ignores all gap-filling heuristics. Thus, we are not measuring the percentage of time that the application can make a meaningful guess at the user's location, but rather the fundamental coverage of the lowest-level estimation technology.

The coverage of GPS matched our expectations. It has poor user-time coverage and long gaps because satellites are cut off indoors or under cover where many people spend the vast majority of their time. Our subjects saw nearly ubiquitous GSM coverage. This is not surprising because once wireless carriers choose to offer coverage in an area, they strive to provide *complete* coverage. Even in places where the signal level may be too low to make an actual phone call, for example in an elevator or basement, it is still usually possible to see GSM beacons. The measured 802.11 coverage was slightly lower than GSM with similar gap sizes. From our data we can draw two conclusions. First, this data supports our claims that beacon-based location has the potential to provide user-time coverage which significantly exceeds GPS and is possibly ubiquitous. Second, comparing the coverage and gap sizes of GSM and 802.11 and assuming all other factors are equal, it seems GSM beacons are the ideal radio technology for Place Lab. However, all factors are not equal and the smaller cell sizes of 802.11 provide an opportunity for greater accuracy in Place Lab as the results will show in the next subsection.

5.3 Density and Accuracy Results

To confirm our intuition that beacon densities are correlated to population densities, we computed the distribution of the number of 802.11 access points in range per scan for each of the three areas we measured. The three histograms and accompanying satellite photos are shown in Figure 3. As expected, the highest density of APs were seen in the downtown urban setting with an average of over 3 APs per scan, no scans without APs, and a maximum of 15. Also not surprising, the suburban traces saw 0 APs (i.e. no 802.11 coverage) more than half the time and rarely saw more than one. The most interesting result came from the residential Ravenna data in which AP densities were higher than expected. With the exception of the approximately 10% of scans with no coverage, the AP density distribution for Ravenna fairly closely matched the downtown distribution. As we will explain shortly, the Place Lab accuracy in Ravenna actually exceeded that of downtown.

To evaluate the accuracy of Place Lab in our three neighborhoods, we divided each 60 minute trace into two halves: training and evaluation. The training trace was used to estimate beacon positions while the evaluation trace tests the accuracy of Place Lab. During training, beacon positions were estimated by averaging together all locations in which the beacon was observed. We then fed the evaluation trace into Place Lab and computed the accuracy of its estimate using only 802.11, only GSM, and fused 802.11 and GSM. To measure accuracy, the predicted estimates were compared with an interpolation of the two GPS readings closest in time. Note that GPS has an accuracy of 8-10 meters, bounding the accuracy of our measurements to this level of granularity. The position estimate was computed using a Bayesian particle filter tracker [5] with a sensor model that exploits the fact that observed signal strength and beacon-frame loss rate correlate with distance. Per-beacon signal and loss histograms are computed from the training data and these 50-100 bytes of calibration data are stored with each beacon's estimated position in the beacon database. These per-beacon parameters allow our tracker to predict location more accurately than our untrained models. The same technique works for both GSM and 802.11 beacons.

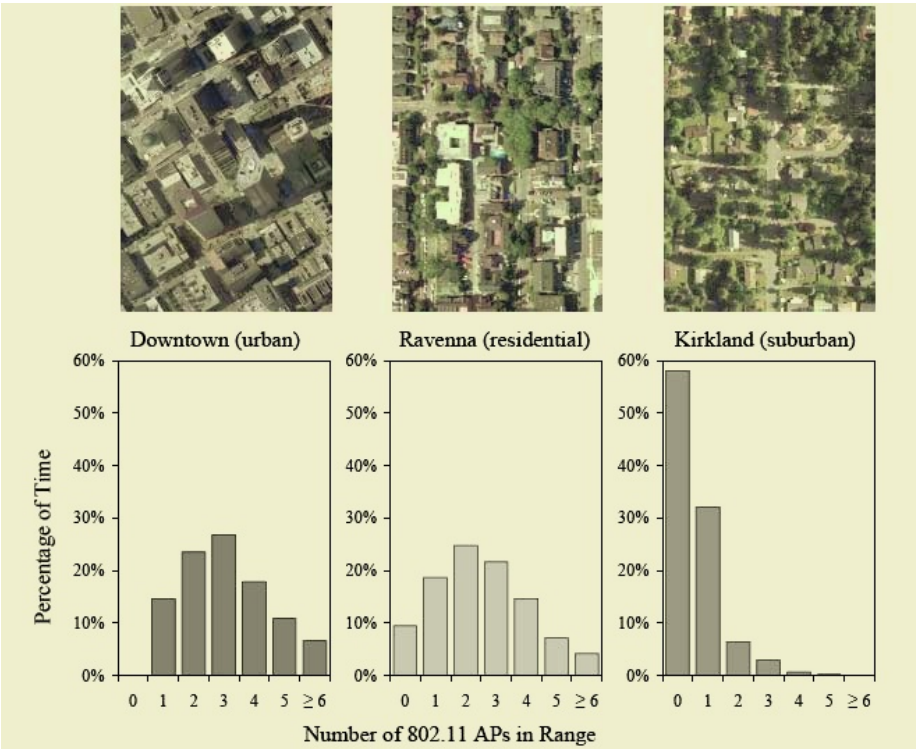

Fig. 3. Density of 802.11 access points (and photos) for the neighbourhoods in which we ran our experiments. For each area 7500 scans were performed at 250 ms intervals, while driving along surface streets. For each scan we recorded the number of APs in range. Satellite photos provided USGS through Microsoft's Terraserver

The following table shows the results of our accuracy tests.

	802.11		GSM		802.11 + GSM	
	accuracy	**coverage**	**accuracy**	**coverage**	**accuracy**	**coverage**
Downtown Seattle (Urban)	20.5 m	100.0%	107.2 m	100.0%	21.8 m	100.0%
Ravenna (Residential)	13.5 m	90.6%	161.4 m	100.0%	13.4 m	100.0%
Kirkland (Suburban)	22.6 m	42.0%	216.2 m	99.7%	31.3 m	100.0%

Two conclusions can be drawn from the results in this table. First, for single types of beacons, 802.11 outperforms GSM in accuracy although its coverage is worse in areas with sparser population. That is to say, when 802.11 beacons are in range, Place Lab's predictions are more accurate than with GSM alone. Given their relatively long range, GSM beacons play a high-coverage, low accuracy role in Place Lab. This tradeoff stands to reason because 802.11 has smaller cell sizes (shorter radio range) and, unlike GSM where cell placement is managed as a system to optimize coverage, 802.11 cells are deployed in small numbers by independent homeowners and institutions. Second, fusing 802.11 and GSM provides a good blend of accuracy and coverage. Consider the sparse suburban area of Kirkland where 802.11 coverage is only 42%. In Kirkland, fusing with GSM yields 100% coverage (up from 42% with 802.11 alone) with only an 8.7 meter decrease in median accuracy, despite the 216.2 meter accuracy of GSM alone in Kirkland. To explain this result, recall from the previous section that gaps in 802.11 coverage tend to be short. An effective location estimation algorithm like a particle filter can model the user's motion and allows GSM beacons to effectively fill in the gaps without the error ballooning.

To investigate the relationship between beacon density and accuracy we combined all data from the three areas and computed the median accuracy achievable by Place Lab using 802.11 alone. Figure 4 shows a graph comparing the accuracy of Place Lab as it relates to the number of unique beacons the client saw during the previous 10 second window. From this figure we can conclude that if 802.11 density is high enough for clients to see at least 3 distinct beacons during a 10 second window, the density is sufficient for Place Lab to achieve its "peak" median accuracy of 15-20 meters or approximately twice the error of unassisted GPS.

5.4 Bluetooth

The beacon technology notably absent from our results is Bluetooth. We found that non-mobile Bluetooth devices have not reached sufficient density where they are eminently useful for beacon-based location estimation in the wild. (Place Lab only looks for Bluetooth beacons likely to remain fixed such as printers, vending machines, and access points; we ignore nomadic Bluetooth devices like personal cell phones or laptops since their unpredictable mobility makes them harder to use to predict location.) Although our results do not report Bluetooth beacon densities, we did scan for them during our data collection and we saw virtually no fixed Bluetooth in any of the test locales. The sparseness of Bluetooth beacons is further exacerbated by the fact the each scan for nearby Bluetooth beacons takes approximately 10 seconds to complete. At this slow scan rate, a mobile device even moving only at human walking speed can miss a Bluetooth beacon it passes.

A simple experiment in our lab showed that due to their short radio range, fixed Bluetooth devices do improve Place Lab's accuracy. We deployed ten Bluetooth devices in our 1000 square meter lab and showed a Place Lab accuracy of slightly better than 10 meters using Bluetooth alone. This suggests that Bluetooth beacons could be deployed strategically in small environments to somewhat improve the client's location accuracy while preserving the Place Lab model of client-side location estimation with commodity devices.

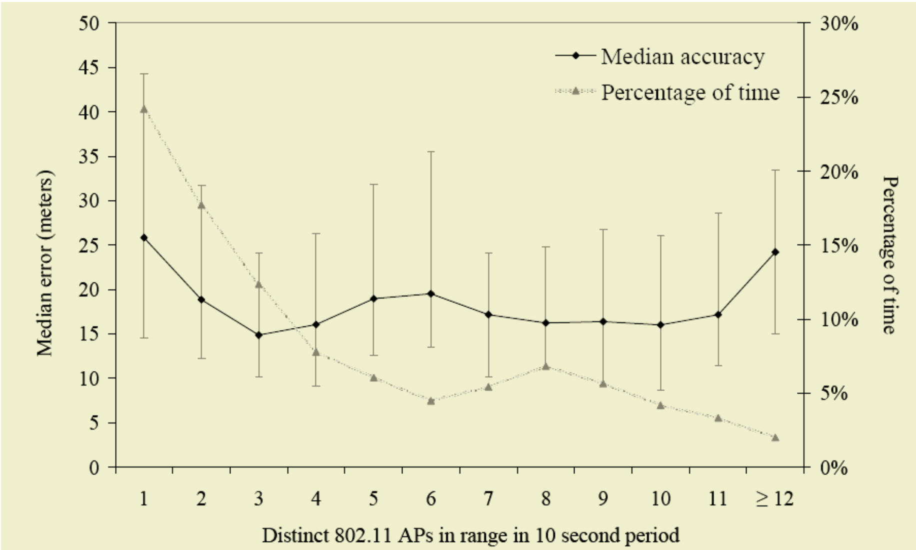

Fig. 4. This graph shows the effect AP density on Place Lab's accuracy. The graph includes all 22,500 measurements from the three neighbourhoods measured. The accuracy line is drawn through the medians, while the error bars represent the 1st and 3rd quartile readings. (50% of the readings fall between the error bars.) The second line shows how often we saw that number of distinct APs

6 Future Work

For many emerging location-aware applications it is much easier to utilize place names like "Bank", "Starbucks" or "Movie Theater", than geo-coordinates such as (48.43456, -122.45678). We are developing techniques that allow Place Lab to automatically learn and estimate places in addition to geo-coordinates. One step in this process is moving Place Lab to "2.5" dimensions. Place Lab currently only generates position estimates in two dimensions (latitude and longitude) and ignores the altitude component of location. This can present a problem in multi-story buildings where floor number is likely a key aspect of location. Our current belief is that generating "2.5" dimension estimates in which altitude is represented with a symbolic name such as "Parking Level A" or "3rd floor" are more meaningful than a coordinate-based altitude like 34.6 meters above sea level. We are planning to augment Place Lab to allow beacons and traces to be annotated with floor information and have our trackers predict this symbolic dimension along with latitude and longitude.

We intend to remove the reliance on GPS as ground-truth for war-driving and mapping new beacons. Given a map of a portion of the beacons, Place Lab should be able to use its *own* location estimates to map new beacons that are encountered in the environment. We plan to study the number of beacons which constitute a "critical mass" such that beacon trace logs *without* GPS can be used to grow and refresh the client's database as beacons are added, moved and decommissioned.

7 Conclusions

We believe that many emerging location-aware computing application are going to require 100% availability of location information in real people's lives, similar to the way cellular phones are held to a 100% availability standard. Place Lab provides the necessary features to move in this direction. In this paper we have shown that a beacon-based approach to location can A) maximize coverage as measured by the percent of time a location fix is available in people's daily lives and B) offer a low barrier to entry for users and application developers thanks to the use of commodity hardware, privacy awareness, and straightforward interfaces.

Our coverage experiment confirmed the intuition that GPS, often thought of as a pervasive location technology, in fact lacks availability in people's daily lives since people are frequently indoors or under cover, whereas 802.11 and GSM beacons are frequently available both indoors and out. This experiment was conducted by logging beacon availability using small recorders carried by people as they went about their daily routines.

To evaluate beacon-based location, we examined 802.11 and GSM beacon density and quantified the relationship between density and accuracy. In studying three distinct neighborhoods of the greater Seattle area (urban, residential, and suburban), we found that beacon density is sufficient to support the Place Lab approach. Specifically, for 802.11 beacons we can conclude that if density is high enough for client devices to see at least 3 distinct beacons during a 10 second window, Place Lab clients can achieve median accuracy of 15-20 meters. This accuracy is lower than GPS, but, unlike GPS, beacon-based location covers nearly 100% of users' daily lives. In the sparsely-populated suburban area we measured fusing 802.11 with GSM readings results in median accuracy just over 30 meters.

We believe Place Lab is a useful artifact for the research community. Binary and source releases of Place Lab are available for many platforms along with sample radio traces at http://www.placelab.org/. Adoption of Place Lab has already been encouraging; our system sees around 500 downloads per month and a number of research projects and web services are using Place Lab as a component of their system. Place Lab is an enabling technology because it is useful for developers and facilitates new research into location-aware computing such as exploring the meaning of place and the studying the utility of location-aware applications that can be deployed to real users.

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