Taking Positioning Indoors

Wi-Fi Localization and GNSS

Solving the challenge of robust, reliable positioning in GNSS signal-challenged environments has long represented a kind of Holy Grail for product designers, systems integrators, and service providers. One promising approach is to combine GNSS with terrestrial systems that use existing wireless infrastructures. This article describes how Skyhook Wireless has succeeded with GPS and wireless local area networks — better known as Wi-Fi. As a result, its technology is now incorporated into a wide range of mobile "connected" platforms, including smart devices such as Apple's iPhone and iPod.

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Wireless local area networks (WLANs), popularly known as Wi-Fi, were originally designed for data applications. Over the past decade or so, WLAN infrastructure has been implemented for high-speed wireless Internet access in homes, "hot-spots," university campuses, and corporate buildings. Hundreds of millions of Wi-Fi access points (APs) are deployed in major urban areas worldwide.

Today, in the lead author's lab on the third floor of the Atwater Kent Laboratory at the Worcester Polytechnic Institute, we can read the addresses of 48 Wi-Fi access points within range of our Wi-Fi–capable devices.

Wardriving or access point mapping is a term commonly used for the process of locating Wi-Fi APs while moving around an area and building a database that can be leveraged later for Wi-Fi localization. **Figure 1** shows a map of 1.2 million Wi-Fi access points obtained by wardriving around in the city of Seattle, Washington.

In 2000, three years after release of the first IEEE 802.11 WLAN standard, articles describing the use of Wi-Fi signals for indoor geolocation appeared in the research literature. During the past few years, Wi-Fi positioning or localization has found its way in metrowide positioning systems.

GPS was not designed for indoor applications and does not perform well in indoor and dense urban areas. Wi-Fi localization complements GPS positioning by providing robust indoor coverage, reduction in time to fix, reduced power consumption, and resistance to interference. GPS complements Wi-Fi by providing outdoor coverage and a universal coordinate reference frame.

Emerging "smart" devices, such as Apple's iPhone, use Wi-Fi localization technology to complement GPS and cell tower localization in numerous everyday consumer applications, particularly in metropolitan areas. Applications range from social networking to tagging photos or videos with the corresponding location information.

In this article, we describe the evolution of the Wi-Fi localization technology with particular emphasis on its recent application in smart devices. We describe how this technology evolved out of time-of-arrival (TOA)-based GPS technology and how these two technologies are intertwined to address the needs of rapidly expanding consumer applications.

Wi-Fi: From Data Transmission to Localization

Since its inception in the 1980s, Wi-Fi has become one of the wonders of the wireless revolution, nurturing groundbreaking innovations in popular applications. Always seeking higher data rates (now on the order of 100 Mbps), Wi-Fi users employ the technology for wireless Internet access and the ever-growing multimedia applications that it supports.

These Internet applications are commonly used in indoor areas, where extensive multipath conditions require robust methods to achieve high data rates. As a result, WLANs introduced the first popular commercial application of spread spectrum technology, orthogonal frequency division multiplexing (OFDM), and more recently multi-input multi-output (MIMO) antenna systems.

In contrast to the WLAN industry, the prosperous cellular telephone business, now with close to five billion subscribers, has focused on voice applications using lower speed data transmission (around 10 Kbps). Mobile phone applications demand comprehensive coverage to support continual quality of service while the user is moving around in a large metropolitan area.

These conditions nurtured the evolution of code division multiple access (CDMA) technology for the 3G cellular networks. Today, the 4G cellular industry is working on WiMax and LTE systems, which have borrowed the OFDM and MIMO technologies from Wi-Fi. Numerous companies have developed systems that utilize the cellular infrastructure for positioning, particularly the network of transmission towers serving local cells. However, such network-based solutions often do not provide the level of accuracy needed for many location-based services.

Meanwhile, the first commercial application of Wi-Fi signals for positioning was in local real-time location systems (RTLS) used for asset and personnel tracking in indoor areas. RTLS provided a relative accuracy of around a few meters. In the past few years, Skyhook Wireless has developed a proprietary version of WLAN localization known as Wi-Fi or Wireless Positioning Systems (WPS).

Metrowide Wi-Fi localization applications commonly work successfully with accuracies on the order of tens of meters. However, driven in large part by user experience and expectations of cellular service, these localization systems must provide almost immediate location fixes and a comprehensive coverage in metropolitan areas.

These expectations pose a challenge to the industry because stand-alone GPS technology is not fast enough and does not operate reliably in indoor and urban areas, where almost all of these applications are initiated. On the other hand, cell-tower and assisted-GPS (A-GPS) positioning techniques are faster, but they may not be able to provide the needed accuracy.

The WPS technology incorporating Wi-Fi localization emerged to solve these deficiencies. Compared to 24 to 31 GPS satellites and hundreds of thousands of cell-towers, IEEE 802.11 WLAN access points number in the hundreds of millions. We can leverage these Wi-Fi APs opportunistically to locate mobile terminals in locations and environments in which other positioning technologies are unavailable or inadequate.

Currently, the lead wonders of emerging smart devices — the Apple iPhone and other so-called smart phones — contain Wi-Fi chipsets that complement 3G CDMA connectivity to provide high-speed wireless Internet access. The iPhone also uses WiFi signals for localization and tracking to complement the GPS and cell-tower localizations in a hybrid positioning system.

This feature in the iPhone generates more than several hundred million transactions per day. A companion video on the website of *Inside GNSS* shows the number of hits on the iPhone server in Manhattan, New York, over a 24-hour period and demonstrates the popularity and traffic behavior of Wi-Fi localization hits in time and space.

The Emergence of Wi-Fi Localization

In the second half of 1990s the Defense Advanced Research Projects Agency (DARPA) launched its small unit operation situation awareness system (SUO/SAS) program aiming at one-meter accuracy for indoor geolocation in military and public safety operations.

FIGURE 1 The AP database of the Skyhook Wireless in Seattle

About the same time, venture capitalists started funding startup companies such as PinPoint in Woburn, Massachusetts, and WhereNet, based in Santa Clara, California. Both were seeking to develop and implement indoor geolocation technologies with accuracies comparable to those required for SUO/SAS.

The success of TOA-based techniques used in GPS positioning started military and commercial researchers to think in that direction. The idea sounded very straightforward.

According to the Cramer-Rao Lower Bound (CRLB), the variance of the ranging error for TOA systems is given by:

$$\sigma_D^2 \geq \frac{1}{8\pi^2}\frac{1}{SNR}\frac{1}{TW}\frac{1}{f_0^2}\frac{1}{1+\dfrac{W^2}{12 f_0^2}} \qquad (1)$$

where T is the observation time, SNR is the signal-to-noise-ratio, f_0 is the center frequency of operation, and W is the bandwidth of the system.

Using the operating frequency, bandwidth, and SNR found in GPS systems, this bound indicates that accuracies around several meters can be achieved within the course of a few minutes.

If we want to extend this technology to practical indoor geolocation, we must overcome four challenges: 1) we need positioning accuracy of better than a few meters to identify objects in different rooms of a building (2) we need to cope with around 20–30 decibels of additional path loss to penetrate into the building within reasonable measurement times (3) we need algorithms to cope with the multipath conditions, and (4) we need to reduce the time to first fix to a few seconds.

The pioneering military and commercial TOA-based systems designed in the late 1990s did not meet these four challenges. DARPA had to compromise on its accuracy requirements and the commercial start-ups simply failed.

Radio propagation studies conducted for the SUO/SAS project revealed that the primary source of the problem for indoor geolocation was severe multipath conditions in obstructed line-of-sight (OLOS) environments that frequently caused large ranging errors. To remedy the situation, developers of military and public safety applications resorted to such methods as UWB (ultrawideband), super-resolution, multipath diversity, and cooperative localization. More recently, inertial navigation systems have been added to some systems in an effort to overcome the deficiencies of RF indoor geolocation.

For commercial applications, other major problems included the cost of new proprietary hardware and deployment of infrastructure. These cost factors led industry to develop indoor geolocation techniques leveraging existing WLAN infrastructures, which were growing rapidly in the variety of indoor environments. In the year 2000 both TOA-based and the received-signal-strength (RSS)–-based WLAN localization techniques appeared in the literature and the Wi-Fi localization industry was born.

Wi-Fi Localization: TOA versus RSS

The idea of Wi-Fi localization created substantial enthusiasm in the industry. Various companies filed numerous patents targeting TOA-based indoor geolocation, and the general idea of using a wireless networking infrastructure for associated applications spread to standardization activities such as IEEE 802.15.3 for UWB communications and IEEE 802.15.4 for sensor networks using ZigBee technology.

Although TOA-based Wi-Fi localization uses an existing infrastructure, designers still need to modify the mobile devices' hardware to extract the TOA estimate from a received Wi-Fi signal. Moreover, implementation of a precision TOA-based system faces the same multipath challenges encountered previously, demanding complex algorithms and solutions.

For these reasons, despite a substantial amount of research, the commercial market is still waiting for popular products based on TOA techniques for indoor positioning. Meanwhile, the burden of research is mostly carried by the military and public safety sectors.

In comparison to TOA, RSS-based systems use existing Wi-Fi infrastructures without requiring hardware modification in the access points and the mobile terminals. A software patch enables the user equipment to measure and process the received signal strength from several Wi-Fi APs in order to generate a position fix.

The relative accuracy of RSS-based localization is not very sensitive to multipath or bandwidth limitations, and such systems do not need synchronization among terminals and the infrastructure. As a result, RSS-based indoor geolocation systems rapidly became a commercial success. A few startup companies such as Ekahau, Helsinki, Finland and Newberry Networks, Boston, Massachusetts quickly designed products to track assets or personnel.

The latest development in RSS-based Wi-Fi localization appeared in metropolitan areas with the growing popularity of iPhones and other smart devices.

This idea was examined in the research community in organizations such as Intel's Place Lab, Seattle, Washington, and was implemented as a commercial product by the Skyhook Wireless, Boston, Massachusetts.

These Wi-Fi or Wireless Positioning Systems (WPS) are substantially different from RTLS systems in terms of application domain, performance expectations, database collection techniques, and localization algorithms.

RSS-Based Wi-Fi Localization

Received signal strength alone is not a reliable metric for range estimation.

The latest development in RSS-based Wi-Fi localization appeared in metropolitan areas with the growing popularity of iPhones and other smart devices.

The general statistical indoor propagation models used for calculating *RSS* at a distance *d* from a transmitter is given by:

$$RSS_d = 10\log_{10} P_r = \\ = 10\log_{10} P_t - 10\,\alpha \log_{10} d + X \qquad (2)$$

in which P_t is the transmitted power, α is the so-called *distance power gradient* of the environment, and *X* represents a zero mean Gaussian random variable describing the effects of shadow fading.

The CRLB of the ranging error, using Equation (2) to relate the distance to the power, is given by:

$$\sigma_D^{\,2} \geq \frac{(\ln 10)^2}{100}\frac{\sigma_{sh}^{\,2}}{\alpha^2} d^2 \qquad (3)$$

in which σ_{sh} is the standard deviation of the shadow fading.

The distance power gradient takes different values ranging from below 2 in corridors, which act as waveguides for radio propagation, up to 6 in buildings with significant metallic infrastructure. For most OLOS scenarios in indoor areas, its value is around 4.

The variance of the shadow fading in indoor areas is typically around 5–10 decibels. Using these numbers in Equation (3), the ranging error for measurement of distance using RSS reaches values on the order of the distance between the transmitter and the receiver — typically a maximum value of around 30–50 meters for Wi-Fi infrastructure deployed in indoor areas.

This magnitude of errors is not acceptable for typical RTLS commercial applications, such as tracking the assets or personnel inside buildings. They are, however, very reasonable for metrowide Wi-Fi localization applications such as turn-by-turn direction finding or location-based services.

As a result, although RTLS and WPS follow the same principles of operation and we can call both of them RSS-based Wi-Fi localization techniques, the technical details of their implementation are different, and they serve two different sectors of the industry.

What *is* common in the two industries is that we “wardrive” the network coverage area, inside a building for RTLS and in a metropolitan area for WPS, to collect a database of the observed RSS measurements from Wi-Fi APs in known locations. Later on, we can apply pattern recognition algorithms to this database to find the location of an unknown device reading certain RSS values from its surrounding Wi-Fi access points.

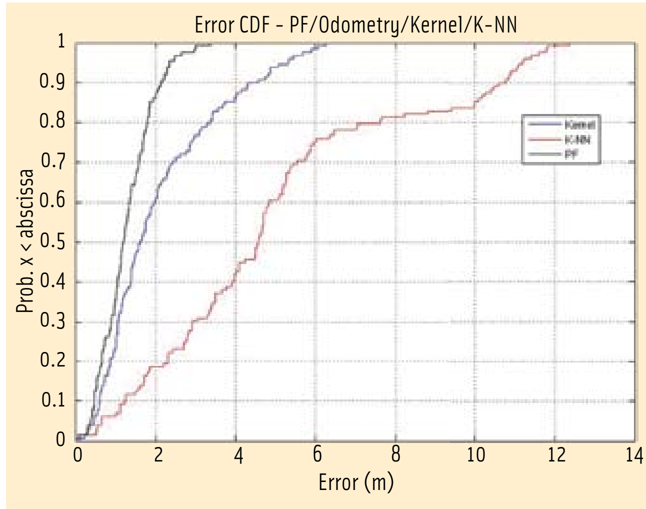

FIGURE 2 CDF of the localization error for two different Wi-Fi localization algorithms and a Particle Filter (PF) combining the results of Wi-Fi localization and an inertial system in the indoor route shown in Figure 3.

A device can measure the RSS of these Wi-Fi access points passively by processing the beacon signals periodically transmitted in the coverage area, or actively by probing the APs from time to time.

Neither RTLS nor WPS can support coverage everywhere and benefit from being combined with GPS or other GNSS systems.

RTLS: Indoor Tracking Using Wi-Fi Signals

The first generation of RSS-based RTLS products were software programs running on laptops and palm-top computers equipped with Wi-Fi devices used for indoor tracking applications. The system included a localization software and a graphical user interface (GUI). The localization software operated in two modes: *data collection*, in which the user builds up the reference database, and *localization*, when the software locates a terminal based on the relative strengths of RSS readings. The GUI in the mobile devices shows the map of building and estimated location of the terminal.

Wi-Fi chipsets were eventually designed into a small localization tag to form an embedded system for RTLS asset and personnel tracking applications. These tags measure the RSS strengths and report it to a server, which determines the location of the tag and shows it in the GUI. More recently, some manufacturers have integrated GPS chipsets with the tag to provide continual tracking when a device is moved between two facilities in which the APs have been surveyed.

When Wi-Fi localization tags are combined with GPS chipsets to provide for outdoor coverage, the algorithm for integration is quite simple: wherever Wi-Fi localization is available we use that and in its absence we resort to GPS readings. Another advantage of this integration is that the Wi-Fi tag coordinates, which are defined in the local coordinate frame specified in the layout of a building, can be mapped into the global GPS location coordinates.

As explained in the previous section and by Equation (3), if we use the RSS and location of the Wi-Fi APs, we cannot attain the few meters accuracy needed for RTLS applications. To remedy this situation, system designers have resorted to using databases derived from site surveys of multiple RSS readings from the surrounding Wi-Fi APs at known locations with much smaller spatial separations than would normally occur among Wi-Fi APs. These systems then use that database with a pattern-matching algorithm to locate a tag with the needed accuracy of around a few meters.

Figure 2 shows the performance of two popular techniques for Wi-Fi localization, K-Nearest Neighbor (K-NN) and Kernel algorithms, compared with a particle filter (PF) combining Wi-Fi localization using a Kernel algorithm with data from an inertial system. The data was gathered on a route in the third floor of the Atwater Kent Laboratory, Worcester Polytechnic Institute, shown schematically in **Figure 3**.

These results indicate that RSS-based Wi-Fi localization can achieve relative accuracies on the order of few meters in a typical indoor area, while integration with an inertial system can further improve the accuracy.

Manual geo-tagging of the measurement locations is time-consuming and expensive. Ideally, we could geo-tag the reference locations automatically to save time and build up the database much more quickly. However, we have no reliable and inexpensive means to know the absolute location in indoor areas.

GPS is not generally available indoors or, if available, does not provide the accuracy of a few meters needed for RTLS applications. Laser-ranging or other optical techniques to gather measurements linked to an external coordinate reference frame are labor-intensive and expensive to keep updated.

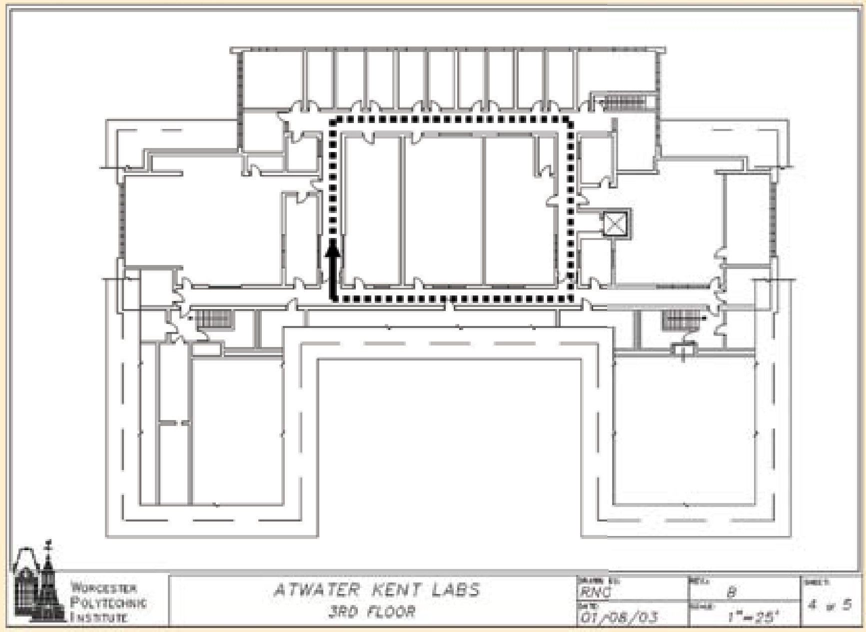

FIGURE 3 An indoor scenario for performance evaluation of the RTLS algorithms on the third floor of the Atwater Kent Laboratory, Worcester Polytechnic Institute, Worcester, Massachussetts.

WPS: A Software GPS

In metrowide Wi-Fi localization, a database is collected by wardriving the streets of a metropolitan area, using GPS to tag the location and time of measurements. Later, when a WPS mobile terminal reads the RSS of surrounding Wi-Fi access points, it sends a request to a server to calculate the terminal's location by comparing its RSS readings with the database and previous GPS readings using a pattern-recognition algorithm.

We might well characterize such a system as a software GPS system, memorizing and refining GPS locations for later use without the need of GPS hardware. Because the locations of the Wi-Fi APs are fixed but the orbital locations of GPS satellites are constantly changing, we can associate several GPS readings with various levels of accuracy to the same Wi-Fi access points, or we can use pattern-recognition techniques to correct GPS readings with the actual wardriving map.

Such methods enable a metrowide Wi-Fi Localization system to provide a better accuracy than GPS itself, depending on the absolute accuracy of the Wi-Fi network's coordinate reference frame. **Figure 4** shows results of performance of WPS in a test route in downtown San Francisco, California (See **Figure 5**).

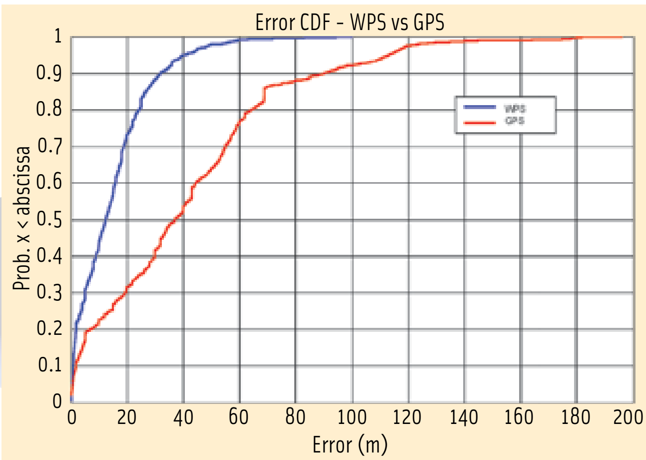

FIGURE 4 Performance of WPS versus GPS on a test route in San Francisco, California, shown in Figure 5.

Figure 4 illustrates that in dense urban areas Wi-Fi localization can perform better than GPS.

This situation reverses itself as we go to suburban areas, where the density of Wi-Fi access points are limited while user equipment has more GPS satellites in view, which typically results in higher accuracy positioning.

This "software GPS" approach provides a low-cost, low-power, and fast-to fix technique that in some situations can provide more accurate localization. Integration of Wi-Fi localization software and GPS hardware provides for a comprehensive metrowide coverage.

Evolution of Hybrid Localization

One of the fundamental advantages of WPS is that it can be used as a standalone software solution for netbooks and laptops when they are not equipped with GPS or cell phone chipsets. This solution is natural, because netbooks and laptops use Wi-Fi chipsets to establish Internet connections. When a Wi-Fi network is available, WPS works.

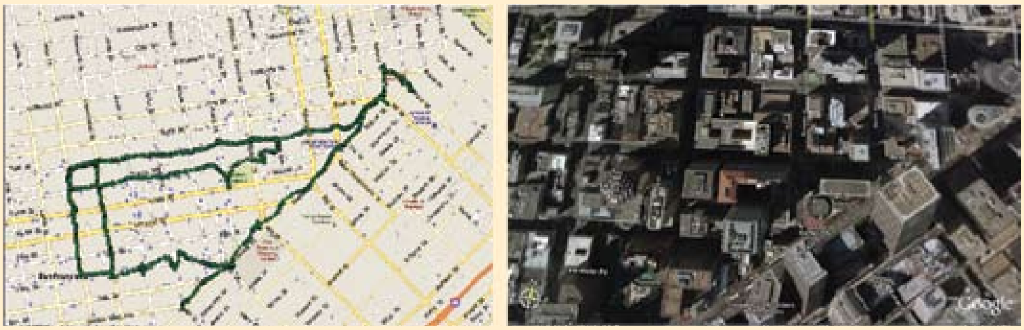

FIGURE 5 (a) The test route in San Francisco, California, for the performance results shown in Figure 4 (b) the satellite map of the downtown area in San Francisco.

Smart phones have cellular network connections as well as Wi-Fi chipsets. Wi-Fi signals from hot spots, home routers, and public access and enterprise wireless networks cover most of the indoor and urban areas where Internet applications are commonly used. In locales such as interstate highways, where Wi-Fi signals may not be available all the time, less accurate cell-tower localization can complement this coverage.

This combination of RSS-based WPS and cell tower localization was used in legacy iPhones, when they were first introduced to the market. Today, the latest versions of the iPhone as well as most other leading smart phones also carry GPS chipsets. This combination strengthens the coverage and increases the accuracy of localization in outdoor areas.

Integration of WPS and RSS-based cell tower localization is very straightforward: cell tower provides the coarse and Wi-Fi, the fine localization. WPS becomes the default mode and cell-tower localization serves as the backup. The two location estimates can be cross-examined to make sure that a cell tower or the Wi-Fi AP has not been moved to a new location. Both technologies are implemented in software and provide comparable power consumption, battery life, and time-to-fix performance.

Integration of WPS with GPS, however, is much more complex and technically involved because GPS and WPS measurements are derived independently using substantially different technologies with significant complementary attributes, which depend on the operating environment. WPS provides a better performance than GPS in indoors and in dense urban areas, but most of the time a warm GPS system on the open road is preferred to WPS localization.

GPS needs a few minutes in indoor areas, where most applications begin to provide an initial position fix. During that period the hardware is draining the limited battery life of the smart phones or netbooks. Therefore, in these areas WPS is the default mode. If the application is something like turn-by-turn direction guidance, after the GPS receiver is warmed up and acquiring satellite signals, the integrated system can switch over to GPS as the user moves into open areas.

How to combine these two location technologies to optimize the accuracy, power consumption and time to fix is a multi-dimensional engineering challenge demanding complex engineering solutions. This demand has stimulated the design of specialized algorithms for integration of WPS and GPS for metropolitan area applications. These algorithms need to sense the environment and use that information in the integration process exploiting non-linear adaptive algorithms such as extended Kalman or particle filters.

In the military and public safety applications further research is needed to address rapid database collection and the electromagnetic and radio signal interferences effects on WPS and GPS localization techniques, as well as finding efficient methods to integrate the two approaches to optimize time to fix, power consumption and accuracy.

Database Collection and Algorithms

The size of a Wi-Fi AP database can be huge compared to the database of a RTLS system in a single building. On a national basis, the collection procedure requires many wardrivers across many metropolitan areas.

In general the distribution of the actual Wi-Fi access points in metropolitan areas forms a stochastic process with particular spatial and temporal characteristics, because the number of the access points and their locations are constantly changing. During any given time interval, new access points are installed and some old access points are re-located or even disestablished.

Service providers such as Skyhook Wireless cannot control the ownership, installation, and relocation of these APs, and we cannot practically find out the actual location of all Wi-Fi APs at a particular moment. Therefore, the database obtained by wardriving is a snapshot of a stochastic phenomenon and does not contain the entire ground truth.

As time passes, the coverage and accuracy of a Wi-Fi AP database decay and need to be refreshed — a challenging, expensive, and on-going process that demands careful planning of the wardriving and AP re-scanning schedule. The quality of a database varies substantially, depending on the depth and complexity of the data collection method.

One possible way to reduce the cost of maintenance, expand the coverage, and increase the re-scanning intervals is to take advantage of user-generated content to update the database. Such "organic" data can be collected by the user terminal and made available in a more or less automatic fashion to the organization maintaining the Wi-Fi AP database. Organic data is used to locate the reported unknown APs based on the

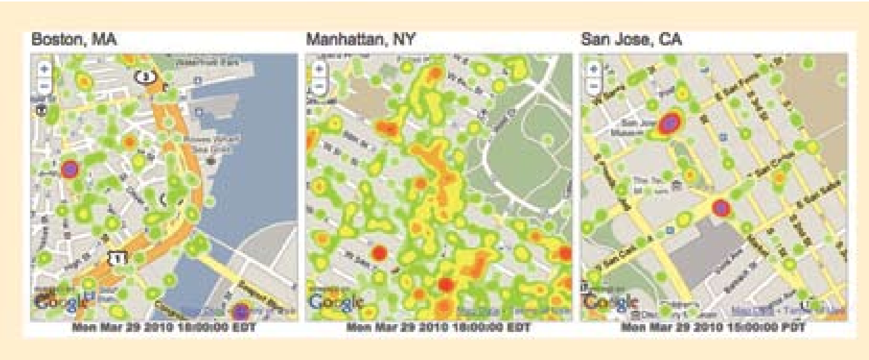

FIGURE 6 SpotRank is a new data intelligence service from Skyhook that predicts the density of people in predefined urbn square-block areas worldwide at any hour, any day of the week. Darker colors (e.g., purple, red, orange) indicate higher concentrations.

location of the proximity APs already exiting in the database.

Whether gathered at the beginning of a localization application or periodically during the application, we have to consider the terminal owner's privacy and the effects of such organic data collection on the terminal's power consumption. Access to user-generated content would enable us to update and expand the size of the database and while lengthening the intervals between coordinated wardriving campaigns, thus reducing the database maintenance costs.

Integration of organic data with the content systematically collected by means of coordinated wardriving requires data-mining algorithms to ensure that the user-generated data does not reduce the overall accuracy. In the Wi-Fi mapbase collected for WPS, for example, geo-tags include estimates of GPS positioning errors, and the density of measurements depends on the size of the coverage area and the speed of the wardrivers.

Algorithms are incorporated during data postprocessing to minimize GPS geo-tagging errors and to ensure that the spatial distribution of the data is sufficiently uniform. These algorithms are separate from the actual WPS localization algorithms.

The localization algorithms designed for WPS need to cope with the uncertainties of the database caused by stochastic spatial and temporal characteristics of Wi-Fi APs and the uneven distribution of the data associated with individual APs. These algorithms have to process information from a huge database for which use of nearest-neighbor–based algorithms may not be the optimum solution in all situations.

The propagation environment for GPS/Wi-Fi positioning often involves a variety of complex indoor-to-outdoor scenarios that are more unpredictable than RTLS applications taking place entirely indoors. However, such scenarios have characteristics that can be utilized to improve the performance of these integrated systems. For example, absolute GPS positioning can be used to recalibrate the subsequent Wi-Fi localizations and Wi-Fi–aiding for faster GPS fixes.

The design complexities of metrowide Wi-Fi localization have opened a field for innovative engineering by companies engaged in Wi-Fi AP database collection and post processing.

On March 15, 2010, Skyhook Wireless announced a new service called Spot-Rank and its availability via SimpleGeo, a provider of a comprehensive location application programming interface (API) for developers. Figure 6 shows examples of how SpotRank is presented at three different locations. SpotRank data is based on hundreds of millions of anonymous location lookups processed daily through Skyhook's Core Engine.

This location platform powers positioning requests on tens of millions of devices and applications around the world. Skyhook continually mines this data to create detailed behavioral intelligence profiles for more than half a billion 100-meter "spots" around the world. Providing new insight into the movement of crowds through out urban areas, these profiles are based on historical trends in location lookup volume and time of day

Conclusions

Wi-Fi localization is emerging as a new technology that complements GPS in coverage, time to fix, and power consumption. This began with the introduction of RTLS technology tailored for more precise indoor applications in specific buildings and then extended to WPS technology with less rigorous requirements for accuracy but a wider geographic coverage— i.e., a metropolitan area.

RTLS is currently combined with GPS to provide accurate indoor tracking and coarser outdoor tracking when the asset or personnel is moving between two specific building destinations. WPS is integrated with GPS to provide for a comprehensive coverage in numerous everyday consumer applications. To extend the Wi-Fi localization applications to the military and public safety, we need to understand the effects of electromagnetic and radio frequency interference in this technology to have an optimum solution for its integration with GPS techniques.

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Additional Resources

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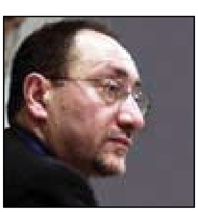

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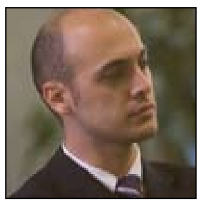

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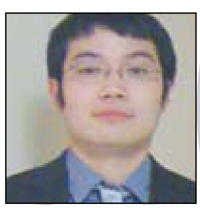

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