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# Seamless Indoor/Outdoor Positioning Handover for Location-Based Services in Streamspin

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*Abstract*— **This paper presents the implementation of a novel seamless indoor/outdoor positioning service for mobile users. The service is being made available in the Streamspin system (www.streamspin.com), an open platform for the creation and delivery of location-based services. Streamspin seeks to enable the delivery of truly ubiquitous location-based services by integrating GPS and Wi-Fi location fingerprinting. The paper puts focus on key aspects of the seamless handover between outdoor to indoor positioning. Several different handover solutions are presented, and their applicability is evaluated with respect to positioning accuracy and battery consumption of the mobile device.**

## I. Introduction

Location-Based Services (LBSs) are set to be an important aspect of many mobile Internet services, but two obstacles may be identified that keep LBSs from realizing their full potential.

First, geo-positioning is not yet truly ubiquitous. In outdoor settings, accurate GPS-based positioning has been available globally for almost a decade. However, GPS relies on lines of sight to GPS satellites and is generally unavailable indoors. Indoor positioning technologies encompass various RFID technologies and Bluetooth-based and Wi-Fi-based positioning. While little infrastructure is as of yet available for RFID and Bluetooth-based positioning, an infrastructure that enables Wi-Fi-based positioning is emerging rapidly. Thus, many indoor environments are equipped with Wi-Fi, and increasing numbers of mobile devices support Wi-Fi. This development renders it relevant to attempt to combine GPS and Wi-Fi-based positioning into a single, seamless positioning service.

Second, we are witnessing a lack of service "integration" [1]. Currently, most LBSs are designed to support a single purpose, and multiple services are often needed to meet a user's needs. GPS-based services such as Nokia Maps [2] and Google Maps for mobile [3] may be used for outdoor navigation and for identifying points of interest, while other outdoor services are available at specific locations, e.g., child-finder services at amusement parks.

Similarly, companies such as Ekahau [4] and Blip Systems [5] offer indoor services for various application domains. Thus, making full use of available services entails juggling several applications on a mobile device. A related aspect is service discovery. How do users go about finding relevant services that are available at some location?

Streamspin [6] seeks to overcome these obstacles. Streamspin is an open platform for the creation, sharing, and deployment of context-aware services. Streamspin simplifies the process of sharing location context by encapsulating client-server communication, heterogeneous mobile clients, and positioning behind an easy-to-use web service interface. Streamspin is able to deliver ubiquitous location services by pushing location-dependent content to users in both indoor and outdoor settings. To enable this, Streamspin relies on GPS in outdoor settings and existing Wi-Fi infrastructures in indoor settings.

To support accurate indoor positioning, Streamspin makes use of the so-called *location fingerprinting* technique which works by using a radio map of signal strength information for locations in a building. The positioning service uses a central server to store such Wi-Fi radio maps which are downloaded on demand to the mobile devices when the users enter the vicinity of a given building. The handover between GPS and Wi-Fi occurs transparently. This paper presents several different strategies for performing this handover and examines important properties, most notably positioning accuracy and impact on battery consumption.

The remainder of the paper is organized as follows. The next section offers an overview of Streamspin. This is followed by a discussion of Wi-Fi based positioning. Section IV describes the architecture of the system that facilitates the downloading of Wi-Fi radio maps to mobile devices, which is a prerequisite for performing Wi-Fi positioning on the users' own devices. Section V offers several different solutions to performing handover between GPS and Wi-Fi positioning. Section VI reports the findings from an application of the solutions in a real-world setting. Finally, Section VII concludes and presents research directions.

## II. The Streamspin Platform

### A. Overview

Streamspin [6] supports the creation, sharing, and deployment of location- and context-based mobile services. The system is designed to be open and scalable, and it offers easy-to-use service creation and subscription interfaces. By encapsulating the server-to-client communication and the heterogeneity of mobile terminals, the system eases service development.

The system makes it possible to push content (HTML) to mobile devices using a simple web-service interface. In addition, it supports the tracking of devices with accuracy guarantees, subject to user acceptance. The system can to some extent be viewed as a publish/subscribe system with added support for location-related context and with special focus on

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the mobile Internet. Streamspin also enables service providers to advertise services in a service directory, from where users can then subscribe to the available services.

Several different uses of Streamspin rely on the availability of positioning. This includes functionality for route collection and prediction [13], for efficient tracking [14], and for location privacy [15], [16].

By tracking their users, service providers receive timely updates about the users' locations. The tracking should be transparent to the users, i.e., if a user's device is capable of automatically producing a position, by such means as GPS, Wi-Fi, RFID, or GSM, the system should use this position with no user intervention. This transparency becomes difficult to provide when several competing positioning technologies are available. The user could be allowed to choose between the different technologies or could be asked to state whether the current position is indoor or outdoor. This would, however, be counter to one of the main purposes of the system, namely that services should be consumed as easily and ubiquitously as possible.

### B. Positioning in Streamspin

Service developers can use Streamspin's web-service API to subscribe to the movements of users who have subscribed to their services. When the user is being tracked the mobile device sends updates to the server when the user's position deviates from the previously reported position by more than a supplied threshold. The service provider who owns the service is then notified.

Streamspin is designed to offer both indoor and outdoor tracking. The system currently exploits GPS and Wi-Fi to achieve this. The mobile clients contain two components, the GPS and Wi-Fi location components, which are responsible for delivering positions.

To be able to achieve a seamless and transparent handover between the different positioning technologies, the technologies use the same positioning model when they report positions. Streamspin uses the geo-positioning scheme of the GPS system (i.e., latitude and longitude values). This makes it easy for Streamspin services to utilize existing geo-tagged content, e.g., photos from Flick or content found using the Google Maps API.

## III. Wi-Fi-Based Positioning

The use of GPS is simple: GPS receivers emit positions in the right format at a regular interval, e.g., each second. However, due to the strong signal attenuation caused by buildings, GPS is unable to serve as a reliable means of indoor positioning. Thus, recent years have seen a surge in the study of alternative technologies for indoor positioning, including Bluetooth [5], Infrared [17], Ultrasonic [18], Ultra-wideband [19], and RFID [20] technologies. These technologies generally rely on specialized infrastructures, which hampers their potential for widespread use.

In contrast, the ubiquity of Wi-Fi networks and the increasing availability of Wi-Fi-enabled devices combine to make Wi-Fi the most promising technology for widespread indoor positioning.

Wi-Fi signals can be used for localization since the signals emitted from Wi-Fi access points attenuate over distance and when passing through physical obstructions. This means that spatially different locations will have different signal strength characteristics. However, the exact signal strengths at different locations are extremely difficult to predict accurately. Signals are attenuated, reflected, and scattered; and interference is introduced from other signals on the 2.4 GHz band.

These difficulties are overcome by means of *location fingerprinting*, which denotes the explicit measurement of the actual access point signal strengths in different indoor locations. Location fingerprinting—pioneered by the Radar project [7] and further refined subsequently (e.g., [8], [9], [10], [11], [12])—works by recording signal strengths at a number of locations throughout the intended coverage area of the positioning system. The resulting database of signal strengths, commonly referred to as a *radio map*, then consists of $(location, measurement)$ pairs, where $location$ is the location (e.g., latitude, longitude, altitude) of the measurement and $measurement$ is a vector $(ap_1, .., ap_n)$ containing the strength of the signal received from each of $n$ access points that can be observed at the location.

The radio map is built in the *offline phase*, before the system is deployed. In the ensuing *online phase*, or operational phase, a location estimate is obtained by searching the radio map for a closest match to the signal strength currently measured by a user's device. Thus, positioning in the online phase is an iterative process of measuring signal strengths and deriving position estimates by comparing the measurements with the entries saved in the radio map.

## IV. Architecture

In an indoor environment where the users have a high degree of freedom of movement, the update interval between consecutive positioning iterations has to be kept short (e.g., a couple of seconds) in order to continuously capture the user's actual position. For this reason, client-based positioning, i.e.,positioning on the mobile device, is preferred over server-based positioning, where the mobile device measures the signal strengths and then sends the measurements to the server that calculates a position and then sends a reply back to the device. Client-based positioning avoids congesting the network with location-related messages.

However, for client-based positioning to work, the radio map must be present on the mobile device. Streamspin maintains a central data store from which Wi-Fi radio maps for each building covered can be downloaded to the user's mobile devices on demand.

A building is uniquely identified by the set of the MAC addresses of the access points in the building. Each MAC address is in itself unique, but adjacent buildings may share overlapping access points. The data store maintains a list of the available access points for each building. This enables transparent and on-demand download of the appropriate radio map.

Specifically, a building's radio map is downloaded on demand when a user enters the vicinity of the building's access points. The mobile device scans for nearby access points and records their MAC addresses. These are sent to the central data store that finds a matching building. A unique identifier for the building is sent to the client which checks whether a radio map of the building is already present. If not, the radio map is fetched from the server, upon which the client is able to perform positioning.

## V. Handling Handover

We present four solutions for the handover between GPS and Wi-Fi. In the following, both the GPS and the Wi-Fi location-provider components in the Streamspin client will run simultaneously and continuously. That is, each will attempt to infer a position at all times. When no signals can be observed, both components will loop trying to establish a connection.

The handover solutions control which location source is used as the authoritative source. It was found empirically to be attractive to delay the switching between sources so that these occur at most every 5 seconds.

*1) Always Prefer GPS:* In this solution, GPS is always preferred. That is, GPS is used whenever available, regardless of whether Wi-Fi signals can also be observed. The rationale is that GPS generally provides the most accurate positioning outdoors. Moreover, GPS signals can often be registered indoor near windows.

Outdoor positions can of course also be fingerprinted, i.e., added to a Wi-Fi radio map, with accuracies that may be similar to GPS. However, outdoor fingerprinting adds to the manual overhead of maintaining the radio map, and the resulting accuracy might not justify this extra effort. For Wi-Fi to provide comparable accuracy, locations would have to be fingerprinted in a dense grid surrounding the building in question. Moreover, the positioning accuracy will gradually decrease as the distance to the building increases, fewer and fewer access points will be in range, thus resulting in less detailed radio maps.

The solution is implemented as follows: If the GPS receiver has recently reported a position (within the last 5 seconds), any Wi-Fi position obtained is discarded. A possible drawback of this solution is that when a user is indoor, but is near windows or materials that allow GPS signals to penetrate, GPS is preferred although GPS positions obtained under such circumstances can be of low quality; better Wi-Fi positioning may be available.

*2) Always Prefer Wi-Fi:* Opposite to the previous solution, this solution always prefers Wi-Fi over GPS. That is, whenever Wi-Fi readings are available, they are used exclusively until the Wi-Fi signal is lost. This occurs when the Wi-Fi location-provider has not reported a position for the last 5 seconds.

This solution seeks to overcome the main drawback of the "Always Prefer GPS" solution, namely that low quality GPS readings indoor adversely affect the positioning accuracy. However, its weakness is that the positioning accuracy will be low in non-fingerprinted areas. If the outdoor area has not been included in the radio map, the system will continue to report locations within the building although the user is outside and GPS is available.

*3) Prefer GPS Until Lost Signal—Then Prefer Wi-Fi Until Lost Signal:* With this solution, GPS is preferred until the signal is lost (nothing was reported by the GPS receiver the last 5 seconds). Subsequently, the Wi-Fi is preferred until the Wi-Fi signal is lost (again, nothing was reported the last 5 seconds).

This approach tries to counter the effect of poor GPS readings indoor as well as poor Wi-Fi positioning in outdoor, non-fingerprinted areas. By relying on GPS until no signal can be received, this solution ensures the best overall outdoor positioning. The loss of GPS signals is an indicator that a user has moved indoor and that Wi-Fi positioning is preferable. By sticking with the Wi-Fi positioning until the Wi-Fi signal is lost, poor indoor GPS readings are disregarded.

However, this solution fall short when a user leaves a building in the same way as does the "Always Prefer Wi-Fi" solution. If the outdoor area is non-fingerprinted, the user can move a substantial distance before getting out of range of the access points and switching back to GPS.

*4) Prefer GPS Upon Continuous Readings:* This solution aims at overcoming the drawback of the previous solution where Wi-Fi, once acquired, is used until it is lost. This solution always prefers GPS over Wi-Fi when the GPS has reported positions every second for the last 5 seconds. This way, GPS will be preferred until the 5 consecutive second mark has been broken, which indicates that the GPS signal is no longer reliable. Then Wi-Fi is used until the GPS signal once again is observed for 5 consecutive seconds.

This strategy does not entirely avoid the problem of using inferior GPS signals inside a building. However, the effect is not as pronounced due to the 5-second requirement. Moreover, it is likely to produce good results when users are actually on the move indoor and only sparse GPS readings are available. Such more or less random position reports, which are often off by more than 50 meters, are then eliminated because the user moves and no new GPS positions are reported. In addition, the problem with the Wi-Fi locations continuing outdoors is reduced, as the GPS receiver will pick up positions very quickly after the user exists a building.

## VI. Empirical Study

Following a description of the setting of the study, we cover the prediction accuracy for each of the proposals and end with a coverage of battery consumption.

### A. Experimental Setup

The experiments occur inside a two-story office building as shown in Figure 1. The building is mainly constructed of bricks that effectively block GPS signals. However, its main hallways are equipped with large window panes, which occasionally allow GPS signals to penetrate. These are the white parts of the building, running all the way around the center of the building with a branch towards North.


Fig. 1. Walking Route

As described in Section IV, the client downloads a radio map when its Wi-Fi receiver has seen enough access points to uniquely identify a building. In the experiments, this occurs when the Wi-Fi receiver can pick up a single access point, as no access points are registered for nearby buildings. Because Wi-Fi signals can be observed in the parking lot, both GPS and Wi-Fi positioning are available when the test starts.

In the study, a user follows the black curve in Figure 1 from start to end. All reported positions from both location providers are collected and used to visualize the route that would be reported by the mobile device (the study was carried out three times with very similar results).

### B. Evaluation of Positioning Accuracy

We consider the actual reported positions for the four solutions. The applicability of each solution is evaluated in terms of how well the captured route matches the actual route followed, as shown in Figure 1.

*1) Always Prefer GPS:* Figure 2 shows the positions reported using the "Always Prefer GPS" solution. This solution

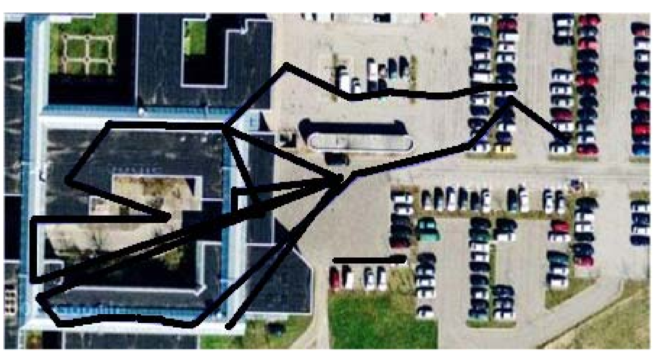

Fig. 2. Always Prefer GPS

clearly has severe shortcomings. A number of times, the position jumps in and out of the building. This effect is caused by the GPS receiver reporting faulty positions as a result of seeing some, but not enough, GPS satellites through the window panes. This behavior is problematic in several respects. When tracking a user, the Streamspin client sends an update to the Streamspin server when the user's position deviates from the most recently reported position by more than a given threshold. Therefore, these jumps may incur "false" updates. Every large jump will typically cause one update when jumping away and one when jumping back to the correct position. This behavior is undesirable, in terms of extra messages and, not least, in terms of the quality of service delivered.

*2) Always Prefer Wi-Fi:* Figure 3 shows the reported route when the "Always Prefer Wi-Fi" solution is used. Again, there

Fig. 3. Always Prefer Wi-Fi

are problems. Because the radio map only covers the interior of the building and because Wi-Fi access points can be seen throughout the route, the user's position is always reported as being inside the building. This is obviously suboptimal as we know from our previous experiment that accurate GPS positions are reported outside.

This solution will only use GPS positions when the out of reach of all Wi-Fi access points. A possible fix could be to extend the radio map with outside positions. However, this would need to be done in the range that Wi-Fi signals can be observed around the building, increasing the overhead of maintaining the radio map. Moreover, the Wi-Fi accuracy decreases as the distance to the building increases because access points gradually "fall off."

Finally, we have seen that GPS is able to produce good accuracy right up until the doorstep. Therefore, fingerprinting outside locations will at best result in inferior outside positioning. A good general choice seems to be to fingerprint close surroundings of the building where the signal strengths can be expected to be strong, e.g., around main entrances of the building. This may help prevent dead spots where GPS signals are blocked by walls.

*3) Prefer GPS Until Lost Signal—Then Prefer Wi-Fi Until Lost Signal:* Figure 4 illustrates the route obtained when using the combined approach where we start by preferring the GPS positions, but switch to Wi-Fi when no GPS position has been reported for 5 seconds. Wi-Fi is used subsequently as long as it reports positions. As the figure illustrates, this solves

Fig. 4. Prefer GPS Until Lost Signal - Then Prefer Wi-Fi Until Lost Signal

half of the previous problem. The user is now positioned correctly moving towards and inside the building. However, the user is not positioned correctly when leaving the building. The reason is the same as for the last solution. When Wi-Fi can be observed, the locations reported are chosen among the available indoor entries in the radio map.

*4) Prefer GPS Upon Continuous Readings:* Figure 5 shows the last approach where GPS is preferred exactly when it has reported positions for (at least) the last 5 seconds. As

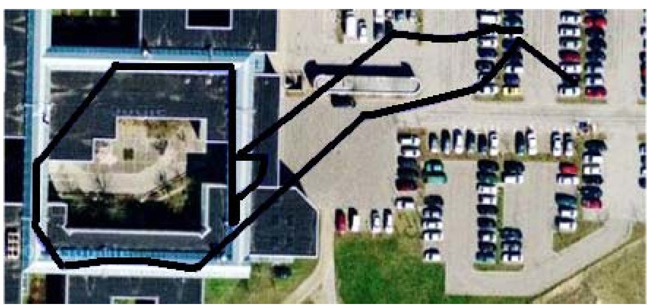

Fig. 5. Prefer GPS Upon Continuous Readings

can be seen, the very error prone indoor GPS positions are avoided. The system is now also able to track the user both entering and exiting the building. The solution is, however, still not completely flawless. Note that a number of wrong indoor positions are reported just after the user leaves the building. Comparing with Figure 1, it is easy to see that parts of the route are missing (from the GPS provider). One could, of course, set the number of continuous readings to a lower value, but this would likely increase the number of error readings like the ones in Figure 2.

### *C. Discussion—Position Accuracy*

We first note that although the first two solutions, i.e., always use either GPS or Wi-Fi, did not yield good accuracies, they are much better than the straightforward approach of simply using whatever position is available. Using both Wi-Fi and GPS can yield excessive amounts of updates because the Wi-Fi positions can be off by far when the user is outdoors and, similarly, because the GPS positions can be off by far when the user is indoor. More importantly, this would result in the service providers obtaining wrong positions.

The study clearly shows that it is, at least in our setting, preferable to use GPS as the main source, whenever continuous readings are available. This could, however, be different in other settings. For example, an urban setting with tall buildings might yield different results. In such a setting, the GPS might only report positions every second or third second due to the obstacles, thus enabling the more frequent use of low-quality Wi-Fi positions.

### *D. Battery Consumption*

In addition to position accuracy, another important aspect is battery life as it directly affects how much a user can benefit from the mobile device. To evaluate the battery consumption of the sensing technologies, the Streamspin client was run on a mobile device for 60 minutes. One run was performed with none of the location providers turned on (for reference), one was performed using only the Wi-Fi provider, and one was performed using only the GPS provider. The device tested was an HP-iPAQ model hw-6915 that had been used extensively during the past 2 years (which has some impact on the battery capacity).

The results, in Figure 6, show clearly that both Wi-Fi

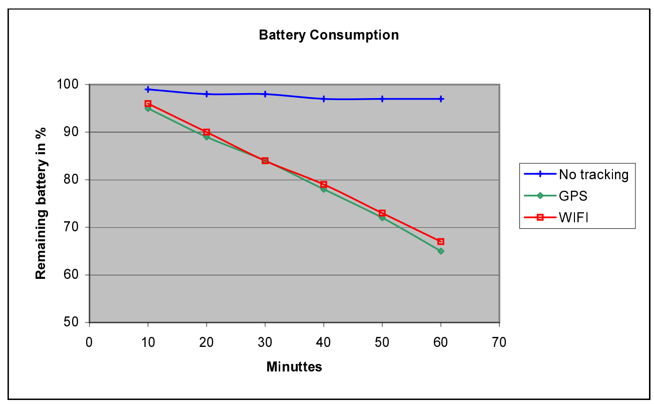


Fig. 6. Battery Consumption

and GPS use substantial, and similar, amounts of power compared to just running the Streamspin client. In fact, the Wi-Fi provider uses the same amount as accessing the Internet in a normal manner. The reason is that the Wi-Fi provider continuously performs an active scan every second for the signal strength of nearby access points, which is a very expensive operation in terms of power. The Wi-Fi provider gradually decreases the scanning interval to an eventual "idle mode" where it scans every 30 seconds when no nearby access points are observed. However, as long as nearby access points are observed, frequent scanning operations are performed—even though the mobile terminal may just be lying on a desk.

### *E. Discussion—Battery Consumption*

Substantial improvements are desirable with respect to power consumption. GPS uses significant power, although network-assisted GPS will yield reductions; and if the user does not already use the Wi-Fi connectivity for other purposes, the Wi-Fi-based positioning will also add significantly to the power consumption. Although newer mobile devices have better batteries and have GPS and Wi-Fi components that use less power, GPS and Wi-Fi will still use substantial power.

One approach to reducing the power consumption is to use the location components more intelligently. In the cases of non-movement it would be beneficial to reduce the update interval. Krumm and Horvitz [9] devise a method to infer whether or not a user is moving that uses the signal strength variations measured by a device's Wireless Network Interface Card. Further, many newer mobile terminals have in-built gyroscopes or accelerometers that may be used to detect movement.

Being able to detect non-movement makes it possible to turn off positioning when the user has not been moving for some time. Now the positioning components wake up at regular intervals and check whether the user has moved; if so, tracking is resumed. This approach greatly reduces power consumption, depending, of course, on the duration of the interval between the checks (the interval can be increased gradually, and there is a direct tradeoff between accuracy and power consumption).

Finally, assuming that the "Use GPS upon continuous readings" solution is used, Wi-Fi scanning can be disabled altogether until the GPS positioning fails. This effectively doubles the time a user can be online in situations where the user is moving, can observe access points, but where GPS is preferable.

## VII. Conclusion and Research Directions

In the context of a novel approach for handling handover between indoor and outdoor positioning, the paper presents and studies empirically the design properties of four handover solutions. The most accurate solution, "Prefer GPS upon continuous readings," produced only a small number of relatively minor errors in the studies reported upon.

The paper proposes an architecture where Wi-Fi radio maps that enable Wi-Fi positioning are downloaded transparently and on demand to a mobile device when access points are observed by the device. The appropriate radio map is found by matching the access points seen by the mobile device against server-side lists of known available access points for different buildings.

While this functionality was not evaluated since there was only one registered building in the study, improvements may be possible. Consider a user passing by several registered buildings on the way to a destination. If radio maps are downloaded as soon as access points are observed, this will lead to excessive downloading of radio maps. A possible optimization is to defer a download until the GPS signal is lost, which indicates that the user has moved indoor. This arrangement is still not entirely bulletproof. In so-called urban canyons where tall buildings block the GPS signal, radio maps may still be downloaded prematurely. A solution can be to extend Streamspin beyond the exclusive use of radio maps. Tracking based on triangulation (of either GSM or Wi-Fi signals) and RFID tags are quickly becoming available, and it would therefore be beneficial to be able to adjust the system to always use the best current positioning technology.

GPS and Wi-Fi are considered the primary sensing technologies in Streamspin due to their predominance. However, Streamspin is open to integrating further positioning technologies, which would allow the system to choose the most reliable positioning. GPS reports reliability by the *Dilution of Precision* metric, and work has also been done in quantifying the error of GSM and Wi-Fi Positioning [21], [22]. Finally, it is possible to perform sensor fusion, i.e., combine the readings from several sources if this yields better results.

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## References

[1] J. Krumm and S. A. Shafer, "Data store issues for location-based services," *IEEE Data Eng. Bull.*, 28(3): 35–42, 2005.
[2] Nokia, "Nokia Maps," http://europe.nokia.com/A4509271.
[3] Google, "Google Maps for mobile," http://www.google.com/mobile.
[4] "Ekahau," http://www.ekahau.com/.
[5] "Blip Systems," http://www.blipsystems.com/.
[6] R. Wind, C. S. Jensen, K. H. Pedersen, and K. Torp, "A testbed for the exploration of novel concepts in mobile service delivery," in *Proc. MDM*, pp. 218–220, 2007.
[7] , P. Bahl and V. N. Padmanabhan, "RADAR: An In-Building RF-Based User Location and Tracking System," in *Proc. INFOCOM*, pp. 775–784, 2000.
[8] A. Agiwal, P. Khandpur, and H. Saran, "Locator: location estimation system for wireless LANs," in *Proc. 2nd ACM International Workshop on Wireless Mobile Applications And Services on WLAN Hotspots*, pp. 102–109, 2004.
[9] J. Krumm and E. Horvitz, "Locadio: Inferring motion and location from Wi-Fi signal strengths," in *Proc. Mobiquitous*, pp. 4–13, 2004.
[10] A. M. Ladd, K. E. Bekris, A. Rudys, G. Marceau, L. E. Kavraki, and D. S. Wallach, "Robotics-based location sensing using wireless ethernet," in *Proc. MOBICOM*, pp. 227–238, 2002.
[11] S. Saha, K. Chaudhuri, D. Sanghi, and P. Bhagwat, "Location determination of a mobile device using IEEE 802.11b access point signals," in *Proc. IEEE Wireless Communications and Networking Conference*, pp. 1987–1992, 2003.
[12] , R. Hansen and B. Thomsen, "Accurate and Efficient WLAN Positioning With Weighted Graphs," in submission.
[13] A. Brilingaite, C. S. Jensen, and N. Zokaite, "Enabling routes as context in mobile services," in *Proc. ACM GIS*, pp. 127–136, 2004.
[14] A. Civilis, C. S. Jensen, and S. Pakalnis, "Techniques for efficient road-network-based tracking of moving objects." *IEEE Trans. Knowl. Data Eng.*, 17(5): 698–712, 2005.
[15] M. L. Yiu, C. S. Jensen, X. Huang, and H. Lu, "Spacetwist: managing the trade-offs among location privacy, query performance, and query accuracy in mobile services," in *Proc. ICDE*, pp. 366–375, 2008.
[16] L. Liu, "From data privacy to location privacy: models and algorithms," in *Proc. VLDB*, pp. 1429–1430, 2007.
[17] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Trans. Inf. Syst.*, 10(1): 91–102, 1992.
[18] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proc. MOBICOM*, pp. 32–43, 2000.
[19] "Ubisense," http://www.ubisense.net/.
[20] L. Ni, Y. Liu, Y. C. Lau, and A. Patil, "Landmarc: Indoor location sensing using active RFID," in *Proc. PERCOM*, pp. 407–415, 2003.
[21] D. Dearman, A. Varshavsky, E, de Lara, and K. N. Truong, "An Exploration of Location Error Estimation," in *Proc. UBICOMP*, pp. 181–198, 2007.
[22] H. Lemelson, M. B. Kjærgaard, R. Hansen, and T. King, "Error estimation indoor 802.11 location fingerprinting," in submission.