

# A Pervasive Indoor-Outdoor Positioning System

Lionel Reyero<sup>1</sup>, Gilles Delisle<sup>2</sup>

<sup>1</sup>INRS-EMT, Université du Québec,  
Montréal, Canada, H5A 1K6,  
lionel.reyero@iitelem.com

<sup>2</sup>International Institute of Telecommunications,  
Montréal, Canada, H5A 1K6  
gilles.delisle@iitelem.com

**Abstract**—A new concept called Always Best Located (ABL) is introduced to achieve a pervasive indoor-outdoor positioning system. Designed as a combination of WLAN and GPS, this hybrid positioning system is shown to yield ubiquitous coverage and best-effort accuracy in any environment. An original mapping algorithm has been conceived to enable the system to discover the location of nearby WLAN access points on the fly, without requiring human intervention or connection to an existing database.

Following an outline of positioning algorithms and location based application requirements, a comparative study of positioning technologies based on GPS, GSM, WLAN, and Bluetooth is presented. As revealed by this benchmark, none of the existing technologies suffice to provide ubiquitous coverage; however a combination GPS and WLAN is shown to provide excellent coverage and accuracy indoors as well as outdoors. New algorithms are then presented to illustrate how these two technologies can be combined to provide a continuous service by switching from one technology to another, to accurately locate the user indoors, and to automatically discover location of nearby WLAN access points. Finally the ABL system is validated over time by several users and is shown to yield 97% availability – the equivalent of more than 23 hours of service a day.

**Index Terms**— positioning, location, GPS, WLAN, GSM, ubiquitous

## I. INTRODUCTION

Wireless positioning has enabled computer systems to calculate their own geographic position. This has led to the apparition of a wide set of applications of which navigation, fleet management, and local search are just a few examples. Wireless positioning is now seen as an enabler which is part of most of new generation applications.

Numerous wireless positioning systems have been developed for all kind of communication interface – FM radio, GSM networks, WLAN networks, Bluetooth networks, RFID devices, UWB radio, and even ultrasound. Despite this large number of systems, creating a location-aware application for the masses is still a technical challenge. Most of the existing positioning systems operate in a confined environment, such as inside a building, and therefore they are not yet able to offer a service in any place users may travel to, indoors as well as outdoors. Moreover, existing systems require investment in a new infrastructure as well as a complex calibration phase.

In our opinion, an ideal positioning system should be capable of tracking the user location in any place he or she may travel to, indoors as well as outdoors. Similarly

to the principle of 99.999% availability of telecommunication networks, positioning systems should offer a service at any place and any time users may travel to. Moreover, as applications value increases with respect to the accuracy of the positioning, an ideal positioning system should offer an accurate service, indoors as well as outdoors. Finally, an ideal positioning system should use an existing infrastructure, and should have a calibration phased reduced to the minimum.

Our objective is to create such a positioning system, by following a hybrid approach consisting in combining existing technologies to offer an accurate and ubiquitous service [1].

Our research methodology starts by evaluating accuracy and coverage of positioning based on four existing technologies – GPS, GSM, WLAN, and Bluetooth – in different environments of the city of Montreal, Canada. These measurements have shown that GPS and WLAN offer the most complementary accuracy and coverage, and have therefore been selected to develop our hybrid positioning system.

This system has been developed as the combination of three different positioning components. The first component is a place detection algorithm, based on WLAN, offering a room level accuracy inside buildings. GPS is used as the second component to offer an excellent accuracy and coverage in outdoors environments. Finally, our third component is a WLAN positioning algorithm which is used in unfamiliar indoors areas and outdoors where GPS is unavailable. Sophisticated discovery algorithms have been created so that WLAN access points can be located automatically as users go ahead with their daily activities.

All of these components have been separately tested before being integrated in a final prototype, which has been carried by three participants for a week, in order to validate its intended ubiquitous coverage.

## II. POSITIONING APPROACHES, ALGORITHMS AND TECHNOLOGIES

### A. Positioning Approaches

Positioning systems are either designed to be network-based or terminal-based, as illustrated on fig. 1.

Network-based positioning systems are typically running on a server in a telecommunication network and are using measurements from several antennas to calculate users' location, e.g., GSM base stations or WLAN access points. These systems are usually more accurate, as they have access to fine grained data such as

the antenna location, tilt, transmission power, which terminal-based systems have not. In addition, network-based systems are more reliable as the infrastructure is managed by a single company. However, these systems may suffer from a limited coverage, as they can only operate where the company network is deployed. Consequently they suffer from scalability, as they require deployment of new infrastructure to extend the coverage.

Terminal-based systems calculate the user location on the terminal itself by using the available communication interfaces to make radio measurements. This approach has the advantage to use the existing infrastructure of GSM antennas or WLAN access points. However, the location of these antennas has to be known so the user location can be inferred from their detection. Creating a database of known antenna location is one of the main issues of the terminal-based approach. It is often built by discovering antennas' location while driving in each and every street, which is time consuming and lead to scalability issues. Terminal-based positioning systems are also more flexible, and can easily combing several technologies such as GSM, WLAN, and Bluetooth which are present on most high-end terminals.

All research results in this paper are obtained by following a terminal-based approach.

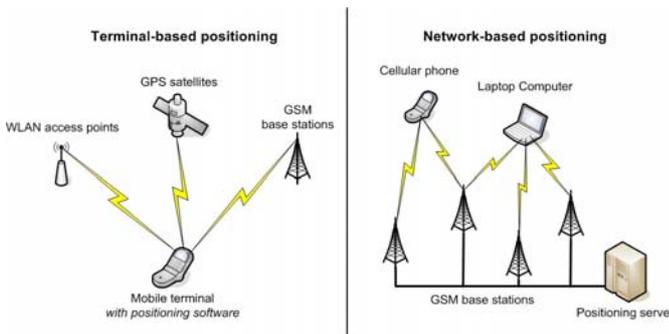


Figure 1. Terminal-based and network-based positioning

**B. Location types**

Geographic information using a broad variety of expressions such as a name, an address, an intersection, a description, a distance, or a coordinate, is communicated everyday. These expressions can be sorted in three main categories of location: absolute, relative, and symbolic.

Absolute locations are coordinates whose origin is the center of the Earth and which can be used to represent any location on the surface of the planet. Relative locations are coordinates relative to a building or a district, which can be used to represent locations into that limited area. Symbolic locations are names, tags, or any addresses that can be understood by users, such as "Home" or "Work" for instance. These types of location are usually more meaningful in interpersonal communications.

**C. Positioning Algorithms**

*Proximity*

Positioning algorithms based on proximity consist in associating the user location to the location of a reference point. For instance, the most popular proximity algorithm is referred to Cell-ID in GSM networks. It calculates the user location as the location of the GSM base station to which the user is currently connected. Accuracy of these algorithms is function of the distance at which a reference point can be detected, which is typically between 100 meters and 10 kilometers for GSM networks.

*Trilateration*

Trilateration algorithms calculate the user location from a measure of the distance between the user and 3 or more reference points. This distance can be inferred from a measure of the signal strength or the time difference of arrival between signals coming from the three reference points. Accuracy of these algorithms is function of the distance at which reference points can be detected, the accuracy of the distance measurements, and the quality of the algorithm.

User location is calculated by solving equation system illustrated in fig. 2.

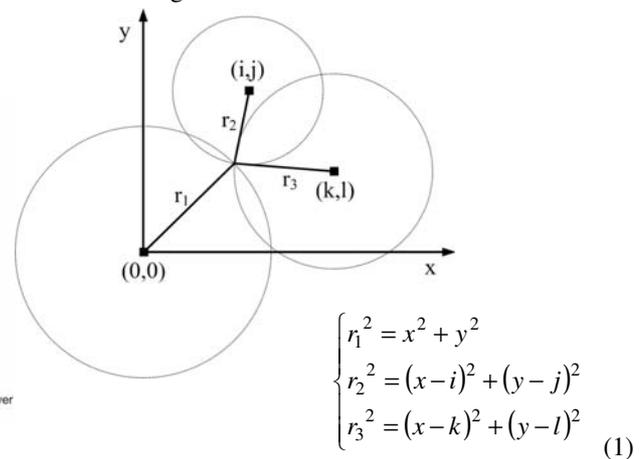


Figure 2. Trilateration algorithm

*Triangulation*

Triangulation differs from trilateration by relying on the measurements of angles instead of distances to infer the user location. As shown on fig. 3, the user location is calculated by measuring the signal angle of arrival from 2 or more reference points. Accuracy of these algorithms depends on the distance at which reference points can be detected, as well as the quality of the angle measurements and of the algorithm. The user location is calculated as the intersection of two lines, as represented in fig. 3.

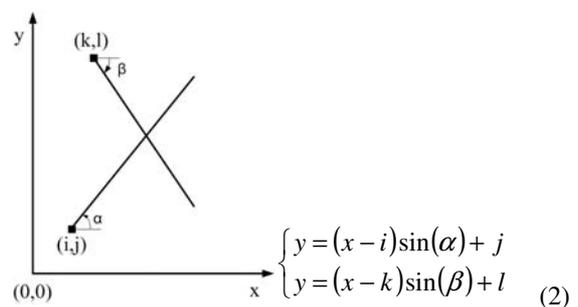


Figure 3. Triangulation algorithm

*Centroid*

Positioning algorithms of type centroid calculate the user location as a weighted average of the location of several reference points. A weight  $w_i$  is calculated for each detected reference point as a function of the received signal strength, the reference point coverage, or the reliability of the reference point. Each algorithm may calculate it in a different way. Then, the user location is calculated as a weighted average of the detected reference points' location  $(x_i, y_i)$ , as described in fig. 4.

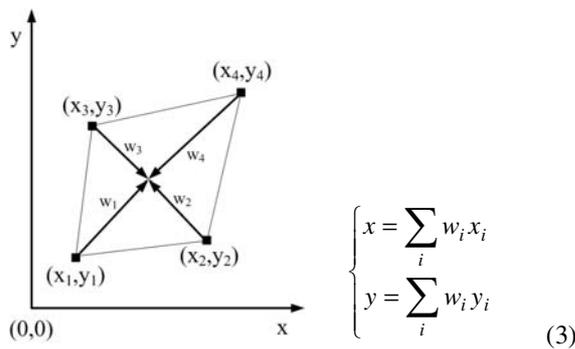


Figure 4. Centroid Algorithm

Accuracy of these algorithms depends on the number of reference points used, the distance at which these reference points are detected, as well as the number of information used to calculate the weight of each reference point. These algorithms have the advantage to be simple and to require minimal computational power, which make them especially suitable for mobile devices.

*Place Detection*

Place detection algorithms significantly differ from the other types of algorithms, as they do not calculate the user location as a coordinate from the detection of reference points of known location. Place detection algorithms determine the user location as a place recognized among a list of known places. These algorithms operate in two phases: place definition and place recognition.

During the place definition phase, a place detection algorithm creates a profile for each place to be recognized. A place profile contains a signature of the place, unique information that differentiates it from any other. This can be create from signal strength measurements, or simply contains the list of antennas identifiers detected from the place in question.

During the place recognition phase, radio measurements are recorded and compared to each place profile. The probability the user is located at each of these places is calculated, and the user is considered to be located at the place of highest probability.

These algorithms have the advantage not to require a large database of known reference points' location. However, they may also suffer from a lack of coverage, since they will only operate when the user located at one of the known places.

*D. Technologies**Global Positioning System (GPS)*

GPS is a global positioning system developed by department of defense of the United States of America [2]. A constellation of 24 satellites transmit signals containing their location as well as accurate timing information. A receiver is able to calculate its own location by measuring the time difference of arrival of the signals coming from at least 3 satellites. As receivers require a direct line of sight to the satellites, GPS does not operate indoors. It also operates with higher positioning errors in urban centers, due to multipath caused by signal reflection on large buildings. This is a serious drawback for social applications targeting end users, as it is indoors and in urban centers that users are spending most of their time. GPS coverage is typically available less than 10% of the time, during a day of a regular user [3]. Therefore GPS is inappropriate to develop social applications requiring to a positioning service in any place user may travel to. However, GPS global outdoor coverage has made it a success for navigation and fleet management applications.

GPS offers an excellent accuracy outdoors, which is typically inferior to 10 meters in more than 95% of the time [4], but it can easily reach 50 meters of inaccuracy in urban centers. Improvement systems such as DGPS and WAAS make use of terrestrial antennas and satellites to broadcast a correction signal to the receivers. WAAS receivers typically yield errors lower than 3 meters in more than 95% of the trials [4].

*Cellular network based positioning*

Wireless positioning based on cellular networks consists in using base stations as points of reference to locate the wireless terminals. There are numerous wireless positioning systems such as E-OTD (Enhanced-Observed Time Difference) for GSM [5], A-FLT (Advanced-Forward Link Trilateration) for CDMA 2000, which are using one or more base stations as point of references. Their accuracy ranges from 100 meters to 800 meters, depending on the base station density. This relatively low accuracy makes these systems inappropriate to navigation applications. However, the ubiquity of cellular networks in urban centers, make it a great solution for local search applications and interpersonal communication. The investment required to deploy the positioning systems, as well as the per request charge applied by network operators, have slowed down the adoption of location-aware applications. However, the Enhanced-911 rules adopted in the United States by the FCC, imposing 97% of emergency calls to be located within 50 to 300 meters, is helping to accelerate wireless positioning systems adoption.

*WLAN based positioning*

WLAN access points too can be used as points of reference to locate wireless terminals. Numerous positioning systems based on WLAN have been subject to research and even commercialization [6], [7], [8], [9],

[10], [11]. Most of these positioning systems are using trilateration or fingerprinting algorithms based on signal strength measurements. WLAN access points' short coverage enables these systems to be very accurate indoors, with mean errors between 1 and 20 meters depending on the algorithm used. This excellent accuracy coupled with WLAN infrastructure's low cost make WLAN based positioning an excellent solution for indoors enterprise applications such as asset and staff tracking.

WLAN positioning systems have also been developed for outdoor environments [3], [12], [13], [14]. Since the massive adoption of WLAN technology, access points have been deployed in enterprise, residences, coffee shops, and public places. In urban centers, several access points have overlapping coverage at any given place, thus enabling a continuous positioning service in these urban areas. However, this coverage rapidly disappears as the population density lowers, such as in rural areas. In order to use WLAN positioning outdoors, the location of detected access points has to be known. Obtaining the location of all access points in a city is a complicated, time consuming process, which requires driving in each and every street to detect and infer access points' location.

TABLE I.  
LOCATION-AWARE APPLICATIONS REQUIREMENTS

Applications	Required coverage	Required accuracy	Adequate positioning system
Navigation	Outdoor	~20m	GPS
Fleet Management	Outdoor	~10m	GPS
Inventory and staff tracking	Indoor	~5m	WLAN, RFID
Interpersonal communication	Indoor, outdoor	~25m	-
Local Search	Indoor, outdoor	< 100m	GSM
Gaming	Indoor, Outdoor	~30m	-
Virtual Tours	Outdoor	~30m	GPS
Local interaction	Indoor	~10m	-
Local advertising	Indoor, outdoor	~50m	-

*E. Applications*

A synthesis of existing location-aware applications, as well as their requirements in terms of positioning accuracy and coverage, is presented in Table I.

As it appears, most professional applications can be achieved by existing positioning systems. However, lots of end consumer applications cannot be built on existing positioning systems. They require an ubiquitous coverage, both indoors and outdoors, which cannot be provided with the required accuracy by existing positioning systems.

*F. Hybrid Positioning Technologies*

The principle behind hybrid positioning is to recognize that there is no single positioning technology able to accurately locate users indoors as well as outdoors. However, existing technologies are complementary, and can be combined to meet these objectives. For instance, GPS operates very accurately outdoors but does not indoors, while WLAN based positioning is accurate indoors, but lack of coverage outdoors. A hybrid positioning system combining these two technologies could then offer coverage both outdoors, using GPS, and outdoors, using WLAN.

This approach appears ideal to meet requirements of end-user applications requiring a positioning service in any place users may travel to.

To go even further, an ideal positioning system should provide the following specifications:

- Ubiquitous coverage
- Outdoor accuracy
- Indoor accuracy
- Use existing infrastructure
- Minimal configuration

Our objective is to create a hybrid positioning system combining existing technology which is going to meet these requirements.

III. EXPERIMENTAL EVALUATION OF POSITIONING TECHNOLOGIES AND ASSOCIATED ALGORITHMS

As presented in the previous section, there is no positioning technology able to offer an accurate positioning in any place users are traveling to. However, existing technologies seem to be complementary in term of coverage and accuracy. For instance, GPS operates accurately outdoors but is out of coverage indoors, while WLAN is accurate indoors, but lack of coverage outdoors. Therefore, it seems intuitive that combining technologies can lead to a ubiquitous positioning system.

In order to validate this statement a coverage and accuracy survey of four existing technologies – namely GPS, GSM, WLAN, and Bluetooth – have been conducted in different environments. The obtained results have revealed the most complementary technologies, which would be best combined together.

*A. Methodology*

*Experimental setup*

Experimental data are recorded using a laptop computer, equipped with WLAN and Bluetooth adapters, and connected to a GPS and a GSM phone. Fig. 5 illustrates the experimental setup. An application, developed for the experiment, records wireless measurements for each technology in a separate trace file.

The application records every second the GPS location, the number of GPS satellites, the identity and signal

strength of detected WLAN access points, the identity and signal strength of detected GSM base stations, and the identity and type of detected Bluetooth devices. Bluetooth scanning being significantly slower, it was only completed at a rate of one scan every 15 seconds.

#### Procedure

Outdoors, the equipment is placed in a car, which is driven as slowly as possible across the different experimental environments. Traces are recorded twice in each environment. The first trace is used to learn where the detected WLAN access points and GSM base stations are located in order to create a database of known wireless reference points. The second trace is used to compute the user location, and estimate coverage and accuracy for each technology.

Coverage is calculated as the percentage of samples for which a valid location could be calculated. Accuracy is calculated as the distance measured between the estimated location and the one obtained using GPS.

Indoors, the equipment is placed on a tray and is moved at walking speed. As GPS is not available indoors, it could not be used as a reference to estimate accuracy of the other technologies. Therefore, accuracy has not been measured indoors, and a single trace has been recorded in every environment. Coverage has been measured as the percentage of samples for which a wireless reference point has been detected.

#### Environments

Outdoors, accuracy and coverage have been measured in 5 distinct environments of varying population density: downtown, residential, suburban, countryside, and highways. Indoors, coverage has been measured in different types of building including campus, libraries, shopping centers, offices, transportation hub. A total of 5 hours of measurements have been recorded.

#### B. Algorithms

Unlike GPS, wireless interfaces for WLAN, GSM, and Bluetooth do not directly compute the user location. These interfaces only reveal the identity and signal strength of nearby wireless beacons. Therefore, a positioning algorithm has to be developed to calculate the user location from the measured information.

An algorithm of type centroid has been developed and used for WLAN, GSM, and Bluetooth. This algorithm requires the location of the detected wireless reference points in order to operate. So our first step is to develop an algorithm to create a database containing the location of these reference points.

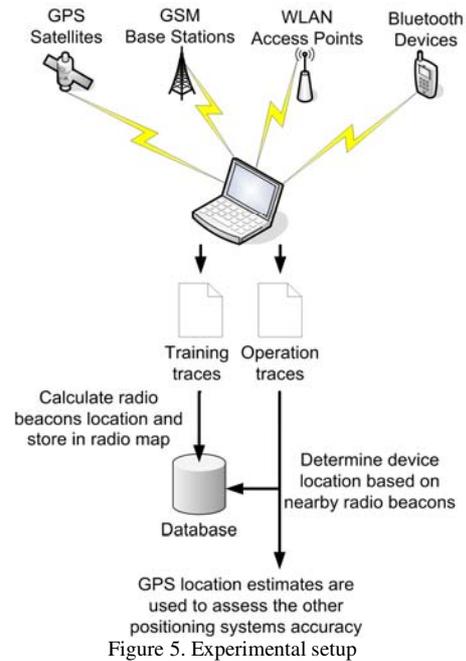


Figure 5. Experimental setup

#### Building the database of known reference points

The first phase is to discover the location of reference points – namely WLAN access points, GSM base stations, and Bluetooth devices – present in our experimental environments. In order to do it, an automatic algorithm that calculates reference points' location from a detection trace and associated GPS locations has been deployed. For the sake of simplicity, the algorithm is presented for the particular case of locating WLAN access points, but it is also applied to GSM base stations and Bluetooth devices.

As the car carrying the experimental equipment is driving on a street, it is going to detect a WLAN access points several times, as illustrated on fig. 6.

Each time this access point is detected, the signal strength is recorded along to the current GPS location. The access point is then supposed to be located where it has been detected with the strongest received signal strength. So the access point location is not based on a single GPS location, a mean of the GPS locations recorded for the 10% strongest signal strength is used. The estimated location of this access point is then recorded in a database along to the access point identity, its estimated coverage, its maximum measured signal strength, and its total number of detection. The estimated coverage is calculated as the distance between the estimated access point location and the location of the detection the furthest away.

This process is used to locate WLAN access points, GSM base stations, and Bluetooth devices using the trace recorded in each experimental environment.

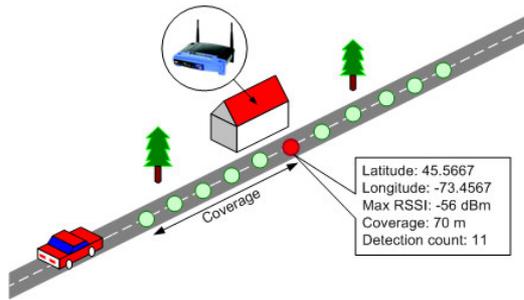


Figure 6. Discovery of a WLAN access point.

*Calculating the user location*

Once the wireless reference points have been located, using our first trace, the user location can be calculated for each technology, using the second trace.

An algorithm of type centroid is used to calculate the user location, as a weighted mean of the location of detected wireless reference points, as illustrated on fig. 7. Our algorithm calculates the weight given to a reference points as a function of its received signal strength, its coverage, and its total number of detection.

This generic algorithm is detailed below for the particular case of calculating the user location using WLAN, but it is used similarly for GSM and Bluetooth.



Figure 7. Centroid Algorithm

Let's suppose the user terminal detects  $M$  WLAN access points, among which only  $N$  have known location. Let  $x_i$  and  $y_i$  be the latitude and longitude of access point  $i$ , belonging to  $[1, N]$  and let  $w_i$  be the weight associated to it. Then the user location is calculated as:

$$X = \sum_{i=1}^{i=N} w_i x_i \quad ; \quad Y = \sum_{i=1}^{i=N} w_i y_i \quad (4)$$

The weight  $w_i$  of an access point is calculated as a function of an estimation of the distance  $d_i$  separating the access point and the user, an estimation of the coverage  $c_i$  of the access point, and an estimation of the access point reliability  $f_i$ , as represented by the following expression:

$$w_i = \frac{f_i}{d_i \cdot c_i} \quad (5)$$

The variable  $d_i$  is an estimation of the distance between the access point  $i$  and the user. This distance is calculated using the expression

$$d_i = d_0 \times 10^{\frac{p_{iMAX} - p_i}{10 \cdot \sigma}} \quad (6)$$

where  $p_i$  is the signal strength of access point  $i$  measured by the user terminal, and  $p_{iMAX}$  is the maximum signal strength of access point  $i$ , as stored in the database of known access points. Variable  $d_0$  is chosen to be equal to 5m and  $\sigma$  to be equal to 2. The greater is the difference between the measured signal strength  $p_i$  and its known maximum  $p_{iMAX}$ , the longer is the distance  $d_i$  between the user and the access point  $i$ . The higher is the distance  $d_i$ , the lower is the weight  $w_i$  associated to the access point  $i$ .

The variable  $c_i$  is an estimation of access point  $i$  coverage, as it is stored in the database of known access points. Coverage is significant information, since the smaller it is, the smaller the uncertainty of the user location is. Therefore, the smaller the coverage of access point  $i$  is, the greater the weight  $w_i$  associated to it is.

Finally, the variable  $f_i$  is an estimation of the reliability of the data related to access point  $i$  stored in the database of known access points. The location, maximum received signal strength, and coverage of access points  $i$  are not exact values. They have been empirically measured during the discovery phase, and thus may be largely erroneous for some access points. The variable  $f_i$  is used to diminish the weight of access points with such unreliable data. An access point is considered to have reliable data if it has been detected a sufficient number of times during the discovery phase. For instance, an access point detected a single time during the discovery phase must have an estimated location and coverage largely erroneous. The variable  $f_i$  is given the value of the following expression:

$$f_i = \max(\text{detection}_i, f_{\max}) \quad (7)$$

where  $\text{detection}_i$  is the total number of detection of access point  $i$  during the discovery phase, and  $f_{\max}$  is a threshold set to 20, above which all access points are judged to be equally reliable. This expression has the effect to lower the weight with data inferred from less than 20 detections during the training phase.

*C. Results*

*GPS*

As ground truth was not used during the experiment, GPS accuracy could not be determined. The fidelity of the measurements has been calculated instead, as the mean distance between the two traces of GPS measurements for each environment.

Results of Table II confirm that GPS is an excellent outdoor positioning system, as it offers a complete outdoor coverage as well as an excellent accuracy. Even downtown, where large buildings are causing multipath, valid location could be obtained at any time. However, positioning was not as accurate as in other environments, and the error was higher than 50m in certain streets, as shown in fig. 8.



Figure 8. GPS positioning error in dense urban environment

Indoors, satellites signals have only been detected for 7% of the measurements and have never been strong enough to compute a valid location.

### GSM

Accuracy has been measured with GSM by using two different algorithms. The first is trivial and associate the user location to the location of the cell tower it is currently connected to. The second algorithm is the centroid algorithm presented above, which make use of several cell towers in the user vicinity. GSM is the only technology to offer a ubiquitous coverage in all considered environments. However, the obtained accuracy is much lower than other technologies, with a mean error between 150 and 900 meters. Accuracy is mainly dependent on the base station density. Using several nearby cell towers instead of one yields an increase in accuracy between 20% and 30%, which does not change the scale of the results.

TABLE II. ACCURACY AND COVERAGE OF WIRELESS POSITIONING BASED ON GPS, GSM, WLAN, AND BLUETOOTH.

	Indoor	Outdoors				
		Downtown	Residential	Suburban	Countryside	Highways
GPS	0% -	100% 27m	100% 3m	100% 2m	100% 5m	100% 5m
GSM Cell-ID	100% same as outdoors	100% 219m	100% 384m	100% 438m	100% 941m	100% 704m
GSM Centroid	100% ~5m <sup>a</sup>	100% 177m	100% 301m	100% 318m	100% 680m	100% 572m
WLAN	98% ~5m <sup>a</sup>	100% 26m	100% 27m	92% 45m	46% 77m	73% 155m
Bluetooth	31% ~2m <sup>a</sup>	0% -	0% -	0% -	0% -	0% -

<sup>a</sup> accuracy has not been measured indoors. These values are given as examples of what has been obtained by previous research projects [15], [16], [17], [18].

### WLAN

Results obtained for WLAN shows that it is a good positioning technique in urban areas, as accuracy is below 50m and coverage is almost complete.

Buffering is an important factor in the coverage measurements. A typical WLAN adapter is listening for the presence of access points – beacon frames – during a short time interval on each channel, usually between 50 and 120 ms. As beacon frames are sent periodically, usually every 100ms, there is a high probability the WLAN adapter will not be listening to the right channel when the beacon frame will be transmitted. Consequently, a WLAN adapter will not detect all surrounding access points in a single scan. Buffering the results of several scans is necessary to obtain a complete list of these access points. Using a sliding buffer of several scans has for consequence to increase the number of access points detected, and therefore to increase the coverage of the wireless positioning system.

This buffering technique significantly improves the coverage measured in the experimental environments.

### Bluetooth

The obtained results show there is not enough Bluetooth devices in the environment to provide a significant coverage for a positioning system. No Bluetooth devices have been detected outdoors. Indoors, Bluetooth devices have been detected for only 31% of the scans. Furthermore, around 90% of these Bluetooth devices were mobile devices that can not be used as a reference point for positioning. Therefore, there are not enough static Bluetooth devices in the environment that could be used to develop a wireless positioning system.

### C) Toward an ubiquitous positioning system

According to the results in Table II, it appears that none of the considered technology is able to offer an accurate and ubiquitous positioning service by itself. However, GPS and WLAN provide complementary coverage – GPS is excellent outdoors while WLAN operates best indoors and in urban centers – and could therefore be combined to create a ubiquitous positioning system. This is the approach of our “Always Best Located” positioning system.

## IV. OUR APPROACH

Our approach is to create a hybrid positioning system combining GPS and WLAN to offer an accurate and continuous positioning service in any place user may travel to. Three different positioning methods have been developed on top of these two technologies and have been integrated into a sophisticated switching mechanism to locate the user with the most accurate method available.

### A. The “Always Best Located” (ABL) prototype

“Always Best Connected” is a popular concept in new generation networks consisting in a mobile terminal’s

ability to automatically select the best connection available to communicate. For instance, a multi-mode terminal is able to automatically switch between UMTS to WLAN to offer the fastest connection available. By analogy, the term “Always Best Located” (ABL) have been defined as the ability to automatically select the best positioning method available. This is the ability we have integrated into our prototype, called ABL, to automatically switch between three positioning methods: place detection, GPS positioning, and WLAN positioning, to offer the best accuracy and the broadest coverage.

Place detection, which is used by default, makes use of WLAN to recognize the place at which the user is currently located among a list of user defined places. This positioning method is very accurate, and can be used to distinguish the room in which the user is currently located. Users are required to create a profile for each place to be recognized. Therefore, place detection is only used in familiar places, such as home, work, and anywhere users are spending a significant amount of time.

If the user is currently not located at a known place, the prototype automatically switches to GPS positioning, which is used to provide excellent accuracy and coverage outdoors.

If GPS coverage is unavailable, WLAN positioning is used. This positioning method is relying on the centroid algorithm presented in the previous section to calculate the absolute user location. Selected as a last resort, WLAN positioning is used in any area deprived of GPS coverage and user defined places.

Each of these positioning methods is summarized in Table III, and the switching mechanism integrating them together is illustrated in fig. 9.

Detailed operation of the place detection and WLAN positioning methods are presented in the following section. The final section of the paper emphasizes the ABL prototype and an experiment to validate its coverage in real situations.

TABLE III.  
POSITIONING METHODS OF THE ABL PROTOTYPE

	Place detection	GPS positioning	WLAN positioning
Algorithm	Histogram model	None	Centroid
Positioning type	Symbolic	Absolute	Absolute
Accuracy	~ room level	~ 5m	~ 30m
Environments	Familiar places, e.g., home, work	Outdoors	Anywhere else

V. INDOOR POSITIONING AND PLACE DETECTION

Place detection is the main positioning method of our prototype. It is used to distinguish the place, or room, in which the user is location among a list of user defined places. As numerous place detection algorithms have already been subject to intensive research [7], [8], [19], [20], it was decided to implement some of them and compare their accuracy in a real situation in order to

select the most accurate algorithm. The first part of this section presents the analytical foundation of these algorithms, and the second one presents the comparative accuracy experimentation.

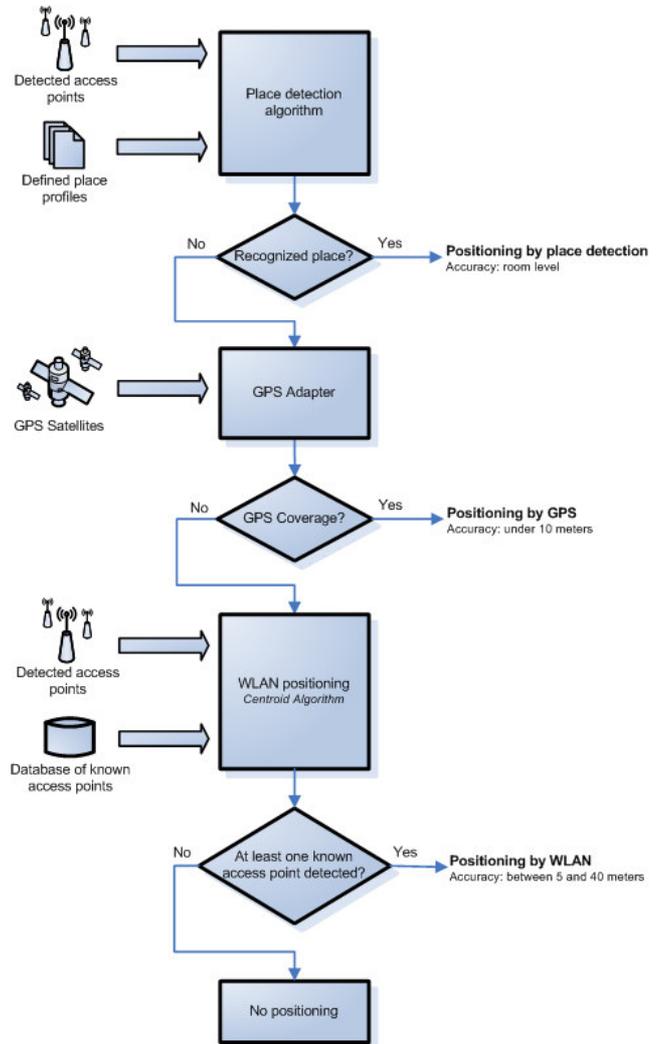


Figure 9. Operation of the Always Best Located prototype.

A. Place detection algorithms

Algorithms presented in this section have already been presented [30] and only the minimum essential to understand our paper is presented here. The three different algorithms compared in our experiment are variants of a generic place detection algorithm, which operates in two phases: place definition, and place recognition.

The first phase, place recognition, consists in defining a profile for each place to be recognized. This profile contains a mathematical of the received signal strength of each access point  $i$  detected at the current place. This model is represented by the following expression,

$$f_{l,i}(x) \tag{8}$$

where,  $f_{l,i}(x)$  returns the probability an access point  $i$  is measured with signal strength  $x$  at the place  $l$ . The profile of a place  $l$  is the set of models obtained each access point detected.

The second phase, place recognition, consists in recognizing the place in which the user is located among the list of defined places. The algorithm compares the current WLAN measurements to the place profiles to calculate the probability the user is located in each place  $l$ , and assumes he is located in the place of highest probability. In order to do it, the probability  $P(L|O)$  is calculated, where  $L$  is the event corresponding to the user presence in place  $l$ , and  $O$  is the event corresponding to the current WLAN measurements.  $P(L|O)$  is calculated using the following expression,

$$P(L|O) = \frac{P(O|L)}{P(O)} \quad (9)$$

As  $P(O)$  is constant for any place  $l$ , it is dismissed. Only  $P(O|L)$  is calculated, which is the probability of obtaining the current WLAN measurements at the place  $l$ . The event  $O$ , which is represent the current WLAN measurements, is defined as the vector  $\langle o_1, o_2, o_3, \dots, o_b, \dots, o_M \rangle$  where  $o_i$  is the signal strength measured for access point  $i$ . Then,  $P(O|L)$  is calculated by the following expression,

$$P(O|L) = \prod_{i=1}^{M'} f_{l,i}(o_i) \quad (10)$$

which is equivalent to calculate the product of the probability of measuring each access point  $i$  with signal strength  $o_i$  at place  $l$ .  $P(O|L)$  is calculated for every place  $l$ , and the user is assumed to be located in the place of highest probability.

Three variants of this algorithm, each differing by the function  $f_{l,i}(x)$  used to model the access points' signal strength distribution have been implemented. The three variants respectively use a Gaussian model, a histogram model, and a Kernel model. The mathematical details can be found in [8].

## B. Experimentation

### Method

The objective of this experiment is to compare the accuracy of the three algorithm variants in order to select the most accurate one to be integrated into our positioning prototype. This experience has been conducted in the office of the International Institute of Telecommunications (IIT), which are composed of small offices, a few large meeting rooms, and 5 WLAN access points, which have not been moved or added for this experiment.

A total of 18 places have been defined for the experiment. For each place, 400 samples of the access points signal strength have been recorded, and used to create the place model for each variant of the algorithm.

Once the places have been defined, a mobile terminal is moved from a place to another and its location is calculated using each of the algorithms variant. The mobile terminal is recording nearby WLAN access points signal strength, and calculates it own location using the three algorithms. The place recognized by each algorithm

is compared to the actual user location, and the accuracy of an algorithm is calculated as the percentage of trials leading to successful place recognition. The mobile terminal is moved across the office space and remains immobile at least one minute in each of the 18 places defined. The samples recorded while the mobile terminal was moving in between two defined places are dismissed.

### Results

As illustrated in Table IV, the obtained results show that the algorithm relying on a histogram model of the access points' signal strength distribution yields the best accuracy, by recognizing the correct place in 87% of the trials. Therefore, this algorithm has been selected to implement the place detection component of our prototype.

The measured accuracy is lower than what was reported in existing publications [7], where 95% of successful place recognition has been obtained. However, this difference can be explained by the number of access points present in the environment. For instance, [7] have used more than 30 access points, while only 5 access points have been used in this experiment. As our positioning system is targeting end users, it is also highly probable they will not have to define as many places as we did. Indeed, users will certainly only define places where their activities are the most intense. Consequently, the obtained accuracy will rise as the number of place is reduced.

TABLE IV. ACCURACY OF EACH PLACE DETECTION ALGORITHM

Algorithm variant	Accuracy
Gaussian Model	74%
Histogram Model	87%
Kernel Model	80%

## VI. WLAN POSITIONING

WLAN positioning is used to calculate the absolute user location, latitude and longitude, when the user is in an area deprived of GPS coverage and of user defined places. This positioning method uses the signal strength of nearby access points to calculate the user location using the centroid algorithm presented in section III.

The location of detected access points has to be known so this algorithm can be used. Usually, the location of these access points has to be manually discovered by driving in each and every street. In order to avoid this time intensive phase, automatic discovery algorithms have been designed, enabling the mobile terminal to build its own database of known access points. These discovery algorithms are executed in parallel to the positioning operations, so the newly discovered access points are fed into the database and can be immediately used by positioning algorithms. Two algorithms have been designed. The first algorithm is relying on GPS to infer nearby access points location, while the second algorithm is able to operate independently to discover access points' location in GPS deprived areas such as inside buildings.

A. Discovery Algorithms

Discovery with GPS

Discovery with GPS is performed using an ordinary algorithm, such as the one presented in section III. This algorithm periodically scans for nearby access point. Every time an access point is detected its signal strength is measured and associated to the current GPS location. An access point is then assumed to be located where it has been detected with the strongest signal strength, as illustrated in fig. 6.

This algorithm operates very well and enable simple discovery of access points where GPS coverage is available. However, when GPS is out of coverage, a new algorithm has to be used.

Discovery without GPS

Discovery without GPS is performed using a newly designed algorithm operating in three stages: creation of a meshed network of proximity links, calculation of the shortest path, and calculation of the access points' location.

Stage 1 consists in creating a meshed network of proximity links, which represent the topology of WLAN access points in the environment. In this stage, the algorithm periodically scans for nearby access points. If two access points are detected simultaneously, or at a small time interval, a proximity link is created between each of them. A proximity link is just virtual information meaning that two WLAN access points are close to each other. Indeed, if two access points are detected simultaneously, it means their coverage overlaps and therefore they are located at a close distance from each other.

In addition, each proximity link is given a cost which represents an estimation of the distance separating the two access points. This cost  $c$  is calculated as the sum of distance  $d_1$ , in between the user and access point 1, and distance  $d_2$ , in between the user and access point 2, as in the following expression,

$$c = d_1 + d_2 = d_0 \cdot 10^{\left(\frac{P_0 - P_1}{10\mu}\right)} + d_0 \cdot 10^{\left(\frac{P_0 - P_2}{10\mu}\right)} \quad (11)$$

$P_1$  and  $P_2$  are the measured signal strength of access point 1 and 2. The other variables have been empirically chosen so that do is equal to 0.3m,  $P_0$  is equal to -20 dBm, and  $\mu$  is equal to 3. For instance, if two access points are simultaneously detected with received signal strength -60 dBm and -80 dBm, the cost of the proximity link created in-between them is equal to the sum of distance  $d_1$ , 6.5m, and distance  $d_2$ , 30m, which adds up to 36.5m. Every time these two access points are detected simultaneously the cost is calculated, and only its minimal value is recorded.

Of course, the cost is not an accurate estimation of the distance separating the two access points, as the presence of concrete walls or metal objects may alter the received signal strength even over a short distance.

Some of these access points have a known location, obtained using the discovery algorithm with GPS, while others have an unknown location, as they have only been detected out of GPS coverage. These links connected access points of known location to access points of unknown location are systematically created as users travel in and out of the GPS coverage. In fine, the discovery algorithm without GPS has created a meshed network of access points covering the area out of GPS coverage, such as illustrated in fig. 10. The following stages of the algorithm consist in using this meshed network to infer the location of unknown access points.

Stage 2 consists in calculating for each access point of unknown location the shortest path to the access points of known location, as illustrated in fig. 11. The cost of the shortest path is also calculated, therefore providing a notion of the distance between the access point of unknown location, and the surrounding access points of known location. Shortest paths are calculated using Dijkstra [21]. Overall, this stage consists in finding for each access point of unknown location the reference points that will be used to infer its location.

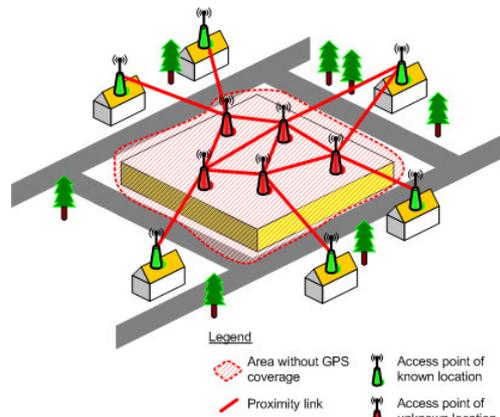


Figure 10. Stage 1: creation of a meshed network of access points.

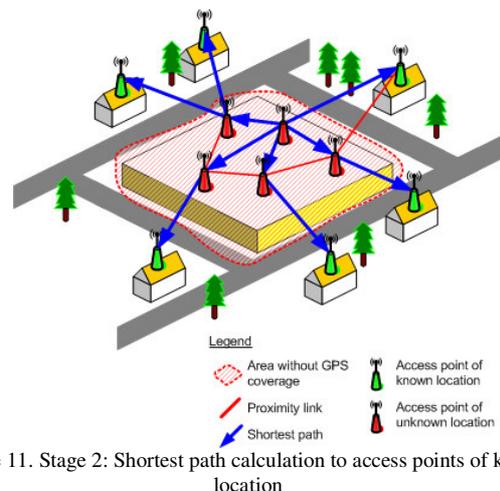


Figure 11. Stage 2: Shortest path calculation to access points of known location

Stage 3 consists in calculating the location of access points of unknown location by using the information obtained at stage 2. A positioning algorithm of type centroid is used to infer the location of each unknown

access point as the weighted average of the location of known access points linked to it. The weight given to each access point of known location is equal to the cost of the shortest path to that access point, as calculated at stage 2.

This algorithm enables our discovery process to automatically infer the location of nearby access points even in areas out of GPS coverage. The discovered access points and their estimated location are stored in a database, which is later used by our WLAN positioning algorithm to locate the user when GPS is unavailable.

**B. In situ experiment**

The objective of this experiment is to assess the quality of our discovery algorithms by comparing the accuracy of WLAN positioning when it is based on a database built using discovery either with GPS or without GPS.

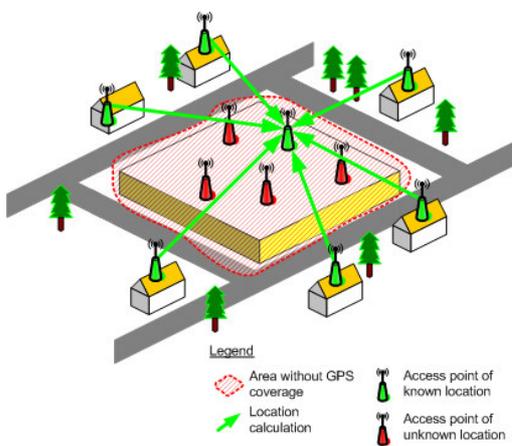


Figure 12. Stage 3: Calculation of unknown access points' location.

The experimental district is a residential area of medium population density, of approximately 1 km<sup>2</sup> area, which is illustrated in fig. 13.

In order to do it a test environment in the city of Montreal has been selected. All access points have been discovered using the two different algorithms, with and without GPS, and have been stored the discovered access points in two separate databases. For the discovery algorithm without GPS, a complete meshed network of access points have been created by walking in each street three times, so their location have been inferred with the best accuracy. As this algorithm requires knowledge of a few access points location to infer the location of the others, a set of known access points located on the border of the experimental district has been used as input.

Once the databases have been created, a mobile terminal has been moved across the experimental district, and its location has been calculated by GPS, and WLAN using each of the two databases. Ground truth from digital map from Navteq has been used as a reference to calculate the accuracy of the three positioning technique.

The obtained results, presented in Table V, confirm GPS excellent accuracy, with a positioning error inferior than 7m for 95% of the samples. WLAN positioning has yield an excellent accuracy when it has been using the

database of access points located using the discovery algorithm relying on GPS. When the database created by our new discovery algorithm without GPS has been used, the positioning error has approximately doubled.



Figure 13. The experimental district.

TABLE V. POSITIONING ACCURACY OF GPS AND WLAN BASED ON DISCOVERY WITH AND WITHOUT GPS.

Positioning method	Positioning error	
	Average	95th percentile
GPS	3.7m	7.2m
WLAN discovery with GPS	8.5m	22.1m
WLAN discovery without GPS	16.4m	38.7m

**C. Indoor – Outdoors transitions**

Our prototype has then been tested in real situations in downtown Montréal. Transitions from indoors and outdoors environments has been examined to validate the continuity of the positioning service.

Our first remark was the proper operation of the discovery algorithms. Discovery with GPS is reliable outdoors, and just one or two passages across a building are enough to discover the location of indoor access points.

As a result, WLAN positioning can be used as a relay to GPS in areas where it is unavailable, in order to offer a continuous positioning service. For instance, the prototype will automatically switch to WLAN positioning as a user enters a building, and switch back to GPS once coverage is recovered, as illustrated in fig. 14.

Outdoor to indoor transitions occur when GPS coverage is lost as a user step into a building. As soon as that happens, the prototype automatically switches to WLAN positioning. This technology transition is completed in less than a second, therefore providing an uninterrupted service. However, accuracy drops as soon as WLAN is used, especially in the first seconds after the transition. This may occur as access points from nearby buildings are still detected when the user step in a building. In order to make transitions smoother, the last GPS location can be repeated for a few seconds to let time to the user to walk deeper into the building so that access points from

surrounding buildings do not interfere in the location calculation.

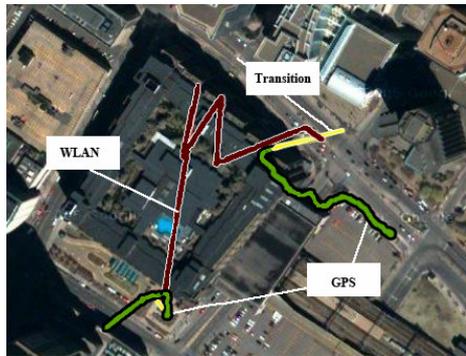


Figure 14. WLAN and GPS transitions as a user walks across a building.

Indoor to outdoor transitions happens when GPS coverage is recovered. These transitions occur a few seconds after the user step out of a building, as delay of approximately 10 seconds is required to acquire a satellite fix. Awhile, WLAN positioning is used.

Finally, a field test has been completed in Montreal’s underground city – a kilometer long series of underground tunnels connecting offices and shopping centers in the downtown core. There, the ability of our prototype to discover WLAN access points’ location over a large distance in order to provide a continuous positioning service could be validated. For the first part of the field test, the user was walking outdoors, then entered in an underground tunnel, and kept going for a distance of approximately 1km.

The user location could be calculated almost all the way – during 87% of the time to be exact – except in a few tunnels of the underground city where WLAN access points could not be detected.

The database of access points used for this experiment was created by walking outdoors on the main streets parallel to the underground city, and then by passing twice inside the tunnels. This has shown that just a few passages are necessary to create a dense database of access points, even over large indoor distances, and offer a continuous, yet fairly accurate positioning.

## VII. THE ABL PROTOTYPE

The ABL prototype is integrating the three positioning methods, namely place detection, GPS, and WLAN positioning, into a switching mechanism, as previously described on fig. 9. The prototype should be able to keep track of the user location indoors as well as outdoors to offer a ubiquitous service with the best accuracy available. Our objective is to validate this claim by conducting a coverage survey in real situations. In order to do it, our prototype has been carried by three participants for the duration of a week, and detailed coverage statistics have been recorded for each positioning method supported by the prototype and are presented in this section.

### A. Experiment

The objective of the experiment is to measure the coverage offered by the ABL prototype during users’ every day activities. In order to do it, the prototype has been given to 3 participants for the duration of a week. The prototype had to be kept on during the entire week to record every second the user location with the three different positioning methods and their combination. The coverage of each positioning methods and their combination into the ABL prototype have been calculated from these measures.

A total of more than 600,000 samples have been recorded in a week for each participant. The coverage of a positioning method is calculated as the percentage of samples containing a valid location. As samples are recorded every second, the measured coverage represents the time percentage during which a positioning method was available.

Initially, the prototype had an empty database of known access points. Access points had to be discovered as users were moving in their daily activities. In addition, no place had been defined. Participants were asked to define at least two places, one at home and at work.

Participants 1 and 2 have a similar profile. They both live in a house in suburban area and use their car to commute to work in downtown Montreal. They are back home early and do not leave home afterward. Participant 3 lives in a small residential building in a district of medium density. He walks 30 minutes and takes the subway for 1 hour to commute to work in downtown.

The ABL prototype has been developed as an application for Pocket PC, using Microsoft Visual Studio 2005, and .NET Compact Framework. It has been deployed on HP Ipaq hw6945 terminals which integrate both GPS and WLAN.

### B. Results

Results of Table VI show the coverage measured for each positioning method and for their combination into the ABL prototype.

Place detection has yield approximately 90% coverage for every participant. As all participants has only defined two places, home and work, this simply means that they spent approximately 90% of their time either at home or at work. This result also shows that it is crucial for a positioning system to operate properly in these two places, as it is where users will spent the vast majority of their time.

GPS coverage reaches 40% for the two first participants but is only 6% for the third. These low results confirm that GPS, alone, is not adapted to end user applications, as it is not available in place users spend most of their time. It is exactly what has been observed for participant 3, as GPS was out of coverage both home and at work, and was only available during short outdoor commutes. Comparatively, the first two participants have obtained much higher results, only because they have obtained a sporadic GPS coverage while at home as they placed the terminal at proximity of a window.

WLAN positioning coverage is measured to approximately 80%, which confirms that access points are sufficiently numerous to offer a vast coverage.

The ABL prototype, combining the three positioning methods, yields approximately 95% coverage for all participants. 97% coverage is even reached for participants 1 and 2. The 3% during which a location could not be calculated only represents a time period of 45 minutes in a day. So the ABL prototype was able to successfully locate participants 1 and 2 during 23 hours and 15 minutes per day. Results obtained for participants 3 are slightly lower, with coverage of 94%, representing a period of 1 hour and 30 minutes a day without coverage. That could have been expected as participant 3 commutes to work by subway for approximately 45 minutes a day, a period during which no wireless signals can be received.

TABLE VI. MEASURED COVERAGE FOR EACH POSITIONING METHOD AND THEIR COMBINATION.

Positioning method	Participant 1	Participant 2	Participant 3
Place detection	91%	93%	88%
GPS positioning	37%	45%	6%
WLAN positioning	91%	87%	88%
ABL positioning	97%	97%	94%

Results of Table VII present the role that each positioning method plays in the coverage obtained by the ABL prototype.

Place detection represents 90% of the prototype's coverage, and is therefore a crucial component. The combination of GPS enables to grow the coverage of 4%. Even though this result may seem small, it represents an hour a day of additional service, covering users' outdoor trips. Finally, WLAN positioning adds an additional 1% to the prototype's coverage, which represents 15 minutes of service per day.

TABLE VII. COVERAGE COMPOSITION OF THE ABL PROTOTYPE.

Coverage composition	Participant 1	Participant 2	Participant 3
Total ABL	97%	97%	94%
% obtained by Place detection	91%	93%	88%
% obtained by GPS	4%	3%	5%
% obtained by WLAN positioning	2%	1%	1%

## VIII. CONCLUSION

Our research objective was to conceive a wireless positioning system able to meet end user applications requirements of ubiquitous coverage, outdoors and indoors accuracy, use of existing infrastructure, and absence of configuration.

Our approach was to develop a hybrid positioning system combining existing technologies to accurately operate in any place users may travel to.

An in situ coverage and accuracy survey of the four main wireless technologies, namely GPS, GSM, WLAN,

and Bluetooth, has been conducted to select the most complementary technologies. The results obtained in numerous environments of the city of Montreal have shown that GPS and WLAN offer complementary coverage, the first operating at best outdoors and the second indoors and in urban centers.

Then, a hybrid positioning system on top of these two technologies has been built, by developing an algorithm capable of switching to the most accurate positioning method depending on the circumstances.

Our first positioning method used WLAN access points and existing place detection algorithms to recognize the room in which the user is currently located. If no room could be recognized, GPS was used as our second positioning method. WLAN positioning, the last positioning method, was used when GPS was unavailable, in areas such as unfamiliar buildings. Discovery algorithms have been developed to automatically locate WLAN access points as users go, so they can later be positioned.

Finally, all of these positioning methods have been integrated into one positioning system, which have been carried by 3 participants for the duration of a week. This experiment has shown that our hybrid positioning system is able to keep track of the user location during 95% of the time, or 22 hours and 45 minutes a day.

This positioning system constitute another step toward the creation of truly pervasive positioning services, by offering nearly ubiquitous coverage, excellent accuracy outdoors using GPS, room level accuracy indoors, and the use of an existing infrastructure.

New research projects could lead to improvements of the current positioning system by allowing the combination of any radio interface such GPS, GSM, WLAN, Bluetooth, or RFID, and developing a flexible framework so the positioning system could be deployed on any terminal and use the best positioning method available at any time. Power consumption could also greatly be improved by designing new algorithms using a sample interval of a few minutes instead of a second.

Finally, the ability to locate a user in any place he may travel to open new perspectives of research, especially in presence and context awareness. By relying on an accurate position of the user at any time and any place, new applications could be develop to infer the user activities, surrounding environments, habits, and intentions, in order to better serve him.

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**Lionel Reyero** was born in France in 1982. He has received a M.Sc. in telecommunications from INRS-Telecommunications, in Montreal, Quebec, Canada in 2007 and a M.Sc. in telecommunications from National Institute of Applied Sciences, in Lyon, France in 2005.

Since 2007, he is a Software Consultant for Summit-Tech Communications Inc., in Montréal, Quebec, Canada. Previously, he has worked as Researcher at the International Institute of Telecommunications.

Mr. Reyero is a member of the Order of Engineers of the Province of Quebec and a member of the IEEE. He was awarded a Grant of Excellence from the International Institute of Telecommunications in 2006.



**Gilles-Y. Delisle** is currently Director, Technology Integration Centre at Technopôle Defense and Security in Valcartier, Québec, Canada. From June 2004 to March 2008, he was Vice-President Research at the International Institute of Telecommunications in Montréal, Canada. Previously, he was Director and Professor at the School of Information Technology and Engineering at the University of Ottawa from 2002 to 2004 and he has been a Professor of Electrical and Computer Engineering at Laval University, Québec, Canada, since 1973, where he was head of the department from 1977 to 1983. From June 1992 to June 1997, he was also Director of INRS-Telecommunications, a research institute which is a part of the Université du Québec. He is involved in research work in intelligent antenna array, radar cross-section measurements and analytical predictions, mobile radio-channel propagation modeling, personal communications and industrial realization of telecommunications equipment.

Dr. Delisle is a member of the Order of Engineers of the Province of Québec and Professional engineers of Ontario, Past-President of the Canadian Engineering Accreditation Board, Fellow of the Canadian Academy of Engineering, Past Canadian President of URSI, Past President of ACFAS, Fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Canadian Engineering Institute, the Canadian Academy of Engineering and of the Institution of Engineering and Technology (IET-UK). In 1986, he was awarded the J. Armand Bombardier prize of ACFAS for outstanding technical innovation and his work in technology transfer has been recognized by a Canada Award of Excellence in 1987. The Canadian Council of Professional Engineers has recognized its contribution to the profession by awarding him the prestigious " Meritorious Service Award for Professional Service " in 2004 .Dr Delisle has supervised the work of over a hundred graduate and post-graduate students over the last 30 years. He has been elected to the Canadian Hall of Fame in telecommunications in October 2007.