Indoor and Outdoor Positioning in Mobile Environments— a Review and some Investigations on WLAN-Positioning

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Abstract

This paper reviews existing indoor and outdoor positioning technologies for mobile users, including GPS and its extensions, wireless communication-networks and others. Accuracy and limitations of these technologies and methods are examined in more detail. Furthermore, results of own investigations concerning Wireless LAN are presented.

Keywords

Positioning, GPS, WLAN, GSM, Mobile Computing

I. CLASSIFICATION OF POSITIONING METHODS FOR MOBILE COMPUTING

Figure 1 provides an overview on existing and future indoor and outdoor positioning technologies for mobile users. Mobile computing is a combination of mobile Internet, communication, and position location and information technologies. The key to successful mobile computing is real-time positioning of the mobile user, enabling a large number of applications including wireless mapping, emergency response, fleet tracking, traveler information services, location-based marketing, etc. Depending on the task and the environment, mobile users may be positioned by different methods, which we will classify in indoor and outdoor methods. Even though, in general, the technologies are often divided into network-based or satellite-based systems (cf. Karimi, et al., 2004). Another classification is based on the actual device that performs the positioning solution, i.e., mobile user or the base station, leading to mobile terminal (user)-centric (such as GPS, A-GPS, E-OTD), network-centric (COO, TOA, TDOA, AOA, RSS, multipath pattern matching), or hybrid solutions. In the network-centric systems, the user's position is determined by the base station or a control center and sent back to the user's set, while in the terminal-centric solution, the position computation is performed by the user's set.

Due to recent developments, the borders between these groups seem to be rather artificial. GPS, formerly only feasible outdoor, is now also becoming available indoor. The increasing density of in- and outdoor WLAN networks may offer further opportunities with respect to the positioning of mobile users. In the future, a mobile user may no longer be interested in taking care for the selection of the appropriate positioning methods, i.e. the seamless switching between the different approaches should be done more or less automatically.

Additionally, semantic positioning methods (e.g. a location enhanced web, such as URL's with lat/long coordinates or with names of points of interest or address input combined with GIS-databases) may become more important.
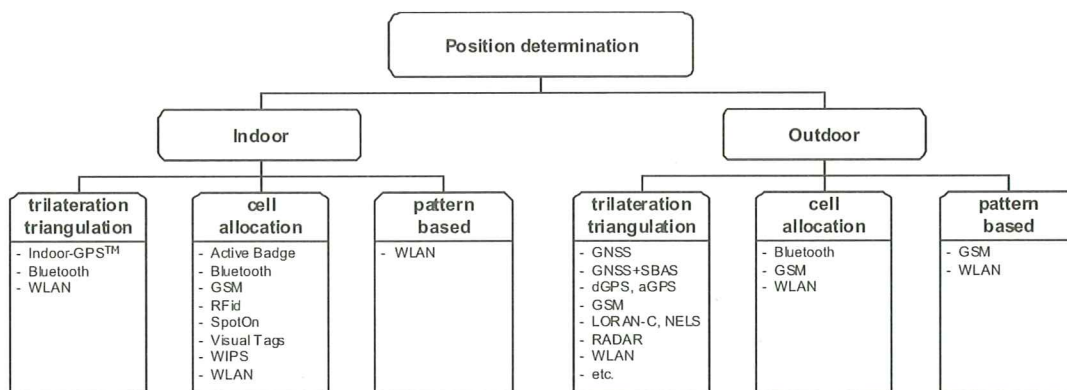

Figure 1. Positioning methods

II. CRITERIA FOR SELECTING APPROPRIATE POSITIONING TECHNIQUES

Typical criteria for positioning methods in mobile environments are accuracy, operational availability, expense, robustness, and sensitivity for disturbances and position losses, size and cost of devices, relative or/and absolute positioning. Additionally, relevant services delivered with the positioning might also be important for the selection of an appropriate technology. The following table characterizes existing positioning technologies taking some of the mentioned criteria into account.

Table 1. Criteria for selecting appropriate positioning techniques

Localization technology	Range/operational availability	Accuracy	Services and content
GSM-based approaches			
COO(Cell-of-Origin)	In principle globally	250m − 35km	Traffic information, information services
E-OTD(Enhanced Observed Time Difference)	In principle globally	100 − 500m	Location based billing, mobile yellow pages, information services
TOA(Time of Arrival)	Only after enormous capital investment globally	100 − 500m	Location based billing, mobile yellow pages, information services
OTDOA(Observed Time Differ-ence of Arrival)	Only after enormous capital investment and with modified end devices globally	30m	Fleet management, routing functions, mobile advertisement, information services
Fingerprint	Only after enormous capital investment, feasible in urban areas	< 150m	Fleet management, routing functions, mobile advertisement, information services
GPS-based approaches			
GNSS/SBAS/DGPS	Globally	1cm − 100m	Positioning and navigation services
A-GPS(Assisted GPS)	Only after enormous capital investment globally	5m	Navigation services, security services, localization services
Indoor GPS	Indoor/special chips	20m	Localization services
WLAN/Bluetooth			
WLAN outdoor	Up to 500m around sender; cell-of-origin; distance; fingerprint	10 − 150m	Cell-of-Origin and information transfer
WLAN indoor	Up to 30m around sender; cell-of-origin; fingerprint	ca. 3m	Cell-of-Origin and information transfer
Bluetooth	Around sender/range up to 100m indoor (Class 2)	< 30m	Cell-of-Origin and information transfer
Other techniques			
Infrared beacons/Active badges/WIPS	Around sender/range up to 10m indoor	< 10m	Cell-of-Origin and information transfer
Ultrasonic	Around sender/no hindrances	accurate	Localization services
Visual tags	Within visible range, typically indoor	Room	Localization services
Semantic positioning	In principle globally	Depending on data set	Mobile web location and information service
Relative positioning (INS, odometer etc.)	Locally, short time	meter − cm	Support technology for other localization services

III. POSITIONING METHODS AND SENSORS

Several positioning methods known as radiolocation are presented (e.g. GPS) in this chapter. The most popular technique of finding the user's location is triangulation or trilateration, based either on angular or distance observations (or combinations of both), between the mobile terminal and the base stations. The base stations in this radiolocation approach are either the cellular service towers, the WLAN access points, GPS satellites, or auxiliary satellites.

A. GNSS and related

The Global Navigation Satellite System (**GNSS**) usually refers

to the US system NAVSTAR-GPS since it is the most accurate system to position a mobile user. GPS is a very prominent technology. For more detailed descriptions we refer to Bauer (2001), Hofmann-Wellenhof et al. (2001), Parkinson et al. (1996), Resnik, Bill (2003) or with special emphasis to mobile applications see Grejner-Brzezinska (2004). NAVSTAR-GPS consists of a constellation of 24 active satellites that communicate with a ground control system operated by the US. A mobile user with a GPS receiver is provided with accurate latitude, longitude, time and bearing 24 hours a day, worldwide. From a user's point of view, GPS is a passive system making use of the infrastructure that was set up by the US military (NAVSTAR-GPS) or Russian military (GLONASS). In the future, the European system GALILEO will enrich the existing GPS technologies with improved robustness and better positioning accuracy due to additional active satellites.

GPS is used in surveying and positioning (tracking and navigating vehicles) since many years. The basic principle is to measure the distance from the user's receiver to at least 4 satellites, whose position in orbit is known. This allows for a 2D- and 3D-positioning worldwide, independent of weather conditions and time. *Pseudorange* defines the geometric range between transmitter and receiver, recovered from the measured time difference between the epoch of the signal transmission in the satellite and the epoch of its reception by the receiver on the ground. Pseudoranges may be derived from the C/A-code and P-code, its precision is partially determined by the wavelength. *Carrier phase* is defined as a difference between the phase of the incoming carrier signal and the phase of the reference signal generated by the receiver. The receiver can measure only a fractional phase of one wavelength. The carrier phase observable contains the initial unknown integer ambiguity, a number of full phase cycles between the receiver and the satellite at the starting epoch, which has to be solved by ambiguity resolution algorithms.

There are two primary GPS positioning modes: absolute and relative positioning, and there are several different strategies for GPS data collection and processing, relevant to both positioning modes. For absolute positioning a single receiver may observe pseudoranges to multiple satellites to determine the user's location. Of major interest are differential GPS techniques (**DGPS**) being a relative positioning technology. DGPS employs at least two receivers, one defined as the reference (or base) receiver, whose coordinates must be known, and the other defined as the user's receiver, whose coordinates can be determined relative to the reference receiver by differencing the simultaneous measurements to the same satellites observed by the reference and the user receiver.

Using pseudoranges in post-processing mode one can achieve an accuracy of 1–5m for absolute positioning, whereas a relative positioning with pseudoranges is able to achieve ca. 50cm. With carrier phase measurements accuracies in static and kinematic mode are possible within the range of some millimeters (Grejner-Brzezinska, 2004).

Many different devices (stand alone, cards in smart phones, PDA's, etc., see Figure 2) are available at different cost levels ranging from 100$ to some 10.000$ to be used for various purposes. There are only some smaller limitations related to GPS sensitivity:

• As GPS needs at least a signal level above -130dBm, it may have problems in forest and dense settlements areas (attenuation impedes signal reception and multi-path effects cause interference).

• Within buildings, tunnels, etc. the GPS signal gets extremely absorbed. In order to use a satellite based system indoors the reception has to be significantly improved. This can either be done by improving the receiver itself or by the installation of local GPS transmitters (often referred to as pseudolites).

Figure 2. Different GPS devices

Furthermore, so called satellite based augmentation systems (**SBAS**) provide online correction signals for wide areas. There are three systems available: WAAS (Wide Area Augmentation System) built by the U.S., EGNOS (European Geostationary Navigation Overlay Service) built by the European Union and MSAS (Multi-Functional Satellite Augmentation System) by Japan and other Asian countries. All these systems are technical identical and are developed mainly for the use of air traffic control. However, civil users can greatly benefit by this service – if they receive the very flat signal. Since the satellites are geostationary, the elevation may fall below 10 degrees in Northern Europe. Possibilities to broadcast SBAS services through other networks (GSM, LORAN etc.) are already available (http://galileo.cs.telespazio.it/egnostran/home/files/egnostran_introduction_%20rome_%20pubdemo.pdf).

Assisted-GPS (A-GPS, Djuknic, et al., 2002) provides a GPS receiver with data (or equivalent information) that it would ordinarily have to download from the GPS satellites. This technique speeds up the satellite acquisition time, and the time-to-fix of the GPS receiver. With A-GPS data, GPS receivers can operate much faster. Any GPS receiver with the appropriate modifications can benefit greatly from A-GPS data. GPS uses Code Division Multiplex (CDM) which is generated by a Pseudo Random Number unique for each satellite. The period time is 1023 chips. Besides this, satellite motion generates a Doppler shift between ±4.2 kHz. In order to acquire a precise correlation the receiver has to search the entire space (40 frequency bins×1023 delay bins). The acquisition process takes up to 40 seconds with traditional receivers. Van Diggelen/

Abraham (2001) introduced a system that decreases the searching time by a factor of 10. This is achieved by receiving the almanacs simultaneously from all satellites under very good conditions (outdoors) via a world wide network of stations and by delivering this information to the receiver. The almanac contains the ephemeris, which can be used by the receiver to predict the Doppler Shift and thereby reducing the search space. Hence, the receiver has 10 times more time to integrate the satellite signal, which leads to a gain of 10dB (Van Diggelen, Abraham, 2001). For the delivery service of the almanac information GSM or other wireless technologies could be used.

Global Locate (www.globallocate.com) implements A-GPS using its owned-and-operated worldwide reference network of GPS stations that pre-calculates the satellite orbits. Each satellite needs to be visible from at least two base stations. A world wide digital terrain model (1 billion points with a height accuracy of ±18m) supports positioning with less satellite measurements. A server computes the positions from pseudorange-measurements without precise GPS-time tags. These are delivered by GSM-networks. Together with A-GPS servers, this network performs all the A-GPS data functions. For mobile devices a special chip is available.

Another approach to increase the receiver's capability to detect the signal is to use integrated circuits with thousands of massively parallel working correlators. Highly sensitive receivers equipped with those correlators recognize the signal and analyze it. Traditional GPS receivers have two or four correlators per channel (less than 50 at all). These correlators are used sequentially to search over the possible correlation delays to find the signal correlation peak. The number of correlators is limited by the size of the chip. Recent improvements in chip manufacturing have shrunk the size to less than a square centimeter for 16.000 correlators (Van Diggelen, Abraham, 2001). This large number of correlators dramatically reduces search time and leads to an additional gain of 20dB. With both technologies together Indoor GPS works in the top two to four storeys of concrete buildings. First tests in buildings, even some floors below ground level, showed accuracies of around 20m.

While A-GPS and enhanced correlators improve the receiver's capabilities, the signal quality can also be improved by boosting the received energy. It is obvious that one cannot influence the NAVSTAR satellites. However, it is possible to add additional "satellites" to the system. These additional "satellites" are most often referred to as pseudolites. Pseudo-satellites can be regarded as a mini-satellite that can be used for autonomous navigation and positioning in the indoor and outdoor environments. These transmitters send a signal in the same frequency band as the "original" satellites. The principle is directly derived from GPS. The system is able to triangulate the position of an object by accurately measuring the distances from the object to the array of pseudolites, whose location coordinates are known in a given reference frame

(Barltrop, et al., 1996).

B. Cellular networks

Mobile communication systems such as GSM (Global Standard for Mobile Communications) or UMTS (Universal Mobile Telecommunication System) are based on a set of cellular networks. Since some years location-based services (LBS) are delivered by these cellular approaches. LBSs are made possible through a suitable relationship between the cellular service provider, cellular networks and mobile user's terminals, which work in synch, to locate the user (mobile terminal), and then transfer the position data either upon the request or as a continuous stream. The major issue is to locate the user with a required accuracy and limited latency. A popular approach to finding the user's location is again a radiolocation technique, which uses parameters of radio signal that travels between the mobile user and reference (base) stations to derive the user's location. The signal parameters most commonly used are: angle of arrival, time of arrival, signal strength, and signal multipath signature matching, whereby the time of arrival and the signal strength can be directly converted to the range measurements. Nevertheless one has to keep in mind, that the radio channel is a broadcast medium subject to interference, multipath and fading causing significant errors.

In principle there are the following different positioning technologies in GSM networks (Ingensand, Bitzi, 2001):

- cell-of-origin (COO) evaluation and partitioning of cells
- Distance measurements (Baseline methods and hyperbel intersection methods)
- Multipath-finger prints

The **cell-of-origin method** determines at the mobile which antenna is the closest one delivering the signal to the user. The antenna density varies very much. In rural areas antennas serve zones of up to 35 km radius, whereas in urban areas cell radius may shrink to some 100m. Two methods allow a verification of the original approach:

- The GSM network consists of cells which may have omni-directional (360°) or sectorized coverage area (typically 3 and up to 5 sectors per station, horizontally ca. 65–85 degrees, vertically 5–15 degrees). Since the GSM system automatically selects the best available cell, the information in which cell a mobile phone is logged in can be used for positioning.
- Furthermore, GSM utilizes Time Division Multiple Access (TDMA) with short time slots. TDMA is a technology for delivering digital wireless services using time-division multiplexing (TDM). TDMA works by dividing a radio frequency into time slots and then allocating slots to multiple calls. In this way, a single frequency can support multiple, simultaneous data channels. This requires the mobile phone to adjust their own timing in order to receive the burst within the correct time slot. The adjustment is

controlled by the base station (BTS). Therefore, the BTS signals model a timing advance as an integer value between 0 and 63 which is interpreted as time between 0 and 233µs resulting in an accuracy of 550m (63×550m gives the maximum cell radius of 35km mentioned above) provided there are no reflections and delays. In urban areas typical delay spreads are 3µs (900m at the speed of light). This timing-advanced effect (TA) allows a positioning accuracy of better than 1km and it may be combined horizontally with a sector determination. Nevertheless, these factors make GSM almost unsuitable for indoor use. The signal strength cannot be taken into account because GSM uses power adjustment mechanisms in order to avoid interferences with neighboring cells. With adapted GSM base stations trilateration or triangulation might be feasible. However no current implementations are yet known.

These methods make use of distance measurements between the several antennas and the mobile and require modifications in the existing sender (e.g. antenna arrays of 4 to 12 single antenna or smart-antenna) and receiver technology.

By measuring the distance to at least three antennas, positions of mobile users can be computed. Therefore all base stations need to be equipped with GPS for precise time transfer system. Further more, all signals need to be synchronized. Signals are called bursts and may be send either by the mobile or by the antenna. The uplink-approach uses a burst sent from the mobile to the base station. The position is determined at the base station by measuring the arrival time of the burst (Time Difference of Arrival (TDOA). This allows to correct clock errors as well as systematic errors. But again, it requires modifications within the base stations. If the burst originates at the base station, the downlink-approach is selected. The mobile phone computes the position from the signal run time (Enhanced Observed Time Difference E-OTD). Modifications in the mobile are necessary.

- TOA (Time Of Arrival) is a network based positioning method that measures the time it takes for radio signals to arrive at multiple points.
- RSS (Received Signal Strength) determines the distance from the measured signal strength. Normally the signal strength is diluted quadratic related to the distance sender-receiver. The distance is a function r=f (field wave resistance, directivity and characteristics of the antenna, radiation power, effective field intensity). RSS is the worst positioning approach related to GSM because it is influenced by antenna direction and multi-path effects.
- TDOA (Time Difference of Arrival TDOA) is based on an improved time corrected run time method (Enhanced Time Difference of Arrival (E-TDOA) or Enhanced Observed Time Difference (E-OTD)). E-OTD uses the cellular signals themselves to determine location. The difference between the time of arrival of the cellular signal at the handset and at a nearby fixed receiver is compared.

Time differences from at least three non-collinear cell-towers are required to be able to compute positions. A position obtained, accuracy is in the order of 150m to 300m.

A completely different approach is the so-called fingerprint method. This method uses the disturbing multi-path-effects to detect a typical pattern. Within dense cities the various antenna signals are creating a signal pattern (phase and amplitude characteristics), which might be measured and stored in a data base. By comparing the multi-path pattern at a unknown position with all patterns in the data base the best position may be computed by pattern recognition methods. The assumption is that the pattern stays stable over time. Major advantages are that the positioning is independent from visible connections to the antennas and that a positioning is possible with only one antenna. First tests showed accuracies better than 150m.

C. WLAN (Wireless local area network)

As the deployment of WLAN increases they will the first candidates for delivering web services in limited scale mobile applications such as classrooms, campus areas of universities and enterprises, malls, and other indoor areas. For these types of applications WLAN positioning may be an interesting approach. Recently, there are efforts to use the WLAN infrastructure itself for positioning in indoor areas (Prasithsangaree, et al., 2002). Location finger-printing has been used for such approaches where information in a database of prior measurements of the received signal strength at different locations is matched with the values measured by a mobile station.

The obvious method to achieve a position is to determine the distance by either measuring the signal propagation delay or by measuring the signal strength. Due to the structure of modern buildings and the incapabilities of WLAN network cards and normal access points both values cannot be used in practice. Instead an inferring approach has been developed and is commercially available as the EKAHAU positioning engine (www.ekahau.com). The basic idea (Roos, et al., 2002) is to utilize a general propagation model and to parameterize this model through a number of test measurements. The mathematical calculation of such a model would be too complex. An example propagation model for a building is depicted in the following Figure 3:
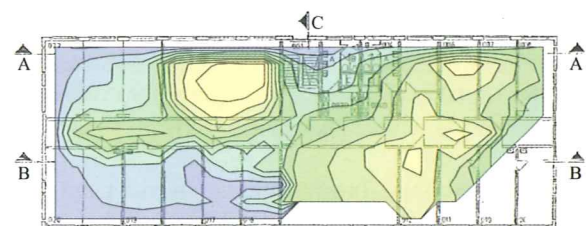

Figure 3. Propagation model around 5 WLAN access points

The mobile client measures the signal strengths of all surrounding access points and delivers these data to the positioning engine which in turn calculates the position by solving a maximum likelihood problem. The system is not affected by the fact that several access points transmit at the same frequency because it uses the integrated signals.

Other approaches utilize modified access points in order to determine the distance to the mobile client via measuring the signal run time. Devices for this approach are manufactured by companies such as WhereNet (www.wherenet.com).

D. Bluetooth

Bluetooth is a short range radio technology expanding wireless connectivity to personal and business mobile devices. Bluetooth may be seen as an example of a WPAN (Wireless Personal Area Network), that considers networking in a 10m space around a person who is working stationary or in motion. The idea is to network devices such as sensors, cameras, handheld computers, audio devices etc. within a short range around the person. Positioning based on Bluetooth works similar to the methods described for WLAN. Due to the shorter range a better accuracy might be expected, but the standard does not provide measurement of signal strengths. In addition, the usage of RSSI (received signal strength indicator) is hampered by poor implementations of the hard- and firmware which may vary by manufacturer. However, Feldman's et al. (2003) investigations add up to an accuracy of 2 meters, but measurements are limited to 8 meters around class-2 senders.

E. Other positioning methods

Other radio based systems can be found in the area of aircraft navigation systems where different types of radio **beacons** are used. These beacons can be either sectorized or use a phase shift to determine the direction towards a beacon. Additionally infrared beacons can be used-see Want et al. (1992) and Schilit et al. (1993).

Since the early 60s of the 20th century **Loran-C** has been used as a world wide system for aircraft and ship navigation. Loran-C uses a small network of usually four synchronized radio transmitters. The phase shift between pairs of those transmitters allows mobile stations to determine their position with an accuracy of 200–500m (Resnik, 2000).

Conventional **radar** systems are also widely used for positioning and tracking in aeronautics and maritime navigation. New passive radar systems do not transmit an own radar signal but use reflected signals, for instance from radio stations and mobile phones-see Koch, Westphal (1995).

Natural or artificial **landmarks** such as structures or geographical formations can be used for optical positioning as well as laser scanning and triangulation of the surrounding area. In Addlesee et al. (2001) an overview of such systems is presented.

RFid tags enable tracking of goods and persons within a small range. The available technology and there respective usage domains are very wide-see Finkenzeller (2003).

Inertial navigation concepts and other dead-reckoning systems should not be described in detail here. On the one hand side the size of the equipment usually does not fit to a mobile user – they are used in vehicles such as cars or airplanes. On the other hand these methods and devices usually support relative positioning, i.e. they may be seen as add-on to absolute positioning if these fail (such as GPS in narrow city blocks). **Inertial navigation systems** (INS) consists of multiple inertial measurement units (IMUs), such as accelerometers and gyroscopes, each one treated as a separate dead-reckoning system. Dead reckoning means that the present location is deduced or extrapolated from a known prior position , modified by the known (observed) direction of motion and the velocity (Grejner-Brzezinska, 2004).

A digital compass is another device used for orientation tracking in navigation, guidance and vehicle compassing.

Additional location tracking systems are most commonly used for indoor positioning, for further details see Grejner-Brzezinska (2004). An **ultrasonic (acoustic) tracker** utilizes frequency sound waves to locate objects either by triangulation of several transmitters, time-of-flight method, or by measuring the signal's phase difference between the transmitter and the receiver.

Magnetic trackers use magnetic fields to determine 3D location coordinates, attitude and heading relative to the transmitter.

Optical trackers make use of light to measure angles (ray directions) that are used to find the position location.

Relative positioning methods such as inertial navigation systems, odometers, freehand measuring devices, etc. may offer additional location information in cases where other methods such as GPS have difficulties (e.g. in forests, narrow building gorges, etc.). These are already used in vehicles (cars, ships, and airplanes) because of their size and weight.

IV. INVESTIGATIONS RELATED TO WLAN POSITIONING

A. Outdoor tests

The density of WLAN networks is increasing constantly. At airports, railway stations, university campus areas, but also in dense urban areas WLAN base stations will be delivering Internet access in the future. Assuming that a mobile user has access to more than one WLAN node, we may use similar

methods for distance measurements and positioning as we have described for GSM networks.

In some tests outdoor we tried to determine a functional relationship between signal strength and distance measuring with two WLAN nodes. The following figure illustrates the relation for one of our WLAN sender-antenna configuration, where we measured a total length of 240 m in 20 m discretisation steps moving forward and backward over an agricultural field. At each of the 20 m points between 20 to 40 measurements were registered. The standard deviations range between 1 and 4 dB. The root mean square error of the differences is around 1.2 dB. The estimated logarithmic function as well as the polynomial function of degree 4 do have a fairly good similarity. The Pearson correlation coefficient is better than 0.85 for the logarithmic and better than 0.95 for the polynomial functions. Nevertheless other WLAN combinations are showing some problems. Especially close to the sender almost no signal changes happened. For each combination of WLAN nodes different calibration functions need to be determined. Under good conditions one might expect a distance accuracy of around 50m. In addition multi-path-effects and other impacts may result in even worse accuracy.
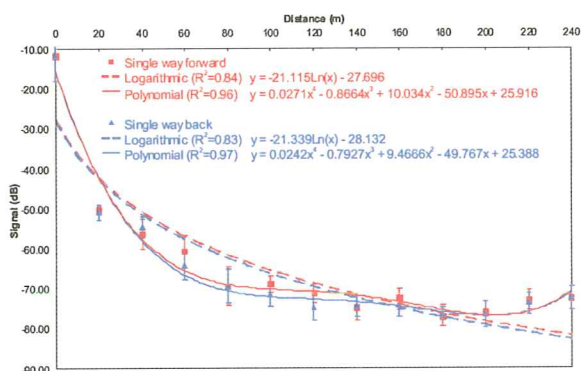
Figure 4. Outdoor investigations with WLAN

B. Indoor tests

We accomplished several tests with indoor WLAN positioning (Eckhoff, 2003). In a standard office building the typical errors, without any modifications to the available access points, are less than 5m. By installing additional dummy access points without a wired network connected we were able to minimize the error even further. The following figures illustrate the results geometrically and graphically.
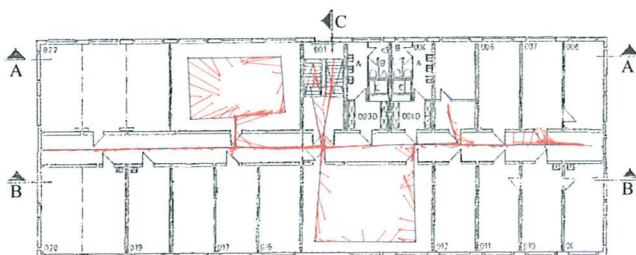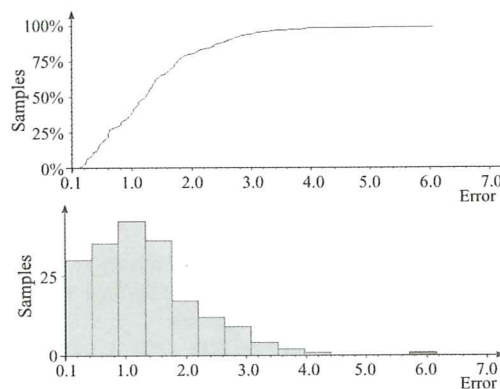
Figure 5. Error between real and determined positions

Figure 6. Test results for position errors

V. SUMMARY

In this paper we reviewed existing indoor and outdoor positioning technologies for mobile users. It should be mentioned that the existence of such a variety of positioning technologies, without a standardized method, may pose a problem to both the users and the providers, as the user is only covered in the area serviced by his/her provider and may not be covered elsewhere, if another provider uses different location-identification methods. It is rather difficult to define a single best technology, as each has it is own advantages and disadvantages. Limitations are related either to the associated physical phenomenon, system design specifications, or application environmental constraints. Perhaps hybrid solutions offer the best choice, as they normally combine highly accurate with highly robust methods, resulting in multiple inputs improving both the robustness and the coverage. Sensors and techniques need to be combined with each other to provide redundancy, complementary and fault resistance. A typical example for a hybrid approach used in airplanes to capture photogrammetric imagery is the combination of GPS, INS and digital cameras.

In the future, it is also expected that there will be hybrid networks for communication – where there will be seamless roaming between cellular networks (GSM, UMTS) and WLANS depending on availability, cost-service requirements, and so on. Thus, it may be expected that there will be hybrid positioning technologies, too. A major issue for the future will be to cross the borders between the different existing technologies. Therefore a network infrastructure needs to be developed allowing to combine signals from different sensors and to compute best feasible positions taking all available sensors at that time and place into consideration. Adjustment theory and Kalman filtering might be the appropriate mathematical framework for hybrid position computations.

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