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WI-FI SIGNAL STRENGTH VS. MAGNETIC FIELDS FOR INDOOR POSITIONING SYSTEMS

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Abstract In this research we compare Wi-Fi received signal strength indication and magnetic field based real-time location systems (RTLS) from various perspectives such as system complexity, accuracy and stability. To evaluate the performance of these systems we built several test fields with different types of environments. We will compare both approaches side-by-side and answer such issues as optimal calibration step (measurement interval), location accuracy, effect of minor and major environment changes to fingerprint DB and overall system accuracy.

Key words: indoor positioning, wi-fi, rssi, magnetic fields

AMS Mathematics Subject Classification: 00A72, 94A40, 94A15

1 Introduction

In the recent years increasing popularity of wireless networks and growth of mobile devices opened a new niche for researchers and developers, so-called location-based services. Real-time locating systems (RTLS) that monitor the location of mobile devices and applications that act differently depending on the location of user are considered to be a promising market [1]. Currently, the most widely used and commercially deployed location-sensing system is Global Positioning System (GPS), which provides relatively high degree of accuracy and available globally. However, GPS signals originating from satellites fail to reliably reach a mobile device in indoors and high dense urban areas. Thus, considerable research has been devoted to studying how to conduct signal positioning through signals from existing wireless infrastructure, such as cellular networks, digital television, WiMAX, Wi-Fi and etc [2].

Recently, the most popular and inexpensive technology is WLAN based positioning. This approach uses fingerprint method to measure relative signal strength from nearby access points (AP) when the positions of the APs are unknown. This method relies on a map of fingerprints (received signal strengths (RSSI) distribution) of corresponding locations in order to infer locations. The overall location accuracy depends on WLAN infrastructure complexity (more APs gives more unique RSSI fingerprints) and environment stability (RSSI values are sensitive to large-scale environment changes).

Another interesting aspect to be studied is the utilizing the magnetic field information inside buildings for localization and navigation purposes. This approach also relies on fingerprint DB but rather than collecting RSSI values, unique features of the indoor magnetic field are used to create a map. Magnetic field variations inside the buildings are found in iron, cobalt, or nickel and also occur from manmade sources such as steel structures, electric power systems, and electronic appliances [3]. If these variations or anomalies are identified, they provide a unique fingerprint for places inside the buildings where they exist.

In this manuscript we compare both (WLAN RSSI and magnetic field) RTLS from various perspectives such as system complexity, accuracy and stability. The rest of the manuscript is organized as follows. We explained the basics of Wi-Fi based positioning and geomagnetic positioning in Sections II and III, respectively. Research methodology is described in Section IV. Field experiments and computer simulations' results are discussed in Section V. Concluding remarks are given in Section 6.

2 Wi-Fi signal strength based positioning

There have many localization techniques been proposed, and positioning systems such as Global Positioning System (GPS) have already been successfully deployed in markets. However, GPS has a number of drawbacks, namely, GPS users have difficulties in urban areas, as well as in indoor environments, where buildings and other objects block the weak signals that are transmitted from geostationary satellites [4]. There are also hybrid methods that utilize both GPS and cellular infrastructure, and provide accurate location estimation in urban areas. Nonetheless, when the mobile user is located in deep indoor environment surrounded by obstacles, the positioning accuracy dramatically decreases [5].

Different physical requirements of the indoor environments need alternative systems to provide accurate location information. Various technologies have been suggested as a base for indoor positioning systems (IPS), such as Bluetooth and Infrared, Ultra-Wideband and Ultrasonic technologies [6]-[9]. On the other hand, most of these systems are difficult to deploy because of high-complexity and necessity of building new network infrastructures. Thus, IEEE 802.11 based WLAN (Wi-Fi) can be a good option for indoor positioning systems due to its wide-range deployment in urban areas and the growing number of mobile gadgets equipped with Wi-Fi chipsets.

Many researchers have suggested different ways to solve the problem of location determination in WLANs. Certain types of positioning algorithms have been used for location estimation, such as received signal strength information (RSSI), angle of arrival (AOA), time-of-arrival (TOA) and time difference-of-arrival (TDOA).

Indoor environment characteristics and specific requirements of time and angle measurement based schemes made received signal strength information based positioning techniques more attractive for indoor location estimation. Several algorithms based on RSSI have been proposed. The best locating results can be achieved with 802.11-based RTLS that utilizes the so-called RSSI fingerprinting approach [9]. Fingerprinting does not need modification of hardware, and no time synchronization is necessary between devices.

Fingerprinting localization technique is based on comparison the unique signal data from external sources sensed at a particular location with a map of prerecorded data [10]. This technique has two phases: offline (calibration) and online (localization). During the calibration phase the received signal strengths from surrounding APs at different locations are acquired and then stored in a database. In the next phase

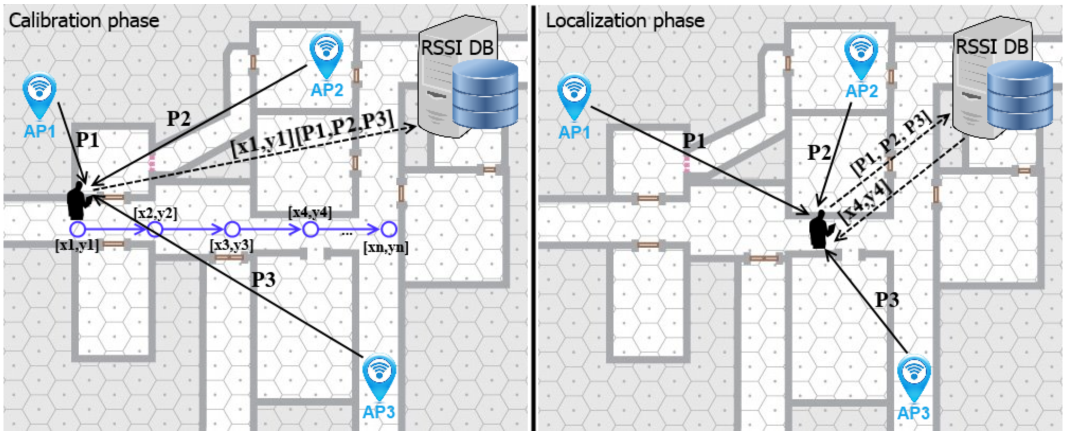

Figure 1: Two phases of RSSI fingerprinting: calibration (left) and localization (right).

(localization), the mobile user measures the RSSI at a place where it requires it position, and the measurement results are compared with the data in the database. The outcome is the likeliest location of the mobile user [11]. Both procedures are demonstrated in Figure 1.

An advantage of WLAN based fingerprinting is the relatively small number of APs that are required for mobile users' localization. Also, due to the rapid growth of wireless networks in indoor environments, often no investment in infrastructure is required as existing APs can be used [3]. On the other hand, creating a fingerprint DB is often time consuming and, furthermore the newly collected DB may not be reliable if there are major changes in the indoor environment. Consequently, large-scale deployments of fingerprinting localization for indoors become non-trivial [10].

3 Geomagnetic positioning

Indoor positioning technologies can be classified into three categories: technologies based on signals-of-opportunity, technologies based on pre-deployed infrastructure, and others. Using a magnetic field for positioning could be categorized in either of the first two categories depending on the ways in which the magnetic field is used. If artificially generated magnetic fields are used, pre-deployed coils are required. The received strength of the magnetic field (B) can be converted to a measurement of range or distance. If the coordinates of the coils are known, trilateration can be applied to estimate the receiver's position [11]. A significant advantage of this type of system is that the artificially generated magnetic field is not affected by most obstacles, hence multipath or non-line-of-sight errors are avoided. In most of applications, the geomagnetic field is used to determine the orientation of a device [12]. However, significant magnetic disturbances in indoor environments impact on the positioning accuracy. Mitigating such perturbations is not an easy task [13]. On the other hand, the anomalies caused by magnetic disturbances could be used as a "fingerprint" to describe the environment - the more variable the local anomalies, the more unique the fingerprint. Hence the fingerprinting methodology can possibly be applied for positioning. In such a case, this approach can be considered as a technology based on signals-of-opportunity. Using the geomagnetic field for outdoor navigation is not new.

Goldenberg [14] reviewed the terrain navigation research efforts (using land topography and geomagnetic maps) in past decades. Wilson et al. [15] developed a magnetically-aided dead reckoning system to provide navigation for aircraft. In 2000, Suksakulchai [16] realized that the magnetic field disturbances could be used for indoor localization. The researchers collected and stored the magnetically-derived heading information as a robot travelled along a hallway. Next time, the robot measured the magnetic field features and matched them with the pre-stored data. If a match was found, the robot could determine its location. Similarly, [17] investigated a leader-follower scenario whereby a lead vehicle measures the magnetic field and sends the collected information to the follower vehicle which uses it to follow the same path as the lead vehicle. A small area map-matching scenario was also investigated, and decimeter-level positioning accuracy was achieved. In [18] a magnetic sensors array was used to detect the indoor magnetic field intensity, and several meters accuracy was c1aimed. Using Magnetic field for Simultaneous Localization and Mapping (SLAM) was also investigated [19].

An obvious advantage of using the magnetic field for positioning is that no infrastructure needs to be pre-deployed, which makes such a system cost effective. In general, in each fingerprint, the more elements, the better for positioning. Unfortunately, the magnetic field intensity data only consists of three components - intensities in X, Y and Z directions. Since true north (or magnetic north) is unknown even with aid of an accelerometer to detect the direction of the gravity, only two components can be extracted, i.e. the horizontal intensity and the vertical intensity (or total intensity and inclination). Furthermore, moving objects containing ferromagnetic materials and electronic devices may affect the magnetic field.

The term "magnetic field" can refer to a magnetic B field or a magnetic H field. These two fields are distinct but closely related. In vacuum $B = \mu_0 H$, where μ_0 is the magnetic constant ($4\pi \times 10^{-7} Vs/Am$). When there is magnetic material, the relationship of these two magnetic fields can be expressed as $B = \mu_0(H + M)$, where M is the magnetization field, or $B = \mu_0 \mu_r H$, where μ_r is the relative permeability.

Magnetic B field is more commonly used [20] as it reveals the real cause of the magnetic field is the moving electric charge. The units of B is Tesla (T) or Gauss (G) ($1T = 10000G$).

Many animals use the geomagnetic field naturally to navigate their way around the Earth [21]. In ancient times, Chinese and Greek scholars observed the attractive power of a magnet, and the Chinese are credited with having invented the first magnetic compass. The magnetic declination was discovered over a thousand years ago. However, the representation of the geomagnetic field in mathematical form was first made by Gauss about 200 years ago [22].

The geomagnetic field acts as a dipole magnet located at the center of the Earth. The axis of the dipole is tilted at an angle of approximately 11 degrees with respect to the axis of the Earth's rotation. According to the widely accepted "geomagnetic dynamo" model, differences in temperature, pressure and composition within the fluid outer core (convection) and the spin of the Earth (swirling whirlpools) cause currents

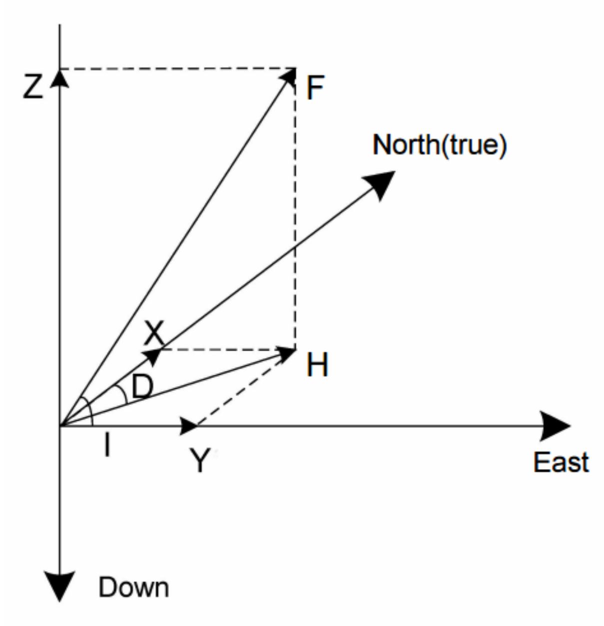

Figure 2: The seven parameters of the Earth's magnetic field.

which in turn produce magnetic fields [22]. The Earth's magnetic field is characterized by direction and intensity. The geomagnetic field intensity ranges between approximately $23,000$ and $66,000nT$ [23]. The direction of the geomagnetic field is always towards magnetic north. The horizontal components of the geomagnetic field are used to determine the compass direction.

The Earth's magnetic field is described by seven non-independent parameters: declination (D), inclination (I), horizontal intensity (H), vertical Intensity (Z), the north (X) and east (Y) components of the H and total intensity (F) (refer to Fig. 2). A compass can be used to find magnetic north, which is different from so-called "true north". The true north (geographic north) is at the Earth's rotational axis and referenced by the meridian lines, while the magnetic north refers to the geomagnetic pole position. Declination is used to describe the difference between these two north directions. The value of declination varies depending on the location of magnetic north on the surface of the Earth. Inclination is the angle between the horizontal plane and the total field vector, measured positive into Earth. A common representation of the Earth's magnetic field is in X, Y and Z coordinates (refer to Fig. 2). It can also be represented by F, D and I.

4 Methodology

In an IEEE 802.11 system RSSI is the relative received signal strength in a wireless environment, in arbitrary units. RSSI is an indication of the power level being received by the antenna. Therefore, the higher the RSSI number (or less negative in some devices), the stronger the signal. The strength of received power from a signal can be used to estimate distance because all electromagnetic waves have inverse-square relationship between received power and distance. WLAN infrastructure with several access points provides unique combination of RSSI values from different APs at particular point. This combination is used to pinpoint the user location in the future.

Magnetic field variations inside arise from both natural and man-made sources, such as steel and reinforced concrete structures, electric power systems, electric and electronic appliances, and industrial devices. Assuming that the anomalies of the magnetic field inside a building are nearly static and they have sufficient local variability, the anomalies provide a unique magnetic fingerprint that can be utilized in self-localization. For instance, a specific room could be characterized by its magnetic field intensity profile or an office can be profiled to help in the future by identifying whose office are you presently in [24].

If RSSI based locating systems uses Wi-Fi access points as location signal sources, geo-magnetic system utilizes pillars and other structures that show high magnetic field values inside the building. Both, WLAN and magnetic, approaches work in two steps: calibration and online tracking. The calibration process builds a fingerprint DB (RSSI or magnetic) of a target site by moving around [1],[25]. Online tracking is the scanning process for a mobile device to estimate its location. Both approaches use map matching location algorithm which is a correlating technology between the field reference (magnetic or RSSI) map and the online measurements.

4.1 Offline stage (calibration)

During the offline stage, a site survey should be performed in the target environment. In case of WLAN based locating systems RSSI values of the radio signals transmitted by APs are collected at certain calibration points for certain periods of time and then stored in the fingerprint DB [2]. Varying combination of APs with different RSSI values result in a unique fingerprint for each calibration point. As for the magnetic localization technique the magnetic field of the target site is measured producing a three dimensional vector $m = [mx, my, mz]$ consisting of three components [3], in units of μT, of the magnetic flux density in x,y and z directions, respectively [25].

4.2 Online stage

Magnetic map matching is similar to RSSI pattern matching, is a correlating technology between the field reference map and the on-site measurements to find the point at where the correlation values reaches to the maximum or the sum of the differences squares reaches to the minimum.

For further evaluation, we apply the Nearest-Neighbor (NN) indoor positioning algorithm. NN is based on some context-dependent distance measure that assigns a non-negative distance value between any two observation vectors. Given a set of training data and a test observation vector, a location is estimated from the closest training sample whose observation vector has the minimum distance to the observation, assuming the use of Euclidean distance. The observation vectors are a set of measured received signal strength values of individual APs. For example, let the received signature of a mobile node be $P = (P_1, P_2, \cdots, P_{i,} \cdots, P_n)$, where n is the number of APs and P_i denotes the measured signal strength to the ith AP. The RSSI-fingerprint database Q consists of a number of reference signatures. For example, jth reference signature q_j is $(q_{j_1}, q_{j_2}, \cdots, q_{j_n})$ where $q_j \in Q$. The nearest signature distance d^* is then calculated as follows:

$$d^* = \text{argmin}_{q_j \in Q} dist(q_j, p) \tag{1}$$

where $dist(q_j, p) = \sum_{i=1}^{n} (p_i - q_{j_i})^2$.

To handle the missing signature values that are not observed from the access points, we substitute the missing values with a small constant that is guaranteed to be smaller than any of the measured values.

5 Experiments

To evaluate our new algorithm, we built a test field in one of the campus buildings. The test area represents a high-density office environment that is filled with a number of obstacles such as partitions, cubicles, electronic devices, home appliances, and etc. (Figure 3). The WLAN's infrastructure consists of 10 APs at fixed locations. During the calibration and online tracking, we used a HP dv4000 laptop that has a Cisco Aironet 802.11a/b/g wireless adapter. As for magnetic measurements we used MicroMag3 integrated 3-axis magnetic field sensing module. The module can provide 3D acceleration, 3D rate-of-turn and 3D geomagnetic field measurements. The magnetic field output is normalized to Earth field strength, hence it is in arbitrary units.

To reduce any human errors during the measurement, we partitioned the test space into an equally-spaced grid, whose side length is chosen to be one meters for WLAN based system and $20-100cm$ for geo-magnetic locating system. On every grid crossing point, we collected 100 observations. The final fingerprint value for every calibration point is then averaged by the one hundred observation data samples data, and this value is then stored in the database.

5.1 System complexity and stability

In order to provide high level of accuracy WLAN based RTLS requires as many as possible APs to be installed in target area, whereas geo-magnetic locating system uses natural anomalies of the magnetic field inside the building. On the other hand Wi-Fi access points are these days installed almost everywhere people live and work [2]. Furthermore, an increasing number of manufacturers are integrating Wi-Fi chips with mobile handheld devices, such as smartphones, multimedia players, tablet PCs, netbooks etc. This means that nearly any device can be used for making RSSI fingerprint DB of the environment, whereas geo-magnetic locating system requires special hardware for both map building and location estimation.

Huge drawback of WLAN based systems is that even minor changes in environment may result in RSSI fluctuations. Since the RSSI constructs site-specific parameters, a newly constructed database may no longer be valid if there are any major changes in the target site [2]. Consequently, large-scale deployments of indoor locations become non-trivial. Figure 4 compares signal fluctuations of both systems at particular points.

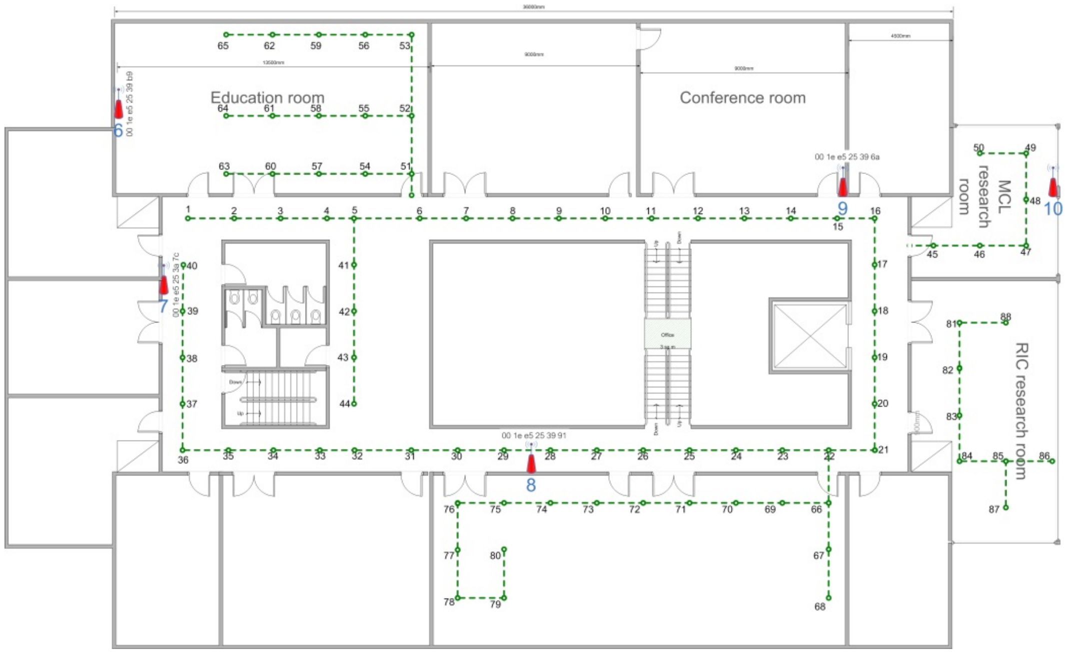

Figure 3: A plan of the building where experiments were conducted.

It can be observed that RSSI fluctuations are much higher compared to magnetic field fluctuations. This is the main reason of larger grid size (1m) for WLAN based systems as the RSSI fingerprints within 1m interval have less uniqueness characteristics.

5.2 Location accuracy

Next we evaluated the location accuracies of both systems. As mentioned above we chose 1m measurement interval for WLAN based system and 20-100cm for geomagnetic system. Figure 5 compares the location accuracy of both systems. It's clear that even with larger grid size, magnetic locating system can provide quite accurate location estimation. Figure 6 summarizes the location accuracy results with cumulative distribution function. For this simulation we consider 1m measurement interval. Again it's clear that geomagnetic RTLS provides much higher accuracy compared to WLAN RTLS. In WLAN based RTLS, location accuracy depends on location estimation method used as well as on many parameters, such as the number of APs and their allocation layout, the adapted locating algorithm, the calibration accuracy, and etc. However, recent researches showed that in general such systems provide 1-3m location accuracy [1] whereas geo-magnetic systems can achieve up to cm level accuracy [3].

6 Conclusions

In this research we compared WLAN RSSI and magnetic field based real-time location systems (RTLS) from system complexity, accuracy and stability points of view. Both systems have their advantages and drawbacks. WLAN based RTLS is easy for

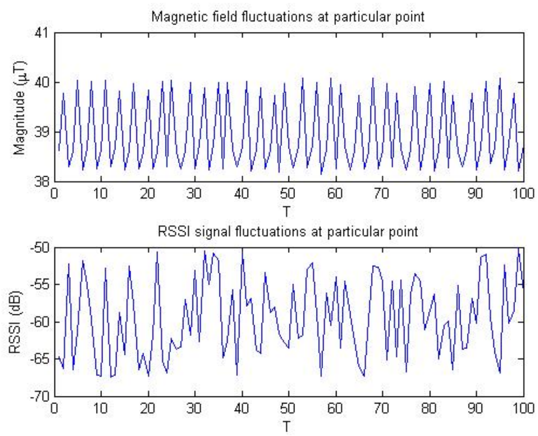

Figure 4: Magnetic and RSSI fluctuations.

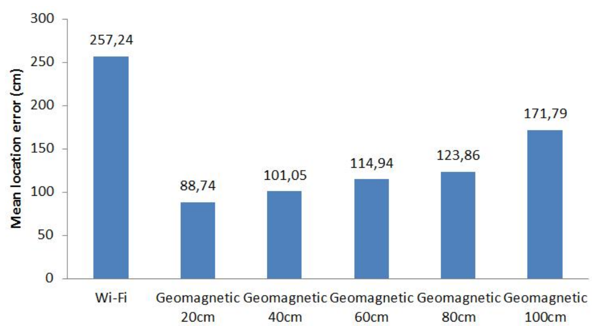

Figure 5: WLAN RSSI based vs. Magnetic RTLS location accuracy.

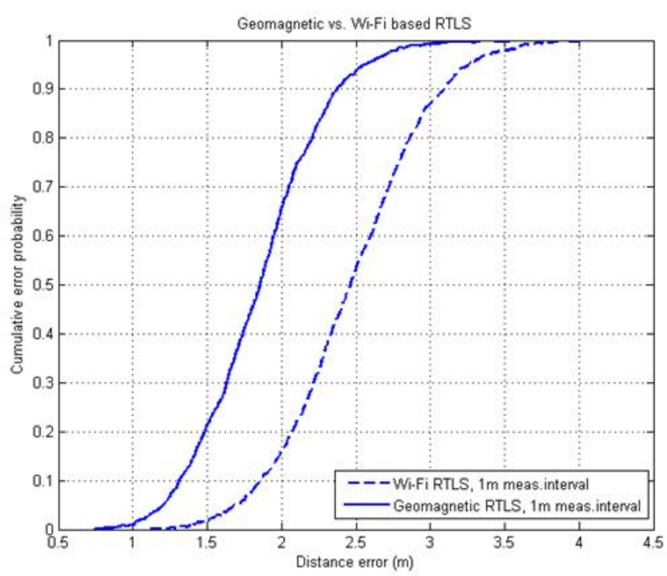

Figure 6: WLAN RSSI based vs. Magnetic RTLS location accuracy.

deployment as the Wi-Fi access points are these days installed almost everywhere. On the other hand geo-magnetic system provides much higher level of location accuracy since the magnetic fields inside the building are nearly static and they have sufficient local variability. Whereas RSSI is sensitive to even small environment changes and recalibration is required when there are major changes. Another advantage of geo-magnetic locating system is its low complexity as it does not require special hardware to be installed in target environments. From commercial deployment point of view wide existence of mobile devices with Wi-Fi support increases the number of potential users of WLAN based RTLS.

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