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Indoor navigation based on fusion of positioning signals

MASTER'S THESIS

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Nikolai Garmaev

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Nazev prace:

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Abstrakt: Zatimco urcovani polohy venku je diky GPS vyreseno, stejna uloha je v interieru je slozitejsi. Satelitni technologie, nemohou tento problem spolehlive vyresit, existuji sice ruzne systemy pro zjistovani polohy v interieru, ale i ty se potykaji s ruznymi problemy. Kombinace techto systemu by ale mohla prinest kyzeny prulom. Tato prace ma dva hlavni cile, zjisteni soucasneho stavu systemu urcovani polohy v interieru a vyber 2 vhodnych kandidatu (z hlediska vlastnosti i z hlediska dostupnosti) pro kombinaci technik urceni polohy za pomoci otisku site a RSSI. V praci provedene experimenty ukazuji, ze fuze ruznych technik muze byt prospesna, prima kombinace technik muze poskytnout presnost okolo 4 metru.

Klicova slova: určování pozice v budovách, knn algoritmus, určování pozice dle otisku wlan, VKV vysílání, rssi

Title:

Indoor navigation based on fusion of positioning signals

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Abstract: Indoor positioning has gained a lot of interest during last years and thanks to GPS, determination of one's position outdoor is almost solved. However, it's not the case indoors, mainly because of multipath, NLOS and interference and so far no technology from the variety of indoor positioning systems can be considered as a general solution. In order to manage these problems a substantial effort was made to combine different technologies together with the idea of emphasizing their strengths and lessening their drawbacks. This thesis has two major purposes: to investigate existing indoor technologies and to fuse the most suitable ones together by employing a Received Signal Strength fingerprinting approach. The experiments in a CVUT faculty building indicate that fusion of different techniques can be beneficial and even direct combination of techniques can provide accuracy of 4 m.

Key words: indoor positioning, knn algorithm, wlan fingerprinting, fm broadcast, rssi

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Introduction

Recently, considerable attention in the area of location-based services has been paid on research and development of indoor positioning and, subsequently, indoor navigation systems.

It covers a wide variety of situations ranging from communication with individuals moving in residential or office buildings, hospitals or factories to location detection of products stored in a warehouse and finding tagged maintenance tools and equipment scattered all over the area.

Thanks to growing popularity of mobile wireless devices and proliferation of the GPS/GLONASS, combined with Wi-Fi and cellular networks, the problem of outdoor localization is practically solved. But for the indoor environment GPS is not applicable, mainly because of impossibility of Line-of-Sight transmission between satellites and receivers - various obstacles, e.g. walls, equipment, moving people influence the propagation of electromagnetic waves. In addition, due to a phenomenon known as "multipath fading ", the transmitted signal often reaches the receiver by more than one path because signal propagation is strongly affected by construction materials, scattering of radio waves and multiple reflections from structures inside the building. [38]

Therefore, an optimal solution for indoor navigation hasn't been proposed yet since existing IPS are either expensive in terms of infrastructure (UWB, ultrasound), have limited coverage (Wi-Fi, Bluetooth, RFID) or low accuracy (cellular networks). Chapter I introduces methods for indoor positioning, while in Chapter II I will review all existing technologies available for indoor positioning together with their advantages and disadvantages. Chapter III and IV make a proposition of an indoor positioning system, which is able to estimate user's location in the particular environment. Results from experiments in a testbed are in Chapter V. This paper is different from the previous survey papers [14] and [21] in several ways. In the first paper, authors only describe known IPS categorizing them on a basis of positioning algorithms as well as the technologies used, while this paper concentrates on comparison of techniques for the purpose of fusing them in a tangible way. The second paper emphasizes security and privacy issues of indoor navigation, which is not in my scope of research.

It should be noted, that design of a complete navigation system may be quite a sophisticated task taking into account that it can be difficult to discover orientation or direction of the object, thus scope of this thesis was limited to detect an object in a certain known fixed location or report its presence.

Chapter 1

Indoor positioning methods

This chapter will review location positioning algorithm, i.e., the method for determining location, making use of various types of measurement of the signal such as TOF, angle, and signal strength.

1. **Proximity based method**, as shown in 1.1, determines position of an object based on its closeness to a reference point in physical space - beacon with known positions and limited range, so that only one or few beacons are visible to the mobile unit at any point. The client location is then approximated as that of the nearest beacon.

Figure 1.1: Proximity-based method

2. **Angle of arrival (AoA)** is a method for determining the direction of propagation of a radio-frequency wave, which requires only two beacons to estimate position in 2D (three beacons for 3D localization). (Fig. 1.2)

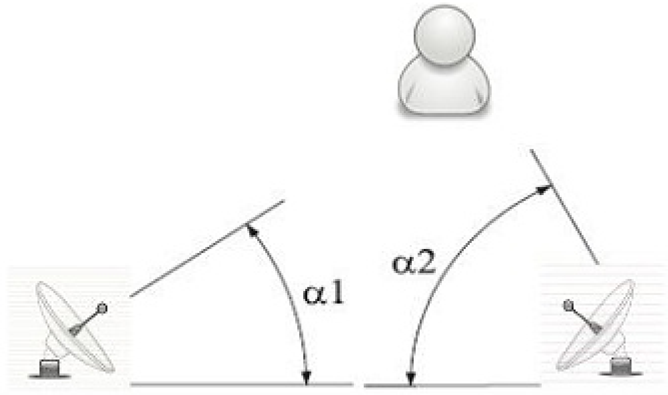

Figure 1.2: Angle of arrival method

3. In **time of arrival (ToA)**, Fig. 1.3, synchronized clocks in the base station and the client are used to measure the time delay between the two, while the time difference of arrival (TDoA) uses the difference of time it takes the signal from the client to reach each of the synchronized beacons.

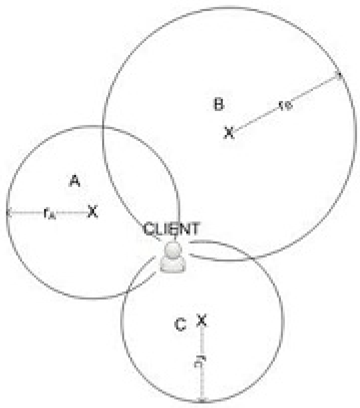

Figure 1.3: Time of arrival method

Finally, there are two different approaches that use Received Signal Strength Indication (RSSI), namely:

1. **Propagation modeling**, which attempts to build a model of the signal propagation in the space in order to identify the distance between the user and beacons, see Fig. 1.4. However, this approach is best suited for line-of-sight and obstacle-free propagation – conditions which are rarely met indoors.

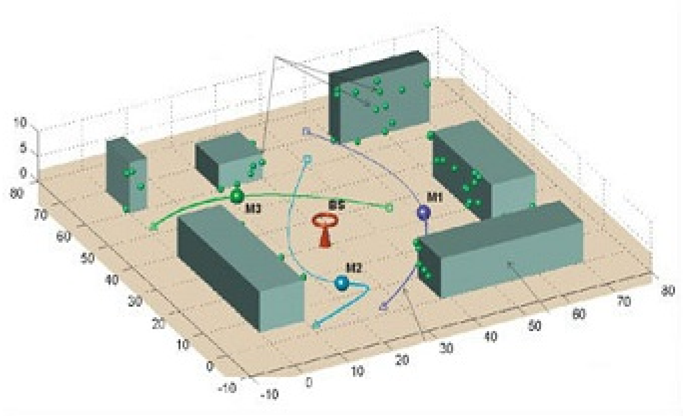

Figure 1.4: Propagation modeling method

2. **Fingerprinting**, as shown in Fig. 1.5, consists of two phases: calibration and localization. It relies on a database associating RSSI measurements with corresponding coordinates and then uses statistics and machine learning algorithms in order to recognize user position among those learned during the training phase [32].

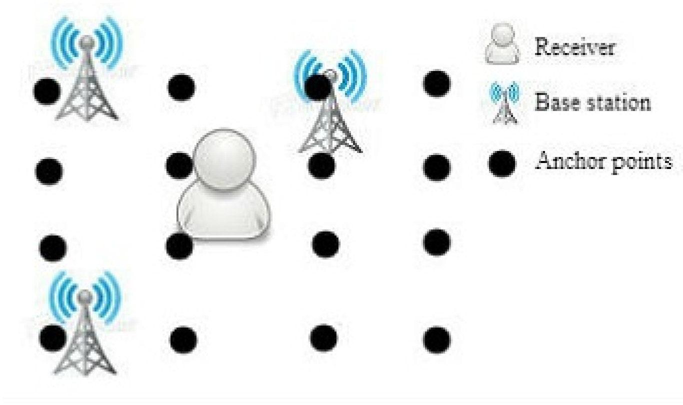

Figure 1.5: Fingerprinting method

Indeed, to handle with ambiguity of signals any locating service requires at least three independent measures per target, to which some mathematical algorithm must be applied subsequently to combine several sensors inputs with the idea to reduce error accumulation or compensate discrepancies in collected values.

In the following section, existing indoor positioning technologies will be described.

Chapter 2

Wireless technologies

2.1 GSM & CDMA

2.1.1 Overview

Cellular networks, such as GSM and CDMA, are well-developed technologies with more than 7 billion worldwide GSM subscribers[1] and more than 500 million CDMA subscribers in 2013[2] were not considered for indoor localization for a long time due to the low accuracy demonstrated in outdoor settings and typically do not show reasonable potential indoors because the signal strength is too low to penetrate a building.

Generally speaking, the accuracy is higher in densely covered areas (e.g. urban areas) and much lower in rural environments.

Indoor positioning based on mobile cellular network is possible if the building is covered by several base stations or one base station with strong RSS received by indoor mobile clients.

2.1.2 System example

Otsason et al.[28] presented a GSM-based indoor localization system, which uses wide signal-strength fingerprints. The wide fingerprint includes the six strongest GSM cells and readings of up to 29 additional GSM channels, most of which are strong enough to be detected but too weak to be used for efficient communica-

[1] http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2014-e.pdf

[2] http://www.statista.com/statistics/206604/global-wireless-subscription-growth-by-technology-since-2010/

tion. The higher dimensionality introduced by the additional channel dramatically increases localization accuracy. The results for experiments conducted on signal-strength fingerprints collected from three multifloor buildings using weighted kNN technique showed that their indoor localization system does a reasonable job differentiating between doors and achieves median accuracy between 2.5 and 5.4 meters.

Speaking about localization using CDMA, CILoS is based on delays finngerprinting, an empirical localization technique that involves a training or mapping phase in which a radio map of the environment is constructed by collecting a series of fingerprints in multiple locations. Using a special Condor CDMA scanner, it was able to evaluate signal delays from nearby stations. Unlike the RSSI, signal delays were found to be rather stable in time and resilient to cell resizing. Using signal delay fingerprints, this system reached median localization accuracy between 4.5 and 6.7 m. [35]

2.1.3 Conclusion

Cellular network based indoor positioning systems have three main advantages:

- Coverage: unlike Wi-Fi, the GSM/CDMA networks are currently widely available in most countries; the size of large macrocells can reach 30 km.
- Low cost: While GSM/CDMA base stations are themselves very expensive (up to 1 million USD)[3], the costs are covered by the cellular network operator (and ultimately, the subscribers). Thus, the positioning system can exploit readily available stations and does not require installation of a dedicated indoor infrastructure as Wi-Fi does.
- Battery life: Although a cellular transceiver module is rather battery consuming even in an idle state, in many scenarios it remains powered in order to provide the voice or data connectivity. Thus, the overhead introduced by a positioning system relates only to location estimation and excludes powering additional wireless module, which is often the case for Wi-Fi.

However, GSM/CDMA positioning has also several shortcomings:

- Low accuracy: The presented works [28] [35] rely on the use of wide fingerprints in order to provide a good accuracy. Acquisition of extended data, however, requires special hardware (programmable GSM modem and CDMA scanner),

[3] Otsason, A.V. Accurate GSM indoor localization, 2005

with the narrow fingerprints which could be acquired with conventional hardware, the localization accuracy was rather low.

- Low reliability: Given that GSM/CDMA beacons are situated outdoors, the signal propagation conditions vary due to environmental factors, such as weather and terrain. In particular, radio signals with frequencies above 1 GHz are affected by rain scatter interference and terrain vegetation; trees in leaf can cause a 20% higher attenuation than leafless trees. In theory, these factors can significantly affect the positioning performance; however, no experimental studies are available yet. [32]

2.2 WLAN (IEEE 802.11) based systems

2.2.1 Overview

This midrange wireless local area network (WLAN) standard, operating in the 2.4-GHz Industrial, Scientific and Medical (ISM) band, has become very popular in public hotspots and enterprise locations during the last few years. With a typical gross bit rate of 11, 54, or 108 Mbps and a range of 50–100 m, IEEE 802.11 is currently the dominant local wireless networking standard.

It is, therefore, appealing to reuse an existing WLAN infrastructure for indoor location as well, which lowers the cost of indoor positioning system deployment. [21]

The accuracy of location estimations based on the signal strength of WLAN signals is affected by various elements in indoor environments such as movement and orientation of human body, the overlapping of Access Points (AP), the nearby tracked mobile devices, walls, doors, etc. The influence of these sources and their impacts have been discussed and analyzed in the literature. [14]

2.2.2 System example

One of the pioneering projects in RSSI-based Wi-Fi positioning was RADAR. The authors applied both propagation modelling and fingerprinting, employing signal strength and signal-to-noise ratio with the triangulation location technique. The multiple nearest neighbors in signal space (NNSS) location algorithm was proposed, which needs a location searching space constructed by a radio propagation model. The RADAR system can provide 2D absolute position information and thereby enable location-based applications for users. In the experiments of the RADAR system, three APs measured the signal strength of the RF signals from the target. Then these measurements were used to calculate a 2-D position of the object. The median error distance of fingerprinting method is 2.94 meters. Also the error distance for tracking the moving user is 3.5 meters that is about 19% worse than for a stationary user, while the radio propagation model with the 50th percentile provides an error distance of about 4.3 m.

It was also stated that despite the physical proximity between points on adjacent floors, signal aliasing between a point on a floor and the corresponding point on an adjacent floor is unlikely because the floor acts as a significant barrier to signal propagation. Based on measurements, authors conclude that RADAR would work well in a multi-floor environment. Of course, a radio map of all of the floors, not just of one floor, would have to be constructed. [5]

2.2.3 Enhancements and remarks

RADAR was improved by the original authors putting Viterbi-like algorithm instead of NNSS and NNSS-AVG. It significantly improves accuracy, outperforming both of them, for instance, the median error distance for NNSS (3.59 m) and NNSS-AVG (3.32 m) are 51% and 40% worse, respectively, compared to Viterbi-like algorithm (2.37 m). [5]

Brunato and Battiti compared the performance of Wi-Fi fingerprinting localization for several machine learning methods, such as multi-layer perceptron (MLP), support vector machine (SVM) and k-nearest neighbor (kNN), both weighted and unweighted. The SVM approach demonstrated the best median accuracy (2.75 m). Notably, the median performance of a simple unweighted kNN classifier was only 0.16 m less, while 95th percentile errors were almost the same (6.09 m for SVM and 6.10 m for kNN). [6]

Chen et al. investigated the dependence of the Wi-Fi positioning accuracy on such environmental factors as humidity, doors, and people presence. Door states (all open or all closed) and people presence in receiver's vicinity were found to have a significant impact on positioning error (236% and 86% increase, respectively), while the humidity had smaller effect (43% increase). While such degradation of performance is typical for fingerprinting based systems, the impact of each component varies with signal frequency: when the obstacles are small in comparison to wavelength, their interaction with the wave is negligible. [12]

2.2.4 Conclusion

After all, Wi-Fi based positioning systems have several advantages, such as:

- Leveraging the already widely deployed infrastructure,
- Wide availability in mobile devices,
- Good accuracy.

However, there are certain limitations:

- Limited coverage. Despite the popularity, the coverage of Wi-Fi networks are mostly concentrated in office buildings and dense urban areas. Wi-Fi networks are rare in less populated cities and developing countries
- Interference. The 2.4 GHz industrial, scientific and medical (ISM) band used by Wi-Fi is shared by many other electronic devices, such as cordless phones and microwave ovens, which may interfere with Wi-Fi signals and affect the positioning accuracy.
- Power consumption. Another factor is power efficiency of the positioning system, especially on the battery powered mobile devices. Wi-Fi modules have a substantial power consumption about 300 mW in idle power-saving mode[4], which shortens the battery life of the mobile device.

2.3 Bluetooth (IEEE 802.15) based systems

2.3.1 Overview

Bluetooth, the IEEE 802.15.1 standard, operates in the 2.4-GHz ISM band. Bluetooth enables a range of 100 m (Bluetooth 2.0 standard) communication and it's highly ubiquitous, being implanted in various types of devices such as mobile phones, laptops, desktop PC's, etc.

Bluetooth chipsets are small size transceivers of low cost: the high expected production volumes (hundreds of millions annually) lead to less than 5 USD per chip, which results in low price tracked tags used in the positioning systems.

[4] Anand, M. et al. Self-tuning wireless network power management

Moreover, Bluetooth hardware and communication protocol have been designed with a focus on low power consumption. All of this makes Bluetooth an interesting technology for indoor positioning, and there are several works [42], [17] dedicated to Bluetooth based localization systems.

However, the coverage of such systems is very limited due to the short range of Bluetooth modules, and, more importantly, the lack of stationary Bluetooth devices. Another drawback is that each location acquisition runs the device discovery procedure, which significantly increases both the localization latency (10–30 s) and power consumption. [32]

2.3.2 System example

The Topaz location system is a local area positioning software and hardware system that calculates local position of Bluetooth tags and other devices (e.g. mobile phones, PDAs, etc.).

By using Bluetooth technology, Topaz can only provide 2-D location information with an error range of around 2 m, which is not sufficient to provide room level accuracy in a multi-obstacle indoor environment. Thus the Topaz system combines the Tadlys' Bluetooth-based positioning infrastructure with IR-based positioning technique, where IR location technology is suitable for this goal.

This modular positioning solution consists of positioning server, IR-enabled wireless access points, and wireless tags as well as software parts for local positioning of Bluetooth tags.

The system's performance makes it suitable for tracking humans and assets. A score of objects can be tracked simultaneously. This system provides roomwise accuracy (or, alternatively, 2 m. spatial accuracy), with 95% reliability. The positioning delay is 15–30 s. And the tags using batteries need to be charged once per week, which is a short period compared with tags used in other positioning systems. [42]

2.3.3 Enhancements and remarks

Another Bluetooth-based system example presented by [17] consists of several fixed stations and a mobile station and then applies the trilateration method to three to five distance measurements. One of the fixed stations is connected to PC, which serves as a position calculation server. Each fixed station and the mobile station are composed of a Bluetooth module and a microcomputer. Density of stations was 0.02 st./m2 (6 stations in 15*20 m area). To overcome the attenuation of a human body an additional mobile station was attached on a subject's back resulting in an improvement of standard deviation from 2.8 m to 1.9 m and with higher density of fixed stations obtained accuracy is 1.2 m, which is satisfactory for positioning in typical workshops or roomwise positioning in cluttered environment.

2.3.4 Conclusion

To conclude, advantages of Bluetooth-based positioning systems are:

- Deployment of devices, already equipped with Bluetooth technology,
- Low-cost solution,
- Low power consumption,

While the disadvantages of Bluetooth-based positioning system are:

- Accuracy only from 1.5 m to 3 m with the delay of about 20 s.,
- Susceptibility to interference in ISM band. [14]

Therefore, Bluetooth is commonly agreed to be unsuitable for localization systems, unless future Bluetooth specification decides to make Received Power (RX) level available not only through Received Signal Strength Indication (RSSI), currently defined very loosely, but directly. [19]

2.4 FM-radio based systems

2.4.1 Overview

Potential of FM-based positioning as-of-yet is not so well-investigated comparing it to Wi-Fi positioning technique, which is prevailing now on the indoor positioning market.

FM radio employs the frequency-division multiple access (FDMA) approach which splits the band into a number of separate frequency channels that are used by stations. FM band ranges and channel separation distances vary in different regions, as shown in Table 2.1

Hereafter, under "FM" we generally imply radio waves of the corresponding frequencies rather than to modulation type.

Table 2.1: FM broadcast frequencies and channel spacing in different region

Region	**Frequency range**	**Channel spacing**
Europe	87.5 – 108.0 mHz	100 kHz
US	87.7 – 108.0 mHz	200 kHz
Japan	76.0 – 90 mHz	100 kHz

Table taken from [32]

The major difference of FM radio signals from other technologies, such as Wi-Fi, GSM or DECT, is defined by the significantly (9 to 50 times) lower operational frequencies. The low frequency provides the FM localization with a number of advantages:

- FM signals are less affected by weather conditions,
- Low frequency radio waves are less sensitive to the terrain conditions,
- The attenuation of radio waves by building materials increases with frequency and thus FM signals penetrate walls more easily than Wi-Fi or GSM.

One of the problems related to FM is the so-called capture effect, the phenomenon in which only the station with the strongest signal will be demodulated and reach the receiver's output, while the other will be attenuated.

The most crucial problem of using an FM signal, however, is that they do not carry any timing information, which is a critical factor in range calculation. Measurements that can be taken from FM signals for navigation purposes are based on: Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Received Signal Strength (RSS). For the first three methods, the lack of timing information in FM signals is critical. Hence, the most appropriate choice is localization based on RSS and signal propagation modeling. [25]

2.4.2 System example

In [25], authors chose a fingerprinting technique of an area 11*23 m consisting of 7 rooms with the corridor, which is a typical indoor office environment and filled it with 150 Reference Points (RP), 28 Test Points, that people are most likely to require and took 17 FM channels from 88 to 108 MHz. Then, applying the K-nearest neighbor and K-nearest weighted neighbor algorithms, they have acquired results around 3 m.

Another example of positioning system based on FM signals so called FINDR [30] also uses short-range FM transmitters as wireless beacons and measures Received Signal Strength (RSS) by a fingerprinting approach.

Their results were strongly correlated to previous works, meaning the results of the system evaluation have shown a median accuracy of about 1.0 m and 5.0 m at 95% confidence level, which was close to Wi-Fi characteristics in chosen conditions.[30]

Further evaluation of FINDR by the same group has shown some improvement by using KNN algorithm and Gaussian Process (GP) regression. The median estimation error (50th percentile) of the system was 0.97 m for GP and 0.93 m for kNN while 95th percentile error was 2.65 m for GP and 3.88 m for kNN. [23]

2.4.3 Conclusion

FM technology has some advantages:

- Availability in majority of stationary and mobile devices,
- Power effectiveness: on average Wi-Fi consumes around 300 mW, while FM receivers consume around 15 mW. [43], [44]
- Safety in particular environments, e.g. medical facilities, where Wi-Fi cannot be used because of interference with many other electronic devices,
- Cost-effectiveness: an FM transmitter is up to 10 times cheaper than a Wi-Fi access point while also widely available off-the-shelf.

Still, there are drawbacks of using FM technology for indoor positioning, mainly

- Multipath,
- NLOS signals,
- Capture effect,
- No timing information.

2.5 RF based systems

2.5.1 Overview

The radio frequency identification (RFID) is a means of storing and retrieving data through electromagnetic transmission to an RF compatible integrated circuit.

It is widely used for asset tracking, shop security systems and complex indoor environments such as office, hospital, etc. Due to the short communication range (dozens of centimeters), it provides a good localization accuracy. The short reading distance, however, also significantly limits its possible application areas.

There are two kinds of RFID technologies, passive RFID and active RFID, as shown in Table 2.2

With passive RFID, a tracked tag is a receiver, thus the tags with passive RFID are small and inexpensive, but the coverage range of tags is short.

Active RFID tags are transceivers, which actively transmit their identification and other information, thus their cost is higher, on the other hand, the coverage area of active tags is larger. [21]

Table 2.2: Active and passive RFID comparison

	Passive	**Active**
Read range	Up to 40ft (fixed reader) and up to 20 ft (handheld reader)	up to 300ft
Power	No power source	Battery-powered
Tag life	Up to 10 years depending upon the environment	3-8 years depending on a tag
Tag costs	from 10cents to 4 USD	from 15 to 50 USD
Perfect use	Assets inventorying, assets tracking	Real-time asset monitoring
Readers	Typically higher cost	Typically lower cost

Source: www.inlogic.com/rfid/passive_vs_active.aspx

2.5.2 System example

From the variety of IPS based on RFID the one that can be regarded as a showcase is LANDMARC. Its prototype uses the RFID reader's operating frequency with 308 MHz. In order to increase accuracy without placing more readers, the system employs the idea of having extra fixed location reference tags to help location calibration.

These reference tags serve as reference points in the system. The LANDMARC approach requires signal strength information from each tag to readers, if it's within the detectable range. Then, the kNN method is adopted to calculate the location of the RFID tags. It is reported that the 50 percentile has an error distance of around 1 m while the maximum error distances are less than 2m for LANDMARC system. [27]

2.5.3 Conclusion

RFID-based IPS have plenty of valuable advantages for positioning, such as:

- Size, weight and cost of tags which could be tracked or embedded in a given location,
- Possibility of unique identification of multiple objects,
- Remarkable accuracy compared to other technologies.

However, while RFID based systems can accurately detect proximity and determine absolute position, its drawbacks are:

- Dense infrastructure is required to fully cover big working area,
- Sporadic location updates,
- Rather short battery life.

Based on the above, RFID based systems are considered unsuitable for general-purpose indoor localization. [32]

2.6 UWB systems

2.6.1 Overview

UWB is based on sending ultrashort pulses (typically <1 ns), with a low duty cycle (typically 1:1000).

Unlike conventional RFID systems, which operate on single bands of the radio spectrum, UWB transmits a series of signals in the time domain, which in turn spreads information over multiple bands of frequencies simultaneously, from 3.1 to 10.6 GHz.

UWB ranging systems often measure the time of arrival (TOA) of signals travelling between a target node and a number of reference nodes. The transmitter is either a mobile unit placed on the pedestrian, or an "access point" mounted on a known location inside the building. Three TOA are necessary to estimate the mobile position, which requires the receiver and the transmitter clocks to be precisely synchronized. This difficulty can be avoided by using time difference of arrival (TDOA), because UWB systems can also measure the angle of arrival (AOA) of radio signals in order to determine positions.

Two different angles are measured for each AOA; one of them is measured in a vertical plane, and the second is measured in the horizontal plane. Two measures of AOA from, at least, two different access points are necessary to compute the target location. [29]

2.6.2 System example

One of the systems, which demonstrated very good localization accuracy, is Ubisense - commercially available indoor localization system, which employs TDOA and AOA methods for UWB radio signals. It consists of a central computer equipped with the Ubisense software platform connected with all access points, which computes 3D positions of the mobile unit and controls the pulses emission frequency to the mobile. Ubisense is capable of achieving 15-30 cm accuracy in three dimensions. However, the system has a very high cost (An active research package costs about 16875 USD) which severely impacts wide adoption. [21]

2.6.3 Conclusion

The main advantages of utilizing UWB for positioning purposes are:

- Extreme accuracy because of a very large signal bandwidth and short pulse duration,
- Less power consumation than conventional RF tags and ability to operate across a broad area of the radio spectrum,
- Reduced interference to other RF signals and systems because of the absence of carrier frequency and the low power spectral density,

- No multi-path distortion: UWB short duration pulses are easy to filter in order to determine which signals are correct and which are generated from multipath, which is essential in localization applications.
- No LOS requirement and high penetration ability resulting in a possibility of a UWB signal to easily pass through walls, equipment and clothing. [21]

Despite promising technical characteristics, the disadvantages of UWB positioning are:

- Strong signal interference with metallic and liquid materials highly affects UWB positioning performance,
- Communication distance of UWB is only 10 m, well lower than Wi-Fi, RFID and other IPSs,
- High infrastructure cost. [29]

2.7 Ultrasound positioning systems

2.7.1 Overview

Making use of ultrasound technology for positioning is rather simple: inexpensive nodes (badges/tags) attached to the surface of persons, objects and devices, which then transmit an ultrasound signal to communicate their locations to microphone sensors.

Because ultrasound signal wavelengths have short reach, they are confined to lesser distant locations than with wireless transmissions with higher susceptibility to multiple reflection, multipath and through-the-wall multiple room responses. Hence ultrasound-based RTLS is considered a more robust alternative to passive radio-frequency identification (pRFID) and even to active radio-frequency identification (aRFID) in complex indoor environments (such as hospitals), where radio waves get multiply transmitted and reflected, thereby compromising the positioning accuracy.

2.7.2 System example

Cricket is a location system with the aim of offering user privacy, efficient performance and low cost. The cricket system uses TDOA measuring method and triangulation location technique to locate a target.

The cricket system includes ultrasound emitters as infrastructure attached on the walls or ceilings at known positions, and a receiver mounted on each object to be located. This approach provides privacy for the user by performing all the position triangulation calculation locally in the located object, which allows the located object to decide how and where to publish its location information.

The Cricket system uses emitters fixed on the ceiling, while the target object receives and processes the ultrasound signals to locate itself, which allows the system is scalable for large area deployment inside a building, and the object receiver is cheap (about 10 USD), so the cost of the whole system is low.

Moreover, the Cricket system can provide a position estimation accuracy of 10 cm and an orientation accuracy of 3°. However, the located receivers in the system perform location estimations and receive both ultrasound and RF signal at the same time.

Thus a receiver in the cricket system consumes more power, and its power supply needs to be designed in an efficient way to bring convenience to the users instead of frequently changing batteries in the receiver [8]

2.7.3 Conclusion

Benefits of ultrasound positioning systems are:

- Low price compared to UWB and RFID-based systems,
- Basically low coverage area.

And as drawbacks of such systems can be stated:

- They usually have to be combined with RF signals, which perform synchronization and coordination in the system,
- Incredible sensibility even to small obstacles, reflected ultrasound signals and other noise sources such as hanging metal objects, crisp packets, etc. [21]

2.8 Optical indoor positioning

2.8.1 Overview

Optical indoor positioning systems can be categorized into ego-motion systems where a mobile sensor (i.e. the camera) is to be located and static sensors that locate moving objects in the images. All camera-based system architectures measure image coordinates that represent only angular information and exclusively built on the Angle of Arrival (AoA) technique. There are different systems approaches in optical positioning classified by reference:

- **Reference from 3D building models**:

  This class of positioning methods relies on the detection of objects in the images and matching those objects with a building data base (such as CityGML) that contains position information of the building interior. The key advantage of these methods is that there is no requirement for the installation of local infrastructure such as the deployment of sensor beacons.

- **Reference from images**:

  The so-called view-based approach relies on sequences of images taken beforehand by a camera along certain routes in the building. Thereby, the current view of a mobile camera is compared with these previously captured view sequences. The main challenge of this approach is to achieve real-time capability. For the identification of image correspondences the computational load is particularly high since operability is assumed without deployed passive or active optical targets. Nevertheless, all systems require an independent reference source from time to time in order to control the accumulated error.

- **Reference from deployed coded targets**:

  Optical positioning systems that rely entirely on natural features in the images lack of robustness, in particular under conditions with varying illumination. In order to increase robustness and improve accuracy of reference points, dedicated coded markers are used for systems with demanding requirements for positioning. Common types of targets include concentric rings, barcodes or patterns consisting of colored dots. There are retro-reflective and non-reflective versions.

- **Reference from projected targets**:

  The projection of reference points or patterns spares the physical deployment of targets in the environment, making this method economical. For some applications the mounting of reference markers is undesirable or not feasible. In contrast to systems relying only on natural image features, the detection of projected patterns is facilitated due to their distinct color, shape and brightness.

- **Systems without reference**:

  The purpose of systems in this class is to observe position changes of objects directly and therefore do not require external reference. The common approach is to track mobile objects with high frame rates in real-time by a single or multiple static cameras. [24]

2.8.2 System example

Kohler et al. have built a model called TrackSense consisting of a projector and a simple webcam. Then grid pattern is projected onto plain walls in the camera's field of view. Using an edge detection algorithm and triangulation, the distance and orientation to each point relative to the camera is computed. The evaluation of TrackSense indicates that such a system can deliver up to 4cm accuracy with 3cm precision. [18]

2.8.3 Conclusion

Main benefits in using optical PS are:

- Low-cost camera can cover a large area,
- Users don't need to carry any additional device and can be tracked only by camera.

But this approach has significant drawbacks:

- The privacy of people is not provided by such kind of a system,
- Vulnerability to many interference sources (light, weather, etc.),
- Less robust in a dynamic changing environment,
- Tracking multiple objects simultaneously can be a hard task even for a smart camera. [14]

2.9 IR-based

2.9.1 Overview

IR-positioning systems are very common positioning systems because IR-technology is available in various wired and wireless devices such as TV, printer, mobile phones, etc.

An IR-based positioning system, which offers absolute position estimations, every node emits IR impulses, which are received by stationary catchspot (receiver) and location then is computed by the TOF. It requires line-of-sight communication between transmitters and receivers without interference from strong light sources. Thus the coverage range per infrastructure device is limited within a room.

2.9.2 System example

OPTOTRAK PROseries was designed by Northern Digital Inc. for congested shops and workspaces. It uses system of three cameras as a linear array to track 3D positions of numerous markers on an object, which can cover a volume of 20 cbm and a maximum distance between tracked targets and the tracker is about 6.0 m. The system is a type of active system, where markers mounted on different parts of a tracked object emits IR light that is detected by the camera to estimate the location of them. The triangulation technique is used in the positioning process to calculate the positions of IR light emitters in the space. The system can offer a high accuracy of 0.1 mm to 0.5 mm with 95% success probability [31]

2.9.3 Conclusion

- Very accurate positioning estimations (mm.),
- IR emitters are small, light-weight and easy to be carried by a person,
- The system architecture is simple and does not need time-consuming installation and maintenance.

However, certain disadvantages of IR-based systems prevent it from general usage:

- Interference from fluorescent light and sunlight,

- Expensive system hardware requirements. Although the IR emitters are cheap, the whole system using camera array and connected via wires is expensive comparing to the coverage area,
- The system fails to work, when an IR device is taken by a person covered by his/her clothes since the IR wave cannot penetrate opaque materials. [21]

2.10 Other positioning systems

MEMS result from the integration of mechanical and electrostatic elements on a common substrate. Sensors based on this technology are essentially accelerometers, gyroscopes and magnetometers. Inertial data from these systems are used for dead reckoning navigation where the current position is estimated by accumulating movements determined using onboard measurements. The advantages of inertial measurements are their regularity and their independence from any existing infrastructure. MEMS hardware is also compact and relatively cheap compared to other high-end inertial systems.

The magnetic positioning systems offer high accuracy and do not suffer from the line-of-sight problems, where the positions are measured in the case of an obstacle between the transmitters and receivers. For example, MotionStar Wireless is a motion tracking system that uses pulsed direct current magnetic fields to simultaneously locate up to 120 sensors within 3 m coverage area in real time. The systems consist of a transmitter and controller, a base station, mounted sensors and RF transmitters. The transmitter and controller send magnetic pulses to the body mounted sensors, which The sensors are connected through wires to the RF transmitter, which is carried by the tracked person. Then RF transmitter transmits the measured data to the base station. Finally, the base station calculates the position and orientation of sensors and transfers the measured data to the user's computer. The error range of the static position estimating is about 1 cm. The update rate of the position measurements is up to 120 measurements per second. However, the disadvantage of the Motion Star system is that the magnetic trackers are quite expensive. The battery life time for continuous motion tracking is around 1 hour or 2 hours, which is a short period for daily position estimations and the performance of the Motion Star system is influenced by the presence of metal elements in the positioning estimating area. In addition, the coverage range of each transmitter is limited within 3 m, which is not scalable for large indoor public applications and services. [26]

Locata Corporation has invented a positioning technology called Locata, for precision positioning both indoors and outside. Part of the "Locata technology" consists of a time-synchronized pseudolite transceiver called a LocataLite. A network of LocataLites forms a LocataNet, which transmits GPS-like signals that allow single-point positioning using carrier-phase measurements for a mobile device. Indoor industrial machine tracking showed subcentimeter precision: crane moved to 9 known points and max position error was 1.8 cm, while max. absolute error in orientation test was 1.2° but multipath still caused problems. [22]

Chapter 3

Fusion proposal and its possible benefits

During last years the main problems in indoor positioning were identified and plenty of efforts were made to mitigate NLOS, multipath and achieve high-accuracy ranging. Compared with satellite channel of GNSS, indoor positioning faces terrestrial channel which is more complex. The high-accuracy ranging information based on time delay and Received Signal Strength (RSS) is the key information for positioning. The phenomenon like multipath and fast fading is much more serious in terrestrial channel, especially in urban indoor environment. [13]

3.1 Grounds for fusion

As it follows from the overview of technologies, at the present moment there is no technology for indoor positioning, which will satisfy various potential users, because neither of them is able to provide an accurate positioning for adequate amount of money.

For instance, Wi-Fi is not suitable for positioning in rural areas and prone to interference from 2.4 GHz devices; RFID and UWB while assuring cm-precision, require investments in a subject area.

The main idea behind this thesis is that by combining two or more techniques these bottlenecks could be avoided or at least diminished, it is well-known and has shown decent results. [9], [11]

Fusion of techniques, which complement each other, also can provide better accuracy or area coverage, but the selection must be done in an appropriate way in order to emphasize strength of both techniques.

My hypothesis is to use fingerprinting approach based on RSSI values from transmitters of both types (FM & Wi-Fi).

3.2 Selected method for fusion

Positioning methods, stated in introduction, are divided into geometry-based and RSS-based. Geometric positioning technique is widely applied in cellular, UWB, pseudolite, lasers and ultrasound positioning systems. This technology is easy to popularize, but the error increases while NLOS exists.

On the other hand, fingerprint positioning technology was firstly designed to be used with Wi-Fi RSS values and can mitigate NLOS error effectively, but it is limited by the heavy workload of fingerprint acquisition and the large amount of fingerprint database.

A number of factors that may cause fluctuations of fingerprints for a system using local beacons (Wi-Fi or local beacons), such as:

- Furniture layout in the room of interest,
- Furniture layout in nearby rooms,
- Air temperature and humidity,
- Temperature of the beacons' components (Wi-Fi access points may warm up under a heavy load),
- Presence of people.

Systems employing external beacons, such as broadcasting FM stations, have additional sources of uncertainty:

- Buildings and other large structures (especially RF-reflective),
- Weather conditions (rain, clouds, thunderstorms),
- Vegetation, season of the year.

Depending upon the type of the router, transmission power and the antenna (if present) orientation of the router, the RSS by the same receiver and at the same distance may vary. But, from the observations, whatever WLAN routers we use and whichever emitter topology, the statistical RSS distribution models remain rather similar and they depend only on the building structure (e.g., wall and floors materials, number of floors, room and window layout, etc). [37]

That is to say, signal strengths are consistent in time: the signal strength from a given source at a given location is likely to be similar tomorrow and next week, while also elimination the timing problem of FM signals. Also, it reduces the effect of multipath compared to other methods based on distance measurements. To conclude, this means that there is a radio profile that is feature-rich in space and reasonably consistent in time.

In April 2013 the Federal Communications Commission (FCC) Working Group 3 (WG-3) released results of intensive indoor location trials of various technology solutions. The tests trialed thousands of attempted location fixes in four representative morphologies (dense urban, urban, suburban, rural) and various building types.

The technologies used were: Qualcomm's hybrid AGPS/AFLT solution, NextNav's beacon transmitters deployed across an area and Polaris Wireless' RF fingerprinting. Results have shown, that the yield from Polaris was the best (96.9% in rural buildings), while QualComm failed in reliability of getting fix position, obtaining only 85.8% of test calls in all dense urban buildings. Then, from the overall location errors table can be concluded [1], that NextNav came out on top while having in mind that beacons solution is the most expensive, requires beacons infrastructure and specific receiver configured to decode NextNav readings. [46]

Based on the above, I decided to implement for my studies pattern matching approach (fingerprinting) for RSS values to compare signal strength of Wi-Fi and FM waves in order to locate myself in a testbed.

The biggest advantage of this approach is low cost while delivering high network accuracy performance and without need in equipping given building with beacons.

3.3 Techniques to be fused

In the following chapter the techniques, that I'm going to fuse, will be specified.

From all possible techniques used indoor, Wi-Fi-based positioning is the de-facto standard for indoor localization because of its abundance and well-elaborated characteristics.

[1] Overall trials results are in Appendix C

It has certain advantages such as possibility to use an existing infrastructure, decent accuracy and FM radio signals are less affected by weather conditions, such as rain or fog, in comparison to Wi-Fi or GSM. Low-frequency radio waves are less sensitive to terrain conditions, such as woodland and tree foliage. Amount of attenuation of radio waves, caused by building materials is directly proportional to the operating frequency therefore, FM signals penetrate walls more easily in comparison to Wi-Fi or GSM. The FM wavelength of around 3 m (from 2.78 m to 3.43 m in Europe and US) interacts differently with most indoor objects in comparison to the wavelength of 0.12 m of Wi-Fi waves. At low frequencies, when the obstacles are small compared to the wavelength, they do not interact significantly with the electromagnetic fields of the wave. The described considerations suggest that FM based indoor positioning has a number of theoretical advantages over the current high-frequency systems. [33]

Description of each selected technique starts with its basic SWOT analysis followed by properties, directly used for positioning.

3.3.1 Wi-Fi

Table 3.1: Wi-Fi SWOT chart

Strengths	**Weaknesses**
Well-explored Good in urban environment Low-cost infrastructure	Limited coverage in rural areas Interference with other devices Relatively high power consumption
Opportunities	**Threats**
WiMax Rich R&D Leading technology	Security Country-dependent features

Because my approach is to collect fingerprints in order to construct the so called open radio map of a building or a specific area inside it, my main interest in a Wi-Fi signal lies in a received signal strength, penetration and attenuation of a signal.

In an IEEE 802.11 system, RSSI is the relative received signal strength in a wireless environment, actually an indication of the power level being received by the antenna.

It is usually measured in dB and ranges from 0 to -100 and the higher the RSSI number, the stronger the signal. The 802.11 standard does not define any relationship between RSSI value and power level in mW or dBm.

Wi-Fi range is based on power of signal, for example for transmitting power 800 mW range is 30m.

Wi-Fi attenuation varies for different obstacles, for instance, interior office door worsen RSSI for 4 dB, 3.5' brick for 6 dB, interior office window for 3 dB. [34]

I will examine stability of a Wi-Fi signal in detail.

- Human body presence impact

  According to [15], the impact of human body blocking LOS is very small.

  [16] also reviews user's body influence on RSS distribution and states that by spreading the range of RSS values the standard deviation increased from 0.68 to 3 dBm where user was present and mean changed from -70.4 dBm to -71.6 dBm. I consider these values as insignificant for my system and therefore the presense of people were not taken into account later in experiments.

- Human body orientation impact

  During the offline phase the laptop was rotated by different angles in randomly chosen reference points and RSS of desired APs were measured. It is seen from the results[2] that the impact of human body orientation is small and can be neglected.

- Time of day fluctuations

  Of course, the 2.4 GHz range is well occupied by a lot of appliances from cordless phones to microwave ovens and Bluetooth devices and is highly affected by human activities, door openings and AP status changes (e.g. from active to non-active). [15] In order to get rid of such effects, the measurements in both offline and online phases were taken at a time frame from 4 PM to 6 PM.

- Number of APs impact

  Number of APs was picked intentionally, as works [32] show that more APs give better results but only up to some limit, after which system performance remains at the same level or even degrades, so there is little benefit in going beyond 3 APs in case of RF.

- Number of samples impact

  While it may be reasonable to construct the data set with a large number of samples, there may be constraints on the number of samples that can be obtained in real-time to determine a user's location. So investigation in [5] showed that only a small number of real-time samples is needed to approach

[2] The acquired values are in Appendix E

the accuracy obtained using all of the samples. With two samples it's only about 11% worse than using all samples (4 per second at each AP). Therefore, the number of samples was limited to 2 per each Reference Point.

3.3.2 FM

Table 3.2: FM SWOT chart

Strengths	**Weaknesses**
Availability Low power consumption Stable against weather and terrain conditions Better penetration through walls No interference	Capture effect No timing information Prone to multipath and NLOS
Opportunities	**Threats**
DAB and LPFM	Future obsolescense

For the sake of my work, I examine only FM broadcasting stations, which occupy frequencies from 88 to 108 MHz and send VHF (Very high frequency) signals.

VHF signals is less affected by atmospheric noise and interference from electrical equipment, it is less affected by buildings.

Average RX power of a broadcasting station is 40 mW, while range can be up to 40 miles LOS. From the characteristics of FM broadcast three features could be used for positioning purposes with a fingerprinting method: RSSI, SNR (Signal-to-ratio) and SCS (Stereo channel separation).

It was shown in [30], that SCS is suitable only for shorter distances between transmitter and receiver and the stereo-signal must be known and SNR demonstrates worse accuracy than RSSI, thus, only RSSI was used as a definitive feature of FM broadcast. It is usually measured in dB and ranges from 0 to 100 and the higher the RSSI number, the stronger the signal.

In the following I will examine conditions, which may or may not affect RSSI of FM broadcasting stations.

- FM beacon selection impact

  In order to detect the list of active FM channels the FM Pira receiver ran all the frequencies twice and those with the level of RSSI above the threshold of 25 were chosen. It should be noted, that not only stations with highest

RSSIs were chosen, but rather stations distributed in space between, because works show that indoor stronger stations have no advantage over weaker ones in positional sense, because FM signal RSSI varies mainly due to walls and other obstacles, which equally affect all beacons transmitting from the same direction despite their signal strength.

- Number of beacons impact

  Well-known that as the number of beacons increases, the accuracy of fingerprinting approach improves positioning accuracy, but only to some limit and further increase of beacons doesn't affect the accuracy, possibly due to external interference. With the 7 stations total accuracy of the system is only slightly inferior than using all 76 beacons (only 0.4m worse than full system using 10% of beacons).

- Human body presence impact

  It should be noted, that in the presence of people FM signals generally are not affected. The same work of showed, that for 80% of stations the shift in crowded and in empty environment was within 10%. However, the FM signal fluctuations increase manyfold in a crowded room, probably because that radio waves of FM band (about 100 MHz) are scattered by human bodies and not absorbed as Wi-Fi waves. [30]

3.3.3 Conclusion to RSSI properties

Firstly, I should note that modern Wi-Fi Access Points are able to adjust their power according to user needs, for example, via web-interface, but for our purpose it was not taken into account. Secondly, while it's a subject of research, the weather conditions (rain, sun, blocked line-of-sight outside, snow) were not taken into account as well.

Thirdly, no additional antenna was used in both offline and online phases for Wi-Fi receiver and only stock antenna for FM Pira receiver in both phases as well.

Depending on the properties of Wi-Fi and FM signals, I expect that RSS of both signals will be consistent in time, that fusion of techniques could make sense because of the similar nature of measurements and my assumptions will not impede the experiment much.

Chapter 4

System proposition

4.1 General approach

My proposition of localization system is based on the existing infrastructure of broadcasting FM stations and Wi-Fi Access Points as signal sources and embedded FM and Wi-Fi radio modules on client devices. This kind of system does not require any additional infrastructure, which can be a significant advantage over other indoor positioning systems.

The common method of finding active broadcasting stations during seek tuning, employed by virtually all FM receivers, is RSSI thresholding, where the receiver registers a broadcasting station at a specific channel if its RSSI level is above the predefined threshold.

As a fingerprint matching technique k-Nearest Neighbor (KNN) algorithm was employed. To examine the feasibility of fusing FM & Wi-Fi positioning signals to obtain one's position within defined area the experiments were performed in our faculty building.

4.2 Positioning approach

My approach follows the general fingerprinting method and consists of two phases:

1. Offline training (surveying) phase, which collects RSS samples at reference positions and builds a training database,

2. Online determination phase which calculates the location of a mobile user by

comparing the measured RSS values with the training database and subsequently uses kNN algorithm to determine the location of a user.

It should be noted that locations of APs weren't determined, because in fingerprinting approach it's not needed.

4.3 Classification approach

In a fingerprinting-based positioning system there is a task to associate acquired fingerprints with locations using the data collected during offline phase.

The classification approach considers vector with values at each reference location as a discrete class. Given a fingerprint, a classifier returns the class to which this fingerprint most likely belongs. This method considers each location independently and almost immediately returns the closest class. As an output format this approach produces a class label only from those, that were present in the training data. Thus, the positioning accuracy of classification approach is limited to granularity of the calibration data.

4.4 kNN algorithm

The kNN algorithm is a simple yet powerful classification method. It determines the K most likely locations of a mobile user. Among these locations usually the one with the lowest difference from stored value is selected.

The algorithm works as follows:

Given a fingerprint to classify, it evaluates the distances in signal space from this fingerprint to the fingerprints in the training set. Then a specific distance metric has to be used and this thesis utilizes commonly used Euclidean distance metric,

$$D = \sqrt{\sum_{i}^{n} y_i^2}$$

where y_i is a difference between each element of stored vector of measurements and currently recorded vector.

In this case, however, the K most likely locations instead of 1 location were selected and then resulting one was evaluated because experiments show that sometimes actual location may not be the location with the lowest Euclidean distance.

The advantages of kNN algorithm are:

- fast training phase, which comprises only storing training data,
- often the best positioning performance, [20], [36], [41]
- superior performance in obstructed areas (indoors), [10]

Thus, the kNN algorithm was applied as the main classification approach in this thesis.

4.5 Related work

One of the most elaborated works based on FM signals is called FINDR and also uses short-range FM transmitters as wireless beacons and measures Received Signal Strength (RSS) by a fingerprinting approach.

Their results had strong correlation to what was done before, meaning the results of the system evaluation have shown a median accuracy of about 1.0 m and 5.0 m at 95% confidence level, which was close to Wi-Fi characteristics in chosen conditions. [30] Further evaluation of FINDR [23] by the same group has shown some improvement by using KNN algorithm and Gaussian Process (GP) regression. The median estimation error (50th percentile) of the system was 0.97 m for GP and 0.93 m for kNN while 95th percentile error was 2.65 m for GP and 3.88 m for kNN.

Also worth mentioning the work of [11], who used the same principle of RSS and getting database of fingerprints by combining FM & Wi-Fi, which gives notable result that combination of WiFi and FM signals into a single signature provides up to 83% higher localization accuracy compared to WiFi only RSSI fingerprinting. In addition to this, paper discovered that to achieve the maximum localization accuracy (i.e., accuracy when all radio stations or access points are used), 30 FM radio stations and approximately 50 Wi-Fi access points are required.

Altintas et. al. present a short term memory scheme using previous WLAN RSS observations to smooth error distance during the online determination phase. The shorter the distance to the prior position, the higher probability of the current position. [2]

Chapter 5

System implementation

5.1 Testbed

Two rooms in the Konvitska faculty building were used as a testbed, located right above each other.

K305 (Prednaskovy Sal), as shown in Fig. 5.1 and K404 classroom, Fig. 5.2 The former is approx. 17*9 meters, which was transformed into 2D 3*9 grid, while the latter is 9*7, which resulted in 5*3 grid.

In both locations dimensions of each cell are approx. 2m*1.5m.

It should be noted, that K305 is almost 2 times bigger than K404, so only rows from 1 to 5 in K305 are directly adjacent to K404.

Figure 5.1: K305 lecture hall

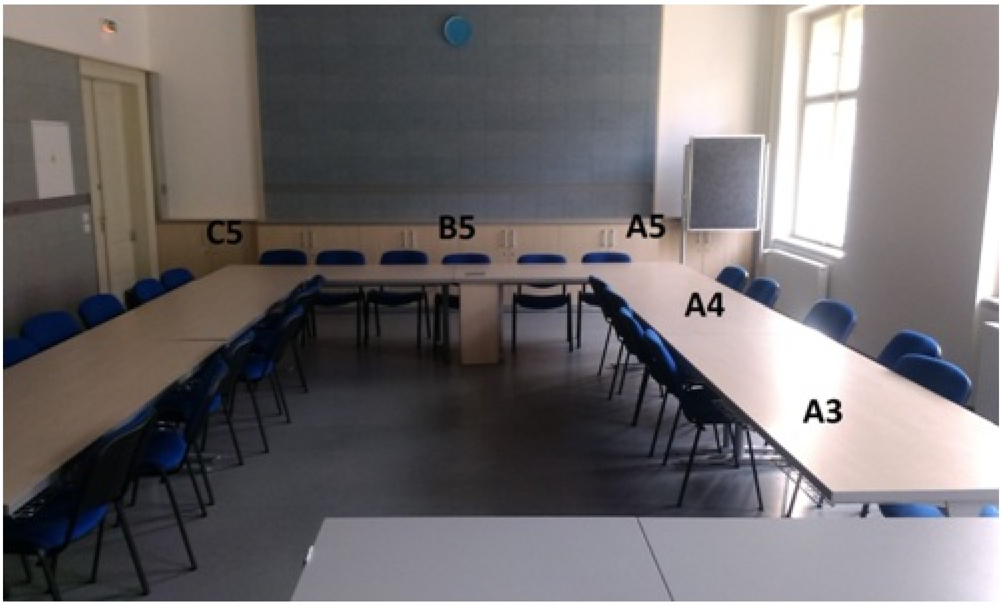

Figure 5.2: K404 classroom

5.2 Data collection setup

First phase in the fingerprinting approach was "training phase", where two mobile devices were moved through the testbed recording the strength of signals. On one side, Lenovo laptop running under Windows 7 with external D-Link DWA-121

Wireless Adapter was collecting RSSIs from 7 Wi-Fi Access Points with the help of MetaGeek© Wi-Fi inSSIDer application, see Fig. 5.3.

Figure 5.3: Experimental setup

First step in the surveying phase is to pick only channels that don't overlap and have a significant distinction in frequencies:

1. eduroam 802.11g, freq: 2427 GHz, channel 4
2. eduroam 802.11n, freq: 2472, channel 13
3. eduroam 802.11n, freq: 2457, channel 10
4. Bagr 802.11n, freq: 2412, channel 1
5. Julka 802.11n, freq: 2472, channel 13
6. Elissei.com 802.11n, freq: 2467, channel 12
7. K401 802.11n, freq: 2437, channel 6

inSSIDer application, as shown in Fig. 5.4 allows to calculate average value, when the signal varies, e.g. when it's oscillates from 82 to 74, the average was taken as 78 dBm.

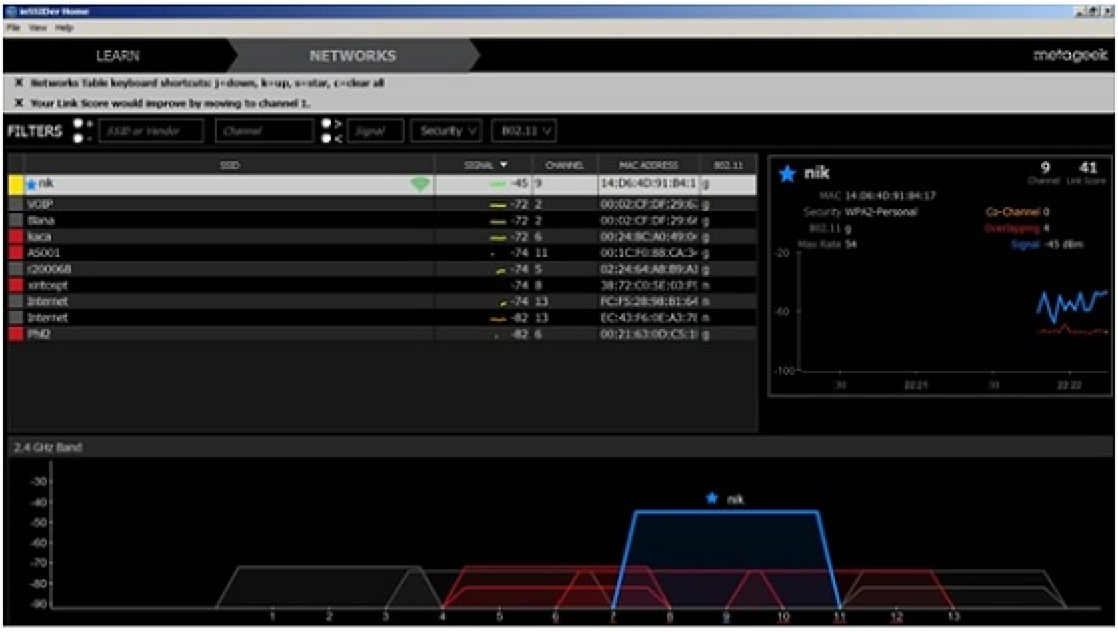

Figure 5.4: inSSIDer application window

Another option to retrieve RSSI values is using "netsh" command in Windows systems and then calculate RSSI values from quality in % to dB with the Signal-to-Noise formula, but it wasn't taken into account.

It should be stated, that values were collected twice within the time interval of 10 minutes and average value was calculated from them.

In total, 294 fingerprints from 7 Wi-Fi APs in 42 cells were acquired.

On the other side, I engaged Pira FM Analyzer and its software "FM scope". FM Scope has a very useful feature "BandScan", which scans all FM range and gives stations, their strengths and frequencies as a result. Thanks to it, we're able to choose 7 broadcasting stations with most diverse signals, while at the same time export RSSI values to a text file for post-processing:

1. frequency 90.3
2. frequency 91.9
3. frequency 92.6
4. frequency 96.2
5. frequency 98.1
6. frequency 99.7

7. frequency 103.6

C6 in K305 is located right under C1 in K404, so these cells' bandscans (Fig. 5.5 and Fig. 5.6) were picked for visibility reasons. While the pattern is basically the same, the chosen frequencies have the biggest differences in these adjacent cells.

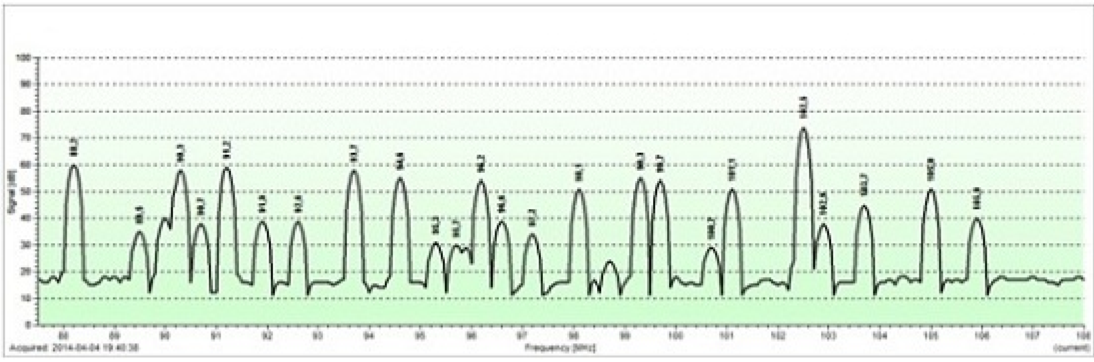

Figure 5.5: Bandscan of C6 in K305

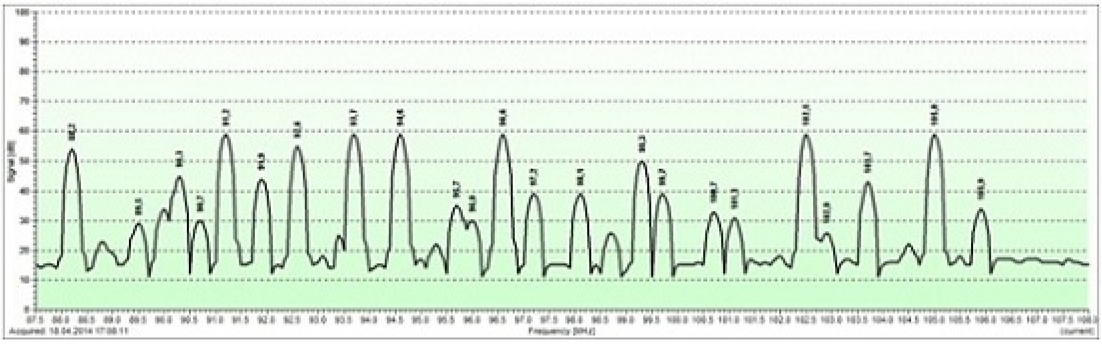

Figure 5.6: Bandscan of C1 in K404

Finally, the database associating RSSI measurements with the corresponding cell on a grid was created.

As I mentioned before, actual locations of APs weren't determined. However, coarse locations of APs, obtained from the Ekahau HeatMapper software are seen in Fig. 5.7.

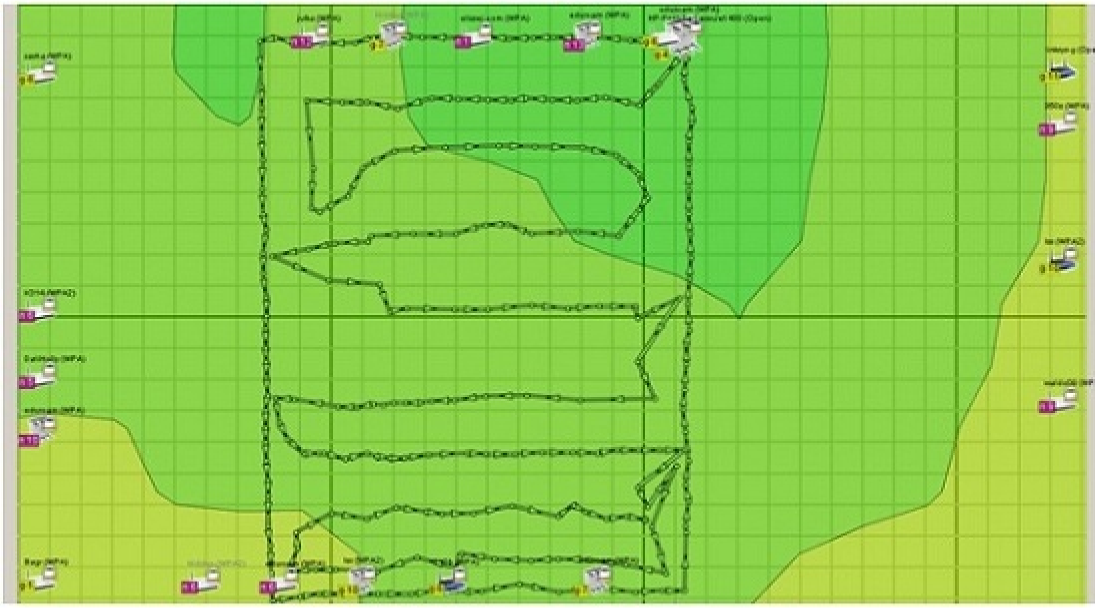

Figure 5.7: Ekahau HeatMapper

In order not to affect results, measurements were collected always on a same height of approx. 1 m. and embedded antenna of Pira were always facing the window and tests were performed between 4 PM and 6 PM.

It should be stated that for the sake of experiment a couple of assumption were made.

Firstly, that user that performs measurement in an online phase, already knows which of the broadcasting stations and access points should be measured.

Another assumption is that APs and BSs are consistent in time, meaning that no one would change the name of AP, its frequency or real position in the building, intentionally or not.

The missing data handling is not an issue, because at the moment measured values are put into software manually and user puts -100dBm for Wi-Fi no signal or signal lost and 0 for no FM signal.

5.3 Data preprocessing

As a preprocessing step, a heatmap was made in Matlab to demonstrate strengths of each signal transmitter in every cell of K305 on a predefined scale, as shown in Figures 5.8 and 5.9.

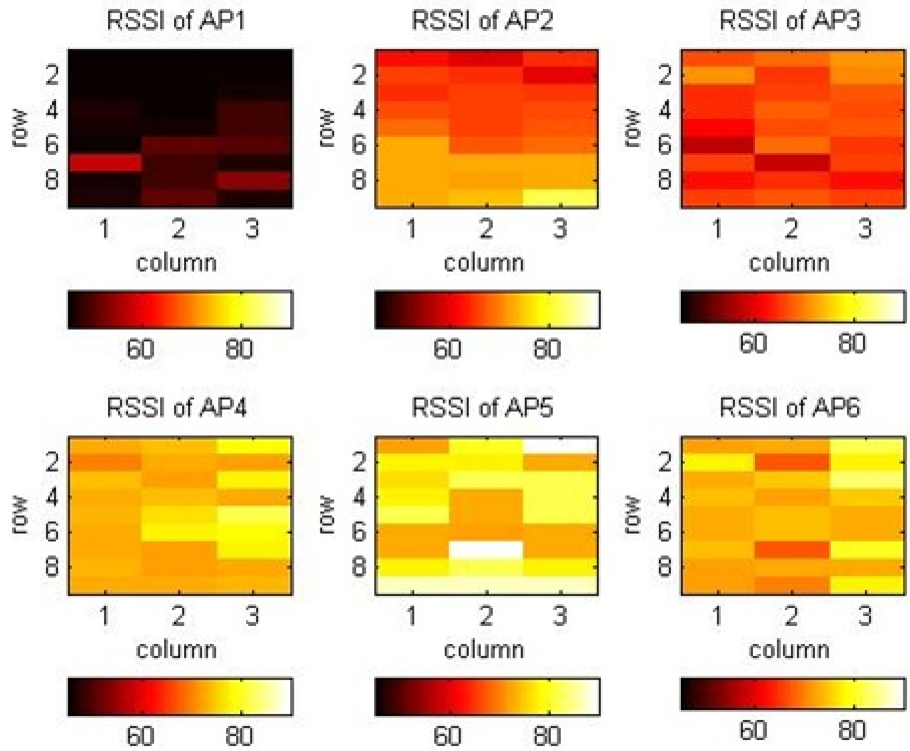

Figure 5.8: Heatmap of Wi-Fi APs in K305

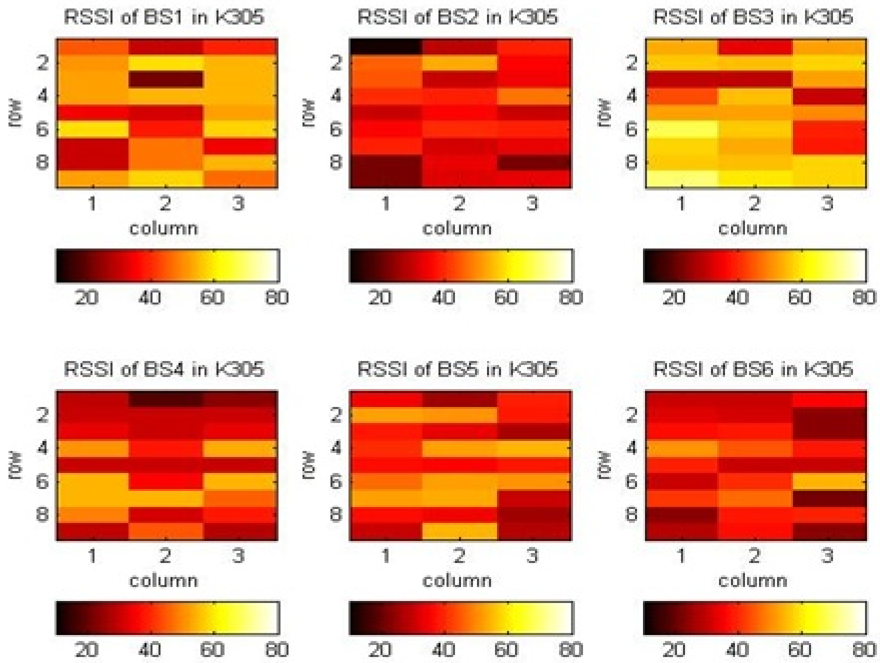

Figure 5.9: Heatmap of FM BSs in K305

To check for statistical dependency between APs a Pearson product-moment correlation coefficient was calculated for Wi-Fi APs and FM broadcasting station.A correlation of 1 indicates that one of APs is redundant and brings no additional information, while 0 indicates that they share no information.

In general, Pearson coefficient showed very weak correlation (from 0.01 to 0.3) meaning that there is a weak linear dependence between each AP and each BS. Sometimes it was moderate (up to -0.63), but either tendency was opposite (higher values of one AP lead to lower values of second AP) or values had remarkable difference (e.g. AP1 ranging from 45 to 69, whilst AP5 takes values from 72 to 100), so no action has been called[1].

5.4 Data processing software

My main contributor is the MatLab software and a GUI, an experimental positioning application for reference locations, namely "cells" on a grid, as indicated in a Fig. 5.10. It estimates the user location using the currently obtained fingerprint of RSSIs, which, up to this moment, have to be put into GUI manually.

For the time being only the k-nearest neighbor (kNN) positioning method has been utilized.

The object (Sample) is being assigned to the closest class amongst its k nearest neighbors from the Training set.

[1]The correlation matrices between APs and BSs are placed in the Appendix D.

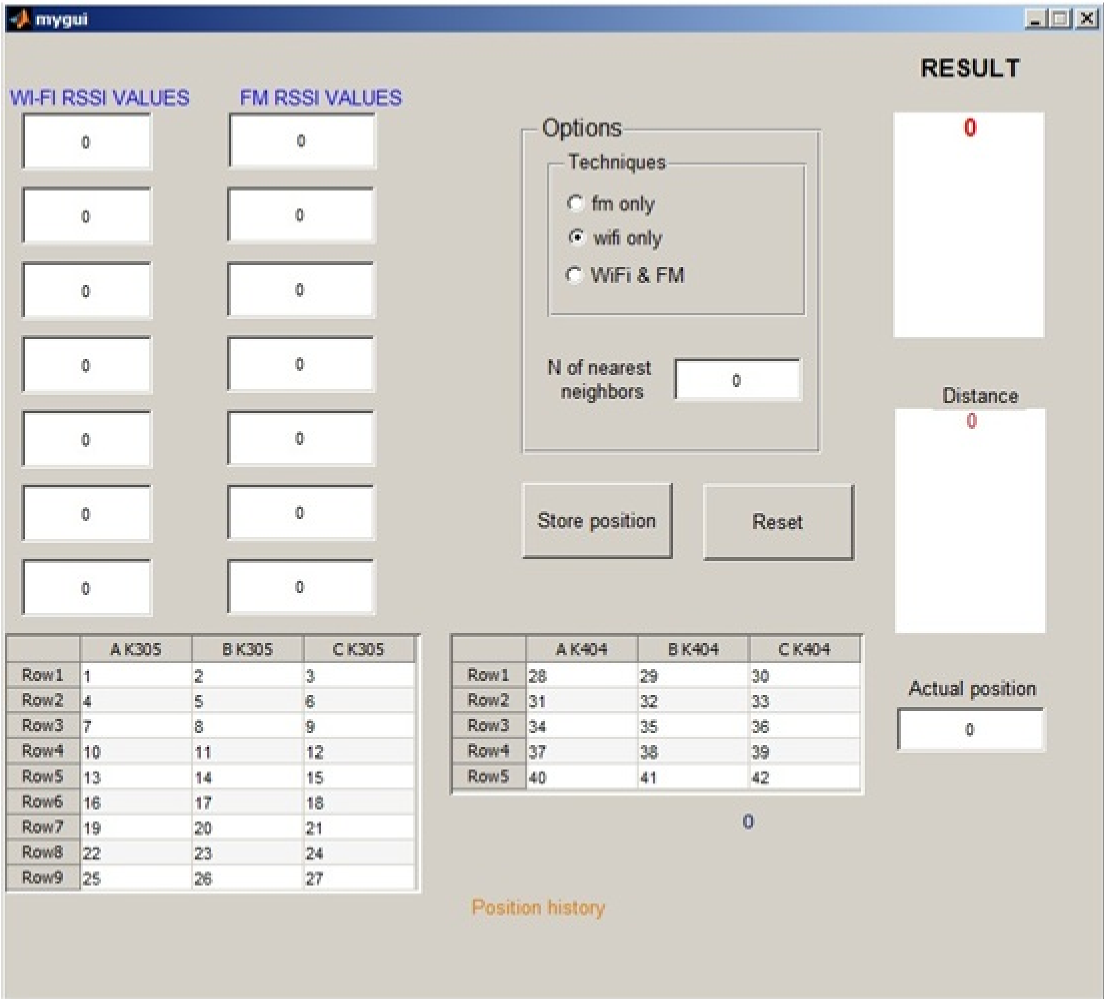

Figure 5.10: Screenshot of a GUI

Designed software offers options to choose from: Radius (currently deactivated), Number of nearest neighbors and selection of techniques to calculate (works on a SelectionChange basis).

Two uitables resemble K305 and K404 and actual position is shown as a colored number in a grid.

Due to the fact, that my positioning method is cell-oriented and not distance-oriented, I can evaluate two types of positioning errors.

First is a wrong number of cell, while the second is a RSSI difference between measured and stored values.

The software uses support function “nearestneighbor” by Richard Brown, because it offers variety of functions not available in the standard matlab knnsearch function like distance or option to choose multiple neighbors.

I'd say that my software is rather positioning than actual navigating, but I did incorporate here a history of movement. It works in such a way:

When result is achieved with sufficient distance level, one can click on a "Store position button" and it will be saved into array "Position history". This procedure has to be done for each new position.

5.5 Software algorithm

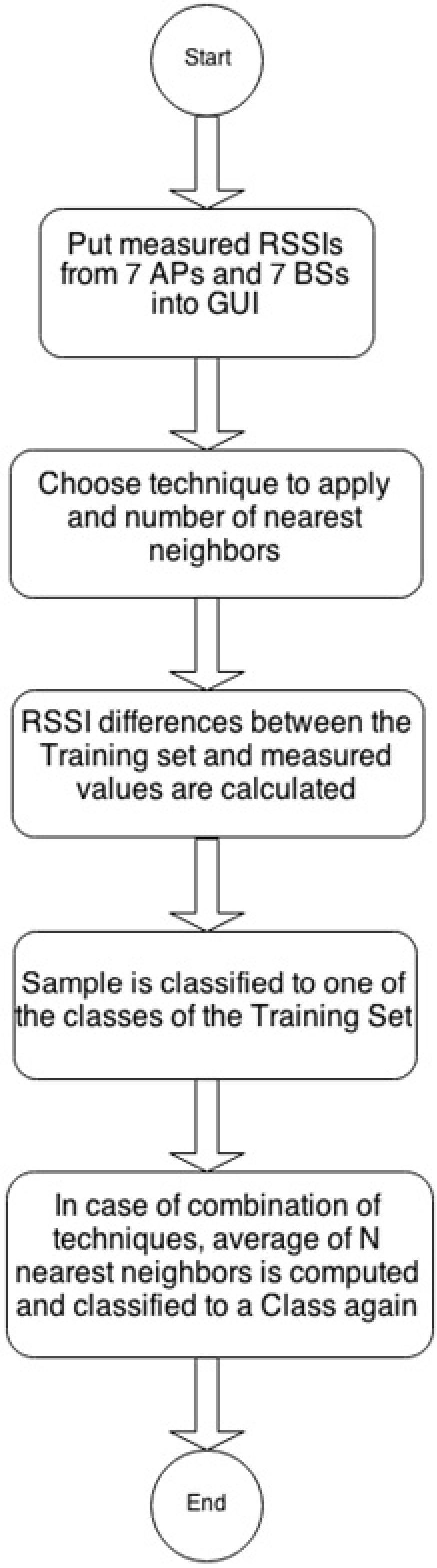

Figure 5.11: Location estimation algorithm

The algorithm, illustrated in a Fig. 5.11, works as follows:

The data is stored in a Training set, then vector or values, that was collected during the online phase was compared to stored data to find desired number of nearest neighbors by using the closest Euclidean distance as metrics.

Result gives N most probable cells with the minimal distances between stored value and readings. Then, this cell number is highlighted in the uitable and distance is a difference between readings from actual position and readings from estimated position.

The possibility of including certain confidence level was investigated, but transition from distance to probabilities with the current metrics doesn't satisfy requirements for a probability.

For instance, it's common, when first nearest neighbor differs from second only by distance equaled to 1, which leads to two close cells both with high probabilities. Another case is when the algorithm assigns biggest confidence to closest neighbor regardless of large distance between estimated and actual cell.

Therefore, current Euclidean metrics was kept.

Regarding the fusion of two techniques, first and easiest way was to combine fingerprints from APs and BSs into one large fingerprint with 14 values, then apply kNN to it.

Algorithm combined in that way was expected to have worse result than each technique alone, because it simply concatenates two sample vectors, thus increasing total distance and results showed it.

Thus, an algorithm utilizing arithmetic average of N nearest neighbors was implemented. After providing N nearest neighbors an arithmetic average of N cell numbers is calculated to improve cell accuracy.

5.6 Testing campaign

In testing campaign three Wi-Fi adapters have been used:

1. External D-Link DWA-121, which was used for both the training and the online phase,
2. Internal QualComm Atheros,
3. Broadcom BCM432, embedded into HTC Desire 500 smartphone.

Unfortunately, it wasn't possible to find an FM signal analyzer apart from the Pira, which would be able to give the signal strength for defined frequencies, so in both training and measuring phases Pira FM Analyzer was used.

During all the testing campaign, both techniques were used to estimate location and a route and best result (technique, which provided minimal distance) was chosen.

First route (Table. 5.1) in K305 was performed with adapter 1:

B4 –> A4 –> A5 –> A6 –> A7 –> B7 –> C7 –> C6;

Table 5.1: Real route 1

	A K305	**B K305**	**C K305**
Row1			
Row2			
Row3			
Row4	2	1	
Row5	3		
Row6	4		8
Row7	5	6	7
Row8			
Row9			

Table 5.2: Estimated route 1

	A K305	**B K305**	**C K305**
Row1			
Row2			
Row3			
Row4		1	
Row5		2	
Row6	5+6		
Row7			3
Row8	8	4	
Row9	7		

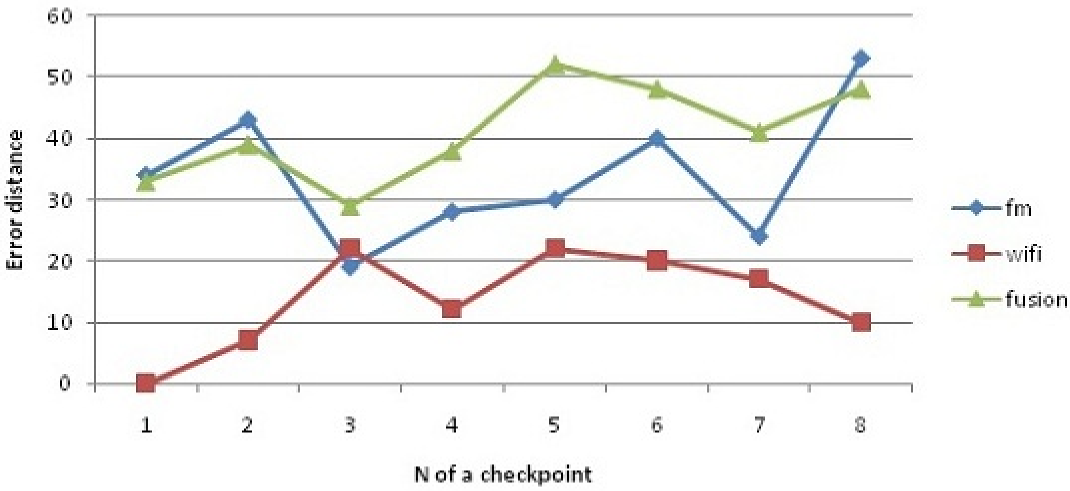

Figure 5.12: Error distance in K305, points

According to Table 5.2, from 8 checkpoints of a route1 only one was estimated correctly. However, in 50% of measurements an adjacent cell was estimated, thus giving cell-circle accuracy.

Taking into account cell dimensions of 1.5m*2m, it gives an error from 2.25 to 4m. Also, in two cases correct cell was the 2nd neighbor with distances only 1 and 3 from the estimated cell's distance.

Most of the time it was Wi-Fi that provided best results[2], while fused performance was somewhat poor because of the chosen mechanism of fusion, which accumulates errors rather then fixes them, as shown in a Fig. 5.12

Then, the experiments with number of nearest neighbors were performed under selected cells.

In my software k affects only fusion of techniques and the effect of increased number k of nearest neighbors was investigated with the help of adapter 1.

The main objective was to determine if small integer number k=1 to 4 is sufficient and that error distance fails to improve afterwards.

[2]Complete results are in Appendix G

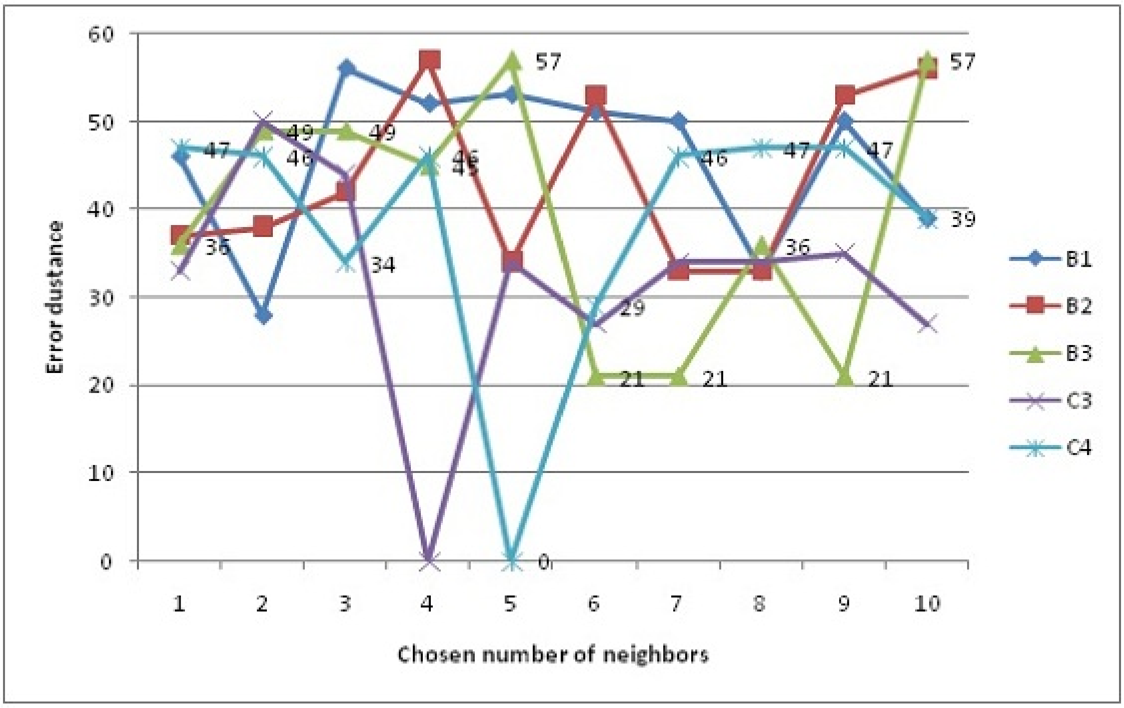

Figure 5.13: Results of number of NN tests

It's visible in a Fig. 5.13, that increasing the number of NN positively affects a distance error, for example, with k=4 and 5 it was possible to obtain zero error, which is a great result.

Besides, overall distance error seems to decrease with more neighbors and in the unknown environment a k=1 would be the most sensible choice, even if it not uses all the advantages of the fusion. Unfortunately, the obtained information wasn't used for the first route; however, it is believed that with the increased number of neighbors result would be better.

Then experiments were performed in the upper room with the smartphone receiver and k was set to 1.

Second route in K404, as indicated in a Table 5.3, was performed with adapter 3 and estimated results are shown in a Table 5.4.

A2 -> A3 -> A4 -> B4 -> B5 -> C5

Table 5.3: Real route 2

	A K404	B K404	C K404
Row1			
Row2	1		
Row3	2		
Row4	3	4	5
Row5			6

Table 5.4: Estimated route 2

	A K404	B K404	C K404
Row1	2+3		
Row2	1		
Row3			
Row4			
Row5			6

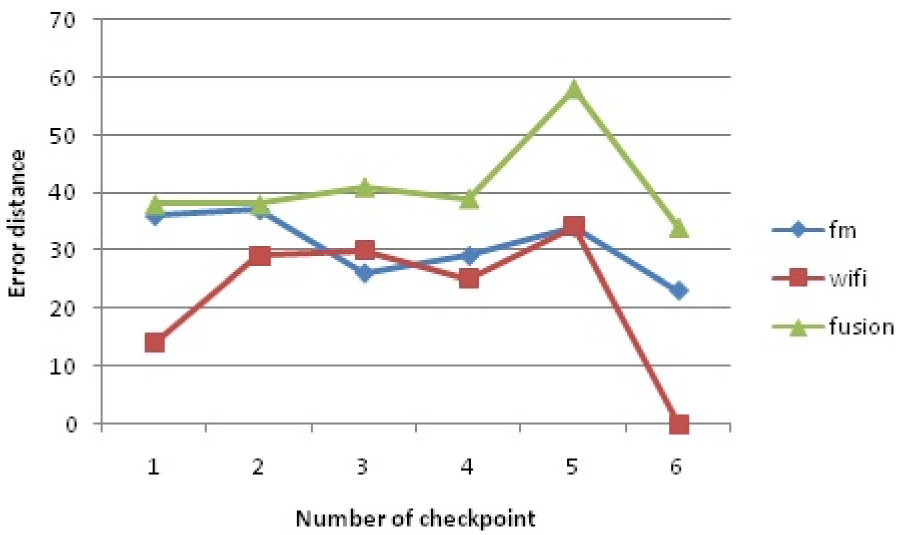

Figure 5.14: Error distance in K404

Wi-Fi showed best results while the combination became a bit farther from other techniques in comparison with first route, which is seen in a Fig.5.14.

The software was able to correctly determine position in two cases, both close to the inside wall.

Checkpoint 5 was wrongly estimated on a different floor and overall performance was unsatisfactory.

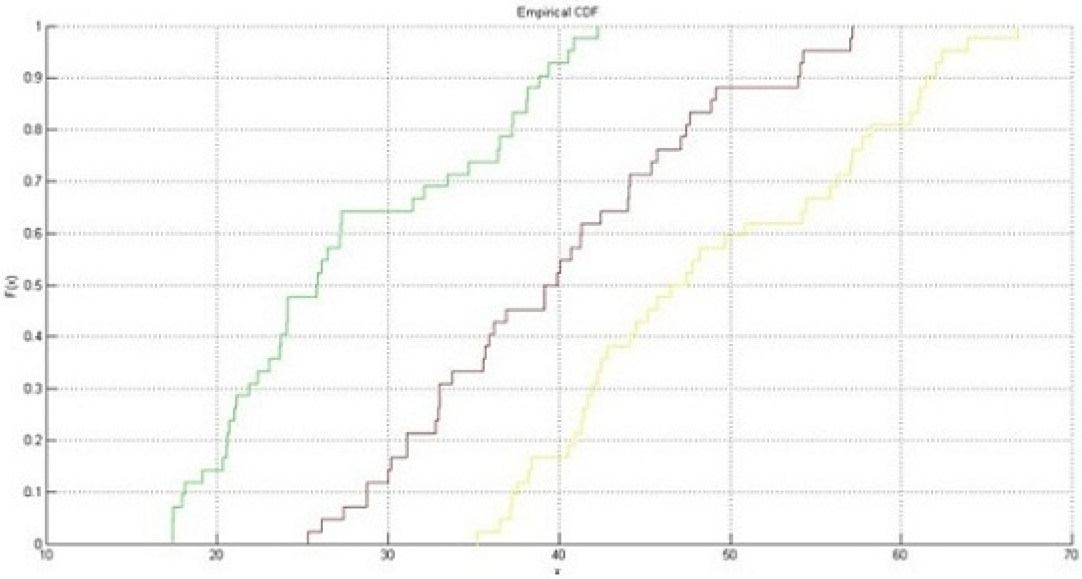

Figure 5.15: Empirical cumulative distribution function

Note: Red line marks – FM, Green – Wi-Fi, Yellow – Combination.

Cumulative distribution function of distances (Fig. 5.15) confirms my hypothesis that Wi-Fi provides the best accuracy, while fusion demonstrates worst results because of concatenation.

Conclusion and future work

I presented the indoor positioning system based on a fusion of two positioning signals. Simulation software proved, that it's able to roughly estimate position of the user, achieving floor-level and cell-square accuracy.

During work on the thesis, the comprehensive elaboration of all existing possibilities in indoor navigation were performed and the Matlab application was constructed, which proved the feasibility of indoor positioning by means of Wi-Fi and FM signals. Experiments have shown that room-wise accuracy can be achieved in any given building without additional infrastructure only with the need of radio map construction.

Most of the time software was able to differentiate between floors mainly because of Wi-Fi eduroam APs, which signal strength degrades significantly on the 4th floor, the reason of it could be that Konviktska building is built from the material, that effectively blocks Wi-Fi signal propagation.

No positional delay is a great advantage of a system, because as soon as fingerprints are obtained, the calculations are done practically immediately.

However, when it comes to cell-determination, software shows only modest results, often failing to follow the movement and correctly estimate position on a grid.

Apparently, the fusion of selected techniques using their direct combination makes no sense, often only worsening results. Possible reasons of it are: capture effect, good penetration of FM signal and random fluctuation of Wi-Fi even when the user is static.

Related work of [32] showed better results because of huge number of FM broadcasting beacons, which equaled 76 and 17 Wi-Fi APs. Also it should be said that positioning accuracy is highly dependent on a device, which was used for both the training and the measure. It was evident, that QualComm and Broadcom adapters deliver weaker RSSIs than D-Link adapter at the same time and the same conditions.

Indeed, a number of future research directions remains to be investigated.

If RSSI values are to be obtained automatically by some low-level application, then some method of filtration, for instance, Kalman filter could be implemented. It operates recursively on streams of noisy input data (location estimates in my case) to produce a statistically optimal estimate of the underlying system state. Even without knowing the nature of measurements it usually significantly improves results by filtering erroneous results.

A modification of kNN algorithm, for example a weighted kNN algorithm could be incorporated in order to assign weights to closest neighbors thus achieving better results.

While continuing with kNN algorithm, a different metric can be included, for example Chebyshev, Manhattan or Hamming distance metrics.

Different learning algorithm can also be deployed, starting from algorithms utilizing Bayesian rule and Support Vector Machine and then neural networks, or some rule-based systems.

Better mechanism of fusion of two techniques, for instance the multiplication of two Gaussian distributions obtained by each technique alone should provide better results.

Finally a completely different combination of techniques could be used, e.g. Wi-Fi + MEMS.

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List of terms specific to the thesis

AoA - Angle of arrival

AP - Wi-Fi Access Point

BS - FM broadcasting station

CDMA - Code Division Multiple Access, a technology used in mobile phone communications

DAB - Digital Audio Broadcasting

Fingerprint - a set of RSSI values from specific location

FM - broadcasting radio waves of corresponding frequency

GSM - Global System for Mobile communication, an ETSI cellular networks technology

IPS - Indoor positioning system

KNN - k-nearest neighbour machine learning algorithm

LPFM - Low power FM broadcast stations

MEMS - microelectromechanical systems

NLOS - Non-Line-of-Sight

RFID - Radio-frequency identification

RSSI - Received Signal Strength Indication

RTLS - Real-time locating system

TDoA - Time difference of arrival

ToA - Time of arrival

UWB - Ultra-wideband radio technology

Wi-Fi (WLAN) - an IEEE 802.11 technology

Appendices

.1 Indoor positioning technologies comparison

Following Table 5 is a short comparison of existing indoor technologies, which reviews the most important parameters for an IPS.

Table 5: Indoor positioning technologies comparison

Technology	**Accuracy**	**Coverage**	**Power consumption**	**Infrastructure cost**
Wi-Fi	medium (10-20m)	low	high	low/medium
Cellular	low (50-300 m)	high	high	low
Bluetooth	medium	low	high	high
RFID	high	low	low/high	low/high
UWB	high	low	low	high
Ultrasound	medium	medium/low	low	high
Optical	medium	medium/low	medium	medium
Infra-red	medium/high	low	low	medium/high
FM	low	high	low	low

.2 FCC WG-3 trials results

Table 6 shows the results of trials, performed by a Working Group 3 of Federal Communication Commission on indoor positioning in different areas, utilizing Qualcomm's hybrid AGPS/AFLT solution, NextNav's beacon transmitters deployed across an area and Polaris Wireless RF fingerprinting.

Table 6: FCC WG-3 trials results

Horizontal error (m)							
Building ID	Total N of calls	67%	95%	Avg. error	Stand. dev.	Max error	Min error
NextNav_All dense urban build.	4859	57.1	154.0	57.5	64.9	1059.2	0.6
NextNav_All urban buildings	4238	62.8	196.1	69.5	99.9	4367.2	2.1
NextNav_All suburban buildings	3581	28.6	62.2	27.2	99.7	5854.2	0.4
NextNav_All rural buildings	820	28.4	60.3	70.3	1231.5	35255.9	1.5
Polaris_All dense urban build.	5372	116.7	569.3	150.3	193.3	1656.1	2.2
Polaris_All urban buildings	3874	198.4	729.9	203	225.9	3131.9	0.4
Polaris_All suburban buildings	3489	232.1	571.4	215.1	161.9	1089.1	8.4
Polaris_All rural buildings	726	575.7	3072.3	845.6	961.3	5809.2	66.2
Qualcomm_All dense urban build.	5145	155.8	328.1	136.4	94.7	722.5	0.5
Qualcomm_All urban buildings	4338	226.8	507.1	233.9	547.7	18236.7	1.6
Qualcomm_All suburban build.	3716	75.1	295.7	92	173.6	4639.4	0.2
Qualcomm_All rural buildings	709	48.5	312.3	639.9	2999.2	27782.4	1.0

.3 Correlation matrices

As shown in the following tables 7 and 8, the statistical independency within Wi-Fi Access Points and within FM Broadcasting stations was proved with the help of Pearson coefficient.

Table 7: Wi-Fi APs correlation matrix

	AP1	**AP2**	**AP3**	**AP4**	**AP5**	**AP6**	**AP7**
AP1	1	-0.3436	-0.6362	-0.3951	0.5956	0.5127	0.3298
AP2	-0.3436	1	0.3682	0.053	-0.1651	-0.2916	0.1813
AP3	-0.6362	0.3682	1	0.4791	0.3159	-0.3502	-0.1688
AP4	-0.3951	0.053	0.4791	1	-0.2324	-0.1551	-0.2031
AP5	0.5956	-0.1651	0.3159	-0.2324	1	0.4128	-0.0234
AP6	0.5127	-0.2916	-0.3502	-0.1551	0.4128	1	0.3165
AP7	0.3298	0.1813	-0.1688	-0.2031	-0.0234	0.3165	1

Table 8: FM BSs correlation matrix

	BS1	**BS2**	**BS3**	**BS4**	**BS5**	**BS6**	**BS7**
BS1	1	0.3531	0.2588	0.2594	0.2578	0.2416	0.0832
BS2	0.3531	1	-0.1858	0.0227	0.4974	0.3651	-0.017
BS3	0.2588	-0.1858	1	0.0943	0.0757	-0.0975	-0.0169
BS4	0.2594	0.0227	0.0943	1	0.3947	0.2025	0.1459
BS5	0.2578	0.4974	0.0757	0.3947	1	0.507	0.0991
BS6	0.2416	0.3651	-0.0975	0.2025	0.507	1	0.2606
BS7	0.0832	-0.017	-0.0169	0.1459	0.0991	0.2606	1

.4 RSS fluctuations due to user's orientation

The additional experiment was performed to examine the change in RSSI values when facing different directions, see Table 9

Table 9: RSS fluctuations due to user's orientation

Rotational angle	90°	180°	270°
AP1 RSS in RL1	44	45	44
AP2 RSS in RL5	53	56	53
AP3 RSS in RL9	53	52	52
AP4 RSS in RL11	38	39	38
AP5 RSS in RL16	47	48	47
AP6 RSS in RL21	22	22	26
AP7 RSS in RL26	32	33	33

.5 Real readings

In the Tables 10 and 11 readings of performed routes are listed.

Table 10: Route 1 in K305

AP B4	BS B4	AP A4	BS A4	AP A5	BS A5	AP A6	BS A6	AP A7	BS A7	AP B7	BS B7	AP C7	BS C7	AP C6	BS C6
45	32	45	29	47	51	51	51	47	54	53.5	36	49	37	48	30
71	38	66.5	27	65.5	29	71	30	73	39	74	34	73	27	73	34
68	46	63	54	60	51	58	59	57	50	59	38	65.5	45	63	37
73	33	72.5	51	74	30	72	30	69	49	74	51	72	30	74	33
73	34	73	35	72	36	80	51	74	38	74	30	82	36	82	29
73	37	78	30	77.5	29	73	*	73.5	30	77.5	36	77	26	71	38
74	29	82	49	90	36	82	31	82	30	80	30	91	30	74	30

Table 11: Route2 in K404

AP B1	BS B1	AP B2	BS B2	AP B3	BS B3	AP C3	BS C3	AP C4	BS C4	AP C5	BS C5	AP B5	BS B5
34	30	57	59	47	50	55	42	56	47	49	52	57.5	56
68	31	74	51	74	46	86	30	75	42	73.5	38	78	40
75	56	78	59	75	44	72	38	80.5	44	76	39	77	39
83	27	83	35	88.5	29	90	35	85	30	80.5	38	88	30
85	33	81	44	85.5	39	87	29	84.5	38	83	39	82	40
79.5	30	83	38	82.5	37	84	*	87	34	86	39	85	34
87	29	88	30	87.5	39	86.5	35	91.5	26	87.5	39	90	39

* . . . no signal

.6 Experiments results

Table 12 demonstrates final results of an estimation, while 13 is a result of experiments on a different number of nearest neighbors.

Table 12: Results of route1 estimation

Actual cell	Predicted cell	Proximity	Number of step	FM error	WiFi error	Fusion error
B4	B4	adjacent cell	1	34	0	33
A4	B5	adjacent cell	2	43	7	39
A5	C7	-	3	19	22	29
A6	B8	2nd neighbour	4	28	12	38
A7	A6	adjacent cell	5	30	22	52
B7	A6	adjacent cell	6	40	20	48
C7	A9	2nd neighbour	7	24	17	41
C6	A8	-	8	53	10	48

Table 13: Results of experiments on a number of nearest neighbors

Number of NN	Error distance B1	B2 K305	B3 K305	C3 K305	C4 K305
1	46	37	36	33	47
2	28	38	49	50	46
3	56	42	49	44	34
4	52	57	45	0	46
5	53	34	57	34	0
6	51	53	21	27	29
7	50	33	21	34	46
8	33	33	36	34	47
9	50	53	21	35	47
10	39	56	57	27	39