Politechnika Wrocławska

Faculty of Computer Science and Management
Field of study: COMPUTER SCIENCE
Specialty: COMPUTER ENGEENERING

Master Thesis

Constructing a positioning model in underground installations with use of mobile technologies.

Rafał Sztandera

keywords:
underground
indoor positioning
smartphone

short summary:
The thesis investigates position finding system model based on a network of reference points using Bluetooth Smart technology and consumer-grade smartphones as a system clients in an underground environment.

Supervisor:	dr inż. Maciej Huk	....	....
	Title/ degree/ name and surname	*grade*	*signature*
The final evaluation of the thesis			
Przewodniczący Komisji egzaminu dyplomowego:	....	....	....
	Title/ degree/ name and surname	*grade*	*signature*

For the purposes of archival thesis qualified to: *
a) Category A (perpetual files)
b) Category BE 50 (subject to expertise after 50 years)
*Delete as appropriate

stamp of the faculty

Wrocław 2018

Contents

Streszczenie

Celem pracy jest stworzenie modelu systemu ustalania pozycji w instalacji podziemnej z poziomu osobistych urządzeń mobilnych klasy smartphone. System jest dedykowany osobom znajdującym się wewnątrz tej instalacji. W pracy omówiono kwestie wymagań wydajnościowych, niezawodności i precyzji systemu ustalania pozycji. Na bazie analizy dostępnych rozwiązań została zaproponowana koncepcja modelu wykorzystująca kilka źródeł danych dostępnych w korytarzach poziemnych obejmująca koncpecję nawigacji inercyjnej na bazie odczytów z sensorów urządzenia klasy smartphone oraz jej korekty na bazie odczytu mocy sygnału RSSI modułów radiowych w technologii Bluetooth Low Energy będących punktami odniesienia. W ramach pracy przeprowadzono próbną instalację zaproponowanego modelu w korytarzu dawnej kopalni węgla w Wałbrzychu i przeprowadzono testy.

Abstract

The purpose of the work is to create a model of position finding system for underground installations accesible from the level of personal smartphone devices. The system is dedicated for people using consumer class smartphone inside installations. The thesis discusses the issues of performance requirements, reliability and precision of the positioning system. Based on the analysis of available solutions, the concept of the model using several data sources available in the underground corridors has been proposed. This concept includes inertial navigation based on smartphone device sensorics and signals strength analysis of Bluetooth Low Energy radio modules that are used as reference points. As part of the work, a trial installation of the proposed model was carried out in the corridor of the former coal mine in Wałbrzych. The test results confirm the correctness of the assumptions stated in the requirements.

Chapter 1

Goals and thesis scope

The following document analyzes a position finding system architecture and reference implementation basing on consumer grade smartphone and a network of reference points using Bluetooth Low Energy technology in underground environment. Goal of the proposed solution is to determine current position of the smartphone in relation to the underground installation.

Thesis consists of the position finding problem oriented description of underground installations consisting of the definition of their elements, structure and purpose. There are discussed key challenges of the position finding problem in underground installations. There are discussed technologies that can be used in underground installations as well as methods and technologies that are applicable for consumer grade smartphones. As part of the work, there are presented currently known position finding solutions dedicated for smartphones and indoor environment. There are highlighted and evaluated factors of chosen method of position finding in context of their behavior in underground environment. Resulting from these findings, a method of position finding in underground installations for use with consumer grade smartphones is proposed. The concept is supported by experiments performed in the real environment and working proof of concept implementation for the mobile device. Finally, future works on integration of the proposed solution with methods of dead reckoning, inertial navigation and other making use of smartphone sensors are proposed. Further future applications include location and location based identification of objects in commercial construction where new ”Building Information Modeling” (BIM) technology is used for planning and documentation of construction work sites.

Chapter 2

Underground environment description

Underground installations are specific environments in terms of their construction and related technical properties:

- their large scale,
- diamensions varying accross the tunnels,
- weak light,
- environmental parameters like humadity, temperature and substances that make up the atmosphere,
- electromagnetic waves propagation,
- specific communication technologies,
- safety restrictions that limits electronic equipment that can be used.

They can be treated as a specific case of indoor environment. As there are already known solutions for position finding dedicated for indoor purposes, it is not possible in most cases to reuse them directly in underground installations due to difficult conditions prevailing there. For example solutions based on the radio waves are not suited to the specific, difficult to model propagation channel, due to the fact that signals are absorbed by earthen walls, bounce off uneven surfaces, and must pass equipment and other obstacles in corridors.

This chapter consists of description of underground installation structure and construction elements on example of room and pillar excavation type and commercial tunneling. There are explained activities connected to those installations, related use cases for the position finding system and potential benefits of using the system in safety and business aspect.

2.1. Underground installation characteristics

This section covers a short description of underground installations as the environment for the positioning system.

The term "Underground Installations" describes underground infrastructures such as tunnels, shafts, caves, halls etc which were excavated for reasons such as e.g. raw material production ("mining") or transportation (road, railroad tunnels), just to mention the most popular. The common phase in those installations is the phase of their creation. There is a need to dig tunnel or shaft at first in order to reach buried ore deposits or just remove not needed rock. Tunnels and shafts are used in this phase to supply material needed to perform ore or coal excavation, for staff transportation and rock transportation to the surface. Mining installations are about continuous rock excavation process (creation phase) while the others, like designed for transportation, ends creation phase and moves to the phase of use and maintenance. Underground installations that can be described as a group of lane ways (main and branch tunnels) and in case of mine: mining areas and mined-out areas.

All underground installations have in common that there is no reference objects like plants, horizon or sun. Corridors and chambers are almost identical, in particular if there is room-and-pillar extraction method used. For orientation special numbering is introduced in order to identify corridor and given meter of the corridor. Symbols are painted on the walls with reflective paint and are regularly repainted. Dust combined from moisture deposit himself on a substrate, the walls and ceiling covering symbols describing the hallways. It worsens the orientation.

As the purpose of underground installation may be different, there are also different environmental characteristics such as dimensions, type of material (rock), amount of dust, frequency of use, what means of communication are placed into, what machines (if any) are being used inside. Along greater depths, the work conditions are decreasing. Underground installations can be affected also by water leaks, coal dust explosions and rock bursts [59]. That is why underground installations are prepared for such disasters as floods, fire, high/low pressure, presence of gas, big carbon monoxide (CO) level, or enormous amount of dust. Further risks are connected to people and material transportation. Poor light and narrow working space causes underground car accidents.

Underground mines, which are characterized by their tough working conditions and hazardous environments, require reliable underground installation-wide communication systems in order to prevent from accident if possible or provide means of early warning of possible disaster [2]. Besides safety purpose, both analog and digital communication is used in order to ensure smooth functioning of workings. For example, it is possible to save the machine breakdown time thanks to immediate messages passing from the vicinity of underground working area to the surface for day-to-day normal operations.

With respect of the areas of the underground working activity there are different communication system used. Because of the differences between on the ground and underground signal propagation environment there are also different communication systems being in use. Underground installations, like mines, use proprietary solutions, which are not standardized worldwide but solve similar problems and fulfills similar requirements [43][58]. Communication technology in underground installations use wired transmission media (twisted pair, coaxial, trolley, leaky feeders, and fiber optic cables), wireless and through-the-earth (very low frequency radio methods) transmissions. In most cases the communication solutions are based on wired technologies. Wireless communication technologies are used in places that are inaccessible or in places affected by disaster where wired communication got broken. It is also heavily used for communication purposes with modern underground equipment such as self-propelled mining machines[39]. Wireless communication is installed also in underground installations where probability of disaster is low as an extension to wired technology. Commercial tunneling equip their corridors with wireless communication technologies such as GSM and Wi-Fi in order to speed up communication between executives on tunnel construction site and on surface[2][16][45]. Tunneling is about digging corridors for transportation purposes in difficult terrains such as mountains or bellow the water.

There is no standard position marking convention that are used across the underground installations. Details about shape, size and current deep and length of corridors are often treated as a company secret as well as their labels. Generally speaking underground installations are labeled with use of sector name, corridor name and a number of meters since beginning of the corridor. Position within given corridor can be labeled with use of corridor name and the meter, for example $C1 - 25$, where $C1$ denotes corridor name and 25 denotes number of meters. Corridor/meter pairs for denoting the position are sufficient in case of an uncomplicated structure of corridors and shafts as well as in complex structured like in case of *room and pillar* layout. An example of a room and pillar corridors layout is presented on the figure 2.1. $A1$ denotes transportation corridor. It can be used for all access to the production block by people, vehicles and machines. $S1, S2, S3, ...$ are corridor names within the production block. Entrance to the production block can be named with use of cardinal directions like south in case of the figure 2.1. Pillar dimensions may vary with respect of depth that works are being performed and the type of rock. Pillars can be 20 m – 40 m thick.

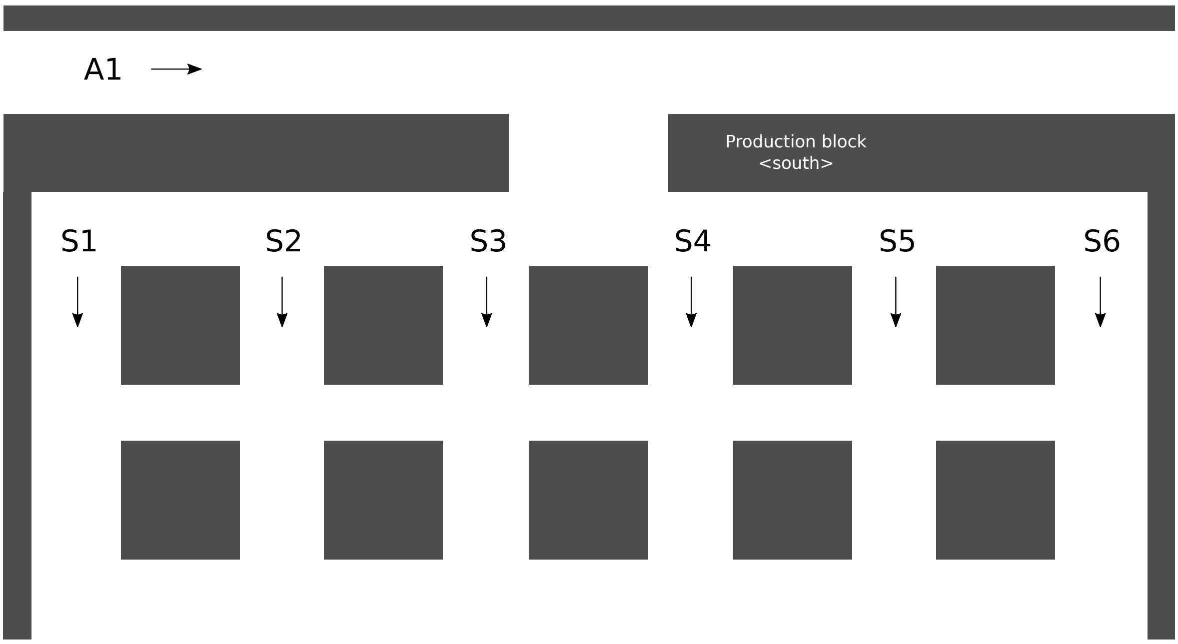

Figure 2.1. Example naming convention in room and pillar production block.

The layout of the corridors can also involve different levels. Figure 2.2 depicts an example of such layout. On each floor there are placed room and pillar production blocks. Naming convention for corridors are the same as in the room and pillar case. The way down is also a kind of corridor with a constant, steep angle (”ramp” in mining terminology). Device which is inside of such corridor can be located by the corridor name and the meter counted from the beginning on a top-level.

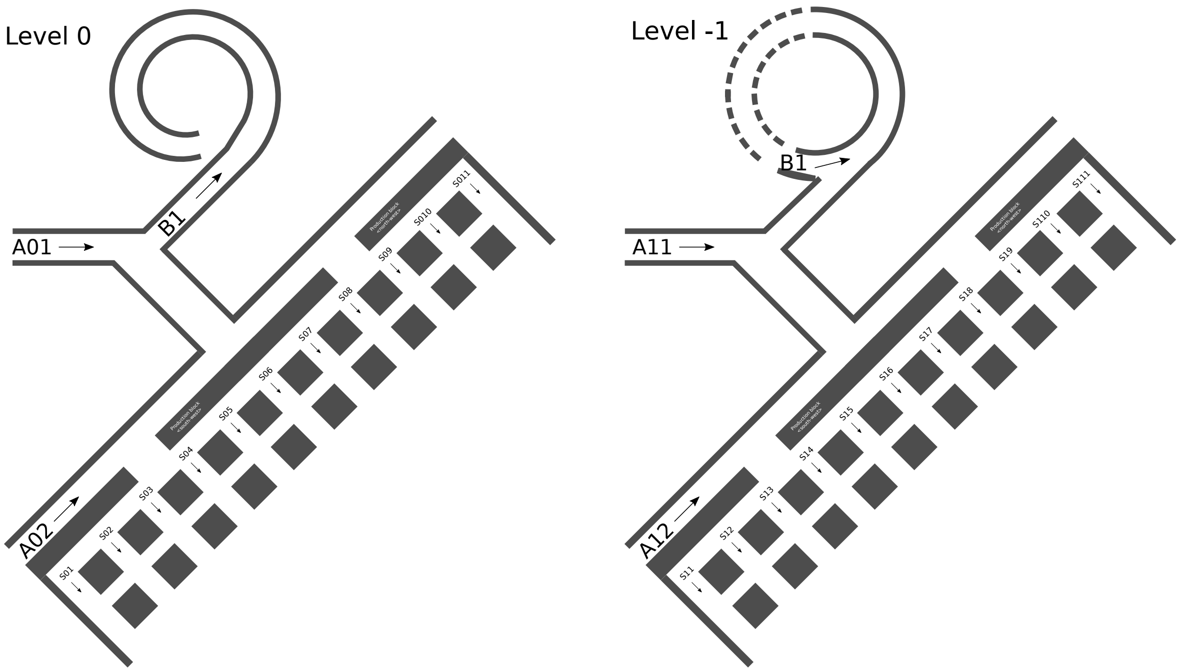

Figure 2.2. Multi-level corridors layout and example naming convention[39].

2.2. Hardware and environmental constratins

Underground installations differ from on the ground environment because of the limited space – mainly tunnels, shafts and intersections. It affects communication methods that can be used because of the different propagation parameters, limited use of electrical and electronic equipment because of hazardous environment which requires special equipment that is ignition-proove. Infrastructure inside tunnels must be suited for poor life conditions, working heavy machinery and possibly to be resistant to movements of the rock mass, ventilation ducts or water dam failures. Specific shape of the corridors and the materials used for walls and ceiling support causes wireless technologies behave differently than they were assumed to work in the on the ground conditions. That is why there is need to explicitly adjust existing technologies or even create new ones to make them useful for communication purposes in underground environment.

The wireless communication systems used on surface cannot be applied straight-away in underground mines due to high attenuation of radio waves in underground strata. Main elements that cause the task of communication and position finding in underground environment more difficult are[45]:

- uneven structure of the corridors: walls causes scattering and reflection phenomenas as well as different rock types causes different signal attenuations. Complex corridors topology and complex geological structures affects both ease of installation and signal link quality (in case wireless technology),
- poor line of sight: direct LOS is an ideal case for radio waves propagation when there is no obstacle on the transmission path between transmitter and receiver. In case of long corridors but with limited dimensions, the direct path is narrow and is affected by the large number of diffractions. Such LOS is denedent on each

element that is located inside the propagation area including the vehicles, people and equipment,
- noise: rock excavation equipment introduces electromagnetic distrortions during their work. Such distrotions may affect radio waves as well as signals in communication wires,
- tunnel as a Waveguide [22][16]: it is observed waveguide effect on electromagnetic waves at certain frequences what makes the wireless technology less predictable in terms of coverage area. It means that propagation models that applies to the signal in normal environment can not be used directly in underground environment. That makes the position finding solutions known from indoor envrionment navigation solutions that bases on wireless communication technologies questionable in terms of their applicability,
- gaseous environment: causes that electric and electronical must be suited to work in conditions where air composition is diffrent than on surface, must be ignition safe and be aware of different radio wave propagation in different substances. Amount of dust present in the air also influences the radio propagation parameters,
- warm conditions and humidity: it happens that humidity level can be high up to 90% – 98% depending on the excavation type, ventilation and depth bellow the surface. Temperature can be as high as 40 celsius degree.

Physics related to wave propagation in underground corridor are explained in details in section 3.1.2 – distance model based on the received radio signal strength on example of Bluetooth technology, and in section 3.1.3 – electromagnetic propagation model on example of communication between WSN nodes.

In that context there can be formed following general requirements for any system dedicated for underground installation[2]:
- must be explosion proof and intrinsically safe,
- should be suited to the ingress protection (IP) standards,
- must have durable housing,
- must be size suited,
- must be complete in terms of design including: power supply unit, cables, base stations, etc
- must be inexpensive, robust, easy to expand.

2.3. Positioning systems

The position finding problem can be categorized with respect of the nature of those problems related to the approaches for problem solution.

In order to perform categorization there is need to introduce terms of node, anchor and user. Node is an element of a network or infrastructure, that can take active part in solving the problem of a localization. An example of a node can be wireless device that is suited to be a part of Wireless Sensor Network (WSN). More details about WSN networks in section 3.1.3. Anchor is a node which position is already known. An anchor plays a role of a reference point that can be used for obtaining the position of nodes or users. User is a mobile entity that is not a part of an infrastructure but make use of it in order to obtain positioning information for himself.

Position finding problems are problems of:

- nodes localisation, where the main interest is to obtain position of entities that build up infrastructure,
- users localisation, where the main interest is to obtain position of mobile entities basing on the infrastructure,
- nodes and users localisation, where there is need to obtain positions of nodes and users at the same time.

Figure 2.3 introduces also a categorization with respect of the fact that position of anchors and nodes are static or can change in time. As it is depicted, localization of users problem is correlated with the localization of nodes problem in cases where nodes are mobile entities. Localization of users and nodes at the same time is a problem which is mainly related to the field of robotics where no information about the environment are provided at once. There are investigated solutions for that sort of problems, called Simultaneous Localization and Configuration (SLAC) and Simultaneous Localization and Mapping (SLAM) [5].

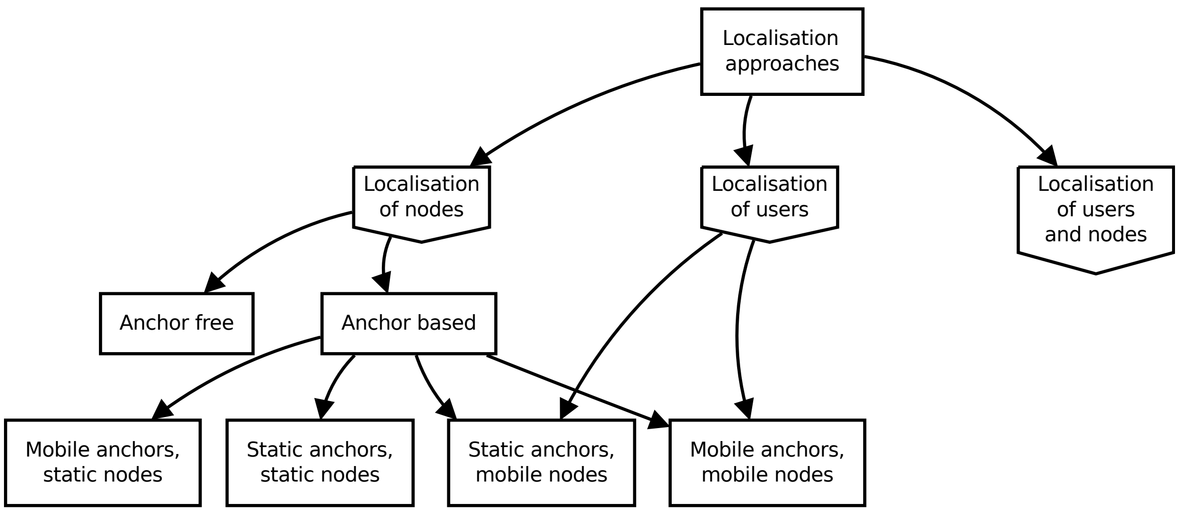

Figure 2.3. Categorisation of localization problems and related solution approaches[5].

This thesis exclusively addresses the problem of user localisation. Solutions for that problem are described in details in chapter 3.

There is need to highlight the fact that purpose of gathering the position information can be different with respect of assumed application of that information. There can be defined three main categories of positioning systems with respect of their main applications:

- positioning systems that are dedicated to acquire and transfer information about objects position to systems on surface,
- systems that are dedicated for on site usage to locate the device inside the underground installation,
- hybrid systems, that combine on site usage of positioning informations and their propagation to the systems on surface.

This paper investigates ”on site usage” of the positioning information under assumption that there is no ready to use technology capable for data transmission nor sharing the position information in the target environment.

Position finding in underground installations is a problem that arised along with the advance in the available technologies. There is big demand on the market of underground installations for such functionality, There two main applications of position finding solutions:

- workers safety,
- extension to the task management, monitoring, resource planning and distribution tools.

Any system, also position finding one, should be suited to actual demands and problems it supposed to address. In order to meet the requirements, there is a need to design a solution that will provide the desired functionality in the expected quality. Position finding systems are not necessary to be available everywhere inside the underground installation but mainly in places with bigger activity where machinery and people work. That means that position finding solution should be independent of the existing infrastructure and scalable in order to be extended to new places, along with the growing of installation. It also means that solution does not have to be maintained in places where there is no activity and such system is not needed.

2.3.1. Safety aspect

Protecting and rescuing people life are one of the most important challenges for the underground construction and mining industry since many years. In case of accident there is need to perform appropriate search and rescue actions immediately as the survival rate decreases rapidly as time passes. As for underground construction and mining industry positioning systems are rather in research stage then in real use, executives doesn’t know exact miners position before accident and how many of them are trapped and how big is the scale of destruction. Currently used techniques for rescuing people after an accident requires counting people that came out to know how many people are trapped and then dig though the fallen corridors and perform searching operations that rely on old low frequency technology like GLON. GLON is a polish old low frequency radio solution for finding signal emitted from miners lamp, allowing on detection from a few meters [54]. Personal safety equipment consists of oxygen masks enabling to survive 50 minutes, and lamps with GLON transmitter. In case of accident in copper mine ”Rudna” in Poland that had a place on 29’th November 2016 [53] rescue action started 20 minutes after rock mass movement. Part corridor with chamber for mobile machines and excavation got collapsed. After 1,5 hour it was discovered that there are trapped miners. Rescue team had to dig fallen rocks from both sides of corridor without knowledge where trapped miners are because steel elements from collapsed corridor housing influenced the GLON system measures. Positioning system with online underground monitoring would give immediate information who and were been in time of accident and speed up rescuing operations. Unfortunately there was no such system. Current safety regulations does not take new technology into account. Mines do not know where exactly their miners are, they know only the region.

Modern emergency systems for underground installations provide a set of functions that improves safety and minimize loss in case of accident. Besides the means of emergency situation prevention like predictions of mass movements or presence of gasses, lots of them provide functions that help coordinate miners if they are in the isolated areas to meet each other, guide them to the emergency equipment, exit points or safe areas and ensure that nobody was left in danger place [39]. All of those functions requires good position finding solution in order to provide fast and reliable information even if connectivity is broken. Each communication system dedicated for underground installations cope with that problem involving wide spectrum of technologies in order to overcome limitations and increase robustness[58].

Positioning system can be used also by people working underground directly from their personal digital equipment[39] as a kind of navigation system which can help to evacuate from underground installation. It could provide information about their current position within mine and there would be given information about dangerous areas and recommended escape paths in case of emergency.

Positioning systems dedicated to monitoring workers are called LAMPS – Location and Monitoring for Personal Safety systems [2].

2.3.2. Business aspect

Another use case for positioning system is that stakeholders want to know where the equipment is placed, how much time it needs to do its operations, if there is some unplanned machine downtime. Delays in case of any underground operations are very costly. Resources monitoring can depict bottlenecks in machine operations, which may provide information on how to balance the workload in order to make operations smoother and more efficient. Data gathered by positioning systems can also be used in time and cost estimations. Mine stakeholders can see in real time what is the current distribution of equipment what enables them to perform real time coordination of ongoing process parts. In day to day operations information where are located operators and machines can increase production efficiency because of less time needed to spend on gathering information about machines position from reports[51]. The positioning systems are mainly used to deliver information to systems that operates above ground. Today underground operations are partly automated with the aim towards full automation. The process of the operations is monitored and managed remotely from operation centers on surface. Supervisor and control of such operations are similar to that known on above ground process plants which are controlled by SCADA – Supervisory Control And Data Acquisition software systems [39].

Underground construction industry use automation technology heavily in nearly all aspects: safety, work automation, work and environment monitoring, internal and external communication, transport, maintaining ventilation, power or fresh water supply and others. Automated solutions are also used for example to control access to mine like entries for cars and mobile mine machines or for safety purpose to quickly cut off rooms where petrol oil are stored in case of accident or fire detection. Those automated systems can be configured and controlled from places they are mounted under ground or from central systems located above ground where central monitoring and work control take a place. Such centers collect information distributed by systems and provide information about environmental parameters or work performance. Devices and mobile machines that work underground are also connected to that system through means of onboard micro controllers or computers and wireless network.

Thanks to it is possible to provide to central system work performance information or device health status that can be useful for service during periodical device checks or repairs. Positioning systems implementations may work together with these devices which allows underground operation executives to have an up to date map of current works and processes being in progress. Positioning information can be used also by mobile devices by themselves. An example of devices that make use positioning data are modern mobile machine gateways devices [39] which are kind of black-box devices for big mining machines like loaders. Those devices can use positioning information as a trigger for reports of work efficiency expressed in load – unload cycles (IREDES Performance Profile report)[36]. An example use case for positioning information by LHD (*Load Haul Dump* truck) can be as follows:

- assumption 1: computer is able to recognise loading and dumping points by data provided by positioning system,
- assumption 2: full cycle is defined as a task of carrying the material from load to dump points plus travel from dump to load point,
- assumption 3: computer acumulates data about machine speed, distance traveled, time, amount of load that is carring,
- use case: computer creates the report that summaries machine's performance each full cycle detected.

Wide application are of the positioning information assisted along with the concept of "Building Information Modeling" (BIM) which is already used on building sites above ground and is currently being extended to cover underground mining and tunnel boring industry demands[27]. BIM is a concept of uniform storage and methods of information exchange about physical parameters and functional aspects of the building. It is the source of information for different stakeholders as well as method of information integration and validation in context of their cross validation. BIM allows for simulation, errors detection on their early state, support resource planning and time and cost estimations. BIM can be used in all phases of construction including planning, development, verification and maintenance.

Nowadays there are available positioning systems for underground installations that can provide approximate localisation of people or equipment. Representative examples are discussed in chapter 3.

2.4. Usage of smartphones in underground installations

Smartphones are handheld mobile devices which incorporates basic functionalities of a personal computer and a cell phone. With respect of the underground installation type usage of the regular smartphone devices can be prohibited because of the safety regulations (see section 2.2) like in case of coal mines in Europe[39]. There are available special versions of intrinsically safe smartphones dedicated for hazardous environments which actually contains same components [1]. It means that it is possible to use smartphones in any type of underground installation.

With respect of the type of the installation there are available different communication technologies. Tunnel boring industry is known from the fact of having all the work site being connected to on ground terrestrial network (GSM) and Internet connection through Wi-Fi networking like in case of underground installation of Brenner Base

Tunnel in Austria. Mining industry communicates with use of leaky feeder radio communication while data transmission are limited to fiber optics and rarely distributed Wi-Fi access points [51]. This limits the smartphones' communication abilities, making them not useful as a regular cell phones. Despite lack of wireless communication smartphones can make use of their sensors as well as radio modules in order to gather the information about the environment and make use of it to estimate its position.

In order to make proposed position finding model applicable for underground installation it must be as generic or abstract to be applicable to environments with rich and advanced infrastructure as well as those with minimal means of communication.

Chapter 3

Position finding solutions for indoor environment

The underground installation is a specific case of an indoor environment. What is the characteristic for indoor environment is a large amount of signal diffraction and attenuation by various materials, weaker signals of terrestrial networks, global navigation satellite systems (like GPS) not available and a need of more precise positioning information than in open space. Underground installations are completely isolated from the wireless networks available on the ground which is good because of lower radio noise. They are also limited in space what makes the diffraction happening as frequent as in ordinary indoor conditions. That arises whether solutions that are working for indoor environments could be also applicable to the underground conditions where radio technologies behaves differently because of rock, steel, concrete, a hexahedral[3][22] alike corridors shape and heavy machinery with powerful motor engines that produce large amount of electromagnetic distortions.

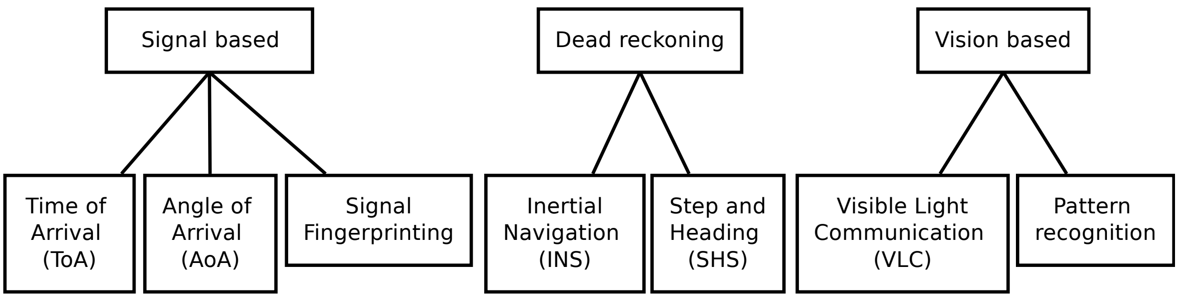

Figure 3.1. Position finding approaches classification for smartphones.[14]

Smartphone based indoor positioning approaches can be classified as shown on figure 3.1. Signal processing is one of the most common used technique for positioning in mobile devices. They are equipped with radio transceivers that works on different frequencies and in different technologies. Radio signals are characterized by measurable physical parameters. Those parameters can be used for positioning purpose. More sophisticated solutions are about introducing the additional modulations into the signal like in case of Global Navigation Satellite Systems (GNSS)[57]. Dead reckoning approach comes from the possibility of measuring the physical state of the handheld device by a set of incorporated sensors such as an accelerometer or gyroscope. Vision based solutions take an advantage from having a camera being mounted on the device in order to run pattern recognition algorithms and map an acquired image to a particular position.

With respect of the necessity of data distribution across the positioning system there are available different solution architectures. Approaches can be categorized as follows:

- server – client: positioning system infrastructure is capable for estimating the position of the system user. End user can fetch information about it's position from the server.
- client – server: user of the system estimate his position himself and provide positioning information to the server,
- WSN and IoT approaches: user is treated as an extension of the positioning system infrastructure where infrastructure consists of a set of interconnected nodes that acquires the positioning related data and passes it through to the sink node while the user can listen to passing messages and interpret them,
- Peer-to-Peer: where user acquires available environmental data and passes it to the next user in range [21].

In this chapter there are reviewed successful approaches for indoor positioning including hardware devices and infrastructure related system architectures and algorithmic approaches that are suitable for smartphone devices, in order to provide an overview of the current state-of-the art.

3.1. Wireless communication technology based solutions

Wireless communication technologies are used for positioning purposes because use electromagnetic waves which parameters are easily measurable, are open for extensions and suitable for hazardous and changing environments and finally they work without wires which can be broken during the works inside the underground installation. Another advantage is the low price of wireless communication modules and the wide application of various wireless communication technologies in computers and mobile devices such as smartphones.

This section introduces existing solutions for position finding that base on the wireless technologies.

Commonly used technologies for solving the problem of position finding in indoor environments are[30]:

- Bluetooth Low Energy,
- ZigBee,
- WiFi,
- Ultra-wideband (UWB).

Bluetooth, ZigBee and Wi-Fi technologies are the common technologies used in Received Signal Strength (RSS) based positioning techniques.

As with the wireless communication technology based positioning, the common way of estimating the position is evaluation of received signal strength measure obtained during signal transmission from the wireless transmitter to the receiver. Value of that express the received signal strength is called RSSI (received signal strength indicator). RSSI denotes the power of received radio signal measured in dBm (decibel-miliwatts). A RSSI is actually the raw value that express the power inducted on the receivers' antenna as a result of transmission. No additional sensors are required to take that measure. A RSSI value is available on most wireless technologies as a part of diagnostic report serving as indicator how good the connection is. It was observed that the higher the RSSI is then the distance between transmitter and receiver is smaller. Such relation between the RSSI value and the distance are captured by distance models. They try to describe the propagation of electromagnetic radio waves with use of some statistical methods or probabilistic distribution and then to map RSSI into the distance[47]. Such models are needed because of the calculus complexity of the real physical model. In order to perform physical calculus there is need detailed description of the environment with every element that may influence the radio wave propagation. Calculus could include d'Alembert equation for signal power density on limited space which requires 6 variables concerning distance and time in 3 axis. Calculus should take into account presence of radio wave diffraction and attenuation on materials present in the indoor environment. As the propagation space is not ideal and the amount of elements influencing the propagation is large such calculations are not being performed.

Example of statistically obtained model that describes relation between received signal strength is *Log-distance path loss model*[47]:

$$RSSI = -10n \log_{10}(\frac{d}{d_0}) + A_0 \tag{3.1}$$

where d is the distance between the receiver and transmitter, A_0 is a reference RSSI value measured at d_0 distance from the transmitter, n is the signal propagation exponent. Taking the measure of RSSI (A_0) at a distance of one meter from the signal source ($d_0 = 1$) simplifies the equation. It is the common practice in Bluetooth beacon technology to attach additional information about reference A_0 RSSI value measured at on meter into the broadcast messages of the beacon. An example of protocol that include that information in message header is *iBeacon* protocol developed by Apple [49].

The *Log-distance path loss model* states that the only variable that influence the RSSI value is the distance from the source. Such model has to be regarded as a rough distance estimation as RSSI is not a stable measure, especially not in multi path and wave guide environments like tunnels. Bluetooth technology operates on a 2,4GHz frequency which means that the wavelength of the signal is equal to 12,5 cm. Such short wavelength is prone to distortion resulting from multi path reflections where signal bounce against objects and material attenuation what results in incorrect or noisy measurements [47]. Compare in this context the findings about WLAN in section 3.1.1.

3.1.1. Signal strength analysis and fingerprinting techniques

This section explains ideas behind Received Signal Strength analysis and fingerprinting techniques used for position finding solutions. Ideas are explained on example of Wi-Fi wireless communication technology.

The Wi-Fi network infrastructure is a one of the available solutions that can be used as a source of information about current position of the device. The basic solution for positioning with use of this technology is about matching RSSI from wireless lan network access points to the position by searching similar RSSI values in the reference signal strengths map [29]. Access points can be identified by their SSID or physical address of network cards. Accuracy of the solution depends on the access points spacing. Those solutions determine position by relation of received signal strength to the position of the nearest access points in range. In addition, positioning information can be adjusted by making estimations about being ”between” access points by simultaneous analysis of two or more link parameters. So the worst case anticipation is accuracy equal to spacing of the access points [39][51].

What is specific for radio waves attenuation at 2,4 GHz frequency is that their signal is present from relative large distances in mine in compare to the same devices signal range in the open space environment. What is also characteristic is that the signal strength, after its peak, is going to stabilize in distance about 10m from source. The pick is related to the close distance to the Wi-Fi transceiver. In the distance above 10m from the source, the signal strength is residing on similar level up to distance of around 300 meters when it starts to heavily attenuate [39].

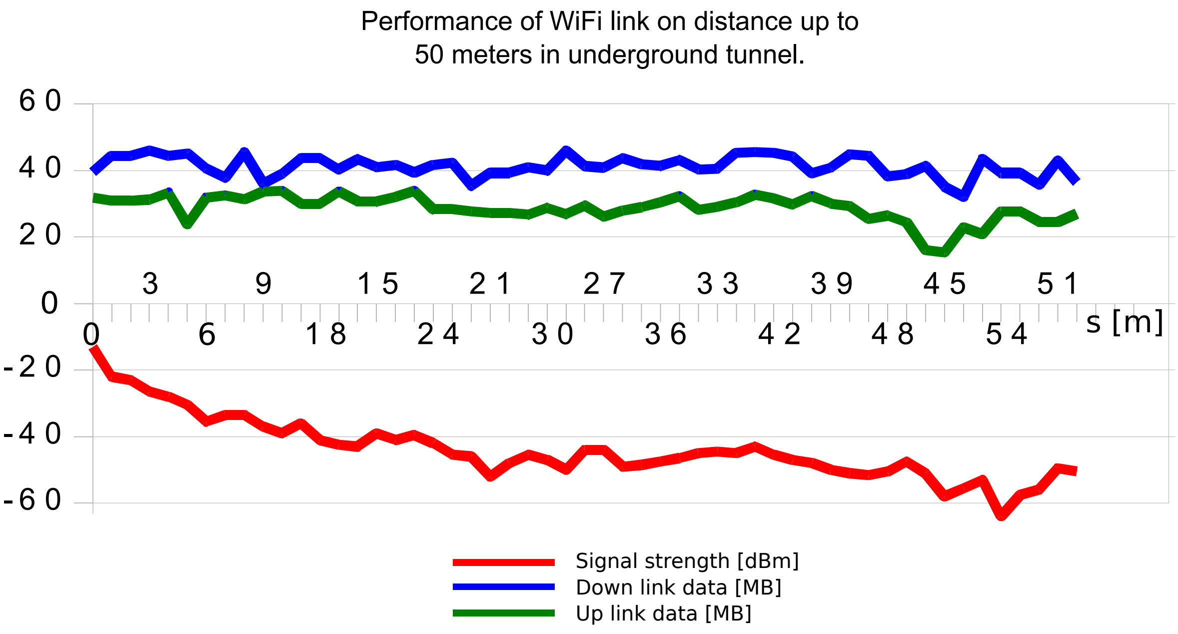

Figure 3.2. Wireless lan throughput and signal strength with respect of distance from the signal source (wireless access point) [39].

On figure 3.2 it is presented how wireless lan link parameters differs with respect of distance between client device and the network access point. Measures presented there are taken from 0 up to 50 meters from signal source. In case of this chart there were presented up link and down link throughput measured by amount of data gathered on each testing probe taken each meter distance from the signal source and the related signal strength expressed in dBm units. Values presented on the chart are medians of all gathered values and factors for given distance. The test was carried out in a straight underground tunnel in the biggest coal mine in Slovenia at Premogovnik Velenje. Connection throughput between client and server remains nearly the same for distances in range from 0 up to 50 meters. Signal strength is presented in logarithmic unit dBm. Signal strength falls significantly in first 10 meters from 0 to $-40dBm$. After the distance of $10m$, the value of signal strength is ranged in between $-40dBm$ and $-50dBm$ with small and not regular deviations. After 45 meters, the value drops slightly bellow $-50dBm$.

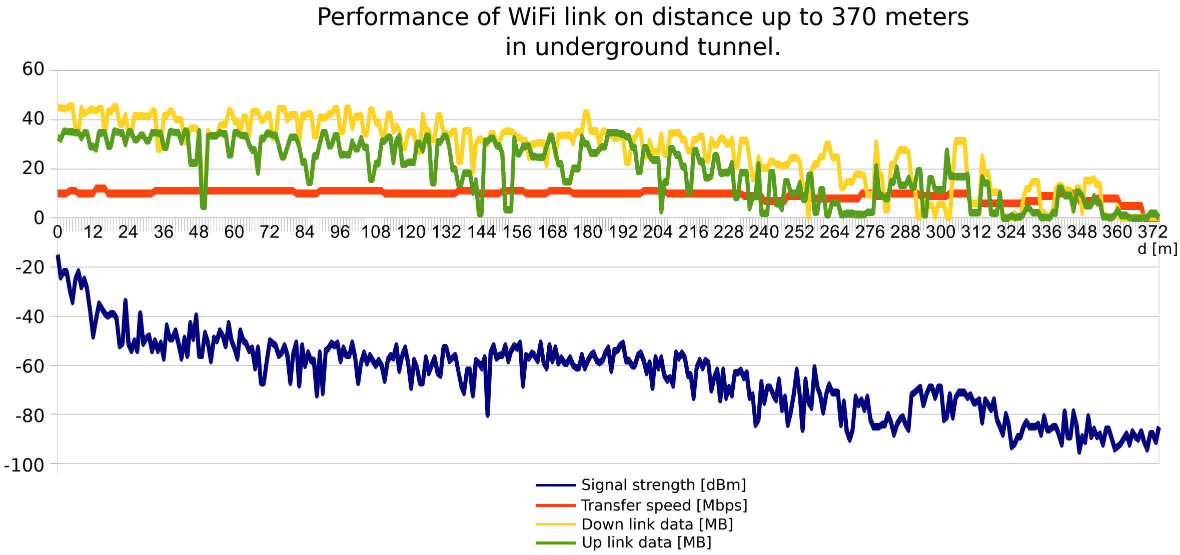

Figure 3.3. Wireless lan range [39].

The figure 3.3 presents tests results performed on longer distance. On distances from 50 up to 240 meters the parameters of the link are similar. Down link data remains at $40MB$ and at $38MB$ after 140 meters with drops to $20MB$. Up link data measurements are more unstable than in case of down link in terms of drops in delivered amount of data, but trend seems to be steady on range from 50 till 220 meters from access point. Then both data up link and down link drops by $10MB$. The data rate between access point and client device remain similar from very beginning till distance around $370m$ where the signal is not strong enough to establish a connection.

Range of 10 meters from signal source can be easily determined from the values of the received signal strength because they are significantly bigger than signal strengths measured on bigger distances. On distances of $10m$–$50m$ received signal strength oscillates between $-40dBm$ and $-60dBm$, then between $-50dBm$ and $-80dBm$ on distances of $50m$–$240m$, then between $-60dBm$ and $-90dBm$ on distances of $240m$ – $320m$ and finally between $-80dBm$ and $-90dBm$ on longer distances.

Resulting from this typical data, a precise straight forward solution by using WLAN signal strength for underground positioning is not possible: One attenuation value (y-axis) can be assigned to too many distances from an access point (values on x-axis).

Basing on the observations of the received signal strength values there can be identified following range zones[39]:

1. near field zone: $0m$ – $40m$ distance from signal source where wave attenuation curve is similar to that in free field distribution,

2. coverage zone: $40m - 200m$ distance from signals source where can be identified symptoms of waveguide propagation and signal strength remain to be around $-50dBm$,
3. monitoring zone: distances since $200m$ from signals source where signal starts to vary from $-75dBm$ up to $-85dBm$ and becomes to be unusable for communication purpose but client and access point are visible for each other,
4. out-of-range zone: where signal is too low and both client and access point are not visible for each other.

A first approach for Wireless LAN based positioning system is to assume that client is present in area of an underground installation if it is inside a coverage zone of one Wireless LAN access point. A client can be registered by the access point software until he leaves the coverage zone. As the coverage zone of a single access point is about $200m$, the worst case accuracy of this solution is about $400m$. The more access points and the smaller distance between them the more accurate positioning information.

A second approach assumes an improvement of the positioning accuracy by signal strength interpretation and recognize if the client is in the near field zone. This approach is easy to be implemented as signal strength values in the near field zone differs from values from the rest of zones due to the unique relation between attenuation and distance following a regular attenuation curve. Such solutions are implemented in mines in Germany [39] and in Swedish Boliden's mines [51].

3.1.2. Positioning with Beacons and Bluetooth technology

Beacons are transmitters that use Bluetooth low energy technology in order to send out small chunks of information. They are designed to be small and energy efficient in order to allow them to be independent of external power source. The main application of beacons are indoor positioning systems.

Common indoor positioning system architecture uses beacons as a set of reference points building up the static infrastructure of the environment. Beacons works as a kind of landmarks. A user position can be determined as a function of received signal strength vales of signals sent by beacons. Beacons can also be mobile. They can be attached to the non static (mobile) objects. Then the responsibility of position estimation lies on the infrastructure that gathers the signals. Sensing infrastructure can be static or mobile [5]. Those possibilities directly addresses the main position finding problems (refer to the section 2.3).

The Bluetooth technology was developed and is maintained by the Bluetooth Special Interest Group (Bluetooth SIG) which is the standard organization capable for licensing the Bluetooth technologies and trademarks to the manufacturers. Bluetooth technology operates on frequencies from $2,4GHz$ to $2,4835GHZ$ which was divided into 80 channels. In order to adapt transmission channel to the current load on given frequencies, Bluetooth implements a mechanism called *Adaptive Frequency Hopping* which allows changing channels being in use during the transmission without interrupting it. Subsequent Bluetooth technologies are aimed to ensure bigger data transfer, lower energy use and increase the transmission security. Since the version 4.0, if Bluetooth standard there is available special protocol that is optimized for lower power consumption. This protocol is called *Bluetooth Low Energy* while the whole Bluetooth 4.0 standard including classic and high speed protocols is called *Bluetooth*

Smart. Since the version 5.0 of the standard, the set of the protocols are called just *Bluetooth 5*. Currently, the market is dominated with Beacons that use Bluetooth Low Energy protocol in version 4.0 that is why thesis exclusively focuses on this version of protocol.

The Bluetooth technology is as set of profiles. Each version of the technology contain definitions of profiles that are up to date to that version and optionally are reverse compatible with older ones. Each profile describes what communication protocols and data format it uses. The protocols available for the profiles are also defined by the Bluetooth technology. The Bluetooth Low Energy protocol uses the *Generic Attribute Profile (GATT)* which is a set of services that can be used within the transaction between devices. Service is a name for collection of characteristics that express the state of the device. Bluetooth defines 59 services within the GATT such as TPS (TX Power Service), IPS (Indoor Positioning Service) or HRS (Heart Rate Service). Services are identified by their UUID number which must be unique. Despite the defined service, there is a possibility to create own services. Characteristics are defined with given format type, properties and security permissions. Such format types are available as signed or unsigned integer ranging between 1 and 8 bytes, float, string or a structure. Allowed properties of the characteristics describe if the value within the characteristic can be read (*read* property), changed (*write* property), required acknowledgment (*indicate* property) or being in use just for notification purposes (*notify* property). There is a possibility to add custom properties as well. Security permissions as part of the characteristic definition are about stating if a given property can be executed with or without an authentication. For example Measurement Interval characteristic of the Health Thermometer Service is defined with Read, Indicate and Write properties and security permissions stating that there is not required any authentication for reading but it is needed for writing.

Broadcast messages are a way how Bluetooth Low Energy devices communicate with themselves. It is called *advertisment mode*. In order to distinguish different types of those messages (aka *advertisement frames*) there were introduced distinct frame formats. On the market of Beacons there are two major protocols that defines Beacons devices behavior, including broadcast frame format. The first – *iBeacon* – was developed by Apple and the second – *Eddystone* – was developed by Google. Those broadcast messages formats are the basis for creating "Ranges" definitions. Usage of ranges are explained further in section 3.3.2. In case of *iBeacon*, an advertisement frame consists of 29 bytes. The first 9 bytes are the constant preamble, defined by the *iBeacon* protocol. The first 3 bytes are standard Bluetooth Low Energy Flags. The next 6 bytes consist of value that described the packet type (in case of *iBeacon* the value represent *Custom Manufacturer Packet* type), manufacturer ID (constant value that represents Apple), sub type that indicates *iBeacon* compatible device and number of bytes that are attached to the *iBeacon* advertisement frame. The *iBeacon* data consists of *Proximity UUID* field which must be unique across different users, *Major* and *Minor* fields that gives the user possibility to differentiate Beacons that he own and the *Signal Power* field which denotes received signal strength observed at distance of $1m$ from the Beacon transmitter. To compute distance between receiver and transmitter the *Signal Power* value is commonly used. The computation bases on the *Log-distance path loss model*. Then the *Signal Power* is assumed to be value of A_0 variable within equation 3.1, where the $d_0 = 1$. That is why the model can be simplified and distance can computed quickly just after receiving the advertisement frame by issuing the following equation:

$$d = 10^{\frac{RSSI - A_0}{-10n}} \tag{3.2}$$

where $RSSI$ is a measure obtained during receiving process and n is constant.

The *Eddystone* protocol introduce three types of advertisement frames. They differ from the *iBeacon* by introducing separate frame types for

- passing encrypted identification data,
- passing information about Beacon state, aka telemetric frame,
- passing address of a web site related to the Beacon.

There are available general concepts for positioning systems based on Bluetooth technology dedicated for underground environment, but their concepts were not verified in real environment [51][30] or are not applicable to be used by smartphones[19].

3.1.3. WSN based position finding systems

There are proposals of position finding and tracking based on the Internet of Things (IOT) solutions [32, 59]. The idea is to create means of wireless communication to locate miners. It is proposed to use network numerous interconnected wireless nodes (Wireless Sensor Network, WSN) that read signals from tag devices (for example RFID passive tags) carried by miners. Wireless nodes are directly connected one or more nodes laying in the range of their wireless communication module. They form together an ad hoc, multi-hop, self-organizing network of nodes that is able to transfer data, reorganize its structure in case of malfunction of one of the nodes and allow configuring nodes remotely due to the implemented wireless communication technology and dedicated routing protocol. A network of nodes can be easily expanded by adding new nodes. Due to the fact that the communication is wireless, nodes can be placed also in dangerous or new areas where wired network devices are not allowed or the related infrastructure doesn't exist. Accuracy of the positioning information obtained by the network is dependent on the number of nodes inside the network. Their placement should guarantee possibility to receive the identification information emitted by the devices carried by miners.

The WSN based positioning systems are designed to serve such functionalities as querying miner information, locating miner, tracking miner and managing tag and reader. It is proposed to use this system along with other monitoring systems that measure safety parameters in an underground installation [59]. This positioning system is dedicated to be used by production monitoring, production scheduling and emergency rescue mine departments located on surface.

Technologies that are recommended for wireless communication between WSN nodes are Bluetooth Low Energy, ZigBee (IEEE 802.15.4 based) or Wi-Fi (IEEE 802.11).

ZigBee technology is the most popular in WSN's as it supports variety of communication modes, contains out-of-box solutions for network topology management and supports low energy solutions like sleep modes [26]. The ZigBee protocol which is dedicated for ZigBee technology uses energy and computational efficient solutions for data collision avoidance which includes CSMA/CA techniques and time division concept [59, 41]. There are three main typologies forced by ZigBee technology that can be used in the WSN network: star topology, tree topology and mesh topology. Star topology limits the network to have all nodes directly connected to a sink. Tree topology enables multi hop functionalities but limits network flexibility in terms of adopting routes in case of failure (however it does not support redundant connections between nodes). Mesh topology requires storing routing tables in each node but provides means of redundancy in terms of routing what makes the WSN network reliable and fault resistant [41]. That is why mesh topology is recommended for WSN based position finding systems.

The figure 3.4 presents proposal of positioning system architecture. Wireless Sensor Network nodes are divided into three groups with respect of their role in the system. There are distinguished:

- routing nodes – that gather information from sensor nodes and transfer it through network of routing nodes to server via sink node [59],
- sensor nodes – their main purpose is to extend the range of sensing the identification information from miners. Sensor nodes have limited possibilities for routing the data,
- sink nodes – they act as an interface between the core network installation and the WSN.

.

Due to the fact that WSN nodes are limited in energy supply, systems that base on that technology need to be designed with aware of energy management and fault management. The idea of routing node deployment along the tunnel in two symmetrical line's comes from the need of link redundancy between nodes. In case of failure of one of the routing nodes, information from sensors can be passed out through the other routing nodes in range.

In order to limit power consumption of sensor nodes they were designed as Reduced Function Devices (RFD). These nodes do not take part within information passing (routing) process. Sensor nodes are designed in purpose of reading signals from miners equipment (for example RFID tags) and to send the information to the nearest routing node. During the installation phase, sensor nodes are switched to network setup mode. Aim of a network setup mode is to detect the nearest routing node and adjust the transmission power to the value needed for communication with this routing node only. It reduces the network module power consumption and signal interference with neighboring nodes. Network setup mode can be described as a sequential procedure:

- sensor node broadcast the testing signal to all of the nodes,
- nodes that were able to reiceve the signal, send responce with value of Received Signal Strength Indication (RSSI)
- sensor node limit its sending power according to the responces.

Network of wireless connected nodes needs must provide features that will ease its maintenance. As the network consists of many nodes, where the number of nodes can be changed during operation, there is need to implement actions that will allow them to organize their topology automatically. Network should be able to work and maintain communication with remote services despite failure of some nodes. There are available

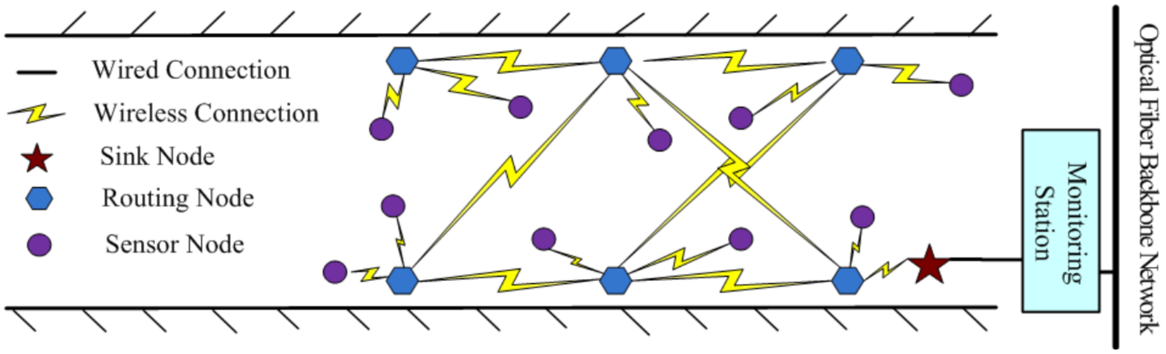

Figure 3.4. Wireless Network Sensor topology in underground corridor example [59].

solutions that allow a network to adapt quickly to the changing environment [28], but in case of statically placed network elements the environment is not changing heavily.

Routing nodes store information about nodes that are used for network purposes in the routing tables. Routing tables may consist of nodes within the radio range. Proposed routing protocol for underground installations suggest maintaining 3 entries in the routing table[59]:

- parent route – points to the parent node,
- minimum route – points to the best node in terms of the most energy efficient way to the sink node,
- backup route – points to the second to the best routing node.

Each entry consists of elements such as: number of hops (routing nodes from itself to the sink node), value expressing link quality of the last communication, flag that describe the role of the entry (parent, minimum, backup route). Routing tables and interconnections between nodes are created during network installation process. The idea is that the sink node that is directly connected to external communication medium creates at first a 1-node WSN. The rest of nodes organize themselves in manner that nodes broadcasts their physical and network addresses. Basing on information gathered during installation they are able to determine their position in the network, obtain network address, assign routing table entries and obtain hop number. The network topology can be build up and maintain after WSN installation process [26]. Nodes are able to pass information to sink node that contains it's routing tables. Thanks to that sink node is able to recreate network topology and then pass the information to the external server. In order to maintain the network there are implemented status messages that contain information about changes in nodes routing tables. They are usually passed through the WSN along with data from periodic sensor readings.

Wireless Sensor Nodes are equipped with batteries that makes them independent of external power source. In order to save the energy and in order to prolong the battery nodes works in energy efficient modes. In these modes the nodes are turned into a sleep mode for certain time. They wake up in order to perform tag readings and transfer the data to the external resources. In order to synchronize their operation, in each cycle the sink node broadcasts initial message which is used to synchronize all attached nodes. Power level of node batteries are monitored. The nodes can send information about their power level as a response for appropriate request. There can be implemented special routines inside a node that can cause sending the information about the low battery level in emergency mode, without any request from the sink node.

Crucial for the positioning system is to determine accurately exact position of given reader node inside the underground installations. Without exact position information about the reader placement all positioning data obtained from them is not useful. Solution for this problem in WSN positioning systems are solved by manual configuration. Each node have its own identification number that is a part of it's initial configuration. This number is attached to their housing making them identifiable directly during the installation or maintenance work in tunnel. Mostly, the deployment of nodes is regular, so the position in the tunnel can be determined by the placement. In case of sudden failure of some node it is possible to determinate which of the node is broken by its ID information, and check were the node is placed. The WSN network should have the possibility to report failures of its nodes. That is why WSN positioning systems are equipped with a failure detection and reporting mechanism. Parent nodes like routing nodes against reader nodes, checks if child nodes responds to the requests. In case of having no response from given node for a given amount of subsequent requests the parent node issues a status request command to the child node and waits a given amount of time. If the child node answers, it is assumed that the given child node is working correctly. In case of no response from the child node, the parent node sends information about failure to the external service. If the reader nodes are connected to the parent node with no routing options then a different policy for parent node must be applied. If the child node does not receive an acknowledgment (ACK) frame from its parent for a given amount of time the node increases it's sending power and transmits its data again. No result after increasing the power causes turning the node into network setup mode and scans channels to rejoin the network.

During operation, the position information of mobile devices acquired by the nodes and transferred to the acquisition server is a combination of three values:

- ID of a node,
- ID of acquried miner identification data (for example RFID tag id),
- signal power of this RFID tag,
- timestamp.

Miner position can be expressed in two-dimensional space (x, y). This is performed by the algorithm searching the database for three nodes which acquired the signal from a given tag with the biggest power. Then the algorithm uses the free space electromagnetic waves propagation model (3.3) to compute the distance between node and tag.

$$P_{ri} = \frac{P_t \cdot G_t \cdot G_{ri} \cdot \lambda^2}{4\pi D_i^2} \tag{3.3}$$

The parameters P_t (signal power generated by tag), G_t (tag antenna gain), G_{ri} (node reader antenna gain) and λ (electromagnetic wave length) are constant and known. The parameter P_{ri} (received signal power on reader's input) is the only variable in the equation that is needed to compute the distance from tag to reader. Maximum likelihood estimation method that base on data from three nodes and their values of received signal power from a given tag produces the relative position of the given tag in (x, y) coordinates. The suggested implementation [32] assumes that nodes look for miners identification signals (for example RFID tags) each 10 minutes.

3.2. Other solutions

Position finding solutions use also other means of sensing the environmental parameters than those making use of wireless communication technologies modules. Potential positioning approaches for underground installations include:

- Passive RFID,
- Inertial Measurement Unit (IMU),
- Magnetic Field strength pattern matching [34],
- Very-low frequency (VLF) electromagnetic waves,
- Visible Light Communication (VLC).

In the underground installations image processing (aka *computer vision*) solutions for positioning systems and solutions concerning pattern recognition (like *activity-based navigation* [38], concept of reading 2D bar codes serving as environmental anchors – reference points [35] or methods for detecting small tabletop objects with use of *RGB-D* sensors [27]) are not investigated due to the poor visibility, lack of patterns that can identify current position admittedly as well as the fact that painted signs are quickly covered by the dust making them difficult to read.

3.2.1. Radio Frequency Identification tags

The RFID technology makes use of electromagnetic field phenomena for simple data transmission. Passive RFID tags are powered by readers though electromagnetic field; they do not use batteries or wired external supply. In order to acquire information from a passive tag, the RFID readers have to propagate electromagnetic waves. The tags accumulate the power from the electromagnetic field in a capacitor. When the tag has accumulated enough power, it transmits the response with the tag's data to the reader and goes to sleep for a given time. Reader get signal from tag and perform filtering and decoding operations on it in order to get tag's data. There are also available variants of active RFID tags which use its own power supply. An important difference in application of passive or active RFID is the fact that active RFID's can be received by readers in a wide area while passive RFID's only respond after being initiated by energy in a very narrow field comparable to a reflective light barrier. This field is determined by the distance of the reader from the tag and the horizontal opening characteristics of the reader's directional antenna used.

RFID technology is used in underground installations in certain locations to serve as check points. In this manner are monitored underground trains or dispatch of materials is being monitored. Passive RFID modules are installed on containers or mobile machines like trains. Those modules can be read by passive RFID readers that are connected to mine network via dedicated control unit like a Mining Infrastructure Computer by Minetronics[39]. This control unit is responsible for RFID reader configuration and translation of its readings into a standardized positioning information format. It also extends data from the RFID reader with its unique name or coordinates which determine the position of a reader in a model of the underground mine. Long

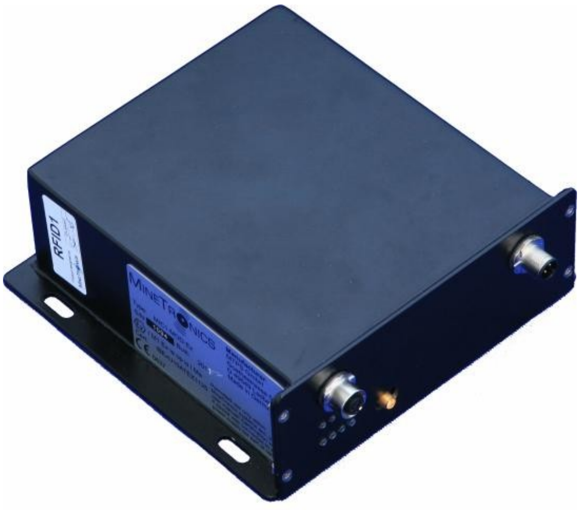

Figure 3.5. Passive RFID reader module by Minetronics[39].

Figure 3.6. Passive RFID tag in use on a container[39].

range passive RFID's operate on the 868 MHz band (Europe). A reader certified for use in underground coal mining using an 8dBi antenna is able to detect passive RFID tags at a range of up to 3 meters[39].

There are known successful implementations of positioning system which use RFID as a supplementary data. The RFID modules serves as static anchors [15][33].

3.2.2. Visible Light Based positioning system

Visible Light Communication (VLC) is a method for using the visible spectrum of electromagnetic waves for exchanging data[42]. The communication system requires a source of the and a light sensor which is able to detect light modulations. In case of simple signal modulations like Pulse Width Modulation (PWM), smartphone using a CMOS image sensor can be used effectively for receiving such modulated data. The source of light in these systems are LEDs. LED is a semiconductor device that can be easily controllable by logical unit. LEDs are characterized by low latency during changing their state from on to off and vice versa. It was measured that rising and falling edges during switching the state are about $4\mu s$ long [31]. The use of LED illumination for wireless communication purposes was already standardized by IEEE 802.15.7.

Advantage of VLC is that LED technology is commonly used as a light source in buildings and outdoors. If the LED lamp is prepared to transmit its unique ID or it's position expressed in 3D dimensions then the VLC system can be used as a positioning system with static anchors working as beacons. Such positioning systems are called visible light positioning systems (VLP). All of them consists of three main components:

- modulated LED light source able to send uniquely identifiable information (aka *light beaconing*[31]),
- distance estimation, which can be obtained by taking the measure of a received signal strength and a signal strength based distance model,
- localization, which provides actual information about the position of a receiver.

This can be obtained with use of trilateration/multilateration techniques[31] or methods like angle of arrival[42].

Trilateration technique defines the difference in time of reception of a signal in order to compute the distance between the transmitter and the receiver. Trilateration can be done using a Received Signal Strength measure. There are available methods for measuring the received signal strength from the LED light source that limits the impact with ambient light interference [31]. Triangulation technique is basing of the sender's angle to the receiver device. Such information can be obtained by the CMOS image sensor [42].

A simple light sensor is the source of the light information. A sensor is not aware the light source relative position or angle but allows for taking the received signal strength measure. The CMOS sensor provides more information about the acquired image as the output consists of a two-dimensional map of charges related to captured image. In this case it is possible to make use of the physical optics laws to get the relative position of a beacon. When there are four or more light transmitters available then it is possible to obtain a mobile receiver position in 3-D coordinates.

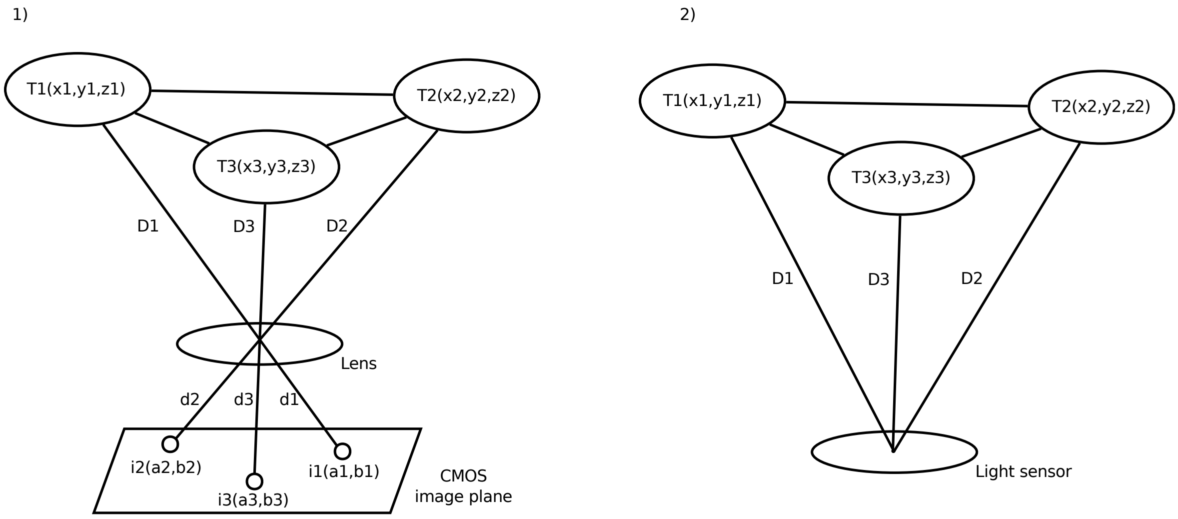

Figure 3.7. Visible Light Positioning system principles. Diagram 1) presents concept of positioning system that make use of CMOS sensor [42]. Diagram 2) presents concept of positioning system that make use of simple received signal strength measures and related distance model [31].

There are investigated various modulation methods that tackle with natural difficulties connected with visible light frequencies. Main of them are sun, ambient and fluorescent light interference with the carrier frequency and specular reflections [42]. As a modulation schemes there are being in use on-off keying, variable pulse-position modulation, color shift keying, binary frequency shift keying, channel hopping and pulse width modulation.

3.3. Applicability of smartphones in position finding solutions

Today's smartphone class mobile devices contain a set of sensors that can be used as a base for an inertial positioning system. In the underground mining and construction industries this idea is not the newest as there were trials of this technology implementations inside handheld devices for people working underground with use of semiconductor based MEMS gyroscopes [39]. Such devices were connected to the underground wireless network through access points which were responsible for transferring positioning information to the central systems above the ground.

Smartphone class devices contains a set of components that are treated as common in the industry. As there is a strong competition in the market, smartphones are offered in various configurations, shapes and features. This thesis exclusively focuses on devices that are compliant with the Android operating system, especially version 7.0 which is currently (in the middle of 2018), the most popular operating system on the market. [18]. The Android operating system forces hardware manufactures to equip devices with at least a minimal set of components needed for the system normal operation and give recommendations of optional components that are natively supported by the system[18]. In this section there are investigated only relevant sensors and technologies which are available for the basic handheld mobile device with the Android 7.0.

Smartphone class mobile devices are treated in the engineering industries as a powerful tool helping the workers with their maintenance work on site and as a handy platform for wide scale of businesses oriented applications for task management and reporting. Factors that attract potential users of such smartphone based solutions are mainly connected with the price of those devices, ease of use, well described and supported programming frameworks and IDE, ready to use libraries, solved main power management and security issues, ease of maintenance, modularity, scalability, support for the most popular data exchange technologies, ease of extending the functionality by adding the support for external, wireless equipment. Smartphones that are available in the market are also equipped with the sensors that allow the users to detect, record and recognise the physical movements or orientation changes. It extends the positioning functionality making it more robust and accurate[9][35].

There is known a university project *GoIn* [4] that develop a concept of combining all the sensors available on the smartphone device in order to make accurate positioning solution for indoor environments.

3.3.1. Mobile device sensorics

There is no limitation in extending smartphones with internal sensors. According to the Android 7.0 Compatibility Definition Document[18] there is no such sensor that must be mounted and implemented into the Android system in order to be compatible with the operating system. It is also stated that device can contain as many various sensors as the producer wishes under the condition of having a compliant software implementation that deals with the sensors. However, the Android compatibility definition recognizes some of them and recommends being installed on the device. There are also technical requirements given under the sensor's recommendation in case of presence of such on the device.

For simplicity reasons the Android defines all components providing external information to the device as sensors. Thus, components such as the GPS signal receiver or a processed and filtered sensor fusion outcome like in case of a rotation vector (fusion of accelerometer and gyroscope data) are recognise as different kinds of sensors. Such abstract definition comes from the Sensor Stack which is the part of the Android framework.

Sensors mentioned in the compatibility definition are:

- Accelerometer,
- Magnetometer,
- GPS,
- Gyroscope,
- Barometer,
- Thermometer,
- Photometer,
- Proximity Sensor,
- Fingerprint Sensor,
- 6-DOF Pose Sensor.

All components listed above, except fingerprint sensor, thermometer and photometer, can be used within the position finding system in order to give extra information about current physical state of the device. The compatibility definition guarantees some quality parameters of sensors mounted in the mobile phone.

A 3-axis accelerometer can be used to detect movement changes. It provides the information how big the change was in terms of force that was imposed to the device during motion. Thanks to this information can be identified if user made a step or to compute the speed of the user in some mean of transport like a robust car by computing integral function over time from the detected acceleration. It is required from that sensor to report events at least at $100Hz$ frequency (recommended minimum frequency is $200Hz$), to detect forces in range of a case of free fall up to forces four times the gravity (4g) or more on any axis, minimal outcome resolution is 12-bits (recommended minimum is 16-bits), it should allow for online calibration and calibration parameters persistence, be temperature compensated and have a standard deviation smaller than $0.05\frac{m}{s^2}$. The document defines also the maximum accepted amount of power that the sensor can consume during its operation – not more than $4mW$ (recommended values are bellow $2mW$ during the operation and bellow $0.5mW$ when the device is in static condition).

A 3-axis magnetometer (aka compass) provides the data concerning detected values of the magnetic field. Data available from the operating system level are expressed are in micro-Tesla(μT). The sensor must be able to measure between $-900\mu T$ and $+900\mu T$ on each axis before saturating with the resolution of $0.6\mu T$ (recommended $0.2\mu T$ or denser). The magnetometer have to compensate hard iron and soft iron effects where hard iron offset have to be less than $700\mu T$. That value forces the producers to place the sensor in as far from current-induced and magnet-induced magnetic fields like speaker. Sensor installation have to support online calibration and compensation methods and store the parameters in persistent memory. It is required from the magnetometer to report at minimum frequency of $10Hz$ (recommended $50Hz$).

The GPS/GNSS receiver is not required component for a smartphone with the

Android 7.0 operating system. If the sensor is mounted then it is required to match set of time, reliability and accuracy requirements like:

- Fast time to first fix requirement - the sensor has to determine its position within maximum 10 secods,
- Accuracy and responsiveness requirement - position have to be determined at least 95% of the time under condition of acceleration up to $1\frac{m}{s^2}$, within $20m$ and speed $0.5\frac{m}{s}$.
- Robustness requirement - it has to be possible to track at least 8 satelite from one constellation simultaneusely (recommended 24 GPS satelites at the time and one from other global positioning satelite system (GPSS) like Glonass, Beidou or Galileo).

It is assumed that the outcome of the GPS "sensor" can be supported by the information issued from the Internet such as information about current satellites position and can be based on some assisted or predicted GPS technique.

The gyroscope is an angular change sensor. If installed on the device it must be able to measure up to 1000 degree change per second, report at frequency not less than 100 Hz (recommended 200 Hz), provide information of 12-bit resolution (16-bits are recommended), be self calibrating and compensating during its work, march variance requirement defined as $1e^7\frac{rad^2}{s^2}$ per 1 Hz.

The barometer is an ambient air pressure sensor. It available is must report its measures at 5 Hz frequency, be temperature compensated and have "adequate precision" for altitude estimation.

The proximity sensor gives the proximity information of an object in the same direction as the screen. The required accuracy is at least 1-bit meaning that proximity sensor produces simple outcome that is interpreted as Boolean value expressed state whether the user is close to the devices screen or not.

A pose sensor with 6 degrees of freedom (6-DOF) is an optional sensor that can be implemented in the Android compatible software. The sensor provides relative position of the smartphone device expressed in 3 dimensional space. The method and related hardware is not discussed within the operating system compliance definition. Only restriction stated to the sensor is that it must be more accurate than rotation vector sensor. Basic implementation can make use of camera or depth sensor to compute the output value. Output is a quaretnion that express the rotation and a translation expressed in SI units. This sensor is used in virtual reality applications.

The Android compliant definition strongly recommends providing implementations of "composite sensors" such as step detector, significant motion detector, gravity, linear acceleration, rotation vector. These measures are computed by the software through digital processing of data from physical sensors like accelerometer in case of step detector or a sensor fusioning basing on multiple sensors like on magnetometer and gyroscope in case of rotation vector and accelerometer and magnetometer in case of geomagnetic rotation vector. The operating system recognize already filtered and processed data directly as an outcome from a composite sensor which is actually a form of abstraction that hides the details of data processing.

Management of sensors has to be implemented accordingly to the definition to allow the operating system to interact with those sensors. All the sensor outcome are yet processed, normalized and expressed in a defined way like in case of an accelerometer and magnetometer where the output is expressed within the "Android sensor coordinate system" format.

3.3.2. Abilities and limitations of smartphone class mobile device in context of available positioning methods

This thesis analyzes the use of regular consumer grade smartphones which are devices with a common setup compliant with the Android 7.0 operating system. No specialized devices are taken into consideration.

Wireless technology is a common way for exchanging the data between the handheld mobile device and the environment. There are available GPS, Bluetooth, Wi-Fi and terrestrial networks(GSM related) technologies. In case of underground applications of these technologies, their infrastructure has to be installed explicitly.

A GNSS (Global Navigation Satellite System) signal receiver is not useful under the ground as there is no signal from satellites available. There are known solutions that make use of GNSS modules in indoor environment by re-sending the acquired GNSS positioning data from satellites by a set of transmitters, that mimic satellites [56]. Such technology cannot be applied to the consumer grade smartphone as the Android applications have access to already processed pseudorange data into satellite positions. Such solution is called Global Navigation Satellite System based indoor positioning system (GNSS-IPS)[57]. The approach where transmitters placed on the earth to fake satellite signals is known as *pseudolite*. In case of indoor environment positioning data acquired from satellites are drifted due to the fact of non-line-of-sight that is why a position obtained in an indoor environment is called as pseudo-position. There are known attempts of using this approach in order to obtain positioning data but there is not known any successful implementation in underground environment.

Terrestrial networks, like GSM, can be also used as a source of positioning information but it requires some modification in order to short come problems with high variance of the signal. There is no possibility to do modification on that level to the Android software on devices available on the market nevertheless some prototype installations of extended terrestrial network by positioning information were done and successful [11][37].

Smartphone class devices are equipped with cameras. Images captured by the cameras can be used for positioning purposes. There are known solutions that make use of visible light [42] that recognise source of light like LED which are called LED beacons and compute the position basing on the angle-of-arrival (AOA) algorithm.

Thanks to the presence of inertial sensors such as accelerometers and gyroscopes there are known implementations of inertial navigation. Pedestrian Dead Reckoning (PDR) is based on the measures from the accelerometer which allows for step detection and an estimation of a step length [13] [12] [14]. There are also developed probabilistic based methods for inertial odometry which aim to be more accurate and robust than PDR [48]. There are investigated various filtering and calibration methods for accelerometer and gyroscope outputs, dedicated to the smartphone class devices making use of Allan variance algorithm, Levenberg-Marquardt algorithm and Runge-Kutta Integration method [40][52]. Other approaches developed the recognition patterns that allows for distinction between transportation mean being in used. Such approaches were used for example in case of prototype navigation application in Chicago, London and Cologne subway [50] or inertial navigation for bikes [46]. There are known solutions for inertial navigation improvement by aligning the outcome to the landmarks or map information [30].

Positioning techniques that involve the following devices are not useful or cannot be connected to the mobile devices:

- laser scanner as long as it requires stable position for doing the environmental mapping and recognition and it needs to explicitly be extended to some wireless communication module,
- ultrasonic sensor as long as it requires a stable position in order to measure signal travel time correctly and it needs means of computational resources in order to process the raw data and send them thorugh some wireless connection to the mobile phone.

Smartphones provides support for Beacons – simple Bluetooth Low Energy devices. There are available libraries that allows monitoring of Bluetooth devices. Two modes are available for searching for Beacons: region monitoring and ranging. Region monitoring is an energy efficient way for searching for Beacons. It allows for long delays between consequent listening periods (like 10 seconds), turning receiver into sleep mode, and background service being active while the positioning application is turned off. In case positioning application is turned off, the background service inform the user that his smartphone found himself in the range of given Beacon region and runs the positioning application. Such functionality is often implemented by shopping malls official applications allowing for location aware push-messages. Such advertising technique is called *geofencing* [10]. Region monitoring gives a rough information whether there is or there is not any Beacon device being in range. On the other hand, ranging gives details about all devices being in range with details such as RSSI, name, and other, protocol dependent data. Ranging use more receiver power as listening time is bigger (like 1 second) and there are smaller time intervals between consequent listening sessions (like 10 milliseconds). As it was explained in section 3.1.2, Beacons communicate their presence by sending broadcast messages called advertisement frames. With respect of the type of protocol being used there are different formats available for advertisement frames, known as beacon layouts. A layout denotes the constraints that characterize a given advertisement frame as well as variables and fields that are being included into frame.

3.4. Positioning model requirements

Positioning system as such have to match requirements related to the reliability and robustness, accuracy, power efficiency, installation and maintenance effort and safety. As the smartphone device is also a part of the solution, then proposed positioning system must be able to interact with this device.

The positioning solution proposed later in the thesis should allow users to make use of it within the ordinary works as well as in case of an accident. The minimum time that the positioning system should work without any external power supply is 72 hours. That value comes from a term of *golden 72 hours* which relates to the period after an accident, after which survival rate decreases rapidly [30]. The system should work also in case when part of its infrastructure is not working properly like in case of an accident where some corridors can be destroyed including the positioning system infrastructure.

The simplicity of maintenance in terms of semi-automated methods for detecting failures and possibility to fix broken positioning infrastructure without necessity of involving specialized engineers should be matched. Such requirement can be met for example by simplicity of the positioning system infrastructure or by automated configuration methods which make the infrastructure self-organising. The infrastructure should be scalable as underground installations are likely to be extended during the excavation process. The infrastructure shall be open for software and internal modules updates and extensions of already mounted devices. That allows the positioning system to be further developed.

Power efficiency is a requirement that causes the system to be more likely independent of the on-site power supply. The infrastructure can have own power source and set of methods that limits power consumption of its devices. The infrastructure can be also extended by some power harvesting methods such as thermoelectric or piezoelectric generators.

The smartphone must provide energy-efficient solutions for exchanging the data with positioning system while there are no battery charging points in underground installations. Smartphone shall be able to work at least for 8 hours and possibly 72 hours with a limited use of a positioning extension. 8 hours is the regular worker shift time in underground mines. The solution must be applicable for different models of Android smartphones.

The solution must be easy to use for the user. In particular, it should be integrated into the user smartphone in such a way that the user will not have to handle it specially to use the positioning system. For example solution must be suited to work while the users' smartphone is kept in his pocket as well as is held by the user in the hand in front of him. The solution must be suited to provide positioning information when the user is not moving as well as he is walking. There should be assumed walking pace as $6\frac{km}{h}$. When people are walking under breathing filter in emergency, walking speed is very low – $1\frac{km}{h}$ or even less[39]. This needs to be taken into account. Possibilities to adopt the solution to work with the higher speed of the user or, for example, users riding inside the vehicles are in plus.

The solution must be able to provide positioning information in real time manner. Under the assumption that a user of the system will be walking inside an underground installation, there is need to ensure a position update frequency of at least one per second. Position of the users should be provided with maximum drift of 10 meters along the tunnel line. Desired accuracy is about $1m$ along the tunnel line (Tunnel Meter level accuracy).

Safety purpose of position finding system is very important for many countries [30]. The European Union encourages searching for a good solution for the miner's localization, which, in one of the postulates of its set of recommendations for the coal and steel sector ('Personnel Tracking' task). There are solutions for underground localization, but they allow only to approximate miner's position (error can be range from 300 m (range of a single radio receiver) to the distance to the next transmitter).

Underground position finding system must be compatible with mobile devices of smartphone class. Special mobile devices that were prepared to work in bad conditions like in coal or salt mines differs mainly with their housing in comparison to their non-commercial, personal-use equivalents. This assumption limits the range of available technologies that can be used in order to provide means of communication between mobile device and the environment.

The position finding system proposed in this thesis bases on the idea of interaction between a mobile device and the underground environment. Devices used within the solution must be compliant with the safety regulations. Safety regulations in this matter differs with respect of the type of underground installation, the regional, country, or even association of countries [39]. This thesis exclusively addresses the general possibilities and state-of-the-art solutions for position finding.

Requirements summary stated for a positioning system and related infrastructure:

- Reliability / robustness
  - must be able to work wihout external supply for at least 72 hours,
  - must be able to work even in case where part of infrastructure is not available.
- Installation and maintenance
  - semi-automated methods for monitoring the positioning system status,
  - support for positioning infrastructure reperation by avoiding manual system reconfiguration,
  - solution should be scalable in order to extend positioning system along with the grow of underground installation,
  - infrastructure devices should be open for software and internal modules updates and extensions.
- Power efficiency
  - Possibly self powered.
- Accuracy related
  - responsiveness: position update with frequency least one per second,
  - position error less or equal to $10m$. Ideal would be sub meter level accuracy along the tunnel line (in direction of the tunnel),
- Smartphone related
  - positioning system must be compliant with technologies supported by customer grade smartphone device,
  - smartphone should be able to work continuously for the 8 hours with activated positioning module.
  - recommended smartphone life time is 72 hours with limited power consumption and use of positioning module.
  - solution applicable for different smartphone models.
- Usability
  - Solution must allow the user to be able to use the solution without forcing him to handle his smartphone in a special way.
  - Suited for the walking man.
  - inftrastructure components must be size suited to the proposed mounting placement,
- Safety
  - must be explosion proof and intrinsically safe,
  - should be suited to the ingress protection (IP) standards,
  - must have durable housing.

Chapter 4

Mobile technology based positioning model

This chapter introduces concept of positioning model for position finding problem in underground installation. Proposal consist of underground environment characteristics evaluation in context of chosen method of acquiring the information about the surroundings needed for estimating the current position as well as the concept of static configuration of the underground installation layout, reference points installation and maintenance, interaction between smartphone and the environment, chosen technologies.

4.1. Position finding techonology selection

As proposed model is a generic solution for positioning inside underground installation there was assumed strict underground environment with the smallest set available technological infrastructure and safety limitations. Decisions regarding model specifics were obtained as a result of prototype solution tests in real environment. Tests are described in chapter 5.

The position in underground installation is a pair of a label of a current corridor and a current meter counted from corridor start. Model assume that position is expressed by that pair, so output of the model is not expressed 2D or 3D coordinate system but in more abstract, installation dependent way. Proposed model make use of the Bluetooth Low energy technology in order to limit impact of difficult electromagnetic propagation conditions (see sections 2.2 and 3.1). It is assumed that smartphone will use build in Bluetooth radio modules in order to monitor presence of beacons and range their signal strength in order to estimate distance from them. Reference installation consists of Bluetooth beacons placed $10m$ each in areas where position finding solution is needed. Assumed accuracy of the proposed model is about $5m$ with possibilities to be more accurate through extensions to positioning algorithm. Bluetooth transmitters are equipped with batteries allowing them to work continuously for at least 2 years – approximate time demanded for positioning solution being in use in given installation area. Beacons broadcasts their name at frequency of $2Hz$ and transmitter power level adjusted to cover the area of at least $10m$ but not more than $20m$ from their placement. Beacons can attach optional information to their advertisement messages if needed. Placement of beacons are given in advance in a configuration file. Each entry in configuration file consists of name of the beacon and his position expressed as a pair of corridor name and meter. "Blind" mode where none of a priori configuration is provided is also possible, when beacons send additional information about their placement (pair of corridor id and meter). Model do not investigate communication possibilities of a smartphone and beacons, smartphone and external network facilities or connections between other smartphones. Positioning model assumes that each user takes a part in system maintenance by verifying the signal presence of the beacons given in the configuration file and reporting installation errors. Placement of the reference points should be planned in advance and beacons configuration should be applied to them before their installation on site. Installation consist of placement verification by engineer and mounting.

The smartphone devices are equipped with sensors which can be used to correct the position estimation accuracy. This thesis exclusively focuses on sensing the environment and "static anchors" giving the possibility to synchronize position estimate of the model implementation with actual environment.

4.2. Solution architecture

General solution architecture for the prototype positioning system is presented on the figure 4.1. Solution consists of:

- installation based on beacon devices,
- a smartphone device with Bluetooth receiver,
- a smartphone application that process the data from the external infrastructure and internal sensorics.

It is assumed that reference points infrastructure is mounted in a way that each beacon is denoted in a configuration file consisting of a list of beacons with placement position assigned. A smartphone application can be adjusted to be more robust and underground installation site independent by providing the position information directly by the reference points. This proposal relies on already defined beacon positions as this approach allows each end-user application to work as a maintenance tool that is able to detect problems of the infrastructure including beacon failures. The system does not include such maintenance feature but it will be included into future works.

The core positioning information is gathered from the reference points(beacons). They have a fixed position, and they are the most correlated with the physical layout of the underground installation. Having only this information it is possible to obtain positioning information as accurate as distance between subsequent beacons mounted on site. There shall be introduced additional distance approximation basing on received signal strength values. The proposed solution introduces a method of increasing the accuracy of position estimation based on RSS.

Figure 4.2 presents the concept of the received signal strength based positioning solution for smartphones. As the application of the distance models on the RSS values are questionable in underground installation environment, the proposed solution relies on predefined values expressing the distance class rather than on approximated distances based on exact received signal strength analysis. The values used for the po-

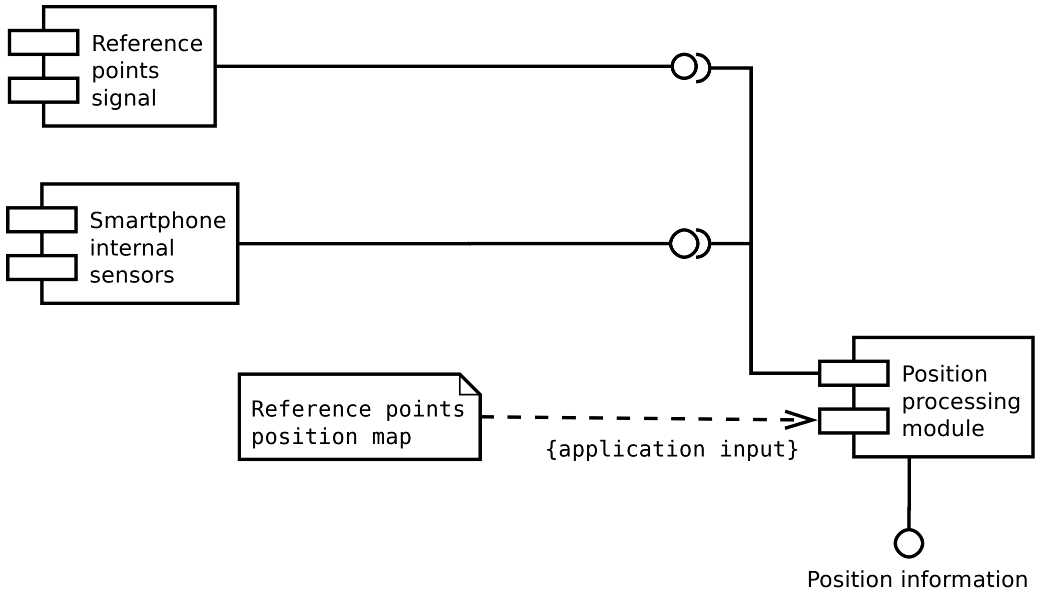

Figure 4.1. General solution architecture. Position processing module gathers data from smartphone sensorics, data and acquired signal parameters from reference points and serves current position as an output.

sitioning system were computed from results obtained during the underground tests. The proposed algorithm for position approximation use three predefined values:

1. FAR threshold - RSS value that describes minimum RSS that can be taken into consideration during approximate position evalutaion. The beacon that send signals with lower RSS than defined by "FAR" is categorised as "far beacon" and signal is treated as a noise,
2. IMMEDIATE threshold - RSS value that descibes minimum RSS that comes from the beacon located "immediate" to the smartphone. Signals with bigger RSS value indicates that beacon that emmited those signals is an "immediate beacon". Signals with smaller RSS, but larger than defined by FAR threshold, indicates that beacon that emmited those signals is a "near beacon",
3. DIFF value - maximum accepted difference between obtained RSS values from signals sent by "near beacons" that allows to approximate the smartphone positinon in the middle of those "near beacons".
4. the beacons that send signals with RSS values smaller than IMMEDIATE, but bigger than FAR thresholds are "near beacons".

Due to the fact that received signal strength has significantly bigger values within the area of $0m - 2,5m$ from the transmitter then this distance was classified as *immediate* (see figure 5.10 in chapter 5.3.2). RSSI values observed in *immediate* range were bigger than $-85dBm$. RSSI values lower than $-95dBm$ are treated as a noise thus frames that were acquired with such RSSI value or lower are classified as *far* and are placed in $20m$ or more from the smartphone receiver. Signals with RSSI between

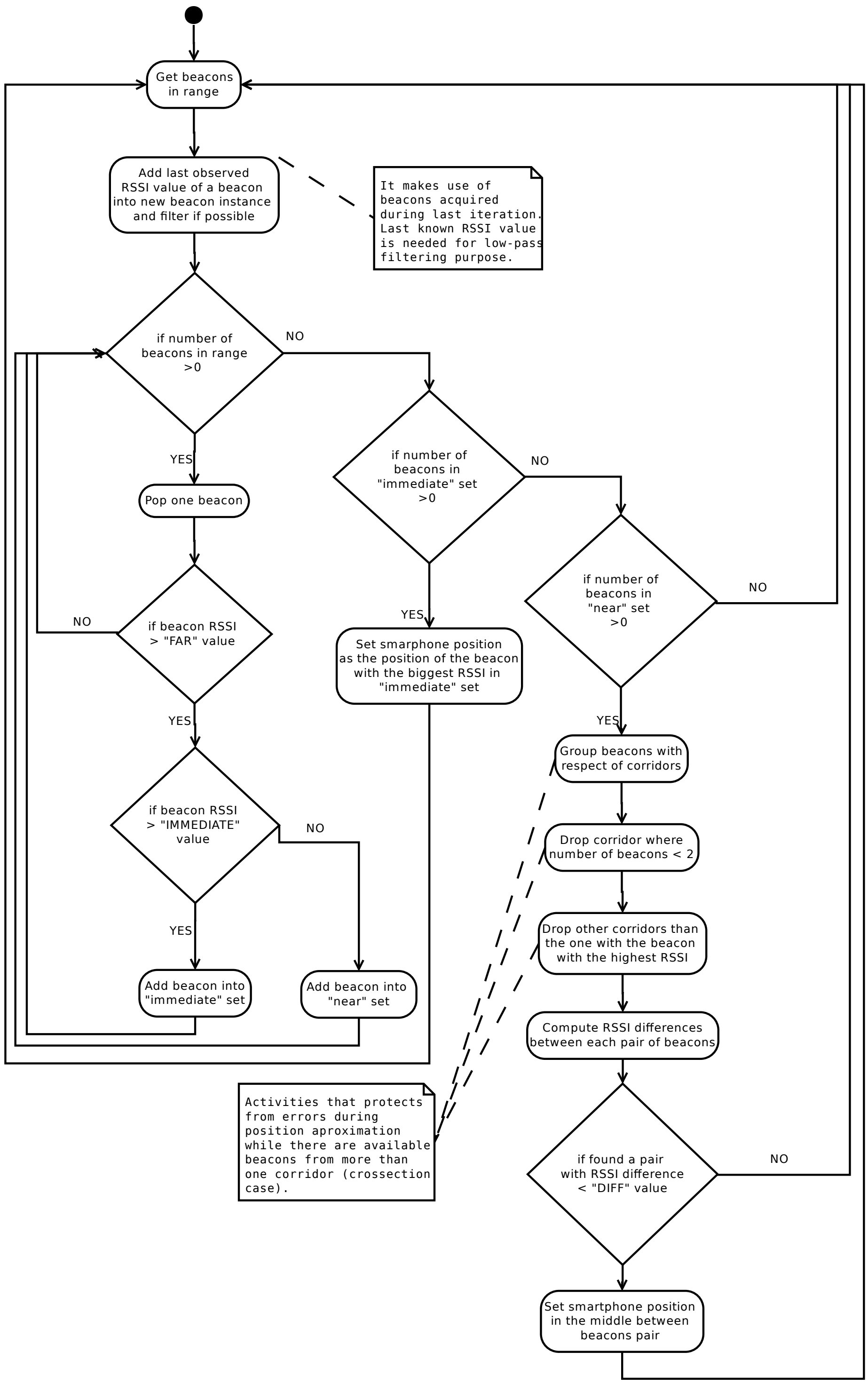

Figure 4.2. The proposed position aligning method based on the received signal strengths from reference points.

$-85dBm$ – $-95dBm$ are assumed that were sent by beacons which are classified as *near*, placed in range $2,5m$ – $20m$ from smartphone.

In the proposed solution the beacons are placed in $10m$ distance from each other. Each beacon is configured to cover distance of maximum $20m$ but minimum of $10m$. These assumptions cause redundancy where in the perfect scenario smartphone located *immediate* to the beacon is acquiring signals also from two other *near* beacons. In case when one of the beacons is not working, smartphone remains in the beacons range.

The accuracy of the proposed RSS based position estimation is equal to the half of the distance between nodes. The estimation is based on the distance ranges assigned to beacons, computed out of the RSS values. If there was found any beacon in the *immediate* range, then smartphone position estimation take the position of the beacon with the biggest RSS value. If there was found two *near* beacons and received signal strength of their advertisement frames are similar, then smartphone position estimation is set as the position is in the middle between the beacons. Similar signal strength means that the difference between each of them is less than $2dBm$ what is equal to $1,25m$ according to *Log-distance path loss model* (see section 3.1).

In order to maintain ability of determining the position by measuring received signal strength from beacons and provide long battery life of the beacon in the same time there were following beacon transmission parameters assumed:

- the beacon will send his advertisement frame once per second,
- the beacon will be set up with $-16dBm$ transmitter power or equivalent that ensure beacon coverage of $20m$ in underground environment,
- the beacons will be placed in $10m$ distances between each other,
- the beacons which advertisement messages were received with more than $-85dBm$ RSSI are assumed to be *immediate* to the smartphone, those with more than $-95dBm$ RSSi are assumed to be *near* to the smartphone, rest are assumed to be placed *far*,
- if there was found at least one *immediate* beacon then current smartphone position is assumed to be same as the beacon with the highest RSSI value.
- if there are two or more *near*-placed beacons and if there was found similar ($+/-$ $2dBm$) RSSI values among them, the current smarthone position is assumed to be in a half way between beacons with these similar RSSI values.

The output of the inertial sensors can produce misleading position information. For example basing on the accelereometer data only it may turn out that the user changed direction of the movement while he is still moving forward. It may worsen the positioning information.

In a simple case, where the smartphone is away from corridor intersections, the position finding algorithm is aware of two positioning scenarios: smartphone is close ("immediate") to the beacon and smartphone is in between two near beacons. In order to determine current scenario, the algorithm categorize them with respect of their RSS values into two sets: "immediate" and "near". If there were found "immediate" classified beacons, then algorithm set current smartphone position to the position of the "immediate" beacon with the biggest RSS value. In case where there are no "immediate" beacons but there were found at least two "near" beacons then the difference between their RSS values are evaluated. If difference is lower than DIFF value then the smartphone position is considered as in the middle of related beacons.

The smartphone located near the intersection can receive signals from beacons located in two or even more corridors (like in case of intersections in room-and-pillar production block – see figure 2.1). In such situation there is a need to adjust the algorithm to make use of information from beacons labeled with different corridors names and meters. The proposed algorithm tries to locate "immediate beacon" first. If there is no such beacon then RSS values from all "near" beacons are evaluated in order to check if there is possibility to estimate smartphone position as position in the middle of two nearby beacons. For that purpose beacons are grouped into sets that represents corridors they belong to. Sets with only one beacon are removed. Within all remaining sets the algorithm look for a pair of similar RSS values (difference must be smaller than DIFF threshold). If such pair was found then smartphone position is estimated as a position in the middle of beacons that emits signals from pair.

4.3. External solution infrastructure

The reference points infrastructure is a vital part of the proposed positioning system. In order to provide reliable reference information there is the need to ensure that the installation is easily maintainable, infrastructure parts are in good condition and were placed in defined way with accordance to the position, orientation and mounting recommendations. For this purpose installation step was defined as it is shown on figure 4.3. Prior to the works on site it is suggested to plan where beacons will be placed in the installation. Outcome of this plan should be a list of beacons names and the positions expressed in pairs of corridor name and a meter counted from the beginning of the corridor. Also, a map with marked places where beacons will be mounted would be a good addon that will help the installation engineer with his works. Then each beacon should be labeled in accordance to the plan and configured with the name from the label and recommended transmitting power. Such preparation will shorten installation time and will avoid potential problems with misconfiguration.

The chosen beacons (hardware equipment) are ready to use modules consisting of the micro controller which implemented Bluetooth stack, power supply management and radio module with antenna. As most of the market use Bluetooth 4.0 and 4.1 technology, chosen beacons are Bluetooth 4.0 beacons. There is no difference between those two versions of technology in case of desired beacon functionality – broadcasting the advertisement messages without encryption nor other restrictions. As the beacon signal are available only on site, often hundreds of meters bellow the surface, there is no purpose of making the signal messages complicated. Newer technology of Bluetooth 5 is fully backward compatible so devices with such modules will also be able to make use of beacons in Bluetooth 4.0 technology.

The beacon modules are easily available on market. Cheap modules can cost about 7$. Proposed positioning model does not force using given model of the beacons but the beacon's configuration must match following criteria:

- transmitter power setting must be adjusted in such a manner that signals will reach distance of $10m$ from them but not more than $20m$. It saves some energy and limits amount of noise inside the tunnel,

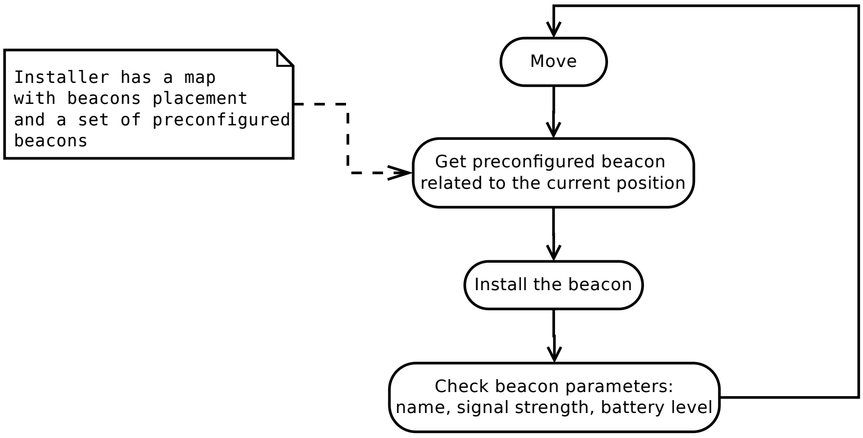

Figure 4.3. Infrastructure installation procedure.

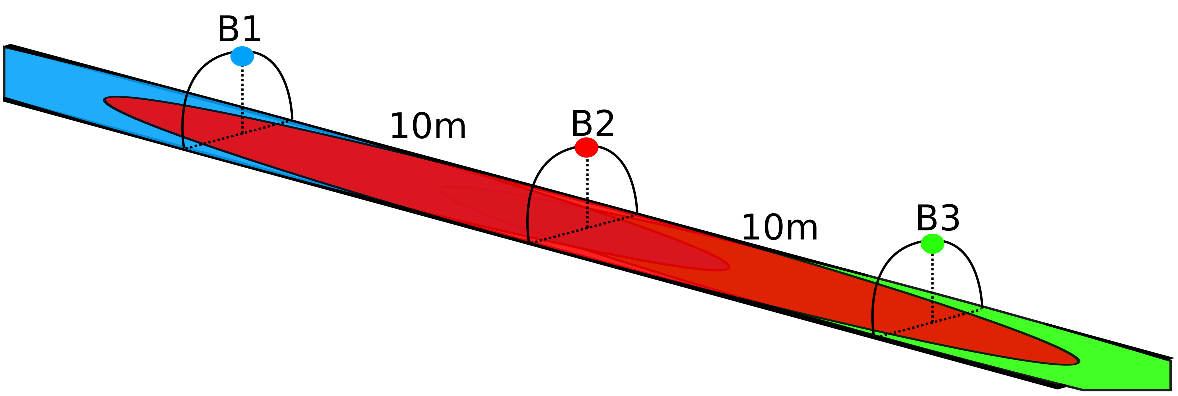

Figure 4.4. Example of reference beacons B1, B2, B3 placement in corridor. Red field denotes approximate signal range of the B2 beacon – more than $10m$ but less than $20m$.

- beacon transmit advertisement message at frequency of $1Hz$. It is enough to detect beacon signal when user maintain walking speed of $6\frac{km}{h}$, and update the current position each second, maintaining the minimum accuracy of $5m$,
- battery must be suited to work containeusly for 2 years,
- beacons have to be placed $10m$ each in order to make the positioning solution more accurate and maintain good signal quality on limited coverage from beacon mounting place,
- beacons have to mounted on ceiling in vertical antenna direction as the experimets shows such configuration most efficient in terms of signal quality and range,
- beacons transmits their unique name.

4.4. Data processing and analysis

The proposed positioning system depends on inputs from the smartphone's wireless receiver. Raw data cannot be used directly by the positioning algorithm because of different nature of those signals and presence of high drift and noise levels that affects wireless transmission. In order to make signal useful there is need to apply filtering that will normalize the outcome of particular information source and possibly improve position estimation.

There were investigated four filtering methods:

- Kalman filter [6],
- Low-pass filter,
- RSSI smoothing approach [24],
- Median filter.

All filters were applied to example signal strength waveform. Results are presented on the figure 4.5.

The median filter is a non-linear moving N–order filter. N denotes number of frames within the sliding window what is directly proportional to the delay it introduces to the result. The aim of this filter is to obtain slow changing estimate of received signal strength curve. As the goal is to provide an energy-efficient solution, the number of signals sent by the beacons are limited in order to save energy. It was assumed that beacons will send their signal two times per second. The value can be increased or decreased with respect of the experimentally obtained responsiveness of the positioning system and power consumption of beacons. For evaluation purposes $N = 4$. As it can be observed, the median filter (purple curve) doesn't filter the RSS drop at about 30'th probe, but filtered most of the fluctuations around 80'th probe. It is not accepted for a filtering function to introduce such big delay without possibility to filter fluctuations like around 30'th signal probe.

The smoothing RSSI approach [24] is a filtering method that introduces a *weighted value* parameter α which can be any value from range $0 - 1$. The equation that express the method is as follows:

$$RSSI_{smooth} = \alpha \cdot RSSI_n + (1 - \alpha) \cdot RSSI_{n-1} \tag{4.1}$$

For evaluation purposes α parameter was set to 0.25. The curve obtained was distinguished on figure 4.5 with blue color. It was observed that this method introduces

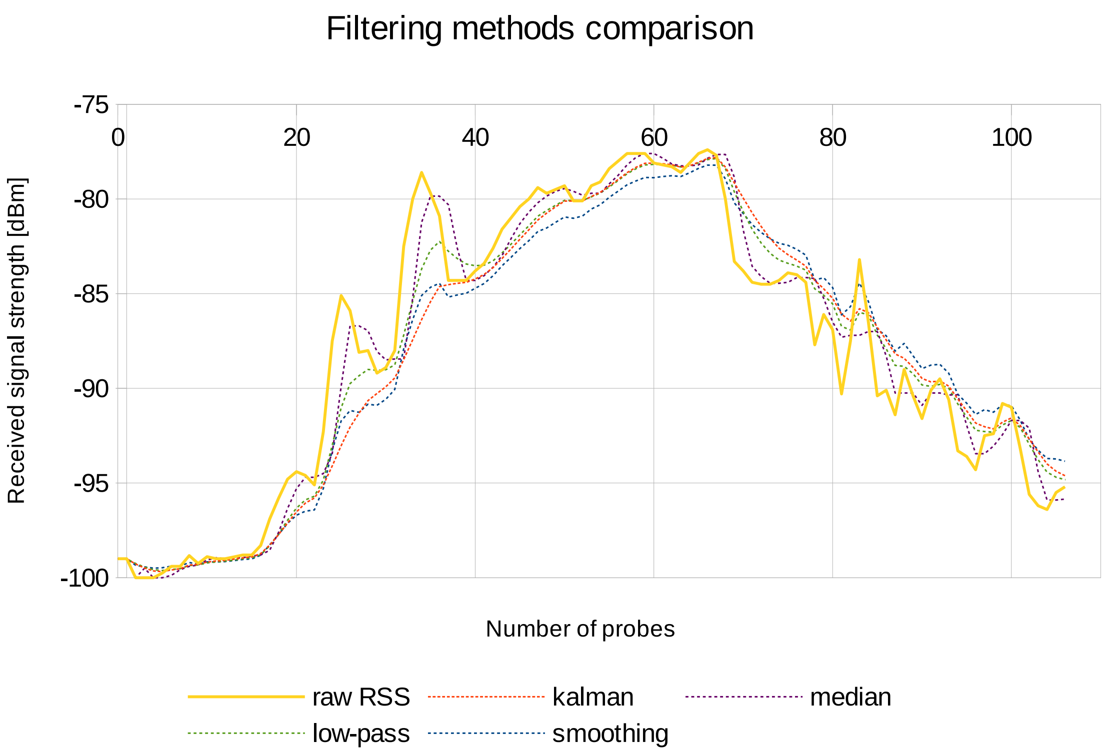

Figure 4.5. Proposed position aligning method based on the received signal strengths from reference points.

a delay of around 4 frames after the actual signal. Another observation is that the estimation slowly reacts on the increasing and decreasing slopes of original signal: when the original curve goes up then estimate values are always below the original slope, when the curve goes down then estimate values are always above the original slope. This is clear because the algorithm with the weighing value of $0,25$, values the previous sample higher, so the curve always shows a phase shift to the right.

The low-pass filter is commonly used to remove short term variance from the signal. It is widely used in indoor navigation applications, mainly for inertial navigation and sensor data analysis [17][20][8][23][44]. This approach uses cut-off parameter α, similar to one from smoothing approach.

$$RSSI_{low-pass} = RSSI_n + \alpha \cdot (RSSI_{n-1} - RSSI_n) \tag{4.2}$$

For evaluation purposes the α parameter was set to 0.25. The low-pass filter introduces a smaller delay than in case of smooth and median filters, about 2–3 frames. It filtered the signal drop around 30'th signal probe and fluctuations around 80'th probe. On figure 4.6 there are presented filtering results with use of different custom extensions to the filtering method.

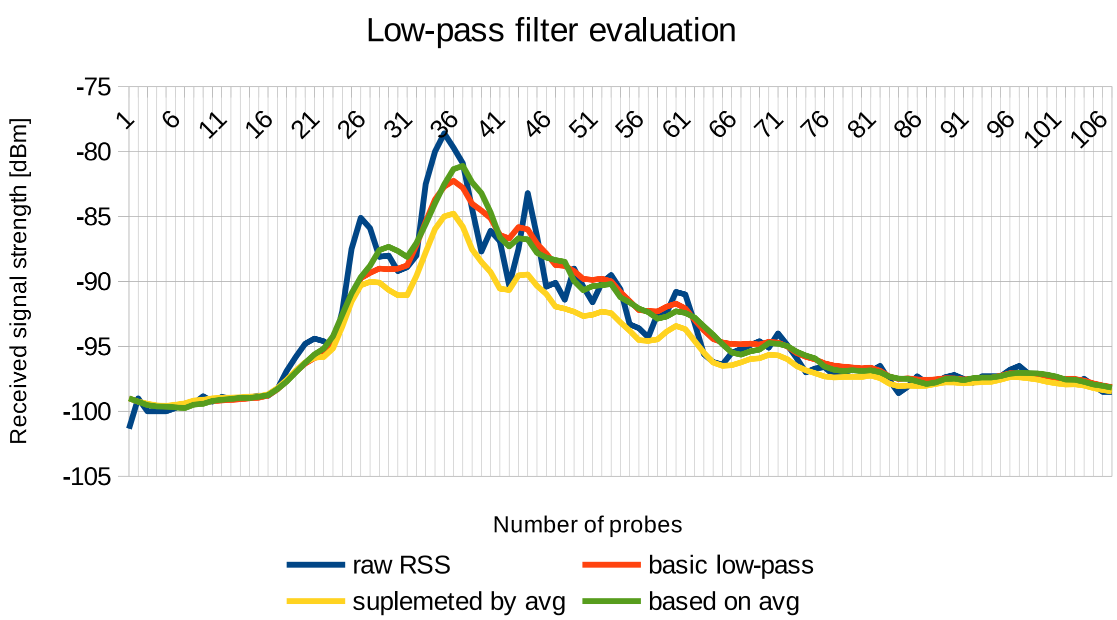

Figure 4.6. Proposed position aligning method based on the received signal strengths from reference points.

Custom variations of low-pass filter are a try of adjusting the responsiveness of the filter and it's fluctuation filtering capabilities. On the figure 4.6 are presented following concepts: low-pass filter based on average and low-pass filter supplemented by average. Following equations describe each of them:

$$RSSI_{low-pass_{as}} = AVG(RSSI_{n-3} : RSSI_n) + \alpha \cdot (RSSI_{n-1} - RSSI_n) \tag{4.3}$$

$$RSSI_{low-pass_ab} = RSSI_n + \alpha \cdot (RSSI_{n-1} - AVG(RSSI_{n-3} : RSSI_n)) \tag{4.4}$$

AVG is an average function over window that consists of 4 frames.

Kalman filter is an extended filter that allows for sensor fusioning by defining observation and transition models, and controls. It is widely used for sensor fusion of inertial navigation purposes[14], also for smartphones [46][55][33] and Bluetooth technology [10][5][7][19]. Simplified Kalman filter assumes that beacons (signal transmitters) are not moving and do not change its state though consecutive RSS readings (transition model is expressed by identity matrices). There was recently proposed extended Kalman filter for RSS signal filtering[6]. Simplified version of a filter can be described as follows:

$$\begin{aligned}
C_n &= P_{n-1} + PN \\
M_n &= |RSSI_n - RSSIk_{n-1}|^P \cdot N + E \\
G_n &= \frac{C_n}{C_n \cdot M_n} \\
P_n &= \max\{PN, C_n - (G_n \cdot C_n)\} \\
RSSIk_n &= RSSIk_{n-1} + G_n \cdot (RSSI_n - RSSIk_{n-1})
\end{aligned} \tag{4.5}$$

Symbols used in equation 4.5:

- $RSSIk_n$ – prediction for the the n'th signal probe (RSS),
- G_n – Kalman gain for the n'th signal probe,
- $RSSI_n$ – real measurement of n'th signal probe,
- C_n – certainity of n'th signal measurement,
- P_n – prediction certainity of n'th signal probe,
- M_n – measurement noise for n'th signal probe,
- P – measurement expotentional constraint,
- N – measurement noise factor constraint,
- E – measurement noise epsilon constraint,
- PN – prediction process noise constraint.

Figure 4.7 presents Kalman filter applied on RSS values recorded experimental session. With respect of chosen to filter constraints it is possible to increase or decrease filter responsiveness. Increasing responsiveness cause filter faster response to changes but make it more sensitive for longer term fluctuations like in case one between 26 and 36 probe. Within this range red curve introduces delay of 3 frames but does not filter the fluctuation, while yellow curve filter the fluctuation with the same delay of 3 frames, but predicted value is about $5dBm$ lower than registered pick. Misconfigured Kalman filter overact on changes and introduces new fluctuations like it is presented on the figure 4.8.

The values of signals strength should not be used directly as an input for because models are sensitive on the provided signal strengths. That is why filtering techniques are needed in order to make the signal free from random changes and more robust in terms of environmental distortions. There are known other filtering approaches dedicated for RSS like Gaussian filter, distance weighted filter or propagation model training [25] – their applicability for underground environment will be evaluated in future works.

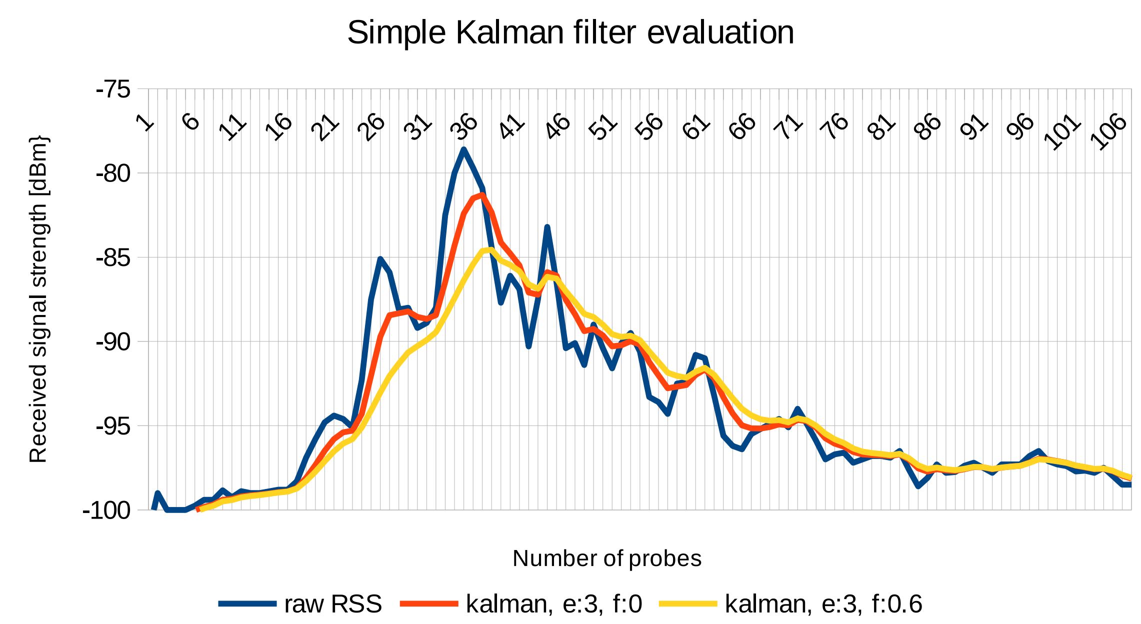

Figure 4.7. Application of Kalman filter. Red curve represent Kalman filter with $E = 3$ noise constraint and $P = 0$ expotentional constraint while yellow curve represent Kalman filter with $E = 3$ noise constraint and $P = 0.6$ expotentional constraint.

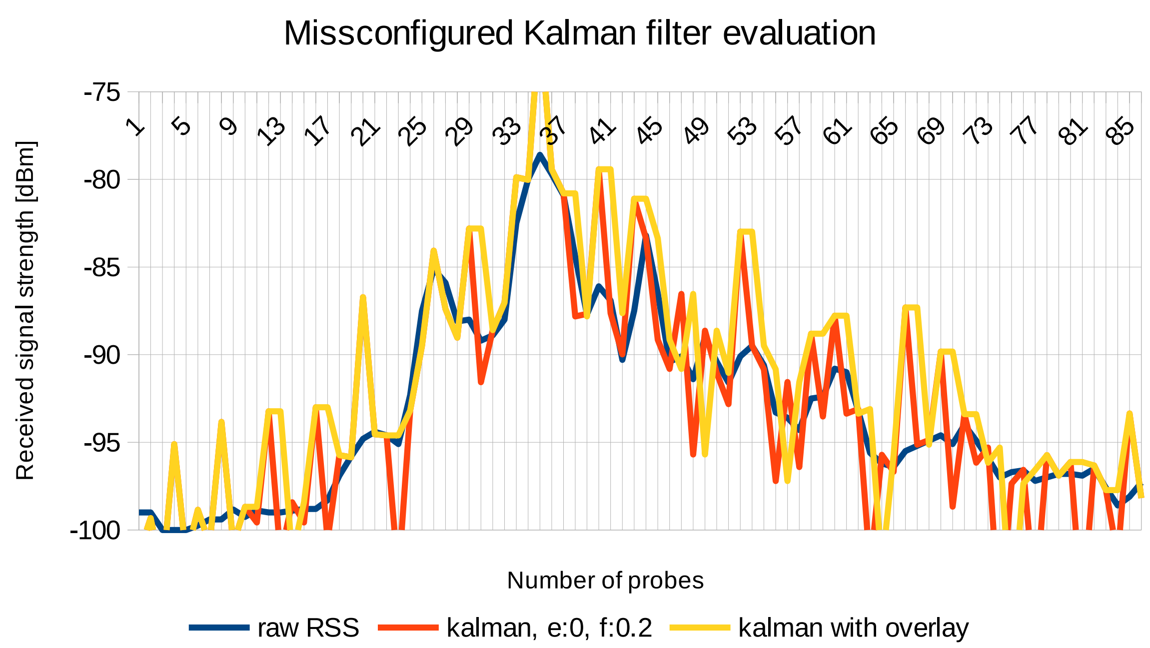

Figure 4.8. Application of Kalman filter. Red curve represent Kalman filter with $E = 0$ noise constraint and $P = 0.2$ expotentional constraint while yellow curve represent Kalman filter but with overlay.

4.5. Position finding proof of concept implementation

There was a proof of concept implementation of the position finding model made. As the basis for the implementation there was used Android framework dedicated to devices with Android 7.0 operating system or higher. There was used open library "altbeacon" that provide means of communication with beacons.

The application consists of two main modules: current position screen which is devoted for finding the current position and beacon ranging settings module.

Despite regular operation mode, there was also implemented background operation mode. Regular operation mode is characterized by shorten times between subsequent radio listening periods and longer listening times. In this mode it is possible to "range" the beacons found, read messages they provide and measure the signal. An example of ranging activity is visible on figure 4.11. Application is able to read all the messages sent by the beacon – in this case beacon named *B1(3)* – measure RSS value, aggregate those values for all packets acquired (default aggregation type is moving window average), count all the sending activities versus number of correctly read packets and compute approximate distance basing on the RSS values. Distance calculation by default makes use of *Log-distance path loss model* and the information about the assumed RSS value measured at one $1m$ distance from the beacon. Details about distance calculation methods are available in section 3.1.2.

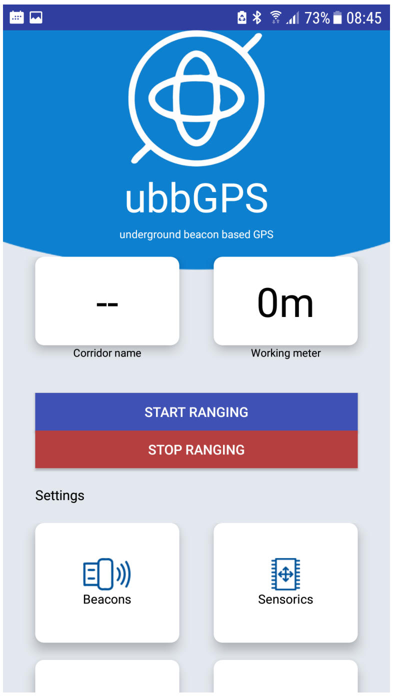

Figure 4.9. View of the main application activity – position finding module.

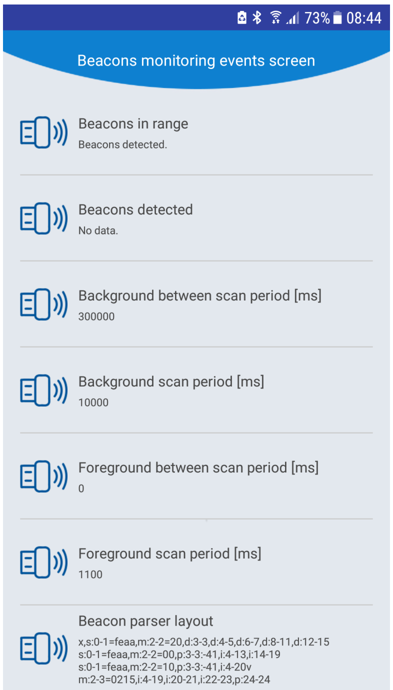

Figure 4.10. Bluetooth beacon ranging and monitoring module setup.

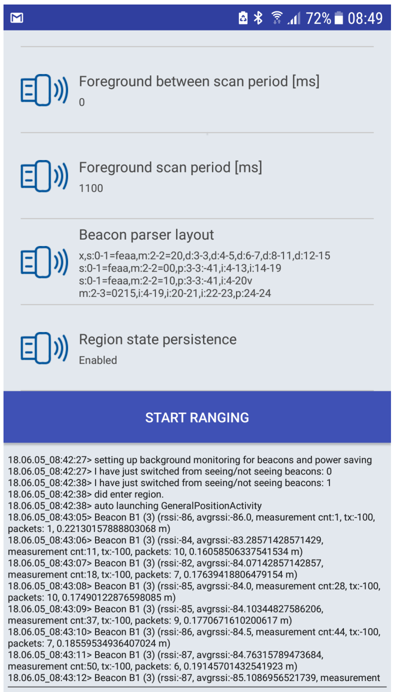

Figure 4.11. Ranging activity log – details about detected beacons.

The background mode allows for lower power consumption of the smartphone device by limiting use of Bluetooth module. It works in a manner of short scan which is aimed to detect if any of beacon was detected in the near area. If so, background activity inform the user that he just accessed the area where positioning information is available. The background mode works even if main application remain not active. The background mode allows the user to start position finding activity immediately after successful detection of the beacon. An example output of background activity can be seen on figure 3.1.2 within the first lines of the log, just bellow the "Start ranging" button. The first message *setting up background monitoring* is related to first start up of the positioning finding application. Then the application can be closed – stopped by the user. If application got killed by the operating system then neither background and regular operation modes are not working. The log entries *switched from seeing / not seeing beacons* and following are related to detection of the beacon and performing related action. In this case view of position finding activity was run.

The parameters of monitoring and ranging activities are about scanning delay times in both background and regular operation modes. Application can define also types of beacons that are accepted by definition of "layout". Syntax of layout relates to the header of the advertisement massages broadcast by beacons. Example of layout is available in section 3.1.2 in part concerning *iBeacon* protocol.

The position finding view presents pair of name of corridor and working meter that is obtained as a result of the proposed position finding algorithm. This pair is aimed to be enough for position identification regardless the complexity and scale of underground installation.

Principals of the proof of concept implementation were used in tests in the real environment.

Chapter 5

Positioning model prototype implementation tests

In order to check if the proposed solution is good enough to estimate the position of the mobile phone there was performed tests of chosen hardware components as well as the proposed Beacon-Infrastructure serving as the referencing system. Finally, there were performed tests the prototype software application in the real environment, in the underground part of Stara Kopalnia museum placed on the site of the former Coal Mine in Wałbrzych.

5.1. Tests criteria and assumptions

In order to test the reference system infrastructure there was need to test reference point device (Beacon transmitter) in context of interaction between this device and the receiver (Smartphone). For the hardware testing, there were following factors being specified:

- receiver distance from the transmitter,
- smartphone – and thereby antenna – orientation,
- smartphone model,
- transmitter type,
- transmitter power,
- transmitter placement,
- transmitter antenna direction,
- distance between transmitters.

Those are the factors influencing the final received signal strength value.

According to the *log-distance path loss model* [47] (see 3.1) the distance between receiver and transmitter is the major factor that impacts on the signal strength. There was the need to check how distance impacts the signal strength in the desired environment in the underground corridor.

As all the transmission path elements can impact the resultant power strength, also different antenna orientations were checked at transmitter and receiver respectively. That is why during the tests there was checked if different antenna orientations of the transmitter and receiver causes different results. In case of the transmitter antenna orientation there were tested two cases:

1. vertical orientation where antenna points to the floor,
2. horizontal orientation where antenna points to the wall (or the opposite wall in case of mounting the antenna on the wall).

During tests there were tested omni directional antennas build into Beacon and mobile phone hardware as they are commonly used in Beacons as well as in Smartphones devices. It was also experimentally proven that in case of 2,4 GHz wireless technologies in underground environment directional antennas do not increase usable coverage as well as sector antennas [39].

As the proposed solution has to be applicable for different models of Smartphone devices it is not acceptable to force users to hold their devices in a given position with respect of the direction of the Bluetooth antennas build into them. Producers are free in terms of designing the Smartphones main boards including the antenna placement. Such information are not published. Even having the possibility to open the device and look for the antenna it is difficult to distinguish the antenna used for Bluetooth from the other used for example for terrestrial mobile networks. In case of Beacons, antenna placement is visible from the first sight. On figure 5.1 antenna placements was highlighted. Beacon 1 and 3 have meandered monopol antennas. The beacon 2 has meandered "IFA" – *Inverted-F antenna*. The antenna of beacon 4 is not visible on the picture.

There are a few big micro controller manufacturers on the market who offer compound units having integrated computational resources, programming buses and data exchange solutions including a Bluetooth Low Energy wireless module[49]. The main three competitors are Nordic Semiconductor with NRF chips, Dialog Semiconductor with DA chips and Texas Instruments with TI and CC chips. They compete on fields of power consumption, usability in terms of set of integrated modules, computational power and permanent storage size of their products. Those integrated circuits are used by Beacon producers as the main processing units with implemented Bluetooth protocols and stack and a set of profiles allowing for beacon name or transmitter power configuration and fetching the data from extra sensors measures build into the beacon like temperature or battery level. Integrated circuits are part of a PCB which also contains a battery slot, power and antenna. For tests there were chosen beacons offered by the various producers form China. Their products were easily available via the Internet, and they were cheaper than from producers from Europe or U.S. like Estimote or Texas Instruments[49]. The aim of the tests with different beacons was to check how much the PCB design influences results in terms of antenna radiation, signal coverage and stability. In order to distinguish beacons during tests, each of them was labeled. There were used following beacons:

1. Wellcore beacon based on Nordic Semiconductor NRF51822 chip, with a 8500 mAh, 3,6V lithium battery (cost: 7$, labeled as $B1$),
2. ByteReal beacon based on Dialog Semiconductor DA14580 chip, with a standard CR2477 battery (950 mAh, 3 V, cost: 8,25$, labeled as $B2$),
3. Wellcore beacon based on Nordic Semiconductor NRF51822 chip, with two standard CR277 batteries (1900 mAh, 3 V, cost: 10$, labeled as $B3$),
4. Radioland beacon based on Texas Instruments TI2640 chip, with a standard CR2032 battery (220 mAh, 3 V, cost: 6,78$, labeled as $B4$).

During tests there were following smartphone related factors taken into consider-

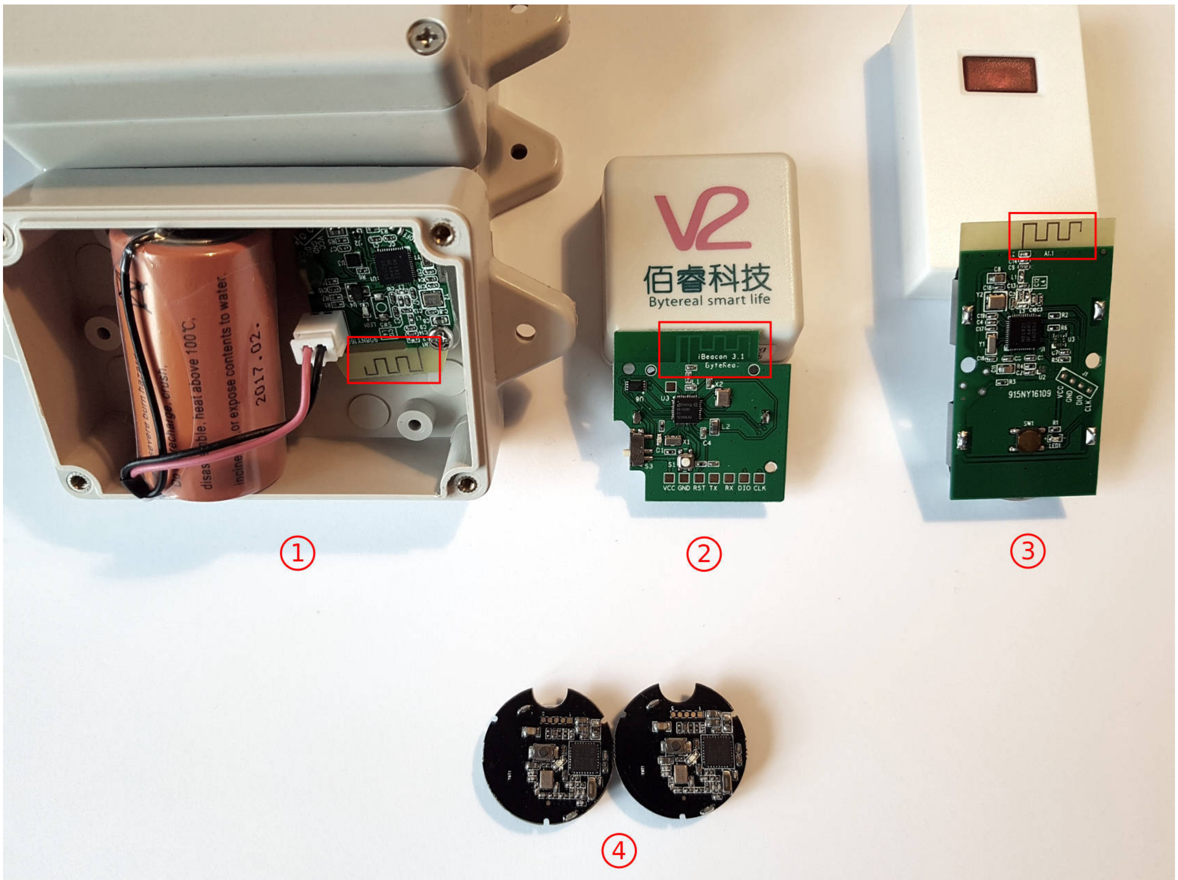

Figure 5.1. Beacons transmitters used during tests. Beacon 1 is a Wellcore procduct based on Nordic Semiconductor NRF51822 chip, Beacon 2 is a ByteReal product based on Dialog Semiconductor DA14580 chip, Beacon 3 is a Wellcore product based on Nordic NRF51822 chip, Beacon 4 is a Radioland product based on Texas Instruments TI2640 chip. On pictures there are highlighted antennas placement.

ation: smartphone orientation and smartphone model. There was tested how differs received signal strength with when smartphone is hold horizontally (screen points to the ceiling), vertically (screen points to the user) or is kept in the pocket. There were also performed beacon ranging tests with use of two different smartphone devices: Samsung Galaxy S7 and Blackberry Z10. Samsung device runs on Bluetooth 4.1, while the Blackberry uses Bluetooth 4.0. The aim of this test was to check how different smartphone models impact the received signal strength. This was performed to verify whether the received RSSI values deviate significantly between different smartphone manufactures.

There were performed following test cases:

1. Obtain signal attenuation curve with respect of the power of the transmitter by measuring the received signal stregth at given distances from the signal source.
2. Signal range per given transmitter power setting and smartphone placed in the pocket. Dynamic tests performed on a distance of 5 meters.
3. Received signal strength per given transmitter power setting and different smartphone orientation. Static test performed directly under the transmitter.
4. Line of sight (LOS) test. Comparison of signal attenuation curve measured in a part of the corridor where smartphone and transmitter were in line of sight and signal attenuation curve measured in a part of the corridor where corridor goes up and transmitter and smartphone are not in a line of sight.
5. Test of line of sight impact the signal attenuation curve where the user itself is and is not an obstacle between transmitter and smartphone.
6. Test how different antenna orientations of transmitter mounted on ceiling impacts signal attenuation curve. Tested vertical and horizontal orientations.
7. Test how different antenna orientations of transmitter mounted on wall impacts signal attenuation curve. Tested vertical and horizontal orientations.
8. Test how beacons from different vendors impacts the signal attenuation curve. For this test beacons transmitting power was adjusted in order to obtain similar signal gain on the radio path.
9. Test how different smartphone models impact the signal attenuation curve. Two different smatphones were used: Samsung Galaxy S7 with Bluetooth 4.1 and Blackberry Z10 with Bluetooth 4.0 module.
10. Walk scenario case test. Dynamic test with three beacons mounted on the wall while the user with a smartphone is walking along them. Tested two distancess between beacons: 10 m and 15 m.
11. Wall scenario case test. Dynamic test with three beacons mounted on the wall while the user with a smartphone is walking along them. Tested how smartphone kept in the pocket influence the attenuation curve.
12. Compare signal attenuation curve when transmitter is placed on the wall and when it is placed on the ceiling.

- Define factors that are important to state if solution is good or not
- Will allow to check if system fulfills requirements
- Test features stated in 'Localization system choise section'

5.2. Tests metodology

Tests were performed in part of XIX century excavation corridor which is available for sightseeing as a part of Stara Kopalnia museum in Walbrzych in Poland. The tunnel used during tests is placed 10 m bellow the ground and it is 185,7 m long. The tunnel is 3,2 m high and 3,2 m wide. The tunnel inclines on its northern side. Cross section in the tunnel is slightly horseshoe shaped.

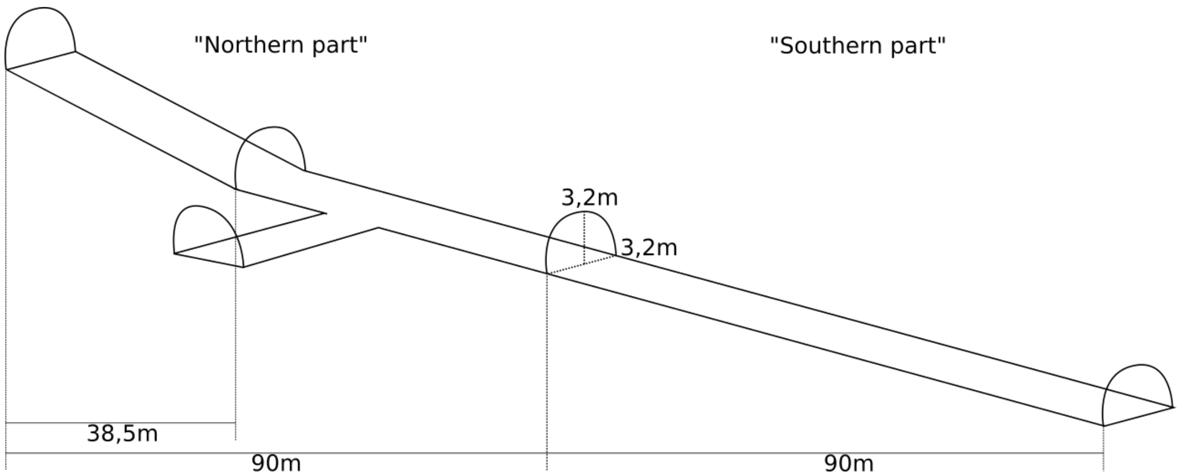

Figure 5.2. Test place scheme.

During the tests in the corridor there was 10°C and 71% of humidity. In order to avoid diffraction from corridors endings, beacons (Bluetooth transmitters) were placed in the middle of the corridor at it's $90m$ in case of single beacon test and in $\pm 15m$ from this place in case of multiple beacons test.

During the test there was used

- a measuring wheel for measuring the distance between subsequent distances taken into consideration for signal attenuation charts,
- smartphones with application that was collecting and storing the data (Bluetooth Low Energy receivers) and
- prepared beacons – Bluetooth Low Energy transmitters.

The beacons were prepared in a manner that their names were changed into B1(1), B1(2), B1(3), B2, B3 and B4 in order to distinguish them during evaluation. Beacon names were included into advertisement frame, which were then written into log files from the signal recording sessions.

The scope of tests performed underground as well as the values of distinguished variables chosen for the tests, got summarized in the table 5.1.

Symbols and terms used in the table 5.1 are following:

- **Receiver** – smartphone device that listens to the messages sended by transmitters (beacons),
- **Transmitter** – bluetooth low energy device that broadcasts ”advertisment” messages (beacon),
- | – receiver orientation: smartphone is held in a vertical position, display in front of an user, user is an obstacle on line of sight, smartphone is $1m$ above the ground,

Figure 5.3. Side view on the test place (at the end of the corridor) from perpendicular corridor perspective.

- **F–** – receiver orientation: smartphone is held in a horizontal position, display points to the ceiling (content is visible to the user), user is NOT an obstacle on line of sight, smartphone is $1m$ above the ground,
- **B–** – receiver orientation: smartphone is held in a horizontal position, display points to the ceiling (content is visible to the user), user is an obstacle on line of sight, smartphone is $1m$ above the ground,
- **P** – receiver orientation: smartphone is held in an user pocket, smartphone is $1m$ above the ground,
- **B** – smartphone „Blackberry Z10" device,
- **S** – smartphone „Smasung Galaxy S7" device,
- **TEST** – parameter that was evaluated during the test.

Test case number	Description	Distance from transmitter	Receiver orientation	Receiver type	Transmitter type	Transmitter power	Transmitter placement	Transmitter antenna direction	Amount of transmitters	Distance between transmitters
		[m]	{ |, F-, B-, P}	{B, S}	{B1, B2, B3, B4}	[dBm]	{Ceiling, Wall}	{↓, →}	{1, 3}	{-, 10m, 15m}
1	Obtain transmitters power attenuation curve	TEST	F-	S	B1	TEST	Ceiling	↓	1	-
1,1	* 4dBm transmitter power; power density measured on discrete distances from signal source					4dBm				
1,2	* -16dBm transmitter power; power density measured on discrete distances from signal source					-16dBm				
2	Signal range per given tx power setting and rx in „pocket” orientation. Dynamic tests in a sequence: * 5 sec under the tx, * move 5 meters away (actor is an obstacle), * 5 sec on 5 meters distance	{0m, 0-5m, 5m}	P	S	B1	TEST	Ceiling	↓	1	-
2,1	* -12dBm tx power					-12dBm				
2,2	* -16dBm tx power					-16dBm				
2,3	* -20dBm tx power					-20dBm				
2,4	* -30dBm tx power					-30dBm				
3	Singal range per given tx power setting and different rx orientation. Static test: directly under the tx	0m	TEST	S	B1	TEST	Ceiling	↓	1	-
3,1	* -12dBm tx power; orientation: -		B-			-12dBm				
3,2	* -12dBm tx power; orientation: |		|			-12dBm				
3,3	* -12dBm tx power; orientation: P		P			-12dBm				
3,4	* -16dBm tx power; orientation: -		B-			-16dBm				
3,5	* -16dBm tx power; orientation: |		|			-16dBm				
3,6	* -16dBm tx power; orientation: P		P			-16dBm				
3,7	* -20dBm tx power; orientation: -		B-			-20dBm				
3,8	* -20dBm tx power; orientation: |		|			-20dBm				
3,9	* -20dBm tx power; orientation: P		P			-20dBm				
3,10	* -30dBm tx power; orientation: -		B-			-30dBm				
3,11	* -30dBm tx power; orientation: |		|			-30dBm				
3,12	* -30dBm tx power; orientation: P		P			-30dBm				
4	Line of sight (LOS) test. Tests performed with no LOS condition. Rest parameters same as in test 1,1. Test is designed to be compared with results of analogue test no. 1,1	TEST	F-	S	B1	4dBm	Ceiling	↓	1	-
4,1	* With LOS (source not shadowed, same as 1.1)									
4,2	* Without LOS (source not visible due to corridor shape)									
5	Impact of actor position; obtain attenuation curve in case where an actor is an obstacle between transmitter and receiver	TEST	TEST	S	B1	4dBm	Ceiling	↓	1	-
5,1	* 4dBm transmitter power; power density measured on discrete distances from signal source		F-							
5,2	* 4dBm transmitter power; power density measured on discrete distances from signal source; actor in an obstacle		B-							
6	Obtain tx signal attenuation curve per different tx antenna directions for tx mounted on ceiling	{0m, 1m, 2m, 3m, 4m, 6m, 8m, 10m, 12.5m, 15m, 20m, 25m, 35m}	F-	S	B1	-16dBm	Ceiling	TEST	1	-
6,1	↓direction							↓		
6,2	→direction							→		
7	Obtain tx signal attenuation curve per different tx antenna directions for tx mounted on wall	{0m, 1m, 2m, 3m, 4m, 6m, 8m, 10m, 12.5m, 15m, 20m, 25m, 35m}	F-	S	B1	-16dBm	Wall	TEST	1	
7,1	↓direction							↓		
7,2	→direction							→		
8	Obtain tx signal attenuation curve for different transmitters microcontrollers and hardware	{0m, 1m, 2m, 3m, 4m, 6m, 8m, 10m, 12.5m, 15m, 20m, 25m, 35m}	F-	S	TEST	-16dBm	Wall	↓	1	-
8,1	* B1				B1					

Test case number	Description	Distance from transmitter	Receiver orientation	Receiver type	Transmitter type	Transmitter power	Transmitter placement	Transmitter antenna direction	Amount of transmitters	Distance between transmitters
8,2	* B2 - default tx power (not changed for tests)				B2					
8,3	* B3 – was set to -8dBm, but result was observable like -16dBm in B1				B3	-8dBm				
8,4	* B4				B4					
9	Obtain tx signal attenuation curve for different reicevers (smartphones)	{0m, 1m, 2m, 3m, 4m, 6m, 8m, 10m, 12.5m, 15m, 20m, 25m, 35m}	F-	TEST	B1	-16dBm	Wall	↓	1	-
9,1	* Samsung Galaxy S7 (BLE 4.1)			S						
9,2	* Blackberry Z10 (BLE 4.0)			B						
10	Dynamic tests with 3 beacons. Tested two distances between beacons. Tests start with 5s measurement of signal strength 20m before first transmitter, consists of walk along corridor (70/80m), ends with 5s measurement of signal strength 20m after last transmitter	20m before first tx – 20m after last tx (beacon)	F-/B-	S	B1	-16dBm	Wall	↓	3	TEST
10,1	* tx in 10m intervals (two tests: there + way back)									10m
10,2	* tx in 15m intervals (two test: there + way backs)									15m
11	Dynamic tests with 3 beacons. Tested two orientations of receiver. Tests start with 5s measurement of signal strength 20m before first transmitter, consists of walk along corridor (70m), ends with 5s measurement of signal strength 20m after last transmitter	20m before first tx – 20m after last tx (beacon)	TEST	S	B1	-16dBm	Wall	↓	3	10m
11,1	* F-/B- (due to movement) rx orientation		F-/B-							
11,2	* P rx orientation		P							
12	Wall and ceiling tx placement comparison	{0m, 1m, 2m, 3m, 4m, 6m, 8m, 10m, 12.5m, 15m, 20m, 25m, 35m}	F-	S	B1	-16dBm	TEST	↓	1	-
12,1	* tx on the ceiling						Ceiling			
12,2	* tx on the wall						Wall			

Table 5.1. List of test cases and related parameters.

5.3. Tests of wireless reference points in underground environment

The first series of tests were about observation how different factors influence the received signal strength. Factors taken into consideration, beacon and smartphone devices used during tests are listed in section 5.1.

5.3.1. Signal stability analysis

Several probes of received signal strengths taken at different distances from the signal source were used as a test base. As it is shown on the figure 5.4, signal strengths are not stable. The general rule of *log-distance path loss model* (see 3.1) where the short distance between transmitter and receiver causes bigger signal strengths are observed, but there are strong fluctuations. The respective model was discussed in section 3.1.2.

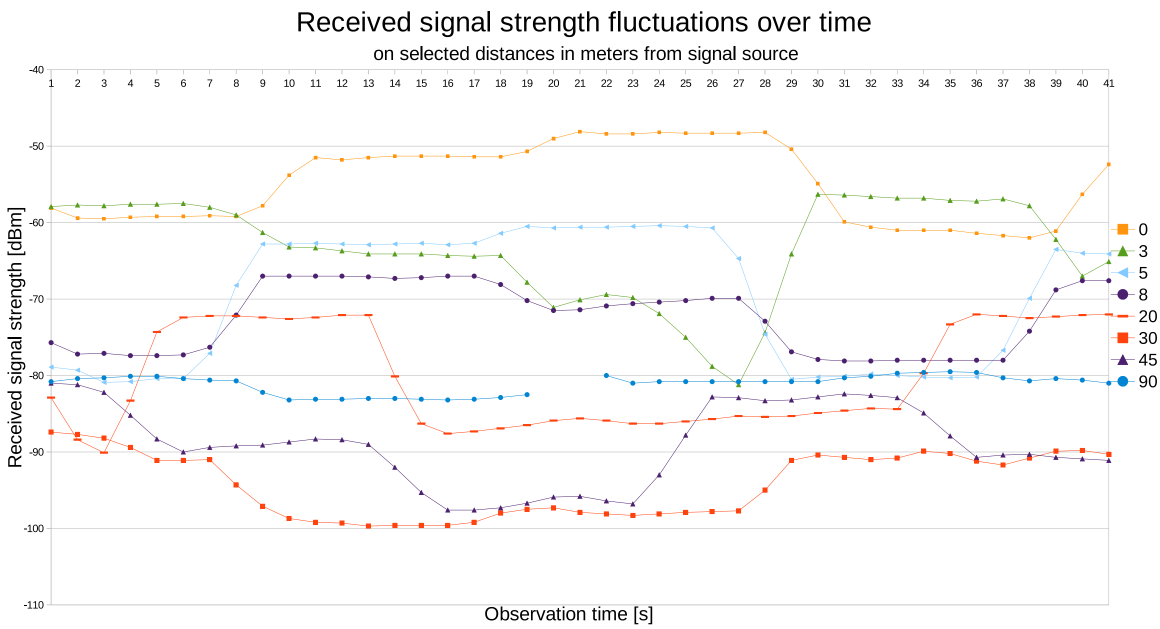

Figure 5.4. Received signal strengths measured each second at different distances between signal source and smartphone. Each line represents received signal strength obtained at given distance.

Basing on results from this test there was made observation about the relation between the distance and the scale of fluctuation affecting the signal strengths. The biggest fluctuations are present between 0 and 10 meters from the signal source. On the distance of 70 meters and more signal strengths got flatten thus also a standard deviation is low. This relation is depicted on the figure 5.5.

The *log-distance path loss model* assumes only one input (received signal strength) what is directly a basis for distance estimation. As the model is based on logarithm (see equation 3.1) then fluctuations around reference value have smaller impact the obtained distance approximation than the fluctuations around the values that are away from the reference value. In order to verify how the model fits into the measurements

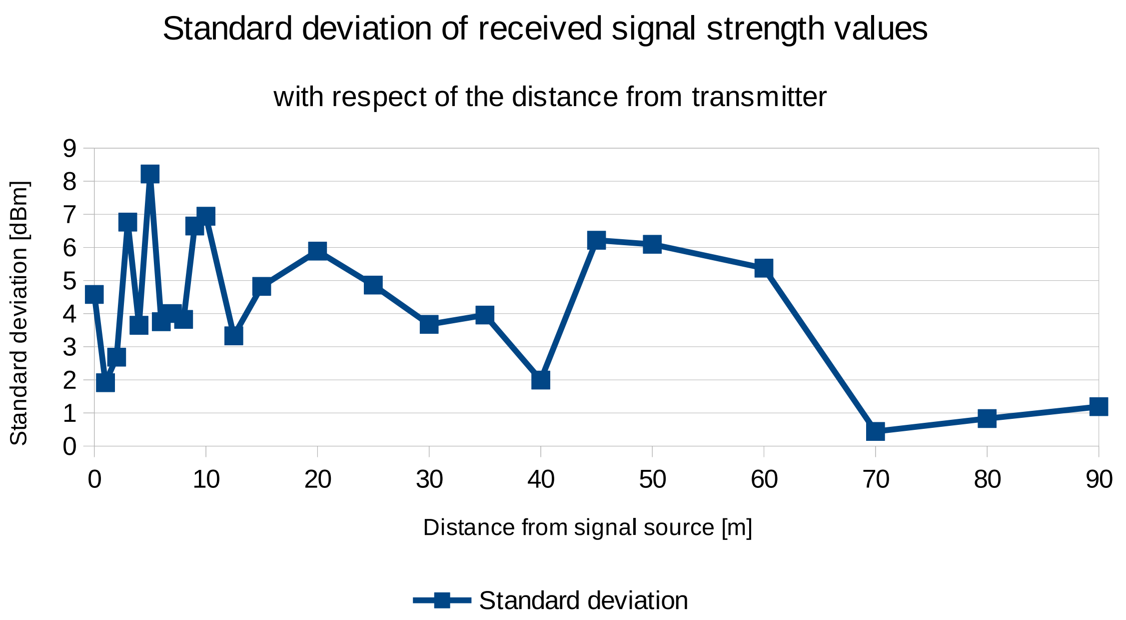

Figure 5.5. Standard deviation taken from received signal strengths measured each second at different distances between signal source and smartphone.

then distance approximations based on that model was computed on average values of the received signal strengths measured at given distances. There was more than 25 probes of the signal strengths taken to the average. Figure 5.6 depicts estimated distances from beacon placed on the ceiling with the highest possible signal strength of $4dBm$ on a range of $90m$. X-axis described the actual distance, y-axis describes the approximated distance – output of a model. Estimations in longer distances were not accurate – they error was about $\pm 30m$ on a 20 meters distance and more.

The figure 5.7 focuses on range in between 0 and 20 meters from signal source. In this range approximation error was about ± 1.5 meters. Such result leads to the assumption that on distances lower than $20m$ from the signal source, proposed model can provide approximation which fits to the required accuracy stated for the positioning system.

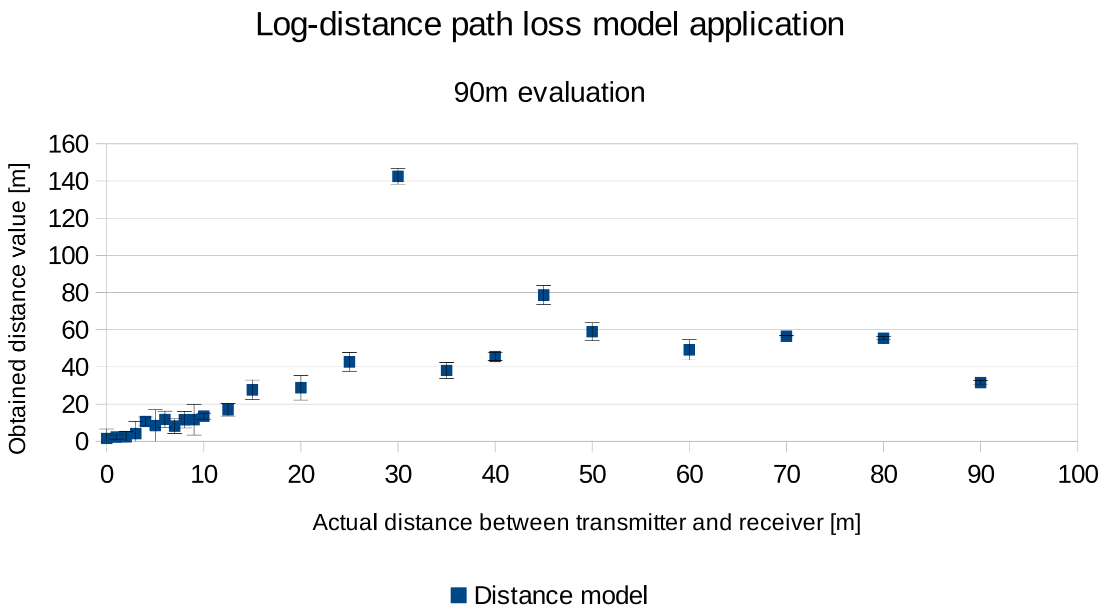

Figure 5.6. Application of *log-distance path loss model* on received signal strengths measured at discrete distances from signal source at range of $90m$.

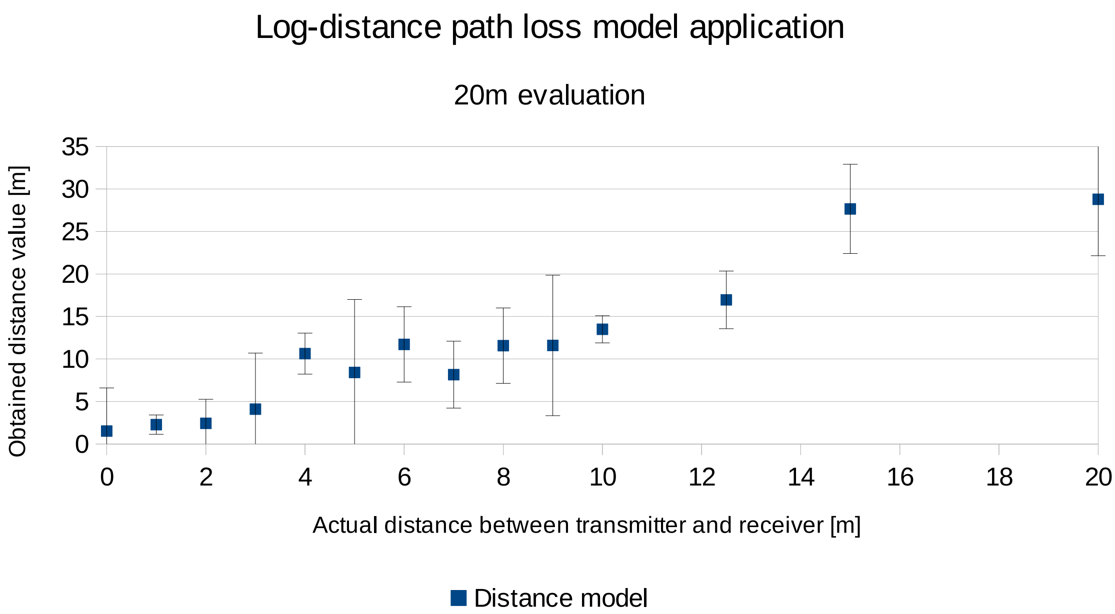

Figure 5.7. Application of *log-distance path loss model* on received signal strengths measured at discrete distances from signal source at range of $20m$.

5.3.2. Robustness of received signal strenght measures

One of the objectives of the tests was to check how placement, orientation and different models of the devices impacts the received signal strength values. List of variables taken into consideration with explanation were written in section 5.1. Pictures 5.8 and 5.9 presents how beacon was mounted on a ceiling with its different orientations related to the antenna direction.

Figure 5.8. Beacon 1 mounted on a ceiling with horizontal antenna direction.

Figure 5.9. Beacon 1 mounted on a ceiling with vertical antenna direction.

In order to check what is the signal range of a single beacon device there was taken a series of received signal measures at given distances from the signal source. Two transmitter power settings were selected for the test: $4dBm$ which is the highest possible transmitter power setting and $-16dBm$ which was taken experimentally. Distances were located at 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12,5, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90 meters in case of $4dBm$ setting and at 0, 1, 2, 3, 4, 6, 8, 10, 12,5, 15, 20, 25, 35 meters in case of $-16dBm$ setting. For this test, the B1 beacon was mounted vertically on the ceiling. Figure 5.10 presents the results of these tests.

The range of the beacon with the highest available power setting exceeds the available space in corridor, that is why the measurements end at $90m$ for the $4dBm$ TX power setting. The received signal strengths measured on distances larger than $20m$ from the source of the signal are getting stabilized while measures closer than $20m$ from the signal source are falling significantly. Measures taken between $20m$ – $90m$ from signal source are between $-80dBm$ and $-90dBm$, while the drop on the first $5m$ from the signal source is about $15dBm$. There was made an interesting observation that received signal strength values were not decreasing on distances between $50m$ and $90m$. The reason of such behavior is the wave guide effect [39][16]. There was also observed that the signal strengths get stabilized on larger distances what was depicted on figure 5.5 expressing standard deviation of received signals, as well on figure 5.4 where can be observed the source of the received signal strength values. This observation matches with the observations about the *log-distance path loss model*.

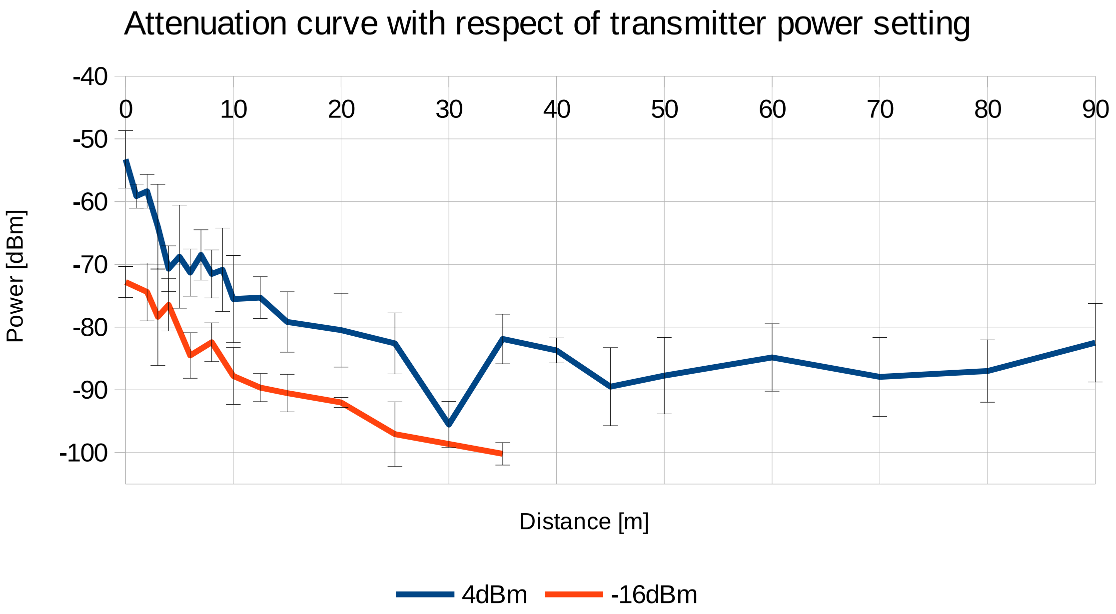

Figure 5.10. Attenuation curve for $4dBm$ and $-16dBm$ trasmitter power.

The results of test how smartphone orientation influence the received signal strength is presented on the figure 5.11. The test consisted of three phases:

- measure received signal strength for $5s$ directly under the transmitter,
- walk $5m$ away,
- measure signal for $5s$ on $5m$ distance from signal source.

Test was performed 4 times, each for different transmitter power values: $-12dBm$, $-16dBm$, $-20dBm$ and $-30dBm$. Beacon was placed vertically on the ceiling.

Signal strengths received by the smartphone kept in the pocket are same or even lower at $0m$ distance (smartphone is directly under the beacon) than measured $5m$ away from signal source. In case of $-12dBm$ transmitter power setting test the received signal strength was about ($10 \pm 4dBm$ change) lower at $0m$ than on $5m$. That is because of "Near Field Effect" where the coverage area of the antenna is "shaded". The smartphone made use of reflections to gather the signal. This is also the reason why the $-30dBm$ setting completely blanks out in the near field. That is why setting $-30dBm$ was rejected as one that provides so week signal, that in case of smartphone kept in the pocket can be filtered out as a noise. In case of $-16dBm$ and $-20dBm$ transmitting power settings, the received signal strength values remain the same for the whole test ($\pm 3dBm$).

The figure 5.12 presents the comparison of RSS values for different smartphone orientations and transmitter power settings. There were tested three values of the transmitter power in order to see if the transmitter power impacts on the all smartphone orientations equally. Setting of $-30dBm$ transmitter power was omitted in the evaluation. RSS measures were performed directly under the beacon.

Ideally, change of the transmission power expressed in dBm should cause the same change in the received signal strength. It was not observed. Change of $4dBm$ and

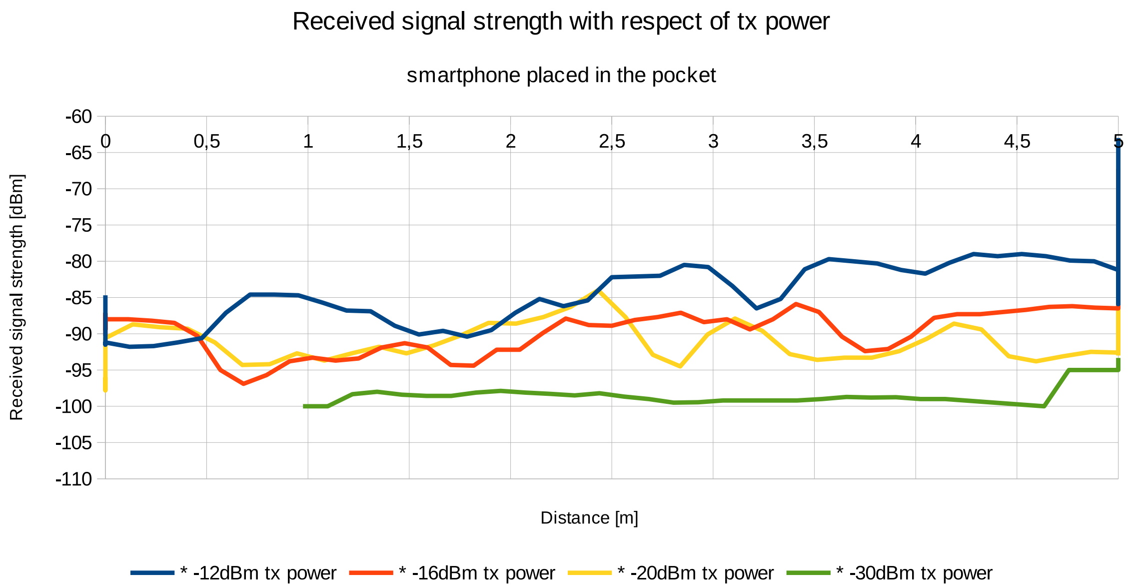

Figure 5.11. Received signal strength values measured by the smartphone kept in the pocket with respect of the trasmitter power and the distance from the signal source.

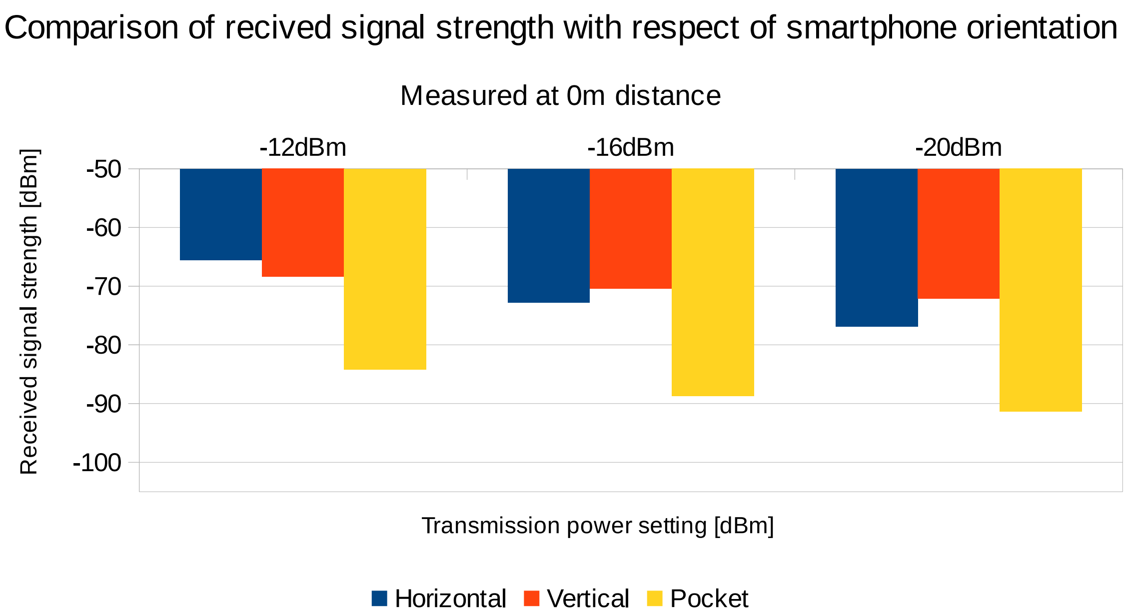

Figure 5.12. Received signal strength measured just under the beacon device mounted on the ceiling in vertical orientation. Tested three transmitter power values: $-12dBm$, $-16dBm$ and $-20dBm$ and the three smartphone orientations: vertical, horizontal and kept in the pocket.

$8dBm$ respectively caused following change in observed signal strengths per smartphone orientations:

- horizontally: $7.3 \pm 2.4dBm$ and $11.3 \pm 5.1dBm$,
- vertically: $2 \pm 4dBm$ and $8.5 \pm 5.1dBm$,
- kept in the pocket: $4.5 \pm 4.8dBm$ and $7.1 \pm 3dBm$.

Received signal strengths obtained by the smartphone in horizontal and vertical orientation differs by $2dBm - 4dBm$ while standard deviations taken from the set of probes are about $2.5dBm - 5dBm$. It means that in this test setup, horizontal and vertical orientations do not impact the signal observably. Fluctuations as well as obtained RSS value are on the same level. Significant difference is between horizontal or vertical orientation and the placement in the pocket. In all cases the received signal strength was about $18 \pm 2dBm$ lower. It means that there is need to ensure such setup of the wireless reference point installation that will ensure such transmission power that allow for correct identification of the beacon with some safety factor, even the receiver is in the pocket – so reflecting additional is $18dBm$ needed for this placement. Such safety factor is determined as the lowest acceptable value for the positioning system – every signal with a lower value is treated as a noise.

Another factor that influence radio frequency transmission is a presence of obstacles between transmitter and receiver. The situation where radio waves can come in direct path from the signal source to the receiver is called line-of-sight (LOS) propagation. There were taken two types of obscuration into consideration: obscuration that results from the shape of the tunnel and obscuration made by the user itself. The first case is illustrated on the figure 5.13.

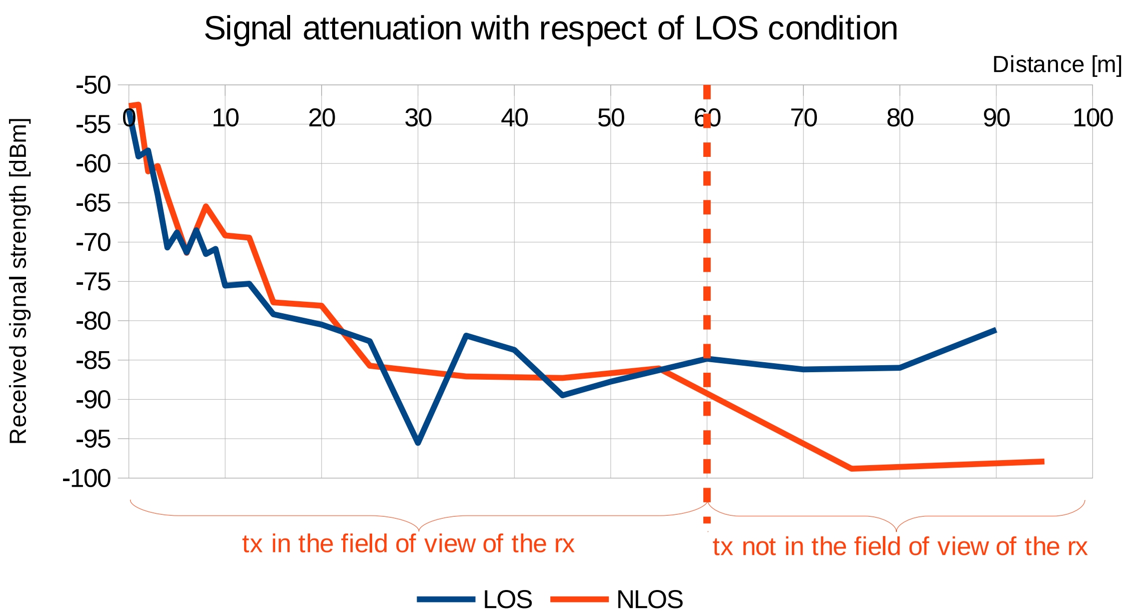

Figure 5.13. Attenuation curve based on received signal strenght measured at discrete distances from the signal source. Test taken in corridor which goes up starting from $61.5m$ from the signal source. Red remarks concerns NLOS propagation and highlights the meter since when steep part of the corridor starts.

The test consisted of taking probes of the received signal strengths at discrete distances from the signal source in the "southern" part of the corridor, labeled as **LOS** and in the "northern" part of the corridor, labeled as **NLOS** (refer to the test place scheme on the figure 5.2). The southern part of corridor is flat and there were no obstacles between the beacon and the smartphone during the test. Northern part of the test place starts to go up at $61.5m$ from the signal source. Steep grade is about 17% so at $71.5m$ from the signal source there is no direct path between beacon and the smartphone.

Despite fluctuation observed at $30m$ from the signal source in LOS session, the shape of both LOS and NLOS curves of received signal strength with respect of the distance was comparable until the start of the steep part of the corridor. Then NLOS curve goes down so at $75m$ from the signal source the value of RSS is -98.8 ± 2.1 which is $18.6dBm$ lower than in case of RSS values observed at similar distance in LOS case. It means that despite the wave guide effect that was supposed to be observed in case of electromagnetic waves in underground installations [22][16], the influence on the received signal strength is so high that have to be taken into consideration during system planning and installation.

On the figure 5.14 there are presented received signal strength values obtained within the test of the propagation path obscuration by the user.

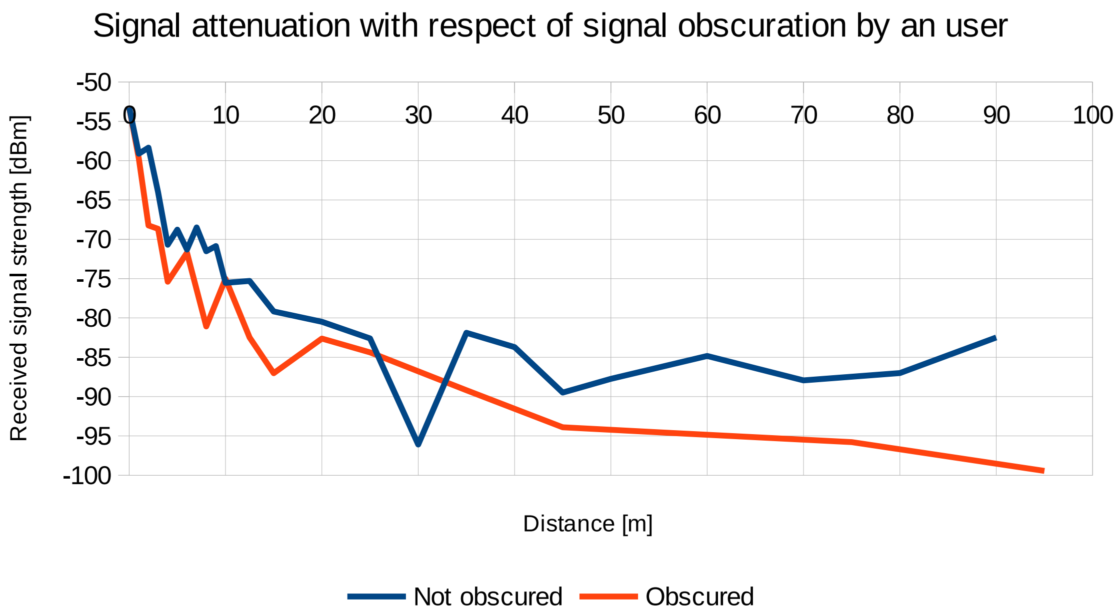

Figure 5.14. Received signal strength with respect of the distance from the signal source and the LOS condition where user is an obstacle on the propagation path.

Test was performed two times: one session was about taking the measures while user was an obstacle in between the smartphone and the beacon (labeled on the chart as "Obscured") and the second session which was about taking the measures while the user was not an obstacle (labeled as "Not obscured"). Whole "Obscured" curve is bellow the "Not obscured". The difference between received signal strengths in both conditions is about the same in first $3m$ from the signal source, then is up to $10dBm$

lower, despite the fluctuations. It means that there is need to reflect the need of additional signal strength required in case of user obscuration into the power setting of the beacons.

The next test, depicted on the figure 5.16, is about checking how different beacon placement and its orientation impacts the received signal strength.

Figure 5.15. Beacon B3 mounted on the wall in its vertical orientation.

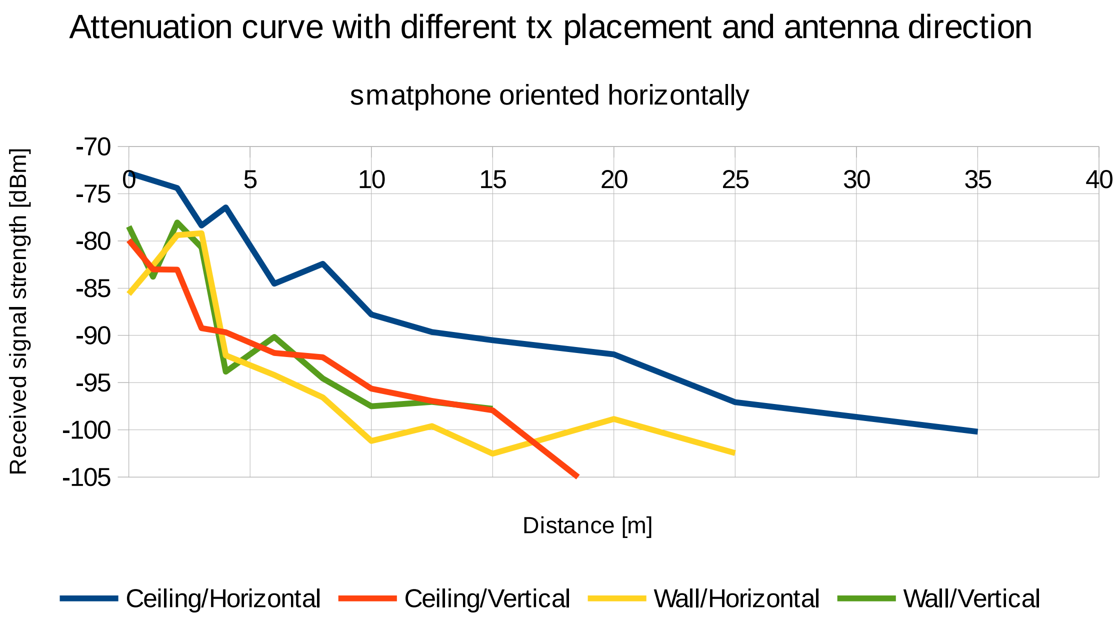

Figure 5.16. Transmitter position and orientation impact the received signal strength.

The goal of this test was to deduce the best mounting place and orientation of the beacon inside the underground corridor. There were taken into account four possibilities: placement on the ceiling, placement on the wall, with vertical and horizontal antenna directions. On figure 5.15 there is presented mounting point on the wall. The test was a static one, when probes were taken at discrete distances from the signal source. For test purpose the transmitter power got reduced to value of $-16dBm$. Smartphone was oriented horizontally.

The biggest received signal strength values were obtained with the beacon mounted on the ceiling in horizontal antenna direction. Signal strengths were at least $7dBm$ higher for this setting than for any other. There was also observed the biggest signal coverage for this setting – $35m$. Vertical antenna orientations in both cases of mounting on the ceiling and the wall causes similar ($\pm 5dBm$) RSS values measures, despite the pick on $2m$ from the signal source of beacon mounted on the wall. Both vertical and horizontal orientations of beacon mounted on the wall characterizes with the signal strength pick on $2m$–$3m$ distance from the signal source. The results of the tests points to the fact that beacon placement affects the signal strength as well as the coverage and the part of the fluctuations.

Test of different beacon hardware was difficult because of different electronic solutions being used inside them. Figure 5.17 presents result of this test.

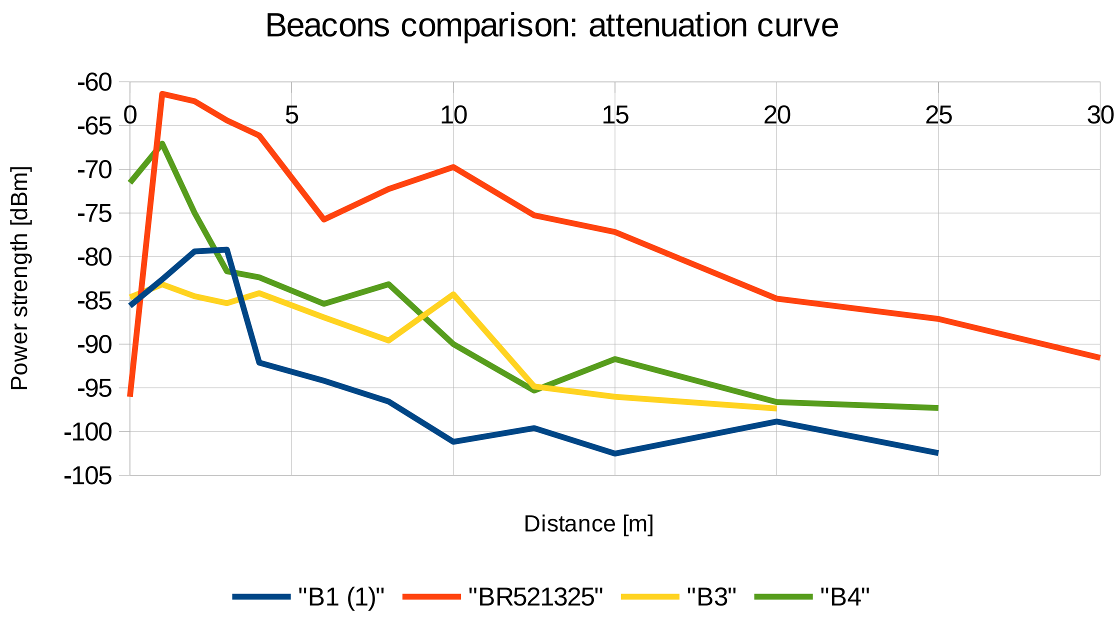

Figure 5.17. Attenuation curve obtained with use of different beacons and their similar power setting.

There is no standard for creating beacon devices. As many beacons as many hardware solutions for power management, additional sensors mounted, and the antenna type and installation. In case of beacons that were bought in order to perform the tests, each had to be individually configured in order to achieve similar coverage and received signal strengths. That is why the signal strength value obtained during the test is not an object of investigation but the curve shape and fluctuations. There were tested beacons B1, B2, B3, B4. Details about the beacons are available in section 5.1.

All the beacons were mounted on the wall, with vertical antenna direction. Each of them was tested separately. What is characteristic for that placement is that received signal strength measured at $0m$ from the beacon is lower than 1–2 meters away. Each measure proves that such rule is true despite different transmitter hardware. There can be also observed that signal strength is the biggest near the source, then drops about $10dBm$ on a distance of $5m$ from the signal source. Situation repeats with smaller amplitudes till the minimum acceptable signal strength values. In case of beacon B1, B2 and B4 there were observed such values in the close distance to the signal source (about $0m$–$5m$) that significantly differs from those observed in bigger distances. Only B3 beacon emit its signal on not distinguishable power levels within the close range.

The next figure (5.18) presents results of test with different smartphones being used as receivers of the signal.

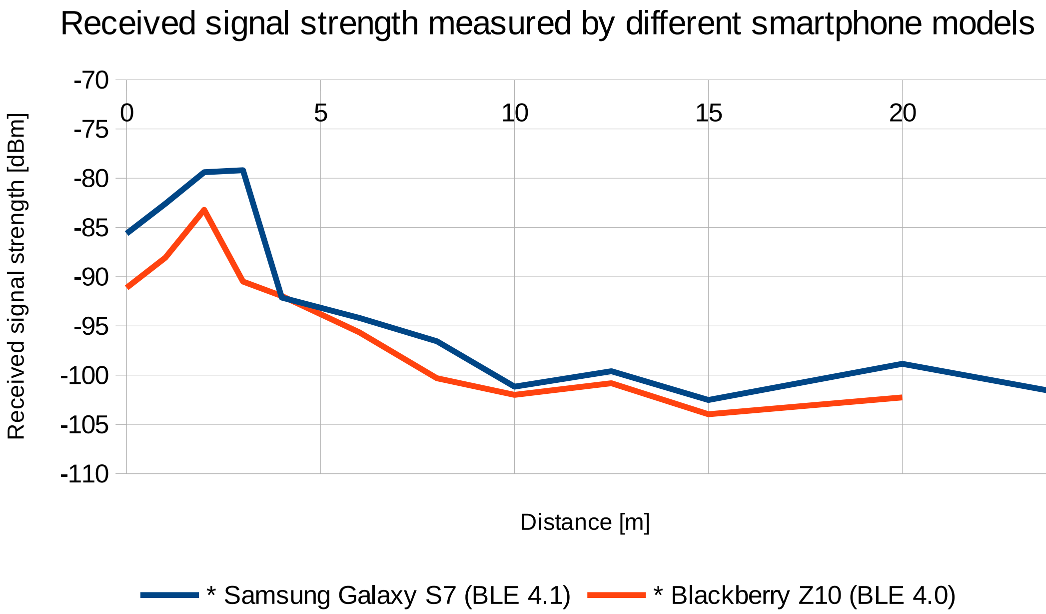

Figure 5.18. Comparison of received signal strength values caputered by two different smartphone models: Samsung Galaxy S7 and Blackberry Z10.

For this test there was used beacon B1 mounted vertically on the wall. There were performed measures of the RSS signal taken by two models of smartphones at 0, 1, 2, 3, 4, 6, 8, 10, 12.5, 15, 20, 25, 35 meters from the beacon. Curve shapes for both smartphones are moved with respect to each other by $5dBm$ on $0m$–$4m$ distances. Then the difference is about $2dBm$. Difference may come from the type and the amount material that was used to cover antennas inside the devices. Despite slight differences between signal strength, the receives signal strength pick is distinguishable by both smartphones. Bluetooth standard implemented by two smartphones also do not affect shape of attenuation curve. That means that the solution build on the Bluetooth technology based beacons behaves same for different types of smartphones being used.

5.3.3. Real case scenario evaluation

Second part of the test session in the underground installation was devoted to check if proposed position finding system based on the wireless reference points (Bluetooth beacons) can take received signal strength as a factor determining the distance between the user device and the reference point. The aim of the tests was to record RSSI values of signals emitted by beacons during the walk along the tunnel with sample positioning infrastructure and check how the observed values fits to the proposed positioning solution.

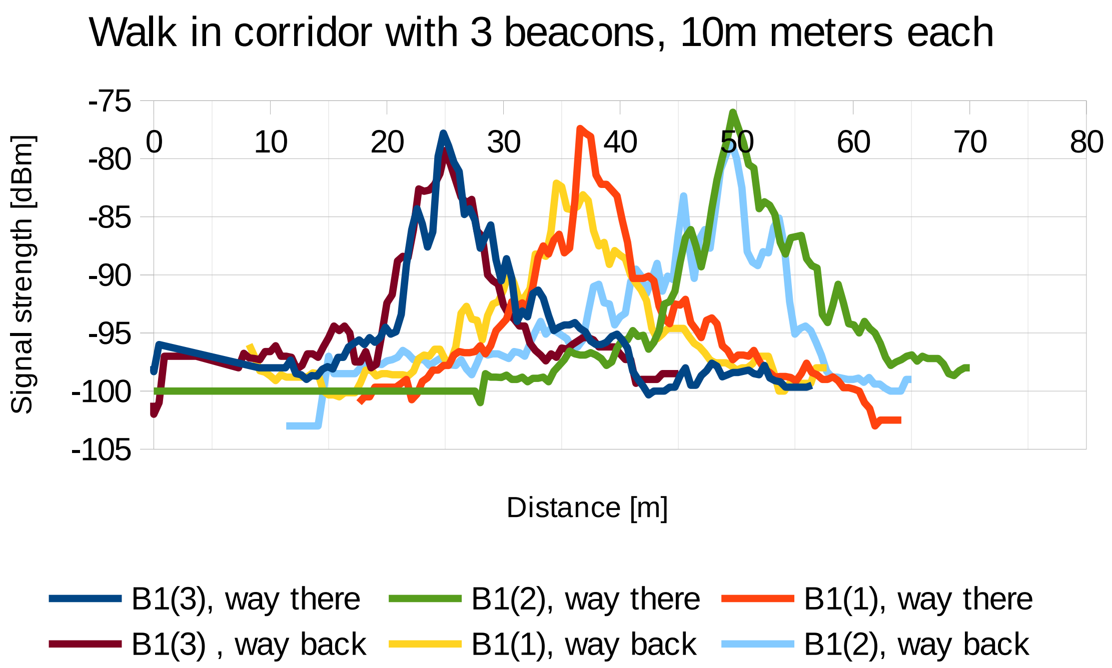

Figure 5.19. Signal strengths of the beacons placed $10m$ each, measured during the walk with smartphone hold in hand in it's horizontal orientation.

During tests there were 3 scenarios taken into consideration. One was about position of the smartphone: evaluation of the signal strength values recorder by the smartphone carried in the pocket and smartphone held by the user in his hand (horizontal orientation). The second scenario concerned distance between the reference points. There were evaluated $10m$ and $15m$ distances between the beacons. There were used three B1 beacons with $-16dBm$ power setting placed vertically on the wall. The last scenario was about checking how direction of user movement impacts on the observed signal strength values. That case is a direct extension to the static tests of shadowing direct signal path by the user (see figure 5.14).

Each test that cover first and the second scenario, was performed two times, named as: "way there" and "way back". That is how the third scenarios was included into two first. That way creates the possibility to check if walking direction influence received signal strength. Each test round consisted of three phases: warm up, walk, settle down. Warm up phase was about capturing the signal strength values for $5s$, $20m$ before first beacon. Walk was about making a distance of $70m$ in case of beacons mounted $10m$

each or a distance of $80m$ in case of beacons mounted $15m$ each. Settle down phase ends with $5s$ measurement of signal strength at distance of $20m$ after last beacon mounted on the wall.

Walking pace and speed was not arbitrary set and controlled during test. That is why distances assigned to given values are approximated under assumption that the pace was constant during the walk. Instead of matching distances to signal strength values picks there was evaluated how signal strength values changes during the walk.

First test concerns walk with the smartphone hold in hand horizontally and beacons placed in $10m$ distances between each other. Figure 5.19 depicts RSS values recorded by the smartphone. Approximate placement of the reference point can be determined because of characteristic picks. There can be also observed that at level of $-95dBm$ signals strength from beacons got stabilized. Because of fluctuations, these signal strength values are not useful. Beacons emit their signal with such power level that when the user was just under the second beacon B1(1) (about $35m$ on the chart) he was still received signals from the nearby beacons: B1(3) – $-95dBm$, B1(2) – $-97dBm$. It can be observed that in the middle of the distance between nearby beacons, they have similar power values like in case of B1(3) and B1(1) at 31 meter: B1(3) – $-91,6dBm$, B1(1) – $-91dBm$.

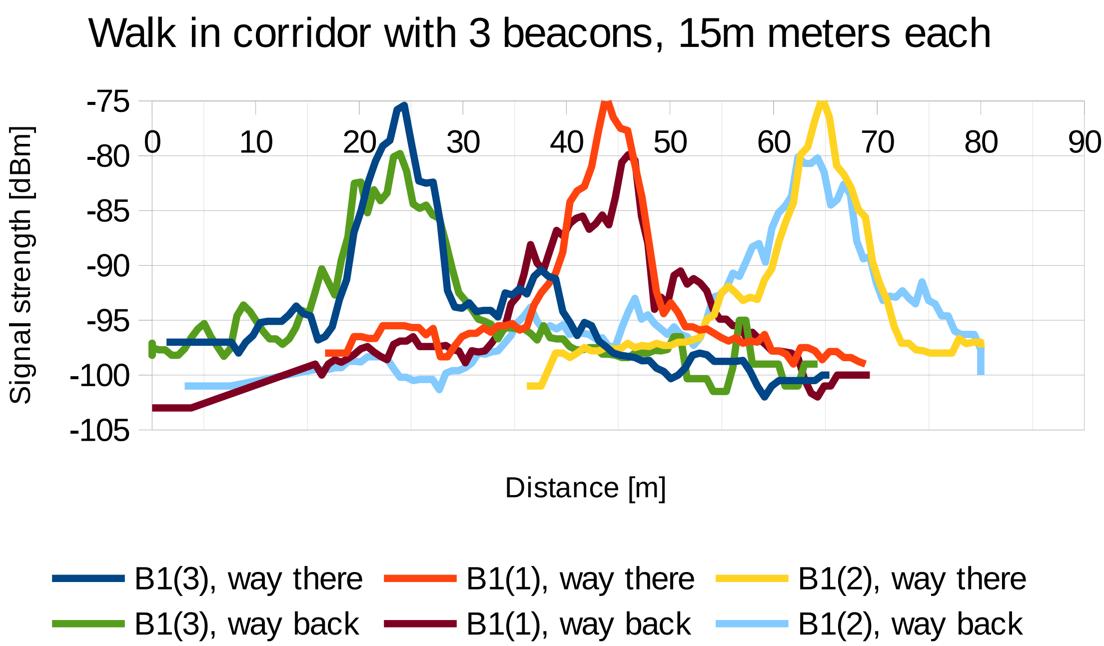

Figure 5.20. Attenuation curve with respect of the trasmitter power.

It can be observed that slope of the curve after reaching its peak is slightly smoother than just before the peak. There are possible two reasons of such results. Values could get smoothed during the signal processing by the hardware or software before value evaluation. It may also mean that the user presence on direct path between beacon and smartphone can influence the observed signal strengths.

Figure 5.20 presents values obtained during test with beacons placed $15m$ each. Absolute values recorded during the test are similar to those from previous test. In test with $10m$ gaps, values in peaks were about $-78dBm$ – $-76dBm$; in test with $15m$ gaps, values in peaks were about $-75dBm$ – $-74dBm$. Also, the RSS values in the middle of distances between two nearby beacons are similar, about $-95dBm$.

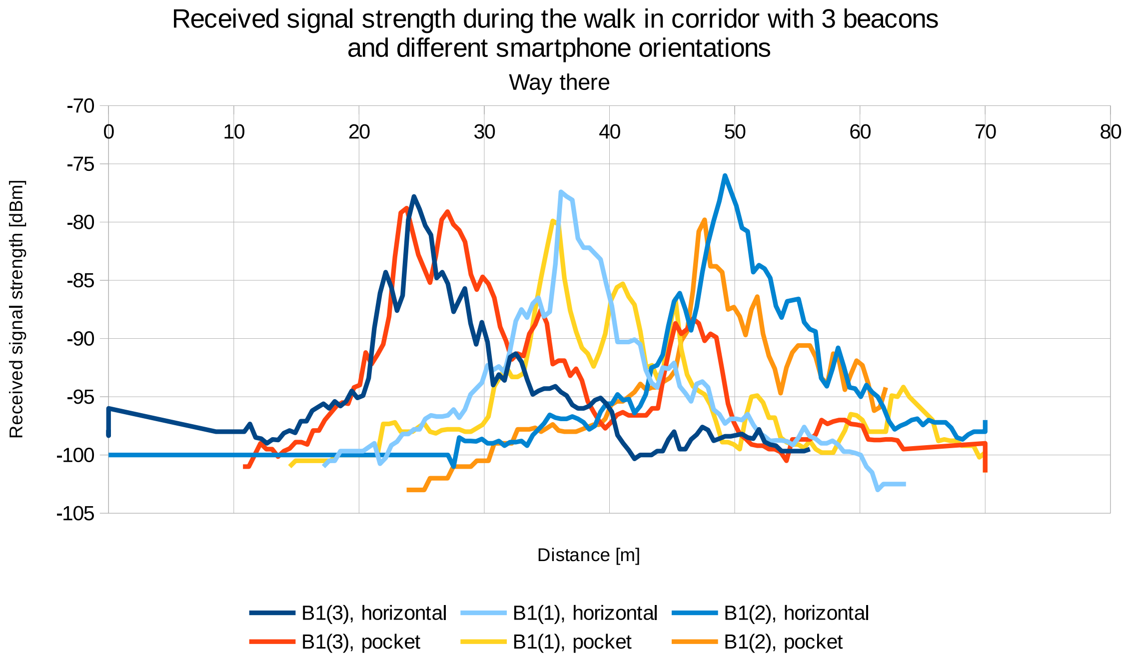

Figure 5.21. Attenuation curve of three beacons with respect of the placement of the smartphone.

Figure 5.21 presents results of a test where beacons were placed $10m$ each and the smartphone was kept in the pocket. The main difference between signals recorded by smartphone in its horizontal orientation and when it was kept in the pocket is the strong fluctuation near the signal source. It is most visible on meter 35 and 38 where yellow curve of RSS of beacon B1(1) drops from $-79dBm$ to $-92dBm$ and then goes up to $-85dBm$ at 40 meter.

5.4. Application of signal filtering

In order to improve the accuracy of the signal strength based positioning, there was applied low-pass filtering to the measures. Filtering aim is to limit signal strength fluctuations. Figure 5.22 presents filtered values obtained during dynamic test presented before on figure 5.19.

Low-pass filter does not smooth the signal in a way that no fluctuations can be observed but it limits their amplitude. For example drop at $23m$ of an RSS from beacon B1(3) got reduced from $-2dBm$ to $-0.3dBm$.

Drawback of such data filtering is that it introduces some delay to dynamically changing values. For example: RSS value pick of B1(3) beacon in not filtered data (fig. 5.23) was observed at $0m$ while pick on filtered data was observed $1m$ further (3 RSS probes later), assuming $1.6\frac{km}{h}$ test device speed and $1Hz$ frequency of RSS probing.

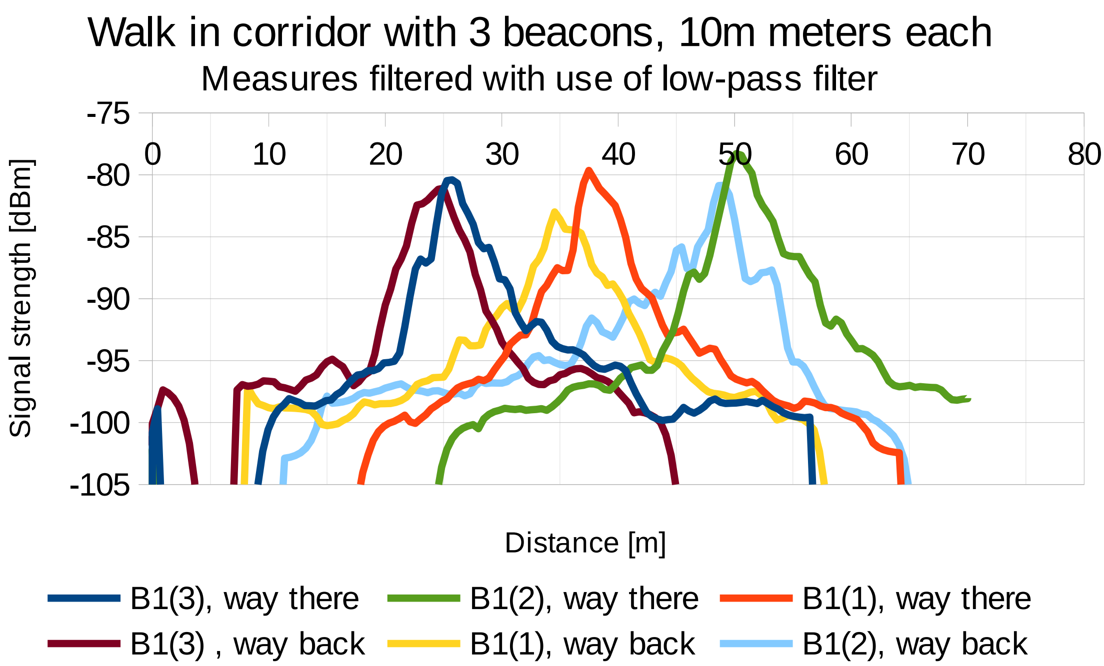

Figure 5.22. Attenuation curve with respect of the trasmitter power.

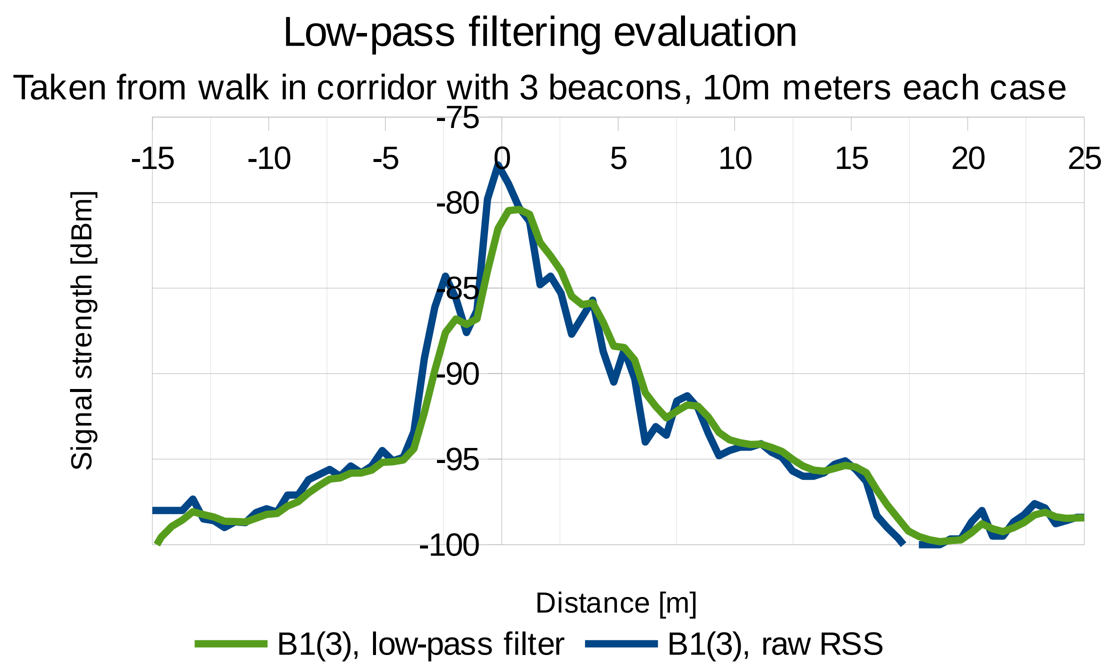

Figure 5.23. Comparison of raw and low-pass filtered RSS values of B1(3) taken from dynamic test with 3 beacons.

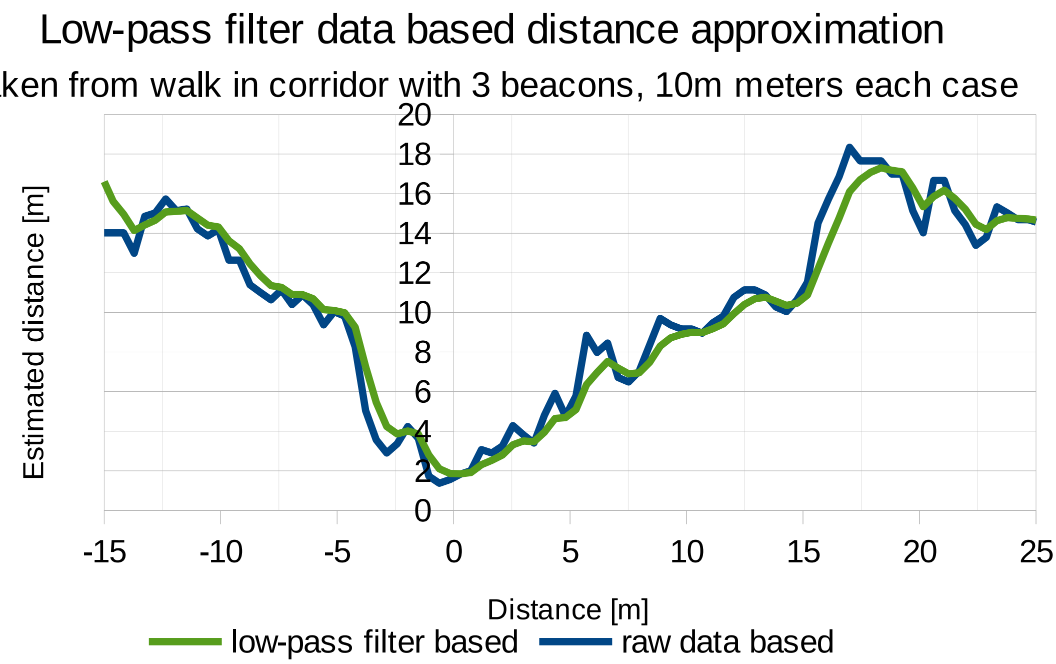

Figure 5.24. Comparison of distance model approximation based on raw and low-pass filtered RSS values.

Problem may be overcome by increasing probing frequency but decreasing the beacon battery life.

The figure 5.24 presents how low-pass filter affects distance approximations of *log-distance path loss model*. Model was adjusted to match lower transmitter signal power ($-16dBm$ used during the test). Filtering does not improve or decrease accuracy of the model, just smooth resulting values.

Low-pass filtering does not solve the problem of RSS values fluctuations but it is a good solution to limit effects of a random, highly different values of RSS happening during the measurement session.

Chapter 6

Conclusions

Position finding methods in underground installations are different from those that operate on the surface of the earth. The thesis evaluates known solutions in their applicability to underground environment aspect. The proposed solution uses state-of-the-art technologies and methods applicable for such environment. The outcome of the position finding solution allows for integration with business oriented applications. In order to extend reporting functionalities the information can be attached to management applications. It can also be used as a base for the tracking functionalities or navigation. The solution can easily adapt to the changing shape and sizes of the underground installation because of the usage of self-powered wireless devices.

The proposed solution makes smartphone devices usage possible in the underground installations without the need their modification. It is suited for smartphone components recommended for the Android 7.0 operating system. All the components were reviewed in context of their applicability for position finding task. The proof of concept implementation of the smartphone application was made and used in the underground tests.

6.1. Tests summary

The experiments made within the thesis confirm the assumptions about the specific propagation conditions in underground environment.

It was observed that on the short distances from the signal source ($0m$–$10m$) the attenuation curve is similar to that in free field distribution. That means that on such distances there can be applied same RSS analysis methods as are used in the indoor positioning techniques.

The tests verified the values of recommended beacon parameters. The proposed value of transmission power resulted with expected signal range that matches with the concept of signal redundancy. It was also verified that the proposed value is sufficient for different orientations of the smartphone.

Different beacons requires calibration in order to make their signal propagation parameters similar. The attenuation curves of their signals have similar shape. It means that signal related methods chosen for the proposed solution can be applied to various beacon models. Different smartphone models do not influence the signal strength readings as well. The attenuation curve obtained from the both of Samsung and Blackberry devices have the same course and signal levels $\pm 2dBm$.

The beacon placement and it's orientation highly impacts the attenuation curve. It has been experimentally proven that beacons mounted horizontally on the ceiling have better signal coverage than in other configurations. It was also observed that signal is less prone to the distortions caused by objects located inside the tunnel.

6.2. Future works

The accuracy of proposed solution can be improved by introducing the model of the underground environment into the position estimation module [30]. The concept of aligning the inertial navigation outcome to the environmental model were already suggested but there are no solutions that have integrated it into the positioning estimation. In that context applicability of the concept should be verified. There should be evaluated methods of environment model representation, methods of integration with the proposed solution and the environment model update procedure.

The RSS values can be adopted into new distance-propagation model that will be suited for the underground radio propagation conditions. The future works on the propagation model can increase the accuracy of the proposed solution.

The solution can be extended by the concept of automated maintenance. The smartphone application can implement on-the-fly verification if the underground infrastructure is complete. The works should investigate the methods of verification as well as the methods of reporting the status of the infrastructure.

The further step for the proposed solution is to evaluate higher level filter in order to integrate all the position related factors acquired by the smartphone into the one estimation algorithm. This will increase the estimation accuracy and allow for solution extension by the smartphone internal sensor's fusion. The proof of concept implementation should be extended by multiple sensor fusioning with use such filtering. Then the accuracy should be verified in the underground environment.

Bibliography

[1] AIRACOM. *Introducing the IS520.1 for Emergency Response, Security Military.* `http://www.airacom.com/wp-content/uploads/2016/12/Airacom_Brochure_IS520.1.pdf`. [Online; accessed 05-June-2018].

[2] Bandyopadhyay L., Chaulya S., Mishra P. *Wireless Communication in Underground Mines.* New York, Springer Science+Business Media, 2010.

[3] Bandyopadhyay L. K., Mishra P. K., Kumar S., Narayan A. *Radio frequency communication systems in underground mines*, 2005. Dhanbad, India.

[4] Ben-Moshe B., Reisberg S., Shvalb N., Yozevitch R. *GoIn – An Accurate InDoor Navigation Framework for Mobile Devices.* `https://www.microsoft.com/en-us/research/wp-content/uploads/2015/10/ben-moshe.pdf`, 2016. [Online; accessed 04-June-2018].

[5] Bulten W. *Human SLAM - Simultaneous Localisation and Configuration (SLAC) of indoor Wireless Sensor Networks and their users.* Master's thesis, Radboud University, 2015.

[6] Castro-Arvizu J. M., Vilà-Valls J., Moragrega A., Closas P., Fernandez-Rubio J. A. *Received signal strength–based indoor localization using a robust interacting multiple model–extended Kalman filter algorithm.* International Journal of Distributed Sensor Networks, 2017, 13(8).

[7] Chai S., An R., Du Z. *An Indoor Positioning Algorithm Using Bluetooth Low Energy RSSI.* In: International Conference on Advanced Material Science and Environmental Engineering (AMSEE 2016), Thailand, 2016. s. 331–343.

[8] Chandgadkar A. *An Indoor Navigation System For Smartphones.* Master's thesis, Imperial College London, London, Great Britain, 2013.

[9] Dabove P., Ghinamo G., Lingua A. M. *Inertial sensors for smartphones navigation.* SpringerPlus, 2015, 4(1):834.

[10] Dahlgren E., Mahmood H. *Evaluation of indoor positioning based on Bluetooth Smart technology.* Master's thesis, Chalmers University of Technology, Göteborg, Sweden, 2014.

[11] Deng Z., Mo J., Jia B., Bian X. *An Acquisition Scheme Based on a Matched Filter for Novel Communication and Navigation Fusion Signals.* Sensors, 2017, 17(2):1766.

[12] Deng Z.-A., Wang G., Hu Y., Wu D. *Heading Estimation for Indoor Pedestrian Navigation Using a Smartphone in the Pocket.* Sensors, 2015, 15:21518–21536.

[13] Diaz E. M. *Inertial Pocket Navigation System: Unaided 3D Positioning.* Sensors, 2015, 15:9156–9178.

[14] Don R. L. H. *Enhanced Indoor Localization System based on Inertial Navigation.* Master's thesis, The University of Western Ontario, 2016.

[15] fei Zhang K., Zhu M., jia Wang Y., jiang Fu E., Cartwright W. *Underground mining intelligent response and rescue systems.* Procedia Earth and Planetary Science, 2009, 1(1).

[16] Forooshani A. E., Bashir S., Michelson D. G., Noghanian S. *A Survey of Wireless Communications and Propagation Modeling in Underground Mines.* IEEE Communications Surveys Tutorials, 2013, 15(4).

[17] Glass R. B. *Mobile Indoor Positioning for Augmented Reality Systems.* Master's thesis, Virginia Commonwealth University, Richmond, Virginia, 2014.

[18] Google I. *Android 7.0 Compatibility Definition Document.* `https://source.android.com/compatibility/7.0/android-7.0-cdd.pdf`, 2016. [Online; accessed 23-May-2018].

[19] Hlophe K. *An Embedded Underground Navigation System.* Sensors, 2015, 15(9):24595–24614.

[20] Holčík M. *Indoor Navigation for Android.* Master's thesis, Masaryk University, Brno, Czech Republic, 2012.

[21] Hui F. C. P., Chan H. C. B., Fung S. H. *RFID-based Location Tracking System Using a Peer-to-Peer Network Architecture.* In: Proceedings of the International MultiConference of Engineers and Computer Scientists 2014 Vol I, IMECS 2014, Hong Kong, China, 2014. Newswood Limited, s. 181–185.

[22] Ilic M., Ilic A., Notaros B. *Higher Order Large-Domain FEM Modeling of 3-D Multiport Waveguide Structures With Arbitrary Discontinuities.* IEEE Transactions on Microwave Theory and Techniques, 2004, 52(6):1608–1614.

[23] Infante E. *Development and Assessment of Loosely-Coupled INS using. Smartphone Sensors.* Master's thesis, University of New Brunswick, Fredericton, N.B. Canada, 2016.

[24] Jayakody A., Lokuliyana S., Chathurangi D., Vithana D. *Indoor Positioning: Novel Approach for Bluetooth Networks using RSSI Smoothing.* International Journal of Computer Applications, 2016, 137(13):26–32.

[25] jianyong Z., zili C., haiyong L., zhaohui L. *RSSI based Bluetooth low energy indoor positioning.* In: 2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN), Busan, South Korea, 2014.

[26] Kaushal K., Kaur T., Kaur J. *ZigBee based Wireless Sensor Networks.* International Journal of Computer Science and Information Technologies, 2014, 5(6):7752–7755.

[27] Khoshelham K., Zlatanova S. *Sensors for Indoor Mapping and Navigation.* Sensors, 2016, 16(5):655.

[28] Klempous R. *Collective Behavior in Wireless Sensor Networks.* Acta Polytechnica Hungarica, 2014, 14(4):101–118.

[29] Li B., Wang Y., Lee H. K., Dempster A., Rizos C. *A New Method for Yielding a Database of Location Fingerprints in WLAN.* In: IEEE Proceedings-Communications, 2005.

[30] Li B., Zhao K., Saydam S., Rizos C., Wang J., Wang Q. *Third Generation Positioning System for Underground Mine Environments: An update on progress*, 2016.

[31] Li L., Hu P., Peng C., Shen G., Zhao F. *Epsilon: A Visible Light Based Positioning System.* In: Proceedings of the 11th USENIX Symposium on Networked Systems Design and Implementation (NSDI '14)., Seattle, USA, 2014. s. 331–343.

[32] li Ji W., Sun K. *Locating and Tracking System of Underground Miner Based on IOT.* In: International Conference on Applied Mathematics and Mechanics, 2016.

[33] Loulier B. *Using smartphones for indoor navigation.* Master's thesis, Purdue University, West Lafayette, Indiana, USA, 2011.

[34] Makkonen T., Heikkilä R., Kaaranka A. *The Applicability of a Geomagnetic Field based Positioning Technique with Mobile Phone to Underground Tunnels.* In: The 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014), Sydney, Australia, 2014. I.A.A.R.C., s. 953–959.

[35] Marotto V., Serra A., Carboni D., Sole M., Dessi T., Manchinu A. *Orientation Analysis through a Gyroscope Sensor for Indoor Navigation Systems.* In: SENSORDEVICES 2013 : The Fourth International Conference on Sensor Device Technologies and Applications, Pula, Italy, 2013.

[36] McBain J., Timusk M. *Software architecture for condition monitoring of mobile underground mining machinery: A framework extensible to intelligent signal processing and analysis.* In: 2012 IEEE Conference on Prognostics and Health Management, Beijing, China, 2012. IEEE, s. 1–12.

[37] Mo J., Deng Z., Jia B., Bian X. *A Pseudorange Measurement Scheme Based on Snapshot for Base Station Positioning Receivers.* Sensors, 2017, 17(12):2783.

[38] Mulloni A., Seichter H., Schmalstieg D. *Handheld augmented reality indoor navigation with activity-based instructions.* In: MobileHCI '11 Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services, Stockholm, Sweden, 2011. s. 211–220.

[39] Müller C. *Applicability of Wired and Wireless Ethernet Networking Systems as Unified Safety Relevant Communication System in Underground Mines.* PhD thesis, Universitatea Transilvania din Braşov, Brasov, Romania, 2013.

[40] Niu X., Wang Q., Li Y., Li Q., Liu J. *Using Inertial Sensors in Smartphones for Curriculum Experiments of Inertial Navigation Technology.* Education Sciences, 2015, 5(1):26–46.

[41] Pan M.-S., Tseng Y.-C. *ZigBee Wireless Sensor Networks and Their Applications.* National Chiao Tung University. not published.

[42] Pan W., Hou Y., Xiao S. *Visible light indoor positioning based on camera with specular*

reflection cancellation. In: 2017 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR), 2017.

[43] Patri A., Nayak A., Jayanthu S. *Wireless Communication Systems For Underground Mines – A Critical Appraisal.* International Journal of Engineering Trends and Technology(IJETT), 2013, 4(7):3149–3153.

[44] Persa S.-F. *Sensor Fusion in Head Pose Tracking for Augmented Reality.* Master's thesis, Inginer Universitatea Tehnica din Cluj-Napoca, Cluj-Napoca, Romania, 2006.

[45] Ranjan A., Sahu H. B. *Advancements in communication and safety systems in underground mines: present status and future prospects.* In: International Engineering Conference on Design and Innovation in Sustainability 2014, Amman, Jordan, 2014.

[46] Rodrigues C. *Smartphone-based Inertial Navigation System for Bicycles.* Master's thesis, Universidade do Porto, Porto, Portugal, 2015.

[47] Seidel S., Rappaport T. *914 MHz path loss prediction models for indoor wireless communications in multifloored building.* IEEE Transactions on Antennas and Propagation, 1992, 40(2):207–217.

[48] Solin A., Cortes S., Rahtu E., Kannala J. *Inertial Odometry on Handheld Smartphones.* CoRR, 2017, abs/1703.00154.

[49] Stambulskyy O. *System inteligentnej lokalizacji wykorzystujący technologię Bluetooth Smart dla zwiększenia bezpieczeństwa oraz zwiększenia wydajności w górnictwie podziemnym.* Master's thesis, Politechnika Wrocławska, Wroclaw, Poland, 2017.

[50] Stockx T., Hecht B., Schöning J. *SubwayPS: towards smartphone positioning in underground public transportation systems.* In: SIGSPATIAL '14 Proceedings of the 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, Dallas, Texas, 2014. s. 93–102.

[51] Svensson J. *Investigation of Inertial Navigation for Localization in Underground Mines.* Master's thesis, Uppsala University, Uppsala, Sweden, 2015.

[52] Tedaldi D., Pretto A., Menegatti E. *A Robust and Easy to Implement Method for IMU Calibration without External Equipments.* In: 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, 2014. IEEE, s. 3042–3049.

[53] Wilczyńska E. *Strong shock at the KGHM Rudna mine. Eight miners are dead.* Gazeta Wyborcza online: `http://wroclaw.wyborcza.pl/wroclaw/1,35771,21049452,silny-wstrzas-w-kopalni-kghm-siedmiu-gornikow-wciaz-pod-ziemia.html`, 2016. [Polish; Online; accessed 13-January-2018].

[54] Wojaczek A. *Application of leaky feeder in vehicle positioning system in mines.* Przegląd Górniczy, 2014, 70(1):1–8.

[55] Xin J. *An Indoor Navigation System Using a Sensor Fusion Scheme on Android Platform.* Master's thesis, Marquette University, Marquette, Wisconsin, USA, 2009.

[56] Xu R., Chen W., Xu Y., Ji S. *A New Indoor Positioning System Architecture Using GPS Signals.* Sensors, 2015, 15(5):10074–10087.

[57] Xu R., Chen W., Xu Y., Ji S., Liu J. *Improved GNSS-based indoor positioning algorithm for mobile devices.* GPS Solutions, 2017, 21(4):1721–1733.

[58] Yarkan S., Guzelgoz S., Arslan H., Murphy R. R. *Underground Mine Communications: A Survey.* IEEE Communications Surveys Tutorials, 2009, 11(3):125–142.

[59] Zhang Y., Yang W., Han D., Kim Y.-I. *An Integrated Environment Monitoring System for Underground Coal Mines—Wireless Sensor Network Subsystem with Multi-Parameter Monitoring.* Sensors, 2014, 14:13149–13170.