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Master Thesis

Constructing a position finding system model for underground installations

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

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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 koncepcję 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. System is dedicated for people using customer class smartphone inside this installations. The paper 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 aboveground corridors has been proposed. Concept include inertial navigation based on smartphone device sensorics and signals strength analysis of Bluetooth Low Energy radio modules that are used as a 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. Results from tests confirm correctness of assumptions stated in requirements.

Chapter 1

Goals and thesis scope

Following document investigates position finding system implementation basing on consumer grade smartphone and network of reference points using Bluetooth Low Energy technology.

As part of the work, there are presented currenty known position finding solutions within underground environment, available technologies and a method of position finding for consumer grade smartphones in underground installations is proposed. There are presented test cases and experiments supported by data analysis from measurements of given factors of the solution. Experiments are focused on stability, repeatability, accuracy and reliability factors. The work do not discuss the mining model representation but general architecture and data exchange model. but there are proposed soluin terms of the location of the reference points, the location of the miner (system user), the safety points and the evacuation exits. The model should allow both the user to navigate to the nearest safety point, taking into account the current state of the corridors, and to allow presentation of the current position in graphical form. As part of the work, a complete model of the solution are be proposed along with the prototype of application for the mobile device. Finally, there are proposed future works that would base on a concept of integration of the location system with the function of remotely updating corridors. There are be provided example use cases.

Chapter 2

Underground envioronment description

Underground installations are specific environment in terms of electromagnetic waves propagation, their diamensions, varying accross the tunnels, large scale, weak light, available communication technologies, environmental parameters like humadity, temperature, substances that make up the atmosphere and safety restrictions that limits electronic equipment that can be used on site.

As for the position finding problem in indoor environments there were already developed sucessful solutions, the underground environment make some of assumptions no more valid. That is because of the propagation channel which is difficult to model due to the fact that signals are absorbed by earthen walls, bounce off uneven surfaces, and must pass equipment and other obstacles in corridors.

Description of:

- Construction (very briefly):
  - how can look like: from complicated (room and phillar) to simple (tunneling)
  - distances
  - how big it is: corridor diamensions, room diamanesions, etc.
- Conditions in therms of light and air.
- What wireless communication methods are available?

Answer questions:

- if we need the navigation in whole installation? if yes, why?
- if we need the navigation only in some places inside installation? if yes, why?
- what factors may require from navigation system its extensive lifetime?

2.1. Underground installation characteristics

This section covers a short description of underground installations in general that are the environment for the positioning system.

Underground installation therm is a general description of places such as tunnels and shafts that were digged into the earth in purpose of valuable material extraction, transportation, touristics or other reasons. The common phase in those installations is the phase of their creation. There is a need to digg 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 exchavation, for personel transportation and rock transportation to the surface. Mining installations are about continous rock exchavation process (creation phase) while the others, like designed for transporation, ends creation phase and moves to the phase of use and maintenance. Underground installations that can be descibed as a gorup of laneways (main and branch tunnels) and in case of mine: mining areas and mined-out areas.

What is the common in underground installation is that there are 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 regurally 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 diamensions, type of material (rock), amount of dust, how freqent is in use, what means of communication are placed into, what machines (if any) are being used inside. Along greater depths, the work conditions are decreasing. The probability of coal and gas outbursts increases because of bigger gas emission on deeper levels. Underground installations can be affected also by water leaks, coal dust explosions and rock bursts [28]. 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. The another risk is 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 [1]. 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. 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 techonologies are used in places that are inaccessible or in places affected by disaster where wired communication got broken. It is also havily used for communication purposes with modern underground equipment such as self-propelled mining machines. Wireless communication is installed also in underground installations where probability of disaser is low as an extension to wired technology. Commercial tunneling equip thier corridors with wireless communication technologies such as GSM and WiFi in order to speed up communication between executives on tunel construction site and on surface. Tunneling is about digggin a corridors for transportation purposes in difficoult terrains such as mountains or bellow the water. Operations that are performed it high latitudes where gas is not present are safer then in mines which operates deep under the surface.

There is no standard position marking convetion that are used accross the underground installations. Details about shape, size and current deep and length of corridors are often trated as a company secret as well as their labels. Generally speaking underground installactions are labeled with use of sector name, corridor name and a number of meters since beggining 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 suffincient in case of not complicated structure of corridors and shafts as well as in complex structured like in case of *room and pillar* layout. Example of room and pillar corridors layout is presented on the figure 2.1. $A1$ denotes transportation corridor. It can be used for example by drill rigs or load-haul-dump machines that are doing the excavation. $S1, S2, S3, ...$ 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 diamensions may vary with respect of depth that works are being performed and the type of rock. Pillars can be 20 m – 40 m thick.

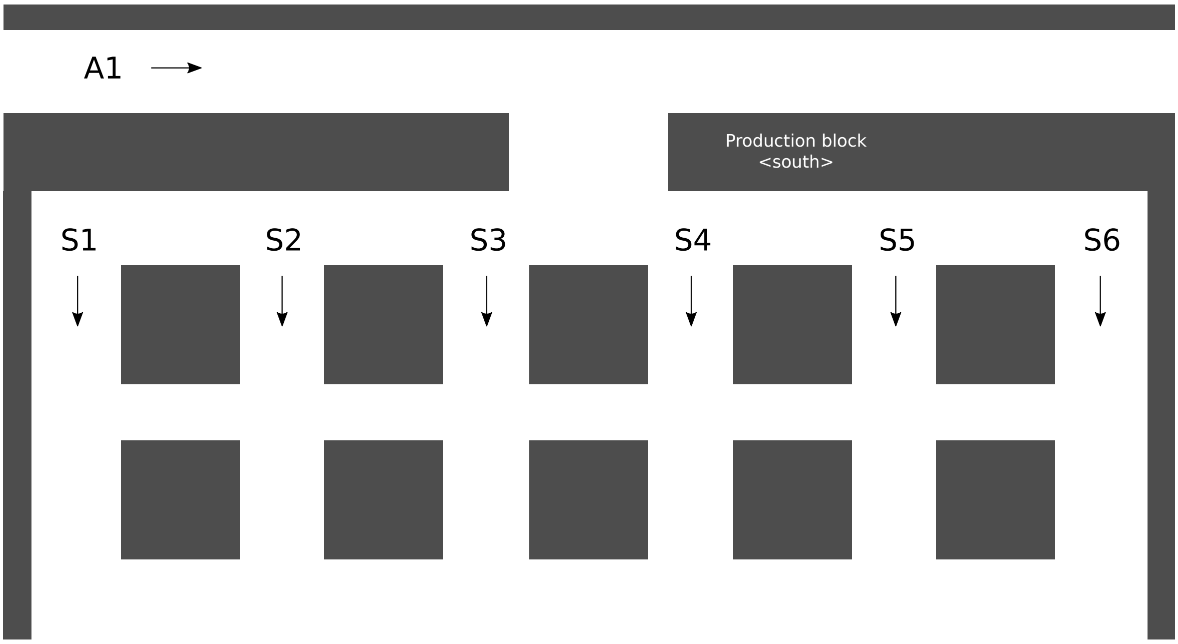

Figure 2.1. Naming and convention in room and pillar excavation type.

2.2. Hardware and environmental constratins

State of the art in underground navigation solutions. Theoretical topic.

Phisics related to waves propagation in underground corridor

- Waves difraction, <tłumienie>
- What are known issues related to wireless communication in underground installations

*TO be adapted; book-wcin Requirements stated for communication system for the undeground operations:

- must be intrinsically safe and explosion proof
- should adhere to the ingress protection (IP) standards;
- must be rugged in structure
- must be size flexible
- must have totality in design including cables, power supply unit, base stations, etc
- must be value-added priced;e stations, etc
- must be robust, inexpensive, easy to expand, and enable fast and secure connections

*** The wireless communication systems used on surface cannot be applied straightaway in underground mines due to high attenuation of radio waves in underground strata. Undergorund radio waves propagation envioronment differ also because of

- presence of inflammable gases,
- hazardous environment,
- complex corridors topology (mines case),
- complex geological structures,

2.3. Positioning systems

The position finding problem is a known problem, deeply investigated in field of robotics and automation. [3]

Position finding in underground installations is a problem that arrised along with the advance in the available technologies. Demand for such functionality comes from two main reasons:

- safety of mine workers,
- the need of tool that will support human and equipment resource planning and distribution.

2.3.1. Safety aspect

Protecting and rescueing people lifes are one of the most important challanges for the underground construction and mining industry since many years. In case of accident there is need to perform appropriate search and rescue actions immediatley 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 position af miners before accident and how many of them are trapped and how big is the scale of destruction. Currently used techniques for rescueing people after an accident requires to count people that came out to know how many people are trapped and then digg though the falled 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 emmited from miners lamp, allowing on detection from a few meters [25]. 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 [24] 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 was in time of accident and speed up rescueing 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 minimise loss in case of accident. Besides the means of emergency situation prevention like preditions 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 [16]. All of those functions requires good position finding solution in order to provide fast and realiable information even if connectivity is broken.

Positioning system can be used also by people working underground directly from their personal digital equipment[16] 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 informations 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.

2.3.2. Business aspect

Another use case for positioning system is that stakeholders want to know where the equipment is placed, how many time it needs to do it's operations, if there are some unplanned breakes in machine work. Delays in case of any underground operations are very costly. Resources monitoring can depict bootlenecks in machine operations may provide informations how to balance the workload in order to make operations smoother and more efficient. Data gathered by positioning systems can be also 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 efficency because of less time needed to spend on gethering information about machines position from reports. [23] The positioning systems are mainly used to deliver information to systems that operates above ground. Todays underground operations are partly or fully automated. The process of the operations is monitored and managed remotely from operation centers on surface. Supervior and control of such operations are similiar to that known on above ground process plants which are controlled by SCADA – Supervisory Control And Data Acquisition software systems [16].

Underground construction industry use automation technology heavily in nearly all aspects: safety, work automation, work and environment monitoring, internal and external communication, transport, maintainig 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 informations distributed by systems and provide information about envioronmental parameters or work performance. Devices and mobile machines that work underground are also connected to that system through means of onboard microcontrollers or computers and wireless network. Thanks to it it is possible to provide to central system work performance information or device health status that can be usefull for service during periodical device checks or repairs. Positioning systems implementations may work togehter with these devices which allows underground operation executives to have a up to date map of current works and processes being in progress. Positioning information can be used also by mobile devices by themselves. Example of devices that make use positioning data are modern mobile machine gateways devices [16] 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).

Nowadays there are available positioning systems for underground installations that can provide aproximate localization of people or equipment.

2.4. Usage of mobile devices in underground installations

Define 'mobile device'

Answer questions:

- If mobile device (smartphone class) can be used in undergorund installations?
- How usage of mobile device in underground installations may differ from usage in normal conditions (outside underground installation)?

Chapter 3

Position finding solutions for indoor environment

Underground installation is a specific case of an indoor environment. What is the characteristic for indoor environment is a large amount of signal diffractions and attenuarions by various materials, weaker signals of terrestial networks and global navigation sattelite systems and a need of more precise positioning information than in open space. Underground installations are completaly isolated from the wireless networks available on 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 arrises the question wether solutions that are working for indoor environments could be also applicable to the underground conditions. It is not obvious question as it is known that radio technologies behaves differently in underground corridors because of rock, steel, concrete, a hexahedral[2][9] alike shape and a working heavy machinery with powerfull motor engines that produce large amount of electromagnetic distortions.

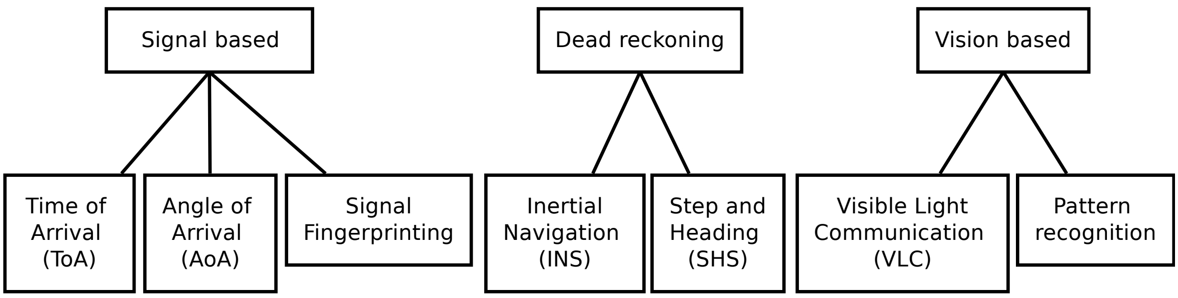

Figure 3.1. General position finding approaches for smartphones.

Smartphone based indoor localization application can be classified as shown on figure 3.1.

In this chapter there are revieved successful approaches for indoor positioning including hardware devices and infrastructure related system architectures and algorithmic approaches that are suitable for smarpthone devices.

3.1. Known solutions analysis

Positioning systems with respect of the what is the target of acquired data. There can be defined three categories of positioning systems: 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 and systems that combine both approaches.

Computer recognise loading and dumping points by data provided by positioning system. It acumulates data about machine speed, distance traveled, time, amount of load that is carring and put into the report which creation is triggered by positioning information.

- Advantages and disadvantages of solutions
- How the solutions fulfil given criteria (ex. how accurate given solution can be)

Possible subsections that will discuss in detail given technologies. Inertial system https://en.wikipedia.org/wiki/Inertial$_n avigation_s system$

Currently available indoor positioning systems rely on informations provided by radio transmitters placed on fixed positions and Inertial Measurement Units (IMU). Potential positioning approaches for underground installations[13] include:

- Passive RFID,
- Inertial Measurement Unit (IMU),
- Received Signal Strength (RSS) based positioning:
  - Bluetooth Low Energy,
  - ZigBee,
  - WiFi
  - Active RFID
- Ultra-wideband (UWB),
- Magnetic Field strength pattern matching,
- Very-low frequency (VLF) electromagnetic waves,
- Visible Light Communication (VLC).

In the underground installations image processing (aka computer vision) solutions for positioning systems are not investigated due to the lack of the patterns that can identify current position admittedly and poor visibility.

With respect of the necessity of data distribution accross the positioning system there are avilable different solution architectures. Approaches can be categorised in a following way:

- 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 envioronmental data and passes it to the next user in range.

3.1.1. WiFi signal strength analysis and WiFi fingerprinting

WiFi 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 recognising wireless lan network access points by thier SSID or physical address of network cards [12]. As there exists working position finding solution that base on that technology the accuracy of the solution is about 100-300 meters [23].

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 close to the WiFi transceiver antenna its going to stabilize in distance about 10m from source and then the signal strength is residing on similiar level up to distance arround 300 meters from its source when it goes down [16].

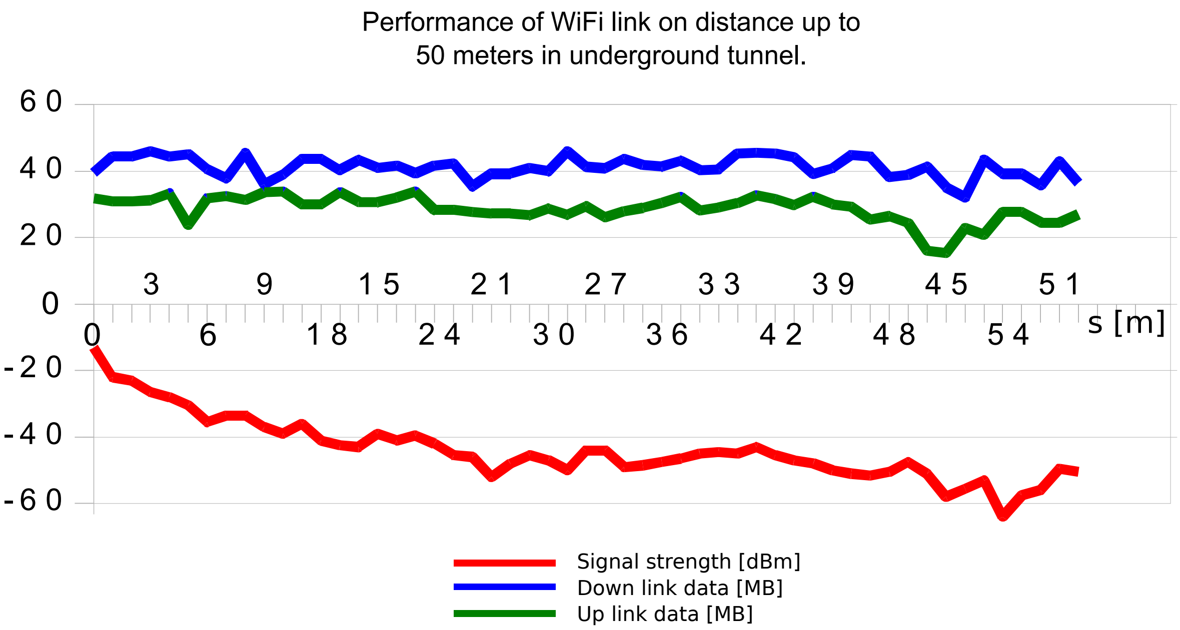

Figure 3.2. Wireless lan throughput and signal strength with respect of distance from the signal source (wireless access point) [16].

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 uplink and downlink 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 chart are medians of all gathered values and factors for given distance. Test was caried out in straight underground tunnel in the biggest coal mine in Slovenia: Premogovnik Velenje. Connection throughtput between client and server remains nearly the same for distances in range from 0 up to 50 meters. Signal strength is presented in logarithimc unit dBm. Signal strength falls significantly in first 10 meters from 0 to -40 dBm. After distance of 10 meteres value of signal strength is ranged in between -40 and -50 dBm with small and not regular diviations. After 45 meters from source the value drops slightly bellow -50 dBm.

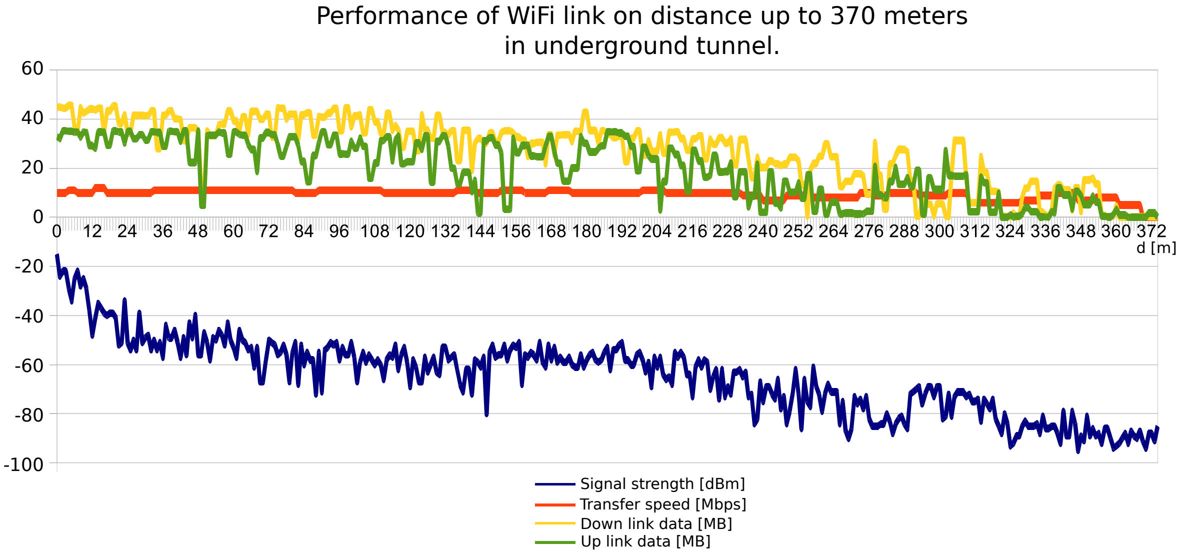

Figure 3.3. Wireless lan range [16].

Figure 3.3 presents tests results performed on longer distance till connvectivity was not possible due to too low signal strength. On distances from 50 up to 240 meters parameters of link are similiar. Down link data remains at 40 MB and at 38 after 140 meters with drops to 20 MB. Up link data measurments are more unstable than in case of down link in therms 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 uplink and down link drops by 10 MB. Speed of data transfer between access point and client device remain similiar from very beggining till distance around 370 where signal is not enogh to conduct connection. Signal strength is characteristic only for first 10 meters from signal source. Then signal strength oscilates between -40 and -60 dBm on distances 10 – 50 meters, between -50 and -80 dBm on distances 50 – 240 meters, between -60 and -90 on distances 240 – 320 meres and between -80 and -90 on longer distances. Following data does not represent any straight forward solution to adjust positioniong information to make positioning more precise and accurate. Only on distances close to the signal source it is possible to estimate more precise position while signal strength values differ significantly from the values that occures on the rest of distances. There can be identified following range zones with respect of WiFi signal behaviour [16]:

1. near field zone: 0 – 40m distance from signal source where wave attenuation curve is similiar to that in free field distribution,
2. coverage zone: 40 – 200m distance from signals source where can be identified symptoms of waveguide propagation and signal strength remain to be arround -50 dBm,
3. monitoring zone: distances since 200m from signals source where signal starts to vary from -75 up to -85 dBm 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.

One of the approaches for the Wireless LAN based positioniong system is to assume that given client is present in given area of underground installation if it is in coverage zone of one of Wireless LAN access point. Client can be registered by access point software and followed until he leave coverage zone. As the coverage zone is about 200 meter distance from access point then total accuracy of this solution is about 400 meters. Second approach assume positioning accuracy improvment by signal strength interpretation and recognistion if client is in near field zone. This approach is easy to be implemented as signal strength values in near field zone differs from values from the rest of zones. Such solutions are implemented in mines in Germany [16] and in Swedish Boliden's mines [23].

3.2. Positioning with Beacons and Bluetooth technology

Beacons are transmitters that use Bluetooth low energy technology in order to send out small set of informations. They are designed to be small and energy efficient in order to allow them to be independent from the external power source. The main application of beacons are indoor positioning systems while beacons can be treated as a set of reference points building the static infrastructe of landmarks where the position is a funtion of received signal strength from beacons by the user. Beacons can be also attached to the non static objects or even user can emmit beacon information. Then the responsibility of position estimation lies on the infrastructure that gathers the signals.

Common way of estimating the position is taking into account the measure of received signal strength from the beacon transmitter called RSSI (received signal strength indicator). RSSI denotes the power of received radio signal measured in dBm (decibel-miliwatts). The measure is actually the raw value that express the powerd inducted on the receivers antenna as a result of transmission. None additional sensors are required to take that measure. Value is available on most of wireless technologies as a part of diagnotic report serving as indicator how good the connection is. The higher the RSSI value then the higher the signal strength so transmitter is closer to the receiver. Such relation between the RSSI value and the distance is known under a various of models that tries to describe the propagation of electromagnetic radio waves with use of some statisic and probabilitic distribution [20]. Such models are needed because of calculus complexity while using actual physical model of the phenomena. In order to perform physical calculus there is need detailed description of the envioronment including every element that may influance 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 diffractions and attenuations on materials present in the indoor envioronment. As the propagation space is not ideal and the amount of elements influences the propagation is large such calculations are not being performed.

Example of statisically obtained model that descibes relation between received signal strength is *Log-distance path loss model*:

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

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. That is the common practise which was even implemented into iBeacon protocol developed by Apple company by attaching additional information about reference A_0 RSSI value into the broadcast message of the beacon.

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 treaten as a rough distance estimation as RSSI is not a stable measure. 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 distrortion such as multi-path reflections where signal bounce against objects and material attenuation what makes the resultant measures noisy.

Bluetooth technology was developed and is maintened by the Bluetooth Special Interest Group (Bluetooth SIG) which is the standard organisation capable for licensing the Bluetooth technologies and trademarks to the manufacturers. Bluetooth technology operates on frequencies from 2,4GHz to 2,4835GHZ which was devided into into 80 channels. In order to adopt transmission channel to the current load on given frequencies, Bluetooth implement a mechanism called *Adaptive Frequency Hopping* which allows to change 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 version 4.0 if Bluetooth standard there is availablable special protocol that is optimised 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 5.0 version of the standard the set of the protocols are called just *Bluetooth 5*. Market is dominated with Beacons that use Bluetooth Low Energy protocol in version 4.0 that is why this paper focuses only on this version of protocol.

Bluetooth 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 describe what communication protocols and data format it use. Protocols available for the profiles are also defined by the Bluetooth technology. Bluetooth Low Energy protocol use *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 state of 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 idenfied 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. There are available such format types 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 characterisic can be readed (read property), changed (write property), required acknowledgement (indicate property) or being in use just for notification purposes (notify property). There is possibility to add custom properties as well. Security persmissions part of the characteristic definition are about definining if 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 way how Bluetooth Low Energy devices communicate with them selves. It is called *advertisment mode*. In order to distinguish types of those messages (aka advertisement frames) they are different frame formats being in use. 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*, advertisement frame consists of 29 bytes. First 9 bytes are constant preamble, defined by the *iBeacon* protocol. First 3 bytes are standard Bluetooth Low Energy Flags. Next 6 bytes consists of type definition of the packet (in this case it is a *Custom Manufacturer Packet*), manufacturer ID (constant value that represents Apple company), subtype that indicates *iBeacon* compatible device and number of bytes that are attached to the *iBeacon* advertisement frame which is a constant number of 21 bytes. *iBeacon* specific data consists of *Proximity UUID* field which must be unique accross 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 1 m from the Beacon transmitter. *Signal Power* value is commonly used to compute distance between receiver and transmitter using the *Log-distance path loss model*. Then *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 cumputed quickly just after receiving the advertisement frame by issuing the following equation:

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

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

Eddystone protocol introduce three types of advertisement frames. They differ from *iBeacon* by introducing seperate 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.

3.2.1. RFID tags

RFID technology make use of electromagnetic field phenomena that allows to transfer information to reader from special component, RFID tag. 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 tag readers have to propagate electromagnetic waves. Tags cumulates power from electromagnetic field in capacitor. When tag have enough power then it transmits the response with 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 wich use it's own power supply.

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 the mine network via dedicated control unit like Mining Infrastructure Computer [16]. Control unit is responsible for RFID reader configuration and translation of its readings into standarized positioning information format. It also supplement data from RFID reader with its identificator or coordinates which express position of a reader on mine model. RFID can operate at 868MHz band. RFID with 8dBi antenna is able to detect RFID passive tags at range of up to 3 meters.

3.2.2. WSN based position finding systems

There are proposals of position finiding and tracking systems based internet of things (IOT) soultions [14, 28]. The idea is to create means of wireless communication to locate miners during their daily basis. It is proposed to create a network of wireless nodes (WSN) that read signal from tag devices (RFID) carried by miners and transfer it through nodes network to sink nodes that are directly connected to the mine core data transfer installation such as industrial Ethernet. Miners position data is sent to acquisition server. Intermediate and nodes are directly connected one or more nodes laying in the range of their wireless communication module. They form together ad hoc, multi-hop, self-organizing network of nodes that is able to transfer data, reorganise its structure in case of mailfunction of one of the nodes and allow to configure nodes remotely due to the implemented wireless communication technology and dedicated routing protocol. Network of nodes can be easily expanded by adding new nodes. Due to the fact that communication is wireless, nodes can be placed also in danger or new areas where wired network devices are not allowed or the related infrastructure doesn't exists.

WSN and RFID based positioning system is 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 simillary implemented monitoring system that measure safety parameters in mine [28]. This positioning system is dedicated to used by production monitoring, production scheduling and emergency rescue mine departments located on surface. Bigger precision can achived by adding more nodes into the network. Technology that is used for wireless communication between WSN nodes can be a Bluetooth Low Energy, ZigBee (IEEE 802.15.4 based) or WiFi (IEEE 802.11). ZigBee technology is the most popular in WSN's as it supports variety of communication modes, contain out-of-box solutions for network topology management and support low energy solutions like sleep modes [10]. 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 [28, 17]. There are three main topologies 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 sink. Tree topology enables multihop functionalities but litmits network flexibility in therms of adopting routes in case of filure (doesn't support redundant connections between nodes). Mesh topology requires to store routing tables in each node but provides means of redundancy in therms of routing what makes the WSN network reliable and fault resistant [17]. The WSN positioning network proposal base on ZigBee technology and it's mesh topology. Placement of WSN nodes should guarantee signal coverage of RFID readers modules build into nodes. On order to achive that there are proposed variety of topologies that can be used on site during network installation. On image 3.4 it is presented the network topology proposal that introduces intermediate nodes – routing nodes – that gather information from sensor nodes and transfer it through network of routing nodes to server via sink node [28]. Due to the fact that WSN nodes are limited in energy supply, systems that base on that technology needs to be designed with aware of energy management and fault management. Idea of routing nodes deployment along the tunnel in two simmetrical lines comes from the need of link redundancy between nodes. Thanks to that even if some of routing nodes are down the information from sensors can be passed out through the other routing nodes that are in range. In order to limit power consumtion of reader nodes they were designed as Reduced Function Devices (RFD). These nodes do not take a part within information passing process. Reader nodes are designed only in purpose of reading signals from RFID tags and to send the information to the nearest routing node. In order to achive that the information will be sent only to the nearest reouting node there is performed initial configuration process that involve both reader nodes and route nodes in its signal propagation range. The process is such: reader node send 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). Reader node limit its sending power according to the responces. Thanks to it power consumtion of reader node and interference with neighboring nodes are reduced.

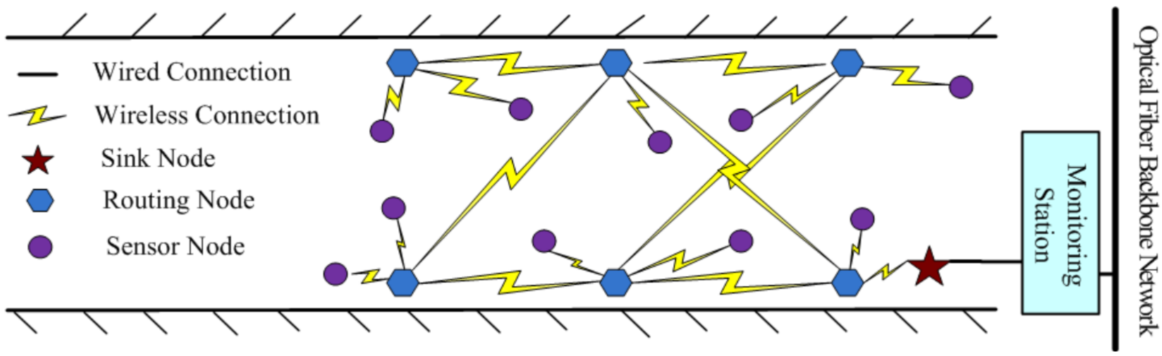

Figure 3.4. Wireless Network Sensor topology in underground corridor example [28].

Network of wireless connected nodes needs be designed with respect of its maintability. There is need to assume that some nodes may fail during their operation. As the network consits of many nodes, where the number of nodes can be changed during thier operation, there is need to implement actions that will allow them to organize their topology automatically. Even if particural nodes will fail, the rest of nodes should be able to work and maintain communication with remote services. It is the role of implemented routing protocol. There are available solutions that allow network to adapt quickly to the changing environment [11], but in case of statically placed network elements the environment is not changing havily. As it is in common practise, routing nodes stores information about nodes that are used for network purposes in the routing tables. Rounting tables are created with the manner that there are promoted link to nodes that ensure the lowest cost (distance) of packet travel from given node to the sink node. Routing table can have many entries. In case of topology for underground installation there are suggested 3 entries: parent route, minimum route, backup route [28]. Parent route points to the parent node, minimum route points to the best node in therms of the most energy efficient way to the sink node and backup node that 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 quality of link 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 1-node WSN. Rest of nodes organize themselves in manner that nodes broadcasts their physical and network adresses. 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 [10]. 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 pass through WSN along with data from periodic sensor readings.

Nodes are equiped with batteries that makes them independent from external power source. In order to save the energy and in order to prolong device live on the battery nodes works in energy efficient modes. In these modes nodes are turned into sleep for certain time. They woke 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 the initial message which is used to synchronize all of attached nodes. Power level of nodes batteries are monitored. Nodes can send information about their power level as a repsponce for appropriate request. There can be implemented special routines inside node that can cause sending the information about the low battery level in emergency mode, without any request from the sink node.

The crucial for the positioning system is to determine accurately exact position of given reader node inside the underground installations. Without information about readers placement positioning data obtained from them are not usefull. Solution for this problem in WSN positioning systems are solved by manual configuration. Each node have it's own identification number that is a part of it's initial configuration. This number is atteched into their housing also so given nodes can be identified directly during the installation or maintenance work in tunnel. As nodes deployment is regular it is assument in advance what will be the position of the node within the tunnel. In case of sudden failure of some node it is possible to determinate which of the node is broken by it's ID information, and check were the node is placed. WSN network should have possibility to report failure of its nodes. That is why WSN positioning systems are equiped with 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 then parent node issue status request command to the child node and wait given amount of time. If child node give an answer then it is assumed that the given child node is working correctly. In case of no response from child node, the parent node send information about failure to external service. As the readers nodes are connected stright to the parent node with no routing options then different policy for borken parent node must be applied. If the child node does not reiceve acknowledgement (ACK) frame from it's parent given amount of times then the node increase it's sending power and retrainsmits it's data again. If there is no result of increasing the power then node goes into network setup mode and scan channel to rejoin the network.

Positioning algorithm in WSN positioning system base on mine layout and assume fixed position of nodes. Information about mine layout and nodes position wihin mine is stored in database on server above ground. Data transferred from nodes into acquisition server is a combination of three values: ID of a node, ID of acquried RFID tag in range of RFID reader module of that node, signal power of this RFID tag, and timestamp. Data is being stored in simplified relational database. This positioning system uses algorithm for finding exact position of RFID tag in dwo diamensional space (x, y). In order to do that algorithm search in database for 3 nodes that acquired given tag sinal with the biggest power. Then it uses simple free space electromagnetic waves propagation model (3.3) to compute distance between node and tag.

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

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. Parameter P_{ri} (received signal power on reader's input) is the only variable in the equation that is needed to compute distance from tag to reader. Maximum likelihood estimation method that base on data from three nodes and thier values of reiceved signal power from given tag produces relative position of given tag in (x, y) coordinates. Suggested implementation [14] assume that nodes look for RFID nodes each 10 minutes.

3.2.3. Visible Light Based positioning system

3.3. Mobile device dedicated positioning systems

Todays smartphone class mobile device contains set of sensorics that can be used as a base for interial positioning system. In underground oprations industry this idea is not the newest as there were tryies of this technology implementations inside hand-held devices for people working underground with use of semiconductor based MEMS gyroscopes [16]. Such devices were connected to the underground wireless network through access points which was responsible for transfering positioning information to the central systems above ground.

Smartphone class devices contains set of components that are treated as common in the industry. There is no strict definition what components should or should not the smartphone class mobile device contain as there is a strong competition in the market offering those devices in various configurations, shapes and fetures. This paper focus on devices that are compliant with Android operating system, especially version 7.0 which is currently (in the middle of 2018), the most popular operating system on the market. TODO - reference needed - TODO. 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 - TODO - take from Android 7.0 Compatibility Definition - TODO. In this section there will be investigated only those technologies that are available for the basic handheld mobile device with Android 7.0.

Smartphone class mobile devices are treated in the engeener industry as a powerfull tool set helping the workers with their maintenance work on site and as a handy platform for wide scale of businesss 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 equiped with the sensorics that allow the users to detect, record and recognise the phisical movements or orientation changes. It extends the positioning functionality making it more robust and acurate.

3.3.1. Mobile device sensorics

There is no limitation in extending smartphones with internal sensorics. Acording to the Android 7.0 Compatibility Definition - TODO - there is no such sensoric 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 sensorics as producer wish under condition of having a compliant software implementation that deals with the sensorics. Although Android compatibility definition recognise some of them and recommends to be installed on the device. There are also technical requirements given under the sensorics recommendation in case of presence of such on the device.

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

Sensorics mentioned in the compatibility definition are:

- Accelerometer,
- Magnetometer,
- GPS,

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

All of components listed above, except fignerprint 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. Compatibility definition guarantee some quality parameters of sensorics mounted in the mobile phone.

3-axis accelerometer can be used to detect movement changes. It provides the information how big the change was in terms of force that the device was affected. Thanks to the information there 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 detected acceleration. It is required from that sensor to raport events at least at 100 Hz frequency (recommended minimum frequency is 200 Hz), to detect forces in range of frefall case up to forces at value of four times the gravity (4g) or more on any axis, minimal outcome resolution is 12-bits (recommended minimum is 16-bits), should allow for online calibration and calibration parameters persistance, be temperature componsated and have a standard deviation no grated than $0.05\frac{m}{s^2}$. Document defines also the maximum accepted amount of power that the sensor can consume during its operation - not more than 4 mW (recommended values are bellow 2 mW during the operation and bellow 0.5 mW when the device is in static condition).

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). Sensor must be able to measure between -900 μT and +900 μT on each axis before saturating with the resolution of 0.6 μT (recommended 0.2 μT or denser). Magnetometer have to compensate hard iron and soft iron effects where hard iron offset have to be less than 700 μT. 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 10 Hz (recommended 50 Hz).

GPS/GNSS receiver is not required component for a smartphone with 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 - sensor have 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 requitement - have to be allowed to track at least 8 satelites from one constellation simultaneusely (recommended 24 GPS satelites at the time and one from other global positioning satelite system like Glonass, Beidou or Galileo).

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

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.

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.

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 wether the user is close to the devices screen or not.

Pose sensor with 6 degrees of freedom (6-DOF) is an optional sensor that can be implemented in the Android compatible software. Sensor provides information about himself as part of the environment in perspective of end point of maniplator with 3 kinematic pairs, each with rotation possibilities. The method and related hardware is not discussed within the operating system compliance definition. The only rescriction stated to the sensor is that it have to be more accurate than rotation vector sensor. Basic implementation can make use of camera or depth sensor to compute the output value. Output is an quaretnion that express the rotation and a translation expressed in SI units. Sensor is used in virtual reality applications.

Android compliant definition strongly recommends the procudents to provide implementations of 'composite sensors' such as step detector, significant motion detector, gravity, linear acceleration, rotation vector. These measures are an efect of digital processing of data from single sensor like accelerometer in case of step detector or a sensor fusioning basing on multiple sensors like on megnetometer and gyroscope in case of rotation vector and accelerometer and magnetometer in case of geomagnetic rotation vector. The operating system recognise already filtered and processed data directly an outcome from an composite sensor which is actually a form of abstraction that hides the details of data processing.

Management of sensorics have to be implemented in a compliant manner in order to allow the operating system to interact with those sensorics. All of the sensor outcome are yet processed, normalized and expressed in a defined way like in case of an accelerometer and magnetometer where 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

In sake of generalization this paper investigate case of regular consumer grade smartphone which are devices with a common setup compliant with 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 envioronment. There are available GPS, Bluetooth, WiFi and terrestrial networks(GSM related) technologies. In case of underground each of these technologies has to be installed explicitely beacause bellow the ground none of these signals are available. GNSS (Global Navigation Satelite System) signal receiver is not usefull under the ground as there is no signal from sattelites available. There are tryies to make use of that technology by re-sending the acquired GNSS positioning data from sattelites in indoor environment by a set of transmitters that mimic sattelites [26] but it cannot be applied to the consumer grade smartphone as the Android applications have access to already processed pseudorange data into sattelite positions. Such solution is called Glonal Navigation Satelite System based indoor positioning system (GNSS-IPS)[27]. Approach where transmitters places on ground fake sattelite signal is known as pseudolite. In case of indoor environment positioning data acquired from sattelites are drifted due to the fact of non-line-of-sight that is why position obtained indoor is called as pseudo-position. There are known tryies of using this approach in order to obtain positioning data but there is not known any sucessful 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 shortcome 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 terrestial network by positioning information were done and sucessful [5][15].

Smartphone class devices are equiped with cameras. Images that captured by the cameras can be used for positioning purposes. There are known solutions that make use of visible light [18] that recognise source of light like LED which are called LED beacons and compute the position basing on the angle-of-arrival (AOA) algotithm.

Thanks to the presence of intertial sensors such as accelerometers and gyroscopes there are known implementations inertial navigation. Pedestrian Dead Recokoning (PDR) is based on the measures from the accelerometer which allows for step detection and an estimation of a step length [7] [6] [8]. Other approaches developes the recognition patterns that allows for distiction between transportation mean being in used. Such approaches were used for example in case of prototype navigation application in Chicago, London and Cologne subway [22] or inertial navigation for bikes [19]. There are known solutions for interial navigation improvment by aligning the outcome to the landmarks or map information [13].

Positioning techniques that invole 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 stable position in order to measure signal travel time correctly and 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. There are available two modes 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 where positioning application is turned off, the background service inform user that his smartphone found himself in the range of given Beacon region and run 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* [4]. Region monitoring gives a rough information wether 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 3.2, Beacons communicate their presence by sending broadcast messages called advertisement frames. With respect of the type of protocol being used there are available different formats for advertisement frames known as beacon layouts. Layout denotes the constraints that characterise given advertisement frame as well as variables and fields that are being included into frame.

TODO - describe each of pros TODO - describe each of cons

- Which of them will be useful to increase positioning accuracy
- Why mobile device is good for positioning purposes? What are the factors?
- What means of communication (ex. wireless) can be used in context of positioning system
- Battery limitations
- Sensitivity of receivers

3.3.3. Position finding basing on localization system and mobile device model

Localization system choise (system based on beacons)

- Motivation
- Prototype system description
- Mobile device - system interaction description
  - Method of detecting reference points description
  - What are the possibilities to improve positioning on your mobile device?
  - How could the process of installing a localisation system in a mine look like?
  - How the parameters of the environment (corridor height, corridor width, type of rock, type of corridor corridors, presence of other networks operating on similar frequencies (WiFi, GSM (harmonic frequencies)), others) affect reference point signal quality.

3.4. Solution 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.

Provided positioning solution 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 of time after the accident, after which survival rate decreases rapidly [13]. System should work also in case when part of it's infrastructure is not working properly like in case of an accident where some corridors can be destroyed including the positioning system infrastructure.

Ease of maintenance in terms of semi-automated methods for detecting the pitfails or failures and posibility to fix broken positioning infrastrucrture without necessity of involving specialised engineers should be matched. Such requirement can be met for example by simplicity of the positioning system infrastructure or automated configuration methods that makes the infrastructure self-organising itself. Infrastructure should be also scallable as underground installations are likely to be extended during the excavation process. Infrastructure should 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 an requirement that causes the system to be more likely independent from the on-site power supply. Infrastructure can have own power source and set of methods that limits power consumption of its devices. Infrastructure can be also extended by some power harvesting methods such as thermoelectric or piezoelectric generators.

Smartphone must provide energy-efficient solution for exchanging the data with positioning system while there are no battery charging points in underground installations. Smartphone with positioning extension activated should 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.

Solution must be able to provide positioning information in real time manner. Under assumption that user of the system will be walking inside underground installation, there is need to ensure position update frequency of at least one per second. Position of the users should be provided with maximum drift of 10 meters.

Safety purpose of position finding system is very important for many countries [13]. European Union encourages to search for a good solution for the miners 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 localisation but they allows 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 compare 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 enviornment.

Position finding system bases on idea of interaction between mobile device and the undeground envioronment. In case of the nessesity of extension that enviornment by electionic devices that will provide positioning data or means of connection with mine network there is need to state that such devices must be safe. Safety regulations in this matter differs with respect of the type of underground installation, the regional, country, or even association of countries [16]. The goal of this paper is not to provide solution that will be adjusted to each installation type or safety regulation, but to investigate possibilities and propose state of the art solution. As the enviornmental restrictions for devices and related infrastructure that can be needed for given solution there will be assumed general rules that are being in use in commercial tunneling [16].

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 infstratructure 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 scallable in order to extend positioning system with the new corridors,
  - 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.
- 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.

Requirements as the position of the mobile device will be determined by the environment model.

Define criteria that are the basis for position finding solutions comparison (existing or conceptual):

- How to save a corridor model in computer memory
- wireless communication
- resistance to power outages and communications
- Do I need the ability to change configuration of reference points (configuration of devices that perform role of reference points)?
- What parameters can be read from the reference points (range, distance, ?)
- How long should the network work properly?
- How to detect irregularities in reference points?
- How to fix problems in reference points?
- What problems may occur with points of reference?
- If there are restrictions upon existing network topology (ex. in order to get access to servers located on surface)

- ◦ Can the mobile device be useful in case of lack of signal (GSM/Wi-Fi/BLE)?
- ◦ example: accuracy, durability, cost, maintability (energy, fault)

Chapter 4

Mobile device position finding algorithm

* Algorithm that will make use of chosen localization system and mobile device internal sensors.

4.1. Position finding requirements

- Should repeat and answer requirements stated for localization system.
- example:
  - Reading signal and its parameters from reference points;
  - Identification of reference points
  - Current location presentation on the environment model

4.2. Solution architecture

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

- reference system installation based on beacon devices,
- smartphone device with Bluetooth receiver and inertial sensorics (at least accelerometer),
- application for smartphone that process and combines the data from the environment and internal sensorics.

It is assumed that reference points infractructure is mounted in a way that each beacon is denoted in configuration file consisting of a list of beacons with placement position assigned. It is possible to make application more robust and underground installation site undepentent while position information can be provided by reference points itselves. This proposal rely on already defined beacon positionis 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. Proposal system does not include such maintenance feature but it may be an addon into the next release.

The core positioning information is gathered from the reference points. They have constat position and they are the most corelated with the physical layout of under-

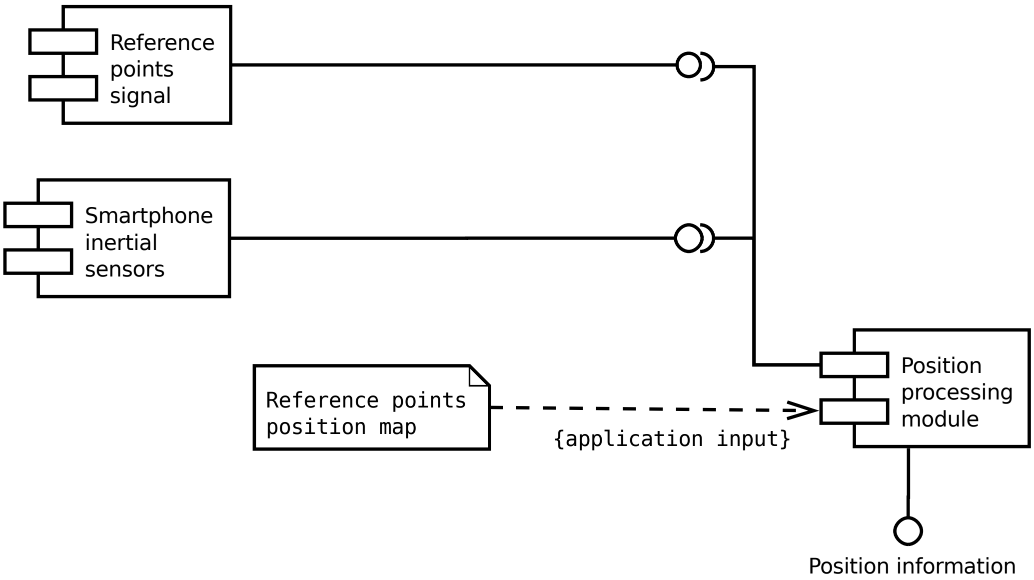

Figure 4.1. General solution architecture. Position processing module gathers data from smartphone sensorics, data and acquired signal parameters from reference points and serves current position as an output.

ground installation. Having only this information it is possible to obtain positioning information as accurate as distance between subsequent beacons mounted on site. In order to make the position more accurate than in case of aligining the smartphone position to the position of the nearest beacon, there can be involved distance model that will allow for distance aproximation basing on the received signal strength value. As the signal strength in a tunnel varies havily there was no such model found or defined yet (refer to the section 3.2). Although there was proposed a solution that make positioning solution more accurate.

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 trasmission parameters assumed:

- beacon will send his advertisement frame once per second,
- beacon will be set up with $-16dBm$ transmitter power or equivalent that ensure beacon coverage of $20m$ in underground environment,
- beacons will be placed in $10m$ distances between each other,
- 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 similiar

($+/-2dBm$) RSSI values among them, the current smarthone position is assumed to be in a half way between beacons with these similiar RSSI values.

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

In proposed solution each beacon is placed in $10m$ gaps. Each beacon is configured to cover distance of maximum $20m$ but minimum of $10m$. Such assumptions causes redundancy where in the perfect scenario user that is staying *immediate* to the beacon is aqcuiring signals also from two other *near* beacons. In case when one of the beacons is not working there is still possibility to align current user position to the place where faulty beacon is mounted. That is possible due to the assumption that if smartphone detect two beacons that are *near* and received signal strength of their advertisement frames are similiar then smartphone is in the middle of the beacons. similiar 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*.

Output of the intertial sensorics can produce missleading position information. For example basing on the accelereometer data only it may turn out that the user have changed direction of the movement while he is still moving forward. It may effect with worsen the positioning information instead of making the position more accurate.

- Simple algorithm will use localization system only (no internal sensors)
- Algorithm will use localization system and internal sensors
- Explain how beacons will interact with the positioning system

4.3. External solution infrastructure

Reference points infrastructure is a vital part of the proposed positioning system. In order to provide realiable reference information there is need ensure that installation is easily maintable, 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 4.2. 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 beggining 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 label and recommeded transmitting power. Such preparation will shorten installation time and will avoid potential problems with missconfiguration.

There is need to mention in this secion

- Beacons choisen as the hardware equipment.

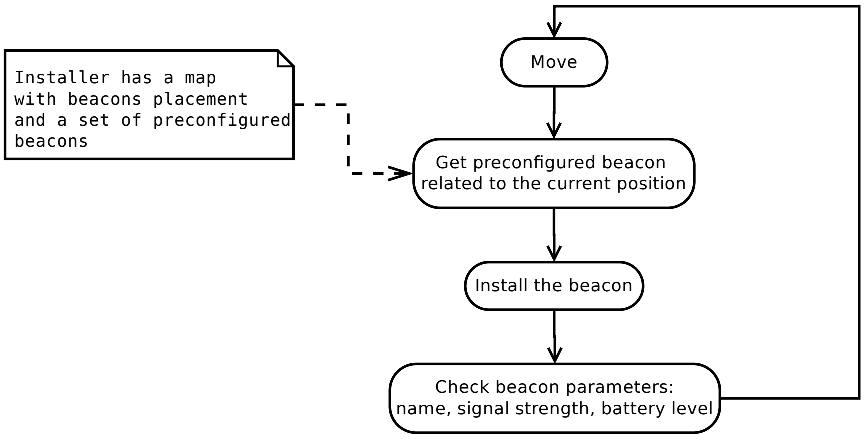

Figure 4.2. Infrastructure installation procedure.

- Constraints assumed - power settings, batteries sizes (capacities), distances, placement, etc
- Draw schematic way of infrastructure placement
- Mention someting about installation and maintenance procedure
- How beacons will be recognisable (names). What other parameters will they contain

4.4. Data processing and analysis

Proposed positioning system depends on inputs from the smartphone's wireless receiver and internal sensorics. Raw data cannot be used directly by the positioning algorithm because of different nature of those signals and the high dirfts and noise levels that affects both wireless transmission and inertial sensorics measures. 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.

- - todo - filtering; sensor fusion

4.5. Position finding algorithm implementation

Description of android framework, project components, problems occured, pitfails and remedies

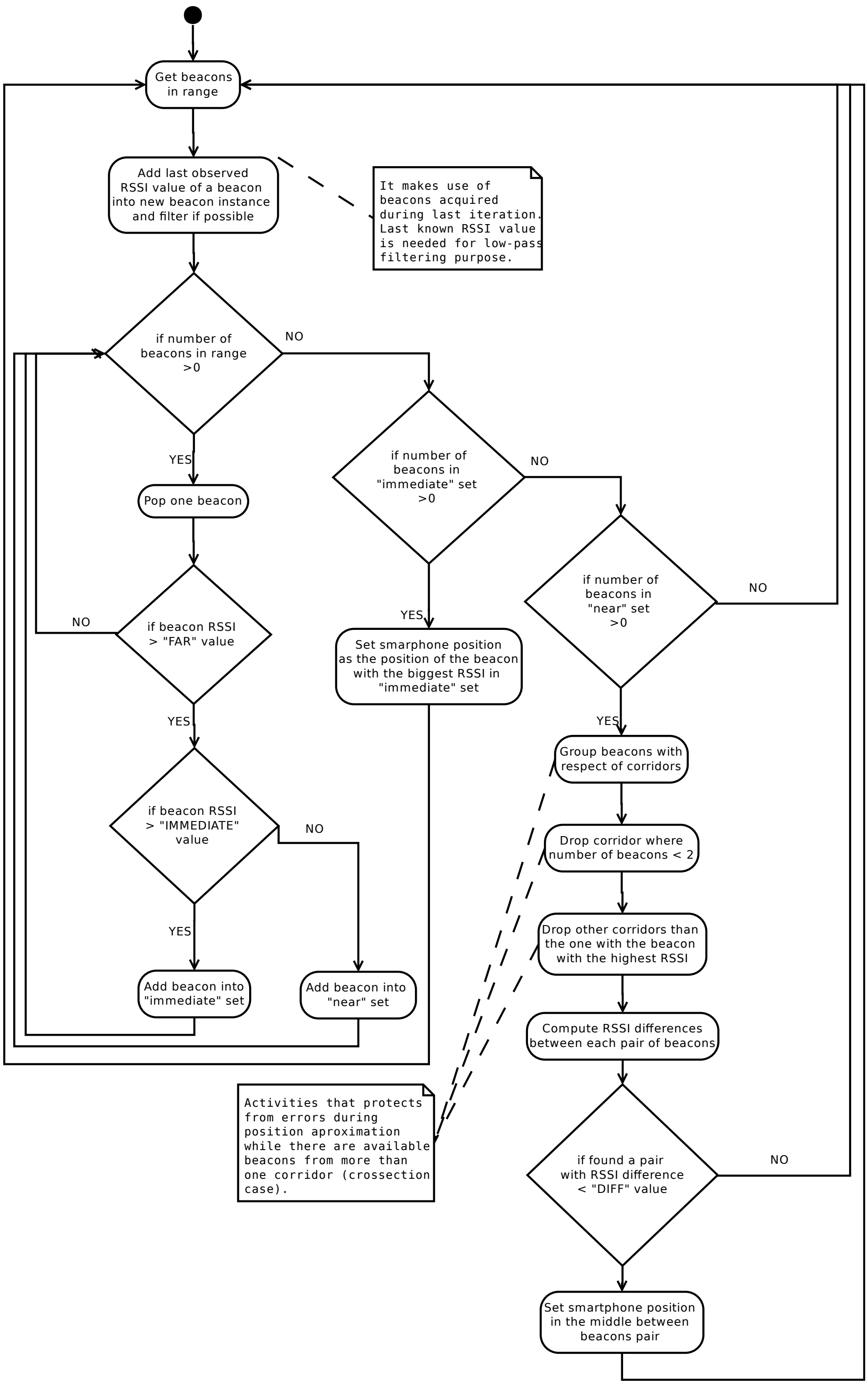

Figure 4.3. Porposed position aligning method based on the received signal strengths from reference points.

Chapter 5

Localization system 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 proposed infrastructure that extends the environment and serve as the referencing system. There were performed tests of inertial navigation part of the solution by reviewing the outcome of the internal sensorics of the chosen smartphone under perspective of thier applicability to the positioning estimation algorithm. Finally there were performed tests the prototype software application that combines both environmental information from the reference points and the inertial navigation in the real environment, in 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 orientation,
- smartphone model,
- transmitter type,
- transmitter power,
- transmitter placement,
- transmitter antenna direction,
- distance between transmitters.

Those factors were assumed that impacts the final received signal strength value.

According to *Log-distance path loss model* [20] the distance between receiver and transmitter is the major factor that impacts on the signal strength. There was need to check how distance impacts on the signal strength in the desired environment in the underground corridor.

As the Beacon operates on the 2,4 GHz fequency then it is assumed that all of the transmission path elements can impact on the resultant power strength. 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 oposite 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 envioronment directional antennas do not increase usable coverage as well as sector anntennas [16].

As the proposed solution have to be applicable for different models of Smartphone devices it is not acceptable to force users to held their devices in a given position with respect of the direction of the Bluetooth antennas build into them. Producents are free in terms of designing the Smartphones main boards including the antennas placement. Such informations are not published. Even having the possibility to open the device and look for the antenna it is diffcult 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. In case of Beacon 1 and 3 there are mounted meander monopol antennas, in case of Beacon 2 there is mounted called meander "IFA" – *Inverted-F antenna*, in case of Beacon 4 antenna is not visible on the picture.

There are a few big microcontroller producents on the market that offers compound units having integrated computational resources, programming busses and data exchange solutions including Bluetooth Low Energy wireless module. The main three competitors are Nordic Semicondutor with NRF chips, Dialog Semicondutor with DA chips and Texas Instruments with TI and CC chips. They compete on fields of power consumtion, usability in terms of set of integrated modules, computational power and permament storage size of their products. Those integrated circuts are used by Beacon producents as the main processing units with implemented Bluetooth protocols and stack and set of profiles that allows the users to configure Beacon parameters such as name or transmitter power and get information from extra sensorincs measures build into the Beacon like temperature or battery level. Integrated circuts are the part of PCB which also contains a battery slot, power circut and antenna circut. For tests there were chosen Beacons offered by the various producents form China thus their products were easily available via the Internet and they were cheaper than from producents from Europe or U.S. like Estimote or Texas Instruments[21]. Aim of tests with different Beacons was to check how much 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 $B2$),

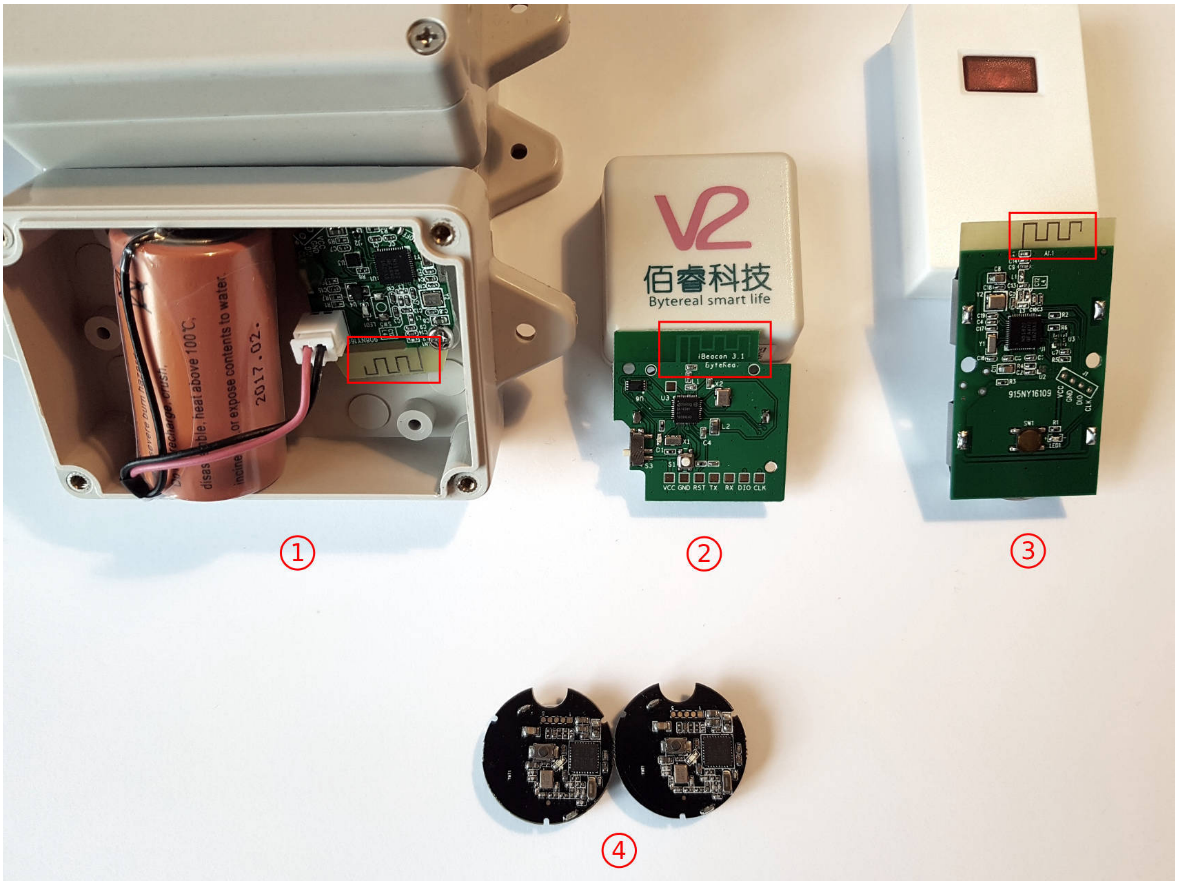

Figure 5.1. Beacons transmitters used during tests. Beacon 1 is a Wellcore procduct based on Nordic Semiconductor NRF51822 chip, Beacon 2 is a ByteReal product based on Dialog Semiconductor DA14580 chip, Beacon 3 is a Wellcore product based on Nordic NRF51822 chip, Beacon 4 is a Radioland product based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

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 consideration: 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 smarphone devices: Samsung Galaxy S7 and Blackberry Z10. Samsung is equiped with Bluetooth 4.1 while Blackberry is equiped with Bluetooth 4.0. The aim of this test was to compare the result in order to check how different construction impact on the received signal strength. There was need to verify assumption about having defined constraint values on received signal that regardless the smartphone model will allow to qualify distance from signal source basing on acquired signal value.

Hardware tests were designed in a manner that each of those factors were tested separately. 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 corrdor 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 on the signal attenuation curve where user is and is not an obstacle between transmitter and smartphone.
6. Test how different antenna orientations of transmitter mounted on ceiling impacts on signal attenuation curve. Tested vertical and horizontal orientations.
7. Test how different antenna orientations of transmitter mounted on wall impacts on signal attenuation curve. Tested vertical and horizontal orientations.
8. Test how beacons from different vendors impacts on the signal attenuation curve. For this test beacons transmitting power was adjusted in order to obtain similiar signal gain on the radio path.
9. Test how different smartphone models impact on 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 XVIII century exchavation corridor which is available for sighseeing as a part of Stara Kopalnia museum in Walbrzych in Poland. Corridor used during tests is placed 10 m bellow the ground and it is 185,7 m long. Corridor is 3,2 m high and 3,2 m wide. Corridors goes up on it's north side so this part of the corridor was used only once during line of sight test case. There is also one "T" shaped crossection with a similiar corridor that is 157 m meter length.

During the tests in the corridor there was 10°C and 71% of humadity. In order to avoid diffractions from corridors endings, transmitters were placed in the middle of the corridor at it's 90 m.

During the test there was used

- 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.

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 advertisment frame, which were then written into log files from the signal recording sessions.

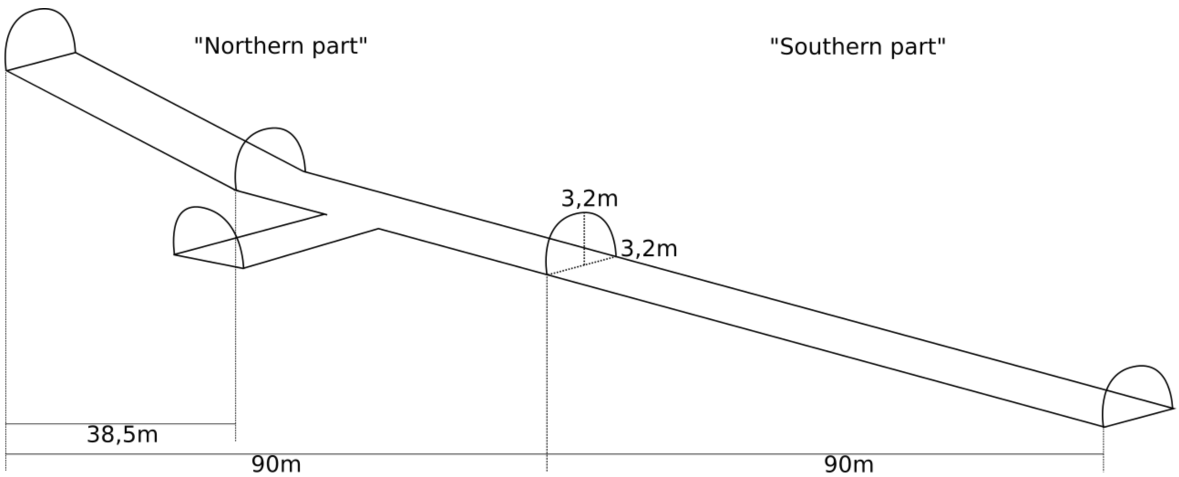

Figure 5.2. Test place scheme.

- Testing environment descipription
- Equimpent used during tests. Example:
  - using a representative wifi router, 801.11g techonology, simple circular antenna (eg Minetronics MMG) - for charts.
  - using a representative beacon
  - dBm signal strength depending on the distance and polarity of the mobile device from the signal source
- Pictures

5.3. Tests of system and basic algorithm

- Check if system works with basic algorithm
- Tests in few configurations
- State if some factors have impact on signal quality
- State if some factors have impact on position finding

5.4. Tests of extended algorithm

Capture data that will be base for comparison between simple and extended position finding algorithm accuracy.

5.5. Experiments results

Resluts with analysis.

5.6. Tests summary

Chapter 6

Conclusions

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