Indoor Localization

White Paper

An Indoor Localization System, also called Indoor Positioning System (IPS) or Real-time Location System (RTLS) is like a GPS, but for indoor environments.

Because GPS receivers cannot receive the transmitted GPS signals from satellites indoors, the receivers cannot locate themselves. This is different in indoor localization systems. An indoor localization system has its own "satellites" which are often called "anchors". The mobile receivers are called "tags" and can locate their position based on the available anchors inside the buildings. Each person or object carrying a tag can be localized.

This paper draws typical applications for indoor localization systems and explains the localization technologies and their differences in detail. It compares existing indoor location systems and helps the reader to select the best technology for his application.

Localino
Solutions for indoor localization

Dr. Steffen Heuel, May 2018

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1. Typical applications for indoor localization

Indoor localization systems are useful in any application where a position of a person, a device or robot is of interest. Many indoor localization systems are for example applied in shopping malls, hospitals, airports, logistics, sports, farming or robotics. This variety of applications request different technical realizations. This can range from single objects, that require high speed positioning, to many objects with extremely low position update rates, but long battery lifetime. Also the accuracy of the desired indoor location is important.

The application and desired localization accuracy mostly defines the technology to be selected. It is therefore important to know which requirements the application demands. From these requirements, conclusions can be drawn to select an appropriate technology with all its features and constraints. As always in engineering, unfortunately there is most likely not **the** technology which can do all.

Retail Analytics

In shopping malls and retail stores customer motions and behaviors are tracked by using their recorded indoor positions for data analysis. Intelligent software counts customers, offers customer flows, motion maps, heatmaps, point-of-sale analytics and even demand management which can be based on indoor localization systems.

Industry 4.0 and Logistics

Information about the exact positions, speeds, and tracks of forklifts, vehicles or operators at any time in your production facility or warehouse is a valuable piece of information to analyze traffic and identify workflow bottlenecks to save time and money. But not only traffic analysis becomes possible, also access control to certain areas, navigation to relevant positions with new tasks on optimized routes can reduces time and improve efficiency.

Sports

In any sport precise localization and tracks of players are of interest to analyze players, record their motion and just monitor their performance over a certain period. Specific optimizations can be drawn even during the game, when real-time data is available and the trainer realizes a player is not in focus.

Healthcare and assisted living

Hundreds of million euros are lost every year due to search and loss of equipment, like monitors, wheelchairs, beds, etc. By tracking the location of equipment searching is reduced to a minimum and purchasing decisions can be evidence based. Also a continuous log of patient - caregiver interactions, from continuous improvement to litigation or compliance can be covered by a RTLS. Even a patient can be located quickly for medication, staff routines, when his family wants to pay a visit and he is gone somewhere else, or even to alert staff immediately if he left the facility. A localization system improves the efficiency in your daily job and increases comfort and security in healthcare and assisted living.

2. Technologies

There are different technologies available, which allow estimating the indoor position of a person or an object. Depending on the requirements like accuracy, battery lifetime, corporative/non-corporative systems, positioning update rate, maximum range, etc. one technology is more attractive for the end user then another.

In general, indoor positions are estimated by using radio frequency signals from different sources, such as Wifi, Bluetooth, RFID or Ultra-wideband Systems. These radio signals mainly allow the estimation of the distance of a tag to one or several distributed anchors / RF sources. Special anchors have multiple coherent receivers build-in from which angular information can be estimated. The distance information is drawn from a physical value, either RSSI (received signal strength indicator), TOA (time of arrival), TDOA (time difference of arrival) or AOA (angle of arrival) techniques.

While most approaches like Wifi, Bluetooth, RFID are based on RSSI measurements, Ultra-Wideband (UWB) allows to measure time accurately.

This paper does not introduce sensors like radar, lidar, ultrasonic devices which are dedicated to detect and measure range, angle and radial velocity of an object, but rather focuses on collaborative devices emitting radio frequency signals.

2.1. Wifi and Bluetooth

Indoor positioning systems that make use of present Wifi or Bluetooth (Bluetooth Low Energy (BLE)) signals at 2.4 GHz (or 5 GHz (Wifi)) frequency measure the radio frequency signal strength indicator (RSSI) at the receiver. As the attenuation of radio waves is proportional to its distance, the distance of an object to the receiver can be estimated. Using several of these sources, a receiver can estimate its position in space using triangulation methods or fingerprinting.

When using Bluetooth for indoor localization, the devices (also called beacons) transmit radio signals in regular intervals. Each beacon has an unique ID, name (optional) and calibrated RSSI level either in 1 m or 0 m distance (depends on beacon type, e.g. Eddystone beacon) which is broadcasted. Once a mobile phone or dedicated BLE-tag receives these signals it can estimate the distance to each of them based on a signal propagation formula. Due to lower transmission power Bluetooth has less maximum range (< 50 m).

Wifi localization operates on the same RSSI principle. Unfortunately, there is no standard implemented in the Wifi protocol, which allows timing based localization. As of today (2018) Wifi is optimized for data throughput and not for localization purposes. The maximum range that Wifi can reliably cover is in the domain of 100 m depending on the infrastructure and space.

Some publications show that the channel state information (CSI) Wifi of the physical layer can be used for localization techniques. The CSI can be more accurate, but requires access to the physical layer information, which is usually only available inside the Wifi chip.

Due to radio signal propagation effects (fading) the attenuation of a radio link is not always constant, this is why the received signal strength varies quite an amount. This causes also the distance measurement to vary, which then results in less accurate estimated indoor positions.

Several different techniques, such as "fingerprinting", try to improve accuracy by reducing the physical effect of signal propagation variation by measuring the signal strength at each particular position in space and store this as a reference point inside a database. However, this calibration is complicated and needs to be performed every time the radio channel changes (which is quite often).

The accuracy of the RSSI technique is in the domain of 5m - 15m.

2.2. RFID

In the 1980s commercial RFID (Radio frequency identification) products came to market and - available for everyone - this hardware was being utilized not only in supply chains, transport, access control or toll roads, but also in indoor localization. In general, the RFID system can operate as an active, passive or semi-passive system. Similar to other indoor localization approaches, there are anchors and tags. In an RFID system a *tag* is also called a *transponder* or *label*. *Anchors* are referred to as *readers*, *decoders*, *transmitters* or *transceivers*.

An RFID tag is used to wirelessly transmit information, for example a unique serial number. Considering a passive RFID system, a reader would transmit a wireless signal to a tag, which "utilizes the energy in the air" to transmit a certain response. The reader provides the power source for the tag in this case. The higher the output power and the more directive the antenna of the reader, the longer the distance that a tag can be read out. Due to power restrictions, passive RFID systems are usually only very short-range applications.

In an active RFID system, the tag operates as an active transmitter. The build in battery powers the tag, which periodically transmits messages that are used for localization.

RFID systems have different RF spectrum regions where they are allowed to operate. Depending on the choice of application, desired maximum distances, ability to be read close to metal obstacles, an active or passive system operating at

433 / 860 MHz or 2.4 GHz / 5.7 GHz is favorable. A 2.4 GHz system has smaller size, but shorter ranges compared to UHF frequencies at ISM bands 433 MHz / 860 MHz.

Just as Wifi or Bluetooth indoor localization, RFID readers estimate the received signal strength of a tag and estimate the distance. Variable signal strength caused for example by multipath-effects causes the system to be relatively inaccurate compared to timing-based indoor localization systems.

Depending on the receiver hardware additional phase-coherent receive channels can be used to utilize the phase information of the incoming radio signal. From the phase information, the direction of arrival (DoA, angle of arrival AoA) can be estimated. An enhanced system with several RFID receivers and multi receiver channels is able to perform direction estimation and increase accuracy compared to RSSI (received signal strength indicator) based systems.

The accuracy of RFID is relatively good in very short range applications. In long range applications, accuracies get worse.

2.3. UWB

Ultra-wideband (UWB) defines a signal, which occupies more than 25% of the bandwidth compared to its carrier frequency. The term is also used for signals with large instantaneous bandwidth that are operational at carrier frequencies at 3.1 GHz to 10.6 GHz with extremely low power. In indoor localization an impulse Ultra-wideband signal is used as it has high precision due to the large instantaneous bandwidth and high time resolution.

This allows measuring timing delays between transmission and reception of pulse signals very accurately even though these are travelling at speed of light with 300.000 km/second. Additional processing techniques estimate the line of sight (LOS) and non-line of sight (NLOS) (even though this effect is rather small) components of a single distance measurement, which improves accuracy even further.

Compared to the RSSI based localization systems, UWB utilizes a time-based approach. The accuracy depends mainly on the timing accuracy and stability, but also on signal to noise ratio, propagation delay of antennas etc. Accurate systems reach positioning accuracies of 0.1 m.

According to the standard a spectral density of -41.3 dBm/MHz is allowed. Using a 500 MHz wide signal and a receiver sensitivity of approximately -100 dBm one can estimate the free space propagation loss or link budget.

Compared to Wifi or BLE, the relatively low output power of UWB signals causes the maximum range to be more limited. Serious indoor installations can reach up to 20-100 m line of sight (LOS) conditions.

2.4. Comparison

A fair comparison of these technologies is not straight forward, as we compare different measurement methods and setups for a single application. However, for a comparison of these indoor localization techniques we look at parameters such as

- positioning accuracy,
- battery lifetime,
- active or passive tags,
- scalability to large spaces and many rooms,
- integration effort,
- requirement of synchronization using cables,
- requirement of master control nodes,
- number of trackable devices,
- price

Depending on the application this leads to one or the other technique.

Due to the fact that Wifi, Bluetooth and RFID were not intentionally designed for indoor localization purposes, but rather for data throughput and information exchange, these systems estimated distances to tags mainly RSS-based. These systems do a good job when localization should be offered in addition and it does not matter when being inaccurate or offset 5 - 15 meter.

In addition, if non-cooperative Wifi or BLE devices are used for localization, one has to make sure they broadcast their MAC address on a regular basis. This is done by Android devices every some seconds (to the knowledge of the author). Apple devices only broadcast their MAC address when searching for Wifi accesspoints, which is done on activation of the display (to the knowledge of the author). This behavior depends on the operating system and may change between firmware updates of the mobile device. Unfortunately, the user has no/less influence on this behavior and software updates may cause devices not to function anymore.

UWB is dedicated to localization and the exchange and generation of exact timing data that can be used to estimate distances between UWB devices with range accuracies of < 10 cm. If accuracy is of major interest, UWB is your choice.

This white paper draws a comparison of localization systems based on several distributed anchors using a single antenna only that receive signals from mobile tags. The system operates in a server based environment, where the location is available in a PC application and not at the tag.

	Wifi	Bluetooth	Passive RFID	Active RFID	UWB
Accuracy [m]	< 15	< 10	< 0.1	< 3	< 0.3
Range[m]	<10	<50	< 1	< 5…30	<100
Battery lifetime	Medium (weeks – months)	High (years)		High (years)	Low-medium (days-month)
Number of tags per area	High	High	Low	Medium	Low-high
Scalability to large spaces	Medium	Medium	Easy	Medium	Complex
Price	$$	$$	$	$$$$	$$$

3. Localization principles

After the description of several different high frequency based technologies for indoor localization the distance and angle measurement is explained in more detail. Besides that, the distance / angle measurement from a satellite (anchor) to a specific tag is only enabling the position estimation. It is necessary to have several anchors measuring the distances to a tag in order to estimate the position in two- or three dimensional space.

3.1. Distance and angle measurement

There are several different physical principles that are being used to estimate the distance between devices and from there locate the two-dimensional (XY) position or even three-dimensional (XYZ) position of an object indoors. This section names just the most common distance measurement principles and explains them briefly.

RSSI

The received signal strength indicator (RSSI) can be used to estimate the distance from a transmitter to the receiver.

Theoretically the receive signal strength decreases quadratically with distance as shown in the figure below. Due to fluctuation of the radio channel caused by any small changes like obstruction, multi-path propagation, occlusion, change in polarization of devices etc., the receive signal strength can vary quite an amount of level. This causes great changes in the estimated distance in turn, especially when the signal strength level is low anyway. Wifi and BLE beacons usually use RSSI to estimate the distance between a device and transmitter.

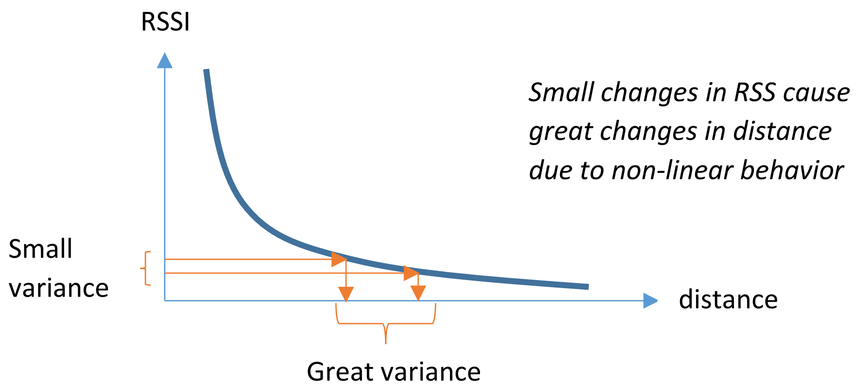


Figure 1: RSSI measurement

The time of arrival / time difference of arrival make use of the physical property of speed of light to estimate the distance between devices. Therefore the transmit time and receive time have to be know very accurately as the speed of light is approx. 3*10^8 m/s. Any nanosecond inaccuracy in the time sampling will already cause 30 cm of distance error.

Symmetrical Two-way ranging (TWR)

Two-way ranging makes use of time of flight between transmission and reception between the anchor and tag. As the electromagnetic waves travel with the speed of light high resolution timestamps are required.

To measure distance between anchor and tag, one of the devices has to initialize a message exchange. In the example displayed in Figure 1 the anchor sends an INIT message to the tag and records the time of transmission. The tag replys to the anchor within a certain time. Upon receive of the tag answer, the anchor can compute the time difference between transmission and reception. Based on this time the distance between anchor and tag can be estimated.

TWR reduces the error and time drift between anchor and tag distance estimation. This way each anchor can measure the time difference of arrival between transmission of its own signal and the reception of the answer of the tag.

Angle of arrival

With several phase coherent receivers the phase difference of an incoming planar wave can be estimated. The angle of arrival (AoA) is proportional to the phase difference. With a known aperture and distance between the receive antennas the angle of arrival can be calculated. Hence a single anchor with several receive antennas would measure direction and distance of a single tag. The accuracy of AoA depends on several factors, such as accuracy of the aperture, phase center accuracy, receive path calibration, signal to noise ratio of the signal, phase noise. Accuracies of several degree are possible with two channel receivers.

Comparison

Based on the chosen technique a range and direction estimation scheme can be selected. The advantages and disadvantages are compared below.

Scheme	Advantages	Challenges
Received Receive Signal Strength Indicator (RSSI)	no time sync required, no timestamps necessary, easy implementation, “free” range information from standard devices using Wifi, Bluetooth, RFID	Line of sight is assumed, propagation channel and loss has to be known very accurately, accuracy approx. 5m - 15 m
Time of Arrival (ToA)	Good accuracy, much better accuracy compared to RSSI,	Time synchronization across all receiver nodes is required.

Time difference of arrival (TDoA)	Long battery lifetime (longer than TWR)	Synchronization is done by cables between nodes (wireless sync is possible but less accurate) Accuracy is lower compared to TWR approx. 0.1m -0.5m
Two way ranging (TWR)	Higher accuracy compared to TDOA and TOA, no time synchronization between anchors required	Battery lifetime is lower compared to TDOA Accuracy approx. 0.1m - 0.3m
Angle of Arrival (AoA)	two phase coherent required, no time sync required (if using TWR in addition), additional angle information	Higher cost compared to single channel receivers

The mentioned algorithms estimate the range (and maybe also direction when using AoA) of a device to a specific anchor. The 2D or 3D positioning itself is based on trilateration or multi-lateration for timing-based systems. RSSI-based systems make use of fingerprinting or cell-of-origin methods are preferred, but lateration methods would also be possible.

3.2. Position estimation

In a trilateration system the intersection point of three range measurements from three anchors to a single tag is estimated. The higher the accuracy of the range measurements, the more defined the intersection - and hence of the 2D position. In case four anchors are used, the fourth range measurement can be used to estimate the height of the tag in case the reporting anchor is located at a different height as well. However, the height component is typically less accurate compared to the two-dimensional x- and y- coordinates.

The figure below shows the triangulation estimation. It is essential to know the position of the three anchors (green, yellow, blue). By measuring the distances r1, r2, r3 from each unique anchor to the unique tag, the intersection of three circles can be calculated.

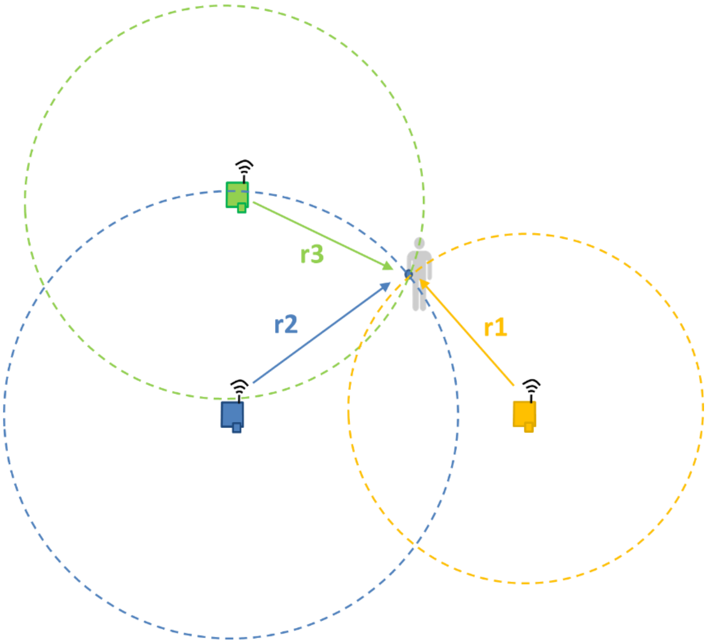


Figure 2: Trilateration

For fingerprinting principles a database / map of the environment with the RSSI levels from several anchors is linked to exact a-priori known positions. This data has to be recoded beforehand with a reference receiver. Therefore the environment is separated into grids, where each grid stores the power level values of the beacons / transmitters from which a signal is received (see figure below). This data is stored in a database. Now if a tag receives the different RSSI levels from all anchors it can compare these values to the database. The database has to be updated continuously, which is essential for measurement results. Also as receive strength can vary quite an amount because it depends on the tag antenna, housing, facing direction, environment etc. the inaccuracy of this approach can be quiet significant.

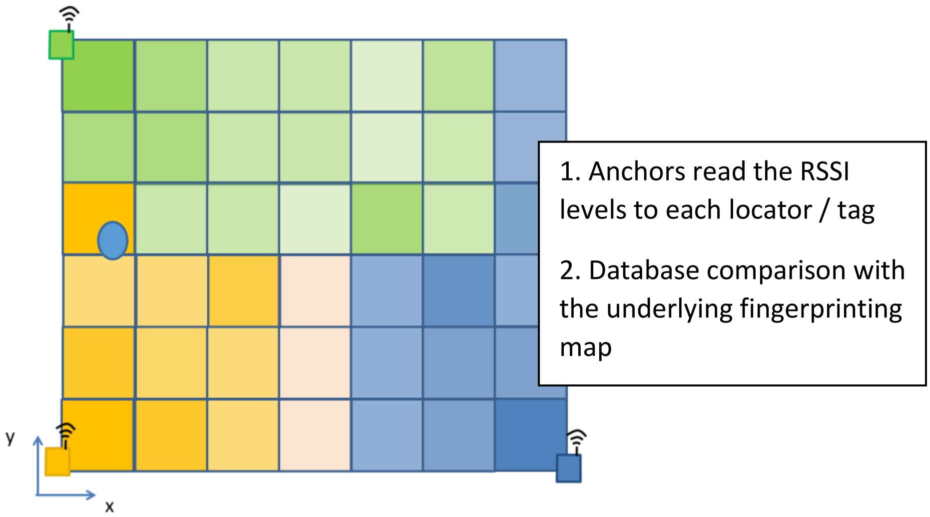


Figure 3: Fingerprinting map

4. Localino Indoor Localization

Localino indoor localization uses ultra-wideband (UWB) signals to locate a tag inside buildings. The anchors have additional Wifi capability onboard to minimize cabling efforts. Wifi can operate as a backhaul to send the estimated position data to a PC application. Localino can also operate without Wifi in case you cannot add additional Wifi transmitters in your environment.

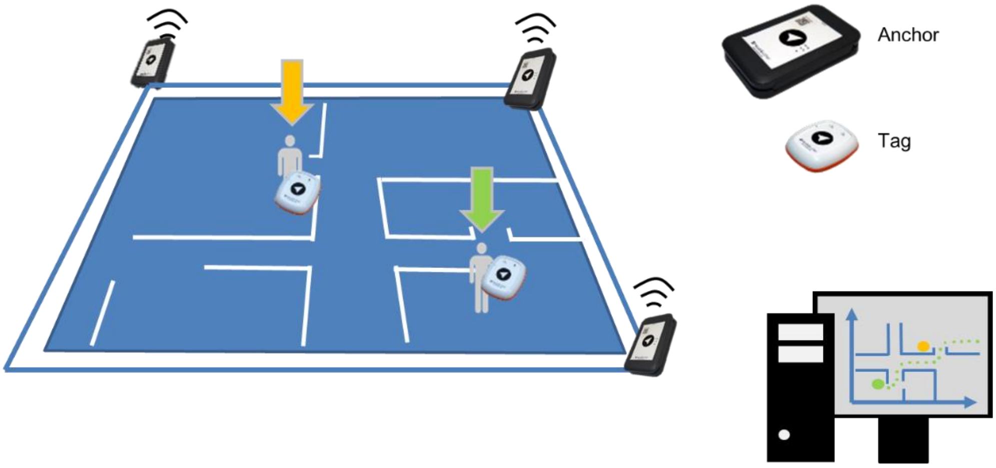
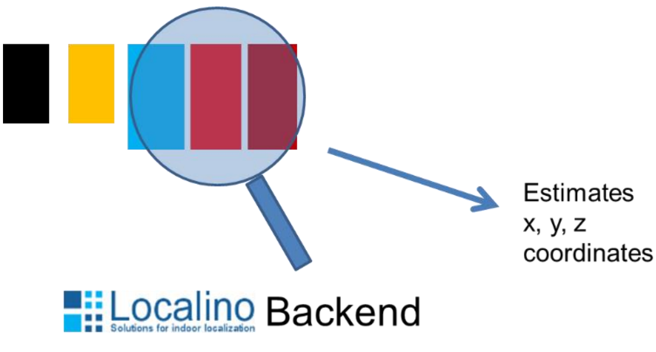


Figure 4: Localino setup

Backend and Frontend

The anchors measure the distance to each of the tags and send the information to the **Localino backend** application, which processes the datapackets and estimates the position of the tag.



An optional **Localino frontend** allows configuration of the backend, add and move the anchor positions and show the position of the tags on a floorplan etc. The frontend is not required for Localino operation. The backend can also be configured via a text editor. It is a standalone application that retrieves the raw data from the anchors and estimates the position in space, which is again broadcasted into the local network.

This allows the user to tailor his application without the need of a complex overhead.

Accuracy

The accuracy of Localino is in centimeter range. While range measurements are as accurate < 0.1 m in line of sight conditions, positioning with three anchors is approximately 0.3 m accurate. The accuracy can be improved significantly when using additional anchors.

Figure 5 shows the accuracy of three tags in a room of 4m x 4m measured with four anchors. The standard deviation of the measurements are less than 2 cm.

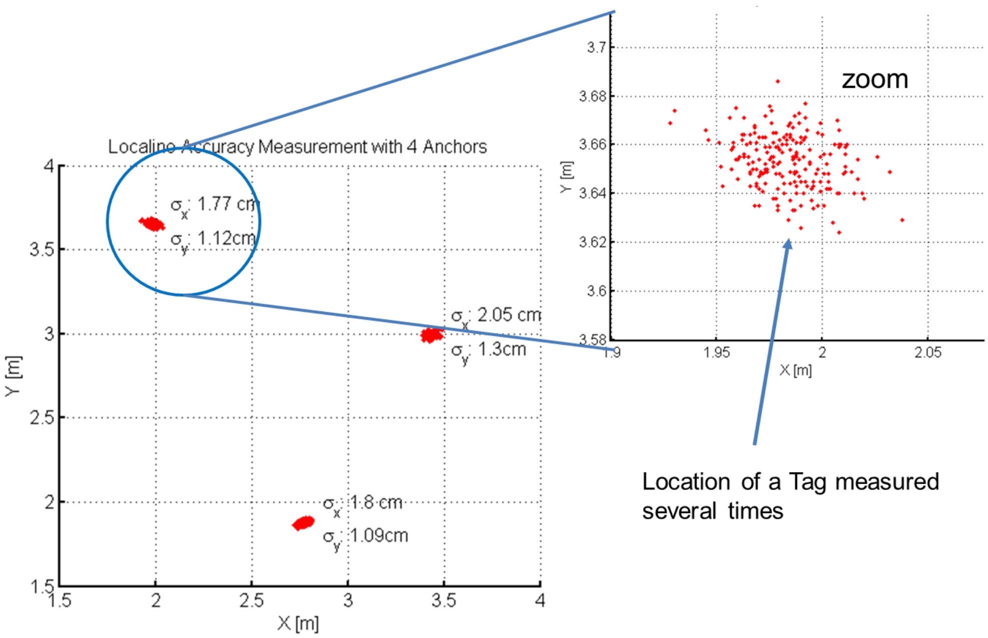


Figure 5: Localino accuracy, short range mode, 4 anchors, 3 tags in LOS

Battery Lifetime

The battery lifetime of a tag depends on several factors. Main driver for power consumption is signal transmission duration, which depends on the mode, e.g. long range or short range (high density mode), localization scheme (TWR or TDoA) and positioning update rates.

Localino tags are active devices and can localize themselves about 300.000 – 600.000 times with a single 100 mAh rechargeable battery. This means, using a positioning update rate of 1 second Localino tags will last several days (measured). Slower update rates increase the battery lifetime, e.g. with a 10 second update rate a tag lasts several month (measured).

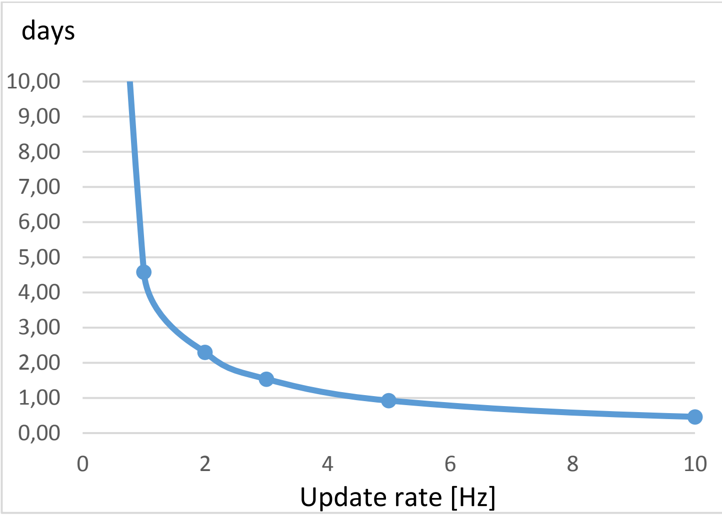


Figure 6: Typical battery lifetime, Localino tag, short range mode, 100 mAh rechargeable battery

Figure 6 shows the typical battery lifetime of a Localino tag in short range mode when using a single 100 mAh rechargeable battery. Batteries with higher capacity will increase the tag lifetime, for example when using 500 mAh, the tags will last 5 times as long.

Scalability to large spaces

Due to its scalability, Localino can cover arbitrary rooms, buildings, stores, factories, etc. and does not need to be synchronized to a master system or does not need any Ethernet or synchronization cables. Therefore, easy deployment is possible.

Even exchange of a single anchor or extension of a device during operation of the system is possible.

The anchors can wirelessly be configured using a **Localino Configuration Bridge**.

Number of tags

Localino can locate an arbitrary number of tags in principle. The tags are not located at exactly the same time. This would cause the anchors to get confused. Our smart control algorithm mitigates this challenge such that as much tags as possible can be located as fast as possible.

Abbreviations

RF – Radio frequency

RSSI – Radio Signal Strength Indicator

Wifi – Wireless LAN

BLE – Bluetooth Low Energy

UWB – Ultra Wideband

TWR – two-way ranging

TDoA – Time Difference of Arrival

AoA – Angle of Arrival

ToA – Time of Arrival

LOS – line of sight, the radio signal of a tag can reach an anchor on a direct path.

NLOS – non-line of sight, the radio signal of a tag cannot reach an anchor on a direct path. Often the radio signal is reflected somewhere, for example at a metal wall, which causes the distance to be greater compared to a LOS condition. NLOS conditions can lead to higher inaccuracy.

Heuel & Löher

Localino is a product of Heuel & Löher GmbH & Co. KG. Since its foundation in 2015, we have been constantly improving our products. With our experience in diverse technical areas, we are the partner of choice for your individual requirements. Continuous enhancement and further development of our products is important for us. Thanks to our qualified staff and thanks to our development partners, we can optimally adapt localization systems to your needs.

The company is headquartered in Lennestadt, Germany.

Heuel & Löher GmbH & Co KG

Dr. Arnoldi Str. 38

57368 Lennestadt

mail: info@localino.net

web: www.localino.net

Solutions for indoor localization