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GPS FREE GEOLOCATION IN LORA NETWORKS

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I. Summary

Internet of Things (IoT) has been growing over the last few years in multiple applications and due to a growing need for geolocation and tracking capabilities, an innovative opportunity arises. Whereas geolocation is traditionally based on GPS units this project focus on a analyzing, design and implementation of a LoRaWAN tracking system which is capable exploiting transmitted packages to calculate the current position without the use of GPS or GSM. This is done using the low power technology LoRa where the geolocation is calculated applying algorithms on the gateways timestamps from received packages. In this scenario the whole system consisted of an end-node, gateways, a server and a C# application to store the obtained data in an Excel database. Two implemented algorithms called Nearest Neighbor localization (NNL) and Weighted Nearest Neighbor localization (WNNL) with their final diagrams, shows that the error (distance) calculated by assigning the position to the nearest base station position is not the best solution for all cases, in some cases it has the minimum error compare to the other solution like weighted nearest inversely proportional to the time of the arrivals as well as in some other cases weighted nearest has better (less) error, but both algorithm are not enough to know the exact location of the sensors due to the existence of different source of errors in the row data collected from installed infrastructures .Also to figure out that the all received dataset has good accuracy that allows to have correct location estimation, distance versus time correlation for all sets of the message payloads and their relatives gateways for each sensor type was computed. Results shows that due to the different environmental phenomena that affects the received signals intensity and time together with the problem of gateway synchronization and in consequences the dataset accuracy, we did not get the accurate localization form our deployment infrastructure which leads to the unacceptable errors in unknown position estimation.

II. Introduction

GPS-free Geolocation using LoRa in Low-Power WANs

Nowadays, tracking system in outdoor environments is mainly done using Global Navigation Satellite Systems (GNSS) receivers [1]. GNSS type receivers are also used in other application for tracking pets or wildlife. Currently, there are affordable GPS receivers available on the market, but their main problem is their battery lifetime and need to be recharged every few days. The current consumption of a GPS receiver is about 30-50 mA, which is considerable more energy required by most low power IoT devices. For instance, a LoRaWAN module operating in the 868 MHz band consumes 2.8 mA, in the “on” state, 38.9 mA transmitting data and 14.2 mA receiving data [2]. Therefore, the motivation of this work arises from the need of designing a low-power consumption system allowing geopositioning without using GPS and GSM. At this point, LoRa plays an important role due to its interesting features and also to the new innovative applications that are growing. A low-cost device enabling geopositioning with a long battery lifetime would be useful for securing successful tracking. LoRaWAN presents interesting features, so it becomes a powerful technology in geolocation applications. For instance, the long range that can be reached, up to 15 km in rural areas and 5 km in urban areas due to the good sensitivity of the receivers (-136 dBm) [2] [3]. Consequently, the total path of the link budget could reach up to 150 dB, assuming the maximum transmitted power of 14 dBm [2]. Another interesting characteristic is the bandwidth, which is bigger than other IoT technologies in LPWANs, so it is better to distinguish different paths from the same signal (useful for tracking capabilities in urban scenarios where reflections are present) [4].Finally, LoRaWAN is an open source technology, there is information about its implementation, layers, packet structure, protocols of communications and other relevant features. The LoRaWAN protocol is defined and standardized by the LoRa Alliance.

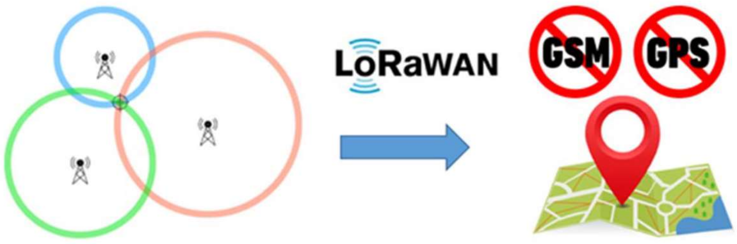


Fig. II-1. LoRaWAN geolocation. No GPS or GSM units were used.

1. Technical overview of LoRa and LoRaWAN

In this context, it is an important to distinguish the difference between LoRa and LoRaWAN. On one hand, LoRa is a modulation based on a variation of chirp spread spectrum (CSS) with integrated Forward Error Correction (FEC) [5]. Therefore, it uses the entire channel bandwidth to broadcast a signal, making it robust to channel noise and resistant to multipath, fading and the Doppler effect, even at low power. In the CSS modulation, 6 spreading factors (SF) are defined, from SF = 7 to SF = 12, that ensure orthogonal transmissions at different data rates. On the other hand, LoRaWAN is a media access control (MAC) protocol designed to allow low-powered devices to communicate with Internet connected applications over LPWAN. It is fully bidirectional and was architected by security experts to ensure reliability and safety [6]. LoRaWAN can be mapped to the second and third layer of the OSI model, on top of LoRa modulation. Low–Power, Wide-Area Networks (LPWAN) are projected to support a major portion of the billions of devices forecasted for the Internet of Things (IoT). LoRaWAN™ is designed from the bottom up to optimize LPWANs for battery lifetime, capacity, range, and cost.

1.1. WHAT IS LoRa®? LoRa® is the physical layer or the wireless modulation utilized to create the long range communication link. Many legacy wireless systems use frequency shifting keying (FSK) modulation as the physical layer because it is a very efficient modulation for achieving low power. LoRa® is based on chirp spread spectrum modulation, which maintains the same low power characteristics as FSK modulation but significantly increases the communication range. Chirp spread spectrum has been used in military and space communication for decades due to the long communication distances that can be achieved and robustness to interference, but LoRa® is the first low cost implementation for commercial usage. The advantage of LoRa® is in the technology's long range capability. A single gateway or base station can cover entire cities or hundreds of square kilometers. Range highly depends on the environment or obstructions in a given location, but LoRa® and LoRaWAN™ have a link budget greater than any other standardized communication technology. The link budget, typically given in decibels (dB), is the primary factor in determining the range in a given environment.

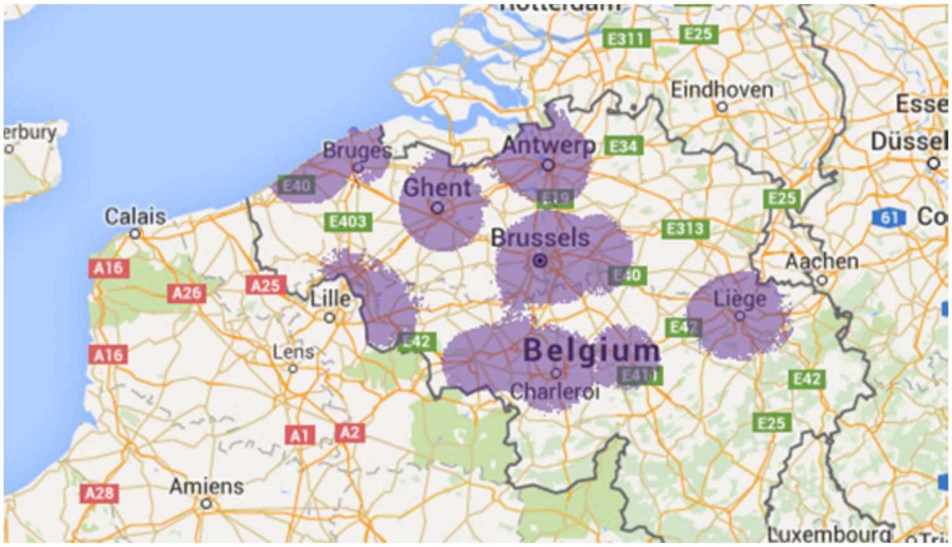
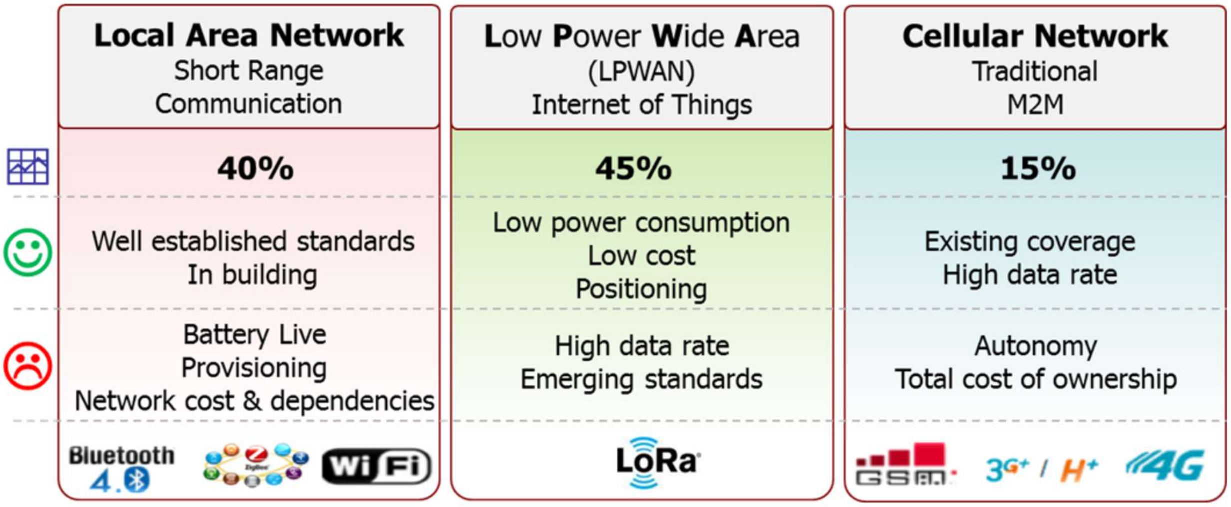


Fig. 1-1. Proximus network deployed in Belgium. With a minimal amount of infrastructure, Entire countries can easily be covered.

One technology cannot serve all of the projected applications and volumes for IoT. WiFi and BTLE are widely adopted standards and serve the applications related to communicating personal devices quite well. Cellular technology is a great fit for applications that need high data throughput and have a power source. LPWAN offers multi-year battery lifetime and is designed for sensors and applications that need to send small amounts of data over long distances a few times per hour from varying environments.



	Local Area Network Short Range Communication	**Low Power Wide Area** (LPWAN) Internet of Things	**Cellular Network** Traditional M2M
📈	**40%**	**45%**	**15%**
☺	Well established standards In building	Low power consumption Low cost Positioning	Existing coverage High data rate
☹	Battery Live Provisioning Network cost & dependencies	High data rate Emerging standards	Autonomy Total cost of ownership
	Bluetooth 4.0 ZigBee WiFi	LoRa	GSM 3G+ / H+ 4G

Fig. 1-2. Different technology applications in Communication Field

The most critical factors in a LPWAN are:

- Network architecture

- Communication range
- Battery lifetime or low power
- Robustness to interference
- Network capacity (maximum number of nodes in a network)
- Network security
- One-way vs two-way communication
- Variety of applications served

1.2. WHAT IS LoRaWAN™? It defines the communication protocol and system architecture for the network while the LoRa® physical layer enables the long-range communication link. The protocol and network architecture have the most influence in determining the battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network.

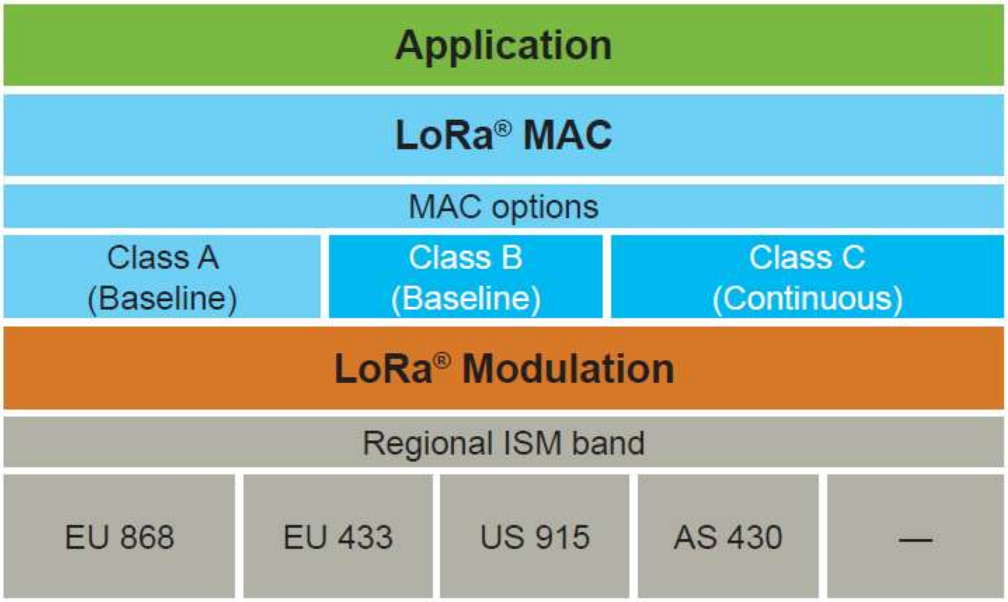


Fig.1-3. Different layers of LoRaWAN

1.2.1. Network Architecture: Many existing deployed networks utilize a mesh network architecture. In a mesh network, the individual end-nodes forward the information of other nodes to increase the communication range and cell size of the network. While this increases the range, it also adds complexity, reduces network capacity, and reduces battery lifetime as nodes receive and forward information from other nodes that is likely irrelevant for them. Long range star architecture makes the most sense for preserving battery lifetime when long-range connectivity can be achieved.

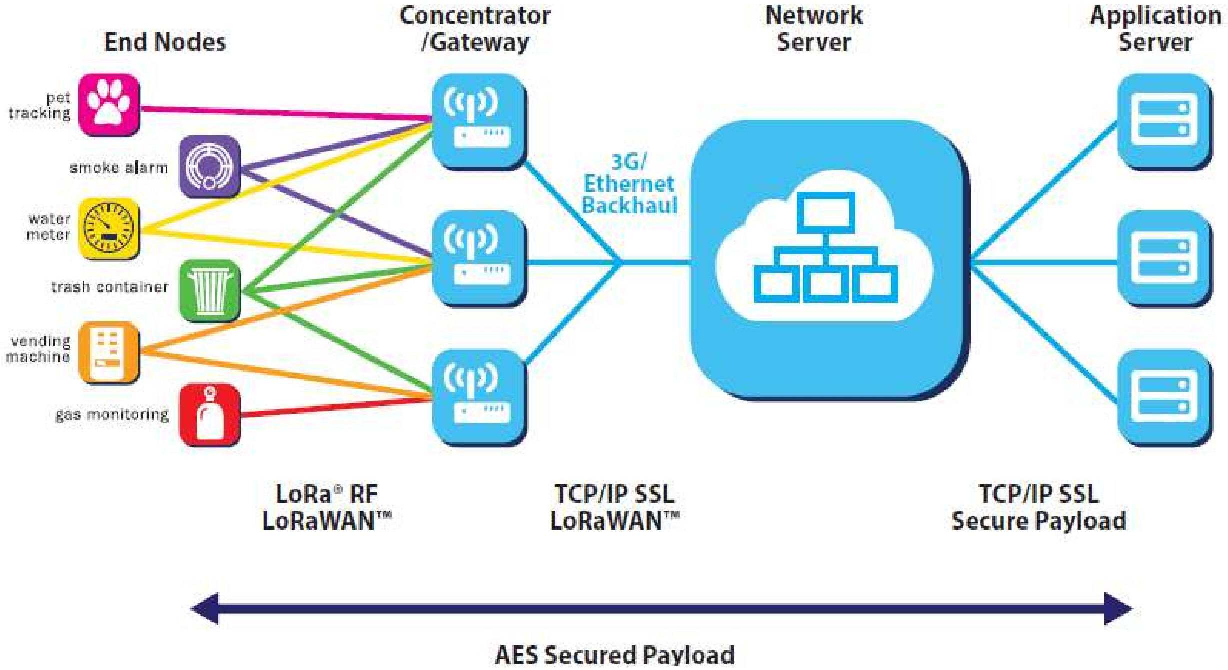


Fig. 1-4. LoRaWAN Network Architecture

In a LoRaWAN™ network nodes are not associated with a specific gateway. Instead, data transmitted by a node is typically received by multiple gateways. Each gateway will forward the received packet from the end-node to the cloud-based network server via some backhaul (either cellular, Ethernet, satellite, or Wi-Fi). The intelligence and complexity is pushed to the network server, which manages the network and will filter redundant received packets, perform security checks, schedule acknowledgments through the optimal gateway, and perform adaptive data rate, etc. If a node is mobile or moving there is no handover needed from gateway to gateway, which is a critical feature to enable asset tracking applications a major target application vertical for IoT.

1.2.2. Network Capacity: In order to make a long range star network viable, the gateway must have a very high capacity or capability to receive messages from a very high volume of nodes. High network capacity in a LoRaWAN™ network is achieved by utilizing adaptive data rate and by using a multichannel multi-modem transceiver in the gateway so that simultaneous messages on multiple channels can be received. The critical factors effecting capacity are the number of concurrent channels, data rate (time on air), the payload length, and how often nodes transmit. Since LoRa® is a spread spectrum-based modulation, the signals are practically orthogonal to each other when different spreading factors are utilized. As the spreading factor changes, the effective data rate also changes. The gateway takes advantage of this property by being able to receive multiple different data rates on the same channel at the same time. If a node has a good link and is close to a gateway, there is no reason for it to always use the lowest data rate and fill up the available spectrum longer than it needs to. By shifting the data rate higher, the time on air is shortened opening up more potential space for other nodes to transmit. Adaptive data rate also optimizes the battery lifetime of a node. In order to make adaptive data rate work, symmetrical up link and down link is required with sufficient downlink capacity. These features enable a LoRaWAN™ network to have a very high capacity and make the network scalable. A network can be deployed with a minimal amount of infrastructure, and as capacity is needed, more gateways can be added, shifting up the data rates, reducing the amount of overhearing to other gateways, and scaling the capacity by 6-8x. Other LPWAN alternatives do not have the scalability of LoRaWAN™ due to technology trade-offs, which limit downlink capacity or make the downlink range asymmetrical to the uplink range.

1.2.3. Battery Lifetime: The nodes in a LoRaWAN™ network are asynchronous and communicate when they have data ready to send whether event-driven or scheduled. This type of protocol is typically referred to as the Aloha method. In a mesh network or with a synchronous network, such as cellular, the nodes frequently have to 'wake up' to synchronize with the network and check for messages. This synchronization consumes significant energy and is the number one driver of battery lifetime reduction. In a recent study and comparison done by GSMA of the various technologies addressing the LPWAN space, LoRaWAN™ showed a 3 to 5 times advantage compared to all other technology options.

1.2.4. Device Classes: Not All Nodes Are Created Equal, End-devices serve different applications and have different requirements. In order to optimize a variety of end application profiles, LoRaWAN™ utilizes different device classes. The device classes trade off network downlink communication latency versus battery lifetime. In a control or actuator-type application, the downlink communication latency is an important factor.

1.2.4.1. Bi-directional end-devices (Class A): End-devices of Class A allow for bi-directional communications whereby each end-device's uplink transmission is followed by two short downlink receive windows. The transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol). This Class A operation is the lowest power end-device system for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission. Downlink communications from the server at any other time will have to wait until the next scheduled uplink.

1.2.4.2. Bi-directional end-devices with scheduled receive slots (Class B): In addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. In order for the end-device to open it's receive window at the scheduled time, it receives a time-synchronized beacon from the gateway. This allows the server to know when the end-device is listening.

1.2.4.3. Bi-directional end-devices with maximal receive slots (Class C): End-devices of Class C have almost continuously open receive windows, only closed when transmitting.

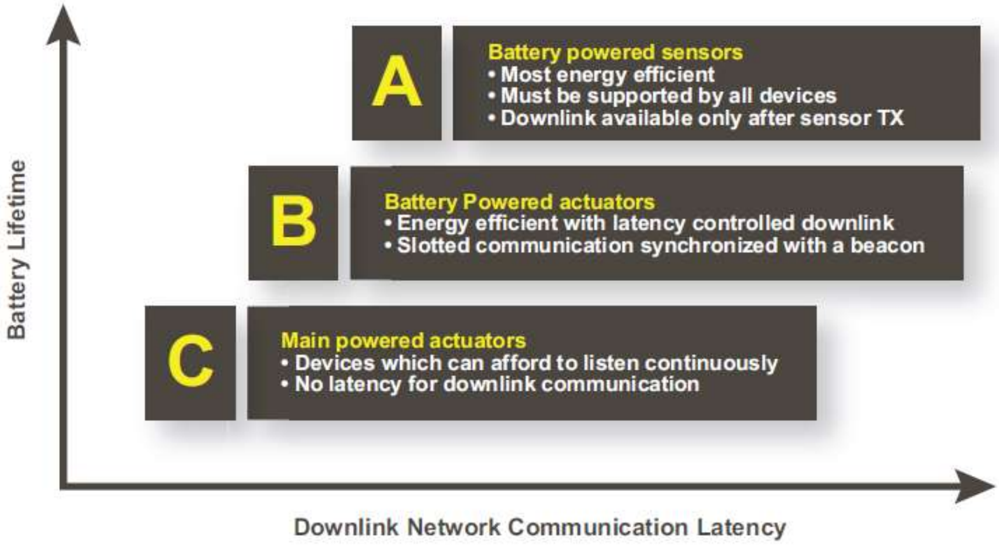

A
Battery powered sensors
• Most energy efficient
• Must be supported by all devices
• Downlink available only after sensor TX
B
Battery Powered actuators
• Energy efficient with latency controlled downlink
• Slotted communication synchronized with a beacon
C
Main powered actuators
• Devices which can afford to listen continuously
• No latency for downlink communication
Battery Lifetime
Downlink Network Communication Latency

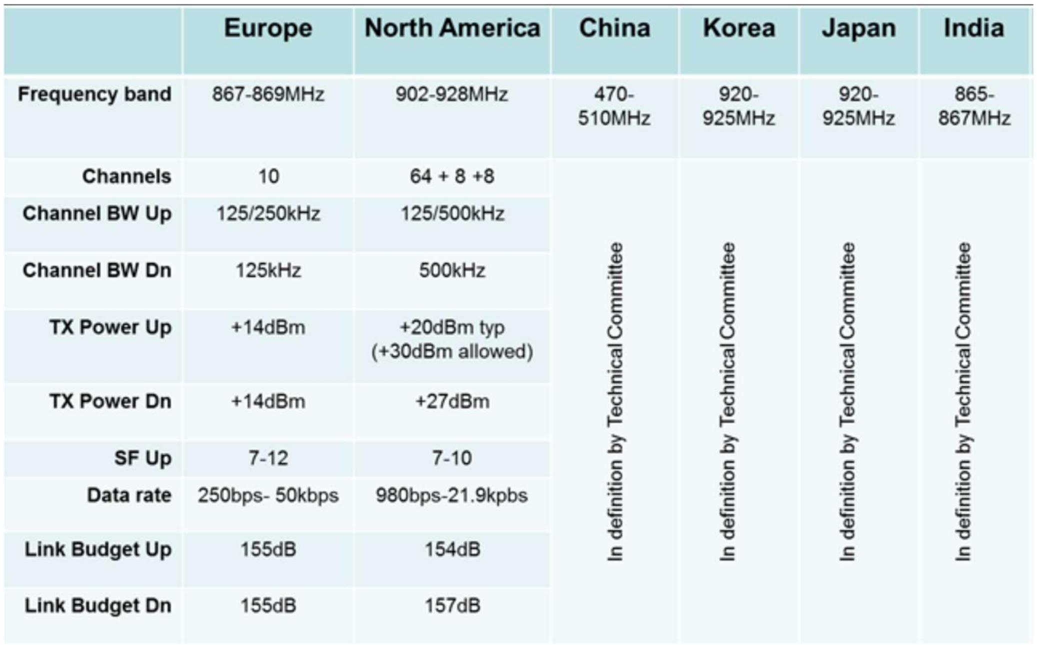
Fig. 1-5. LoRaWAN End-device Class

1.2.5. Security: It is extremely important for any LPWAN to incorporate security. LoRaWAN™ utilizes two layers of security: one for the network and one for the application. The network security ensures authenticity of the node in the network while the application layer of security ensures the network operator does not have access to the end user's application data. AES encryption is used with the key exchange utilizing an IEEE EUI64 identifier.

There are trade-offs in every technology choice but the LoRaWAN™ features in network architecture, device classes, security, scalability for capacity, and optimization for mobility address the widest variety of potential IoT applications.

1.3. LoRaWAN™ REGIONAL SUMMARY: The LoRaWAN™ specification varies slightly from region to region based on the different regional spectrum allocations and regulatory requirements. The LoRaWAN™ specification for Europe and North America are defined, but other regions are still being defined by the technical committee. Joining the LoRa® Alliance as a contributor member and participating in the technical committee can have significant advantages to companies targeting solutions for the Asia market.

1.3.1. LoRaWAN™ for Europe: LoRaWAN™ defines ten channels, eight of which are multi data rate from 250bps to 5.5 kbps, a single high data rate LoRa® channel at 11kbps, and a single FSK channel at 50kbps. The maximum output power allowed by ETSI in Europe is +14dBM, with the exception of the G3 band which allows +27dBm. There are duty cycle restrictions under ETSI but no max transmission or channel dwell time limitations.

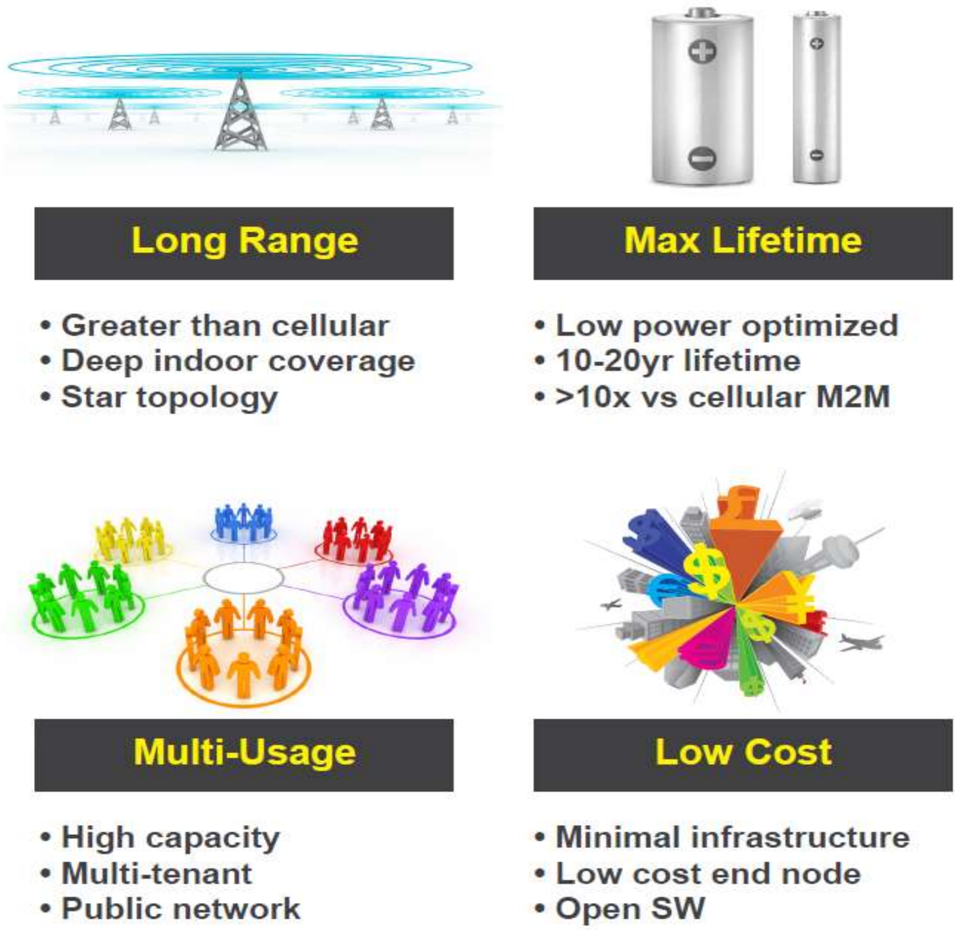


	Europe	North America	China	Korea	Japan	India
Frequency band	867-869MHz	902-928MHz	470-510MHz	920-925MHz	920-925MHz	865-867MHz
Channels	10	64 + 8 +8	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee
Channel BW Up	125/250kHz	125/500kHz				
Channel BW Dn	125kHz	500kHz				
TX Power Up	+14dBm	+20dBm typ (+30dBm allowed)				
TX Power Dn	+14dBm	+27dBm				
SF Up	7-12	7-10				
Data rate	250bps- 50kbps	980bps-21.9kpbs				
Link Budget Up	155dB	154dB				
Link Budget Dn	155dB	157dB				

Fig.1-6. LoRaWAN REGIONAL SUMMARY

1.4. COMPARING LPWAN TECHNOLOGY OPTIONS: There is a lot of activity in the IoT sector comparing LPWAN options both from a technical comparison but also from a business model perspective. LPWAN networks are being deployed now because there is a strong business case to support immediate deployment, and the cost to deploy the network in unlicensed bands requires much less capital than even a 3G software upgrade. The questions that should be answered to compare different LPWAN technologies are:

- Flexibility to target a large variety of applications
- Is the communication protocol secure?
- Technical aspects – range, capacity, two-way communication, robustness to interference
- Cost of network deployment, cost of end-node BOM, cost of battery (largest BOM contributor)
- Ecosystem of solutions providers for flexible business models
- Availability of end-products to ensure ROI of network deployment
- Strength of ecosystem to ensure quality and longevity of the solution



Long Range

- Greater than cellular
- Deep indoor coverage
- Star topology

Max Lifetime

- Low power optimized
- 10-20yr lifetime
- >10x vs cellular M2M

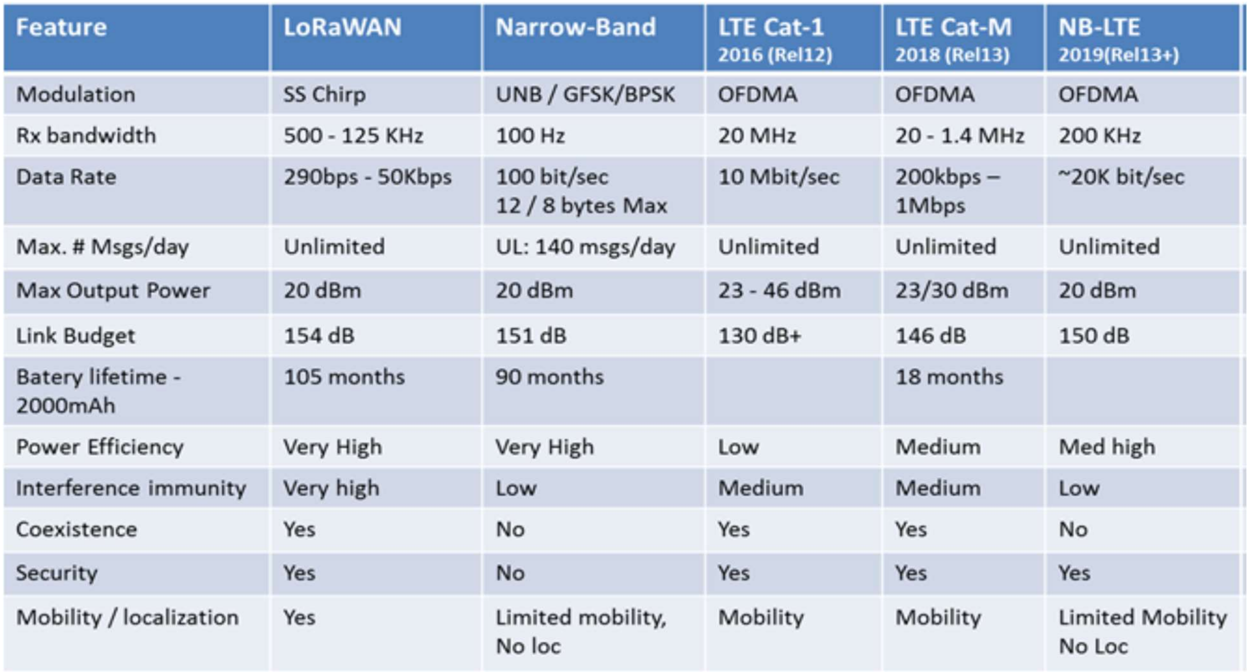
Multi-Usage

- High capacity
- Multi-tenant
- Public network

Low Cost

- Minimal infrastructure
- Low cost end node
- Open SW

Fig. 1-7. LoRaWAN specifications



Feature	LoRaWAN	Narrow-Band	LTE Cat-1 2016 (Rel12)	LTE Cat-M 2018 (Rel13)	NB-LTE 2019(Rel13+)
Modulation	SS Chirp	UNB / GFSK/BPSK	OFDMA	OFDMA	OFDMA
Rx bandwidth	500 - 125 KHz	100 Hz	20 MHz	20 - 1.4 MHz	200 KHz
Data Rate	290bps - 50Kbps	100 bit/sec 12 / 8 bytes Max	10 Mbit/sec	200kbps – 1Mbps	~20K bit/sec
Max. # Msgs/day	Unlimited	UL: 140 msgs/day	Unlimited	Unlimited	Unlimited
Max Output Power	20 dBm	20 dBm	23 - 46 dBm	23/30 dBm	20 dBm
Link Budget	154 dB	151 dB	130 dB+	146 dB	150 dB
Batery lifetime - 2000mAh	105 months	90 months		18 months	
Power Efficiency	Very High	Very High	Low	Medium	Med high
Interference immunity	Very high	Low	Medium	Medium	Low
Coexistence	Yes	No	Yes	Yes	No
Security	Yes	No	Yes	Yes	Yes
Mobility / localization	Yes	Limited mobility, No loc	Mobility	Mobility	Limited Mobility No Loc

Fig. 1-8. LoRaWAN and LTE comparison

The LoRaWAN™ protocol provides two methods for geolocation determination: Received Signal Strength Indication (RSSI) based, for coarse positioning, or Time Difference of Arrival (TDOA), for finer accuracy. This project will discuss TDOA, which is particularly well suited for applications requiring low-cost, battery powered end-devices. rural deployments with clear line of sight and recommended gateway-deployment geometry will achieve accuracies near the lower end of the scale. multipath issues inherent in urban and dense urban environments will provide accuracies toward the higher end of the scale. In general, accuracy improves as operators densify their gateway networks. Mobile assets requiring more frequent position determination will transmit more frames, consume more power, and increase end-device costs (e.g., batteries) and will often need to be implemented as Class B or Class C end-devices. Usage of a higher data rate (say SF7) will help bound the increased power needs.

LoRaWAN TDOA/RSSI advantages:

- Lowest cost solution. Works natively with any LoRaWAN sensor
- LoRaWAN enables long battery life use cases
- TDOA: 20-200m accuracy range depending on conditions
- RSSI: 1000-2000m accuracy WiFi Location
- Cost efficient solution for outdoor and indoor solution
- Accuracy increases with hotspot density BLE Requires a BLE beaconing system Indoor solution GPS/AGPS
- 1 GPS adds $5-$10 to the BOM
- Most accurate but power consuming solution
- AGPS brings battery consumption improvement

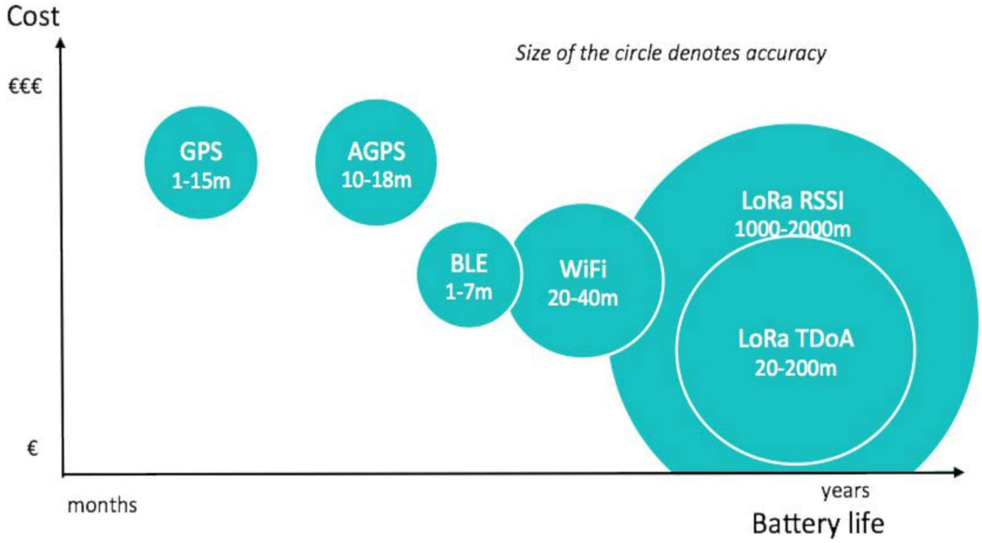


Fig. 1-9. Comparison of Geolocation Technologies

2. System Design, Implementation and Challenges

The overall system consisted mainly of many blocks: an end-node (LoRa sensors), The Private Network Gateways (PNG) and its database server (PNDS) and a third-party application (Fig. 2.1). The end-node sent the data over the air using the LoRaWAN protocol and the gateways that were close enough (around 5 km) received the data then, the gateways forwarded the packets to the database, together with information from the received signal such as the exact time when the packet was received measured in microsecond, the RSSI, the working frequency, gateway and sensor position measured by GPS, etc. Afterwards, server processed the data from the different gateways and store a messages to the database server. Finally, the algorithms to estimate the position was applied in a third- party application so the overall information provided from the whole system will be such that, for each end-node (Sensor-ID) at specific location, which it's position pre calculated by GPS and stored in database as latitude and longitude coordinate, specific message payload sent which received by many fixed gateways at different location, which also their positions pre calculate and stored in database same as the sensors information, that contain information such as receiving signal time in microsecond, receiving signal intensity and the real distances between the end-node and each gateway which receives relative it's messages.

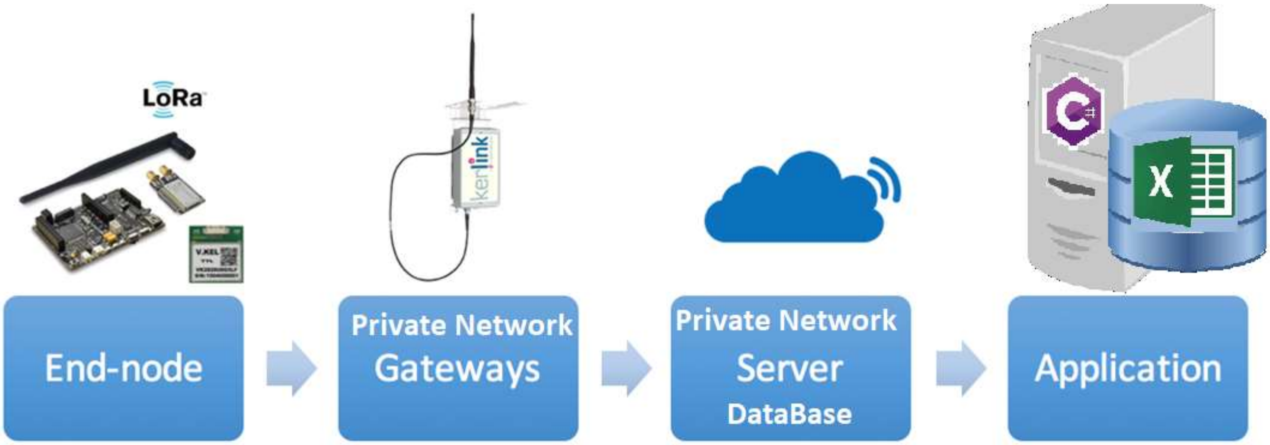


Fig. 2-1. Elements of the whole system

2.1. End-node: The end-node is responsible for sending the data acquired from a GPS receiver over the air through a LoRaWAN module. A LoRaWAN end-device can be located if uplink transmissions from the device are received by three or more gateways. These uplink transmissions need not be specific transmissions for geolocation; they may be typical LoRaWAN application data frames. Several gateways simultaneously receive the same uplink message. There is no additional hardware required on the end-device beyond its LoRaWAN interface. A GPS module was used to be able to benchmark and reference the performance of the investigated geolocation method.

2.2. Private Network Gateways (PNG): The main function of the gateways was to route the data received from the end-node to the server. In order to estimate the location of the device, the received time of the packet from each gateway was needed to apply the algorithms. The geolocation technique used in this systems was in such way that the transmitter is not synchronized with the receivers which maybe stress that it doesn't gave so good row data collection, given the poor distance-time correlation due to the synchronization requirement. The received times of the packet by each receiver are stored in the database. The protocol between the gateway and the server forward packets that runs inside the gateway. There is no authentication of the gateway nor the server which maybe stress that there will be a security issues in real application implementation, but for instance it is not considered in this project and acknowledgements are only used for network quality assessment, not to correct lost packets. Some types of packets could be exchanged between the gateway and the server, one of the packets exchanged contains the payload of the packet received from the end-node. The "time" field contains the information which is relevant for the algorithm: the reception time of the packet in the gateway. Furthermore, other information about the received signal is forwarded to the server: the received signal strength indicator (RSSI), the signal-to-noise ratio (SNR), etc. At the beginning, the value set in the "time" field had microsecond accuracy and in the "position" field location set by latitude and longitude.

2.3. Private Network Database Server (PNDS): PNDS was responsible for decoding data from our gateways and transmitting it to the third-party application. It was important that the packets from the different gateways, with the same payload but with different times, arrived at the network server. The most relevant feature for the algorithm computation was the value of the time field in which was sent. If the goal is to process and analyze such information, a communication with a third-party application is required thus, a packet forward the data to the third-party application. PNGs and its PNDS are infrastructures implemented by a private company whom working in water and gas sensor technologies which distributed their own network around city of Milano, Italy. The datasets information provided for this project comes from their network and it could be used for tracking or localization purposes.

2.4. Third-party application: The third-party application consisted mainly of two parts: an application writing by C# programing language in Microsoft Visual Studio environment and a database which send and store set of data to the Excel file. The main function was to obtain the data from PNDS, parse it and insert it in the database for processing in the following step. As already stated, PNGs allows forward the packets for specific device Therefore, identification of each end-node was done in C# code to the desired sensor with the suitable device identifier in order to obtain all packets from the gateways. The object-oriented C# code was composed by several classes to parse and manage the data from the server, as well as a Microsoft office driver to establish connection with the Excel database. Consequently, in order to enhance the accuracy in the calculation some conversion in the position of each sensor and gateways was done by transforming position from Euclidean space (3D) to the Cartesian coordinate (2D) and at the final step of location estimation, the Haversine formula used to measure the differences in distance (error in this context) in meters form location estimated to the End-node position, which also obtained by GPS devices to be use as reference position, while to figure out that the all received dataset has good accuracy that allows to have correct location estimation, distance-time correlation for all sets of the message payloads and their relatives gateways for each sensor-id was computed, which shows that due to the different environmental phenomena that affects the received signals together with the synchronization of the gateway and in consequences the data, we did not get the accurate localization for our deployment infrastructure which leads to the un acceptable errors in position estimation also note that the similar plot for each sets of specific message payload does not get a unique shape in the final diagram representation and so it cannot be used for future analysis.

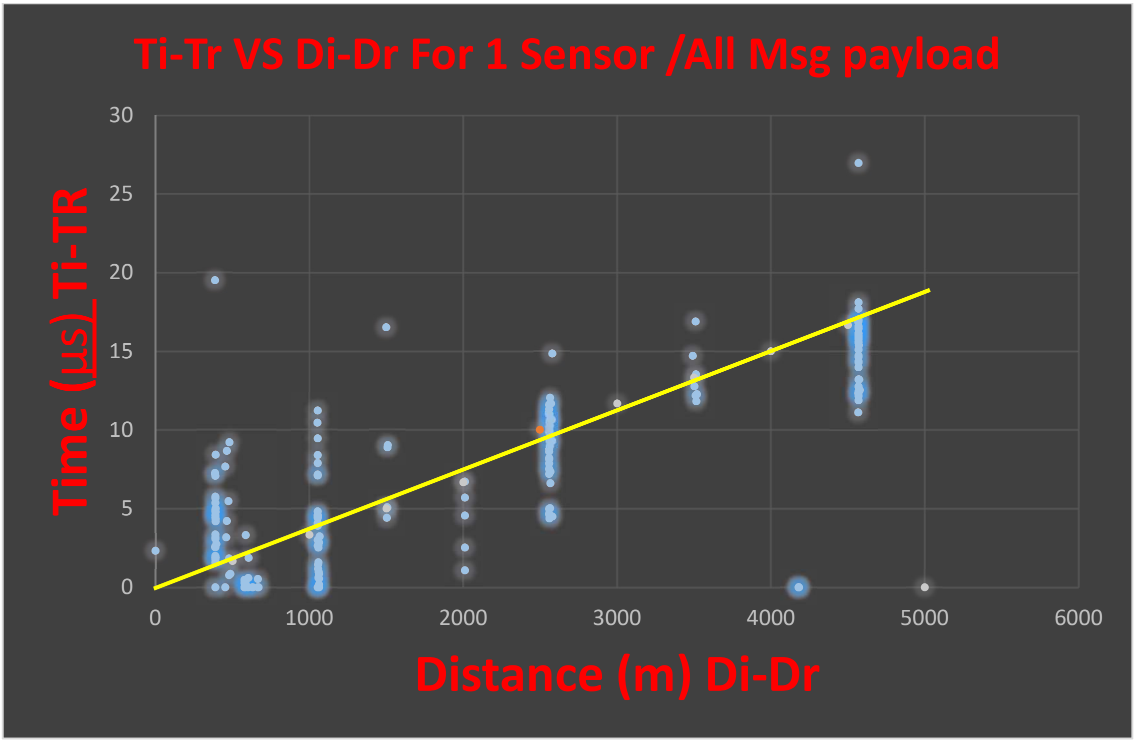


Fig. 2-2. Scatter diagram of time vs distance of the whole system for one sensor

Finally all C# code had to be cross-compiled on a Windows system using the default debugger and Microsoft Excel as database.

2.5. Source of Errors in Data: Wrong measurements of the TDOAs and thus the accuracy of the estimated position depends to the many factors:

- Propagation environment and multipath
- Gateway deployment geometry and density
- Position determination used by the geolocation algorithms
- Quality of gateway's time synchronization
- End-device dynamics and configuration

2.5.1. Impact of Propagation Errors: In a multipath-free environment, LoRaWAN geolocation performance is limited by the gateway's clock accuracy. Conductive geolocation testing typically achieves better than 3m accuracy with signal levels 25dB above sensitivity. At sensitivity level, noise degrades performance to 60m. Within these constraints, accuracy rarely depends on the received signal level. In the presence of multipath, given the system bandwidth limitation of 125 KHz, signal paths are often indistinguishable. Only the average channel delay can be estimated. In some cases the direct signal path is not present, introducing a delay offset into the frame timestamps, as only reflection paths are seen. Figure 2-3 shows the statistics of timestamp errors for different propagation scenarios. These are measurements taken from mobile vehicle testing with timestamp errors estimated using GPS. The urban case has fewer data points than the others (2,000 vs. 10,000), which explains the worse-looking curve. The average distance from vehicle to gateway is 1.5km. On average, the timestamps are late. Note that the timestamp errors may be negative, but they are never smaller than -1/bandwidth (never lower than the basic resolution of the system). There are various ways to mitigate timestamp errors

- Repetition of frames at different frequencies
- Antenna diversity at the gateway (typically two antennas)
- Higher-density gateway deployment, which increases the number of available samples (frame receptions) and increases the chance of line-of-sight measurements, thus increasing the accuracy of the TDOA
- Lower latency frame timestamping at the gateway
- Incorporation of out-of-band propagation error corrections to mitigate multipath (simulations, predictions, calibration or fingerprinting)

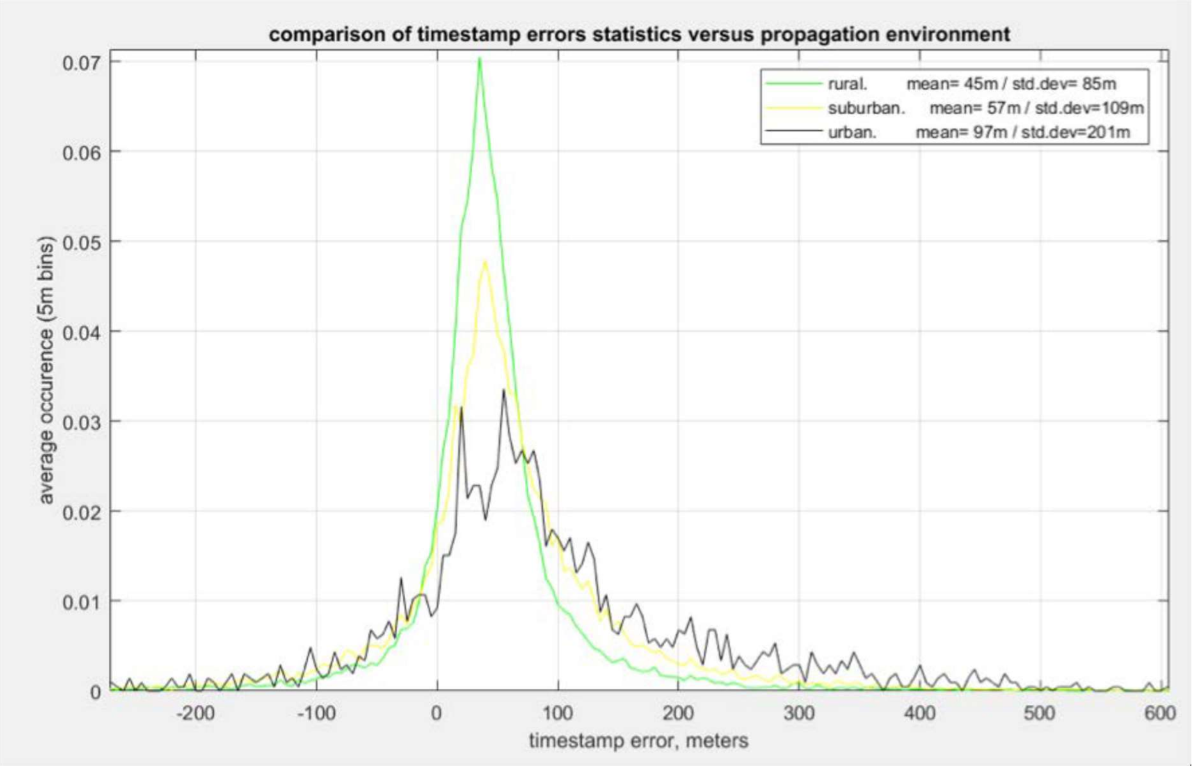


Fig. 2-3. Statistics of Timestamp Errors

Multipath propagation fundamentally limits the accuracy of the system, but gateway-deployment geometry also plays a significant role.

2.5.2. Impact of Deployment Geometry: As with other radio navigation systems (e.g., GPS, LORAN), the accuracy of a LoRaWAN geolocation position fix depends on the placement of the gateways versus the end-device. The metric used to determine the quality of gateway placement is the Geometric Dilution of Precision (GDOP), which is a measure of the "goodness" of the receiving gateway's relative geometry.

2.5.3. Impact of Time Errors: Quality of GPS reception also impacts accuracy. For mobile service providers, gateways deployed close to cellular sites may experience periodic blockage of GPS; therefore, special antennas should be used. GPS is not a significant source of geolocation error for deployments unable to approach this 10m accuracy but when very dense LoRaWAN networks are deployed, improving gateway clock accuracy can further improve geolocation accuracy.

2.5.4. Filtering of Errors: Improves accuracy depending on the application, it is possible to filter the output results of the geolocation algorithm to provide better accuracy. For example, if the end-device is known to maintain a fixed position, time averaging can be applied to derive the location. In the case of LoRaWAN geolocation, as the pre-filtered position estimates are sparse and noisy, the filter has a strong impact on performance. Geolocation performance is improved if the filter knows to apply a specific end-device speed profile. This information comes from general knowledge of the end-device (stationary, mobile, etc.) and is application specific. Another use of application-specific knowledge is a map-matching filter. If, for instance, the end-devices are to be moved between warehouses, the filter will first classify end-devices as stationary or moving. If the end-device is stationary, it can be assumed to be located at one of the warehouses. If the end-device is moving, it will be located on a road.

3. Geolocation Algorithm on Third-party application

There are several techniques which can be used to estimate the position of the device, each one of them with different features. It is important to select the most suitable one depending on the known information from the end-node. The three most common methods used for performing the geolocation are triangulation, trilateration and multilateration. Triangulation uses angles of incidence of the signal received from the transmitter. A triangle is defined with two of them and the end-node position is estimated applying trigonometric formulas. Trilateration requires the distance between the transmitter and the receiver, which can be obtained from the time of arrival (TOA), the time of flight (TOF) or from the received signal strength indicator (RSSI). Therefore, it requires synchronization between the transmitter and the receiver. The position is the intersection of the three circles obtained from the different distances. Multilateration is quite similar to trilateration; however, the main feature to compute the location is the time difference of arrival (TDOA). The transmitters are synchronized to each other, whereas the receiver does not need to be. Thus, the location in this technique is the intersection of at least two hyperbolas (three antennas required). The tracking IoT system does not have synchronization with the end-node, only the gateways can be synchronized with each other. Therefore, the information available was the time when the packet was received by each gateway. The TDOA was computed with this information and, for this reason, the Nearest Neighbor Localization (NNL) and Weighted Nearest Neighbor localization (WNNL) algorithm was chosen for this project. The RSSI was also known, so trilateration could also be applied. However, recent studies demonstrate a better accuracy using TDOA instead of RSSI. Algorithms implementation consisted of several phases as shown in Fig. 3-1.

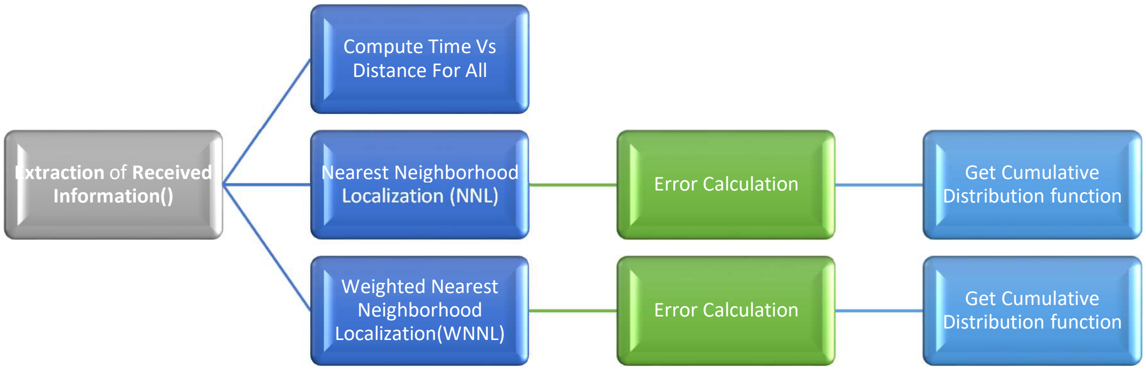

xtraction of Received Information()
Compute Time Vs Distance For All
Nearest Neighborhood Localization (NNL)
Weighted Nearest Neighborhood Localization(WNNL)
Error Calculation
Error Calculation
Get Cumulative Distribution function
Get Cumulative Distribution function

Fig.3-1.Geolocation Algorithm structure

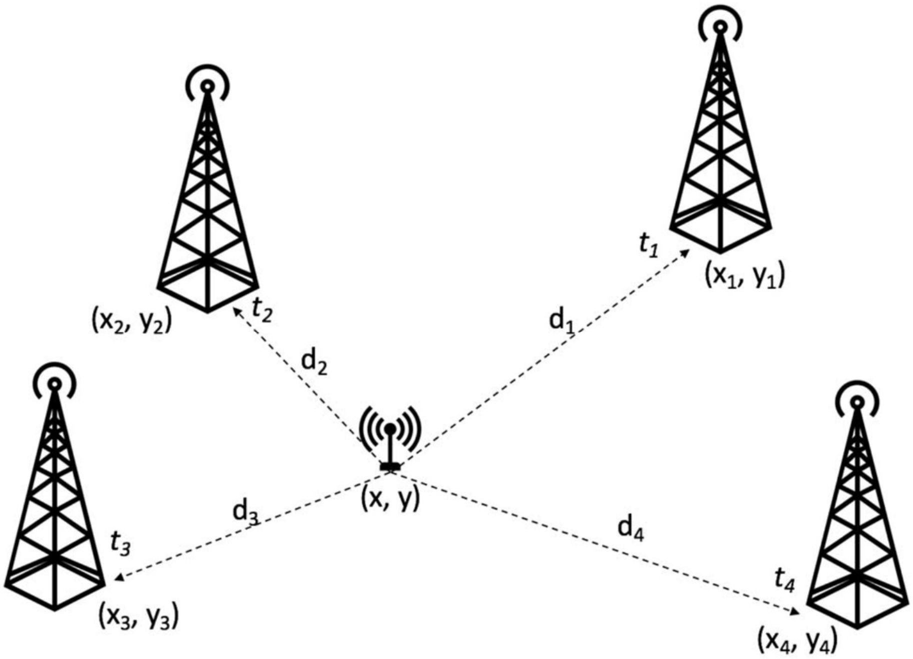


Fig.3-2. Scenario of the algorithm

3.1. Extraction of Received Information: after receiving packets and storing their information in database, the application used by network administrator will run some pre calculation and conversion on the data sets before running the algorithm itself as well as getting information about the it such as how many gateways, message payload, etc... Are involving, also removing points (outliers) that have unsolvable localization since some specific payload type of specific sensor was received just by two or one gateways in order words keeping outliers in a dataset can lead to wrong results, so it is important to detect the true outliers. However, in some cases it may not be possible to determine if an outlying point is bad. In case of data conversion the position over the globe can be expressed in Cartesian coordinates (x, y, and z) or in Geodetic coordinates (latitude, longitude and height). The first set of coordinates is useful for mathematical calculations and easier to manipulate, but not for providing understandable information. The second one provides understandable information, but it is useless for mathematical calculations. Therefore, the known Geodetic coordinates from the gateways and sensors could not be used directly into the algorithm and a transformation was needed. Such transformation was done just two times, one before running the algorithm and the other at the runtime when the error (distances) was computed using the Haversine formula. Once the coordinates from the gateways were transformed to Cartesian, the nearest and weighted nearest algorithms could be applied. The gateways coordinates were denoted as (Xi, Yi) as well as (Xr, Yr) for the reference one and the estimated unknown position of the end-device as (X, Y).The two function below are responsible for initialization step and information extraction and conversion:

```
private void Cal_Click(object sender, EventArgs e)
private void Convertpos_Click(object sender, EventArgs e)
```

Meanwhile columns 34 to 37 of excel file included these information.

3.2. Compute Time Vs Distance Correlation: One important step after the initialization step is to determine the reference gateway (base station) and it is done by choosing the best gateway which received message payload first among the others which obviously has the minimum time of the arrivals in this case. By selecting the reference gateway 's data such as time and distance together with data's of the other gateways the algorithm will be able to compute the pairs of time (ti-tr) and distance (di-dr) differences in microseconds and meters for each sensor which related to the each message payload of sensor that was sent at specific time instances at the specific location to the gateways and finally sorted these differences ordered by the minimum time, also these differences will be added to the another list that contains all differences for all message payload of just one specific sensor to be used as the final scatter plot diagram for that sensor to know that what is the time and distance correlation and their distribution. note that in some cases the difference in distance becomes negative due to the propagation effects, even if message received by references gateway first but it travels more distances compare to the some other gateways and in this case simply assuming positive value will cause no changes on the final result also in some other cases we see that the time differences is zero and this is due to the fact that even if distances are different but propagation effects cases that signal received late in compare to the another end-node that are more far away. The function in the third party application which implement correlation between time and distance exists in the body of below function

```
private void MWNNL_Click(object sender, EventArgs e)
```

Columns 39, 44 to 47, 68 and 69 of excel file provided mentioned differences, sorted differences and all sorted differences results.

3.3. Nearest Neighbor Localization (NNL): Present the localization in the simplest scenario in such way that the estimated unknown position of the end-device (X, Y) is the location of the reference gateway (Xr, Yr) then compute the distance (error) of this position from the ones obtained by GPS using the Haversine formula therefor, for each message payload of specific sensor which propagated at specific time instances at specific location, algorithm will compute an error which measured in meters and at each execution loop it will be added into a list that contains all errors for specific sensor which will be used for cumulative distribution function. Must note that error (distance) calculated in this way by this algorithm should be exactly same as the pre-computed distances stored in database which refers to the real distance between the reference gateway and sensor, in other words distance between real geodetic location of sensor obtained by GPS and real geodetic location of reference gateway which computed and stored at the time of installing infrastructures. final computation of this algorithm shows that the differences between the distance calculated by algorithm and the ones exists in excel files have just one meter error which for better accuracy and simplicity this error added to the final value computed by algorithm to be the same as the real distances scenario. The function in the third party application which implement nearest neighbor localization (NNL) algorithm is

```
private void NNL_Click(object sender, EventArgs e)
```

Column 65 of the excel file shows the final computed error and the real distance which separated by two “*” to emphasis that the two values are close enough as far as showing the algorithm implementation accuracy.

3.4. Weighted Nearest Neighbor Localization (WNNL): Present the localization algorithm with the same structure as the nearest neighbor but more math used for estimation of unknown position of the end-device (X, Y).structure of this algorithm is such that, first of all for each message payload of specific sensor it gets all its gateways message receiving times (TOA), which measured in microsecond ,including also the references ones then a weight will be assign to each gateway inversely proportional to the arrival time or the RSSI of the signal base on the algorithm specification, in other words more higher weight will be assign to the gateway that have shorter arrival time(nearest gateway) or higher RSSI. The below diagram shows how the weighting algorithm is implemented using time of arrivals:

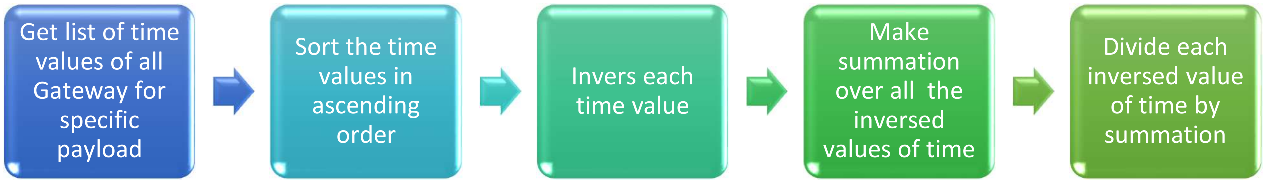

Get list of time values of all Gateway for specific payload
Sort the time values in ascending order
Invers each time value
Make summation over all the inversed values of time
Divide each inversed value of time by summation

Fig.3-3. Basic process of weighting algorithm using time of arrivals

The obtained value of the weight used by algorithm to apply to the coordinate of each related gateway and then make summation of all computed weighted coordinate to get the final estimated unknown position of the end-device (X, Y) for specific message payload at certain location. either directly by applying weight to the each latitude and longitude of position of each gateway than summed or indirectly multiplying weight to the Cartesian coordinate, which computed at the initialization step, than convert the summed weighted Cartesian coordinate to the latitude and longitude, both gives the same value of estimated location. finally at the last step same as the previous algorithm, the distance (error) between this estimated weighted position to the ones obtained by GPS computed using the Haversine formula therefor, for each message payload of specific sensor which propagated at specific time instances at specific location, algorithm will compute an error which measured in meters and at each execution loop it will be added into a list that contains all errors for deterministic sensor which will be used for cumulative distribution function for the weighted algorithm. The function in the third party application which implement weighted nearest neighbor (WNNL) algorithm is

```
private void WNLL_Click(object sender, EventArgs e)
```

Columns 40 to 43 and 48 to 51 dedicated to the computed weighted coordinate and estimated weighted position.

3.5. Error Computation: Base on the source of errors which discuses in section 2, error may present in our datasets which collected from our installed infrastructure and also the way that error computed in both algorithms by third party application, results shows that if Assuming estimated location is the location of the nearest base station(using NNL), calculating distances(error) of this position with the position obtained by GPS we get the distances exist in database which is the minimum error obtained with compare to the other algorithm Just in *some cases* *but not all* as shown on the figure 3-4 and 3-5

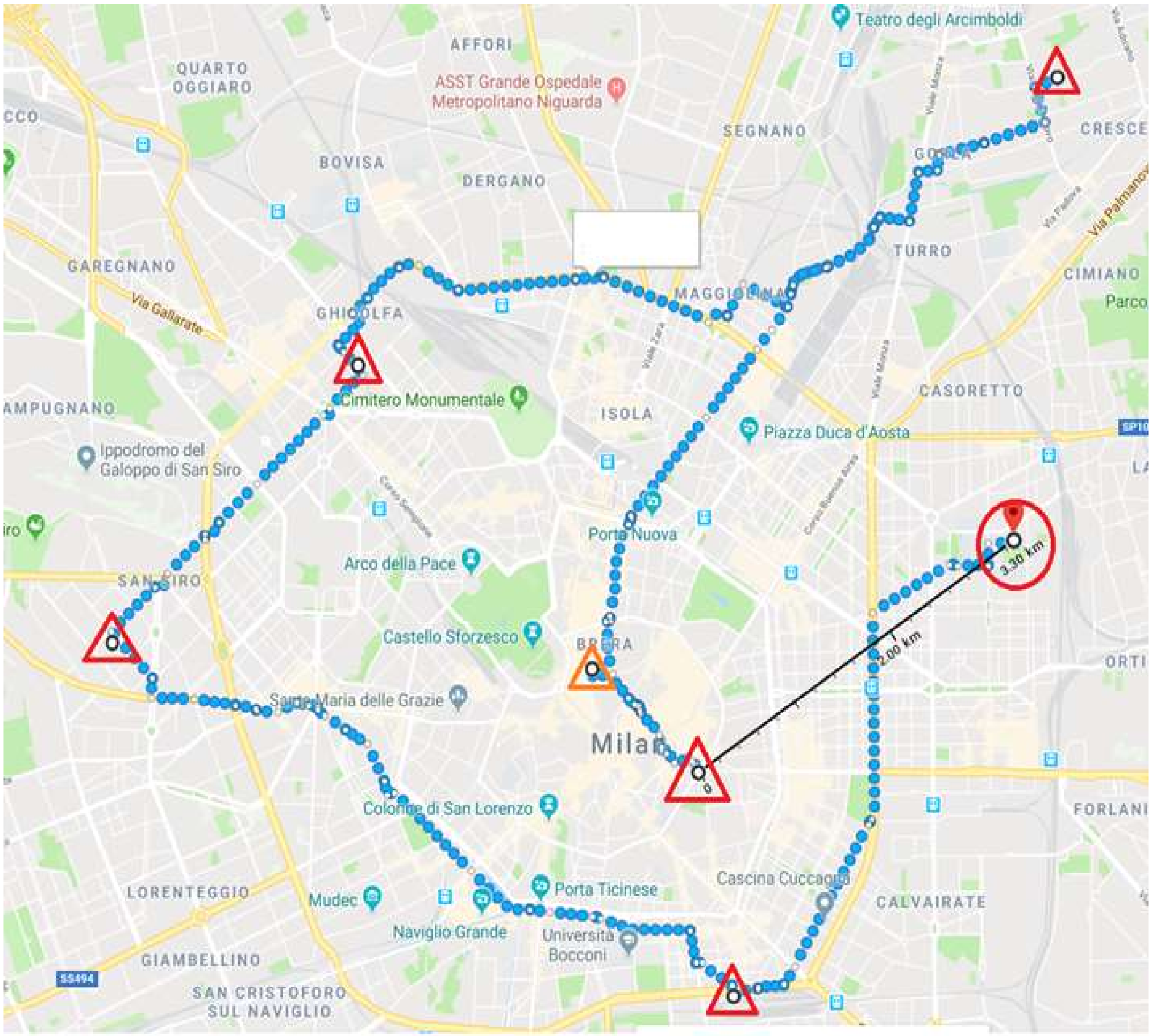


Fig.3-4. Better(less) Error obtained by NNL=3.30KM, Distance between Nearest Gateway (estimated sensor position) and sensor location obtained by GPS for four gateways of one message payload

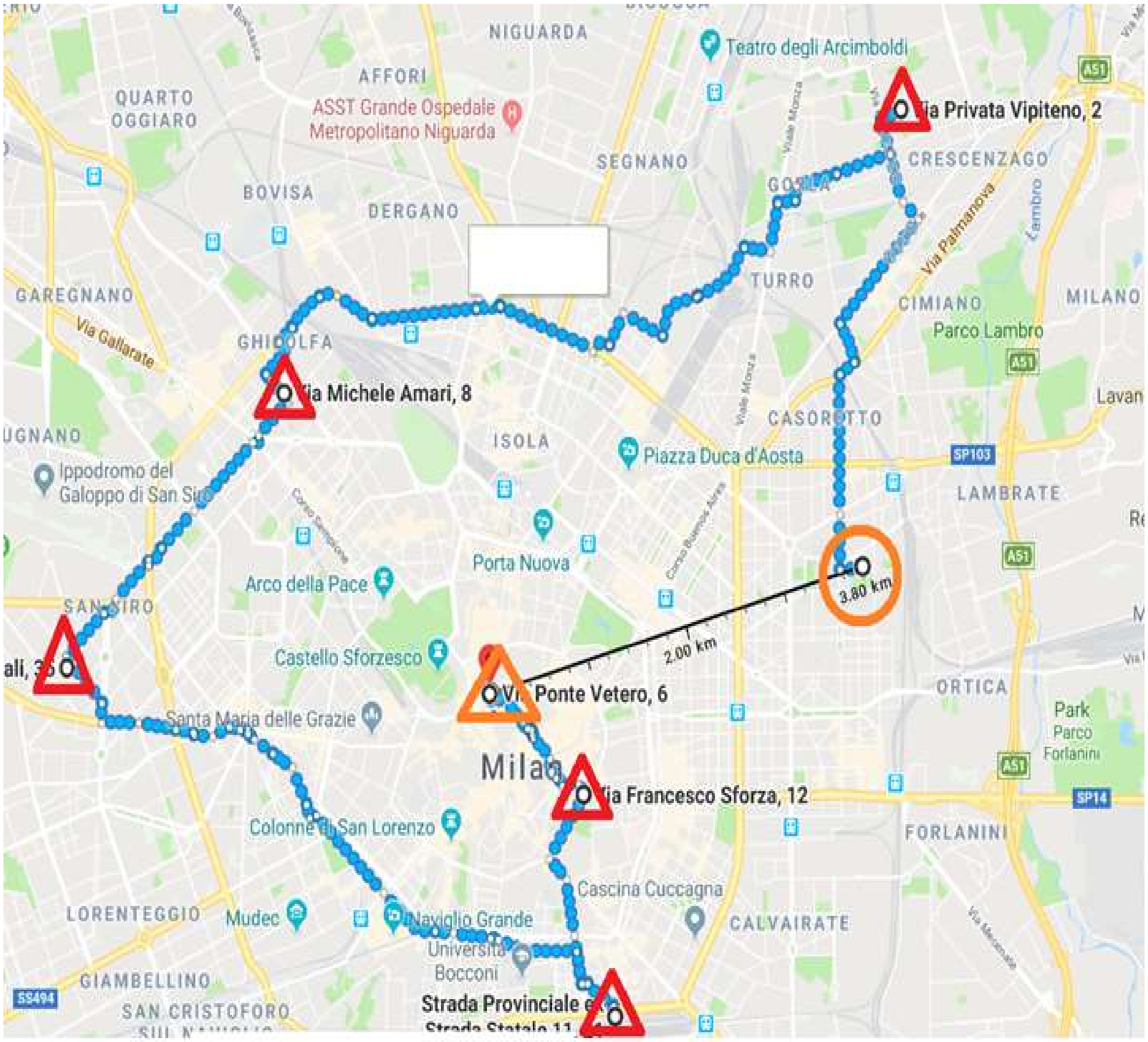


Fig.3-5.Worse (higher) Error obtained by WNNL= 3.80KM > 3.30KM (in previous case), Distance between estimated sensor location and sensor location obtained by GPS for four gateways of one message payload

While if assuming estimated location is the location of the Weighted nearest base stations inversely proportional to the time of their signal arrivals by applying WNNL algorithm, calculating distances (error) of this position with the position obtained by GPS we get the distances which has less error in compare to the NNL algorithm Just in *some cases but not all* as shown on the figure 3-6 and 3-7

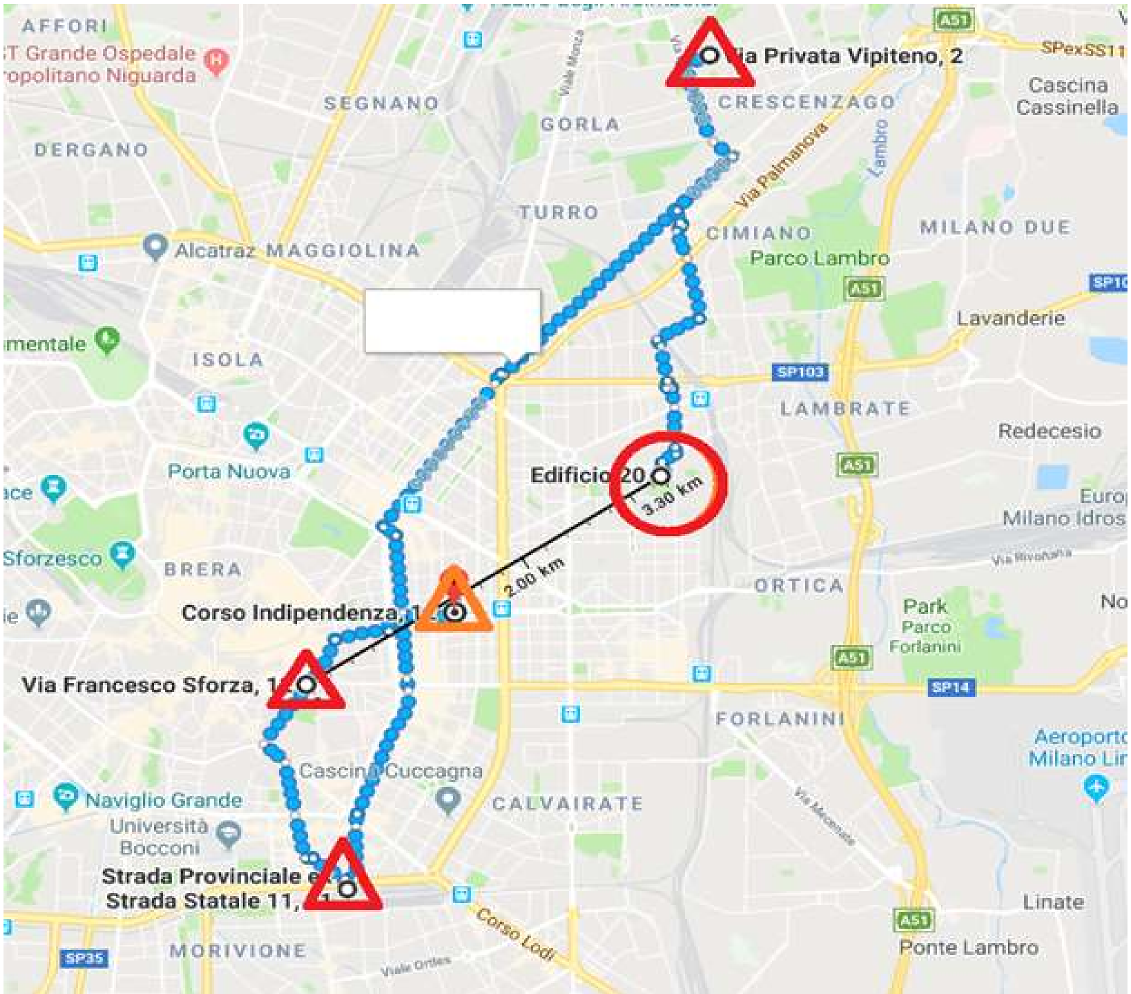


Fig.3-6. Worse (higher) Error obtained by NNL=3.30KM, Distance between Nearest Gateway (estimated sensor position) and sensor location obtained by GPS for three gateways of one message payload

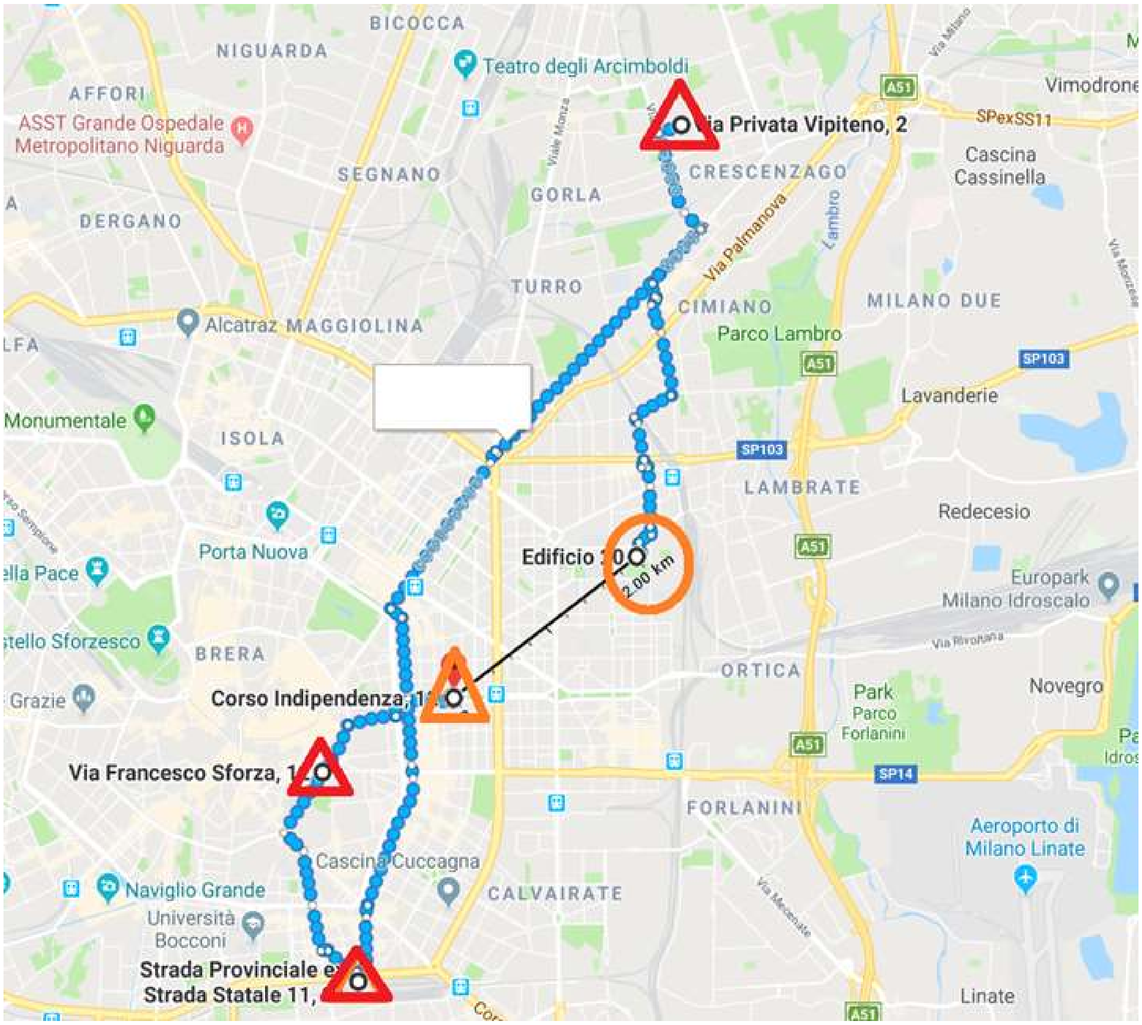


Fig.3-7.Better(less) Error obtained by WNNL= 2KM < 3.30km (in previous case), Distance between estimated sensor location and sensor location obtained by GPS for three gateways of one message payload

3.6. Cumulative Distribution function (CDF): Base on the definition of CDF and the two type of data collection that computed from both NNL and WNNL, final CDF diagram of both algorithm shows that it does not presents straight line as expected that should be exists in the CDF of high accuracy data collection obtained from good infrastructure and it is due to the fact that different source of errors may cause the row data does not provided very well representation and thus the final algorithm results becomes not very well precise in this model.

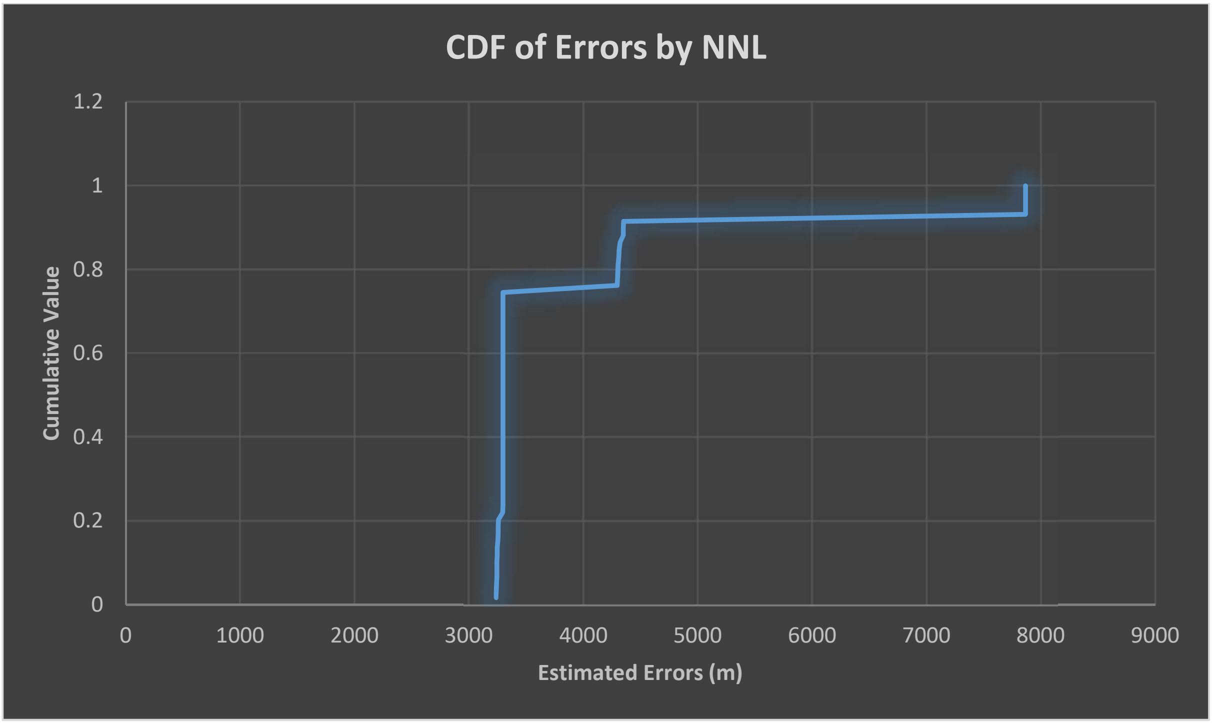


Fig.3-8. CDF of Errors obtain by NNL for all message payload of one sensors

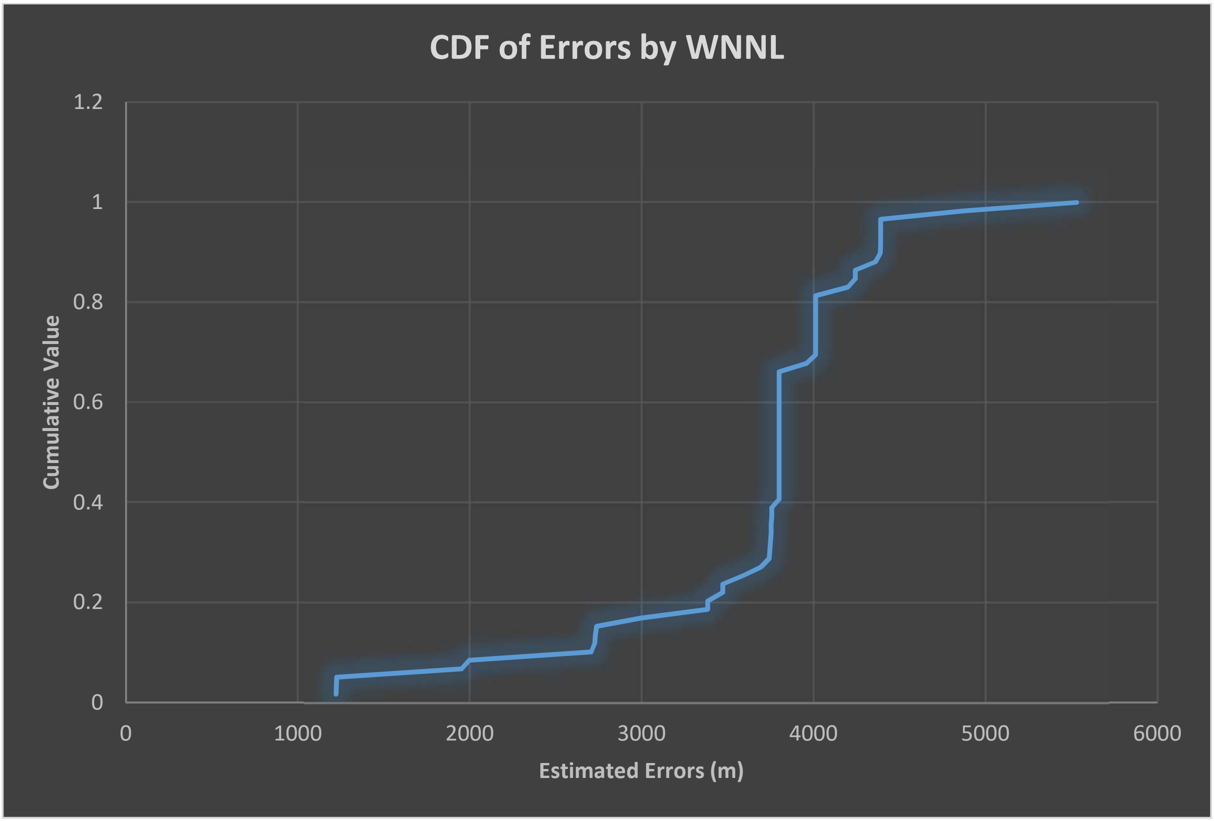
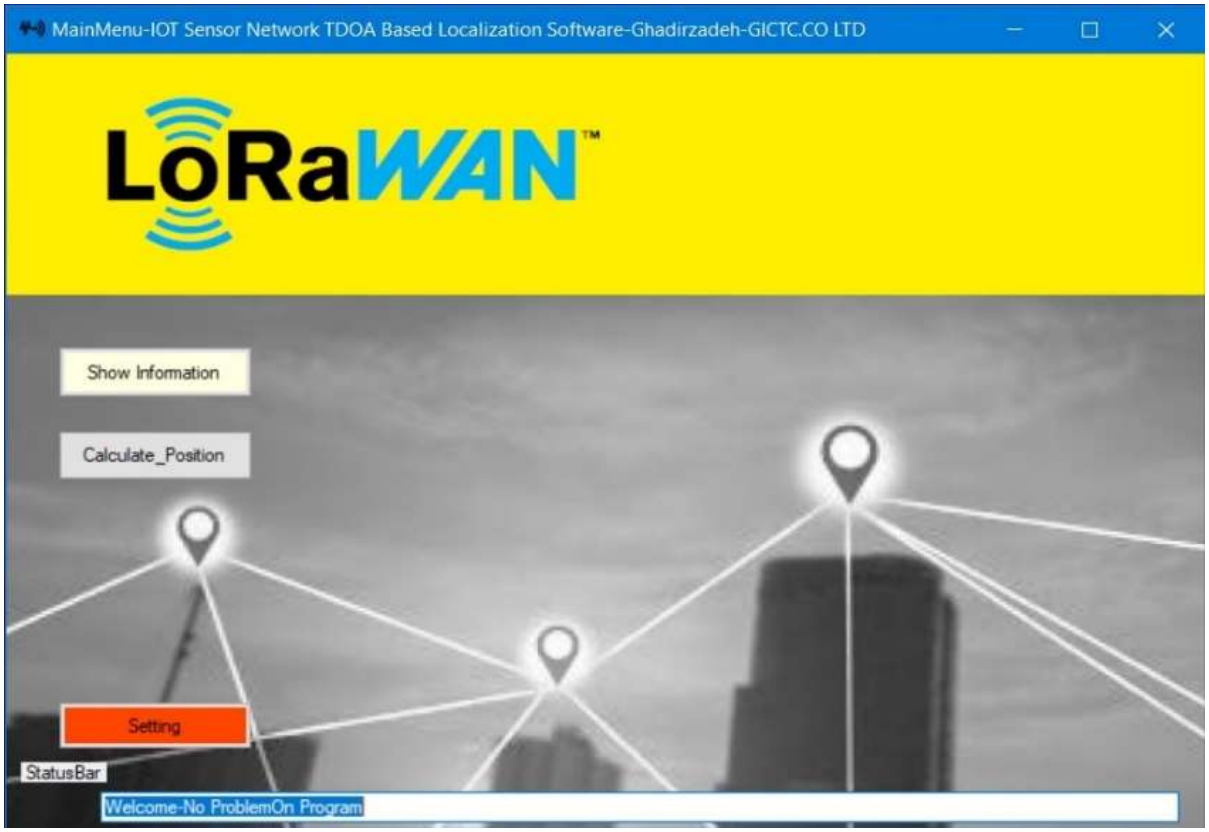


Fig.3-9. CDF of Errors obtain by WNNL for all message payload of one sensors

The two CDFs shows that WNNL algorithm has better accuracy (less error) when distance between reference sensor position and reference gateway is less than 3KM while NNL has better accuracy (less error) when these distances is more than 3KM, in other word using NNL we have 3.30KM error in 78% of cases while in WNNL 18% of cases have 3KM errors and 70% 4KM errors.

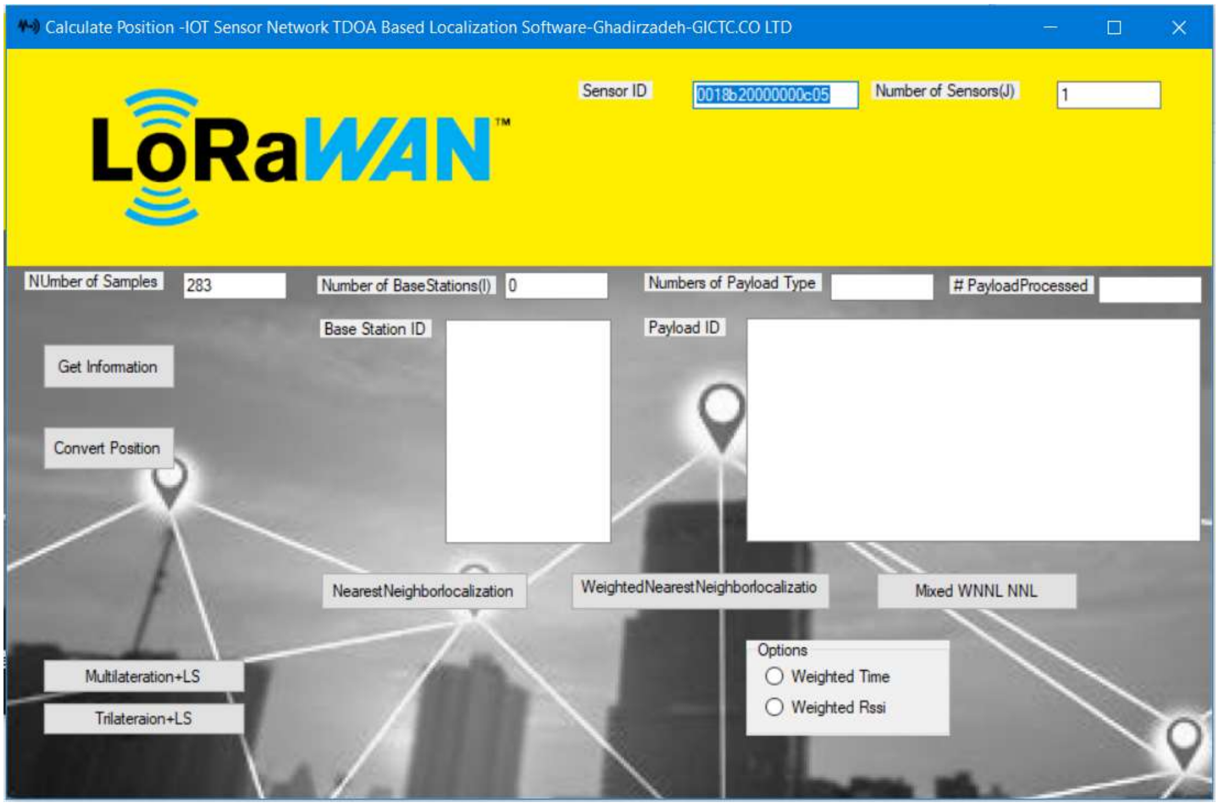
3.7. Software and Application User Interface: The user interface of third-party application designed with Microsoft Visual studio coded in C# language and it could be run on any operation system which could support Microsoft dot.net framework 4.5 or above, meanwhile the software itself tested on Microsoft Windows 10 operation system which run on a computer with Intel® Core™ i7-6700k with 4.00 GHz and 16 GB of physical memory specifications. On the main page of the software two buttons allows to access the database for viewing it and the position estimation algorithms. On the position calculation windows, top right boxes show the information got at the initialization step also a button provided for coordinate conversion from geodetic location to the Cartesian ones, which needed to allow coordinate converted before running the algorithms while at the middle of this windows three buttons provided separated and joint execution of NNL and WNNL algorithms with their specification. From localization window, first by using get information button software will get some information about end-node (Sensor_Id) and it's numbers and using number of samples input as number of rows that should be browse from database it will able to get number of relatives gateways and message payload of corresponding samples message payload than using convert position button it will convert latitude and longitude of both sensor and gateways to the Cartesian coordinate used in the next step during algorithm executions. Finally at the last step of location estimation by using different buttons different localization could be selected to be applied on the datasets. Figure 3-10 and 3-11 show the main and localization windows of software.



MainMenu-IOT Sensor Network TDOA Based Localization Software-Ghadirzadeh-GICTC.CO LTD

StatusBar: Welcome-No ProblemOn Program

Fig.3-10. Main window of the application



Calculate Position -IOT Sensor Network TDOA Based Localization Software-Ghadirzadeh-GICTC.CO LTD

Sensor ID: 0018b20000000c05

Number of Sensors(J): 1

NUmber of Samples: 283

Number of BaseStations(I): 0

Numbers of Payload Type:

PayloadProcessed:

Base Station ID

Payload ID

Options
○ Weighted Time
○ Weighted Rssi

Fig.3-11. Localization window of the application

4. Conclusion

In this project, a whole IoT tracking system was analyzed as far as its application implemented in order to present accuracy results using LoRa technology. The two designed algorithms demonstrated that it can be feasible to locate a device in a static spot with an accuracy of around 1000-3000 meters. However, for a real-time tracking application it can only be seen as a first approach, and not as a usable one. In general, the computational resources needed in such algorithm are much higher since all the coordinates are tested. But, as the algorithm is in the server site, this should not be a problem because the available resources there are unlimited. The software itself allowed to detect the main outliers to improve the accuracy. Regarding the power consumption. Typical GPS + GSM based devices use 400–600 mA during transmission so using LoRa tracking system can reduce the power consumption considerably. Another problem is the multipath of the signal, which causes wrong measurements of the TDOAs. Gateways do not always receive the direct path of the signal due to the reflections with terrestrial objects like buildings, forests or mountains. The ability to resolve this phenomenon depends on the bandwidth of the signal. If the bandwidth is large, the resolution is better and vice versa. The bandwidth employed in LoRa is small (125 kHz), so the recorded times in the gateways can be the time of a multipath signal instead of the direct one. Summarizing the discussions above:

- LoRaWAN TDOA geolocation is able to provide positioning accuracies of 20m to 200m in general and in this project up to 1000m to 3000m.
- Benefits of LoRaWAN geolocation are achievable with long-lived, battery-powered Class A end-devices at zero additional BOM cost.
- Mitigation of multipath errors and sound gateway-placement geometry will provide accuracies.

Specification Updates

- LoraWAN ™ 1.0.0 -> 1.0.1 -> 1.0.2 -> 1.1
- 1.1 in development, due mid 2017
- Adds:
  1. Passive & Handover roaming capabilities
  2. Class B clarifications
  3. Class A/C temporary switching
- Needs back-end interfaces to standardize

•Alliance is committed to backward compatibility

A Spread Spectrum Technology
•Chirped-FM modulation, symbols of ramping frequency
•Processing gain = increased receive sensitivity
•Enables longer range at expense of lower data rate

Adaptive data rate(ADR)
•LoRaWAN can auto-magically manage SF for each end-device:
•To optimize for fastest data rate versus range
•For maximize battery life, and
•Achieves maximum network capacity

License free Sub-GHz Frequencies
•Europe: 868 MHz Band
•Network channels can be freely attributed by the network operator
•Three mandatory channels that all gateways should operate on it
•EU gateways are typically using 8 channels
•End-devices must be capable of at least 16 channels

LoRaWAN™ Network Protocol Security
•Based on 802.15.4 Security
•AES-128
•Enhancements:
•Network Session Key (NwkSKey)
•Application Session Key (AppSKey)

Each end-device class has different behavior depending on the choice of optimization:
•Battery Powered – Class A
•Low Latency – Class B
•No Latency – Class C

Low Power Wide Area Network (LPWAN)
•Bidirectional, acknowledged
•Simple Star Network Topology
•Low data rate
•Low cost
•Long battery life
•Long Range

Ideal for:
•Internet of Things (IoT) & Machine-to-Machine (M2M)
•Industrial Automation
•Low Power Applications
•Battery Operated Sensors
•Smart City, Agriculture, Metering, Street lighting
• LoRaWAN TDOA geolocation is particularly well suited for application such as:
•Geo-fencing. Has a normally stationary asset moved? (Anti-theft for construction sites, utility yards, airport, campuses, etc.).
•Tracking slow-moving assets requiring infrequent position updates (people, pets, livestock herds, vehicles, etc.), particularly
Applicable to smart agriculture and smart cities use cases.
LoRaWAN TDOA geolocation may not be well suited for use cases such as:
• Real-time mobile-asset tracking. Higher frequency positioning fixing means more power consumption, usage of Class C end-devices, etc.
•High-dynamics asset tracking.
•High-precision positioning (sub-meter, at least using the current gateway spacing and clock sources).
• The LoRaWAN protocol can be used as the transport layer for use cases requiring GPS capabilities.

5. *F*uture Work

Some improvements must be implemented in order to make this Scenario work as a real-time tracking device. The enhancements should not only be done in the algorithm, but also in the gateways, since they are responsible for recording the time when the packet is received. The clock of the gateways was not intended for using in geolocation techniques so a more efficient and faster radio frontend would be beneficial by allowing to obtain more accurate timestamps. Another solution could be to increase the number of gateways in order to increase the number of TDOA and consequently improve the accuracy. Regarding the algorithm, other lines could be followed to improve the results. First of all, Machine Learning techniques like Decision Tree, Naive Bayes or Support Vector Machine could be applied to combine TDOAs with RSSI measurements. Low values of RSSI might mean that the received signal is not the direct path and can be discarded. In this case, a large dataset would be needed in order to divide it in three different groups: one for training, one for validating and one for assessing the suggested model. In order to improve the accuracy in "realtime", a technique such as the k-Nearest Neighbors could be use,since it processes closer samples ,or Multilateration with least-squares error minimization technique could be applyed, The Haversine formula used by algorithms can be substituted by the Vicenty formula which is more accurate [8]. Having solved the basic TDOA problem, we now turn our attention to the problem of multipath effects in wireless channels. In this particular case, which usually applies to civilian cellular phone networks, noisy measurements are less of a concern since the receiving platforms are stationary. In other words, since the locations of the receivers are known precisely, and since their clocks can be synchronized much more accurately than the clocks in moving platforms, then the accuracy of the measurements is not the dominant source of error. The dominant source of error in this application is the multipath effect, as was demonstrated, the TDOA solution presented here reproduces the coordinates of the emitter not precisely if the problem of the multipath delays is exist. We must emphasize that the assumption here is that the measurements are noise free. In the more realistic case of noisy measurements, a numerical optimization technique may be easily implemented in conjunction with this solution. It is recommended that some experimental investigation be carried out in the case of urban (civilian) cellular networks. Such investigation can reveal the environments (that is, cities, suburbs) where high geolocation accuracy is possible and the environments where high accuracy is unattainable.

6. *R*eferences

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