GEOLOCATION WHITEPAPER

Prepared by:
LoRa Alliance™ Strategy Committee

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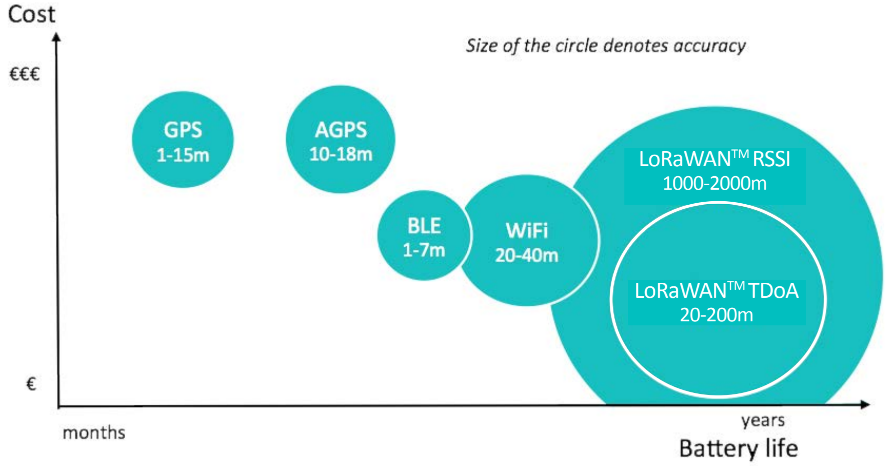
1 INTRODUCTION

LoRaWAN™ infrastructure provides a geolocation solution for low-power wide-area networks (LPWANs), enabling a wide range of applications requiring location determination for battery-powered endpoints. The geolocation functionality is supported by any existing LoRaWAN end-devices, eliminating additional cost and requiring no additional processing power.

2 AUDIENCE

The audience for this whitepaper is LoRaWAN service providers, enterprises and end-device manufacturers intending to develop applications leveraging LoRaWAN geolocation capabilities. This paper will describe the technical capabilities of LoRaWAN geolocation, highlight application use cases that are suited to LoRaWAN geolocation, and provide several deployment case studies.



LoRaWAN TDOA/RSSI
- 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

Figure 3-1: Comparison of Geolocation Technologies

3

GEOLOCATION TECHNOLOGY COMPARISON

The graphic above provides a visual comparison of cost vs. accuracy vs. battery life of several geolocation technologies.

As represented in Figure 3-1, 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 paper will discuss TDOA, which is particularly well suited for applications requiring low-cost, battery-powered end-devices with positioning accuracies in the 20m to 200m range.

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.

Best power efficiency is achieved for end-devices requiring infrequent location determination (days or weeks). These end-devices are typically stationary or infrequently moving assets implemented as Class A. The geolocation capability for these end-devices comes at no additional bill of materials (BOM) cost.
Mobile assets requiring more frequent position determination will transmit more frames, consume more power, 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.

The focus of this paper is outdoor, wide-area geolocation. It should be noted, however, that the LoRaWAN community is investigating various techniques to provide indoor accuracies of 10m or better (100m gateway density, improved clock sources, etc.). This would compete favorably with indoor WiFi Angle of Arrival (AOA) techniques providing 1m to 3m accuracies.

4 THE LoRaWAN™ GEOLOCATION CAPABILITY

This section provides a technical overview of LoRaWAN TDOA geolocation and error factors impacting accuracy.

4.1 Architecture

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, and the end-device location is determined using multilateration techniques. The multilateration process is shown in Figure 4-1.

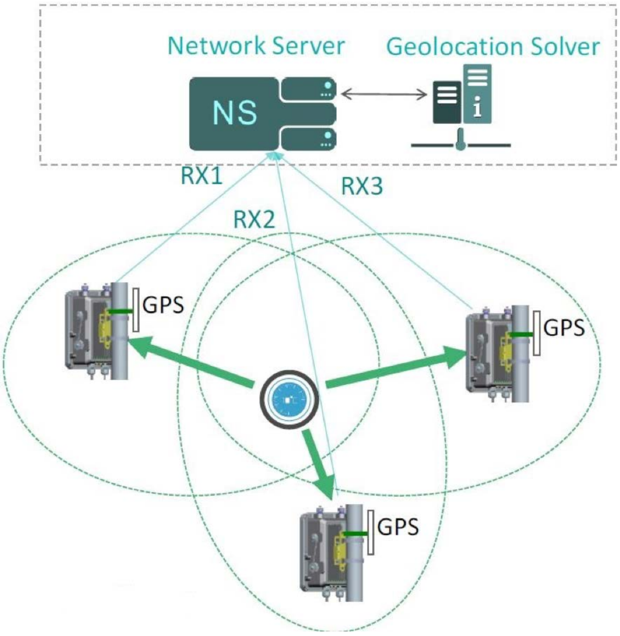


Figure 4-1: Geolocation Architecture

There is no additional hardware required on the end-device beyond its LoRaWAN interface. Gateways do require accurate time synchronization; this is currently achieved with GPS at the gateways (or any means available to synchronize gateway clocks to within a few tens of nanoseconds). Each received uplink frame is accurately time-stamped by the gateway. This time stamp is forwarded to the network server as part of a frame's metadata, which also includes signal level, signal-to-noise ratio and frequency error.

The network server sorts multiple receptions of the same frame, groups all the metadata including the timestamps for this frame, and requests a geolocation computation from the geolocation solver. The elementary geolocation solver function is to compute, for a given frame, the difference in time of reception seen by pairs of gateways. This time difference measures proximity of the end-device to one gateway of the pair compared with the other. When the TDOA is known for a pair of gateways, the end-device can be placed on a hyperbola. With(i) several such time differences, the end-device can be placed on several hyperbolae. The end-device is positioned at the intersection of these hyperbolae.

The accuracy of the position fix depends on several factors:

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

4.2 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 4-2 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.

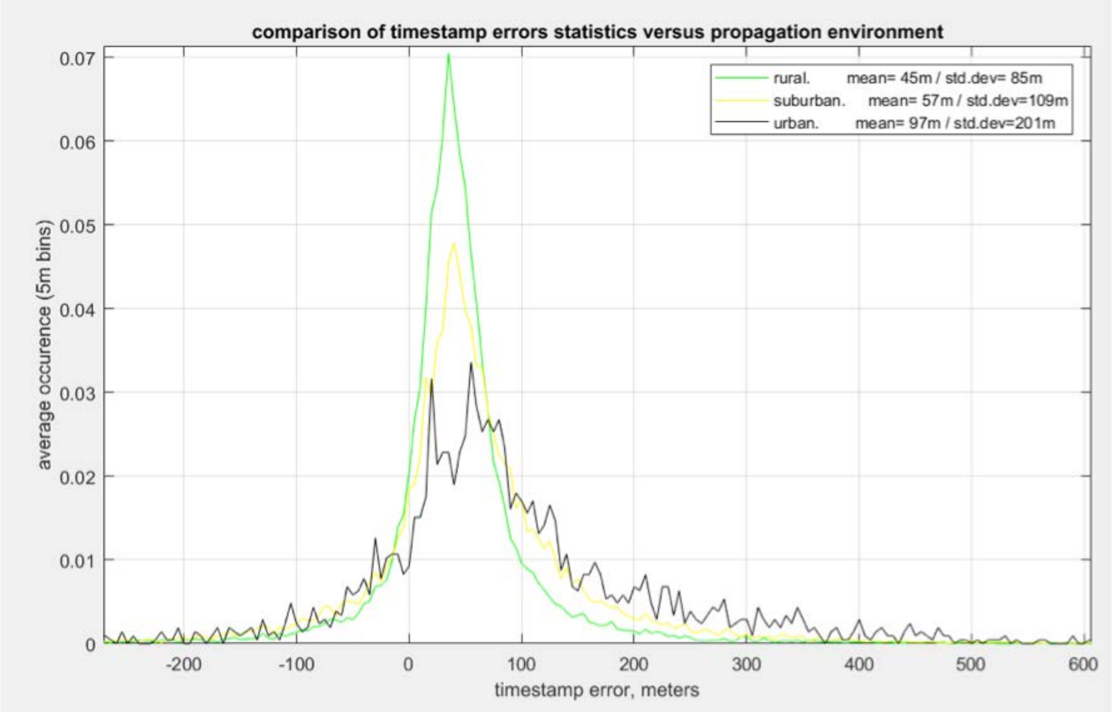


Figure 4-2: Statistics of Timestamp Errors

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).

We can classify the timestamp errors with a bias, which is the average error, and a spread around this average. Bias increases and spread widens as the propagation environment degrades.

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)

The geolocation solver is designed to mitigate multipath. The solver selects a candidate set of timestamps to be processed, ignoring the rest. The solver then aggregates the remaining data and solves for the end-device location.

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

4.3 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 vs. 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.

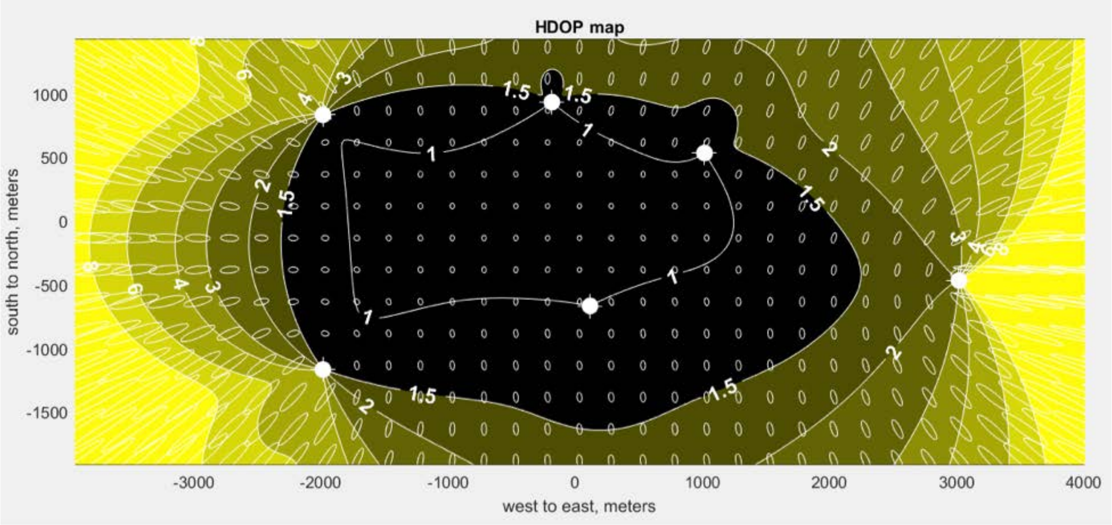


Figure 4-3: HDOP Map

Each time difference computed by the geolocation solver defines a hyperbolic curve(ii). Hyperbolas are open curves, so their intersections can lead to error amplification when the end-devices to be located are not well positioned vs. the receiving gateways.

GDOP captures this error amplification factor, which depends solely on geometry: gateway locations vs. end-device locations. For position fixing in two dimensions, we compute Horizontal DOP (HDOP). When the HDOP is 1, there is no amplification of errors; if the gateways show an uncertainty of, say, 60m on the timestamps (i.e., 200 nanoseconds), the final uncertainty of geolocation will be 60m. With an HDOP of 2, the final uncertainty will be 120m. HDOP can even be lower than 1 if high gateway density is achieved.

Figure 4-3 is an example of an HDOP map simulating a deployment of six gateways. The gateways are represented with red stars and the HDOP is shown as contour zones.

In the middle zone, HDOP is >1 and increases to >8 toward the sides. Outside the polygon formed by the gateways, HDOP increases very quickly. High HDOP significantly degrades geolocation accuracy.

White uncertainty zones are represented at regular spacings, depicting both the amplitude of the position error as well as the orientation of the error (greater along the radial pointing to the center of the polygon). Note the east side of the map where, even inside the gateway polygon, HDOP reaches 2 with larger errors along the north-south axis. This is due to low gateway density along that axis.

Note that closer gateway placement does not always provide for better geolocation performance; what matters most is a regular gridded pattern for gateway placement. Location accuracy will be better at the middle of a square of four gateways, compared with the middle of a rectangle.

For small-scale or trial geolocation deployments, it is highly recommended to compute HDOP and optimize gateway positions accordingly. Poor performance outside the coverage polygon should be treated as a consequence of geometry.

4.4 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. Gateways mounted on low rooftops or billboards in urban locations can also suffer from the “urban canyon” effect of fewer satellites in view.

When GPS reception is of good quality, the time base error is on the order of 25ns (<10m). 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.

4.5 Filtering Improves Accuracy

Depending on the application, it is possible to filter the output results of the geolocation solver 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. Kalman filtering is a more generic technique that can estimate both location and speed from noisy observations (a version of Kalman is used in most positioning systems). 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.

Being optimized for low power operation, LoRaWAN duty-cycle limitations apply in some regions such that an end-device will only transmit a limited number of frames each day. This limitation is an aspect of all LoRaWAN communication in such regions and is not specific to geolocation messaging. The practical implication is that fixed or nomadic devices will be much better located than moving devices, as several frames can be aggregated to provide a filtered location estimate.

5

DEPLOYMENT CASE STUDIES

5.1 Port of Barcelona (Actility/Cisco)

An obvious use case for LoRaWAN geolocation is vehicle tracking. GPS-based vehicle tracking has been available for several years, but the technology is not widely deployed due to complexity of vehicle installation. A typical deployment of GPS for positioning and cellular for reporting is relatively power hungry and requires connection to the vehicle battery.

A new generation of low-power trackers, based on LoRaWAN TDOA geolocation, is now available. At Mobile World Congress 2017, Actility and Cisco installed six IR829/IXM LoRaWAN gateways to cover the ZAL Port of Barcelona with a dedicated LoRaWAN network. The ZAL management group provides security, maintenance and general services to companies within the port.

The network deployed at the port covers an area of 0.43km^2. The six gateways were spaced 400m to 600m apart, ensuring good coverage in this suburban-type area. Three-story metallic buildings were typical. There are no high points in the area for antenna mounts, so the antennas were deployed directly on the rooftops (a suboptimal configuration).

Abeeway Master Trackers were installed on the maintenance vehicles. For the most power-efficient geolocation, the trackers operate in LoRaWAN TDOA mode. Assisted GPS reporting using LoRaWAN uplink is also available for use cases requiring better accuracy (sub 10m) and less concern for power consumption. The trackers provide 50x battery savings vs. typical AGPS/GSM trackers and a five-year lifetime on C-type batteries (24 fixes per day). Installation is simple: The trackers are self-powered, so they were screwed, glued or tied to the vehicles.

The Abeeway ApyApp application was used by ZAL Port to monitor the vehicles' activity on-site.

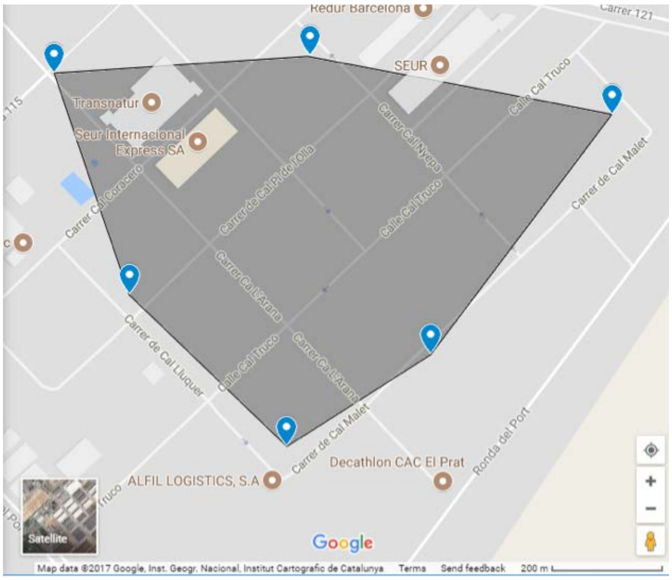


Figure 5-1: Gateway Locations in ZAL Port of Barcelona

In the ZAL Port use case, the application must compute how much time each vehicle has spent in front of each building (i.e., how long it has been parked). The buildings in the logistics area are quite sparse; vehicles are parked >80m from buildings and most often parked for periods varying between 20 minutes and 12 hours. Parked vehicle tracking is a prime application for TDOA-based geolocation; trackers reporting once every 10 minutes are easily located with 60m to 80m accuracy. The geolocation servers can perform averaging over multiple frames when the vehicles are parked and are able to detect when the vehicles start to move again. Figure 5-2 presents the position accuracy achieved for stationary (parked) vehicles.

It is also possible to determine the approximate real-time position of moving vehicles using TDOA. We have measured that a moving vehicle can be tracked to an average precision of 171m. This was adequate to assess in which general direction the vehicle was heading, to understand if it was headed to its next servicing location or back to maintenance parking at the end of the day. In-transit accuracy is less important for this use case, as geolocation is mainly used to trigger alerts when a vehicle enters or exits a designated geo-fenced area. Figure 5-3 presents the accuracy achieved for moving vehicles.

5.2 Issy-les-Moulineaux/Boulogne (Actility/Cisco)

Cisco and Actility have deployed five IXM LoRaWAN gateways near Paris to validate LoRaWAN geolocation capabilities. The gateways cover the urban environment of Issy-les-Moulineaux and Boulogne. Ethernet or cellular gateway backhaul is employed. The testbed is operational 24 hours a day, enabling stationary and mobile test nodes to generate messaging that is recorded for geolocation tools and application development.

The deployed network covers a perimeter of ~1.6km^2. The four gateways are spaced 900m to 1300m apart, forming a pentagon. A fifth gateway, Boulogne, was later added for future test scenarios.

The area contains commercial, municipal and residential buildings mixed with more open environments such as the Seine River, parks and a stadium. Antennae are mounted at heights of 60m to 126m. The high-point (Épinettes, in Figure 5-4) provides maximum long-distance coverage, but ground-level coverage sometimes suffers. As the landscape is hilly, more gateways are required to insure optimum geolocation capability (all end-devices heard by at least three gateways).

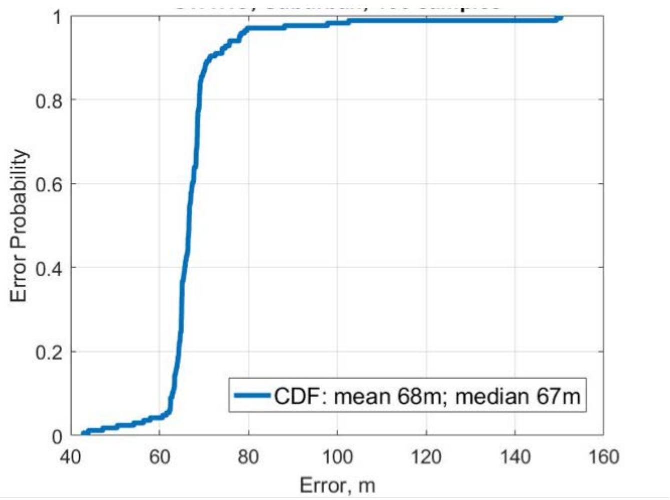


Figure 5-2: ZAL Port TDOA Position Accuracy, Stationary (Parked) Vehicles

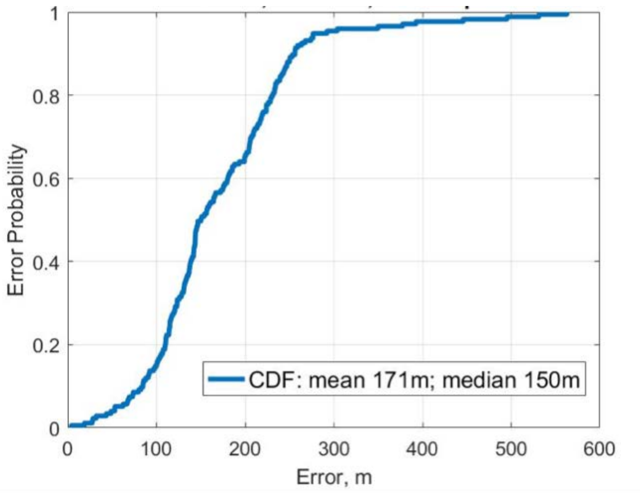


Figure 5-3: ZAL Port TDOA Position Accuracy, Moving Vehicles

Stationary asset geolocation testing was performed using Adeunis V2 Field Test devices configured to uplink every 20 seconds. Eight uplinks were factored into the geolocation solution. The end-devices were configured with a "stationary" profile, with Adaptive Data Rate enabled and a mixture of acknowledged and non-acknowledged uplinks.

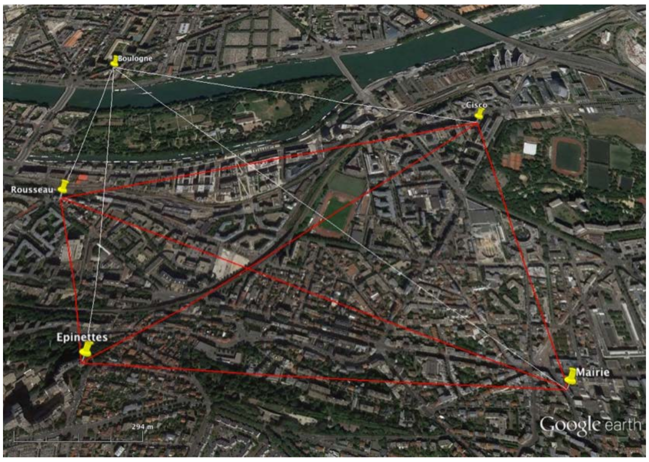


Figure 5-4: Issy-les-Moulineaux/Boulogne Deployment

Accuracies of 75m to 115m (with approximate standard deviation of 25m) were achieved for end-devices placed at various locations within the area bounded by the gateways (good HDOP). Accuracy degrades to upwards of 400m outside the area perimeter (poor HDOP). These results are consistent with the ZAL Port findings in Barcelona. A typical positioning plot is provided in Figure 5-5.

Testing of additional gateway geometries, stationary end-devices and mobile end-devices is ongoing.

Figure 5-5: Paris Stationary Geolocation Sample

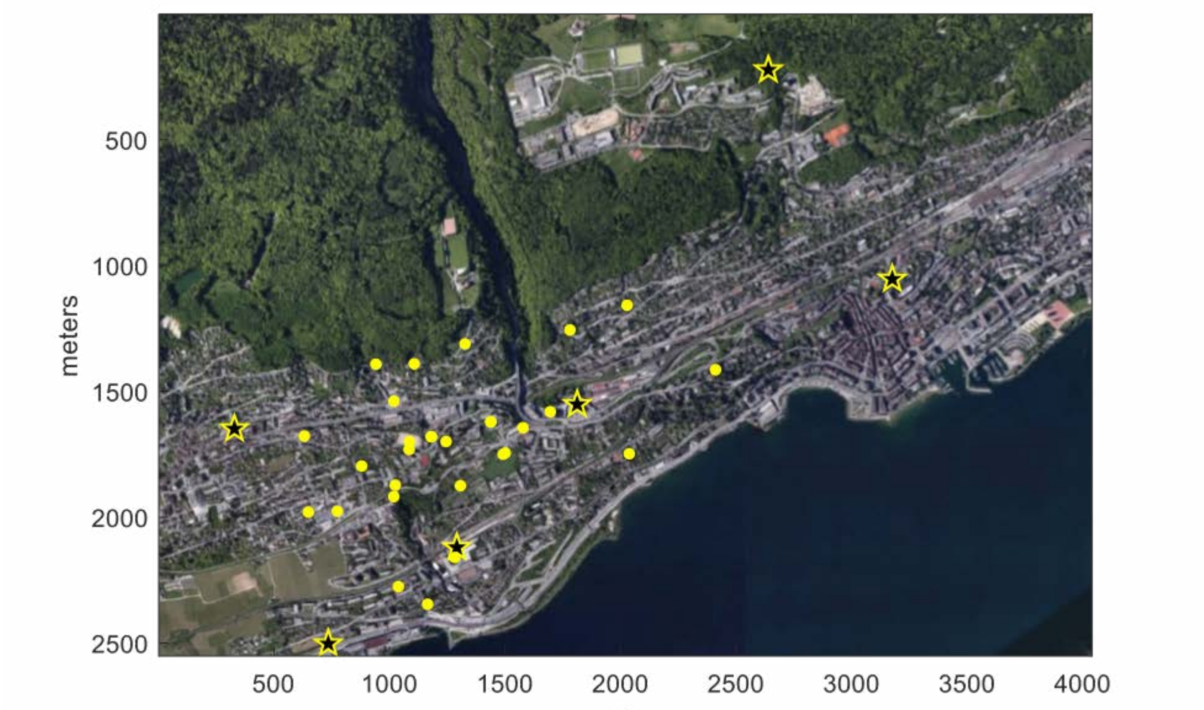


Figure 5-6: Neuchâtel Stationary Geolocation Sample

5.3 Neuchâtel (Semtech)
Semtech is testing LoRaWAN geolocation in the urban environment of Neuchâtel, Switzerland. The city contains many hills and is situated between a lake and a mountain. This makes it a difficult case from a GDOP perspective. There is also long delay multipath from the hills. Figure 5-6 shows the six gateways and the 30 stationary, outdoor testing points.

Figure 5-7 presents the cumulative distribution function of geolocation performance for various numbers of LoRaWAN frames received from the 30 test points. With a single frame, the median accuracy is around 150m, and taking eight frames improves accuracy to 80m. No filter is applied.

Several tests have been carried out at different data rates: SF7, SF10 and SF12. Performance was strictly identical among them, demonstrating that multipath and GDOP are the dominant factors for performance. Note the worst performance coincides with poor GDOP: with eight frames, the 90th-percentile performance is only 205m.

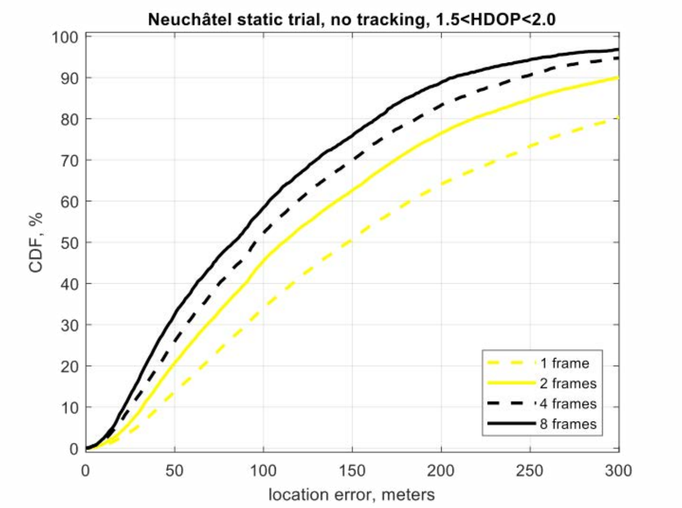


Figure 5-7: Neuchâtel Geolocation Performance

5.4 Mkomazi National Park (Semtech/Kerlink)

The Internet of Life and the ShadowView Foundation are developing LoRaWAN trackers to protect endangered black rhinos in the reserve of Mkomazi National Park, Tanzania with the technical support of Semtech and Kerlink. The LoRaWAN non-GPS trackers are smaller and less expensive, consume less power, are impervious to poachers equipped with GPS jammers, and enable more frequent geolocation reports compared with the GPS trackers they are designed to replace. A first LoRaWAN tracker has been implanted directly into the rhino horn last September and enables the park's security personnel to strategically position themselves to monitor the rhinos.

The rhinos' sanctuary is a fenced area spanning 50 square kilometers. Four geolocation-enabled Kerlink gateways have been deployed to cover the area. The distance between gateways is between 4km and 10km. The geolocation accuracy is better than 50m, and in some cases better than 20m.

Figure 5-8 shows examples of tracker geolocation plots, each point using four frames to compute a location. The first two figures have a median error of 40m, and the corresponding test points are in an area with a HDOP higher than 2. The third point has a HDOP of 1.5. The exact location of test points and gateways cannot be made public. The network will be optimized for better HDOP inside the sanctuary, and deployments in other natural parks are already planned. Other smart park applications used by the park management include solar-powered trackers installed on vehicles to track the whereabouts of personnel and tourists in high-risk areas.

Figure 5-9 shows the performance for a single-frame geolocation estimate, which is also better than 50m but shows more variations than in the four-frames case.

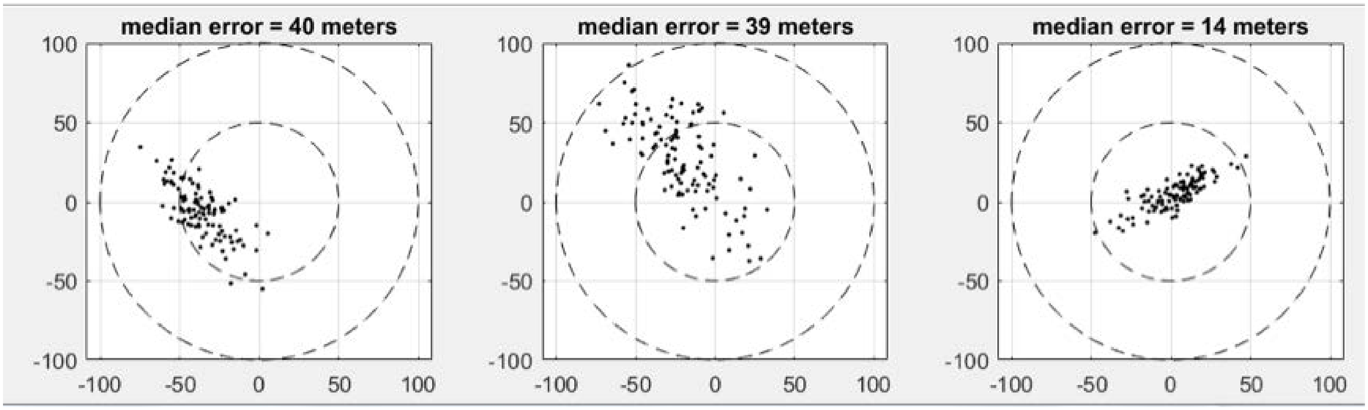


Figure 5-8: Mkomazi Geolocation Trial Plots, Four Frames

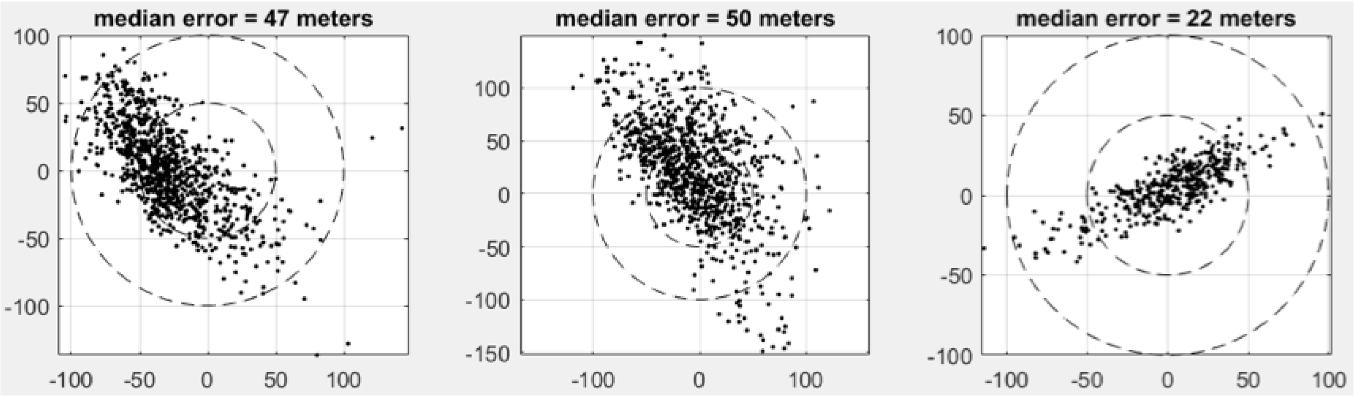


Figure 5-9: Mkomazi Geolocation Trial Data, Single Frame

5.5 Bouygues Construction (Objenious/Sagemcom)
Construction logistics, vehicle fleet management and waste management are promising vertical markets for the Internet of Things (IoT). Objenious (Bouygues Telecom) and Sagemcom together developed Bouygues Construction's Ubysol solution, providing construction waste tracking from trucks as they transit between their loading and unloading sites.

The Ubysol solution supports the "Grand Paris" regional master plan, which is designed to transform the Paris metropolitan area (Paris proper plus 130 surrounding suburbs and communities) into a 21st century city. It is estimated that the project will generate more than 43 million tons of construction waste.

Each truck is equipped with a Siconia™ multisensor end-device. End-device data transmission is triggered by a motion sensor, and loading/unloading is sensed using a gyroscope. The link below provides a video of the use case:

https://youtu.be/TcFXi1ABfDk

For the sake of benchmarking LoRaWAN geolocation, some of the trucks have been equipped with GPS sensors. The GPS traces are compared with the LoRaWAN geolocation trace. As seen in Figure 5-10, the traces match very closely.

Statistical performances (CDF) have been obtained through months of daily traffic collection. The geolocation performance result for the Ubysol solution is presented in Figure 5-11. A median accuracy of 136m was achieved.

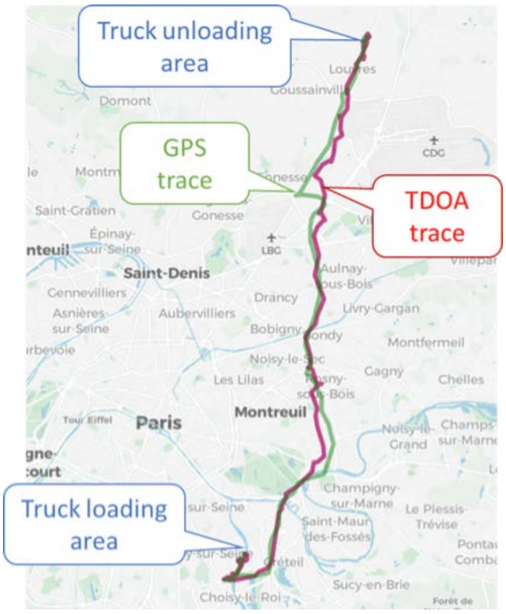


Figure 5-10: GPS Compared With LoRaWAN TDOA Trace

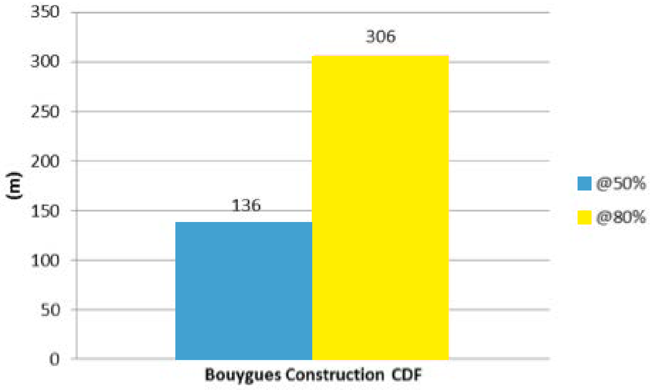


Figure 5-11: Statistical Accuracy Performance (CDF) of the Ubysol Solution

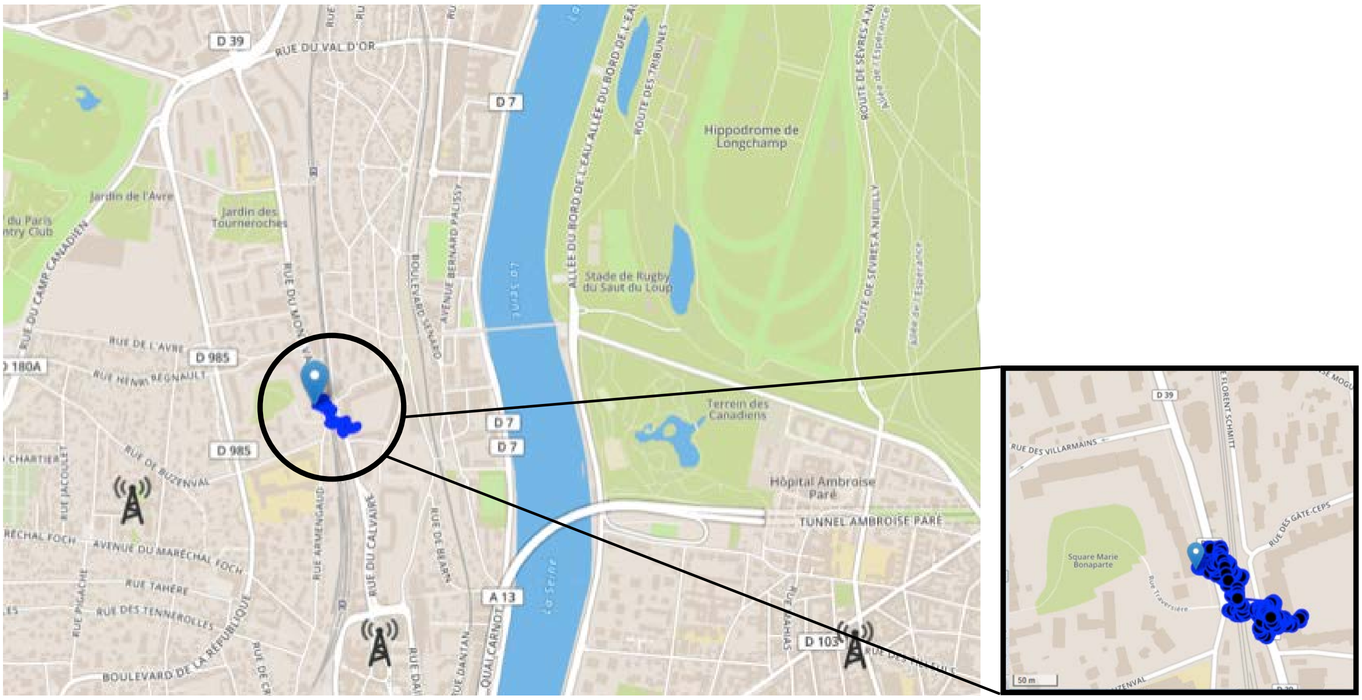


Figure 5-12: LoRaWAN Geolocation Positioning of Hand Trucks in Downtown Paris

5.6 Paris (Objenious/Sagemcom)
Asset management for urban settings presents several challenges: the environment is multipath rich, and non-line-of-sight propagation is typical.

Objenious and Sagemcom have deployed many Siconia™ devices to track the position of (normally) stationary hand trucks (a.k.a. "rolls") in downtown Paris. Geofencing notifications are triggered when a hand truck reports it has left a designated area.

Figure 5-12 illustrates the LoRaWAN geolocation position estimates for these end-devices, as well as the gateway locations, in downtown Paris.

Key performance indicators (KPI) for geolocation of these end-devices are given in Figure 5-13. CDF (upper left) and PDF (histogram, upper right) of the position accuracy are provided (mean: 57m, std: 18m), together with the location error (bottom left). The Instantaneous Inter-Site Distance (ISD; bottom right) seen from the end-device at each time sample is an indicator of the network density.

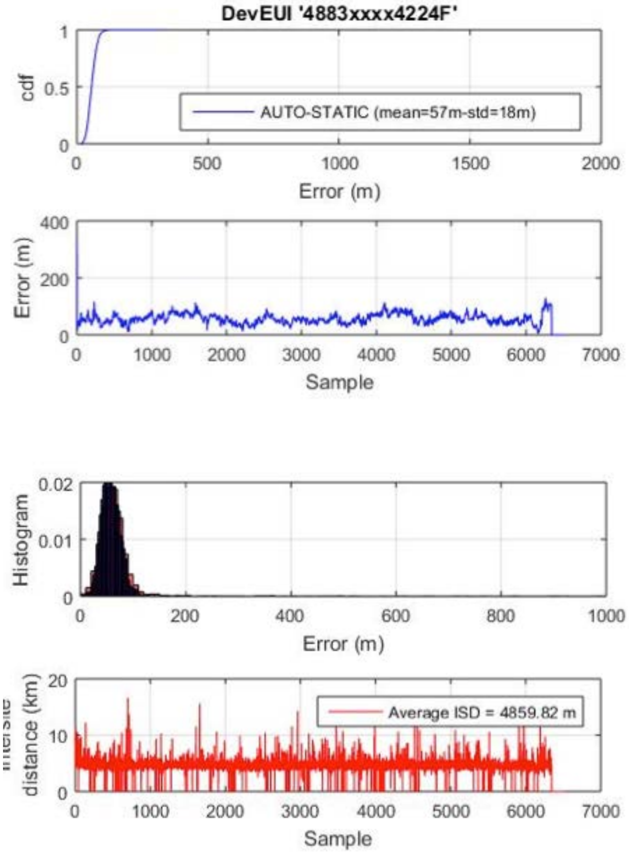


Figure 5-13: Fixed Device Performance (Accuracy CDF, ISD), Downtown Paris

Figure 5-14 presents instantaneous HDOP influence of the network layout on geolocation accuracy.

Prior to gateway deployment, static GDOP should be assessed as explained in section 4.3, taking into account the entire set of gateways available to the deployment area. Figure 5-15 illustrates GDOP obtained from a stationary end-device (in red) in the deployment area.

For the same stationary end-device, Figure 5-16 presents the end-device's measured radio environment (mean RSS) vs. end-device distance from gateways. Clearly for locations outside the corridor formed by the dense gateways, HDOP values are much higher than those obtained for locations aligned with the gateway corridor.

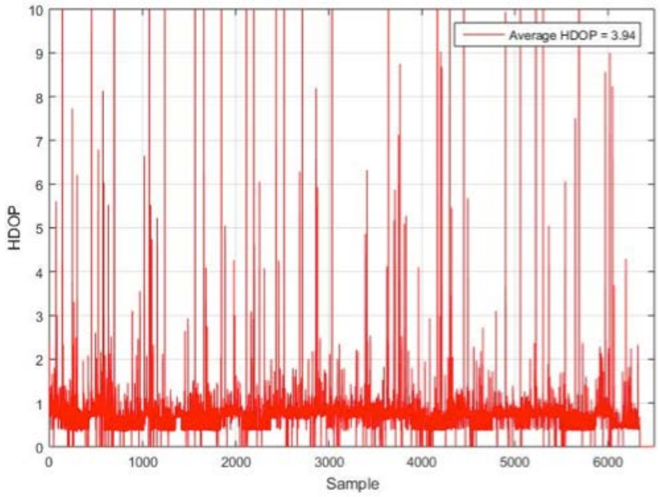


Figure 5-14: Instantaneous HDOP–Fixed Device, Downtown Paris

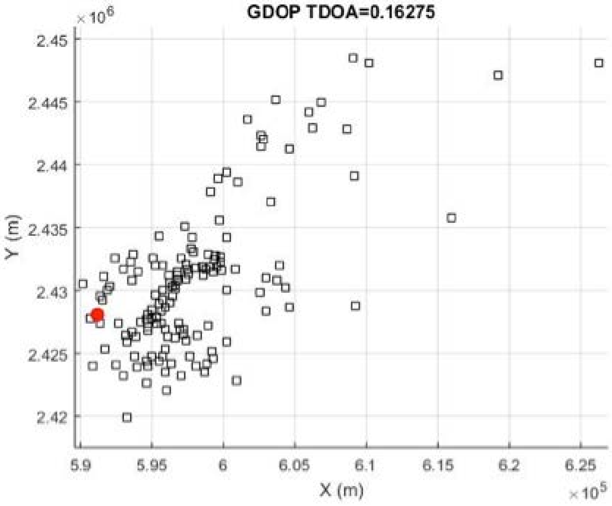


Figure 5-15: GDOP Estimate of a Stationary End-device (Red) Within the Gateway Deployment

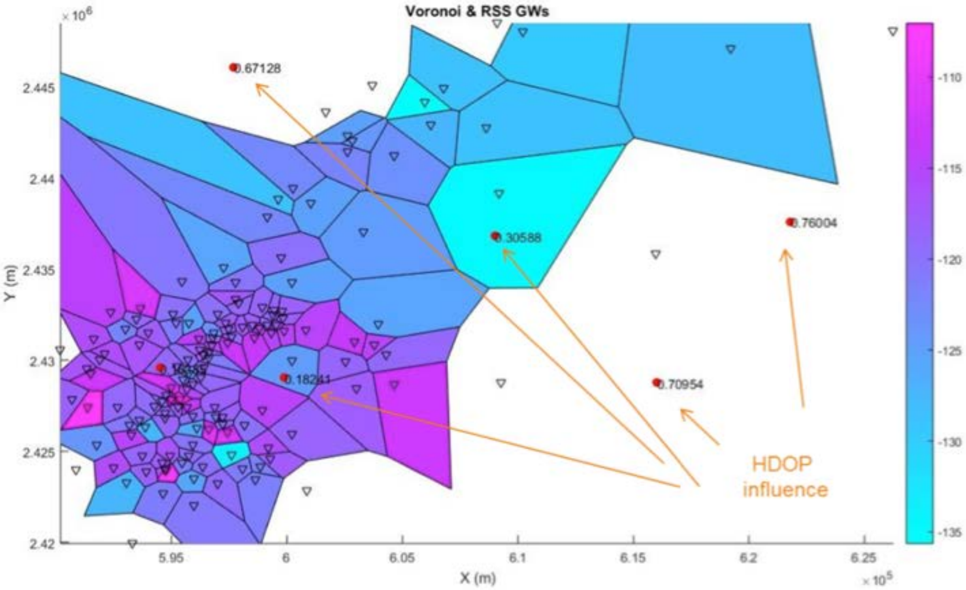


Figure 5-16 HDOP Influence vs. End-device Position From GWs

5.7 Thorigné-Fouillard (Kerlink/Semtech)

Kerlink is offering geolocation-ready stations in its Wirnet IBTS range supporting location-based services (LBS). These new stations provide fine timestamps (using Semtech's license) that can be used for geolocation purposes. A TDOA ranged-based solver has been developed and integrated into a proprietary LBS solution.

Kerlink also set up a few test platforms around the world in various environments and conditions (rural area, semi-urban, urban) to assess and optimize the performance of the solver, especially its calculation accuracy and location precision. One testbed is installed at Thorigné-Fouillard (Kerlink HQ) where it operates permanently. Four gateways are installed around the city and several end-devices have been placed in fixed positions. The solver calculates the position as it receives a message in near real-time, and then returns the result to a dashboard for mapping display.

Figure 5-17(a) and (b) shows the deployed network and the estimated positions obtained for an end-device. An analysis of HDOP (Figure 5-17(c)) allows us to understand the precision of the results. In addition, its information is used in a Kalman filter for post processing. The CDF, given for this end-device in Figure 5-17(d), shows an accuracy of 32m at 50%, 43m at 70%, and 62m at 90%.

Measure the circumference or area of a circle on the ground

Radius: 85.10 Meters

Area: 22,589.84 Square Meters

Circumference: 533.76 Meters

☑ Mouse Navigation

Figure 5-17: (a) Thorigné-Fouillard LoRaWAN network testbed (b) estimated positions for a stationary end-device

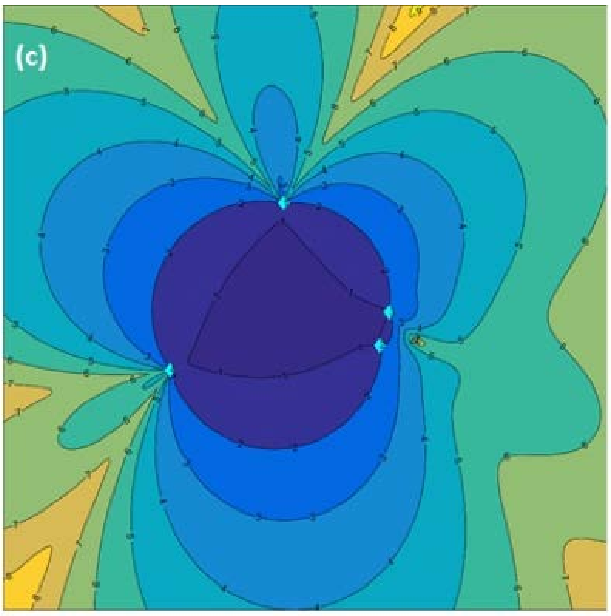
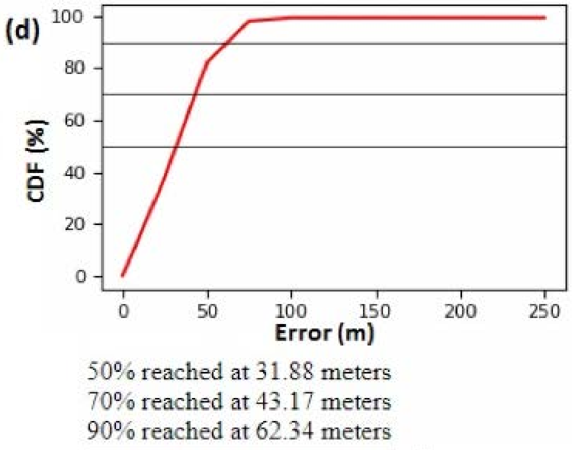
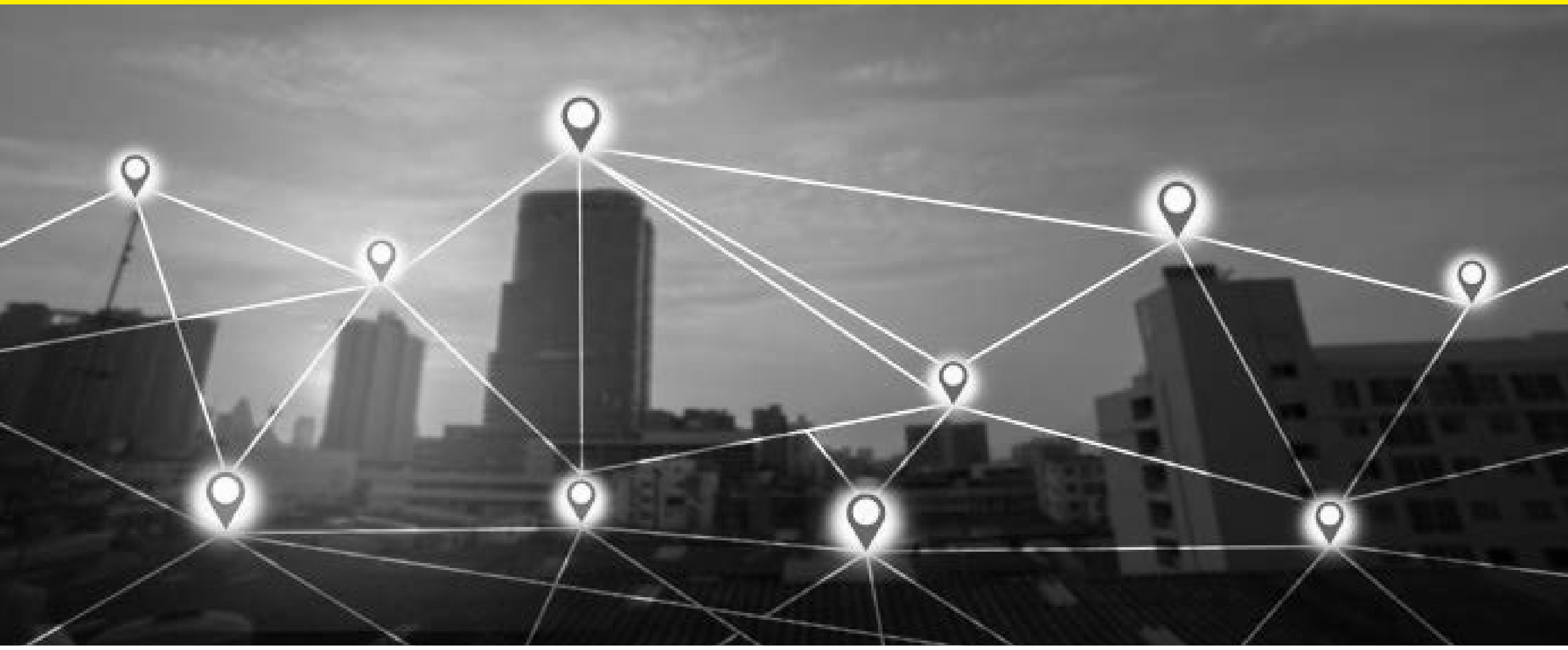


Figure 5-17: (c) HDOP



50% reached at 31.88 meters
70% reached at 43.17 meters
90% reached at 62.34 meters

Figure 5-17: (d) CDF



6

LoRaWAN™ GEOLOCATION TAKEAWAYS

Summarizing the discussions above:

- LoRaWAN TDOA geolocation is able to provide positioning accuracies of 20m to 200m.
- 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 approaching 20m.
- 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.

FOOTNOTES

i. Simplified for two-dimensional positioning. In general, for three dimensions, the time difference defines a hyperboloid.

ii. Simplified for two-dimensional positioning. In general, for three dimensions, the time difference defines a hyperboloid.