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Comparison of Performance and Power Consumption Between GPS and Sigfox Positioning Using Pycom Modules

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Sigfox is one of the newly-emerging LPWAN (Low Power Wide Area Network) technologies aiming to provide power-efficient solutions to the world of IoT. This study presents a comparison between Sigfox Geolocation and GPS (Global Positioning System) in terms of power consumption and performance which includes three metrics: accuracy and precision, response rate and response time. This study includes for the first part a series of lab tests where Sigfox Geolocation and GPS were studied in a single Sleep, Wake up, Idle, Tx/Rx cycle. For the second part, field tests with different geographical parameters (altitude, population, mobility) were conducted. Results of lab tests show that power consumption difference between Sigfox and GPS is a linear function of Idle time. In field tests, GPS presents a far superior performance than Sigfox in all metrics and marginally better power efficiency for relatively short Idle interval. For both GPS and Sigfox, a correlation between power efficiency and performance was observed. Results show that GPS operates best in rural environments while Sigfox stands out in urban ones. Payload size was observed to affect Sigfox in both power consumption and performance while different transmission rates only affect power consumption but do not seem to impact the other metrics. A solution based on the outcome of this study is suggested for a freight-monitoring system where geolocation is handled by GPS and the coordinates transmitted via Sigfox. As an emerging technology under constant development, Sigfox Geolocation is expected to have improved performance in the near future.
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1 Introduction

Carried out in collaboration with Survey Party AB, Sweden, this project presents a comparative study between the positioning services provided by Sigfox (Sigfox Geolocation) and GPS (Global Positioning System) in terms of performance and power consumption using FiPy development board and sensor shields manufactured by Pycom LTD (see Section 4.1 for detailed information of the modules). Performance in this study is defined by three metrics: accuracy and precision, response rate and response time and the Pycom modules are provided by Survey Party AB. This study includes two parts: lab tests and field tests. In the lab tests the performance and power consumption of Sigfox and GPS were studied in a single Sleep, Wake up, Idle, Tx/Rx cycle with different transmission/location query intervals and in the case of Sigfox, payload sizes. In the field tests, the impact of different geographical parameters (altitude, population, mobility) on performance and power consumption was studied. Results show that in general, GPS presents a far superior performance while being at the same time slightly more power efficient than Sigfox with relatively short location query interval. For both GPS and Sigfox, a strong correlation between power efficiency and performance was observed. For GPS, it works the best in rural environments while Sigfox stands out in urban ones. Payload size was observed to affect Sigfox significantly in both power consumption and performance.

1.1 Background

The Internet of Things (IoT) refers to the inter-connection and exchange of data among devices/sensors. Nowadays an explosion of IoT applications can be seen in many industries, many of which are adverse event-driven (e.g. sudden change in temperature, sudden change in acceleration due to accident) and have specific requirements such as long-range communication, low data rate and low power consumption. These requirements give rise to the emergence of a number of new wireless communication technologies: LPWAN (low power wide area network).

Survey Party AB is a company based in Lund that promotes the growth and development of companies, organizations and institutions by providing sound strategic
decisions based on top quality assays. One client of the company (a logistics company) is consulting about energy-efficient IoT solutions for a real-time freight monitoring system. The requirement is that the IoT device, placed amidst an assortment of freight and powered by a power bank, should function as long as possible without recharging. The system sends hourly report to the company of the freight's location, and in case of an emergency, the system immediately informs the company of the location and the nature of the emergency.

Based on the requirement of the system, Survey Party AB evaluates that LPWAN technologies are the most fitting for this IoT application. Since Sigfox offers a cheap positioning service shipped with every Sigfox module, it has been suggested to the client as a candidate solution. However, existing literature as to how well Sigfox Geolocation performs and how much power it consumes in different geographical environments was not found. Therefore it is the motivation of this study to supply this information. Currently GPS is one of the most widely used and most reliable positioning services; therefore a comparison between Sigfox and GPS is performed in this study.

1.2 Purpose
The purpose of this project is to find out how Sigfox and GPS positioning services compare with each other in terms of power consumption and performance. Based on the findings, a best tracking solution within the constraints of the provided hardware for a freight monitoring system will be suggested to Survey Party AB.

1.3 Related work
LPWAN technologies have attracted a lot of scholarly attention since their emergence. Since they are relatively new, a lot of research was done to assess their performance.

In "A comparative study of LPWAN technologies for large-scale IoT deployment", Mekki et al. provided a comparative study of three leading LPWAN technologies that compete for large-scale IoT deployment: Sigfox, LoRa and NB-IoT. Their conclusion was that Sigfox and LoRa are advantageous in terms of battery lifetime, capacity and cost, while NB-IoT offers benefits in terms of latency and quality of service [1].
In "Comparison of the device lifetime in wireless networks for the Internet of Things", Morin et al. compared device lifetime operating in different wireless networks including LoRa, Sigfox and a number of IEEE standards. According to the research, both Sigfox and LoRa excel in extending device lifetime but Sigfox only matches LoRa for very small data sizes, which is valuable insight for this project [2].

In their master thesis *A Study of Low-Power Wide-Area Networks and an In-Depth Study of the LoRaWAN Standard*, Nordlöf and Lagusson presented a general evaluation of existing LPWAN technologies. [3] Their main focus of study was LoraWAN which they tested on an electromechanical lock system.

Similar, in "Low power wide area networks: an overview", Raza et. al gave a thorough overview of all existing LPWAN technologies. Their main focus was on the challenges each technology faces. They observed that most standards focus on physical and MAC layers and the gap at the upper layers is yet to be bridged [4].

Location tracking is a key functionality in many IoT applications. As one of the most popular positioning services, GPS has attracted a lot of interest concerning its accuracy in different environments. For example, in "Consumer-grade Global Positioning System (GPS) accuracy and reliability" Wing et al. tested the accuracy and reliability of consumer-grade GPS receivers in a variety of landscape settings. They found that the test unit's performance appears to be influenced by canopy cover and satellite availability [5].

In "Investigation of GPS positioning accuracy during the seasonal variation", Dogan et al. observed that seasonal variation is a significant factor for determining the accuracy of GPS measurements and that increasing the observation period hardly improves the horizontal positioning accuracy while improving the vertical positioning accuracy [6].

Due to the processing-intensive nature of GPS in acquiring and tracking satellite signals, there have also been researches done with the purpose of seeking more energy-efficient GPS solutions. For example in "Evaluation of the trade-off between Global Positioning System (GPS) accuracy and power saving from reduction of number of GPS receiver channels", Sathyamorthy et al. examined GPS accuracy with 4 to 12 GPS receiver channels under both full range and obstructed satellite signal scenarios. They concluded that increase of power saving from reducing the number of channels
causes increase of probable errors but reduction of number of channels to match the number of available GPS satellites does not cause degradation of accuracy as there is no reduction in number of trackable GPS satellites [7].

Extensive reading of existing literature about LPWAN and GPS reveals that so far there has been no comprehensive study that compares the positioning performance and power consumption between Sigfox and GPS. Most Sigfox assessment projects focus on coverage, power consumption and deployment without taking positioning into evaluation.

### 1.4 Research questions

The research questions of this project are as follows:

**RQ1:** Using Pycom modules, how does GPS and Sigfox positioning services compare with each other in terms of performance and power consumption measured in one *Sleep, Wake up, Idle, Tx/Rx* cycle?

**RQ2:** How will the performance and power consumption change with different transmission or location query intervals and different geographical parameters (altitude, population density, mobility)? For Sigfox only, will different payload sizes make a difference?

**RQ3:** Based on the experiment results from RQ1 & 2, what would be the best tracking solution for a freight monitoring system within the hardware constraints of this study?

### 1.5 Delimitations

This is a bachelor thesis accomplished by two bachelor students in Engineering at Högskolan i Kristianstad. There are certain limitations as to measurement accuracy resulting from the technical limitations of the school lab equipment. For example, a professional power analyzer would have yielded better results than the Tektronix MSO2002B oscilloscope used in this study. In addition, the locations where the field tests are carried out are all within Skåne region and hence cannot represent the entirety of Sweden. In the mobility test cases, only a commuter bus (SkåneExpressen 1) is used, and its speed and route might differ from freight-carrying vehicles.
2 Theoretical background

In this section a brief introduction to the technical background of Sigfox and GPS is presented. Put in a nutshell, Sigfox positioning service relies on Sigfox backend running an algorithm to determine the location of a device using trilateration of signal strengths of replicas of the same message from that device received by at least three base stations. GPS positioning, on the other hand, relies on trilateration of satellite signals identified by the device's GPS receiver. The quality of communication between GPS receiver and the satellites is a major constraint on performance.

2.1 Sigfox

One of the first LPWAN technologies presented for the IoT market, Sigfox wireless technology is based on LTN (Low Throughput Network). It supports low data rate communication over larger distances and is therefore fitting for applications which transmits only a few bytes per day. One advantage of Sigfox is that it can be interfaced with cellular network to coexist with cellular wireless technologies such as GSM, CDMA, LTE etc [8].

The physical layer of Sigfox uses 192KHz of the publicly available band to exchange messages over the air. The modulation scheme is Differential Binary Phase-shift Keying (DBPSK) uplink and Gaussian Frequency-shift Keying (GFSK) downlink. Each message is 100Hz wide and transferred with a data rate of 100 or 600 bits per second depending on the region. In Europe, for example, the band used is between 868 and 868.2MHz (see Figure 1) [9].

![Figure 1. Sigfox technology based on Ultra-Narrow Band [9].](image)

By using Ultra-Narrow Band (UNB), Sigfox utilizes bandwidth efficiently and experiences very low noise levels, resulting in high receiver sensitivity, ultra-low power
consumption, and inexpensive antenna design. All these benefits come at an expense of maximum throughput of only 100 bits per second [9]. There exists a significant link asymmetry between Sigfox uplink and downlink as downlink was a recent evolvement and can only occur when an uplink message has set the downlink request flag. See Figure 2 for the exact frame structure of Sigfox uplink and downlink messages.

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Frame sync.</th>
<th>End-device ID</th>
<th>Payload</th>
<th>Auth.</th>
<th>FCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 bytes</td>
<td>2 bytes</td>
<td>4 bytes</td>
<td>0..12 bytes</td>
<td>var.</td>
<td>2 bytes</td>
</tr>
</tbody>
</table>

**Uplink MAC Frame**

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Frame sync.</th>
<th>Flags</th>
<th>FCS</th>
<th>Auth.</th>
<th>Error Codes</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 bits</td>
<td>13 bits</td>
<td>2 bits</td>
<td>8 bits</td>
<td>16 bits</td>
<td>var.</td>
<td>var.</td>
</tr>
</tbody>
</table>

**Downlink MAC Frame**

**Figure 2. Sigfox uplink and downlink frame structures [10].**

To conform to the regional regulations on use of license-free spectrum, Sigfox allows a node to transmit at most 140 12-byte messages per day over uplink and 4 8-byte messages over downlink. It means that acknowledging every uplink message is not supported. In order to ensure uplink communication reliability without support for acknowledgements, Sigfox uses two techniques. The first one is "cooperative reception" or "spatial diversity", which means that a node is not attached to a specific base station unlike cellular protocols. The emitted message by the node is received by any base stations that are nearby and on average the number of base stations is 3. The second technique is called "time and frequency diversity": the band between 868 to 868.2MHz (in Europe) is divided into 400 100Hz channels, out of which 40 channels are reserved. As the base stations can scan all the channels to decode the messages, the node autonomously chooses a random frequency channel to transmit its messages [4] and further sends 2 replicas on different frequencies and time [9] (See Figure 3).

A simple overview of the Sigfox network architecture is shown in Figure 4. The responsibility of the base stations is to receive uplink messages from end devices and transfer them to the Sigfox Support Systems (consisting of Sigfox Cloud and other backend services) which are in charge of processing the messages and sending them through callbacks to the customer system. This layer provides as well the entry point to the different actors of the Sigfox system (Sigfox, Sigfox operators, channels and
end-customers) to interact with the system through web interfaces or APIs [9]. What is particularly relevant for many IoT applications is the possibility for client applications to access device messages and synchronize the Sigfox Support System with their own IT systems.

![Figure 3. Sigfox time and frequency diversity feature][9].

Since Sigfox does not support message acknowledgement, in this study the method used to verify if a message has been successfully picked up by the base stations is by checking the device message history at Sigfox backend. Figure 5 is a partial screenshot of the message history of device 4D30EC used in this study. Each message contains information such as timestamp, sequence number, signal quality, location where the message was sent, etc.

![Figure 4. Sigfox network architecture][9].
Figure 5. Part of message history of device 4D30EC at Sigfox backend.

2.2 Sigfox Geolocation

Sigfox Geolocation is a low-energy location service shipped with all Sigfox modules. The only condition for using this service is the availability of Sigfox network. For customers located in a territory covered by Sigfox, the service only requires a monthly operation fee. As was mentioned in the previous section, Sigfox employs the "time and frequency diversity" technique such that an end device sends an uplink message at a random frequency and two replicas of that message at two other frequencies and time points. Three nearby base stations (on average) will pick up the signals with different RSSI (Received Signal Strength Indicator). The RSSI values are then used by a probability model at Sigfox backend with trilateration techniques to determine the location of the device with the highest probability, illustrated in Figure 6. Starting from 2017, Sigfox Geolocation has been endeavoring to increase its accuracy by using machine learning technology [9].

The location calculated by Sigfox has coordinates in latitude and longitude and is delivered through a callback or standard API. Hence, unlike GPS, a Sigfox end device actually does not know where it is. Another fact worth noting is, if messages from a device are not picked up by any base stations, for that device its location cannot be acquired by any means. According to official documentation, Sigfox Geolocation has an accuracy in km (between 1km and 10km for 80% of devices) depending on the base
station density where the device is located [12]; hence it is an already known fact that GPS far surpasses Sigfox in accuracy and precision because the 4th edition of GPS Standard Positioning Service (SPS) Performance Standard states that "well designed GPS receivers have been achieving horizontal accuracy of 3 meters or better and vertical accuracy of 5 meters or better 95% of the time" [13]. The purpose of this study therefore is not to prove this known fact but to quantify their difference in accuracy and precision using GPS as a reference system as well as give client an insight as to whether Sigfox Geolocation can perform well enough in the freight-monitoring system even with some inaccuracy. Sigfox as a LPWAN technology has the advantage of handling both geolocation and wireless communication at the same time, which is highly likely to be more power efficient than using GPS for geolocation and transmitting the location with a wireless technology. Thus the results of this study will help find out whether a trade-off between power efficiency and accuracy is worth making.

2.3 GPS

The GPS (Global Positioning System) technology is currently one of the most popular location services in use. This technology provides location information of any point on earth at any time. A standalone GPS receiver relies solely on satellite data to operate. A network of satellites orbit the globe to ensure that at all times there are 6 satellites ‘in sight’ from any point on earth [14].
This technology works by trilateration of at least 3 satellites' signals where each one of them transmits data regarding its position and current timestamp. The standalone GPS receiver will then receive and interpret the satellite signals and calculate its distance to each satellite, using the time the data take to arrive from the given satellite. By repeating this process to all available satellites the device can then determine its location coordinates at that time point, illustrated in Figure 7.

Every GPS receiver includes a TTFF (Time To First Fix) value which indicates the amount of time it takes to gather all of the necessary data to provide a reliable location. Usually this value hovers around 15 minutes for a “cold start”, meaning that it takes around 15 minutes for the receiver to gather all the satellite data for operation and none is previously stored in the device. The reason why it takes so long is because the data rate of the satellite signal is only 50 bits per second; therefore downloading orbital information directly from satellites typically takes a long time, and if the satellite signals are lost during the downloading process, it is discarded and the downloading has to start from scratch. Other types of TTFF conditions include a ‘warm’ and a ‘hot’ start, referring to the amount of time the device has been inactive prior to reactivation and how outdated the data has become [15]. Therefore, unlike Sigfox which can acquire device location immediately provided there is excellent link quality, the fastest time to get the location of a device with standalone GPS is constrained by TTFF.

In order to overcome lengthy TTFF a system called A-GPS was developed, which is widely used in mobile phone technologies, particularly in indoors urban environments where satellite signals are significantly weakened and exhibit multipath propagation. In essence, it consists in using cell tower data to help pinpoint a more accurate location and overcome slow location querying, mainly upon startup. A-GPS addresses this problem by utilizing the Internet or connection to an ISP. When such connections are available, position fix is calculated offboard the device itself.
3 Methodology

In this project, a series of lab tests and field tests are designed and implemented. The purpose of the lab tests is to answer RQ1 and get a detailed understanding of what exactly happens during one uplink transmission of Sigfox and one location query of GPS, and the purpose of the field tests is to answer RQ2.

The design and implementation of both lab and field tests in this study are inspired by the related works mentioned in 1.3. In the lab tests, a connection circuit is designed to set up an experiment for the single 4-state cycle Sleep, Wake up, Idle, Tx/Rx. The exact set-up of the experiment will be covered in Implementation section. For Sigfox, the location results are obtained from Sigfox backend; for GPS, since it is undesirable that any I/O operation should add extra power consumption to the experiment and I/O operation is the only way to save location data, two sets of lab tests at exactly the same location within the same day were run: one group of tests without I/O for studying power consumption only; the other group of tests with I/O for studying performance only.

For field tests, three pairs of geographical parameters are designed, including altitude (elevated vs sea level), population density (urban vs rural) and mobility (static vs moving). For each parameter one location inside Skåne region is picked and the Pycom devices are left there to run for at least an hour to gather enough location and battery consumption data. The exact implementation of the field tests will be covered in Implementation section.

To answer RQ3, the results from RQ1 and RQ2 are statistically analyzed to provide insight for a tentative solution with the right priorities for the freight-monitoring system. The design and implementation of the solution will be covered in Results section as it is based on the results of this study.

The following subsections presents the mathematical models used in this study to analyze performance and power consumption.
3.1 Performance measurement

In this project, the performance of Sigfox and GPS positioning services is measured by three metrics - accuracy and precision, response time and response rate - with different transmission or location query intervals and payload sizes (for Sigfox alone) as parameters. This is because these three metrics, according to client requirement, could greatly impact system performance: accuracy and precision directly affect how closely the location can be tracked; response time exerts a limitation on how promptly the client can be informed of the location, and response rate indicates the probability of the location information being received by the client.

3.1.1 Accuracy and precision

Latitude and longitude in the coordinates returned by GPS or Sigfox Geolocation are treated as two random variables with a Gaussian distribution. For static test cases where the Pycom modules stay at the same location, it is of interest to calculate the mean and standard deviation of the location data set: mean gives an idea about the central tendency of the location data and hence tells about accuracy; standard deviation tells about how spread apart the location data are and hence tells about precision. Given that Sigfox accuracy is known to be inferior to GPS, precision becomes very relevant because, supposing Sigfox is proved to be highly precise in this study, future work can be done to see if there is a way to calibrate the location data.

For Moving test cases where the location data are constantly changing, it is ensured that the moving paths of all test cases are exactly the same and the devices are turned on at exactly the same time point relative to the starting time of the travels. By doing this the location coordinates from GPS and Sigfox with the same timestamps should in theory be acquired from the same physical location. Sigfox data points in this scenario have no direct notion of a mean, since the sampled points move along a trajectory instead of being distributed around a fixed location. As GPS data are taken to be exact, the difference between the Sigfox data points and the corresponding GPS data points with the same timestamps are calculated, both in latitude, longitude and the actual distance in km. It is then expected that these are data sets distributed with a mean and standard
deviation which describe the accuracy and precision of the Sigfox data using GPS as reference when the device is moving.

In this study, the mean is calculated by

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (1),$$

where $\bar{X}$ is the mean value of the data set and $n$ is the number of data items. The standard deviation $S$ is calculated by

$$S = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \quad (2),$$

where $S$ stands for standard deviation.

### 3.1.2 Response time

For GPS, response time is equal to TTFF because before the GPS receiver gets its first fix the coordinates will remain "None". Thus,

$$Response\ time\ of\ GPS = TTFF \quad (3).$$

For Sigfox, whether a location query is successful or not entirely depends on whether the message gets delivered to Sigfox backend or not. Therefore, Sigfox response time is defined as the difference between the timestamp of the first message in the message series that get sent out and the timestamp of the first message that gets successfully delivered to and shown in Sigfox backend. For example, supposing in one test a series of Sigfox messages $M_1, M_2, \ldots, M_n$ get sent out at time $T_1, T_2, \ldots, T_n$, and at Sigfox backend the first message (note that it can be any message in the message series) is shown to be available at time $T_B$, meaning that prior to $T_B$ all messages sent out are lost, the response time in this case is

$$Response\ time\ of\ Sigfox = T_B - T_1 \quad (4).$$

In extreme cases where Sigfox network coverage is extremely poor and no messages get successfully delivered at all, the response time is counted as infinitely long.
3.1.3 Response rate
Response rate tells about the probability of Sigfox or GPS getting location data at a specific physical location. In this study response rate for Sigfox is defined as the ratio between number of successfully delivered messages and total number of sent out messages. For GPS it is the ratio between successful location queries with valid coordinates and total number of location queries. It is expressed by the following formula:

\[
\text{Response rate} = \frac{\text{number of successfully delivered messages \& successful location queries}}{\text{total number of sent out messages \& location queries}} \times 100\% \quad (5).
\]

3.2 Power consumption measurement

3.2.1 Single Sleep, Wake up, Idle, Tx/Rx cycle
The 4-state power consumption model derived from the work by Vilajosana et al. [16] is widely used in power consumption analysis which expresses energy consumption in interval \( t \) as follows:

\[
E(t) = \sum_s P_s \times t_s, S \in \{\text{Tx,Rx,Idle,Sleep}\} \quad (6),
\]

where \( P_s \) is the power consumption in state \( S \) and \( t_s \) is the time spent in the state \( S \) during \( t \). In this study, this model is slightly adjusted to cater to the specificity of Sigfox and GPS. In the case of Sigfox, the new 4-state cycle is Sleep, Wake up, Idle, Tx as due to poor Sigfox coverage in Kristianstad it never succeeded to deliver any message to Sigfox backend from school lab; hence it was not possible to study Rx. In the case of GPS, since the GPS receiver only passively gets satellite data, there is only Rx phase; therefore the new 4-state cycle for GPS is Sleep, Wake up, Idle, Rx. Following that, the formula used in this study to calculate the 4-state single cycle power consumption is:

\[
E(t) = \sum_s P_s \times t_s, S \in \{\text{Sleep, Wake up, Idle, Tx or Rx}\} \quad (7).
\]

This formula is equivalent to

\[
E(t) = \int_0^t I(t) \cdot U(t)dt \quad (8)
\]
where $U$ is the voltage and $I$ the current over the time interval $t$.

### 3.2.2 Field tests with different geographical parameters

In the second part of the project namely the field tests, power consumption is measured by utilizing the power querying function built in the Pymakr library provided for Pycom modules. It has been confirmed with Pycom LTD that the power querying function returns unregulated voltage of power supply from the JST input as opposed to the regulated voltage from the micro USB connector.

In order to run efficient field tests a LiPo 3.7V 1000mAh rechargeable battery is used and the queried battery voltages together with the timestamps of each query are logged in a text file in the SD card mounted on the Pycom sensor shields. Preliminary tests are run to decide on a proper time length $T$ for the actual running time of the field tests. The time length $T$ should satisfy the requirement that the linear drop of battery voltage can be clearly observed.

The timestamp-voltage records in the text file after each test form a time series of battery voltage with one dimension being the timestamp and the other dimension being the battery voltage. Inside MATLAB, linear regression is applied to this time series to get the slope of the approximated linear behavior of battery drop which represents how fast the battery gets drained in its linear region.
4 Implementation

4.1 Pycom modules

The modules used in this project were manufactured by Pycom LTD. In this project the Pycom modules used include: two FiPy modules [17], one Pysense sensor shield [18] and one Pytrack sensor shield [19].

4.1.1 FiPy

The FiPy module is a 5-network development board (see Figure 8). This MicroPython-enabled unit features WiFi, Bluetooth, LoRa, Sigfox and dual LTE-M (Cat-M1 and NB-IoT). It sits on top of one of the shields, presented below, which enables the unit to interface with sensors, power units and debugging tools [17].

![FiPy - 5-network development board](image)

Figure 8. FiPy - 5-network development board [20].

4.1.2 Pytrack and Pysense

The Pytrack sensor shield (see Figure 9) is a GPS capable sensor shield. This module includes Micro USB I/O, JST connector for LiPo battery and a Micro SD card slot. An accelerometer is also present on this module, allowing for a viable solution for energy-efficient real-time tracking systems[19].

Much like Pytrack, Pysense (see Figure 10) is also a sensor shield that can be interfaced with FiPy. In addition to the same basic I/O features as Pytrack, there is also an array of sensors on board doing temperature, humidity, ambient light, barometric pressure and acceleration sensing. Both Pysense and Pytrack shields support ultra low power deep sleep mode, drawing around 25uA of current in this state according to datasheets.
4.1.3 Hardware solutions

In this project, the hardware solution chosen for GPS tests is to have a FiPy module interfacing with a Pytrack module. This enables, in case that Sigfox Geolocation is proven to be unreliable, transmitting GPS locations with Sigfox.

For Sigfox tests, in this project FiPy module mounted on top of Pysense is used as a solution. In this way Sigfox and GPS experiments can be run in parallel to share the same environmental parameters.
4.2 Experiment setup

4.2.1 Single Sleep, Wake up, Idle, Tx/Rx cycle

Inspired by the work of Nordløf and Lagusson where they measured the power consumption of a LoRa development board in a 4-state cycle by measuring the voltage drop over a 1Ohm resistor in series with the power supply and the board [3], in this study the same setup is used: FiPy+Pysense or FiPy+Pytrack is connected in series with a 1Ohm resistor and the power supply. The power supply in the Sigfox test is a LiPo 3.7V 1000mAh rechargeable battery and in the GPS test a 4.0V VGW-GPS-3030 DC power supply (as the former cannot drive the circuit to work). When testing Sigfox, an external antenna is always connected to FiPy to both enhance signal quality and prevent component damage. A probe is attached to both ends of the 1Ohm resistor and its other end is connected to Channel 1 of the oscilloscope (see Figure 13). The location of these experiments is the corridor outside the engineering lab room at Högskolan i Kristianstad. Figure 14 shows that Sigfox only has partial coverage in Kristianstad.

Figure 13. Power consumption measurement circuit in lab tests.
The Sigfox test consists in putting the Pycom modules to deep sleep, waking it up with movement and then continuously sending uplink messages with a certain size of payload at a fixed interval. To examine how Sigfox behaves with different transmission intervals, various lengths of delay is inserted between the uplink messages in each test. For payload, different numbers of the ASCII character "A" are used since each "A" is exactly one byte. Figure 15 shows the flowchart for the experimental procedure.

The GPS test setup is similar to Sigfox. It consists in putting the Pycom modules to deep sleep, waking it up with movement, and then continuously making location queries at a fixed interval. Figure 16 shows the flowchart for this experimental procedure. The GPS timeout period is set to 10s in the experiments and the wake-up condition as well as delay lengths are configured in exactly the same way as in the Sigfox experiment. Since there is no payload involved in the GPS test, there are in total 6 test cases only.
4.2.2 Field test setup

To decide on the time length $T$ for the field tests which should ensure an observable linear behavior of battery drop, preliminary tests are run with the purpose of measuring how long it takes for Sigfox and GPS to completely drain the LiPo 3.7V 1000mAh battery. The preliminary tests are run for 12 hours long at Värnhem, Malmö with transmission or location query interval set to 1s. In the case of Sigfox the payload size is set to 1 byte. A full LiPo 3.7V 1000mAh battery is plugged into the JST connector of the Pycom modules and is taken out 12 hours later. It is worth noting that the logic of the preliminary tests and the actual field tests are exactly the same except that the field tests are given different parameters. Figures 17 and 18 outline the steps of field tests: for Sigfox, after initialization the module keeps sending messages with a certain payload to the network, after which it writes the current timestamp, queried battery voltage and payload data to the SD card before entering a fixed delay period; for GPS it is the same
except that it makes location queries instead of sending out messages and that there is no payload involved.

Figure 17. Flowchart for Sigfox field tests (left).

Figure 18. Flowchart for GPS field tests (right).

Figure 19 shows the results of the Sigfox and GPS preliminary tests. The last timestamp for Sigfox and GPS are respectively 8791s and 9456s, meaning that it takes respectively about 2.44 and 2.63 hours for Sigfox and GPS to completely drain the battery. (For calculation see Eq1 & Eq2 in Appendix.) Based on these results, the value of $T$ is decided to be at least 1 hour.

In the field tests, it is designed that different transmission or location query intervals (30s and 300s respectively) and payload sizes (1 byte, 4 bytes an 12 bytes, for Sigfox only) will be applied. Therefore for each field test location 2 tests will be run for GPS and 4 tests will be run for Sigfox (see Table 1).

Table 1. Test parameters in each field test geolocation.

<table>
<thead>
<tr>
<th></th>
<th>Delay</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>30s, 300s</td>
<td>N/A, N/A</td>
</tr>
<tr>
<td>Sigfox</td>
<td>30s, 1 byte</td>
<td>4 bytes payload, 30s interval</td>
</tr>
<tr>
<td></td>
<td>payload</td>
<td>12 bytes payload, 30s interval</td>
</tr>
</tbody>
</table>

The field test locations chosen for this study are shown in Table 2. Considering that a
successful uplink message delivery relies on robust Sigfox network, there is a strong emphasis on the locations being picked within Lund/Malmö areas because these areas have good Sigfox coverage (see Figure 20). However, it is also of interest to see how Sigfox works with only partial coverage; hence Vattenriket in Kristianstad with exactly 0m altitude is chosen for Sea level test cases.

Table 2. Field test geographical parameters and locations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>Elevate Niagara 6th floor, Malmö</td>
</tr>
<tr>
<td></td>
<td>Sea level Vattenriket, Kristianstad</td>
</tr>
<tr>
<td>Population density</td>
<td>Urban Värnhem, Malmö</td>
</tr>
<tr>
<td></td>
<td>Rural Lerberget, Höganas</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving SkåneExpressen 1 (Malmö-Kristianstad, Kristianstad-Malmö)</td>
</tr>
</tbody>
</table>

Figure 19. Sigfox and GPS voltage drop over time in preliminary tests (left).
Figure 20. Sigfox coverage over Skåne, Sweden and Copenhagen, Denmark (purple-not covered, blue-covered) [23] (right).
5 Results

5.1 Lab test results

To summarize the findings of the lab tests, in general Sigfox was found to be more power consuming than GPS in one Sleep, Wake up, Idle, Tx/Rx cycle. The calculated energy consumption of Sigfox using equation (8) was $0.86924 - 0.0300833T_i(J)$ higher than GPS (where $T_i$ stands for the time duration of the Pycom modules staying in Idle state). This implies that as the device idle time increases, the difference between Sigfox and GPS power consumption will become smaller and if idle time is long enough, Sigfox will be more power efficient. Both Sigfox transmission and GPS location query were found to block (i.e. a Sigfox transmission/GPS location query only starts when the previous one is finished); hence transmission/location query interval does not affect performance or power consumption.

While Sigfox displayed consistent behavior in each transmission, the time it took GPS to get location data appeared to vary a lot with the shortest being 0.6s and longest being about 3s. During the querying phase GPS maintained the same level of power consumption. This suggests that satellite signal quality could greatly impact GPS power consumption: with longer timeout and poorer signal, GPS could easily surpass Sigfox in power consumption. That being said, it is necessary to add that the energy consumption difference between Sigfox and GPS in lab tests was calculated using the average GPS energy consumption measured in the tests.

Payload was discovered to be a great impact on Sigfox power consumption and from the experiment results the relation between energy consumption and payload size seemed to be linear.

As for performance, Sigfox did not manage to send any message to Sigfox backend in lab tests; therefore response rate was 0% and response time infinite. Accuracy and precision could not be calculated since there was no location data. For GPS the response rate was 100% and except for the 0s test case which had 30 minutes TTFF, all the other test cases had a TTFF less than 10 minutes. The average standard deviation of latitude and longitude were 0.0006090104193° and 0.0009416208117°, which proved to be
consistent with what is given in *Global Positioning System Standard Positioning Service Performance Standard*, that GPS has a horizontal accuracy of 3 meters and vertical accuracy of 5 meters.

### 5.1.1 Sigfox

For Sigfox, 30 lab tests were done. The probe attached to the 1Ohm resistor was set to x10 scale; therefore the values shown in the following figures need to be multiplied by a factor of 10. No messages were delivered to Sigfox backend and therefore accuracy and precision cannot be calculated, response time is infinite, and response rate is 0%.

Since Sigfox message transmission was found to block other operations, transmission interval turned out not to play a role in power consumption. Interestingly, Sigfox behaves highly consistent in all test cases when sending out a message and the pattern is shown in Figures 21 and 22, which are when sending 'A' at 0s and 2s interval. As can be clearly observed, each Sigfox message contains one original message and two replicas. The original message stays a bit longer compared with the replicas in the first up-bump in voltage, approximately 320mV, indicated by the semi-transparent red blocks in Figure 22 with name "Bump 1", but the time it stays in the second up-bump in voltage, approximately 420mV, is the same as the replicas, indicated by the semi-transparent blue blocks in Figure 22 with name "Bump 2". Based on this observation, the beginning of a new Sigfox message can be easily distinguished in Figure 21 even though there is no delay between each message, marked by the red line. The voltage of "Bump 1" and "Bump 2" in all test cases were at the same level, i.e. 320mV for "Bump 1" and 420mV for "Bump 2".

![Figure 21. Voltage over 1Ohm resistor with 1 byte payload, 0s transmission interval (probe x10 scale).](image-url)
Payload, however, was found to have a great impact on power consumption because it was observed that while the time length for "Bump 1" remains the same for all payload sizes, the time length of "Bump 2" becomes longer as payload size increases. For example, for 1-byte payload the time length for "Bump 2" was 1.2s but for 12 bytes it was 2s (see Figures 23 and 24).

A detailed calculation of energy consumption for different payload sizes at 2s transmission interval was done using equation (8), the result of which is shown in Figure 25, which suggests a linear relation between power consumption and payload size. This result implies that to design a power-saving system using Sigfox, smaller sizes of payload is preferred over bigger sizes.
Figure 25. Energy consumption of Sigfox with different payload sizes at 2s transmission interval.

The voltage across the 1Ohm resistor in a full *Sleep, Wake up, Idle, Tx* cycle for Sigfox with 1-byte payload is shown in Figure 26. Using equation (8), the energy consumption in this full cycle (with 1 byte payload) is shown in Table 3. Since the device can in theory sleep for any time length as long as there is power, *Ts*, standing for the time duration in *Sleep* state, is used instead of a specific amount of time. Similarly, *Ti* stands for the time length of *Idle* state since it is also a configurable quantity.

![Figure 26. Voltage across 1Ohm resistor in a full 4-state cycle (1 byte payload, probe x10 scale).](image)

Table 3. Sigfox energy consumption in a full 4-state cycle before *Tx*.

<table>
<thead>
<tr>
<th>State</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Time (s)</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep sleep</td>
<td>0.000025</td>
<td>0.000025</td>
<td><em>Ts</em></td>
<td>0.000025*Ts</td>
</tr>
<tr>
<td>Wake up 1</td>
<td>0.08</td>
<td>0.08</td>
<td>1.4</td>
<td>0.00896</td>
</tr>
<tr>
<td>Wake up 2</td>
<td>0.16</td>
<td>0.16</td>
<td>1.4</td>
<td>0.03584</td>
</tr>
<tr>
<td>Idle</td>
<td>0.28</td>
<td>0.28</td>
<td><em>Ti</em></td>
<td>0.28*Ti</td>
</tr>
<tr>
<td>Tx (1 byte)</td>
<td>0.32/0.42</td>
<td>0.32/0.42</td>
<td>8.4</td>
<td>1.05024</td>
</tr>
</tbody>
</table>
Using the result from Table 3, the lowest possible (because payload is 1 byte) total energy consumption of Sigfox in one full *Sleep, Wake up, Idle, Tx* cycle is expressed as:

\[ E_{\text{Sigfox}} = 0.000025T_s + 1.09504 + 0.28T_i \ (J) \]  \hspace{1cm} (9),

where \( T_s \) is the length of *Sleep* and \( T_i \) the length of *Idle*. For detailed calculation steps see Appendix Eq3.

### 5.1.2 GPS

For GPS, 6 lab tests were done. The probe attached to the 1Ohm resistor was set to x1 scale; therefore the values shown in the following figures do not need to be multiplied by any factor.

In all test cases the Pytrack GPS receiver managed to get location data, but they vary in TTFF and response rate. In the second I/O-involved group of tests for getting location data alone, 6 40-minute long tests were performed and the results are shown in Table 4.

**Table 4. Lab test results for GPS performance.**

<table>
<thead>
<tr>
<th>TTFF (min)</th>
<th>0s</th>
<th>2s</th>
<th>4s</th>
<th>8s</th>
<th>10s</th>
<th>15s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response rate (%)</td>
<td>32.26</td>
<td>90.1</td>
<td>96.61</td>
<td>87.63</td>
<td>92.68</td>
<td>96.2</td>
</tr>
<tr>
<td>Mean of latitude (°)</td>
<td>56.04828533</td>
<td>56.04839544</td>
<td>56.04848094</td>
<td>56.04847089</td>
<td>56.04822072</td>
<td>56.04834789</td>
</tr>
<tr>
<td>STD of latitude (°)</td>
<td>0.0004579104716</td>
<td>0.0007563502688</td>
<td>0.0006437085998</td>
<td>0.0005441717637</td>
<td>0.0006482014761</td>
<td>0.0006037200256</td>
</tr>
<tr>
<td>STD of longitude (°)</td>
<td>0.002433964353</td>
<td>0.0008091958148</td>
<td>0.0008891065446</td>
<td>0.0006474028885</td>
<td>0.0005189755904</td>
<td>0.0003510796792</td>
</tr>
</tbody>
</table>

Except for the first test case with 0s location query interval, the rest of the test cases all had fairly short TTFF. Precision also remained at high level in all test cases, proving GPS's high reliability.

As for power consumption, similar to Sigfox, location query was found to block other operations, therefore location query interval does not play a role in power consumption. It appears that it varies a lot as to how long it takes GPS receiver to get location data even after TTFF. For example, Figures 27 and 28 both show the voltage over the 1Ohm resistor when GPS was trying to get location data at 15s interval and the red underline indicates a successful location query. In Figure 27 the query time was about 1.2s but in Figure 28 about 0.64s.
One possible explanation for this observation is that the quality of satellite signals was changing all the time, and power consumption for each location query varied a lot depending on the exact quality of satellite signals the moment when the query was made. This implies that poor satellite signal could potentially lead to fast draining of battery. Besides that, the current level in most test cases was also varying a lot, which is very different from Sigfox. The highest peak voltage in all tests was 0.37V and the lowest 0.29V (see Figures 29 and 30).
The voltage across the 1Ohm resistor in a full Sleep, Wake up, Idle, Rx cycle for GPS is shown in Figure 31. Using equation (8), the energy consumption in this full cycle is shown in Table 5. Because the energy consumption of GPS location queries in Idle and Rx varied a lot, their mean is used in the calculation of the total energy consumption in a full cycle.

Table 5. GPS energy consumption in a full Sleep, Wake up, Idle, Rx cycle before Rx.

<table>
<thead>
<tr>
<th>State</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Time (s)</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep sleep</td>
<td>0.000025</td>
<td>0.000025</td>
<td>$T_s$</td>
<td>0.000025$T_s$</td>
</tr>
<tr>
<td>Wake up 1</td>
<td>0.14</td>
<td>0.14</td>
<td>1.6</td>
<td>0.03136</td>
</tr>
<tr>
<td>Wake up 2</td>
<td>0.24</td>
<td>0.24</td>
<td>1.6</td>
<td>0.09216</td>
</tr>
<tr>
<td>Idle (AVG)</td>
<td>0.3108333333</td>
<td>0.3108333333</td>
<td>$T_i$</td>
<td>0.3108333333$T_i$</td>
</tr>
<tr>
<td>Rx (AVG)</td>
<td>0.29 to 0.37</td>
<td>0.29 to 0.37</td>
<td>varying</td>
<td>0.1022767667</td>
</tr>
</tbody>
</table>

Thus, the total energy consumption in a full 4-state cycle for GPS is:

$$E_{GPS} \approx 0.000025T_s + 0.2258 + 0.310833T_i \ (J) \quad (10),$$

where $T_s$ is the length of Sleep and $T_i$ the length of Idle. For detailed calculation steps see Appendix Eq4. Hence, the difference between $E_{GPS}$ and $E_{Sigfox}$ is:

$$E_{Sigfox} - E_{GPS} = Equation \ (9) - Equation \ (10) = 0.86924 - 0.0300833T_i \ (J) \quad (11).$$

5.2 Field test results

To summarize the results from the field tests, GPS was found to be far superior to Sigfox in terms of performance and marginally better in terms of power consumption - possibly because two thirds of the test cases were with 30s location query interval which is not long enough for Sigfox to exceed GPS in power efficiency. Even with TTFF to overcome, except for the Elevated test cases where GPS failed to get location data, the average response time of GPS was 6.73 minutes compared with Sigfox which had 18.47 minutes average response time. The average response rate of GPS was 73.933% compared to 21.622% of Sigfox excluding the Elevated test case. Although Sigfox officially has an accuracy less than 10km, in the field tests it was proved not to be the case. Except for Urban and Elevated test cases where the average distance to the correct
location was respectively 3.34km and 5.505km, the other test cases all had above 25 kilometers distance with the worst being Rural.

The best performing physical location for GPS was Rural with the lowest power consumption, highest response rate and shortest response time. For Sigfox it was Urban that gave the lowest power consumption, highest response rate and shortest response time. Hence there seems to be a strong correlation between power efficiency and good performance, which is one of the most interesting findings of this study.

For GPS Rural being the best location was an reasonable result as its performance is very dependent on the quality of satellite signal; hence it is naturally in favor of vast, open space. Moving turned out to be the most power consuming location for GPS and Elevated was the worst for performance where it did not manage to get any location data. For Sigfox, results seem to indicate that network quality is not the only factor that affects performance. The Rural test case had equally excellent Sigfox network coverage as Urban and it also gave high response rate and short response time, but its accuracy was the poorest among all test cases, which was on average 34.7625km away from the correct location. This observation could have something to do with the actual locations of the base stations. Another possible factor is the probability model at Sigfox backend mentioned in Section 2.2 which supposedly uses machine learning techniques to calculate the location of the device and it might be the case that in urban environments there are more user data coming in as training data for the model to fine-tune its performance. Moving turned out to be the most power consuming test case for Sigfox, which unfortunately reduces its applicability in a logistics IoT system.

Longer transmission or location query intervals clearly reduced power consumption, and for both GPS and Sigfox, it seems to also slightly increase precision. Consistent with the results from lab tests, payload was also identified as a major source of impact on Sigfox. However, unlike in lab tests, in the field tests although big difference was seen between 1 byte payload and larger bytes payload, there was no linear relation between payload and the metrics.

To give a visual idea of how accurate and precise Sigfox was in each field test compared with GPS before entering detailed analysis of the results, the average coordinates of each test case in each test location are marked as dots in a map view. In Figures 32 to
35, each representing a different geoparameter, the green dot represents the GPS coordinates which is considered to be the correct location (the coordinates for Elevated test case is provided by Google Maps because GPS did not get location data), and the red dots represent the average Sigfox locations in each sub-test case with different transmission intervals and payload sizes as parameters (see Table 1). For Sigfox sub-test cases which did not produce valid location data, no red dot is marked. All Sigfox sub-test cases (i.e. small red dots) form a bigger red dot representing a clustered overview of Sigfox location.

Figure 32. Average locations of Sigfox in Elevated test case with zoomed-in view for Sigfox 30s and 300s intervals test cases.

Figure 33. Average locations of GPS and Sigfox in Sea level test case with zoomed-in view for Sigfox 30s, 300s intervals and 12-byte payload test cases.
Figure 34. Average locations of GPS and Sigfox in Rural test case with Sigfox 30s, 300s invertals and 4-byte, 12-byte payloads test cases.

Figure 35. Average locations of Sigfox and GPS in Urban test case with zoomed-in view for Sigfox 30s, 300s invertals and 4-byte, 12-byte payloads test cases.
Figure 36. Moving locations of Sigfox (blue) and GPS (yellow) in 30s Moving test case (Malmö C - Kristianstad C) with $T_n$ meaning the nth item in the time series of location data.

5.2.1 Field test execution

All the field tests were carried out as planned, but due to unexpected factors a few tests were run slightly below 1 hour. The actual execution of the field tests are shown in Tables 6 and 7. In total, all field tests added up to 2716 minutes or 45.27 hours and the average time length of field tests is 90.53 minutes or 1.51 hour (calculation see Eq5 & Eq6 in Appendix).

Table 6. GPS field tests in actual execution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30s</td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated Niagra building rooftop, Malmö, Sweden</td>
<td>2018.05.06 9:07 - 10:50</td>
</tr>
<tr>
<td></td>
<td>Sea level Vattenriket Kristianstad, Sweden</td>
<td>2018.05.01 13:38 - 14:34</td>
</tr>
<tr>
<td>density</td>
<td>Rural Lerberget, Skåne, Sweden</td>
<td>2018.05.05 10:10 - 12.20</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving SkåneExpressen 1 bus route (Skåne, Sweden)</td>
<td>2018.05.02 9:42 - 11:15</td>
</tr>
</tbody>
</table>
Among all tests the shortest one was Sigfox-Rural-30s which was run for only 36 minutes. The reason is, due to transportation difficulty it was the case that all Sigfox-Rural tests had to be finished within one day, but it turned out that Sigfox response rate was so high in Rural-30s test that if the test were run for 1 hour, the remaining daily quota for uplink messages would not be enough for the other test cases; hence it was cut off when 35 messages (140 divided by 4 is 35) had been delivered to Sigfox backend. That being said, it was still a valid test as it was possible to observe the linear behavior of battery drop.

### 5.2.2 Power consumption

All field test results show observable linear behavior of battery voltage drop. Linear regression is applied to the time series of battery voltages in all tests in MATLAB. For illustrative purpose and to save space, the graphs of Altitude-Elevated-30s test cases are shown in Figures 37 and 38. All values of slopes are shown in Table 8.

In total, the average of battery drop slopes in all tests is -2.85086 for GPS and -2.92127 for Sigfox. Although this suggests that GPS is slightly more power efficient, considering that most tests had only 30s interval and Geolocation is an add-on feature for Sigfox with its main focus being wireless communication, this marginal difference actually proves that Sigfox is very power-efficient. Figure 39 shows the average battery drop slopes in all locations. It can be seen that Rural is the most power-efficient location for GPS and Moving is the most power-consuming. Interestingly, Moving is also the "worst" for Sigfox. The most power-efficient location for Sigfox is Urban.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Delay with 1 byte payload</th>
<th>Payload with 30s delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30s</td>
<td>300s</td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated</td>
<td>2018.05.06</td>
<td>2018.05.06</td>
</tr>
<tr>
<td>Sea level</td>
<td>Vattenriket Kristiansstad, Sweden</td>
<td>2018.05.01</td>
<td>2018.05.02</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>2018.05.05</td>
<td>2018.05.05</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving</td>
<td>2018.05.02</td>
<td>2018.05.03</td>
</tr>
<tr>
<td></td>
<td>(Skåne, Sweden)</td>
<td>9:42 - 11:15</td>
<td>06:42 - 08:18</td>
</tr>
</tbody>
</table>
Figure 37. Linear regression of GPS voltage drop in Altitude-Elevated-30s test case (left).

Figure 38. Linear regression of Sigfox voltage drop in Altitude-Elevated-30s test case (right).

Table 8. Slope of battery drop in all field tests.

<table>
<thead>
<tr>
<th>Geolocation Parameter</th>
<th>Parameters</th>
<th>30s</th>
<th>300s</th>
<th>4 bytes</th>
<th>12 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>Altitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevated</td>
<td>-3.074</td>
<td>-2.2399</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sea level</td>
<td>-3.4703</td>
<td>-2.5271</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Population density</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>-2.4225</td>
<td>-2.6729</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>-1.975</td>
<td>-2.5382</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mobility</td>
<td>-4.2735</td>
<td>-3.3152</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sigfox</td>
<td>Altitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevated</td>
<td>-2.3044</td>
<td>-3.8008</td>
<td>-2.5252</td>
<td>-4.7494</td>
</tr>
<tr>
<td></td>
<td>Sea level</td>
<td>-2.1575</td>
<td>-2.283</td>
<td>-2.4209</td>
<td>-3.7701</td>
</tr>
<tr>
<td></td>
<td>Population density</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>-2.7285</td>
<td>-2.0719</td>
<td>-2.4156</td>
<td>-2.3697</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>-2.3732</td>
<td>-3.1209</td>
<td>-2.1313</td>
<td>-3.4393</td>
</tr>
<tr>
<td></td>
<td>Mobility</td>
<td>-4.128</td>
<td>-2.3595</td>
<td>-3.4003</td>
<td>-3.8759</td>
</tr>
</tbody>
</table>

Figure 39. Battery drop slopes (AVG) of GPS and Sigfox per geolocation.
In both GPS and Sigfox test cases, on average longer transmission or location query interval reduces power consumption (see Figure 40). However, in a few cases, it did happen that 300s tests were more power consuming (see Table 8). Payload was also found to impact Sigfox power consumption (see Figure 41), but unlike lab test results, there was no obvious linear relation. Although 12 bytes payload has much higher power consumption, between 1 byte and 4 bytes there is no big difference.

![Figure 40. GPS and Sigfox battery drop slopes (AVG) per transmission/location query interval (left).](image)

![Figure 41. Sigfox battery drop slopes (AVG) per payload size (right).](image)

### 5.2.3 Performance

#### 5.2.3.1 Response rate

Response rate is calculated by using equation (5) explained in the Methodology section. Table 9 shows the response rates of all field tests.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>30s</th>
<th>300s</th>
<th>4 bytes</th>
<th>12 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Sea level</td>
<td></td>
<td>81.55</td>
<td>87.5</td>
<td></td>
</tr>
<tr>
<td>Population density</td>
<td>Urban</td>
<td>95.98</td>
<td>94.6</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td></td>
<td>97.83</td>
<td>94.74</td>
<td></td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving</td>
<td>92.49</td>
<td>95.24</td>
<td></td>
</tr>
<tr>
<td><strong>Sigfox</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated</td>
<td>17.8</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Sea level</td>
<td></td>
<td>11.7</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Population density</td>
<td>Urban</td>
<td>55</td>
<td>39.3</td>
<td>29.8</td>
</tr>
<tr>
<td>Rural</td>
<td></td>
<td>82.22</td>
<td>7.14</td>
<td>22.33</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving</td>
<td>9.93</td>
<td>21.05</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 9. Response rates of all field tests (%).
Although in general GPS had much higher response rate (73.993%) compared with Sigfox (21.622%), in Elevated test cases it completely failed to get location data. Although Sigfox had much lower response rate, in no locations did it completely fail. Especially with 1 byte payload Sigfox always managed to deliver messages. For GPS the highest average response rate was with Rural, which interestingly was also its most power-efficient physical location. Similarly, for Sigfox its highest average response rate was with Urban (see Figure 42). Thus, it seems to imply that there exists a correlation between power efficiency and response rate.

![Graph showing response rates per geolocation parameter](image)

**Figure 42. Response rates (AVG) of GPS and Sigfox per geolocation.**

In general, Sigfox response rate was observed to be consistent with the quality of coverage. However, a certain degree of unreliability still seems to exist: at the same location, it happened that in some tests no messages got delivered at all although it didn't happen if payload was only 1 byte.

![Graph showing response rates per transmission/location query interval](image)

![Graph showing response rates per payload size](image)

**Figure 43. GPS and Sigfox response rates (AVG) per transmission/location query interval (left).**

**Figure 44. Sigfox response rates (AVG) per payload size (right).**
Transmission or location query interval as a parameter did not seem to impact response rate much (see Figure 43) while payload again shows significant impact on Sigfox response rate (see Figure 44) although no linear relation was found: while there was a big difference between 1 byte and 4 or 12 bytes payload, between 4 and 12 bytes there is no big difference. Possibly there is a threshold for payload and above that threshold it's similar response rate anyway.

5.2.3.2 Response time

Response time is calculated by using equations (3) and (4) explained in the Methodology section. Table 10 shows the response time of all field tests.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>30s</th>
<th>300s</th>
<th>4 bytes</th>
<th>12 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sea level</td>
<td>12.76</td>
<td>5.22</td>
<td></td>
</tr>
<tr>
<td>Population density</td>
<td>Urban</td>
<td>5.55</td>
<td>10.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>1.36</td>
<td>5.19</td>
<td></td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving</td>
<td>8.22</td>
<td>5.19</td>
<td></td>
</tr>
<tr>
<td><strong>Sigfox</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>Elevated</td>
<td>7</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Sea level</td>
<td>21</td>
<td>14</td>
<td>N/A</td>
</tr>
<tr>
<td>Population density</td>
<td>Urban</td>
<td>13</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>8</td>
<td>46</td>
<td>8</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moving</td>
<td>9</td>
<td>39</td>
<td>9</td>
</tr>
</tbody>
</table>

The results of response time in field tests are rather consistent with the results of response rate. The fastest average response time is again with Rural for GPS and Urban for Sigfox (see Figure 45, note that GPS response time for Elevated is infinitely long).

![Figure 45. Response time (AVG) of GPS and Sigfox per geolocation.](image)
Compared with Sigfox with a total average response time of 18.47058824 min, GPS still has faster average response time (6.7325 min) excluding Elevated test cases. Transmission or location query interval doesn't seem to impact either Sigfox or GPS in response time metric (see Figure 46), but payload still impacts response time for Sigfox (see Figure 47) and a big difference can be seen between low and high payload sizes. While in power consumption and response rate Sigfox has shown poor competence in Moving test cases, in response time it gives average performance.

![Figure 46. GPS and Sigfox response time (AVG) per transmission/location query interval (left).](image1)

**Figure 46. GPS and Sigfox response time (AVG) per transmission/location query interval (left).**

**Figure 47. Sigfox response time (AVG) per payload size (right).**

### 5.2.3.3 Accuracy and precision

When analyzing this metric in field tests, the static tests (Elevated, Sea level, Urban, Rural) and the Moving test (Sk1) are treated differently because in the latter case the location was constantly changing. In static test cases, there were a few Sigfox tests with either too few or no messages delivered, including Sea level-300s, Rural-300s, Elevated-4 bytes, Elevated-12 bytes, Sea level-4 bytes, Sea level-12 bytes. In those tests the standard deviation was not calculated because the data sets were not big enough for standard deviation to make enough sense. In the Elevated field tests since there were no GPS data, Google Maps was used to give the correct coordinates as reference. Using equations (1) and (2), the mean and standard deviation of latitude and longitude in all field tests are given in Table A1 in Appendix.

First the mean and standard deviation of GPS and Sigfox coordinates with all geolocation parameters were calculated and the results are shown in Table A2 (see Appendix) and Figures 48 and 49. Then from Table A2 the absolute difference between Sigfox and GPS coordinates are calculated and converted to km (see Figures 52 and 53).
It can be seen that GPS had the highest precision (smallest standard deviation) in Rural test cases, which is again consistent with the previous results (note that Elevated had N/A standard deviation). Sigfox, however, showed in general a much worse precision than GPS (note that in Elevated and Sea level test cases the standard deviation was very small so the column bar is almost invisible in Figure 49). Especially in Rural test cases with good response time and rate, the precision for longitude was as high as 0.67°. Although Elevated and Sea level test cases seemingly gave the highest precision, it could be because the data sets were smaller.

Location query interval seems to impact GPS precision on a small scale. Especially in latitude the standard deviation showed an enhancement of one more "0" after decimal point (note that it is hardly visible in Figure 50 because the numbers are too small). For Sigfox, interestingly, the same can be observed and increase in transmission interval greatly reduced standard deviation (see Figure 50). Payload was also found to influence Sigfox precision. Although no linear relation was found, there was an obvious increase in standard deviation between 1 byte and 4 or 12 bytes payload sizes (see Figure 51). Also, latitude seems to be in general much more precise than longitude.

In terms of accuracy, again consistent with previous results Sigfox has the best accuracy in Urban and it can be observed that latitude has much better accuracy than longitude. One interesting observation is that Rural turned out to be the location with the worst accuracy. This is surprising because Rural had good Sigfox coverage and gave good results in response rate and response time, only secondary to Urban. From Figure 52 it is obvious that this low accuracy directly results from longitude but not latitude. This is
different from Sea level test cases with partial Sigfox coverage where latitude and longitude both had equally low accuracy.

Figure 50. GPS and Sigfox standard deviations (AVG) per transmission/location query interval.

Figure 51. Sigfox standard deviations (AVG) per payload size.

Figure 52. Distance in latitude and longitude (AVG) between Sigfox and GPS in static test cases per geolocation (left).

Figure 52. Distance in km (AVG) between Sigfox and GPS in static test cases per geolocation (right).

43
Transmission interval had no obvious impact on accuracy except that longer interval slightly increases longitude accuracy (see Figures 54 and 55). Unlike the other metrics, there is no obvious relation between payload and accuracy for Sigfox: 1 byte and 12 bytes had almost the same accuracy while 4 bytes had lower accuracy (see Figures 56 and 57).

Regarding the Moving test cases, for Sigfox there was no location data from the 4-byte payload field test; therefore only the location data from the other test cases were analyzed. Longer transmission interval was found to greatly decrease accuracy (see Figures 58 and 59), but its impact on precision is more complicated: it decreases
precision in longitude but increases precision in latitude, the two combined together resulting in increased precision in km (see Figures 60 and 61).

Payload in the Moving test cases also gave consistent results with most static test cases in that larger payload greatly decreased accuracy and precision the decrease was most apparent with longitude (see Figures 62 to 65).

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**Figure 58.** Distance in latitude and longitude (AVG) between Sigfox and GPS in Moving test case per transmission interval (left).

**Figure 59.** Distance in km (AVG) between Sigfox and GPS in Moving test case per transmission interval (right).

**Figure 60.** Standard deviations (AVG) of distance in latitude and longitude between Sigfox and GPS in Moving test case per transmission interval (left).

**Figure 61.** Standard deviations (AVG) of distance in km between Sigfox and GPS in Moving test case per transmission interval (right).
5.3 Suggested solution for the freight-monitoring system

5.3.1 Design and implementation

Based on the results acquired in this study it is possible to propose a tentative solution within the constraints of the given hardware for the freight-monitoring system. Considering that the client would like to have both hourly reports of the vehicle's location and emergency reports when an adverse event has happened to the freight, in the proposed solution the device is set to sleep for most of the time and two different wake up conditions are configured. One is a timeout wake-up condition with 3600s timeout period for hourly report; the other is an emergency wake-up condition. In this
specific demo solution, accelerometer event is used as emergency wake-up condition which simulates accidental falling of the freight. Given the absolute superior accuracy and precision of GPS from the results and considering that freight-carrying vehicles are usually running in rural environments, it is chosen as the tracking solution used in the tentative solution. Since each GPS coordinate (N and E) is 8 digits long with Pytrack including the decimal point, in the tentative solution one pair of GPS coordinates is split into two Sigfox messages with initial letter "N" indicating latitude and "E" indicating longitude. To distinguish between hourly report and emergency report, the letter "H" is added to the beginning of the hourly messages. The apparent downside of this method, however, is that the payload is 9 bytes in the case of emergency report and 10 bytes in the case of hourly report, which is not in good line with one of the main conclusions of this study - the smaller the payload, the better the power efficiency and performance of Sigfox.

Considering that Sigfox has an average response rate of 21.622% from the field test results, for the hourly report it is designed that 10 Sigfox messages are to be sent out for both N and E coordinates. This is to increase the chance of delivering at least one message for both N and E coordinates to the backend. For emergency case, however, since it is of utmost importance that the client gets notified and that from the field test results there is no guarantee that a Sigfox message will 100% arrive at the backend with more than 1 byte payload, in the tentative solution once an emergency case is detected, after acquiring the coordinates of the emergency with GPS the device keeps sending the coordinates to the backend until actions are taken to shut down or reset the device. The exact working procedure of the tentative solution is shown in Figure 66. On the side of the client, the client will receive emails for both hourly report and emergency report, the format of which is configured at Sigfox backend.
5.3.2 Test results of the tentative solution

Ten tests were performed to test the validity of the demo tentative solution. An emergency notification is considered to be successful if both GPS N and E coordinates have been received by the client's email box after an adverse event has happened. The location chosen for these tests was Urban as it gave the best Sigfox performance and power-efficiency. The point is, Sigfox is a newly emerging technology. It is likely that today's best performing case would be the average case in a few years' time.

The most important metric to observe is TTN (Time To Notify) which indicates how fast the client gets notified of the occurrence of an emergency case. Technically, it is defined as the number of minutes that have elapsed from the moment the module detects
strong movement of the accelerometer to the time point where the client's email box has received both N and E coordinates where the emergency takes place. The other important metric in this test is notification rate, which in other words is whether the client gets notified of the emergency case or not. The results of this small-scale test of the tentative solution is shown in Table 11.

<table>
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<tr>
<th>Test</th>
<th>Emergency timestamp</th>
<th>First GPS N Coordinate</th>
<th>First GPS E Coordinate</th>
<th>TTN (min)</th>
<th>Sent Latitude(^\circ) (GPS)</th>
<th>Sent Longitude(^\circ) (GPS)</th>
<th>Sigfox Latitude(^\circ)</th>
<th>Sigfox Longitude(^\circ)</th>
</tr>
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<tbody>
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<td>1</td>
<td>2018.05.11 18:46</td>
<td>2018.05.11 18:53</td>
<td>2018.05.11 18:57</td>
<td>11</td>
<td>55.6058</td>
<td>13.02951</td>
<td>55.57408438</td>
<td>13.05740681</td>
</tr>
<tr>
<td>2</td>
<td>2018.05.11 20:10</td>
<td>2018.05.11 20:23</td>
<td>2018.05.11 20:32</td>
<td>22</td>
<td>55.6058</td>
<td>13.02951</td>
<td>55.57309273</td>
<td>13.0574435</td>
</tr>
<tr>
<td>3</td>
<td>2018.05.11 21:45</td>
<td>2018.05.11 22:09</td>
<td>2018.05.11 21:55</td>
<td>24</td>
<td>55.6058</td>
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<td>55.57595271</td>
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<tr>
<td>4</td>
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<td>2018.05.11 22:47</td>
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<td>2018.05.12 10:25</td>
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<td>9</td>
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<td>13.05743169</td>
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</tbody>
</table>

Results show that the TTN values fluctuate a bit in relation to the achieved average value of 9.8 minutes. Considering that the average urban GPS TTFF was 7.96 minutes from the field tests results and that the average response rate of Sigfox in Urban test cases was 38.85%, the achieved average value of 9.8 minutes for TTN appears to be a positive result. Also, in this group of tests the notification rate for the emergency case was 100% meaning that the client did not miss out any emergency case that happened to the freight - which is exactly the essential purpose of having such a freight-monitoring system. With this test result it can be expected that in a close future, as Sigfox expands its network inside Sweden, this tentative solution has a great possibility to be improved and applied to real use.
6 Discussions

6.1 Observations from results

The most obvious observation from the test results is that GPS has far superior performance compared with Sigfox. One technical explanation is that the communication between Sigfox end devices and base stations might not be line-of-sight and multipath effect adds to the unreliability of signal strength picked up by the base stations; especially if the device is moving, the signal strength varies even more. On the other hand GPS uses time difference instead of signal strength and the line-of-sight nature of the most part of the communication guarantees its performance. The best testing location for GPS turned out to be Rural and for Sigfox it was Urban. Although Sigfox officially claims that it has between 1km to 10km accuracy for 80% devices, the results showed that this is only true for urban environments with good Sigfox coverage. For partially covered locations the accuracy is far worse than that, and even with good coverage if the environment is rural the accuracy is still well above 10km. This is an interesting result because usually good coverage is associated with good accuracy and precision. In the Rural test cases, however, although it gave high response rate and short response time, the average accuracy and precision was the worst among all test cases. This means that coverage is not the only factor when it concerns performance, and very possibly the probability model at Sigfox backend also plays a significant role. One speculation is that perhaps in general more Sigfox messages get sent out in urban environments, which gives more training data for urban environments. In general, the field test results imply that inside Sweden, at least around Skåne region, Sigfox is not ready yet to be used as a tracking solution outside urban environments if reliability is a key requirement of the system. However, indoors environment with high altitude seems to be a location where Sigfox has the potential to have superiority over GPS as in both Elevated tests GPS completely failed to get any location data, which was a surprising fact as high altitude usually implies less signal blockage.

Payload seems to be a factor that has great impact on both power consumption and performance of Sigfox. Lab test results suggest that as payload size increases, both the time to send out the uplink message and the power it consumes to send out the message
increase linearly. Since the transmission of uplink messages blocks, the shortest time it takes for Sigfox to send out one uplink message is 8.4s, which puts a constraint on how fast the message can reach the backend. Results of field tests show strong consistency: not only does larger payload size increase power consumption, it also reduces precision and response rate, although there is no indication that payload has an impact on response time and accuracy. Therefore, one implication from these results is that it is best to use Sigfox with small payload sizes. However, supposing response rate and accuracy is not a major concern, larger payload size is not a problem.

Transmission or location query interval does not seem to have much impact on the performance of either GPS or Sigfox except that in terms of precision, longer transmission interval seems to slightly increase both GPS and Sigfox precision. In terms of power consumption, as expected longer transmission or location query interval generally decreases power consumption although it was observed in a few tests that 300s interval turned out to be more power consuming than 30s, which could be a result from many factors not covered in this study, e.g. temperature conditions, the starting battery voltage, the noise in the signals and so on. Although GPS was found to be marginally more power-efficient than Sigfox in field tests, the energy consumption comparison done in lab tests tells that it could be because the *idle* period (in most cases 30s) was not long enough. By having longer intervals, Sigfox can actually surpass GPS in terms of power efficiency.

Although GPS is a far superior positioning technology, it is to be noted that Sigfox is at the same time a power-efficient wireless technology with a solid backend system that provides many low-cost user-friendly features. As a positioning technology that relies solely on satellite signals, GPS has its inherent weaknesses: it works far better in outdoor open environment than indoors or urban environment. Another observed weakness from the lab tests of GPS is that the time it uses to finish a successful location query seems to vary a lot, and during the timeout the power consumption is maintained at a high level. If timeout is long and satellite signal not so good, GPS could potentially fast drain the battery. By contrast, the consistent behavior of Sigfox observed from the lab tests makes its power consumption a very controllable quantity. In addition, the probability model of Sigfox Geolocation relies only on a well-covered network plus an
intelligent backend algorithm. As the test results for the tentative solution for the freight monitoring system proved to be positive, it can be expected that in close future when Sigfox network further expands and the probability model gets more and more training data, Sigfox Geolocation is likely to give improved performance.

6.2 Future work

Due to the limitation in time, experiment equipment, transportation means and financial resources of this study, it was not possible to achieve better details for the lab tests and in all likeliness in the field tests many parameters that might have contributed to the results were not covered.

First, for lab tests, in future work a power analyzer could be used to calculate power consumption in a 4-state cycle, and preferably a different location with better Sigfox coverage could be used to study Sigfox downlink messages (or $Rx$). The simplistic power consumption measurement circuit design limited by available lab equipment can also potentially lead to that the power consumption of the Sigfox antenna radio circuits was missed out. Whether that part of power consumption is missed out and if so, to what extent and how to design a circuit to measure it would be interesting topics to delve into.

Second, it was observed that in Urban tests Sigfox had adequately high precision. This suggests that future work can be carried out to study if there is a certain pattern of the errors between Sigfox and GPS location data in urban environments. Suppose there is, perhaps a calibration method can be developed to enhance urban Sigfox accuracy.

Third, weather, temperature conditions or the time when the field tests were conducted were not taken into account as parameters when analysing the field test results in this study. It was somehow observed that Sigfox had better response rate and response time in the morning than night - for example in Rural test cases the 30s test was carried out around 10 A.M. with very high response rate and very short response time, but when the 300s test was run at exactly the same spot around 10 P.M., only one message reached backend. Not only Sigfox, GPS TTFF also seemed to be longer in the night than in the morning. Therefore in future work it could be studied whether time, temperature and weather conditions have any influence on GPS and Sigfox power consumption and
performance, which can be very relevant to IoT systems running in very specific environments. The environmental conditions such as warm or cold, moist or dry, night or day are a few good examples of pairs of parameters to be studied in the future.

Finally, in this study tests were only carried out inside the Skåne region, which cannot represent how Sigfox works in the whole of Sweden. Also, only a commuter bus was used in the Moving test case. In future work other regions of Sweden are worth exploring and more types of transportation vehicles, especially typical freight-carrying trucks, should be used to see how mobility impacts Sigfox and GPS power consumption and performance.
7 Conclusion

In conclusion, in this project the power consumption and performance of GPS and Sigfox positioning services were compared. Results show that GPS consistently provided an overall superior performance than Sigfox.

The single cycle tests showed that overall GPS had a slightly better power efficiency than Sigfox excluding the *Idle* state which was found to be linearly power saving for Sigfox the longer it becomes. The time length for GPS to finish a successful location query seemed to vary a lot, and during the timeout the power consumption was maintained at a high level. On the other hand, Sigfox showed unvarying behavior in all tests and the way payload size affects its power consumption was observed to be linear.

In the field tests, the power consumptions of both technologies were similar to one another, possibly because the 30s idle interval in most test cases was not long enough for Sigfox to surpass GPS. As for response rate and response time, even though GPS had to overcome its TTFF, it still outperformed Sigfox, but in Elevated test cases GPS completely failed while Sigfox performed well with 1-byte payload. Smaller payload was found to be overall preferable for Sigfox. Except for the 1-byte payload test cases, in all other payload test cases it had occurred that Sigfox failed to deliver any message to the backend. Most metrics also show a worsening tendency as payload size increases. Since there is no absolute guarantee that a Sigfox message larger than 1 byte will always reach the backend, one strategy to compensate for this observed problem is to send out multiple messages to increase the chance of at least one message getting delivered. This problem, however, has the potential to be overcome as Sigfox network grows. In terms of accuracy, although Sigfox gave an official accuracy between 1km to 10km, it was proven not to be the case except for urban environments.

Sigfox being an emerging technology is still fast developing. In the test results for the suggested solution to the freight-monitoring system, Sigfox proved to be reliable in an urban environment with an average TTN of 9.8 minutes which includes the GPS TTFF. These are promising results which point to a bright future with Sigfox as one of the leading LPWAN technologies.
8 References


9 Appendix

9.1 List of tables

Table A1. Mean and standard deviation in all field tests

(Color scheme: yellow-early morning, orange-afternoon, light blue-evening, dark blue-night,
green-good Sigfox coverage, pink-partial Sigfox coverage).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LATITUDE°</th>
<th>LONGITUDE°</th>
</tr>
</thead>
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<td>Rural</td>
<td>56.1378282</td>
<td>0.1001622826</td>
</tr>
</tbody>
</table>

Table A2. Average coordinates and their standard deviation per test location.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Average coordinates</th>
<th>AVG of STD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude°</td>
<td>Longitude°</td>
</tr>
<tr>
<td>GPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevated</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sea level</td>
<td>56.02852697</td>
<td>14.14746578</td>
</tr>
<tr>
<td>Urban</td>
<td>55.60185993</td>
<td>13.02824268</td>
</tr>
<tr>
<td>Rural</td>
<td>56.17142631</td>
<td>12.56243767</td>
</tr>
<tr>
<td>Sigfox</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevated</td>
<td>55.57471338</td>
<td>13.05758409</td>
</tr>
<tr>
<td>Sea level</td>
<td>56.23992349</td>
<td>14.34556156</td>
</tr>
<tr>
<td>Urban</td>
<td>55.57657656</td>
<td>13.0563844</td>
</tr>
<tr>
<td>Rural</td>
<td>56.09474542</td>
<td>12.02223164</td>
</tr>
</tbody>
</table>
9.2 List of equations

The time for Sigfox to drain the LiPo 3.7V 1000mAh battery in preliminary field test is:

\[ T_{\text{Sigfox}} = 8791 \div 3600 \approx 2.44 \ (h) \]  \ (Eq1).

The time for GPS to drain the LiPo 3.7V 1000mAh battery in preliminary field test is:

\[ T_{\text{GPS}} = 9456 \div 3600 \approx 2.63 \ (h) \]  \ (Eq2).

Sigfox energy consumption in one full Sleep, Wake up, Idle, Tx cycle is:

\[ E_{\text{Sigfox}} = 0.000025T_s + 0.00896 + 0.03584 + 1.05024 + 0.28 \]
\[ = 0.000025T_s + 1.09504 + 0.28T_i \ (J) \]  \ (Eq3).

GPS energy consumption in one full Sleep, Wake up, Idle, Rx cycle is:

\[ E_{\text{GPS}} = 0.000025T_s + 0.03136 + 0.09216 + 0.1022767667 + 0.3108333333T_i \]
\[ \approx 0.000025T_s + 0.2258 + 0.310833T_i \ (J) \]  \ (Eq4).

Average time length of all 30 field tests is:

\[ T_{AVG} = 2716 \div 30 \approx 90.53 \ (min) \]  \ (Eq5), or
\[ T_{AVG} = 45.27 \div 30 \approx 1.51 \ (h) \]  \ (Eq6).