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ULP-Pos

Ultra-Low Power Device Positioning Concepts

ULP-Pos Executive Summary Report

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Table of Contents

List of Figures

List of Tables

1. Scope of the Document

This document is a deliverable of the Project “Ultra-Low Power Device Positioning Concepts” (ULP-Pos) and is provided by Fraunhofer IIS (FhG-IIS) together with its subcontractor TeleOrbit GmbH (TOG). This document contains the Executive Summary Report for the ULP-Pos project. The goal is to concisely describe the objectives of the project and to summarise the performed work and the findings of the Contract.

2. Objectives and Performed Work

2.1. Main Technical Objectives

The aim of the activity was to study, design, develop and assess performance of innovative concepts and paradigms for ultra-low energy (and low-cost) positioning devices, based on space-based PNT systems (GNSS and/or complementary/alternative PNT systems) standalone or in hybridization with terrestrial networks, that can make the adoption of space-based PNT as competitive/preferred positioning enabler for ultra-low energy (and low-cost) positioning devices.

2.2. Proposed Approach

The project started with an extensive search on present tracking devices. This resulted in a listing of the later presenting also their performance due to the calls requirements. A Comparison of state of the art GNSS-ASICs including frontend chips as well as baseband processing chips and fully integrated GNSS-modules followed the search.
The focus of the performance comparison was the power consumption of the different solutions until a position solution is reached.
An investigation of present and future battery technologies and related capacity per volume, self-discharge and aging were included in this study. Moreover, also cost of batteries were a major parameter to be analysed. Besides, energy storage devices and their efficiency also power and battery management circuits from typical semiconductor providers were evaluated and their influence on overall system performance especially lifetime was assessed. Power management algorithms like hybrid storage modules build by a primary battery and a capacitor to improve battery efficiency were evaluated
A detailed analysis of power consumption of communication and localization modules was a major input for this action. Power consumption of different communication alternatives like LPWA (LORA, Sigfox, etc.) as well as cellular communication standards like 4G or NB-IoT were used to assess use cases, estimate battery capacity and required size. Power consumption was analysed in reference to state-of-the-art localization and communication techniques.

2.3. State-of-the-art Review

2.3.1. Satellite-based Positioning

Conventional GNSS Positioning:
The conventional approach uses a full receiver chain with antenna, front-end, baseband and navigation processor to output position, velocity and time (PVT). To do so, the receiver first needs to acquire and track available signals and calculate the position of the corresponding satellites with ephemeris data. This data can either be obtained from an external source, e.g. over network, or directly from the navigation messages sent by the satellites.

A complete overview regarding conventional GNSS receivers available in the market can be obtained from the "Receiver Survey" published yearly by the magazine "GPS-World".

Snapshot Positioning:

In contrast to the conventional approach of calculating the position directly on the receiver, specialized snapshot GNSS receivers only record the incoming raw signal for a very short period of time (in the order of tens to hundreds milliseconds). This so-called snapshot is then forwarded to a server, which processes the signal and obtains a position fix with the help of external information such as rough position estimate and ephemeris data.

LEO-PNT:

Within the past few years, several large low earth orbit (LEO) satellite constellations such as OneWeb or Starlink by SpaceX have been announced besides smaller already existing constellations such as Iridium. Their main purpose is to provide broadband communication links with global coverage. However, these signals can also be exploited for navigation purposes, using for example the Doppler measurements or a Time Difference of Arrival (TDOA) approach.

2.3.2. Terrestrial Positioning

State of the art solutions for LPWAN positioning can be grouped in two categories: LPWAN-based and LPWAN as combination with wireless technologies. For LPWAN-based approaches, power consumption, high coverage and reduced device complexity are the main advantageous. Meanwhile these approaches suffer from poor performance (>100 m), low mobility, and often additional network overhead like synchronization or chipsets supporting OTDOA are needed for NB-IoT.

In most of the approaches being currently adapted, LPWAN is used as a communication link for assistance data or to report measurements. This provides acceptable performance in supported areas. On the other hand it suffers from low coverage, additional hardware, power consumption depends on the scanning and reporting requirements.

2.3.3. Communication

Ultra-low-energy positioning devices require the most energy efficient communication technologies. To date dedicated Low Power Wide Area Network (LPWAN) like Mioty, LoRa, Sigfox and 3GPP NB-IoT technologies fall into that category. Consequently, the achievable transfer data rates are at most moderate, at a very long communication range.

2.3.4. Battery Technology

Commercial available batteries come in standardized geometries, what makes it possible to buy replacement batteries for a given device of the shelf from different manufacturers. Typical geometries in a cylindrical shape are identified with A, AA, AAA, B, C or D. There are also coin cell battery geometries with the prefix CR and a number to indicate the dimensions like CR2032, which indicates a diameter of 20 mm and height of 3.2 mm. The capacity of these standardized batteries depends strongly on the chemistry, which is used. Furthermore, the useable capacity also depends on the average current, which is drawn from the battery. In general, a high discharge current results in a lower useable capacity.

2.4. Performed Work and Results

2.4.1. Scenarios

Cattle tracking:
A farmer with a large herd of cattle needs to be able to track the animals on his farm area located in the mountains. Knowledge about the cattle's positions shall be used to find lost animals, locate specific animals (e.g. for medical reasons) or simple ensure no animal moved out of its designated area. During winter, the animals will stay in a barn on the farm itself, where no position fix is required. The farm area could be several tens of square kilometres and includes small natural obstacles. The accuracy of the position should be less than 10m in order to identify the animal even if multiple animals are present at the same location. The position must be available on demand for emergency cases and in the other cases it should be at least once per hour during the animal's wake time. The operation time of the device should be at least 5 years to fit the life cycle of an average cow.

Container tracking:
Containers are used to transport any kind of goods on trucks, trains or ships. Tracking the position of the container in real-time provides important information for the whole supply chain to optimize the transport and storage of the goods. It could also trigger a potential contingency plan. Since the container can travel on road, rail or water, the environment is unlimited. Position requirements should sometimes be accurate to identify if the container is on the correct street or rail track. The position should be available also on demand, too. Due to the size of a container the accuracy of the position should be 3m. The duty cycle 1 / day and 24 / day but should be adaptable from remote.

2.4.2. Reference Concepts

Positioning:
All devices for cattle tracking as well as container tracking, for which the GNSS receiver could be identified, use low power devices from u-blox or MediaTek. In general, these devices support two different GNSS in single-frequency mode, mostly the combination of GPS/GLONASS. They are all conventional GNSS receivers, meaning after being powered on they need to first acquire at least four satellite signals and track them for a certain amount of time to decode the navigation messages before a position can be calculated.
Apart from GNSS-based positioning solutions, SEMTECH offers a LoRa-based positioning method for cattle tracking. This non-GNSS positioning solution requires additional gateway deployment and was based on an Uplink-TDOA-architecture. Therefore, to obtain position uplink transmissions from the device must be received by three or more gateways.

Communication:
All devices for both reference scenarios, cattle tracking and container tracking, that rely on mobile communications standards such as 2G (GSM), 3G (UMTS), and 4G (LTE) satisfy the requirements regarding uplink and downlink data size per connection as well as mobility, coverage and latency. For approximation of the power consumption of mobile communication modules NB-IoT was selected as the reference. NB-IoT was selected after comparing data sheets of NB-IoT modules and LTE Cat1 modules. For LTE Cat1 the power consumption can be assumed to be two to three times higher than for NB-IoT.

Figure 2-2 shows the contribution of each state to the energy, needed to transmit the location fix data.

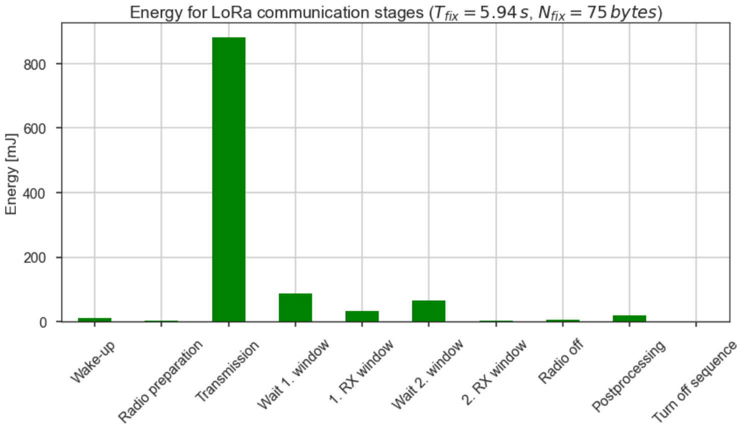

Figure 2-2 Energy for different transmission states (LoRa)

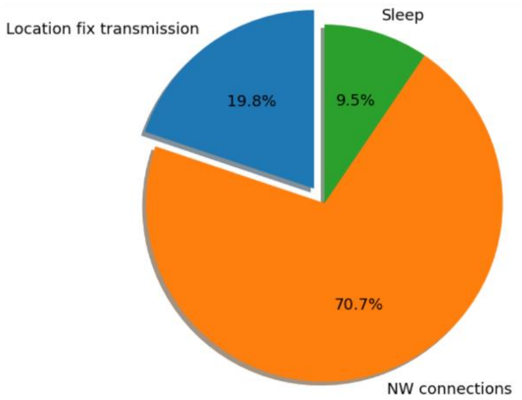

Figure 2-1 Energy contributions of communication phases

The second energy contribution is the periodical connection to the network (base station) to ensure a maximal response time of 5 minutes.
Within one hour, there is one transmission of a 75 byte fix (T_{fix} = 5.94 s), consuming 1.115 J, 11 network connections (T_{NW} = 3.19 s), using 0.361 J (3.97 J in total) each and in sleep mode the rest of the time with 0.533 J of energy. Figure 2-1 shows the contribution of the different phases (transmission, network connections, sleep) to the total energy budget. Due to the very high number of NW connections, this phase consumes about 70 % of the total energy budget.

Energy:
With the LoRa communication energy calculation for Cattle tracking was carried out, see Table 2-2. Note that the connection to the network every 5 minutes (additional 262 transmissions of 0 bytes per day) to achieve a latency time of 5 min is very energy consuming. As a result, the NW connection energy of 95.3 J per day is 3.6 times the energy of the 12 fix transmissions.
Setting up sufficient LoRa base stations should be possible in a defined area (e.g. pasture) for cattle tracking.
For the container tracking scenario, see Table 2-1, NB-IoT communication is considered to arrive at the lowest possible power consumption and thus battery requirement.

Summary:
In summary of the above shown calculations, the target requirements in terms of costs, volume and operation time for cattle tracking and container tracking with an hourly tracking rate are achievable with state-of-the-art technologies. However, the general aim of the project to achieve ultra-low energy positioning devices with a run-time of 15 years and with costs between 1 and 3 € is not possible.

Table 2-2 Cattle tracking reference concept

Total Energy for Operation Time [kJ]	310,18
Losses in Power Management [%]	20,00
Total Energy [kJ]	372,22
Self-discharge [%/month]	0,30
Cell Capacity [kJ]	82,35
Cell Volume [cm^3]	53,00
Cell Costs [€]	1,70
Reduced Cell Capacity [kJ]	67,53
Required Cells	6,00
Volume for Energy [cm^3]	318,00
Battery Costs	10,20

Table 2-1 Container tracking reference concept

Total Energy for Operation Time [kJ]	152,00
Losses in Power Management [%]	20,00
Total Energy [kJ]	182,64
Self-discharge [%/month]	0,30
Cell Capacity [kJ]	82,35
Cell Volume [cm^3]	53,00
Cell Costs [€]	1,70
Reduced Cell Capacity [kJ]	64,56
Required Cells	3,00
Volume for Energy [cm^3]	159,00
Battery Costs	5,10

2.4.3. Innovative Concepts

For Container tracking scenario runtime is 6 years. Reference technologies includes GNSS positioning with a total energy of 77.73 kJ and for communication NB-IoT with 75 bytes payload with a total energy of 23.17 kJ. The snapshot technology acquires a short sample, which must be transferred to a server in order to calculate the position. One snapshot has 16,368 bytes of data. Mioty and LORA do not fit for transmitting such an amount, hence NB-IoT is also used.
Table 2-3 is showing the required energy for the scenario per mission and the required number of battery D-cells and the required volume without considering a fixed battery cell format. Table 2-3 shows clearly the reduction in the number of battery cells and the decrease in required battery volume due to improved battery chemistries at a fixed mission time of 6 years according to the scenarios requirements.

Table 2-3 Analysis of reference and new technologies for container tracking

	NB-IoT + GNSS	**NB-IoT + Snapshot**
Total energy [kJ]	121.08	6946.78
MNO2 Number of Cells	2	108
MNO2 Volume [cm³]	99.40	5702.69
Advanced Li-Ion Number of Cells	2	63
Advanced Li-Ion Volume [cm³]	57.74	3312.99
SSB Number of Cells	1	47
SSB Volume [cm³]	43.31	2484.74
Li-Air Number of Cells	1	6
Li-Air Volume [cm³]	5.42	311.02

For Cattle Tracking the scenario runtime is 5 years. Reference technologies include GNSS positioning with a total energy of 64.78 kJ and communication with LoRA including 75 bytes pyload and a total energy of 246.06 kJ. For positioning GNSS, BLE and Snapshot are taken into account. For communication Mioty and LoRa. The last analysed approach is PDoA with Mioty, here positioning is based on the communication device.
Table 2-4 shows the total energy per scenario and the required number of battery cells (D-cell format) for different battery chemistries and the required battery volume without considering a given battery cell format (like D-cell). For this table a payload of 16 bytes is taken into account. It is obvious that the required number of batteries and especially the required battery

volume is considerably reduced with improved battery technology like Advanced Li-Ion or Solid State Batteries (SSB).

Table 2-4 Analysis of new technologies for cattle tracking

	Mioty + GNSS	LORA + GNSS	Mioty + BLE	LORA + BLE	Mioty + Snapshot	LORA + Snapshot	PDoA Mioty
Total system energy [kJ]	116.83	344.72	93.51	321.40	5804.91	6032.80	8.92
MnO2: Number of Cells	2	6	2	5	86	90	1
MnO2: Volume [cm³]	91.69	270.56	73.39	252.26	4556.10	4734.97	7.00
Advanced Li-Ion: Number of Cells	2	3	1	3	50	52	1
Advanced Li-Ion: Volume [cm³]	53.27	157.18	42.64	146.55	2646.88	2750.79	4.07
SSB in 2030: Number of Cells	1	3	1	3	38	39	1
SSB in 2030: Volume [cm³]	39.95	117.89	31.98	109.91	1985.16	2063.09	3.05
Li-Air (theoretical): Number of Cells	1	1	1	1	5	5	1
Li-Air (theoretical): Volume [cm³]	5.00	14.76	4.00	13.76	248.49	258.25	0.38

2.4.4. Main Conclusions

The main communication energy contributor in the cattle tracking use case is to the network connection requirement. For Lora 70 % and for Mioty 64 % of the total energy consumption is due to network connections. In absolute terms, Lora requires about 6 times more energy than a Mioty solution. The major advantage of Lora is the widely available Lora infrastructure, which Mioty cannot provide at the moment. In the considered uses case, with rural locations, the availability of the infrastructure might not be given, hence a setup with a generic base station was assumed. The expenses of setting up a local infrastructure is similar for both systems. In terms of scalability, i.e. how many end devices (cattle) can be covered with one base station, Mioty is able to deal with 4 times as many end devices as Lora.

Swarm/ Cooperative Localization

A trade-off analysis showed that the positioning requirements for Cattle Tracking can be satisfied while reducing the total power consumption of the positioning portion over the life time of 5 years to 45.34 kJ what is almost 30% less than compared to the reference concept GNSS positioning with 64.78 kJ.

Carrier Phase Measurements

Simulations of this concept showed, that the required positioning accuracy, and the required positioning availability are achievable with such a dedicated setup. The need of dedicated infrastructure, like PDoA nodes, beacons and a location server, increase the acquisition costs and also the costs of maintenance. Based on the parameters of the simulation, the power consumption of the Carrier Phase Measurement concept was estimated. The energy consumption of the positioning part of this innovative concept is 7.43kJ and hence can be reduced by 88% compared to the reference concept based on GNSS positioning with 64.78 kJ.
NB-IoT is a global communication standard and an option for the use case of container tracking due to its design purpose. Combining a standard GNSS receiver with narrowband IoT communication the amount of total energy over 6 years of usage is around half energy for communication and half for positioning. Also the data transfer is expensive regarding power consumption. If snapshot positioning is used instead of standard GNSS positioning the energy consumption for positioning is very small but a lot of data >8kByte has to be transferred. This

leads to a much higher power consumption in total and is therefore not suitable approach for low power container tracking.
Since available battery roadmaps predict an increase in energy density of a factor of 1,7 for 2025 and 2,3 for 2030, this factor will reduce the required battery volume or increase the life-time. Depending on the present and future research and development of promising battery chemistries like Li-Air, Zn-Air or Li-Sulfur the required battery volume can reduced even further or operation times can be prolonged considerably. With these future battery performance considerations, the required battery volume and number of battery cells (standard D-cell volume) were simulated for each scenario and the new localization technologies were considered in these simulations. The results show a serious reduction in required battery volume per scenario where a fixed operation time was taken into account (container tracking 6 years, cattle tracking 5 years). However, by keeping the battery volume constant compared with state-of-the-art battery technologies also a significant increase of operation time is possible with the future battery technologies.

Applicable and Reference Documents

Applicable Documents:

[ESA-CON]	ESA Contract No.: 4000128165/19/NL/MP ULP-Pos - Ultra-Low Power Device Positioning Concepts
[ULP-Pos-NPD]	ULP-Pos_NAVISP-EL1-019-AO9645_NegotiationPointDocument_v1.0
[ULP-Pos-D1]	NAVISP1-DD-FHG-ULP-Pos-D1-UseCases-TradeoffAnalysis_v1.0
[ULP-Pos-D2]	NAVISP1-DD-FHG-ULP-Pos-D2-Performance&Scenarios_v1.1
[ULP-Pos-TN1]	NAVISP1-TN-TOG-ULP-Pos-TN1-LEO-PNT-Overview_v1.0
[ULP-Pos-D3]	NAVISP1-DD-FHG-ULP-Pos-D3-Concept-Definition_v3.6
[ULP-Pos-D4]	NAVISP1-DD-FHG-ULP-Pos-D4-Concept-Analysis_v2.6
[ULP-Pos-D5]	NAVISP1-DD-FHG-ULP-Pos-D5-Conclusions&Recommendations_v1.6

Acronyms and Abbreviations

ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
EU	European Union
FhG-IIS	Fraunhofer Institute for Integrated Circuits
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	American Global Positioning System
GSA	European GNSS Agency
INS	Inertial Navigation System
IoT	Internet of Things
LEO	Low Earth Orbit
PNT	Position Navigation Time
PVT	Position Velocity Time
TOG	TeleOrbit GmbH
ULP	Ultra-Low Power

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