Vision Paper: LoRa on Ice - Live sea ice monitoring using IoT technologies

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ABSTRACT

Sea ice measurements are pivotal for understanding the complex dynamics of polar regions and their influence on global climate patterns. Autonomous sensors, designed for prolonged measurements of sea ice properties, are a central component in the acquisition of data from remote and inaccessible areas. While satellite communication plays an important role in the transmission of data from these autonomous systems, especially in situations where retrieval is not possible, terrestrial radio links and low power wide area networks (LPWAN) are not widely used. In this context, the application of Internet-of-Things (IoT) technologies demonstrates substantial potential, offering advantages in terms of easy integration, extended battery life, and cost effectiveness. Here, we present the design and implementation of a wireless sensor network (WSN) tailored for sea ice research. Our custom-built sensors employ Long Range (LoRa) radio technology and the Long Range Wide Area Network (LoRaWAN) protocol. We describe the deployment of a scientific measurement system in the vicinity of the Neumayer III research station in Antarctica, utilizing IoT technologies. During the first year of operation, multiple tests were conducted to verify the system's ability to collect and transmit data from existing measurement sites that previously relied only on satellite connections. The simple sensor integration and near-real-time availability of the data indicates that the technology is capable of improving the effectiveness of field campaigns. We identify current technological limitations and propose improvements for the next generation of WSN dedicated to sea ice research, aiming to further enhance data quality and reduce logistical efforts.

CCS CONCEPTS

• **Networks** → **Network experimentation**; • **Hardware** → *Networking hardware*; • **Information systems** → Information systems applications.

KEYWORDS

WSN, LPWAN, LoRaWAN, LoRa, sea ice

1 INTRODUCTION

To understand processes in the sea ice, the atmosphere or in the ocean, many different parameters need to be measured on different spatial and temporal scales. In polar research, data collection and sensor behavior monitoring of single sensor platforms are usually carried out with satellite communication links. These sensors are typically deployed by ships or aircraft onto drifting pack ice, where they can collect data as they drift through the polar regions for extended periods. They are also positioned near research stations and ships (distance less than 40 km), which may remain stationary for several days or weeks to facilitate continuous monitoring [4, 17]. Even when sensors are installed close to a central station, conventional satellite connections are used for data transmission, with high costs for transmission and hardware, as well as high maintenance effort due to the individual subscriptions for each sensor.

Various ships and stations are operated in the polar regions conducting scientific measurements. For regular monitoring of sea ice, besides various other tasks, the permanently staffed research station Neumayer III in Antarctica is operated [23]. The station is situated on the ice shelf, approximately 10 km from the shelf ice edge and the adjacent sheltered embayment, Atka Bay. The bay is covered with fast ice, which is sea ice that remains attached to the shelf ice and does not move. This fast ice is accessible via a ramp on the western edge of the bay and breaks up seasonally during the Antarctic summer. During the ice-covered and accessible time period, i.e. May/June to December/January, this allows for both manual measurements of seasonal sea ice properties and the deployment of autonomous ice-tethered systems. Since 2010, the observations are carried out regularly, contributing to the international Antarctic Fast Ice Network (AFIN). A number of sampling sites are visited on a monthly basis to obtain a continuous record of sea ice parameters [1, 2], as shown in Figure 7.

Data from devices deployed on the ice in Atka Bay or around the station is either transmitted via satellite connections or collected manually by replacing data storage media. However, this data acquisition process is inefficient due to weather-related access limitations and the high cost of satellite transmission. Here, new radio and network technologies from the Internet-of-Things (IoT) domain provide new possibilities for collecting scientific environmental data in Wireless Sensor Networks (WSN). Especially the Long Range (LoRa) radio communication technology and the Long Range Wide Area Network (LoRaWAN) protocol are promising developments because of the long transmission range, the low power consumption, and low device costs.

In this study, we present the design and implementation of a WSN and a sensor node, developed to measure sea ice properties of the fast ice in Atka Bay and transmit the data to the Neumayer III station using the LoRa radio technology and the LoRaWAN protocol. Range tests indicate that the WSN can effectively cover a radius of 30 km around the station, providing a viable alternative to conventional satellite connections for nearby devices.

2 RELATED WORK

A time-series measurement of the evolution of sea ice layer thickness was already discussed in [5]. Although the manuscript is currently under review and does not give any details about the measurement system, the idea for an autonomous data acquisition unit with a radio link was adopted and improved for this project.

There are different projects on LoRa and LoRaWAN sensor networks with different sensor configurations and environmental conditions. In [18] the setup of a LoRaWAN in an offshore environment and the experience of 70 days of operation are described. The technology proves to be quite robust and the RSSI and SNR values are only affected by the atmospheric conditions by 1-2 dB. However, the range is only 8.3 km and the sensor node was stationary.

In [9] a LoRa range test was carried out in Antarctica, in which a distance of up to 30 km was covered, but no long-term scientific measurements were conducted.

Suitable replacements for the conventional satellite connections, primarily the Iridium network, are new developments from the field of direct-to-satellite Internet of Things (DtS-IoT), in which the direct connection of IoT end devices with satellites is being developed. The feasibility and limitations of DtS-IoT technologies were discussed in [6, 7], among others. Various services already exist, e.g. the Lacuna constellation [8, 13, 16], an S-band LoRa-enabled IoT network from EchoStar Mobile [15] and the SWARM network [12]. However, these networks only offer temporary availability, low data rates or cannot be used in Antarctica due to geostationary satellites.

3 APPLICATION SCENARIO

To study the change of fast ice parameters on hourly to monthly time scales, a long term measurement is set up on the Atka Bay near the Neumayer III station. The instruments used, include an EM31 conductivity meter from Geonics for ice thickness measurements [10, 11], a temperature sensor, and a GNSS receiver. To monitor the data and the system status from the station, a LoRa radio link will be established as well as a database and visualization. A measurements interval of 30 minutes to 2 hours is expected, while every measurement lasts between 1 and 2 minutes. The measurement system is deployed on one of the established measurement sites, that are visited every month, as long as the sea ice in Atka Bay is accessible. The sampling sites are named ATKAxx, where xx represents the distance in kilometers to the western ice-shelf edge [1, 2]. The furthest point is ATKA24, 28 km away from the station, as shown in Figure 7. The system is first deployed in November until the sea ice breaks away mid-January. The system will be recovered before the opening of the bay and will be deployed again after the refreezing of the sea ice around end of May to early June. The anticipated deployment duration spans up to 8 months. The air temperatures during one year of deployment are expected to fall between +2 °C and -47 °C [21]. Neumayer III station serves as central hub for collecting the data and forwarding it to a land station via a permanent satellite connection. The station is located on the ice shelf near Atka Bay, 43 m above sea level. The antennas of the LoRa receivers will be mounted on top of the station near the meteorological observatory, which is 25 m above the shelf and therefore 68 m above sea level [22].

4 NETWORK AND COMPONENTS

In the following, a more detailed overview of the developed network is provided, describing the elements of Figure 1.

4.1 System overview

The measurement system enables a data flow from the sensor to visualization. The sensor node collects the sensor data, which is stored locally on an SD-card and additionally transmitted through LoRa operating in the 868 MHz band using the LoRaWAN protocol. At the Neumayer III station two gateways are installed. The gateways forward any received data to a server that runs a software stack consisting of the network server, the data base, and the visualization software. The same software stack is set up on a server in our institute, to which the data base from the station is mirrored. The visualization software on land can be reached from the internet and therefore provides global near real-time access to the data.

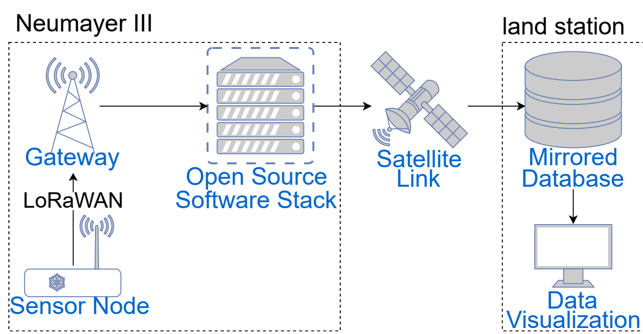

Figure 1: System overview: LoRaWAN based WSN enabling a data flow from the sensor in Antarctica to a globally accessible database with data visualization.

4.2 Sensor node

The sensor node contains the data acquisition unit (DAQ), the battery, and the sensors. The DAQ is a custom-made mainboard built around the LoPy4 development board and Pytrack expansion board from Pycom Ltd. The DAQ controls the power for the sensors, stores the data locally on an SD-card, transmits the data through a LoRa radio link, and puts the whole system in a deep sleep mode between measurement cycles. The LoPy4 provides an ESP32 microcontroller, Wifi connection, and a LoRa transceiver. The ESP32 is programmed using MicroPython [20]. The size of one transmitted dataset is 28 Bytes and the additional overhead for LoRaWAN is 13 Bytes. The transmitter output power is 20 dBm and the used bandwidth is 125 kHz. The coding rate for LoRaWAN is set to 4/5 and the firmware limits the airtime to 1%. The Pytrack expansion board offers a USB connection for programming, an SD-card slot, and a GNSS receiver [19]. The mainboard hosts a real-time-clock (RTC), DC-DC regulators, and two serial connections. Although temperatures as low as -47 °C are expected, as mentioned in section 3, the mainboard and the Pycom development boards are only rated to -40 °C. For protection, the electronics are stored in a water tight case together with the battery, shown in Figure 2. The LoRa antenna is placed on a stick 1 to 2 m above the sea ice. In the deep sleep mode, only the RTC is powered by the main battery. The deep sleep power consumption is 360 μW at 12 V and the power consumption during a measurement cycle is around 2 W.

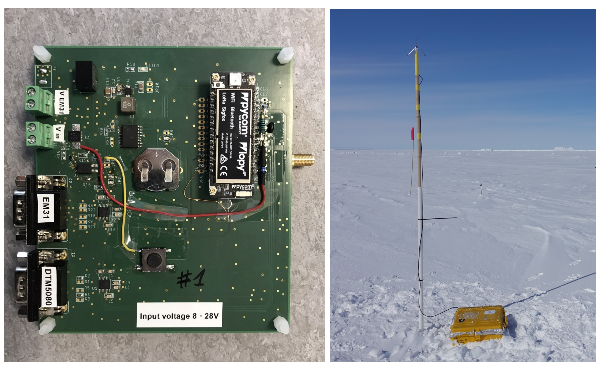

Figure 2: Sensor node electronics. Left: data acquisition unit (DAQ), right: sensor node placed on sea ice with electronics and battery in protective case.

To measure sea ice parameters, an EM31 conductivity meter is used, shown in Figure 3. The instrument emits a time varying magnetic field and measures the response from a conductive ground [10]. To protect the instrument from the harsh Antarctic environment, it is placed in a sealed plastic kayak. The second sensor is a DTM5080 temperature probe [14]. Both sensors are connected to the serial ports of the DAQ and start operating as soon as power is applied.

4.3 LoRa radio link and gateway

For receiving the data from the sensor node at the Neumayer III station, two LPS8 LoRaWAN gateways from Dragino are installed, operating in the 868 MHz band. One gateway is connected to an 3 dBi omnidirectional antenna, one is connected to a 12 dBi directional antenna, directed towards measurement site ATKA11, in the middle of the Atka Bay. Figure 4 shows the installation of the antennas on the roof of the station. The gateways are connected to the station's local network and forward all received data to a network server.

Figure 3: EM31 conductivity meter used to measure sea ice parameters.

Figure 4: LoRa antennas on the roof of Neumayer III station.

4.4 Software stack

On a server at Neumayer III station, a Docker Engine is hosting the software stack for processing the data. The software stack consists of the Chirpstack network server, the InfluxDB data base, and the program Grafana for visualization. Additionally, the same software stack is installed on a server at our institute's computing centre. The data base from Neumayer III station is mirrored to the data base on land using the station's permanent satellite link. The Grafana instance at the institute is available through the internet, enabling world wide access to the sensor data from Atka Bay. Additionally, a gateway can be connected to the software stack at our institute, generating a completely mirrored system of the set up from Neumayer III station, allowing extensive testing of the system before finally deploying it in Antarctica.

5 PERFORMANCE TESTS AND FIELD DEPLOYMENT

Different scenarios were analysed during development and later in the field. A range test from the development phase and several experiences from field use are presented in the following.

5.1 System check and spreading factor comparison

Before being deployed in the Antarctic, the system is tested extensively and the range of the LoRa radio technology is examined. The LoRa technology offers various spreading factors (SF), where a higher spreading factor means a longer transmission time and therefore a lower data rate. However, the transmission range also increases with a higher spreading factor. LoRa offers spreading factors from SF7 to SF12, with SF12 having the highest range, but also the longest transmission time and the lowest data rate. The location of our institute near a large river offers the possibility of a 40 km long route along the waterway without obstacles and with line of sight to the institute, assuming an appropriate antenna height. As a general test and to measure the maximum range for each spreading factor, a motorboat has been equipped with the sensor node, shown in Figure 5. A dipole antenna is mounted on a pole in the center of the boat, 2.5 m above the water line. An aluminium box is mounted next to the steering on the port side of the boat, containing the sensor node without the EM31 conductivity meter. The software of the sensor node has been modified to transmit each dataset with every spreading factor and three times in a row as fast as possible. Afterwards the program is paused for 1 minute. Each dataset has a length of 20 Bytes and is stored locally for comparison with the received data. The overhead of the LoRaWAN protocol is 13 Byte and is transmitted additionally to the 20 Byte payload. The gateway is installed on the roof of one of our institute's buildings approximately 24 m above the water level, at a position where a clear line of sight is established along the river, shown in Figure 5. The same dipole antenna is used for the gateway and the sensor node.

Figure 5: Setup for a range test of the LoRa radio link. Left: motorboat equipped with the sensor node. Right: gateway with a clear view of the river, which serves as the route for the range test.

As the boat travels along the waterway, the sensor node continuously collects and transmits data, sending each dataset with all spreading factors. Table 1 shows the transmission times for a 20 Byte package transmitted with different spreading factors, calculated using an online airtime calculator [3]. One cycle of transmitting a data package with all spreading factors takes around 3.7 s. The boat speed is around 18 kn, which is 33 km/h or 9.3 m/s. Since the relatively high boat speed and the long airtime results in only few measurements per distance, the packages success rate is calculated for 3 km segments.

The comparison between locally stored and transmitted data shows that packets were either received completely or not at all. Figure 6 shows the package success rate for one motorboat drive along the shipping lane. It can be observed that the package success rate is almost 100 % for the first 10 km for all spreading factors. At greater distance, some packages are not successfully received anymore. The higher the spreading factor, the further a successful transmission is maintained. Applying a 50 % threshold for a successful transmission, distances from 15 km for SF7 to 25 km for SF12 were covered. The RSSI values measured by the gateway decreased from an initial -70 dBm to -120 dBm at a distance of around 10 km for all spreading factors and remained at this level until no packets were received. The minimum SNR value until where packages were still received, ranges from -22 dBm for SF12 to -9 dBm for SF7 and increases by 2 to 3 dB between the spreading factors. See available dataset for details.

Table 1: Airtime for transmitting 20 Bytes payload and 13 Bytes protocol overhead with different spreading factors, calculated from [3].

Spreading Factor	Airtime
SF12	1810 ms
SF11	987 ms
SF10	453 ms
SF9	247 ms
SF8	134 ms
SF7	72 ms

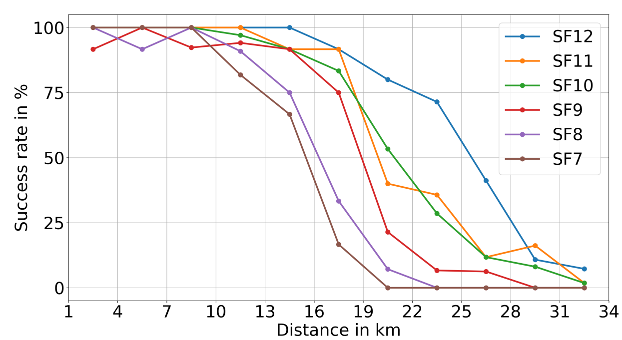

Figure 6: Result of the LoRa range test. Percentage of successfully received data packets over the distance to the gateway.

5.2 Sea ice measurements in Antarctica

After successful testing, the LoRaWAN network was installed at the Neumayer III Station in Antarctica. The sensor node was placed at ATKA11, 17 km away from the station, one of the regularly visited measurements sites shown in Figure 7. For the LoRa radio link, a dipole antenna was installed on a 2 m long stick. The 28 Bytes of each dataset are transmitted using spreading factor 12.

The sensor node was deployed at ATKA11 on December 25, 2022 and was expected to run for at least a month until the sea ice breaks away beginning of February. This season, however, the bay opened already on January 01, 2023 and the sea ice drifted away, including the sensor node. In the evening of January 02, the system was outside the coverage of the LoRa radio link. On January 07 the instrument was recovered by helicopter and the data could still be evaluated. Figure 7 shows the position of the sensor unit and the position data received by the gateway. When investigating the

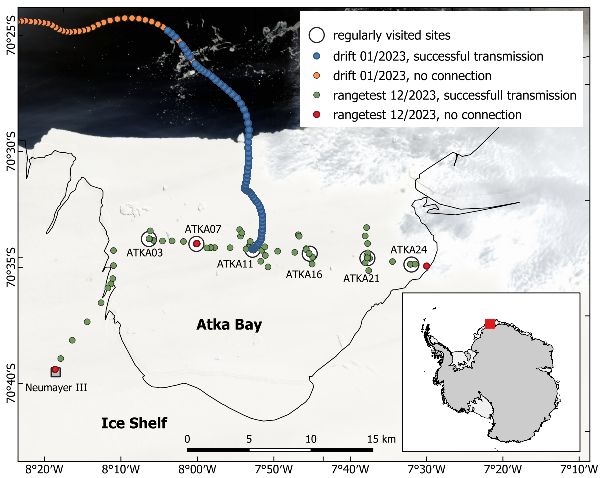

Figure 7: Study area Atka Bay near Neumayer III station with the regularly visited measurements sites of the AFIN program [2]. The data points indicate the covered distance from the station during the unintentional drift of the system with the sea ice in January 2023 and a range measurement with a snowmobile in December 2023. Green and blue: transmitted and successfully received datasets. Red and orange: transmitted but not received datasets.

success rate of the LoRa transmission, again the data packages were either received completely or not at all, as explained in section 5.1. It can be observed that up to a distance of 29 km almost all packages are received and suddenly the connection is lost. The RSSI values measured by the gateway were constantly at -120 dBm, the SNR values dropped from an initial -10 dBm to -22 dBm.

The system was deployed again at measuring point ATKA11 in June 2023 after the refreezing of Atka Bay. However, it was not possible to establish a radio connection via LoRa until the system was recovered in November. While a line of sight to the station existed during the first installation in December 2022, the optical axis was blocked by an iceberg in the winter of 2023, as shown in Figure 8. Attempts to establish a connection by repositioning the antenna were unsuccessful.

After the recovery of the sensor node the range of the LoRa radio link under field conditions was investigated. In December 2023 the sensor node was mounted on a snowmobile and driven to the measuring points ATKA03 to ATKA24. During this survey, the sensor node transmitted at spreding factor 8 and not at 12 as in stationary operation. It was expected that the entire Atka Bay could be covered with a spreading factor of 12, therefore the network coverage with faster data rates was of particular interest and a lower spreading factor was selected for the range test. Figure 7 shows

Figure 8: During winter 2023 an iceberg blocks the line of sight to Neumayer III station from the measuring site ATKA11.

the transmitted and received datasets. Despite occasional data loss, data transmission was generally possible across the entire width of Atka Bay. Only at ATKA07 repeated interruptions were observed, possibly caused by a higher number of surrounding icebergs. The RSSI values decrease with distance from -70 dBm to -120 dBm, the SNR decreases from +14 dBm to -5 dBm.

6 DISCUSSION

The aim of this project was to establish a measurement system that transitions from sporadic manual point measurements to a continuous temporal measurement system, transmitting data without additional logistical efforts or costs. This goal was successfully achieved by setting up a LoRaWAN based WSN in Atka Bay, near the Neumayer III station, and by exploring various system configurations under field conditions.

During the unintentional drift in January 2023, a range of approximately 29 km was achieved, although it can not be clearly resolved if the sensor node drifted behind the shelf ice, drifted outside the main beam of the gateway's directional antenna or left the maximum transmission range.

Another range test in December 2023 in Atka Bay demonstrated that the measurement area can even be covered using spreading factor 8 of the LoRa radio link. Compared to the transmission ranges achieved during tests with a motorboat, the ranges in Antarctica are significantly higher, likely due to the higher receiving antennas of the gateways.

Despite the successful coverage of the Atka Bay, several challenges and data interruptions occurred over shorter distances between June and December 2023. During this period, it was sometimes impossible to establish radio contact with ATKA11 and ATKA07, the measurement points located 17 and 15 km away form the station. It is presumed that icebergs obstructed the line of sight, thereby disrupting the connection.

These intermittent radio connection issues, along with the fact that many sea ice measurement devices are deployed well beyond the range of terrestrial radio networks, highlight the need to combine a WSN with other radio technologies. There is potential to leverage systems from the satellite IoT sector, some of which can be integrated into existing data streams and can dynamically switch between terrestrial and satellite-based connections, as mentioned in section 2.

Following the successful implementation in a single measurement scenario, we plan to explore further potential applications for this system. In November 2024, we intend to deploy multiple sensor nodes to collect data from a temperature chain, as well as a sensor node performing GNSS reflectometry–refractometry (GNSS-RR), all connected to the LoRaWAN network at Neumayer III station.

In exploring further possible applications of the LoRaWAN, we have identified that the limited data capacity per transmission poses challenges for addressing some scientific questions. In this study, data packages ranged between 20 and 28 Bytes, and fewer than 20 packages per hour were sufficient for proper analysis. However, to answer certain questions in sea ice research, data volumes of 1 kB to 1.5 kB have to be transmitted every hour, which exceeds the available transmission time of individual sensor nodes. Therefore, methods for compressing data and reducing transmission time for a given data rate will be evaluated.

7 CONCLUSION AND OUTLOOK

In this work we presented the successful implementation of a LoRaWAN based WSN around the Neumayer III research station in Antarctica. Our findings showcase the system's capability to consistently covering regular visited measuring sites up to 30 km away from the station, which previously depended on satellite connections. However, we encountered intermittent connection issues, likely caused by icebergs disrupting the line of sight to the station. To mitigate these line of sight limitations and enhance data transmission reliability, we recommend integrating terrestrial WSNs with satellite-based IoT technologies in future implementations.

The developments presented not only improve the overall quality of field campaign results, but also facilitate the rapid and efficient answering of complex research questions, which is essential in the context of accelerating scientific developments and changing environmental conditions.

8 DATA AVAILABILITY

The used dataset is available at the following source: https://doi.org/10.5281/zenodo.13693107

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