Acta Universitatis Sapientiae
Electrical and Mechanical Engineering, 15 (2023) 1–13

DOI: 10.2478/auseme-2023-0001

IoT Sensor Network Solution for Monitoring Wind Induced Waves in Shallow Water

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Manuscript received June 7, 2023; revised June 21, 2023

Abstract: This case study presents a possible solution for monitoring wind induced waves in shallow water lakes. Currently widely used instruments for measuring water waves are expensive due to extreme environmental requirements and the technology used. The use of IoT solutions is not common. Water wave measurements require low power consumption and medium to long range communication. Due to the network specifications, it is not obvious that LPWAN technologies are suitable for transmitting the amount of data generated. For the devices developed, LoRaWAN was investigated as the cheapest and 5G as the most reliable network solution, with attention to energy consumption.

Keywords: IoT, WSN, LPWAN, LoRaWAN, 5G, Limnology, Wave monitoring

1. Introduction

Water is an important natural resource. The increasing global population and climate change are putting pressure on the availability and quality of water resources. Field observation is essential for monitoring and evaluating the effectiveness of environmental protection measures, allowing us to identify potential threats and develop strategies to mitigate them. Lake monitoring takes place in extreme environments (e.g. hurricane-force storms and extreme water levels). Information on water quality, temperature and other important factors affecting the ecosystem is crucial for understanding how lakes respond to environmental changes and for developing effective management strategies.

Many of the activities required in lake management can only be accomplished if the lake's current state is monitored on a regular basis. Long-term data can also be utilized to improve forecasts. This is why automated monitoring systems are required to provide real-time data that can be used to make appropriate lake management decisions.

Wind-generated waves have a significant limnological impact. They affect the water quality, sediment transport, and the distribution of aquatic organisms in lakes and reservoirs. The study of wind-generated waves is important for understanding the dynamics of freshwater ecosystems. The monitoring systems must be effective in monitoring and operate for a long period of time without causing harm to the environment or depleting resources. Therefore, it is important to consider the use of renewable energy sources and low-cost materials in the design and implementation of these systems.

Due to the high expense of equipment, it is difficult to conduct simultaneous lake surveys at multiple locations at the same time. This is the reason why there are currently no operational measurements of the waves on Lake Balaton, Hungary's largest lake, only intermittent measurements at numerous sites for research purposes.

2. Wireless Sensor Network and Internet of Things

The extreme environment of the lakes requires on-board power supply and wireless connectivity. The Internet of Things (IoT) provides numerous choices to create low-cost sensor networks, with low energy consumption. Low cost means lower measurement accuracy, but with more measurement nodes the accuracy can be increased. It is better to have several simpler nodes, as a larger area can be monitored with greater overall accuracy, and data from additional devices can be used in the event of a node failure.

Low Power Wide Area Network (LPWAN) technologies provide low-cost but effective long-range connectivity for Wireless Sensor Networks (WSN), making it ideal for IoT devices that need to transmit small amounts of data over long distances. LPWAN networks are designed to be scalable and capable of supporting a large number of devices. The LPWAN technologies sacrifices the data rate and the Quality of Service (QoS) for the low cost and low energy consumption. Communication can take place in the licensed frequency bands or in the unlicensed Industrial Scientific and Medical (ISM) bands. For ISM bands, the duty cycle must also be taken into account. This defines the percentage of time that active communication between devices is enabled [1].

A. ISM based LPWAN technologies

The two most popular LPWAN technologies, that use ISM bands are SigFox and LoRaWAN. In Europe, Sigfox operates on the 868 MHz ISM band, while LoRaWAN operates on the 443 MHz or 868 MHz ISM bands. The applicable duty cycle is 1% [2].

SigFox is available only through one operator. The maximum amount of data that can be sent per day is 140 $\cdot$ 12 bytes. The data rate is 100 bps [3].

LoRaWAN is available through service providers or by self-installation. Service providers often enforce air fairness rules that apply stricter communication rules than the regional standard (e.g. daily message limits). LoRaWAN uses adaptive data rate. The maximal achievable data rate is 5470 bps, which allows 590.76 kB of data to be transmitted per day [4].

B. Cellular LPWAN technologies

In the cellular networks the two available LPWAN solutions are the Long Term Evolution Category M1 (LTE Cat-M1) and NarrowBand IoT (NB-IoT). Both LTE Cat-M1 and NB-IoT offer low power consumption, extended coverage, and support for a large number of connected devices, making them ideal for IoT applications. LTE Cat-M1 has higher data rates and is better suited for applications that require real-time communication, whereas NB-IoT is better suited for applications that require low data rates and long battery life. LTE Cat-M1 and NB-IoT has theoretically no regulations, but service providers may impose their own restrictions or limitations on the use of these technologies. These technologies are available only through operators [5], [6].

C. 5G possibilities

The 5th Generation Cellular Mobile Network, also known as 5G, is the latest and most advanced form of wireless communication technology that promises faster internet speeds, lower latency, and greater connectivity. The design of 5G has been heavily focused on industrial use cases, such as sensor networks and critical IoT applications. LTE Cat-M1 and NB-IoT standards are still available in 5G, as a kind of extension. Offering seamless and future-proof evolution combined with dynamic spectrum sharing. The 3GPP Rel. 16 enables the connection of compliant LTE Cat-M1/NB-IoT devices to the next generation 5G core network. The implementation of the new specifications could be a challenge for the cost-sensitive cellular mobile IoT market, not only due to increased complexity but also due to the fragmented nature of the market [7].

3. Wave measurement

There are several ways to measure water waves in shallow lakes. The most basic measurement technique is the visual observation by an experienced observer. There are so-called in situ mechanical measuring devices, such as the VITUKI type wave tracker, which uses a floating element on the water surface, and there are also water pressure-based measuring devices [8]. The other major group of measurements is remote sensing. This includes all methods where the measuring device is deployed above the water surface and takes measurements on a fixed or moving platform. With today's technology, visual wave analysis can also record increasingly better results using cameras [9].

In addition to the measurement technique, the placement of the instruments can also vary. The most common method of wave measurement is to measure wave properties at a single point over a long period of time (several weeks of measurements). Multi-point measurements allow analysis of a larger area but are rarely used because of the need for precise time synchronisation between measurement nodes and the investment required for a single instrument.

Due to the extreme environment the instruments must be waterproof and resistant to environmental impacts. For this reason, the instruments on the market are very expensive. Therefore, often few instruments are installed, and sampling is done at a single point. Professional water surface measuring devices currently available on the market cost approximately 25 000 – 30 000 EUR.

4. Hardware architecture

A. Challenges in wave sensing

The tools developed had to meet a number of requirements. They had to remain functional in extreme environmental conditions, while being simple and inexpensive to produce, as they compose an IoT sensor network. Devices should be able to operate for as long as possible without intervention, while running on battery power. Measurement data should be transmitted using LPWAN technology to provide quasi real-time information.

The limonological modelling of lakes has slightly different requirements than the average IoT LPWAN sensor networks in the traditional sense. To process the measurements, the sampling density in the measurement cycles should be around 8 Hz in Hungarian lakes to reconstruct the waveform according to the Nyquist-Shannon sampling theorem. The number of samples collected during the measurement cycle should be ideally a power of two for the fast Fourier transform, but at least 1024 samples, as this provides a sufficient number of waves (at least 100 recommended) for the calculation of statistics. In order to test the lake surface as regularly as possible, the more frequent the measurement cycles, the better. The sampling frequency for this study is 20 minutes per measurement cycle. The amount of data generated by such a large number of samples uses only a negligible fraction of the Internet bandwidth but can be very demanding for a LPWAN network [9], [10].

There are many communication solutions for IoT WSN networks. The water monitoring system in question performs 72 measurement cycles per day, generating 290 kB of data per day for a minimum of 1024 measurements per cycle. This amount of data is unusually large for a LPWAN network. Most operators have radio usage restrictions to ensure that all user devices can be served by the network (Fair Access Policy). This is stricter than the duty cycle time in general, which makes SigFox, some LoRaWAN and NB-IoT services unsuitable for transmitting measurements from the water monitoring network nodes. Among the LPWAN technologies discussed, LTE Cat-M1 seems to be the only feasible one. However, with data size reduction, private LoRaWAN can offer a cheaper solution in long-term, as only the deployment is costly.

5G LPWAN technologies are not yet available for general use, but the 5G network places a strong emphasis on machine-to-machine communication and quality of service, so although radio modules are currently expensive, their cost could be reduced as the technology becomes more widespread. Reduced Capability (RedCap) modules (non-LPWAN solutions) are already available, where reduced capability also means lower cost [11]. In the future, the LPWAN integrations mentioned in *1/C* may also become available in 5G networks.

B. Hardware architecture

At the heart of the measurement nodes is an ESP32 System on a Chip (SoC) based microcontroller unit (MCU). Various measurement submodules and operational support devices are connected to this: DS18B20 waterproof thermometer module, JSN-SR04T waterproof ultrasonic distance sensor module, DS3231 real time clock (RTC) module, CNC136X110-6 solar panel + TP4056 charge controller, and NCR18650B Lithium-ion battery. The MCU has integrated LoRa and Wi-Fi radio module, but no cellular capabilities. *Table 1.* shows the submodules and their specifications.

The devices are located on a printed circuit board made for the module, in a waterproof box. The system is designed to deliver multi-point remote sensing. The measuring nodes are mounted above the water level and the distance sensor is positioned vertically to the water surface. *Fig. 1* shows a module in the field.

Table 1: Used submodules

Name	Type	Features	Price
MCU with LoRa capability	LILYGO® LORA32 V2.0 868Mhz LoRa ESP32 OLED	ESP chip: ESP32 PICO-D4; Flash: 4 MB; MicroSD Card slot;	~40 EUR
Thermometer (Waterproofed)	DS18B20	Range: -55 °C to +125 °C; Accuracy: ±0.5 °C;	~3 EUR
Ultrasonic Waterproof Range Finder	JSN-SR04T-2.0	Range: 20–600 cm; Angle: 75°; Accuracy: ±1 cm; Resolution: 1 mm;	~6 EUR
Real Time Clock (RTC)	DS3231	Accuracy: ±2 ppm from 0 °C to +40 °C, ±3.5 ppm from -40 °C to +85 °C; Backup-Battery	~4.5 EUR
Solar panel	CNC136X110-6	Size: 136 x 110mm; Work voltage: 6V; Max power: 2W	~12 EUR
Charge controller	TP4056	Input supply voltage: 4.5~6.0 V; Overcurrent Protection	~1 EUR
Battery	NCR18650B	Capacity: 3400 mAh	~9 EUR

Figure 1: Field deployed measurement node

The communication objective of the study is to achieve low energy consumption with Cat-M1 alternatives. The two feasible options are LoRaWAN network and 5G if low power consumption is achievable. In the lack of an easily integratable 5G radio module, a Wistron NeWeb Corporation (WNC) 5G mobile hotspot has been used for communication.

The LoRaWAN network of the study is self-hosted, based on an open-source ChirpStack Network Server [12]. The 5G network was a Non-Standalone

(NSA) test campus network provided by Ericsson Hungary and Budapest University of Technology and Economics [13].

The data is collected in a PostgreSQL database accessible via the Internet [14]. The data is processed using Matlab Online [15].

5. Description of the network operation

A. Data structure

The wave analysis is performed every 20 minutes, with 2100 measurements in one measurement cycle at 8 Hz sampling. During measurement processing, the number of samples should ideally be a power of 2, with a few extra measurements for error filtering, so more than 2048 measurements are performed per cycle. As sampling is very dense, there is no time to send the measurement results until after the measurement cycle has been completed. The measurement nodes transmit the start time of the measurements, the air temperature and the water surface distances in a chain.

B. Node sync

Since sampling takes place simultaneously at several points in the lake, it is important that the measuring nodes take measurements at the same time. Thanks to the RTC module, this synchronization can be achieved.

Node consumption can be minimized by using the sleep mode of ESP32. Using the RTC module, it is possible to dynamically set how long the devices should be in sleep mode after measurement and data transmission. Thanks to the dynamic sleep timing implementation, device idle time is minimized.

C. Measurement accuracy

The measurement accuracy of the distance sensors should be maximized to recover the waveform as accurately as possible. The rangefinder measures the distance travelled by the ultrasound emitted and returned from the water surface as a function of the sound propagation time. For more accurate measurement results, the sound propagation time can be compensated based on the air temperature, taking into account the measurement data of thermometers. The calculation is shown in (1), where T is the air temperature and v is the sound velocity [16]. The accuracy is increased by 1% for a 5.5 °C change.

$$v\left[\frac{m}{s}\right] = 331\left[\frac{m}{s}\right] + 0{,}6\left[\frac{m/s}{°C}\right] \cdot T\ [°C] \tag{1}$$

The temperature sensor cannot be placed in shade completely protected from the sun, and will return a reading of -127 if damaged. In order to safeguard the distance measurements, for thresholds below -20 °C and above +40 °C, the average temperature of 11 °C in Hungary is substituted into (1).

The ESP32 SoC systems have a big advantage over their similar purpose competitors: they have two processor cores in most cases, which can be used for optimization. The real-time operating system of the microcontroller is designed to run on a single core. The ESP32 in use contains a protocol CPU and an application CPU. The two cores have technically the same architecture and use the same memory. This allows to run tasks alternately between the two cores [17]. To refine the measurement sampling frequency, both cores of the microcontroller were used in the implementation as follows. While the application CPU sets the trigger times and waits for the ultrasound to return to the sensor, the protocol CPU calculates when the next sampling can start. *Fig. 2.* shows the usage of the two CPU cores. Measurements were performed in two ways for comparison purposes using single-core and dual-core operations and sampling every second. The results showed that the variance from the exact timing was around 0.300 seconds for the single-core case. For dual-core use, the same variance was only 0.009 seconds. In the dual-core case, the sampling time accuracy of the devices can be increased significantly.

Despite the different measurement principle, the difference between the results of the reference DATAQUA pressure-based water level meter and the developed measurement modules are within the order of magnitude of the accuracy of the height reference measurement [18].

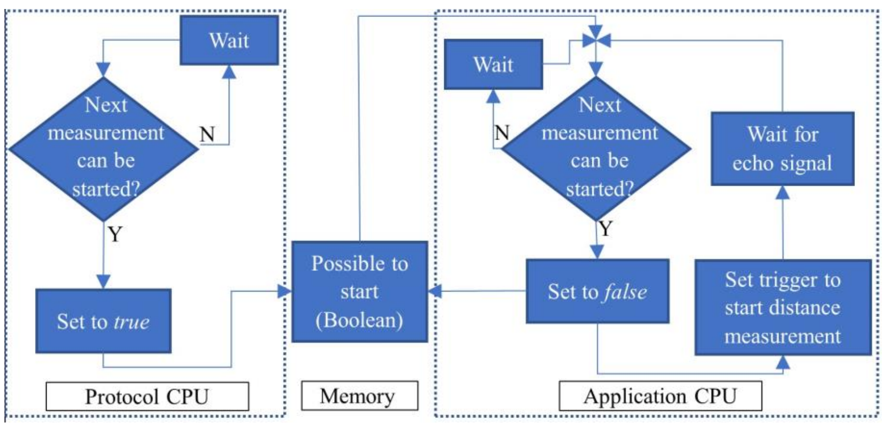

Figure 2: Main tasks during the dual-core measurement

D. Data transmission

The measurement nodes try to transmit the measured data over 2 communication channels: 5G and LoRaWAN. With 5G, data is guaranteed to arrive, while with LoRaWAN the communication distance is greater. The primary communication channel is 5G. If the connection fails, LoRaWAN provides the secondary communication network. In the absence of a 5G radio module that can be easily integrated with the microcontroller, 5G communication was achieved using a mobile hotspot.

The data is stored in a PostgreSQL database running in the cloud. In case of 5G, data can be sent all at once, but for LoRaWAN, measurement results can only be sent in several frames, as the allowed packet size is very small. The spreading factor (SF) is the rate at which the frequency of a signal changes throughout the bandwidth of a channel. Lower LoRa spreading factor provides a higher bit rate for a fixed bandwidth and coding rate. The highest bitrate and packet size is available with SF7. The maximum payload size is 222 bytes. The duty cycle rules must be applied between consecutive packet transmissions [4].

The most significant part of the data to be sent is the distance measurement results. The measured data is stored in approximately 4 bytes, depending on the magnitude of the measured distance. Distance records are concatenated using a separator character, so each measurement represents 5 bytes of data. For 2100 measurements, approximately 10 kB of data are generated. In a measurement cycle, it takes nearly 4.5 minutes to initialise the equipment and perform the measurements. In the remaining time, using LoRa SF7, around 6 kB of data can be sent due to the duty cycle control. Data size can be reduced by converting measurement results to hexadecimal numbers. Since no distance results greater than 4095 mm are expected, 3 B is sufficient to store a single measurement result. If the results are fixed at 3 B, the separator character can be omitted and it is possible to send 2100 measurement results within the measurement cycle.

With Matlab online, data stored in the database can be read and processed automatically using a web browser. The state of the wave in a stationary record can be characterized by the average wave parameters, which can be determined from the recorded surface distance data. The Pierson-Moskowitz or JONSWAP spectrum can be used as a model of the evolved wave. The data processing is beyond the scope of this paper and will not be described in detail.

6. Effectiveness

Two communication solutions were evaluated along the following aspects: network quality and energy consumption.

A. Network

For LoRaWAN, the spreading factor used is SF7 and the frequency range is 868 MHz. The operating class is A, so communication is only one-way, to save energy. Acknowledgement of sent data is disabled (no retransmission if a packet is lost). The coding rate (CR) used for error correction is 4/5. The data rate is 5470 bps. The communication distance is approximately 2 km [4].

For 5G NSA, the N78 frequency band was used. The network was tested using several WNC hotspots. Connected to the outdoor radio units, measurements were made at 3 locations with good (-70 dBm), poor (-106 dBm) and bad (-123 dBm) signal strength. The upload speed decreases steadily as the distance from the radio unit towards the cell boundary increases. The upload speed was 24.95 Mbps at good and 9.42 Mbps at poor signal strength. Response times were measured by sending 150 ping messages. The minimum response time was 15 ms and the average response time was 30 ms for both good and poor signal strength. Under bad signal strength, the response time doubled. In average, the latency variation was only greater than a few milliseconds under poor signal strength. Packet loss did not occur even at bad signal strength.

5G communication provides a reliable data connection, but in safety-critical cases, network problems must be prepared for. In the present study, redundancy is provided by the unified presence of 5G and LoRaWAN networks. The devices will try to send data over the 5G network, but in case of a failed connection, they will send the data as LoRaWAN messages. 5G is the primary channel, as it provides the acknowledgement of incoming packets, so all measurement results are safely stored.

B. Power consumption

The 5G hotspot is a separate device from the monitoring stations. The power consumption of the radio module is recorded separately from the overall energy usage of the device. This gives a more accurate picture of how the consumption of the monitoring stations would be affected if the cellular radio module were integrated. *Table 2*. shows the static power consumption of the MCU and connected modules in different states.

Table 2: Average power consumption

Module	Power consumption
Microcontroller – Hibernation mode	9.5 mA
Microcontroller – Idle state	47.6 mA
Microcontroller – Single core calculation	48.8 mA
Microcontroller – Dual core calculation	52.9 mA
Thermometer	0 mA
RTC module	2.5 mA
Distance sensor – Idle state	3.1 mA

When using 1 processor core, the consumption is stable. When using 2 processor cores, the energy consumption fluctuates, but the average consumption increases only slightly (+8%).

Using the distance sensor, the average consumption of the measuring nodes is 77.7 mA. The peak consumption is 96.4 mA when measurements are taken.

For LoRa communication, radio use statically increases the current consumption by 61.1 mA.

The current consumption of the 5G radio module in the idle state with no connection is 4.4 mA. With active 5G communication, the average increase in consumption was 98 mA for strong and 281 mA for weak signal strength.

The power consumption in a cycle is around 25 mA/20 min in both cases.

B. Energy generation

The measurement modules each have a solar panel connected to a charge control module. Several solar panels were measured in the first week of December 2022. On a lightly cloudy day, when the solar panel was oriented to direct sunlight, the maximum output for the most efficient solar panel was 134.8 mA. On a heavily cloudy day, when sunlight only reached the solar panel through the interconnected clouds, the maximum energy production value for the least efficient solar panel was 17.6 mA. Half an hour before sunset, when the panel was no longer exposed to direct sunlight, the production was 8.4 mA for the most efficient solar panel in the lightly cloudy case and 3.2 mA in the heavily cloudy case. It can be concluded that during periods of high cloudiness the efficiency of photovoltaic charging is drastically reduced.

In the summer months, there can be up to five times the number of hours of sunshine as in December. Summer radiation levels are more than six times higher than in January and December [19]. The operating time of devices can be greatly increased in summer, as most of the time the solar panel produces more than the average consumption of the devices. During the winter months, the batteries of the nodes may need to be replaced and charged from time to time.

7. Conclusion

Operational lake monitoring with multi-point sampling is rare due to the high cost of the equipment. Since it is not possible to prevent the theft of the devices, it is important that they can be replaced as cheaply as possible. The unit price of the developed measuring modules is more than 250 times cheaper than commercially available equipment. Data transmission is key for monitoring. LoRaWAN is the most cost-effective LPWAN solution in this case, as the network can be operated autonomously and uses ISM bands. Given the amount of data that will be generated, it is also worth considering a standard cellular network solution taking into account the consumption. 5G is becoming more widespread, which will also reduce the cost of devices.

Wave measurement has a number of limitations and difficulties. With the self-built IoT measurement system, the desired measurement accuracy was achieved. The data size can be minimized to allow LoRaWAN transmission of the data. Energy consumption was recorded for LoRaWAN and 5G. LPWAN offers a low-cost solution, but in this use case it does not provide energy savings due to the large amount of data to be transported. With the price reduction, 5G could be a good solution.

With wind detection, it may be possible in the future to allow measurement modules to measure only when the wind waves to be monitored are present. This would reduce the amount of non-useful data and reduce the consumption of the measuring instruments. By integrating and properly positioning 5 distance sensors per measurement module, the wave components could be reconstructed even more accurately.

Acknowledgements

This publication is supported by Budapest University of Technology and Economics, and by Ericsson Hungary Ltd. Special thanks to Tibor Cinkler, Tamás Krámer, Csaba Simon and Gergely Seres for their support. The research was supported by the European Union project RRF-2.3.1-21-2022-00004 within the framework of the Artificial Intelligence National Laboratory.

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