Design of a secure data transmission system in NB-IoT environment

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***Abstract*—This work presents the design and implementation of a secure data transmission system for an IoT-based weather station using NB-IoT (Narrowband Internet of Things). The system integrates multiple sensors to measure environmental parameters such as temperature, humidity, atmospheric pressure, light intensity, precipitation, and air quality. A key focus is on ensuring energy-efficient, long-term operation in remote environments while maintaining data security through encryption and secure protocols. The proposed solution utilizes MQTT over NB-IoT for reliable data transmission, with results demonstrating efficient power management and stable connectivity.**

***Index Terms*—NB-IoT, IoT protocols, weather station, security, automation, sensors, electronic components**

I. Introduction

Accurate meteorological data are essential for environmental monitoring and weather forecasting. Traditional weather stations rely on wired communication or high-power wireless networks, which are not optimal for remote, battery-powered deployments. This work focuses on designing a secure, energy-efficient weather station using NB-IoT, a low-power wide-area network (LPWAN) technology, to enable long-range data transmission with minimal energy consumption. The system incorporates robust sensors and security mechanisms to ensure reliable data collection and transmission. The collected data are processed, analyzed, and visualized using suitable platforms to provide actionable insights and demonstrate the system's capabilities.

The primary objectives of this project are:

- Development of a low-power, autonomous weather station for remote deployment.
- Integration of multiple sensors for comprehensive environmental monitoring.
- Secure data transmission using MQTT and TLS encryption over NB-IoT.
- Optimization of energy consumption to extend battery life.

II. Modern weather stations

Mentioned environmental parameters represent basic data that mankind has been trying to measure for centuries. With the passage of time, a number of measuring instruments have been developed, and their measurement principles have been improved. However, in modern times, it is necessary to look at the measurement of meteorological quantities in a more comprehensive way. With rapidly changing and less predictable meteorological conditions, there are increasing demands for accurate and on-time measurements that can predict changes.

Professional weather stations are becoming more and more accessible to ordinary users, who receive early warnings of weather changes and, at the same time, care about the quality of the environment in which they live and thus protect their health. However, their prices can be high, which can be a deciding factor for ordinary users. One of the many aims of this project is therefore to create a weather station that meets the demands and requirements of a professional weather station at a fraction of its price.

III. Internet of Things

All physical addressable devices that are connected to a network and communicate with each other are part of a working concept called the Internet of Things. These are, for example, devices in the smart home, industry, medicine, or transport, and can be connected using central units and intelligent control systems. The Internet of Things connects physical devices called 'objects' with objects in the virtual world, which form a virtual code describing the state of the device and is based on communication technologies.[1]

A. NB-IoT

The technology is used for cellular network devices and services with indoor or outdoor coverage, long battery life, and high-density connectivity. It has a narrow bandwidth of 200 kHz with half-duplex transmission. Peak downlink and uplink speeds are 26 Kbps and 66 Kbps, respectively, with a latency range of 1600 ms to 10,000 ms. The UE bandwidth is 200 kHz with a maximum transmission power of 23 dBm to 33 dBm. Due to the high latency range, it may not be an ideal choice for applications where a high emphasis is placed on response, and it suits stationary applications with occasional data sending and low transmission speed. There is a high level of noise in the transmitted signal, and therefore it transmits small data and not large data streams.[2][3]

B. MQTT

The MQTT, also known as Message Queuing Telemetry Transport, is an IoT protocol. Communication with MQTT is established between devices using TCP. The two main components of MQTT are the MQTT Broker (central server) and MQTT Client (publisher). The client is the one who sends (publishes) messages to the broker. The received data from the client to the broker is then sent to subscribed clients. Due to its reliability and ability to handle high latency, it is recommended for a large number of clients. MQTT is mainly used in automation, smart homes, the automotive industry, and in the health service.[4][5]

IV. System design and implementation

Many electronic components and sensors were tested during the development of the weather station prototype. Not all of them worked reliably, and therefore it was necessary to find replacements that would be reliable and meet the desired purpose and requirements. These include, for example, the TPS63020 3.3 V power supply with automatic buck-boost function, which supports input voltages from 1.8 V to 5.5 V. In the context of a weather station, this is the most reliable method of power transfer with fluctuating battery and solar panel input voltages.

A. Hardware Architecture

The weather station in fig. 1 consists of the following key components:

- **ESP32-S3 DevKitC-1**: Microcontroller responsible for sensor data acquisition and communication.
- **Quectel BC660K-GL**: NB-IoT module enabling long-range data transmission.
- **Sensors**: DS18B20 (temperature), VEML7700 (light intensity), SDS011 (air quality), Vaisala WXT536 (multi-parameter weather sensor).
- **Power Management**: Solar panel with a TP4056 battery management system and TPS63020 voltage regulator.

Fig. 1. Weatherstation created for this project.

B. Sensors

The DS18B20 digital temperature sensor from UMW Youtai Semiconductor in a waterproof design is a replica of the popular and accurate DS18B20 sensor from Maxim Integrated. The DS18B20 measures temperature in degrees Celsius with a resolution of 9 to 12 bits. It is powered by a One Wire bus, which has the advantage of being powered by only one data wire. The operating temperature is from -55 °C to +125 °C with an accuracy of ±0.4 °C (range -10 °C to +70 °C). Due to its waterproof property, it can be used in environments with excessive humidity.[6]

The VEML7700 is a high precision digital light intensity sensor from Vishay. It is manufactured and sold in several versions, for example, in a small transparent housing or in a small transparent housing mounted directly on the circuit board. For this project, the latter version was chosen, which includes a high-sensitivity photodiode, a low-noise amplifier, and a 16-bit A/D converter. The VEML7700 provides a measurement range from 0 to 120,000 lux with a resolution of 0.0036 lux ([lx] - lumen per square meter [lm/m²]). The sensor is also suitable for operating temperatures from -25 °C to +85 °C.[7]

The SDS011 laser dust sensor is designed to monitor dust particles in the air with a diameter greater than 0.3 micrometers [μm]. The sensor measures particles PM2.5 and PM10, which are 2.5 μm and 10 μm in diameter. This value is given in micrograms per cubic metre [μg/m³]. The SDS011 has a low power consumption of less than 4 mA in sleep mode. It can measure dust particles with an accuracy of 0.3 μm and the measurement range is from 0 μg/m³ to 999.9 μg/m³. The operating temperature of the sensor is from -10 °C to +50 °C and the atmospheric pressure is from 86 kPa to 110 kPa. It uses a UART bus or PWM for its communication.[8]

The WXT536 is one of the professional and high-end multi-parameter sensors that can simultaneously measure air temperature, humidity, pressure, precipitation, and wind. The low current consumption makes the sensor suitable for projects using solar panels. Vaisala's sensor series exceeds the IEC60945 marine standard and is a versatile device suitable for monitoring multiple environmental variables with high accuracy. Its rugged design and wide compatibility allow it to be used in a variety of applications including meteorology, industry, and research.[9]

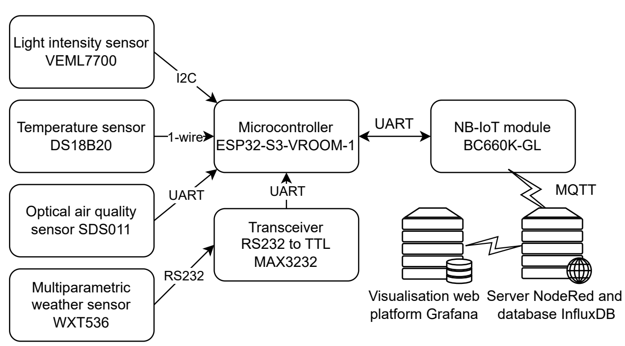

Fig. 2. Weatherstation software block scheme.

C. Software and Communication

The system is programmed using Arduino IDE, with sensor data processed locally before being transmitted via MQTT over NB-IoT. Data integrity and confidentiality are ensured using TLS encryption. The data is sent to a remote server for storage and visualization using Node-RED, InfluxDB, and Grafana.

The main measurement algorithm is able to initialize all sensors and continuously measure the actual values from the sensors. A function is also available to measure the average values of the four measurements, which are later sent via the NB-IoT module Quectel BC660K-GL to the Node-Red server via the MQTT broker Mosquitto. The project also tested the implementation of the MQTT broker HiveMQ.

Within the source code, several functions have been created that work with the batteries and optimize the operation of the weather station so that it does not consume too much power. The algorithm checks several parameters at runtime and adjusts the measurement frequency accordingly, which is advantageous when saving batteries on cloudy days or when using the batteries fully on sunny days.

The algorithm is also capable of estimating the actual charging current based on the solar panel parameters and light intensity. At the beginning of the source code, several macros are created, and they can be set at will by the user, to start individual modes of operation or to virtually disconnect the HW modules used by the weather station. If a sensor fails to initialize, the algorithm automatically continues without the particular sensor. This principle accounts for the possibility that a sensor has been disconnected or damaged.

Measurements can be taken every minute, and between measurements, the sensors and BC660K-GL are completely disconnected from the power supply, and the ESP32S3 microcontroller is in deep sleep mode. When the measurement is switched on, the microcontroller is first initialized, and it is checked that the battery is charged to at least 3.3 V. If the battery is charged, the measurement is performed, and the data are sent. If not, the microcontroller is put into sleep mode again. Data are sent every 6 minutes and are stored in a buffer in the RTC memory of ESP32-S3.

D. Node-RED, InfluxDB, and Grafana

The Quectel BC660K-GL is used to send data through the MQTT Mosquitto server to Node-RED in fig. 3.

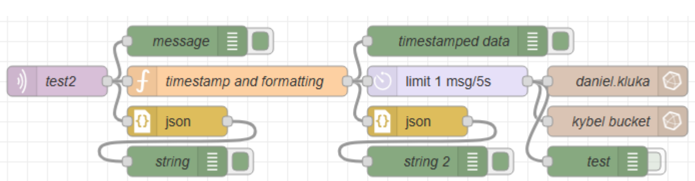

Fig. 3. Created flow on the NodeRED server, which processes the data and stores them in the InfluxDB database.

An MQTT message containing 6 measurements is sent to the server. The server processes these measurements into the form in which they will be entered into the InfluxDB time series database. Since all operating time data is measured in the weather station, it is possible to calculate the exact time in milliseconds when each measurement was taken.

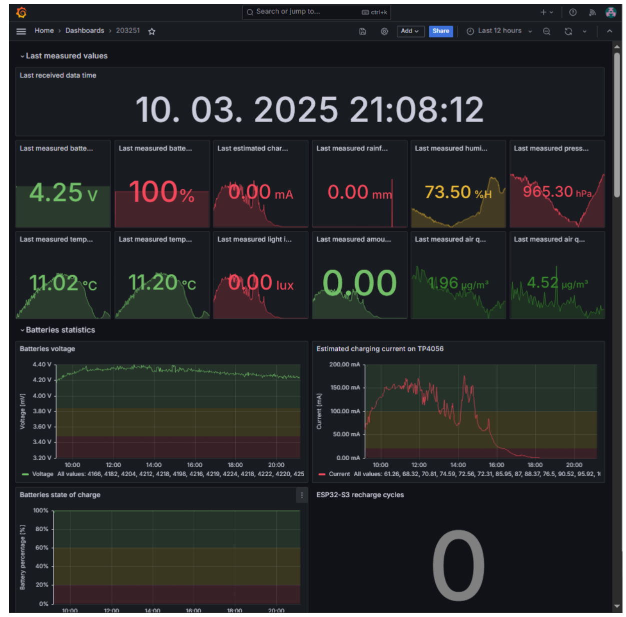

Fig. 4. Grafana dashboard created to visualise measured data.

The data entered into the database are further visualised via the Grafana platform in fig. 4, where all the necessary graphs of meteorological variables as well as diagnostic operational data are created. Grafana highlights the last measured (current) values, but also graphs in which data in any time interval are visualised with color thresholds.

V. Network Consumption Evaluation

The Quectel BC660K-GL module is fully powered off and restarted in each measurement cycle, which requires a complete signaling procedure for registration in the NB-IoT network. It then establishes a TCP connection and sends an **MQTT message of size 182 B** using the User Plane (not the Control Plane CIoT), meaning that the IP and TCP layers are included. For example, with a sending frequency of 24 messages per day, a total of 720 transmissions are performed per month.

As a result, the monthly data consumption ranges from **0,47 MB** (under optimal conditions), through **0,81 MB** in a typical scenario, up to **1,15 MB** when retransmissions or higher protocol overhead are present. According to Table I, a key factor is the signaling and protocol overhead, which often significantly exceeds the payload size, and when messages are sent every 6 minutes, the monthly usage can increase to **8,12 MB** (or **3,31 MB** if the module remains registered in the network).

VI. Power Optimization

To extend battery life, the following strategies were implemented:

TABLE I
PHASES OF MQTT MESSAGE TRANSMISSION IN AN NB-IOT NETWORK

Phase	***Size***	***Source***
Random Access + RRC Setup	200–300 B	3GPP TS 36.331, TS 36.321
NAS Attach (Request/Accept)	300–400 B	3GPP TS 24.301, TS 23.401
PDCP + RLC + MAC headers	50–150 B	3GPP TS 36.323, TS 36.322, TS 36.321
IP + TCP headers	40–60 B	RFC 791, RFC 793
TCP handshake + teardown	200–300 B	GSM IoT Guide
MQTT CONNECT + CONNACK	30–100 B	MQTT 3.1.1 (OASIS)
MQTT PUBLISH + PUBACK	202–232 B	MQTT 3.1.1, RFC 793
MQTT DISCONNECT (vol.)	10–20 B	MQTT 3.1.1
RRC Release (vol.)	∼500 B	3GPP TS 36.331
MQTT message (payload)	182 B	–
Total (typical)	**1000–1500 B**	–

- Duty cycling to put the ESP32-S3 into deep sleep between measurements.
- Selective power control of sensors using transistor.
- Adaptive transmission frequency based on environmental conditions.

Logic has been implemented that measures how much in percentage the batteries are charged, and if the battery value is higher than 80%, the weather station measures normal meteorological data (temperature, humidity, pressure, light values) and diagnostic data (battery charge level in mV and in %, length of initialization, length of measurement, total ESP cycle length, length of registration to the network, estimated recharge current of the weather station, recharge cycle counter) every minute and air quality every 6 minutes. However, if the battery charge drops below 80%, measurement and data sending frequency will be 10 times greater.

This weather station control implements a lightweight battery saving mode. The strong save mode has also been implemented, but it is clear from the measured diagnostic data that it has not been triggered even once. The weather station has been on the roof since mid-January, and due to the gentle battery management, it has not been fully discharged once. The TP4056 charging module works exceedingly well, but lacks the MPPT function that would take full advantage of the solar panel. In poor lighting conditions in January, the battery dropped to 3.72 V in fig. **??**, but it took the weather station up to 9 days to discharge to that level. As can be seen from the graphs, there has been nice, bright weather since January 29, which has recharged the weather station and kept the batteries at a good level of charge.

VII. CONCLUSION

The project proposed a weather station (fig. 1) solution that provides the user with the necessary meteorological data using NB-IoT technology and a battery-friendly design. The developed algorithm interacts with the developed sensor library and implements the measurement methods. The ESP32-S3 collects data from the sensors, stores them in memory, and then sends them to the Node-RED server through the BC660K-GL and the MQTT broker. The data are then written to the InfluxDB database and clearly visualized on the Grafana platform.

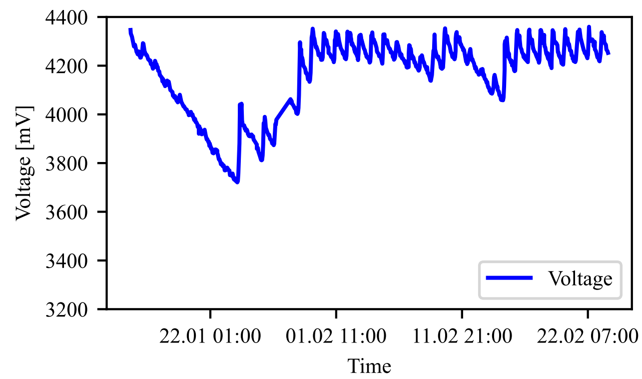

Fig. 5. Battery charging efficiency during cloudy days (2025-01-15 to 2025-01-23) and sunny days.

From the measured data in fig. 6, it is clear that the weather station meets the demands and requirements placed on professional weather stations and thus achieves high accuracy and robustness.

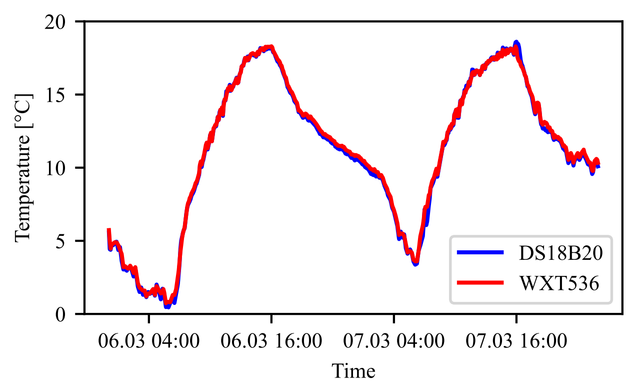

Fig. 6. Differences in measurement between DS18B20 and WXT536.

REFERENCES

[1] D. Kluka, ‘Modular Streaming System with a Cloud Storage,” Bachelor’s thesis, (supervisor: L. Kratochvíla), Faculty of Electrical Engineering and Communication, Department of Automation and Measurement Technology, Brno University of Technology, Brno, Czech Republic, 2023, 87 pages. [Online].

[2] Portal PROMWAD, ‘Low Power Wireless Technologies for Your Future Device: Selection Guide,” 2024-04-15. [Online].

[3] Portal VelosIOT, ‘Different LPWAN Technologies Explained,” 2023-06-12. [Online].

[4] Portal A1 Digital, ‘IoT Protocols: A Comprehensive Guide for Enterprises,” 2024. [Online].

[5] Portal Geeks for Geeks, ‘Introduction of Message Queue Telemetry Transport Protocol (MQTT),” 2024-02-26. [Online].

[6] Distributor láskakit, ‘DS18B20 Digital waterproof temperature sensor 1m,” 2024. [Online].

[7] Distributor láskakit, ‘Light Intensity Sensor VEML7700, I2C,” 2024. [Online].

[8] Distributor láskakit, ‘Nova PM SDS011 Optical Air Quality Sensor PM2.5 PM10,” 2024. [Online].

[9] Vaisala, ‘WXT530 Series User Guide,” 2024. [Online].