Energy self-sufficient sensor node for long range wireless networks

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Abstract. Wireless networks can have different architectures depending on the application context. In this paper, we concentrate on a wireless network that supports a gateway to a server being accessible from the internet. Many typical related applications can be found in IoT and Industry 4.0. Focus of this paper is on the design of a sensor node that is energy self-sufficient and supports the LoRa communication standard. By using LoRa long range wireless communication of up to several kilometres range becomes possible. Therefore, large areas can be covered by using multiple sensor nodes. Special attention had been on low-power design aspects to run the node with rechargeable battery and small photovoltaic cell only. Example application is ambient monitoring and support of an aquaponics project.

1. Introduction

Sensor networks are used in many applications ranging from small size local networks to large size networks having many nodes and covering large areas [1, 2]. An example application for a small size network is a body sensor network connecting only a few nodes able to measure ECG activity, SpO2 rate and context information as accelerations, temperatures and humidity [3]. Here, main design focus was on small size and high energy efficiency, i.e. low power consumption. Therefore, used radio technology was ZigBee operating in 2.4 GHz band. Larger networks are used e.g. for habitat monitoring, security surveillance, inventory control [4] or also for mobile applications like traffic control and vehicle monitoring [5]. Depending on the application context, specific focus has to be on aspects as node and network architecture and topology, energy supply and low power, scalability, node localization features, routing, and Quality of Service (QoS).

Due to the significant advances in microelectronics and radio technology the fields IoT (Internet of Things) and Industry 4.0 became an important area of wireless attached sensors and sensor networks integrating several sensors of same or different modality [6]. Besides the data collection in classic sensor networks, the data processing in IoT applications is an important feature. E.g., by applying big data analysis schemes and techniques from machine learning also complex data sets can be analysed to assist the user of a network or a technical system in decision making [7]. Typical to many IoT and Industry 4.0 applications is the remote access to the system and the data via internet. For this, the sensor system has to integrate a gateway to transmit data to a server or to receive control commands in a bidirectional manner.

Our sensor node is intended to capture sensor data of different modality and to transmit this data to a gateway that realizes the access to a server in the internet. Design requirements are coverage of medium to large areas by using a long-range communication system supporting wireless transmission range up to several kilometres. The node has to be low power using a small buffer battery only. The energy self-sufficiency is realized by integrating a small photovoltaic cell. As transmission technology,
LoRa (Long Range) has been chosen. Together with LoRaWAN it supports network communication features by using a low power routing protocol [8]. The network node integrates a LoRa transceiver module with 868 MHz RF frequency. A gateway device from The Things Network is used as infrastructure to connect to the internet. The first application for our node is environment monitoring, i.e. measuring of ambient temperature and humidity as well as fine dust concentration. A more complex application is an urban farming project: aquaponics. This is the combination of aquaculture with fishes and hydroponics, a concept of soil-less growing of plants [9]. The developed sensor node can support several other applications by integrating application specific sensors. E.g., it could be the monitoring of energy systems as decentralized photovoltaic systems as well as wind or hydro power stations.

This paper is organized as follows: After the introduction in section 1 the features of the LoRa communication system as well as the networking support provided by LoRaWAN are explained in section 2. The sensor node that has been developed is presented in section 3. This node is used in an example application to sense and to transmit ambient data. In section 4 the example application with the developed sensor node is introduced and some details on implemented software stack and performance data are presented. In addition, the remote display of collected sensor data is demonstrated. The paper is concluded in section 5.

2. RF communication: LoRa and LoRaWAN

The LoRa standard describes a proprietary direct sequence spread spectrum (DSSS) modulation developed by Semtech that is commonly used in IoT applications. The additional LoRaWAN technology introduces a medium access control (MAC) layer and a message routing layer on top of the LoRa physical layer. The LoRaWAN protocol stack is suitable for long-range communication in contrast to protocols like WiFi, Bluetooth or ZigBee [10]. LoRaWAN outperforms traditional cellular networks like GSM, 3G and LTE when comparing power consumption and hardware complexity.

2.1. LoRa

The LoRa standard describes the lower physical layer of data transmission that is used in the proposed sensor network (SN). A data frame is built from the raw payload by adding a preamble, a header and a payload CRC [11]. The preamble is required by the receiver to detect the start of transmission. The header includes all information required to process the payload and is expanded by adding redundant bits to achieve a forward error correction (FEC) with a fixed code rate (CR). The payload and its CRC utilize FEC as well but with a variable CR that is defined in the header. The complete packet is transmitted using a modified DSSS coding. Each bit of the data frame is replaced by a sequence of bits (chips) to increase the signal bandwidth. The resulting chip stream is transmitted using chirp spread spectrum (CSS) by a continuously varying frequency. The center frequency and bandwidth (BW) are adapted to the regulatory requirements of a certain region. The Spreading Factor (SF) describes the ratio of chiprate to bitrate. This approach offers the narrow band interference rejection of DSSS while eliminating the requirement of a precise reference clock due to coding based on frequency variation rather than a fixed frequency [12].

| Application Layer |
| LoRa MAC (Media Access Control) |
| Class A | Class B | Class C |
| LoRaWAN |
| LoRa |

| Regional ISM band |
| EU 863-870 MHz | US 902-928 MHz | AU 915-928 MHz | CN 868-870 MHz and 470-510 MHz |

**Figure 1.** Layer based architecture of the LoRa communication system integrating LoRa and LoRaWAN layers with support of different ISM bands (based on [13])
The range of communication modules using the LoRa standard depends on the transmission power, the bandwidth, the spreading factor and the antenna characteristics. A distance of more than 2 km in non-line of sight (NLOS) conditions can be reached without significant packet loss [14]. The air-time of a message of given size is proportional to the SF and reciprocal with the BW. A trade-off between maximum range and data rate, respectively number of devices needs to be found.

LoRa defines mainly the modulation technique, the number of available channels, the channel bandwidth, transmission power and the frequency bands used for transmission. All these parameters depend on the region LoRa is applied. As shown in Figure 1 different ISM frequency bands are used in different regions of the world. As a result, also the data rate varies.

2.2. LoRaWAN

An additional layer needs to be added to the LoRa physical layer to address MAC and routing of messages. For this purpose, the LoRaWAN standard was utilized in this paper. It defines the data format and timing of message exchange between the end-devices (here sensor nodes – SN) and the gateways [8]. The used frequency band and channel plan depends on the region where the network is hosted and is described by LoRaWAN standard as well [15]. Figure 2 shows an example network arrangement.

![Diagram](image)

**Figure 2.** Example LoRaWAN network

The network supports a large number of end-devices, respectively sensor nodes for this application. All end devices must support at least all class A functionality. End-devices that implement class A begin the message exchange on a certain event (e.g. completion of a sensor measurement). The payload is sent as an uplink message over LoRa. The uplink message is received by all gateways that are in range of the SN. The gateways transmit the received message to a network server (NS) over traditional IP which does a deduplication of multiple incoming messages from the same SN. The payload is redirected to an application server (AS) over IP. The specific AS that is used is defined by the node during the network join procedure. The application is able to send a response to the uplink message. The NS decides based on the link quality which gateway is used for the transmission of the downlink message. There are only two time slots (RX1, RX2) shortly after the transmission of the uplink message that a class A end-device is listening for downlink messages. It is only possible to send data to an end-device during these time slots. This further implies that data can only be sent to an end-device after the end-device did a transmission. The LoRaWAN standard also implements AES
based data encryption to increase network security. The messages are encrypted by the network session key (NwkSKey) and include a message integrity check (MIC) between the end-device and the NS to prevent replay attacks. The payload of the message is encrypted using the application session key (AppSKey). The LoRaWAN standard includes the over-the-air activation (OTAA) method that generates the session keys on the AS based on a single application key (AppKey). The AS transmits the generated NwkSKey to the NS of the provider. A third-party network operator is not able to decrypt the payload because the AppSKey is only known by the end-device and the AS. This approach has shown some weaknesses. LoRaWAN does not provide perfect forward secrecy and the join procedure is prone to replay attacks [16]. The LoRaWAN cannot be used in environments where subsequent decryption of data has fatal consequences.

3. Sensor node architecture
This paper proposes a universal sensor node (SN) architecture that can be used for a variety of applications. A SN is made of a base board and optional expansion boards. The base board integrates all general components while the extension boards contain all application specific parts. Multiple expansion boards can be stacked onto the extension header of the base board. The components of the base board are shown in Figure 3. It is theoretically possible to operate an SN in its minimal configuration, i.e. without an expansion board because all essentials components are already included on the base board.

![Figure 3. Structure of the sensor node](image)

3.1. STM32L462 MCU
The used STM32L462 microcontroller (MCU) from STMicroelectronics is based on the commonly used ARM Cortex M4 architecture with an integrated FPU. The MCU is optimized for low-power applications but also includes a massive amount of peripherals. The power consumption depends on the set clock frequency and the enabled peripherals and can be further reduced by a variety of low-power modes with a different trade-off between power consumption, start-up time and available wakeup sources.

3.2. RN2483 LoRaWAN modem
The Microchip RN2483 modem is used for the LoRaWAN communication. This system-on-module (SoM) includes the LoRa modem as well as the LoRaWAN protocol stack. The communication to the host MCU is realised using an UART interface. A PCB antenna was placed on the sensor node PCB that is connected to the antenna pin of the RN2483 module.

3.3. Power supply
One major part of the SN design is the power supply scheme. The system was designed to run on a single rechargeable 3.7V LiPo battery allowing flexible battery life up to multiple years on a single charge depending on the application. The used LiPo battery with a capacity of 2200 mAh is capable of driving big loads in contrast to very cheap non-rechargeable 3V lithium cells, which is required by
some applications. The battery is charged using an on-board battery charger supplied by the USB port. A separate LDO with enable input is used to supply the LoRaWAN modem reducing the stand-by current by disabling the modem when not needed. A hardware under-voltage lockout is integrated that disables all voltage domains if the battery voltage drops under a defined threshold to prevent damage to the LiPo battery.

3.4. User Controls
The SN board includes 3 user controllable LEDs, 2 programmable buttons and 2 DIP switches. These peripherals are accessible by the software through the board support package (BSP). In the developed example application, the LEDs are used to indicate the device state, the buttons enable special boot modes (USB storage mode, configuration reset) and the DIP switches define the used SF of the LoRa modem.

3.5. Expansion Header
The 20 pin expansion header includes multiple supply voltages, one UART, one I2C and one SPI interface and 8 GPIO signals. All GPIO signals are 5 V tolerant and can be mapped to ADC channels to read analog voltages from 0 to 3.3 V. It is intended to stack the expansion boards with the application specific circuit on top of the SN board but it is also possible to connect the boards using a ribbon cable if the package space is constraint.

3.6. Firmware
A basic firmware was developed for the SN, which includes the BSP for the user IOs, a driver for the RN2483 LoRaWAN modem, a SWO (serial wire output) based logging, a configuration parser and a sample application. The logging module outputs debugging messages over the SWO of the debug probe to simplify debugging.

A configuration parser is integrated to allow the integration of user configurable parameters. The configuration file is structured into sections and can hold a variable number of parameters (float or string type) and is stored as a text file in the PC EEPROM. The EEPROM is FAT formatted and can be accessed through the USB interface. This makes it easy to access the configuration file by a standard computer and to edit it, no programming cable is required. The stored configuration is parsed at system reset. A sample application is supplied with the firmware to simplify the development of a custom application. The sample application cyclically measures the battery voltage and transmits it over the LoRaWAN network. The LoRaWAN parameters can be set using the defined configuration file.

4. Node setup and environmental sensing
The example application presented in this paper is inspired by projects like luftdaten.info and hackAIR that are citizen science platforms, which collect fine-dust measurements from SN operated by citizens [17]. In these projects, an ESP8266 WiFi MCU development board plus breakout boards are used. Drawback is the WiFi communication that is not power efficient and does not have long transmission range. Additionally, stationary power supply is used what significantly limits outdoor applications without having certain technical infrastructure. Our proposed sensor architecture can be used to operate an improved energy self-sufficient fine-dust SN with an increased range by replacing the WiFi infrastructure by LoRaWAN and by PV based charging option as well as low-power design.

4.1. Hardware setup
For the introduced application with sensing of fine-dust concentration and other environmental parameters the base board is expanded by a sensor driver board integrating a Sensirion SPS30 fine dust sensor, a DHT22 temperature and relative humidity sensor, a photovoltaic (PV) expansion board and a 5W PV cell, as shown in Figures 4 and 5.
The sensors are connected to the sensor expansion boards that is stacked on top of the base board using the expansion header. An additional step-up voltage regulator with controllable enable input is used to generate the 5V sensor supply voltage.

The PV expansion board integrates a maximum power point tracking (MPPT) battery charger that is supplied by the PV cell. The output of the expansion board is connected to the battery input of the main board. The LiPo battery is connected to terminal of the expansion board instead. All components are fitted onto a carrier board that is inserted into a pipe with 2 bent end pieces. The whole unit can be mounted onto usual rainwater downpipes using a pipe clamp.

4.2. Software stack

The SN measures the current fine-dust particle concentration of different particle sizes (PM1, PM2.5, PM4, PM10 [18]), the current temperature, humidity and battery voltage every 5 minutes. It transmits the measured values using The Things Network (TTN) LoRaWAN network infrastructure. The total payload length is 46 bytes containing single precision float values representing particle mass concentration and particle number concentration for each of the 4 particle size ranges, the particle number concentration of PM0.5, and the average particle size and 16 bit long integer values for the battery voltage, humidity and temperature. The data is captured from the MQTT broker of TTN into a MariaDB database using a Node-RED graphical programming interface. The gathered data is processed and visualized using the Grafana dashboard.

4.3. Performance

The measurement of the fine-dust particle concentration requires a constant airflow through a measuring chamber. The sensor needs to be active for about 15 seconds to gather valid data. During this time, the LoRaWAN modem joins the network. The data is sent after both measurement are done and the modem is ready after enabling. During the active phase of around 20 seconds, the SN draws an average current of 80mA. In idle phase, the current consumption drops below 1mA. The sensor node is able to run for 14 days on a single battery charge without recharging. The 5W PV module is easily capable of recharging the battery even facing poor solar radiation. Therefore, a robust long-term self-sufficient operation is possible.
Figures 6 and 7 show the gathered sensor data for a period of one week. The value for PM2.5 concentration had a maximum of 59.2 µg/m³ and an average of 6.51 µg/m³. The PM10 concentration had a peak of 83.8 µg/m³ and an average of 7.488 µg/m³. With exception of one short period the 24h particle concentration falls short the limit of 25 µg for PM 2.5 and 50 µg PM10 defined by the WHO [19]. The temperature was between 8.9°C and 23.6°C with an average of 15.2°C. The relative humidity range was between 40.5% and 99.9% with an average of 73.3%.

5. Conclusion
Objective of this paper was the design of a long-range sensor node that supports self-sufficient operation for months or even years by combining accumulator and PV cell and using low-power modes. Application context is environment sensing with focus on fine-dust, temperature and humidity. To realize long-range wireless transmission the LoRa standard has been used by integrating a LoRaWAN modem into the designed hardware. The hardware concept of the sensor node follows a modular approach. Therefore, different types of sensors can be easily integrated into the node to adapt the sensor node for various applications. The LoRa wireless communication supports transmission ranges of several kilometers enabling coverage of large areas. Via a LoRa gateway, sensor data is transmitted to an internet located server, which supports IoT applications. Users can easily access the sensor data remotely from any place.

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