Bachelor Project

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Measurement

Long Range Wireless LoRa Based Monitoring System

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Acknowledgements

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Declaration

I declare that this work is all my own work and I have cited all sources I have used in the bibliography.

Prague, May , 2018

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

Bachelor's thesis title in English:

Long Range Wireless LoRa Based Monitoring System

Bachelor's thesis title in Czech:

Bezdrátový monitorovací system s LoRa komunikací

Guidelines:

Design and develop a LoRa communication-based system for monitoring of physical quantities using sensors with digital (temperature, humidity, etc.) and analog output (potentiometer). Use a NUCLEO-L073RZ development kit with the 32-bit STM32L0 microcontroller. Due to low LoRa transmit rate the data should be locally processed by simple statistical evaluation. Create a demonstrative dashboard for visualization of sensor data typical for HVAC performance monitoring.

Bibliography / sources:

[1] STMicroelectronics datasheets, http://www.st.com
[2] The Things Network documentation, https://www.thethingsnetwork.org/
[3[Ganssle, J.: The Art of Designing Embedded Systems, Elsevier Science, 2008.
[4] Ashrae Handbook: HVAC Systems and Equipment, 2008
[5] Bruton, K., Raftery, P., Kennedy, B. et al.: Review of automated fault detection and diagnostic tools in air handling units, Energy Efficiency 7: 335, Springer, 2014.

Name and workplace of bachelor's thesis supervisor:

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Date of bachelor's thesis assignment: **10.01.2018** Deadline for bachelor thesis submission: ________

Assignment valid until:
by the end of summer semester 2018/2019

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student's signature

Abstract

The thesis is aimed at failures of heating, ventilation and air conditioning technology (HVAC). The goal is to design and develop a LoRa communication-based system for the monitoring of physical quantities to decrease the number of long-term undetected errors in the HVAC equipment, and to prevent serious damage to these devices, and the discomfort of customers. We chose LoRa communication for the realization because we need a device with low battery consumption and long service life. We also need to communicate for long distances and Lora communication is a perfect way. For the monitoring of physical quantities we will use sensors with a digital and analog output. Sending data from sensors is performed by using a development kit with LoRa radio frequency (RF) expansion.

Keywords: Monitoring system, Internet of Things, Long Range, HVAC

Supervisor: doc. Ing. Radislav Šmíd, Ph.D.

Abstrakt

Tahle práce je zaměřená na poruchy topení, ventilace a klimatizace. Cílem je navrhnout a vyvinout komunikační monitorovací systém, založený na LoRa komunikaci, pro znížení počtu dlouhodobých nezaznamenaných chyb v HVAC zařízeních a předejít tak vážným poškozením těchto zařízení a nepohodlí ze strany zákazníků. Pro realizaci jsme vybrali komunikaci LoRa, protože potřebujeme zařízení s nízkou spotřebou energie a dlouhou životností a také schopností komunikovat na dlouhé vzdálenosti. Pro monitorování fyzických vlastností použijeme senzory jak s digitálním, tak s analogovým výstupem. Pro zasílaní dat ze senzorů budeme používat vývojový kit rozšířený o LoRa technologii, založenou na rádiové frekvenci.

Klíčová slova: Monitorovací systém, Internet věcí, LoRa, HVAC

Překlad názvu: Bezdrátový monitorovací system s LoRa komunikací

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Chapter 1

Introduction

Nowadays, technologies are everywhere around us. Especially in buildings where we live, work or spend our leisure time, e.g., shopping centres. One of these technologies is for example heating, ventilation and air conditioning system (HVAC), which provides thermal comfort and acceptable air quality in huge buildings. This technology improves our life conditions by exchanging exhaled air for fresh and regulating the temperature in rooms. There can occur some technical failures as in every technology as well. It takes lots of time to detect these failures in such a big system. We decided to come up with the idea of creating a monitoring system for this technology to prevent the long-term undiscovered collapses of HVAC.

1.1 Aims

The main aim is to design and develop a demonstrative system, which can be used in the future to uncover damage in air handling units (AHU). We are supposed to come up with a hardware solution using different kinds of sensors, which will measure the conditions in HVAC. The sensors should be connected to both, the analog and digital output pins of the main board. The values from the sensors will be obtained every minute, and after 10 minutes they will be evaluated by a simple statistical evaluation, e.g., arithmetic mean, minimum, maximum, etc.

There is a need to operate with the data obtained from the sensors, so after evaluation, we have to send and save them to a server or a cloud. We also desire to communicate for a long distance and to save up battery consumption. These requirements lead us to use Long Range (LoRa) technology for the Internet of the Things (IoT) to receive data from the monitoring system and be able to work with them later on.

Our last step is to visualize the data after receiving them in some network server. We should create a dashboard to represent various quantities in a user-friendly environment which enables to monitor the data.

Chapter 2

State of the art

In this part, we are going to focus on the ongoing technologies, which are important for this work. The concept of the Internet of the things (IoT) will be explained as well as the Low Power Wide Area Network (LPWAN) and Long Range communication (LoRa) will be introduced. We will introduce the history and the principles of IoT. It will be shown how LPWAN works, what are the benefits of using it and what protocols does it operate with.

It is also important for this work to present some basic information about the heating, ventilation and air conditioning technology (HVAC). The functionality of HVAC will be described, in order to better understand this technology and to prevent various kinds of damage.

2.1 IoT

2.1.1 History of IoT

The term comes from the year 1999 when Kevin Ashton, the co-founder of the Auto-ID Center at the Massachusetts Institute of Technology (MIT), first used it in his presentation for Procter&Gamble. He was working there in a supply chain optimization. He wanted to get the attention of the senior management with an innovative technology for a machine to machine communication. And since the Internet was a rapidly growing phenomenon, he named his presentation Internet of Things. Nevertheless, the idea of an interconnected network of devices has been around since at least 1970 but it was not until very recently when it really got the attention of the general public. One of the main obstacles that inventors faced was addressing each device uniquely which was allowed with the coming of IPv6 giving us a much broader spectrum of IP addresses and thus the possibility of identifying each device specifically.

2.1.2 IoT definition

The Internet of things is a network of physical devices, vehicles, home appliances, and other items filled with electronics, software, sensors, actuators, and connectivity which enables these objects to connect and to exchange data.[6][5]

[7] Each thing is uniquely identifiable through its embedded computing system but is able to inter-operate within the existing Internet infrastructure.

The IoT can be defined by looking at various characteristics in the broader context. Figure 2.1 denotes seven categories according to which we can define the IoT. [4]

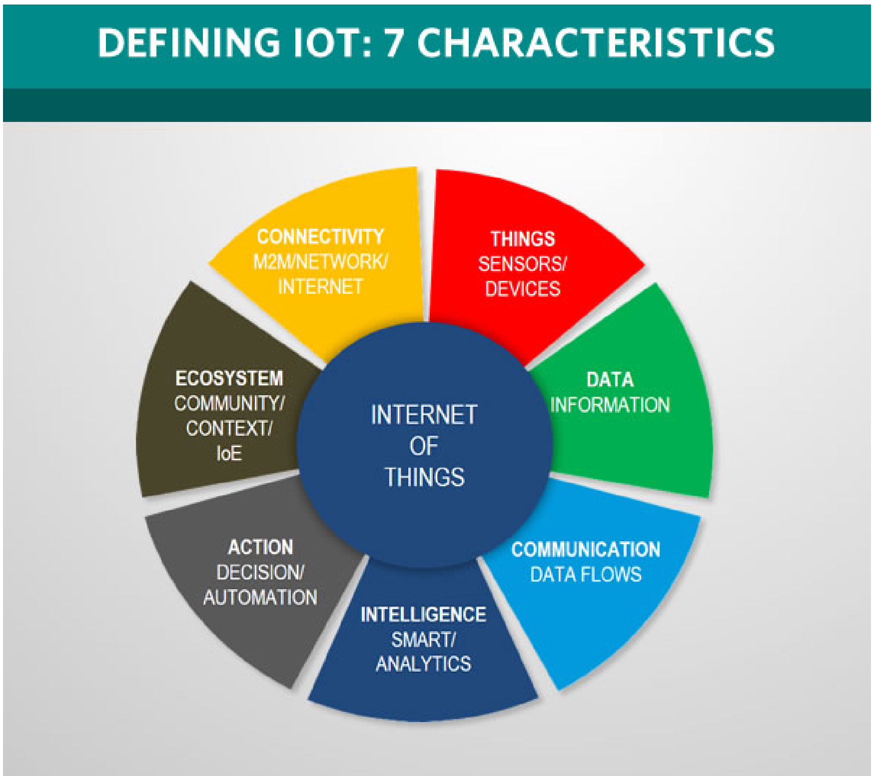


Figure 2.1: Defining IoT in 7 characteristics [4]

The first characteristic is CONNECTIVITY which involves a lot of different devices, and sensors with a need of being connected to each other or to actuators and to IoT or another network. As a consequence of connectivity, there is a COMMUNICATION between devices and also data analysis. DATA is the glue of the IoT. It is the first step towards action and intelligence, which can also characterize the term IoT. The aspect of INTELLIGENCE can be found in the sensing capabilities in IoT devices as well as in the intelligence gathered from data analysis. Additionally, there is the consequence of intelligence, ACTION. This can be manual action, action based on debates regarding phenomenon, and automation. THINGS are also one form of defining IoT. They describe anything that can be tagged or connected, from sensors and household appliances to tagged livestock. These devices contain a type of sensors or sensing materials that have the ability to attach to other equipment. The last on our list is ECOSYSTEM, which is part of the IoT taken from a perspective of other technologies, communities, goals, and from the picture in which the IoT fits, which is the Internet of Everything (IoE) dimension, the platform dimension and the need for solid partnerships. [4]

2.1.3 Industrial IoT

We can divide the IoT into many categories. One of them is the Industrial Internet of Things (IIoT). Nowadays, the IIoT is a major trend with significant implications for the global economy. [17] It brings brilliant machines, advanced analytics, and people at work together. It is the network of a multitude of devices connected by communications technologies that result in systems that can monitor, collect, exchange, analyse, and deliver valuable new insights like never before. These insights can help making smarter, faster business decisions for industrial companies.
To reap the full benefits of IIoT, companies will need to excel at exploiting three technology capabilities, which we can see in figure 2.2.

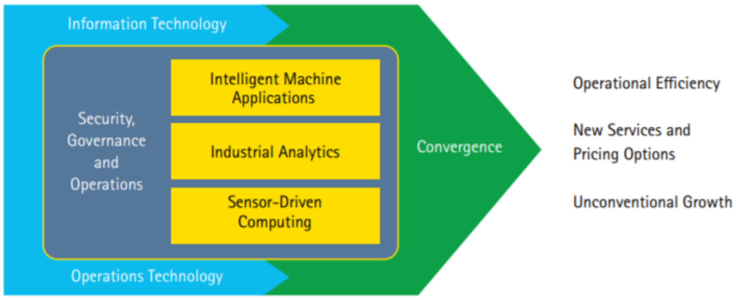


Figure 2.2: Three Industrial Internet of Things capabilities to master [17]

These three IIoT capabilities are Intelligent Machine Applications, Industrial Analytics and Sensor-Driven Computing. We will focus on the last one. Sensor-driven computing converts perception into insights using industrial analytics that operates and system can act on. Sensors give objects the power of perception of conditions such as temperature, pressure, voltage, motion, etc. As with most technological advancements, sensors are becoming smaller, cheaper and more sophisticated. We will work with temperature and humidity sensors to monitor conditions in industrial technologies, concretely heating, ventilation and air-conditioning (HVAC) technologies.

2.2 LoRa

In this section, we will introduce the LPWAN technology, the LoRaWAN protocol, and the LoRa physical layer.

2.2.1 LPWAN technology

LPWAN is a Low Power Wide Area Network. Previous technologies used mesh topology for data transmission, which helped to diminish the distance between single nodes in the topology. LPWAN uses a star topology as a greater receiver of sensitivity, which allows a coverage in a kilometres range. The star topology is the most widely used way for connecting devices to the network. Using the star topology greatly simplifies network management and reduces the required networking firmware for end devices. The communication between the end devices in LPWAN star topology is provided by the main gateway which is the only common node for every connected device.[18] We can see the star and the mesh topology in the figure 2.3 below.

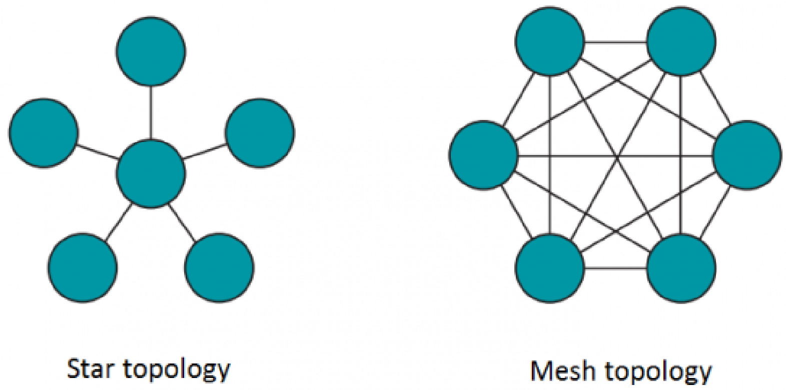


Figure 2.3: Three Industrial Internet of Things capabilities to master [3]

LPWAN topology is used by plenty of other protocols. The most famous are SigFox, RPMA, NB-Fi, Weightless, DASH7 or LoRaWAN. In the following part, we will discuss the LoRaWAN protocol.

2.2.2 Parameters of LoRaWAN protocol

- packets length 250 Bytes
- confirmed and unconfirmed messages
- communication on the port level (1 - 223)
- uplink and downlink communication
- Advanced Encryption Standart (AES)
- unique ID for every end device (EUI64- Extended Unique Identifier 64 bit)
- 2 end devices activation modes
  - OTAA (Over-The-Air-Activation)
  - ABP (Activation-By-Personalization)
- 32 bit end device addresses
- security keys (AES-128)
  - Application Key (128 bits)
  - Network Session Key (128 bits)
  - Application Session Key (128 bits)
- bit rate 250 bps - 50 kbps

2.2.3 Detailed characteristics of the LoRaWAN protocol

LoRaWAN is a communication protocol and system architecture based on the radio network protocol called ALOHA, which was developed at the University of Hawaii in the 1970s. LoRaWAN is provided for networks using the physical layer called LoRa made by Semtech Corporation. LoRaWAN uses the connection between the end nodes and the central network server using the star topology as well as the LPWAN.

LoRaWAN is mainly used in Europe and North America. We will focus on Europe. The bandwidth in Europe is in the range from 125 kHz to 250 kHz. A single FSK (Frequency-shift keying) canal is available for large data transmission.[21]

LoRaWANs in Europe are limited to 10 channels, it has a duty cycle restriction but no channel dwell time limitations. It has 3 common 125 kHz channels for a 868 MHz band namely 868.10, 868.30 and 868.50 Mhz that devices use to join the network. Once a node has joined the network, the network server can provide additional channels to the device. In Europe, the

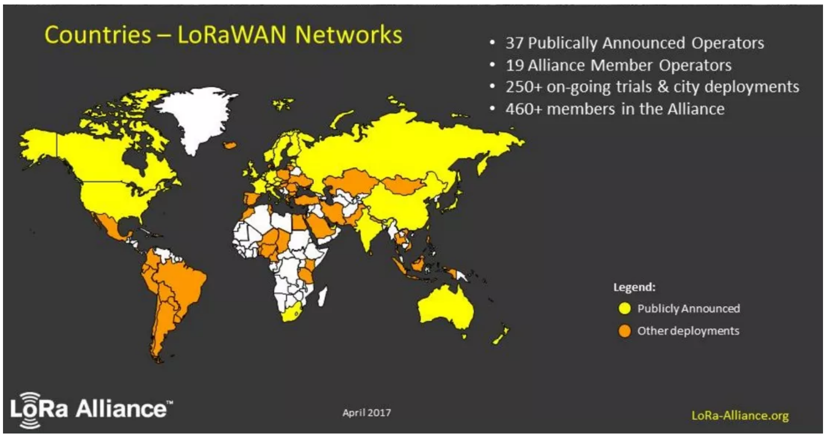


Figure 2.4: LoRaWAN distribution in the world [8]

same channels are used for uplink and downlink.[18]

Uplink[8]
LoRa packets based on an explicit header with a CRC (Cyclic Redundancy Check) at the end of the packet.

Preamble	PHDR	PHDR_CRC	PHYPayload	CRC

Downlink[8]
LoRa packets based on an explicit header without a CRC at the end of the packet.

Preamble	PHDR	PHDR_CRC	PHYPayload

Every gateway implements LoRa functions so the transmitted signal from the end device is accepted by any gateway, that is close. This signal can be accepted by more gateways, which send it to the network server. If the server receives more identical messages, it chooses one and sends it to the appropriate gateway. LoRaWAN uses Adaptive Data Rate (ADR) and multichannel multi-mode broadcast.

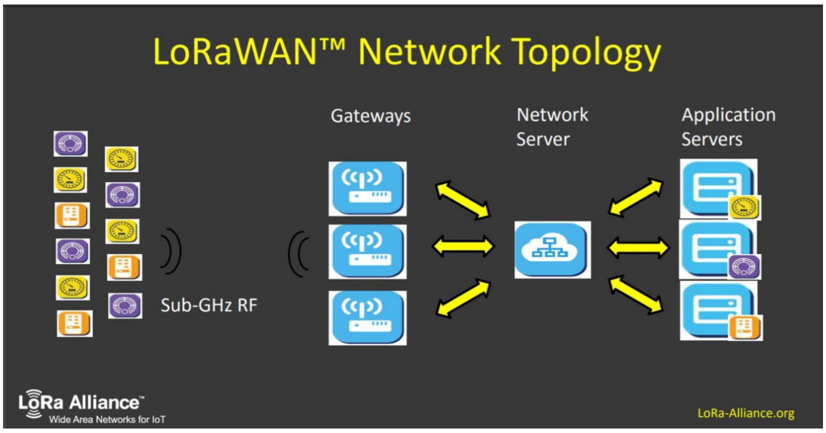


Figure 2.5: LoRaWAN network topology [8]

LoRa Alliance company made an open source for the LoRa protocol. While designing the LoRa protocol they considered various applications for network usage. Three different classes of devices have been designed.

2.2.4 LoRa Class A End Devices

Class A devices have the lowest power energy consumption from all classes. The end device starts communicating with the server if it is needed. After receiving a message from the end device, the server creates two single downlink channels for the communication with the end devices. The communication is being carried out as unicast.[8]

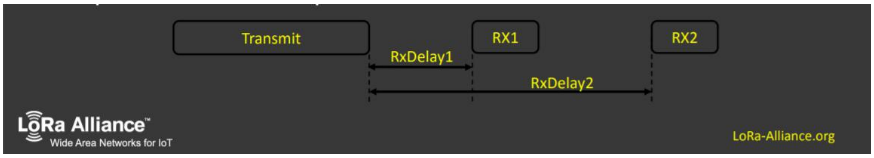


Figure 2.6: Scheme of class A communication [8]

2.2.5 LoRa Class B End Devices

Class B end devices expand by class A devices. A difference between the class A and class B devices is, that class B has a bigger energy consumption, and is able to communicate with multicast. It is caused by a regular communication between the server, and the end device.[8]

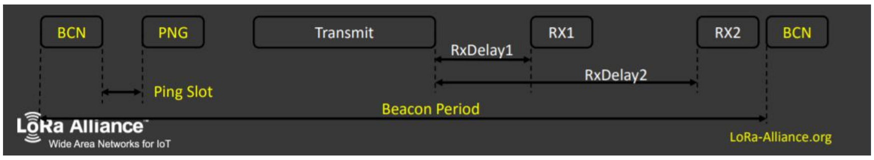


Figure 2.7: Scheme of class B communication [8]

2.2.6 LoRa Class C End Devices

This class has the biggest energy consumption. It expands the functions of the previous classes, but these devices are waiting for the communication the whole time, except they are transmitting. That is why they have no delay while communicating with the server.[8]

Figure 2.8: Scheme of class C communication [8]

2.2.7 LoRa - physical layer

LoRa Physical layer is derived from the Chirp Spread Spectrum (CSS) modulation with Forward Error Correction (FEC). Europe and North America use Industrial, Scientific and Medical (ISM) bandwidths, which are under the frequency 1 GHz. That allows to better compensate the Signal to Noise Ratio (SNR). CSS modulation enables a longer range of communication, than modulation with the help of Frequency Shift Keying (FSK), even without the increase of energy consumption. CSS also ensures immunity to the Doppler's effect.[21]

Thanks to the transmission on higher power levels, the increase of the LoRa's node range is being achieved. In Europe, the maximum transmitting power that is allowed is +14dBm. (The speed of the data transmission is dependent on the location, as well as on the Spreading Factor (SF). By increasing the SF, we can accomplish higher SNR but we also extend the transmission time. Using a higher bandwidth shortens the transmission time but reduces the maximum receiver sensitivity. LoRa can detect channel activity using Carrier Activity Detection (CAD). CAD is faster in activity detection than the Received Signal Strength Indicator (RSSI). CAD brings better recognition between noise and the desired LoRa signal.[18]

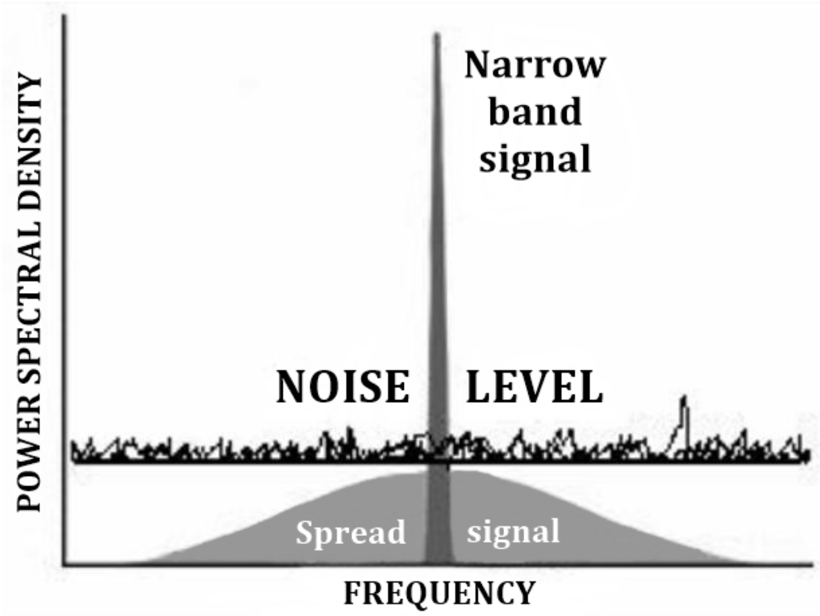


Figure 2.9: Schema of LoRa devices communication under the noise level [9]

2.3 HVAC

This part explains what the Heating, Ventilation, and Air Conditioning (HVAC) is, where is it used and how does it work. Also, we will focus on possible damages to these devices.

2.3.1 HVAC definition

The word HVAC is an abbreviation for Heating, Ventilation, and Air Conditioning. This system is used to provide heating and cooling services to buildings to ensure indoor air quality. The HVAC technology can be used for example in single family houses, apartment buildings, hotels, medium-sized or large industrial or office buildings as well as in skyscrapers or hospitals. The HVAC system can also be responsible for providing fresh outdoor air to the diluted interior air, which can be contaminated by some chemicals.

2.3.2 Mechanism of HVAC

The HVAC technology is based on the principles of thermodynamics, fluid mechanics, and heat transfer. A single schema of HVAC is presented in figure 2.10 below.

It consists of a heat exchanger, a supply air fan, a duct, filters and air mixing dampers. In this figure we can see that the fresh air enters the duct of the

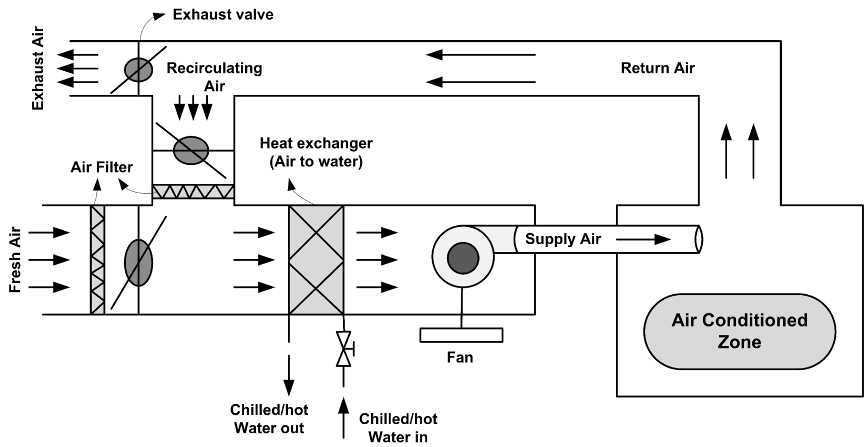


Figure 2.10: Schematic drawing of HVAC equipment [20]

HVAC system, the filters dispose it of any contamination by bacteria, viruses etc. Then the air passes through the exhaust valve and gets into a heat exchanger where it changes its temperature based on the current climate conditions. Subsequently, it is distributed to the room by the supply air fan. The air is taken away from the room by another duct. Then it can be used again after cleaning itself in the filter or it can be taken away from the building. [20]

2.3.3 Possible failures of HVAC

As every technology, HVAC is also not perfect, and there are lots of possible failures that occur. Some of the collapses are not detected immediately, and this can cause significant damaging influence on the technology as well as on people who use it. One of the most significant problems can be that the fresh air does not get into the duct and the same air circulates in the HVAC system without any fresh air. It can decrease the percentage of the oxygen in the building, which can affect people to get sleepy, or even worse. That is why it is so important to find out the failure as soon as possible. In this case, we can use some gas sensors. For the demonstration, we chose the one which is described in the section 3.4.

The complication can be not only with the quality of the air, but also with the temperature and humidity. There are some parameters in the building, which have to be accomplished, and if they are not, it can have a harmful influence on the HVAC system. It can start to behave unexpectedly. Our monitoring system will be beneficial for measuring these quantities and sending the results to the network where they can be potentially processed and evaluated to alert that something went wrong. The possible evaluation process will be introduced in section 5.2.

One of the reasons for invalid values of the temperature and humidity can be a non-functional or damaged exhaust valve. For this case, we will use an incremental rotary encoder to observe the position of the exhaust valve and to detect possible unexpected behaviour. Of course, there are lots of other cases that can happen in the HVAC system, but in our monitoring system we will only focus on these potential failures.

Typical HVAC faults [19] can be divided into categories:

- Stuck or leaking mixing box dampers, heating coil valves, and cooling coil valves
- Temperature sensor faults
- Design faults such as undersized coils
- Controller programming errors related to tuning, setpoints, and sequencing logic
- Inappropriate operator intervention.

Chapter 3

Available hardware

This part focus on individual hardware components, which are used for the final monitoring system. We will need an appropriate development kit and sensors in order to measure the various conditions.

3.1 Development kit

We decided to use the low-power wireless Nucleo pack Nucleo L073RZ and LoRa expansion board. Both of them, the Nucleo L073RZ and LoRa SX1272 expansion board, will be described in the following parts.

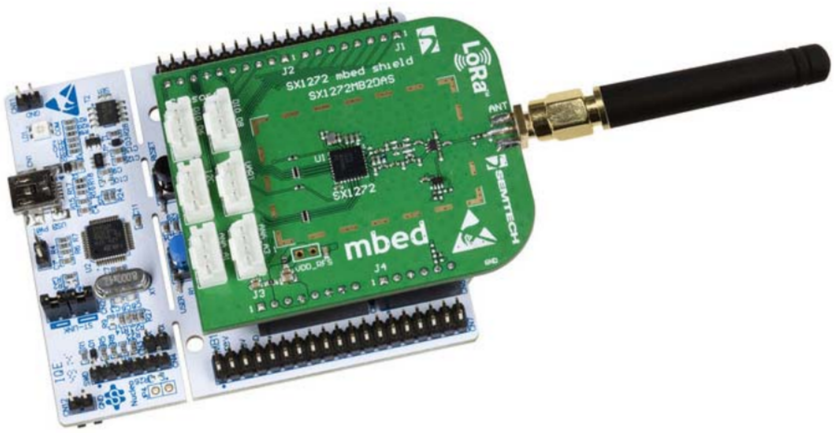


Figure 3.1: Nucleo pack [14]

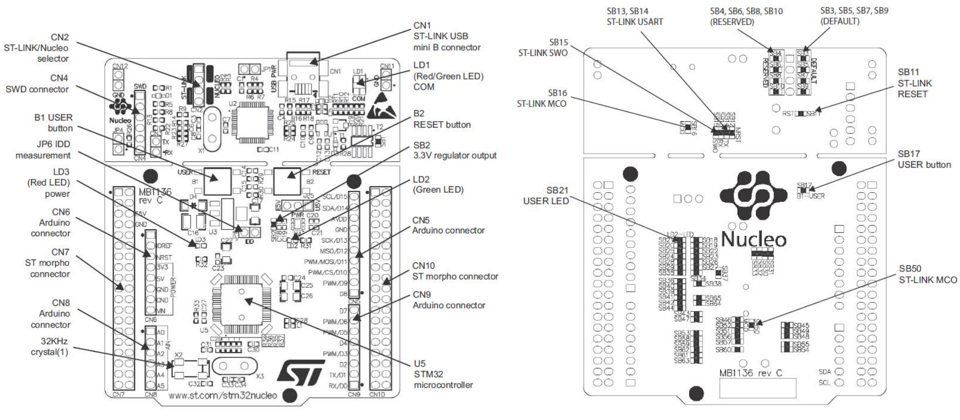
3.1.1 STM32 Nucleo L073RZ board

This board is designated for users to try out new concepts and build prototypes with the STM32 micro-controller ARM® Cortex®-M0+ 32-bit RISC core. It contains ST morpho pins which allow an easy expansion of the functionality of the STM32 Nucleo open development platform. It also contains the Arduino connectors which are used for the LoRa expansion board.[15] The distribution of board components is shown in the figures 3.2 and 3.3

bellow.

Key features[15]

- STM32 micro-controller in LQFP64 package
- External SMPS to generate V_{core} logic supply
- 1 user LED shared with Arduino
- 1 user and 1 reset push-buttons
- 32.768kHz LSE crystal oscillator
- Board expansion connectors
  - Arduino Uno V3
  - ST morpho extension pin headers for full acces to all STM32 I/Os
  - External SMPS experimentation dedicated connector
- Flexible power-supply options: ST-LINK USB V_{BUS} or external sources
- On-board ST-LINK/V2-1 debugger/programmer with USB reenumeration capability. Three different interfaces supported on USB: mass storage, virtual COM port and debug port
- Comprehensive free software libraries and examples available with STM32Cube MCU Package



(a) : Top layout **(b) :** Bottom layout

Figure 3.2: Layouts[15]

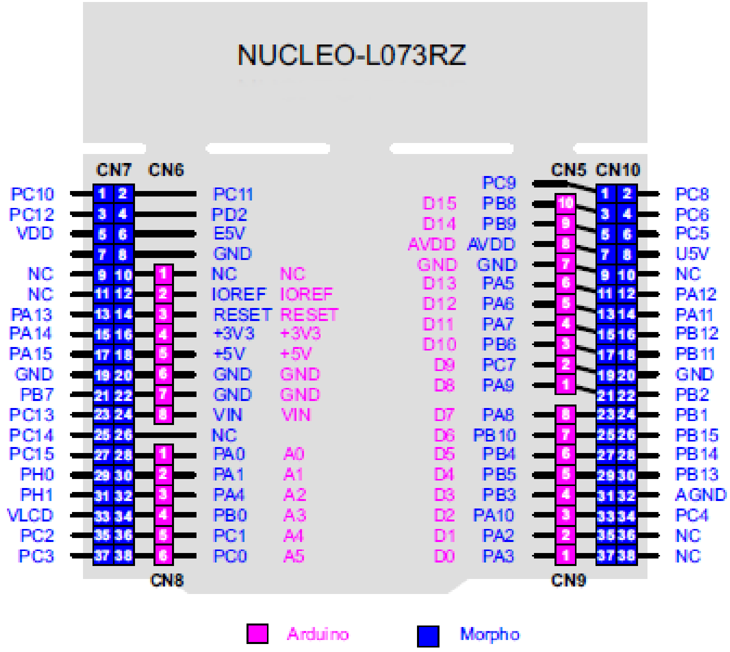


Figure 3.3: NUCLEO L073RZ morpho and arduino pins [15]

3.1.2 LoRa SX1272 expansion board

The expansion board is a transceiver which presents the LoRa long range modem that provides ultra-long range spread spectrum communication and interference immunity whilst minimizing the current consumption.[12] We will use this expansion board to establish communication and send messages to LoRa gateways.

Key features[12]

- LoRa Modem
- 157dBm maximum link budget
- +20dBm at 100mW constant RF output vs. V supply
- +14dBm high efficiency PA
- Programmable bit rate up to 300kbps
- High sensitivity: down to −137dBm
- Bullet-proof front end: $IIP3 = -125$dBm
- 89dB blocking immunity
- Low RX current of 10mA, 100nA register retention

- Fully integrated synthesizer with a resolution of 61Hz
- FSK, GFSK, MSK, GMSK, LoRa and OOK modulation
- Built-in bit synchronizer for clock recovery
- Preamble detection
- 127dB Dynamic Range RSSI
- Automatic RF Sense and CAD with ultra-fast AFC
- Packet engine up to 256 bytes with CRC
- Built-in temperature sensor and low battery indicator

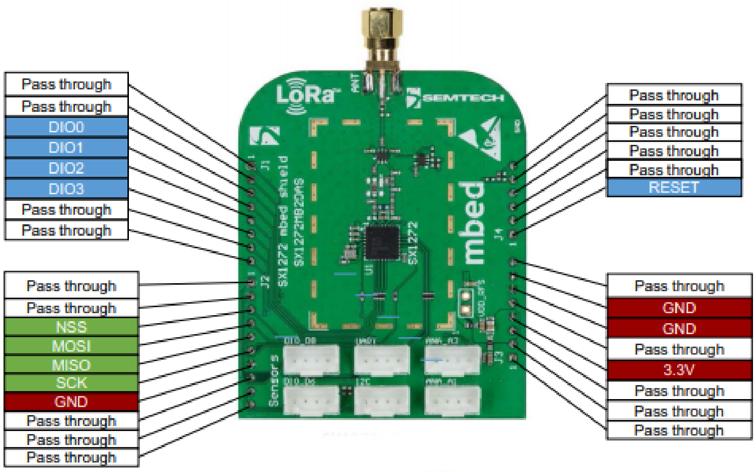


Figure 3.4: Expansion board [14]

3.2 Temperature and humidity sensors

We have chosen the SHT75 and SHT11 sensors to measure temperature and humidity. They are a unique sensor element for measuring the relative humidity, while the temperature is measured by a band-gap sensor. The sensors integrate the sensor elements, and signals processing in a compact format and provide a fully calibrated digital output. The combination of the individual precision calibration, the on-chip calibration memory, and the digital two-wire interface guarantees the best possible sensor performance in demanding applications with easy and fast system integration. The two-wire interface of the SHT75 and the SHT11 is optimized for a sensor readout and an effective power consumption. The sensor cannot be addressed by the I^2C protocol, but it can be connected to a I^2C bus. However, if the I^2C bus is used by another device, we have to switch between the protocols. The SHT75 and SHT11 sensors have 4 pins, for the data (DATA), the serial clock (SCK), the V_{DD} and the ground (GND), as we can see in the figure 3.5 below.

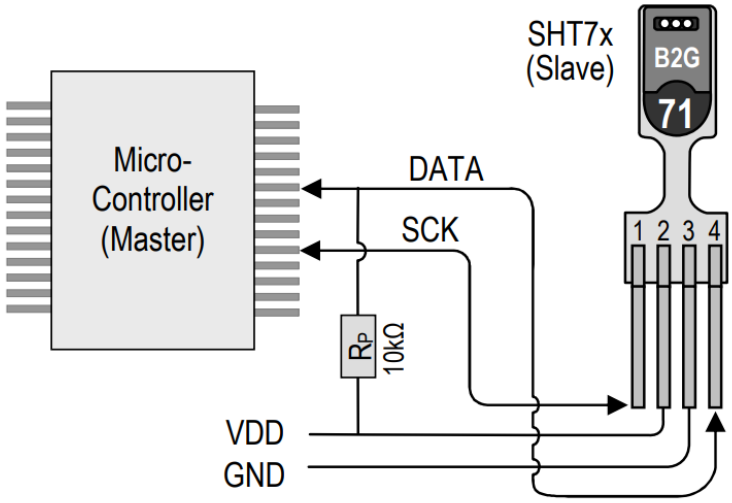


Figure 3.5: Typical application circuit, including pull up resistor [13]

3.2.1 Communication

The communication is initiated by a transmission start sequence which consists of a lowering of the DATA line while the SCK is high, followed by a low pulse on SCK and raising the DATA again while SCK is still high, as we can see in figure 3.6.

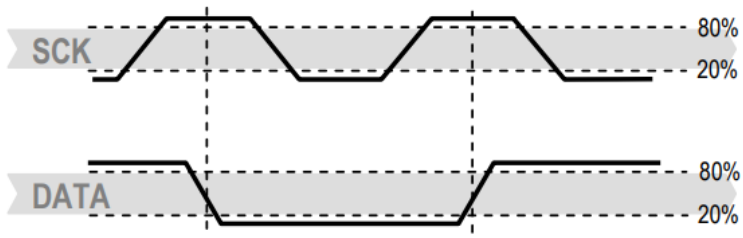


Figure 3.6: Transmission start sequence [13]

The subsequent command consists of three address bits '000' and five command bits. Then the measurement is performed, and it takes 80 ms to obtain 12 bits. The sensors pull the data line low and enter the Idle Mode to signal the completion of the measurement. The controller must wait for this Data Ready signal before restarting the SCK to readout the data. The whole communication is shown in figure 3.7. It is an example of a RH (relative humidity) measurement for value "0000'0100'0011'0001" = 1073 = 35.50% RH. Bold DATA lines are controlled by sensor while plain lines are controlled by the micro-controller.

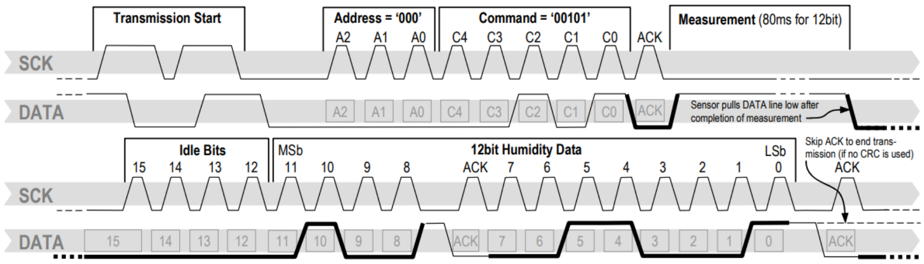


Figure 3.7: Example of SHT75 communication [13]

3.2.2 Conversion of signal output

For obtaining the full accuracy of the sensors it is recommended to convert the humidity readout (SO_{RH}) with the following formula.

$$RH_{\text{linear}} = -2.0468 + 0.0367 \cdot SO_{\text{RH}} - 1.5955 \cdot 10^{-6} \cdot {SO_{\text{RH}}}^2 (\%RH)$$

The band-gap temperature sensor is of very linear design. To convert the digital readout (SO_T) to the temperature value, it is desired to use the following formula.

$$T = -39.7 + 0.04 \cdot SO_{\text{T}} (°C)$$

3.3 Multiplexer

If we want to use more temperature and humidity sensors for our monitoring system, which uses only 2 pins on I^2C bus, we need to use multiplexers to control the communication with sensors. We chose the 74HC4051 multiplexers, from Philips Semiconductor, to control our Sensirion sensors. One multiplexer will be used for DATA communication and the second one for SCK.

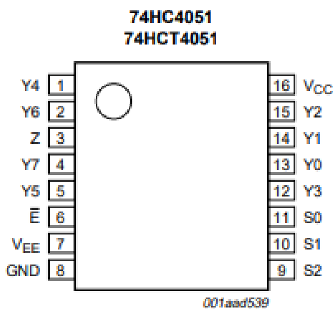


Figure 3.8: Pin configuration of multiplexer[1]

The 74HC4051 is an 8-channel analog multiplexer/demultiplexer with 3 digital select inputs (S0 to S2), an active-LOW enable input (E), 8 independent inputs/outputs (Y0 to Y7) and a common input/output (Z).[1] The individual pins are shown in figure 3.8.

3.4 Gas sensor

The MQ-2 Gas sensor can detect and measure gases like LPG (Liquefied Petroleum Gas), Alcohol, Propane, Hydrogen, CO (Carbonmonooxid) and methane. For the demonstration, we are going to measure only CO and smoke. To measure gas in ppm (parts-per-million), the analog pin has to be used. It works on 5V and can be used with most common micro-controllers. There is also a digital pin which allows operating even without the micro-controller, but we are not going to use it. [10]

Features[10]

- Operating Voltage is +5V
- Can be used to Measure or detect LPG, Alcohol, Propane, Hydrogen, CO and methane
- Analog output voltage: 0V to 5V
- Digital Output Voltage: 0V or 5V (TTL Logic)
- Preheat duration 20 seconds
- Can be used as a Digital or analog sensor
- The Sensitivity of Digital pin can be varied using the potentiometer

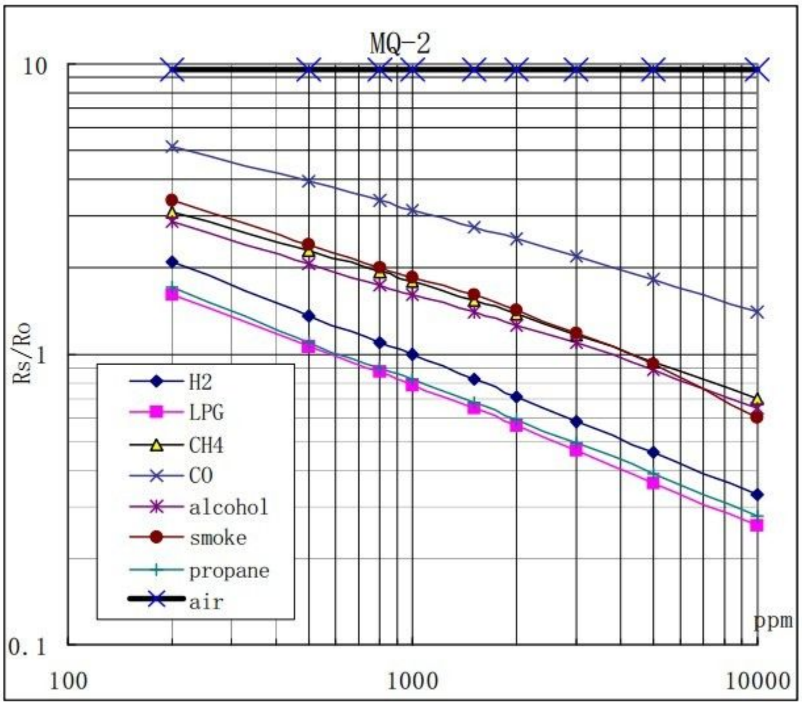


Figure 3.9: Sensitivity Characteristics [10]

The figure 3.9 shows typical sensitivity characteristics of the MQ-2 gas sensor, on the y-axis we have the resistance ratio of the sensor (Rs/Ro), and on the x-axis the concentration of gases can be seen. The value of Ro is the value of resistance in fresh air, and the value of Rs is the value of resistance in Gas concentration. [10]

3.5 Incremental rotary encoder

An incremental rotary encoder ALPS STEC12E08 provides cyclical outputs when the encoder is being rotated. It can be either mechanical, optical or magnetic, but we will only focus on the mechanical. It is used to track motion, and can be used to determine position. It has two analog output channels A and B, which are called quadrature outputs. [16] They are shown in the following figure 3.10, where we can also have a look inside of our incremental rotary encoder. There are A and B output signals, and as we turn a shaft, the pads move, and the outputs are changing in the phases. The single phases are displayed in the table 3.1.

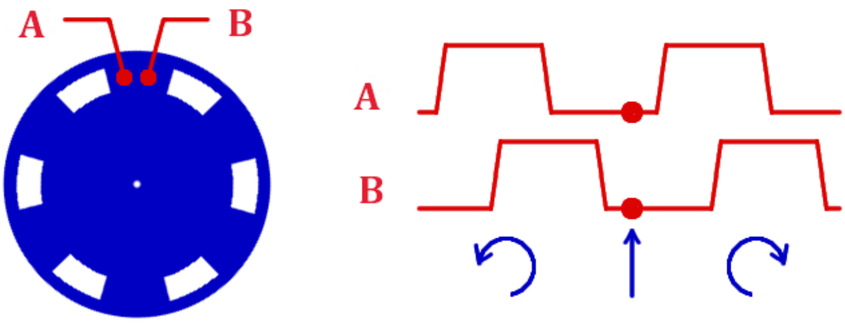


Figure 3.10: Inside schema of incremental encoder

We can detect from the phases in which direction the shaft rotates. For example, when the signals are '00' and the next signals are '01', then we can say that our encoder rotates clockwise.

Phase	A	B
1	0	0
2	0	1
3	1	0
4	1	1

Table 3.1: Increasing phase implies clockwise rotation [16]

Features

- 10 mA max. operating current
- 5V operating voltage
- 360°C endless rotation
- 24 detent positions
- 24 pulses

In the following figure 3.11 is shown how the phases are changing while the shaft is rotating clockwise.

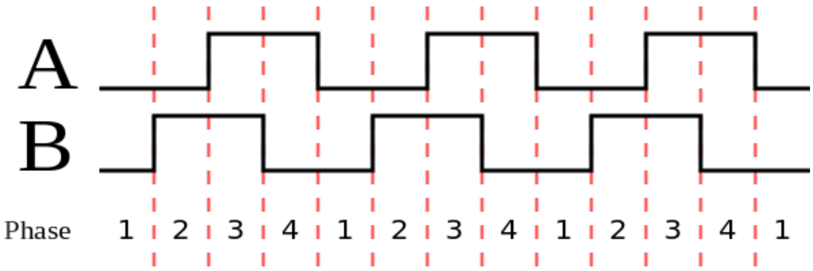


Figure 3.11: Two square waves in quadrature (clockwise rotation) [16]

Chapter 4

System architecture

In this chapter, we will focus on the system architecture of our monitoring system, which means describing the process of the communication, the inside structure of our monitoring system, and last but not least, the multi-threaded loop which controls our monitoring system.

4.1 LoRa communication

The monitoring system contains some sensors which measure suitable quantities for monitoring the HVAC system, evaluating them, and sending the information through LoRa gateways to a Network server, where they are finally saved to the cloud in the Application server as we can see in the figure 4.1.

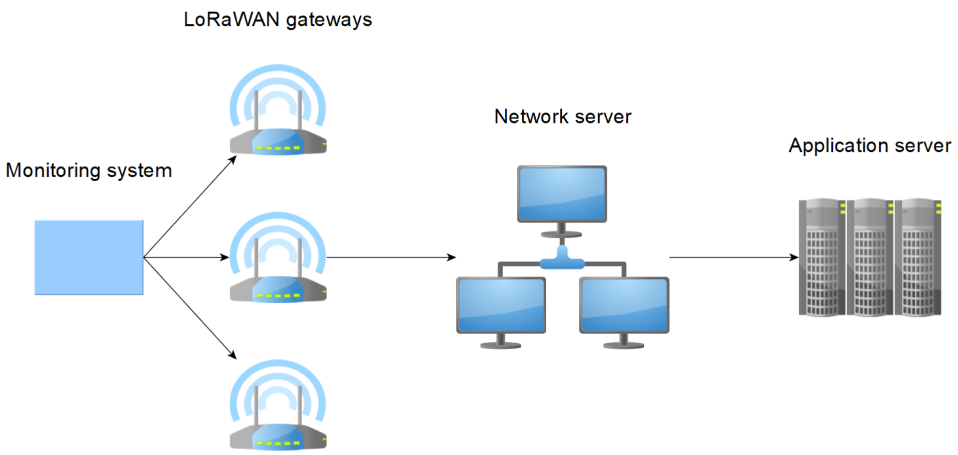


Figure 4.1: Communication of monitoring system

For the better understanding of our monitoring system, we can imagine the sensors being placed inside and outside AHU (air handling unit), where they measure required data, and through the Lora expansion board the data are sent to the LoRaWAN gateways, concretely to thethingsnetwork.org as being shown in figure 4.2.

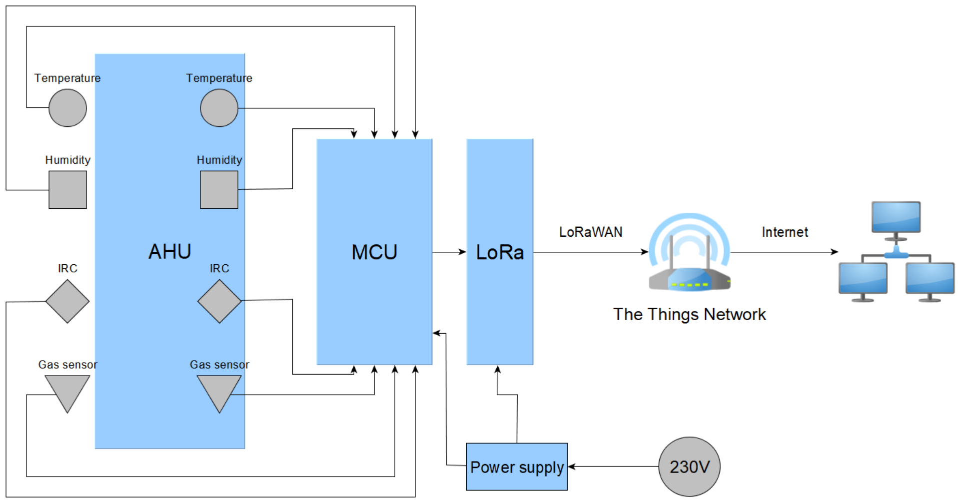


Figure 4.2: Layout of sensors in HVAC unit and communication through LoRa

4.2 System integration

Our monitoring system is controlled by micro-controller built-in STM32 Nucleo development board with STM32L073RZ MCU (micro-controller unit). There are 76 Morpho pins, and 32 Arduino pins leading out of the micro-controller. The used pins are defined in the table 4.1.

Pin	Function	Description
PA0	AOUT	analog output for IRC (channel A)
PA1	AOUT	analog output for IRC (channel B)
PA4	AOUT	analog output for MQ2 gas sensor
PB8	I2C1_SCL	clock for SHT75 sensor on I^2C bus
PB9	I2C1_SDA	serial data line for communication on I^2C bus
PC10	GPIO	digital select input of multiplexer (S0)
PC12	GPIO	digital select input of multiplexer (S1)
5V	POWER	5V power supply
3V	POWER	3V power supply
GND	GND	ground

Table 4.1: Used micro-controller pins [15]

The circuit connection is displayed in figure 6.1. This figure only contains the mentioned sensors, but more can be added in the future. The development kit provides not only the I^2C interface, but also the SPI interface or USART. There are Analog inputs and outputs as well.

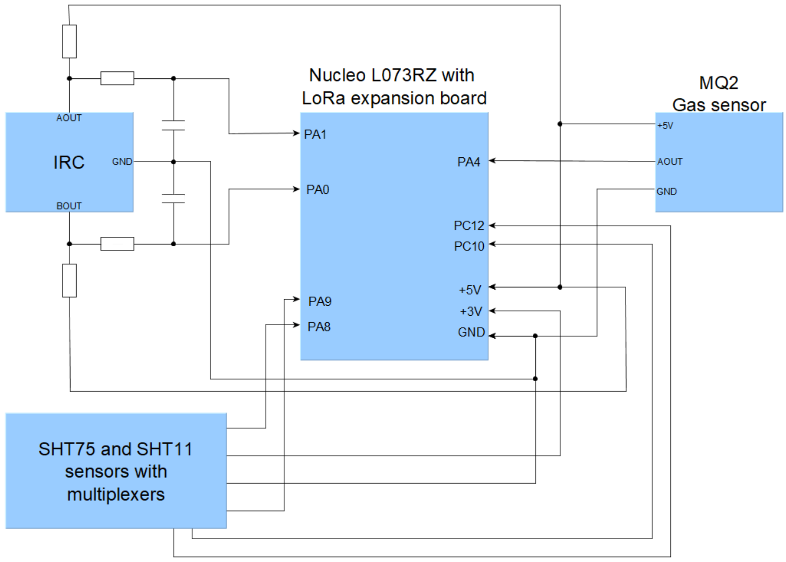


Figure 4.3: Schema of monitoring system

The project is written in C++ for fast and smooth micro-controller programming. The project also uses several libraries for communication with the sensor and development kit through the LoRaWAN protocol.

4.2.1 SHT75 and SHT11 communication

The SHT75 and SHT11 sensors communicate through the I^2C bus and use the I^2C Arduino pins for the communication, concretely pin PB8 and PB9. The pin PB8 is as a clock for communication through the I^2C bus, and the data are exchanged through pin PB9.

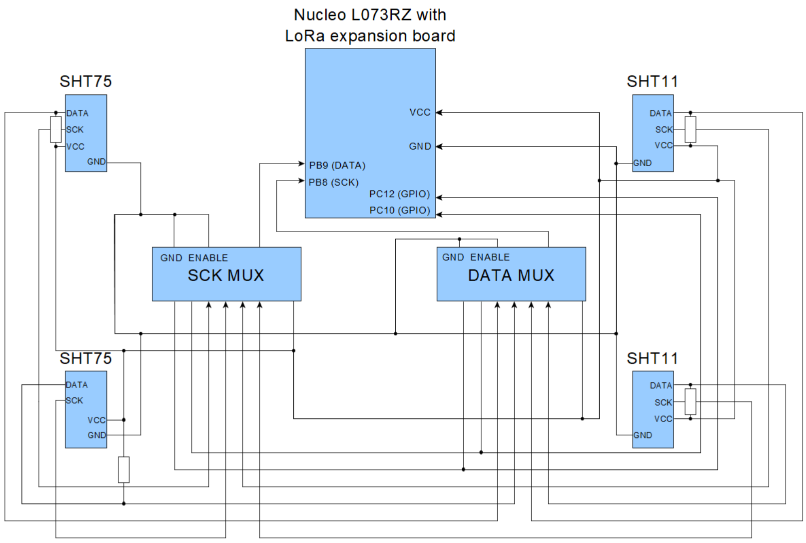


Figure 4.4: Schema of SHT75 and SHT11 sensors with multiplexers

The hardware connection is shown in the figure 4.4 and the 10kΩ resistor, and VCC is +3V are being applied here. We have 4 sensors, 2 SHT75 and 2 SHT11 sensors. Both types have SCK, DATA, VCC an GND pins and they are connected to multiplexers. One multiplexer is used to transmit SCK and the second one is used to transmit DATA, while using 2 GPIO pins on the development kit which control, which sensor should be used.

4.2.2 MQ2 communication

The connection of MQ2 gas sensor is pretty simple as we can see in the following figure 4.5. For communication we use the analog output pin together with the +5V power supply.

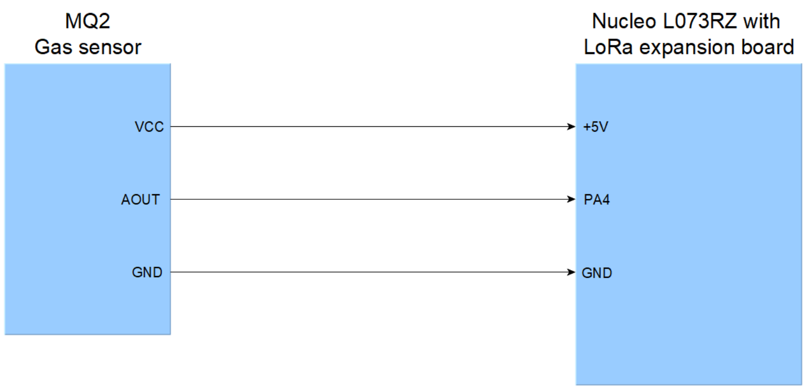


Figure 4.5: MQ2 schema

4.2.3 IRC communication

The incremental rotary encoder uses the analog output pins to communicate with the development board as well. It is powered by +5V supply and the 10kΩ resistors, and 10pF capacitors are used as we can see in the following figure 4.6.

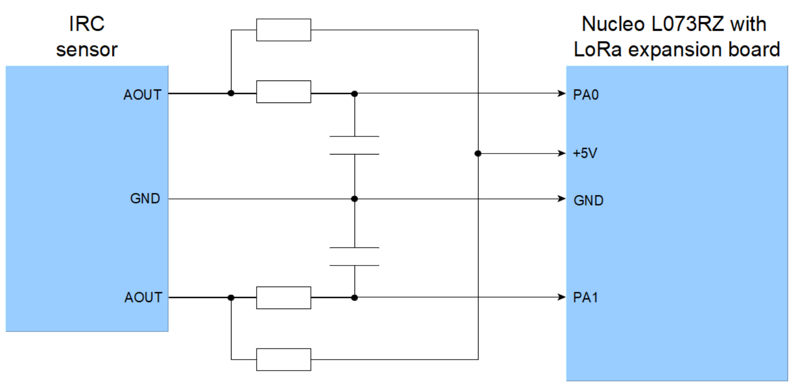


Figure 4.6: IRC schema

4.3 Main loop

The program contains two endless threads because it is necessary to listen to the incremental rotary encoder the whole time to get the right values. One thread receives the position of the exhaust valve thanks to the IRC sensor, and saves the position value of the valve, if it is asked for. Everything else is performed in the second thread. In this thread, it is a ten-step cycle, which is always repeated. Every minute the quantities such as temperature, humidity, CO, and smoke are measured by sensors and saved. The position of the exhaust valve is kept in every cycle as well. After ten cycles, the measured values from all the sensors are evaluated, and sent to the LoRa gateway, where it can be possibly processed. The whole main loop is displayed in the figure 4.7 below.

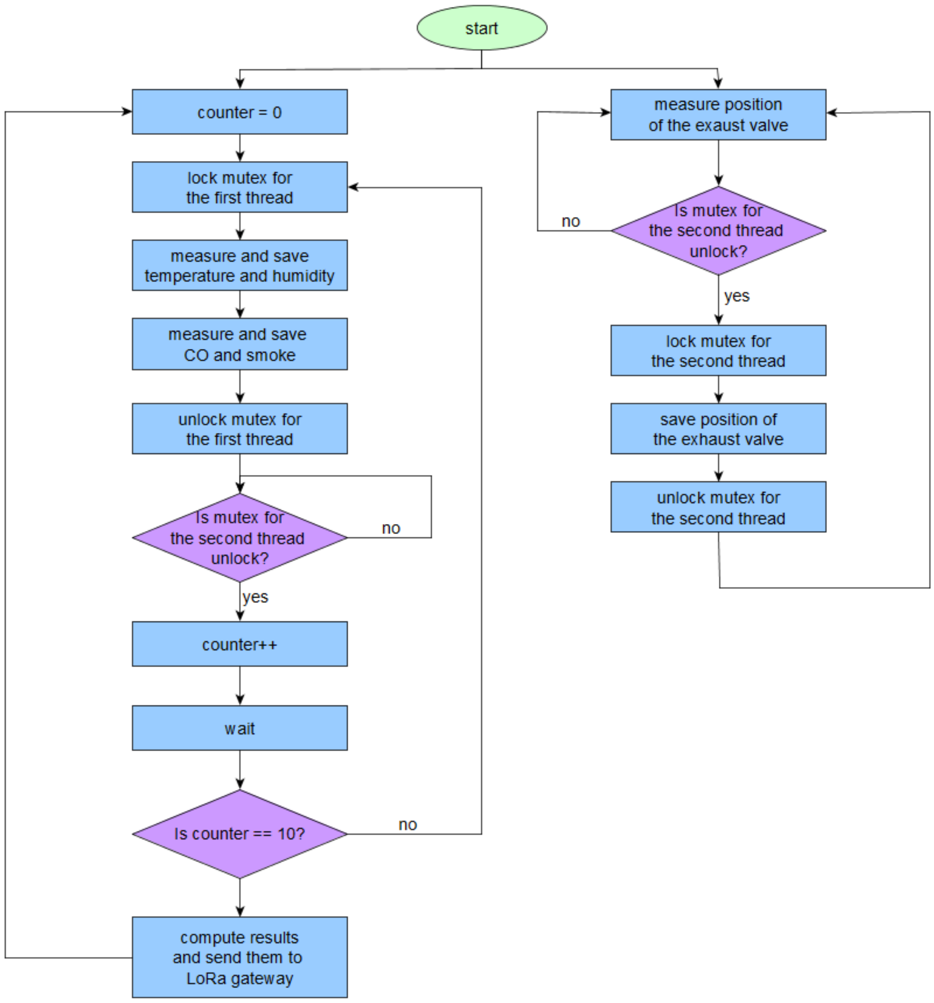


Figure 4.7: Main loop of the monitoring system

Chapter 5

Data processing

This chapter focuses on data processing. We are going to explain how our monitoring system computes data and in what format are the data being sent to the network. We are also going to introduce possible evaluation which should be applied on the data to detect failures.

5.1 Processing of measured values

In our monitoring system we use temperature and humidity sensors, the gas sensor, and the incremental rotary encoder. We explained their usage in the previous chapters. Now we are going to explain, in what format are the data from the sensors being sent LoRa gateway.

We get the values from the sensors once per minute, and once per 10 minutes the data are being sent to the network. It means we need to evaluate these 10 measurements to send only one value from each sensor.

For both types of the temperature and humidity sensors, SHT75 and SHT11, the values are computed by arithmetic mean, and each value is sent in 2 bytes. In our case, we use 2 SHT75 and 2 SHT11 sensors, and each of them gives us information about temperature and humidity. It means, that we need to send 16 bytes to the LoRa gateway.

The gas sensor measures two values, CO and smoke. The value of the measured quantities is zero, if the CO and smoke are not present. The problem occurs, when the gases are present in the HVAC system and notwithstanding the amount. That is why we send 0 if the gases are not attendant, and 1 if they are. Each quantity is sent in 1 byte, therefore 2 bytes are needed in order to transmit the data through LoRa communication.

The last sensor from which we are getting information is the incremental rotary encoder. This sensor monitors the position of the exhaust valve in the HVAC system. The used IRC has 24 pulses, which means that 360° are divided into 24 parts. The IRC can recognize a motion bigger than 15° angle. The values from the sensor are in the range from -24 to 24, where the negative values mean rotating to the one side and positive values mean rotating to the other side. To detect, that there are no huge differences in the position of the exhaust valve, we compute the smallest and the highest number of the position. So the minimum and the maximum, each represented by 1 byte, are being sent to the network.

5.2 APAR

Mode	**Rule #**	**Rule Expression** (true implies existence of a fault)
Heating **(Mode 1)**	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \varepsilon_t$
	2	For $\lvert T_{ra} - T_{oa} \rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} \rvert > \varepsilon_f$
	3	$\lvert u_{hc} - 1 \rvert \leq \varepsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \varepsilon_t$
	4	$\lvert u_{hc} - 1 \rvert \leq \varepsilon_{hc}$
Cooling with Outdoor Air **(Mode 2)**	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \varepsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	7	$\lvert T_{sa} - \Delta T_{sf} - T_{ma} \rvert > \varepsilon_t$
Mechanical Cooling with 100% Outdoor Air **(Mode 3)**	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \varepsilon_t$
	9	$T_{oa} > T_{co} + \varepsilon_t$
	10	$\lvert T_{oa} - T_{ma} \rvert > \varepsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	13	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	14	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$
Mechanical Cooling with Minimum Outdoor Air **(Mode 4)**	15	$T_{oa} < T_{co} - \varepsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	18	For $\lvert T_{ra} - T_{oa} \rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} \rvert > \varepsilon_f$
	19	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	20	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$
Unknown Occupied Modes **(Mode 5)**	21	$u_{cc} > \varepsilon_{cc}$ and $u_{hc} > \varepsilon_{hc}$ and $\varepsilon_d < u_d < 1 - \varepsilon_d$
	22	$u_{hc} > \varepsilon_{hc}$ and $u_{cc} > \varepsilon_{cc}$
	23	$u_{hc} > \varepsilon_{hc}$ and $u_d > \varepsilon_d$
	24	$\varepsilon_d < u_d < 1 - \varepsilon_d$ and $u_{cc} > \varepsilon_{cc}$
All Occupied Modes **(Mode 1, 2, 3, 4, or 5)**	25	$\lvert T_{sa} - T_{sa,s} \rvert > \varepsilon_t$
	26	$T_{ma} < min(T_{ra}, T_{oa}) - \varepsilon_t$
	27	$T_{ma} > max(T_{ra}, T_{oa}) + \varepsilon_t$
	28	Number of mode transitions per hour > MT_{max}

Figure 5.1: APAR rule set[2]

One way of data evaluation is the Air handling unit (AHU) Performance Assessment Rules (APAR). It helps to detect the possible failures of the HVAC systems. The basis of the AHU fault detection methodology is the set of expert rules used to assess the performance of the AHU.[2] The set of rules, shown in the figure 5.1, was developed for AHUs with hydronic heating and cooling coils and relative enthalpy-based economizers, but it can easily be adjusted to different types of AHUs.

Abbreviation	**Meaning**
MT_{max}	maximum number of mode changes per hour
T_{sa}	supply air temperature
T_{ma}	mixed air temperature
T_{ra}	return air temperature
T_{oa}	outdoor air temperature
T_{co}	changeover air temperature for switching between Modes 3 and 4
$T_{sa,s}$	supply air temperature set-point
ΔT_{sf}	temperature rise across the supply fan
ΔT_{rf}	temperature rise across the return fan
ΔT_{min}	threshold on the minimum temperature difference between the return and outdoor air
Q_{oa}/Q_{sa}	outdoor air fraction = $(T_{ma}-T_{ra})/(T_{oa}-T_{ra})$
$(Q_{oa}/Q_{sa})_{min}$	threshold on the minimum outdoor air fraction
u_{hc}	normalized heating coil valve control signal [0,1], where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100 % open
u_{cc}	normalized cooling coil valve control signal [0,1], where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100 % open
u_d	normalized mixing box damper control signal [0,1], where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100 % open
ε_t	threshold for errors in temperature measurements
ε_f	threshold parameter accounting for errors related to airflows (function of-uncertainties in temperature measurements)
ε_{hc}	threshold parameter for the heating coil valve control signal
ε_{cc}	threshold parameter for the cooling coil valve control signal
ε_d	threshold parameter for the mixing box damper control signal

Table 5.1: Meaning of the abbreviations [2]

There are 5 various operating modes, which depend on the heating/cooling load and the outdoor air conditions. Each operating mode can be characterized by a different range of values. Mode 1 is heating, mode 2 is cooling with outdoor air, mode 3 is mechanical cooling with 100% outdoor air, mode 4 is mechanical cooling with minimum outdoor air and mode 5 is unknown. The APAR has 28 rules, where each rule expresses a logical statement, where true means presence of the failure.[2] The meaning of the abbreviations from figure 5.1 we can see in table 5.1.

Chapter 6

Results

In this chapter we are going to summarize our work. We have made a prototype of the monitoring system for HVAC communicating through LoRa technology. We used the STM nucleo L073RZ development kit with LoRa SX1272 expansion board as a base for our monitoring system. The board is capable of transmitting data to thethingsnetwork.org through the LoRa protocol. It can also communicate with sensors and process the data from them. For the demonstration of our monitoring system, we applied 4 temperature and humidity sensors, which communicate with the development board through 2 multiplexers connected to the I^{2}C bus, and powered by 3V.

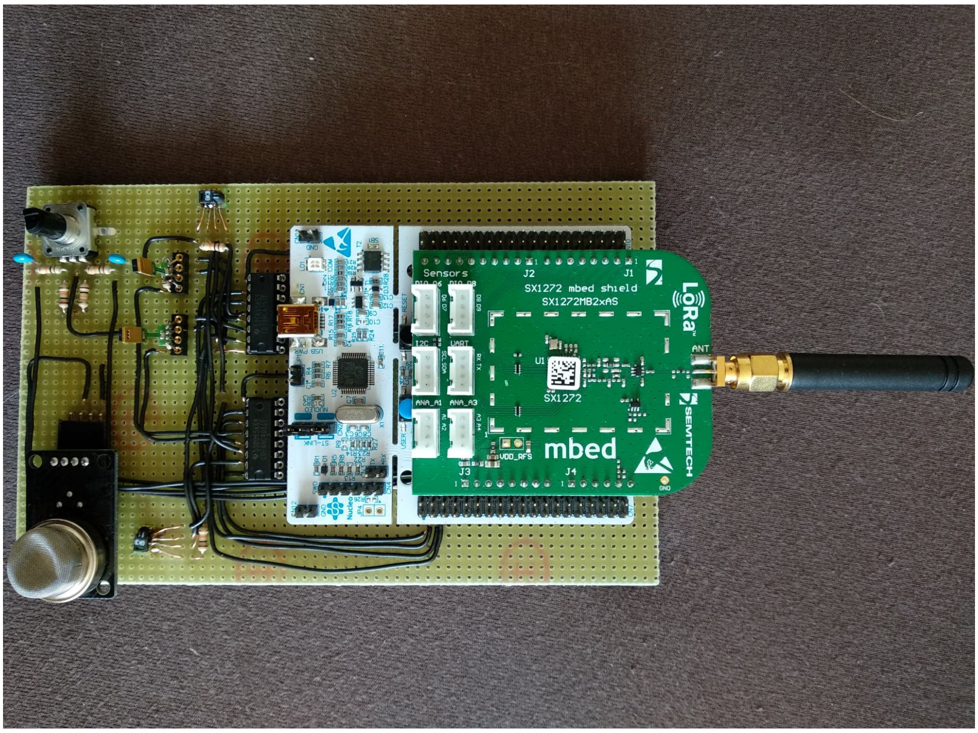


Figure 6.1: Picture of the monitoring system demonstration

Further on, we used the incremental rotary encoder to observe the position of the exhaust valve, which was connected to the board through an analog input pin and was powered by 5V. We also used a gas sensor to monitor the presence of the CO and smoke in the HVAC systems. The sensor was connected to the analog input pin on the development board and powered by 5V as well. The eventual monitoring system can be seen in figure 6.1.

The monitoring system was designed to measure every quantity once per minute, and after ten measurements it evaluated each quantity and sent it in the right format to the network server (thethingsnetwork.org). The data were send in 20 bytes, where 8 bytes were used for temperatures (2 bytes for every temperature), 8 bytes for humidities, 2 bytes for gases and 2 bytes for the incremental rotary encoder. For the data visualization we created a simple dashboard displayed in the next part.

6.1 Dashboard for monitoring system

After completing our monitoring system, the data were received as payload in the network server, concretely thethingsnetwork.org. It is not easy to read the data from the payload, especially for someone who does not know in what order it was sent, and how many bytes were used for a specific quantity. We decided to visualize these received data into the dashboard. We used Node-RED to create our dashboard.

6.1.1 Node-RED

Node-RED is a flow-based development tool for wiring together hardware devices, APIs and online services.[11] In our case, Node-RED allows us to observe the received data from thethingsnetwork.org, parse them to individual values and display them like a number or in various time-dependent graphs.

As we can see in the figure 6.2, we obtained a ttn (The Things Network) message, which contained a 20 bytes long hexadecimal payload, and we used the function to extract these data from the payload to individual values of quantities, that we sent through LoRa to the network server. Then the single values can be displayed on the dashboard as it is shown in the figure 6.3. We used the gauge graphs to present the current value of the temperature and humidity from the several sensors, and we also used a time-dependent line chart to see how the temperature and humidity changed in time. The gases are represented only as numbers and the minimum, and the maximum value of the incremental rotary encoder is shown in the donut charts.

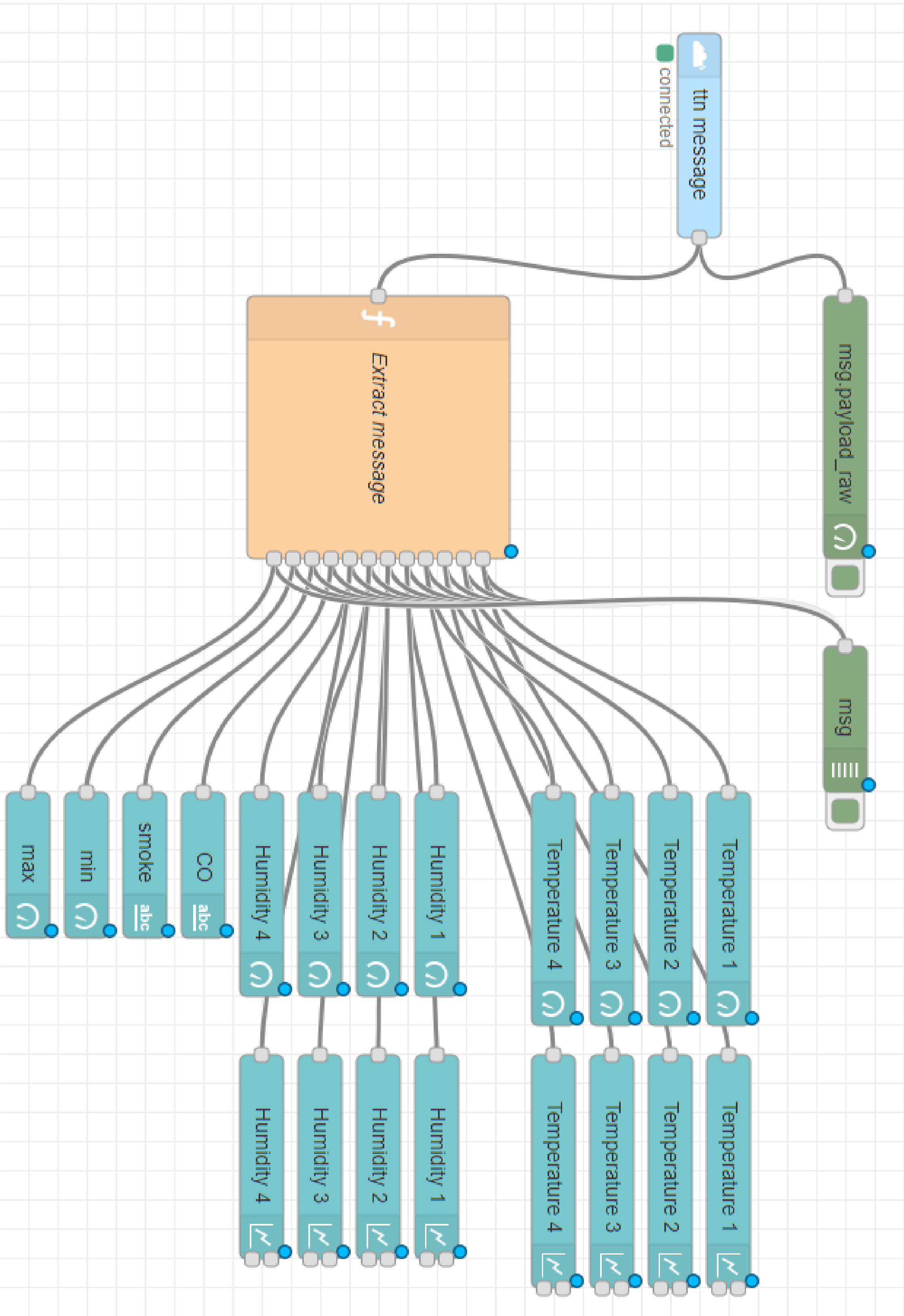


Figure 6.2: Node-RED diagram of our dashboard for monitoring system

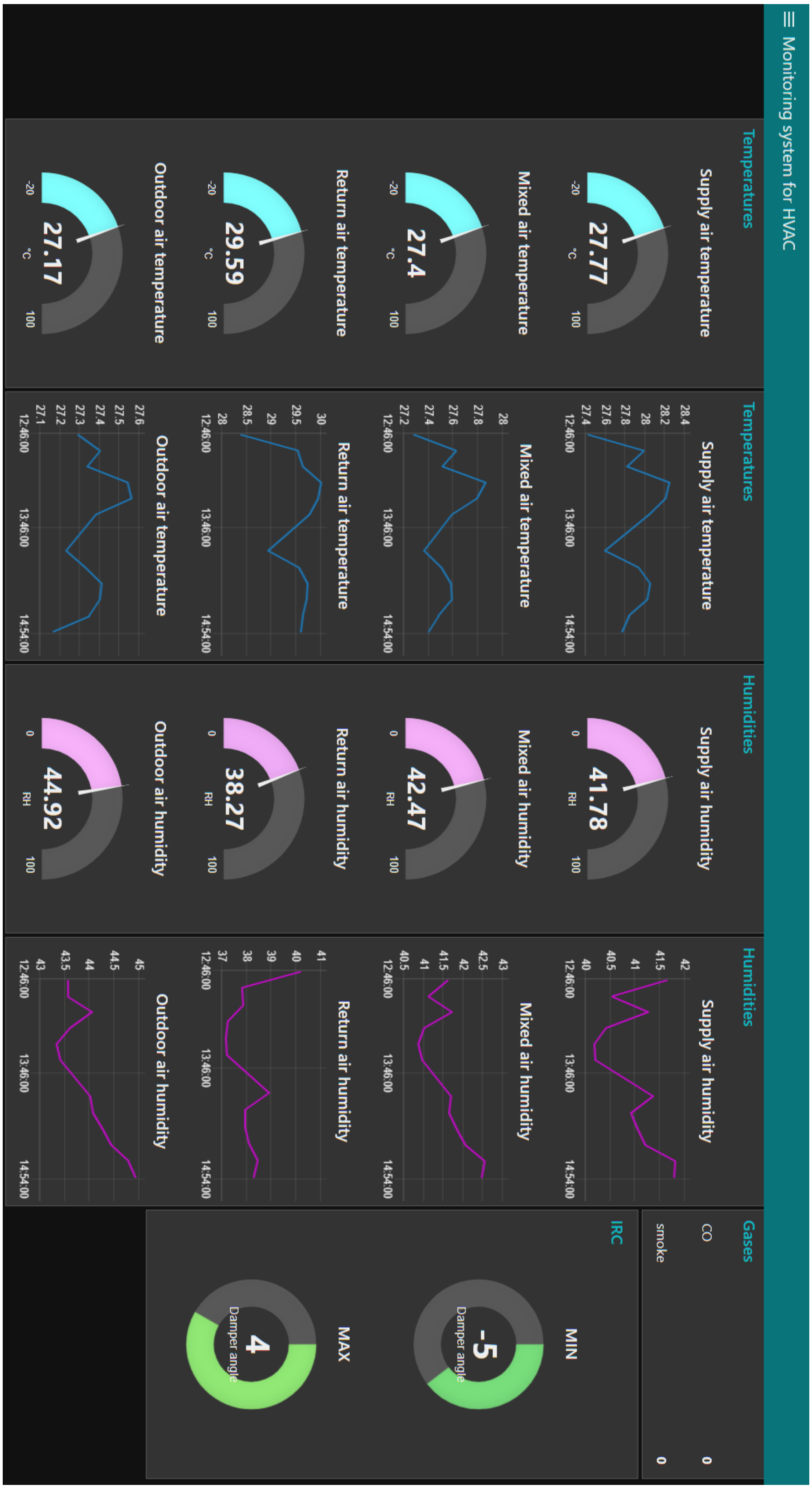


Figure 6.3: The dashboard after few hours of receiving data

Chapter 7

Conclusion

Within this thesis a LoRa communication-based system for the monitoring of physical quantities in the HVAC systems using both the digital and the analog input was designed and realized. The system can be used for detection of faults and degradation in HVAC equipment. We used various sensors to monitor physical quantities within HVAC and enable detection of possible failures of heating, ventilation and air conditioning technologies.

We used 4 Sensirion SHT11/SHT75 sensors to measure temperature and humidity, and one gas sensor and incremental rotary encoder to monitor a position of the exhaust valve (damper). We soldered our own custom PCB (printed circuit board), which contains the STM32 NUCLEO L073RZ kit with SX1272 LoRa expansion board, 2 multiplexers 74HC4051, 2 temperature and humidity SHT11 sensors and 2 SHT75, 1 MQ2 gas sensor and 1 incremental rotary encoder. All sensors are controlled by STM32 micro-controller (ARM® Cortex®-M0+ 32-bit RISC core) on NUCLEO L073RZ board.

We developed a system, which collects data from these sensors, evaluates them and sends to the LPWAN network every 10 minutes, from where they are visualized in the dashboard where the data are more human-readable than in the IoT network console. We used The Things Network (thethingsnetwork.org), IoT network, and LoRa protocol for data communication from the monitoring system. For the data visualization in the dashboard, we used flow-based development tool Node-RED. The system, we have created, serves as a demonstrator and can be used as a basis for the future development of LPWAN based monitoring systems.

7.1 Future work

To improve our eventual monitoring system we could increase the number of the sensors. For example, the multiplexers that we are using, can easily control 8 sensors, but in current status we only use 4 of them. So 4 more can be added, or even more with the application more multiplexers.

We could also place sensors all over the HVAC system to obtain data from various locations and could evaluate them with the APAR set of rules to detect temperature and humidity failures in AHU.

Obviously, the number of the other sensors could increase as well. We could detect other gases like LPG, CH4, propane, and others with the MQ2 gas sensor, not only CO and smoke. Much more sensors could be added to the monitoring system. As an illustration, we could collect data from the accelerometer to observe vibrations of some technical elements in AHU. There are endless possibilities to extend and improve this system with various types of sensors.

After these changes, the dashboard has to be innovated as well. New charts for additional sensors have to be inserted to monitor each quantity. We could evaluate, if the received values from the sensors are acceptable (e.g., by using APAR set of rules, or other techniques for data evaluation) and if they are not, the alert message could be sent to the appropriate person. This message could be sent as an e-mail to the system administrator or the technical specialist. That could be implemented in Node-RED, which has suitable tools to create a message and to send it based on the results from the evaluation function.

The only problem could occur if we have a lot of sensors and too many data to send, because there is a limited number of bytes we can send to the network server. The number of bytes depends on spread factor.

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Appendix A

Content of attached CD

- **monitoring_system.bin -** binary code
- **monitoring_system.zip -** zip folder with source code
- **bp-luciasemanova.pdf -** bachelor thesis in pdf
- **bp-luciasemanova.zip -** zip with bachelor thesis in latex
- **dashboard_code.txt -** source code of dashboard created in Node-RED