Distributed LoRa based CO$_2$ monitoring network – A standalone open source system for contagion prevention by controlled ventilation

Yannic Toschke [a], Janet Lusmoeller [b,c], Lars Otte [b,c], Johann Schmidt [b,c], Svenja Meyer [c], Alexander Tessmer [d], Christian Brockmann [e], Milena Ahuis [e], Emma Hüer [e], Christian Kirberger [e], Dirk Berben [c,*]

[a] Department of Physics, Osnabrueck University, Barbarastrasse 7, Osnabrueck D-49076, Germany
[b] Department of Chemistry Education, Osnabrueck University, Barbarastrasse 7, Osnabrueck D-49076, Germany
[c] Fachhochschule Suedwestfalen, Fachbereich Elektrotechnik und Informationstechnik, Haldener Strasse 182, D-58095 Hagen, Germany
[d] Institute of Computer Science, Osnabrueck University, Friedrich-Janssen-Str. 1, Osnabrueck D-49076, Germany
[e] Evangelisches Gymnasium Nordhorn, Bernhard-Niehues-Straße 51, D-48529 Nordhorn, Germany

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ABSTRACT

In the face of a global pandemic, such as that caused by the SARS-CoV-2 virus, the prevention of new infections is essential to stop the spread and ultimately return to normality. In addition to wearing masks and maintaining safe distances, regular ventilation in enclosed spaces where several people are gathered has proven to be an effective protective measure as advised by the World Health Organization. Additionally, as has been shown in a recent study of other airborne viruses, there is a strong correlation between the CO$_2$level and aerosol content in a confined space under the assumption humans are the only CO$_2$source. This can be exploited by means of a low-cost infrared CO$_2$sensor to indirectly monitor the aerosol content and to provide targeted ventilation if predefined thresholds are exceeded. The distributed CO$_2$monitoring network presented in this paper extends that idea and provides an inexpensive, comprehensive and modular monitoring network based on readily available components and 3D printing. By using a long-range communication link (LoRa) to centrally collect the real-time CO$_2$concentration in a multitude of rooms, this network is particularly suitable for larger building complexes such as kindergartens, schools and universities without requiring partial or even full WLAN coverage.

Specifications table:

Hardware name	*Distributed LoRa based CO_2 monitoring network*
Subject area	• Medical
Hardware type	• Medical hardware
	• CO_2 monitoring
Open source license	This work is licensed under the Creative Commons Attribution-ShareAlike 4.0 International License.
Cost of hardware	CO_2 traffic light + Raspberry Pi B+: 69.00 € + 30.20 € = 99.20 €
Source file repository	https://doi.org/10.17605/OSF.IO/SNHFD

Hardware in context

For some time now, the monitoring of indoor air quality by means of special monitoring systems has been gaining increasing popularity in society [1,2]. Especially during the current SARS-CoV-2 pandemic, monitoring of indoor air quality plays an important role in minimizing the risk of infection with SARS-CoV-2 [3]. Particularly in schools where 20 to 30 people stay in one room for a prolonged period of time, it is important to monitor the indoor air quality. The main transmission of the SARS-CoV-2 virus is via respiratory inhalation of virus-containing particles [4]. These particles are emitted during any form of lung-ventilation, i.e. breathing, singing, coughing, etc. Depending on the particle size, a distinction is made between larger droplets and smaller aerosols. While the larger droplets sink quickly to the ground, the smaller aerosols can also float in the air for a longer period of time and distribute themselves in enclosed spaces [5]. In one study, infectious particles could be detected for up to 3 h in a room [4]. Therefore, especially at the present time, it is important to keep the concentration of aerosol particles in the air as low as possible to minimize the potential infection risk, as described by the Wells-Riley model of aerosol infection [6]. One way of achieving this goal is by sufficient ventilation. It has been shown that exhaled air comprises aerosols which may contain the SARS-CoV-2 virus in case of an infection [7,8]. Thus, poorly ventilated or unventilated indoor environments significantly increase the likelihood of an airborne transmission of the SARS-CoV-2 virus. In addition to aerosols, humans exhale CO_2 with their respiration. The instantaneous CO_2 concentration can be used as a good proxy of aerosol particle concentration since the CO_2 concentration correlates with that of the aerosol particles assuming there is no other significant CO_2 source [9–12]. It should be noted that the potential infection risk is a multi-parameter function, depending on many different aspects from which the cumulative CO_2 amount is only one. Yet, the cumulative CO_2 is still significant and directly linked to the more accessible instantaneous CO_2 concentration through the exposure time, i.e. a 6 h school day.

There are a variety of simplistic CO_2 monitoring devices on the market measuring the indoor CO_2 concentration. However, these CO_2 monitoring systems are very expensive, typically around 200 € [13,15,14]. A less expensive but yet more limited alternative is a commercially available CO_2 traffic light, which uses color coding to display the quality of the indoor air and thus, serves as an indicator for when manual ventilation needs to occur. A large number of CO_2 traffic lights have also recently emerged in the field of open-source solutions [16–19]. These present a cost-effective alternative to the commercially available ones. However, these solutions are usually designed for monitoring a single room and lack the ability to monitor a complete building. Occasionally, the CO_2 traffic lights are networked via WLAN, which enables the monitoring of several rooms. In regard of the fact that not all schools have sufficient infrastructure, for example only 37% of all teachers in Germany are satisfied with the quality of their WLAN [20], a low-cost DIY CO_2 monitoring network with IoT connection was developed by students as part of the "5th. OpenPhotonik Pro Make@thon". Compared to the multitude of CO_2 traffic lights, this distributed CO_2 monitoring network offers a networking of the individual traffic lights by employing LoRa [21]. This means that schools with insufficient infrastructure can also install these traffic lights. The CO_2 traffic lights send their data to a central node via LoRa. This node is connected to a WLAN access point created by a Raspberry Pi. Using MQTT (a Message Queuing Telemetry Transport protocol), the measured CO_2 concentration from different rooms are graphically displayed on any WLAN-enabled terminal device. The classification of the indoor air quality is carried out according to the guidelines of the German Federal Environmental Agency [22].

Hardware description

The distributed CO_2 monitoring network was designed in a way that an additional CO_2 traffic light could always be added to increase the number of centrally monitored rooms. Furthermore, the individual CO_2 traffic light can be easily manufactured with the help of readily available components and additive manufacturing, e.g. 3D-printing. The hardware components used are a microcontroller (ESP32), an infrared CO_2 sensor, an OLED display, an RGB LED, a buzzer and a simple copper plate (as an capacitive touch switch).

The CO_2 monitoring network presented here consists of individual CO_2 traffic lights which are interconnected via LoRa to a central Raspberry Pi B+ that consolidates the data and provides the browser accessible user-interface for easy data retrieval. The underlying concept is to use one of these CO_2 traffic lights in each room of interest in a larger building, e.g. a school,

university or public institution, where the safe gathering of several people is to be supported by ventilation. Each of the CO_2 traffic lights has three distinct indicators to display the CO_2 level in a convenient way. The OLED display shows the current CO_2 level and room temperature in real time. The RGB led acts as a traffic light and signals via three colors (green, orange and red), whether ventilation is required or not. The additional built-in buzzer provides an acoustic signal corresponding to the traffic light colors. A copper plate acts as an capacitive touch button and is used to mute the acoustic signal when desired. This state automatically resets to the un-muted state once the predefined threshold is undercut. In addition, the real-time data as well as the temporal trend can be tracked through a browser by means of any WLAN capable device, e.g. a tablet, laptop or smartphone, via the access point of the Raspberry Pi. The great advantage is that the ventilation of an entire building can additionally be monitored centrally and, if necessary, logged. A connection station identical in construction to the CO_2 traffic lights but with a different software setup enables the real-time data to be transmitted via LoRa and forwarded directly to the Raspberry Pi via MQTT. This Pi potentially provides real-time data to the entire home network or can be set up to provide its own access point in case of unavailable WLAN. It can be considered as an important feature that no existing WLAN is necessary. If the Raspberry Pi is used as an access point, it provides the WLAN for the connection station and any central monitoring device (computer, laptop, tablet, etc.). A schematic of the above described interconnections is shown in Fig. 1.
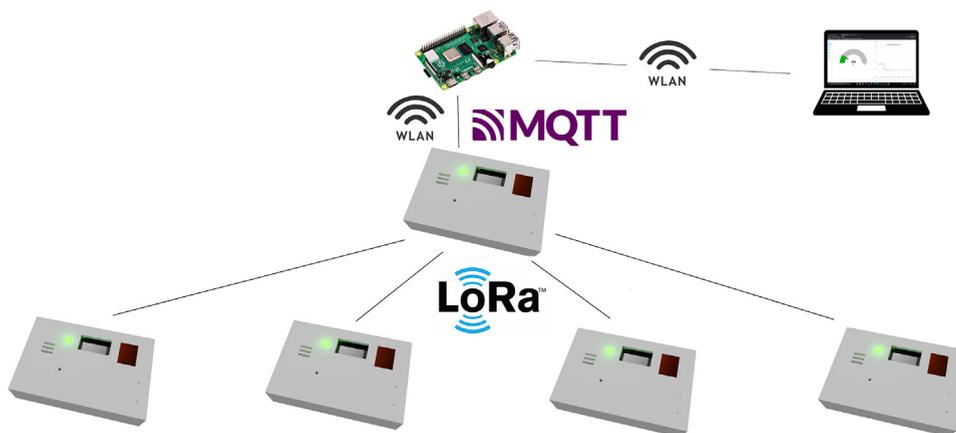
Fig. 1. Shown is the concept of the CO_2 Monitor System. Each individual transmitter node is equipped with a display, a visual and an acoustic signal. The communication with the receiver node is done via LoRa. The receiver node additionally transmits the real-time data to a Raspberry Pi using the MQTT protocol over the Pi's own access point, thus allowing integration into other systems.

The housing provided was kept simple and is equipped with corresponding mounting holes in the back for a wall-mounted installation. The housing is provided with ventilation cutouts at the position of the CO_2 sensor module (MH-Z19B) to ensure optimal functionality. The micro-USB port of the ESP32 (DevKit C V4) is easily accessible from the outside. In this way future firmware updates can be easily deployed without the need to take the whole traffic light apart. Over-the-air-updates are a possibility for future improvements. There are basically two options for the power supply. The direct use of a USB power supply or the external use of any kind of power bank.

The clear innovation of this CO_2 monitoring network compared to simple, independent CO_2 traffic lights is the use of LoRa for regular transmission of the measured values to a centrally monitored location. While simple CO_2 traffic lights only display the CO_2 concentration in real time and thus warn the user of rising CO_2 concentrations, there is no direct control according to the four-eyes principle. Although some models use MQTT via an existing WLAN, the latter is not met in many places. This applies not only to German schools but also to countries with a less developed infrastructure. Since the amount of data to be transmitted is small and the distances, for example in schools, can quickly become relatively large. The use of LoRa is an excellent solution at this point. With a range of several hundred meters, the CO_2 concentrations are transmitted at random intervals (approx. every 2.5 minutes with a random jitter of 60 seconds), as is usual with LoRa collision avoidance, which is perfectly sufficient to map the CO_2 concentration of a classroom over the course of a day.

- The presented network centrally monitors the instantaneous CO_2 concentrations of a whole building and thus, allows to indirectly infer the aerosol load and hence the viral load in the assumed presence of an infected person.
- The presented network can easily be expanded in a modular fashion across a multitude rooms.
- The distributed devices directly provide optical and visual clues to ventilate when reaching predefined thresholds.
- The presented network does not rely on an existing wireless local area network (WLAN) by using a long range communication link (LoRa).
- The distributed devices are cheap to build, easy to install and configure.

Design files

Design filename	File type	Open source license	Location of the file
'casing (front)'	.stl	Creative Commons Attribution-ShareAlike 4.0 Int. License	https://doi.org/10.17605/OSF.IO/SNHFD
'casing (back)'	.stl	Creative Commons Attribution-ShareAlike 4.0 Int. License	https://doi.org/10.17605/OSF.IO/SNHFD
'CO2-Monitor-Station'	.JSON	Creative Commons Attribution-ShareAlike 4.0 Int. License	https://doi.org/10.17605/OSF.IO/SNHFD
'CO2-Monitor_v7f'	.ino	Creative Commons Attribution-ShareAlike 4.0 Int. License	https://doi.org/10.17605/OSF.IO/SNHFD
'requirements'	.txt	Creative Commons Attribution-ShareAlike 4.0 Int. License	https://doi.org/10.17605/OSF.IO/SNHFD
'Adafruit_GFX_Library.zip'	OLED graphics library	BSD License	https://doi.org/10.17605/OSF.IO/SNHFD
'Adafruit_SSD1306.zip'	OLED library	BSD License	https://doi.org/10.17605/OSF.IO/SNHFD
'Heltec_ESP32_Dev-Boards.zip'	Heltec ESP32 library	MIT License	https://doi.org/10.17605/OSF.IO/SNHFD
'LoRa.zip'	LoRa library	MIT License	https://doi.org/10.17605/OSF.IO/SNHFD
'MH-Z19.zip'	CO2 sensor library	GNU GPL v3	https://doi.org/10.17605/OSF.IO/SNHFD
'PubSubClient.zip'	MQTT client	MIT License	https://doi.org/10.17605/OSF.IO/SNHFD

Bill of materials

Designator	Component	Number	Cost per unit - EUR	Total cost - EUR	Source of materials
casing (front)	casing front panel	1	0.68 €	0.68 €	Prusa Polymers a.s.
casing (back)	casing back panel	1	0.78 €	0.78 €	Prusa Polymers a.s.
CO_2 sensor	MH-Z19B infrared-CO2-sensor	1	18.09 €	18.09 €	Alibaba Group Holding Ltd
ESP32	ESP32 NodeMCU DevKit C V4	1	9.49 €	9.49 €	AZ-Delivery Vertriebs GmbH
OLED display	SSD1306 0,96 Zoll OLED Display	1	6.99 €	6.99 €	AZ-Delivery Vertriebs GmbH
LoRa module	RFM9X LoRa Packet Radio	1	19.59 €	19.59 €	Adafruit Industries
PI B+	Raspberry PI B+	1	30.20 €	30.20 €	reichelt elektronik GmbH & Co. KG
RGB led	KY-016 LED RGB Modul	1	4.29 €	4.29 €	AZ-Delivery Vertriebs GmbH
Buzzer	TMB12A05 Buzzer	1	0.64 €	0.64 €	Conrad Electronic SE
Jumper Wire	Jumper Wire Set	1	5.99 €	5.99 €	reichelt elektronik GmbH & Co. KG
R1 820 Ω	Resistor 820 Ω	1	0.06 €	0.06 €	Conrad Electronic SE
R2 1 kΩ	Resistor 1 kΩ	1	0.12 €	0.12 €	Conrad Electronic SE
Transistor	PNP Transistor BC557C	1	0.19 €	0.19 €	Conrad Electronic SE
DOT PCB	DOT PCB 100 mm x 65 mm	1	2.00 €	2.00 €	Conrad Electronic SE
Touch plate	Copper plate 15 mm x 20 mm	1	0.09 €	0.092 + 0,09 €	Conrad Electronic SE

Build instructions

This chapter is subdivided into three sections, each providing information and focusing on a different aspect of the CO_2 monitoring network. First, a brief setup of the Raspberry Pi, second assembling a single CO_2 traffic light by means of its electrical wiring and third uploading and configuring necessary firmware to said traffic light.

A rudimentary understanding of working with the ESP32, Raspberry Pi and Node-RED is presumed in the following. Extensive tutorials and instructions on the corresponding topics are available online within the DIY and Maker community [23–25] (see Fig. 2).

Setting up the Raspberry Pi

This section briefly covers the requirements when setting up the Raspberry Pi with Mosquitto broker and Node-RED. The emphasis is on the final Node-RED 'flow' for monitoring the individual rooms.

(a) Set up the Raspberry Pi with an operating system of your choice. The Raspberry Pi OS (*Raspbian*) is perfectly adequate. For this purpose, *balenaEtcher* or the *Win32 Disk Imager* can be used to flash the corresponding image onto an SD card. Recommendations regarding brand, capacity, and speed can be found on the Raspberry Pi foundations homepage (raspberrypi.org) [23].

(b) If no monitor or keyboard is available Secure Shell (*SSH*) can be used for the setup. Make sure to create an empty file within the boot section of your SD card and name it 'SSH' with no extension.

(c) Connect your Raspberry Pi via Ethernet to your computer or laptop. To establish a connection PuTTY (Windows) or the build-in Terminal application (Mac OS) can be used.

(d) Install the Eclipse Mosquitto Broker (randomnerdtutorials.com) and Node-RED (nodered.org) on the Raspberry Pi. Make sure to enable the Node-RED service and configure autostart on boot. The default port is 1880 [24,25].

(e) When configuring the Raspberry Pi as a WLAN access point make sure to write down the **ssid** and **password** along with the **IP-address** for the following setup of the individual CO_2 traffic lights.

(f) To load and edit the provided Node-RED flow use any browser from your computer or laptop. The editor is available from 'http://**IP-address**:1880'.

(g) The provided Node-RED flow **CO2-Monitor-Station.json** is designed to be loaded into the editor once for each CO_2 traffic light used. Afterwards the unique hexadecimal identifier needs to be configured accordingly to the ones used with each CO_2 traffic light.

(h) Tip: The unique number used to identify each CO_2 traffic light is displayed as a decimal number each time you start or touch the copper, touch-sensitive switch. Ascending numbering is recommended, the use of unique numbers is mandatory.

(i) After configuring the identifiers, the corresponding sources must be assigned to the display elements in the UI menu. After this minimal setup, the CO_2 concentrations of different rooms can be monitored through any device with a browser which is connected to the access point.

Assembling the CO_2 Monitor

In this section we focus on wiring and assembly of the CO2 traffic light. We provide some additional tips on the recommended 3D-printing and address aspects of planning.

(a) Print the.stl files 'casing (front)' and 'casing (back)' using a FDM 3D-printer of your choice with 20% infill and 0.2 mm layer resolution. We recommend the use of PLA filament for ease of printing and good mechanical stability. Whilst printing the wiring can already be carried out.

(b) The complete wiring diagram used is shown in Fig. 3 and will be broken down in separate steps below. The necessary layout for the components on the DOT PCB is shown in Fig. 4. If no dimension is provided the exact position does not have to be followed.

(c) It is recommended to follow the layout to ensure that all cutouts of the housing are in the correct position. This ensures optimal visibility of the display and undisturbed ventilation of the CO_2 sensor.

(d) Crucial components for the casing to fit are the 'CO2 Sensor' (MH-Z19B),'RGB led' (KY-016), the 'OLED display' (SSD1306) and the 'Buzzer' (TMB12A05). Once the DOT PCB is completely wired it is intended to be press-fitted into the casing.

(e) To connect the 'CO2 Sensor' (MH-Z19B) wire GPIO32 with **RX** and GPIO33 with **TX** as shown in Fig. 5. For the power supply, wire the 5 V to **VIN** and GND to **GND** or a common ground.

(f) To connect the 'OLED display' (SSD1306) wire GPIO21 with **SDA** and GPIO22 with **SCL** as shown in Fig. 6. For the power supply, wire the 3V3 to **VCC** and GND to **GND** or a common ground.
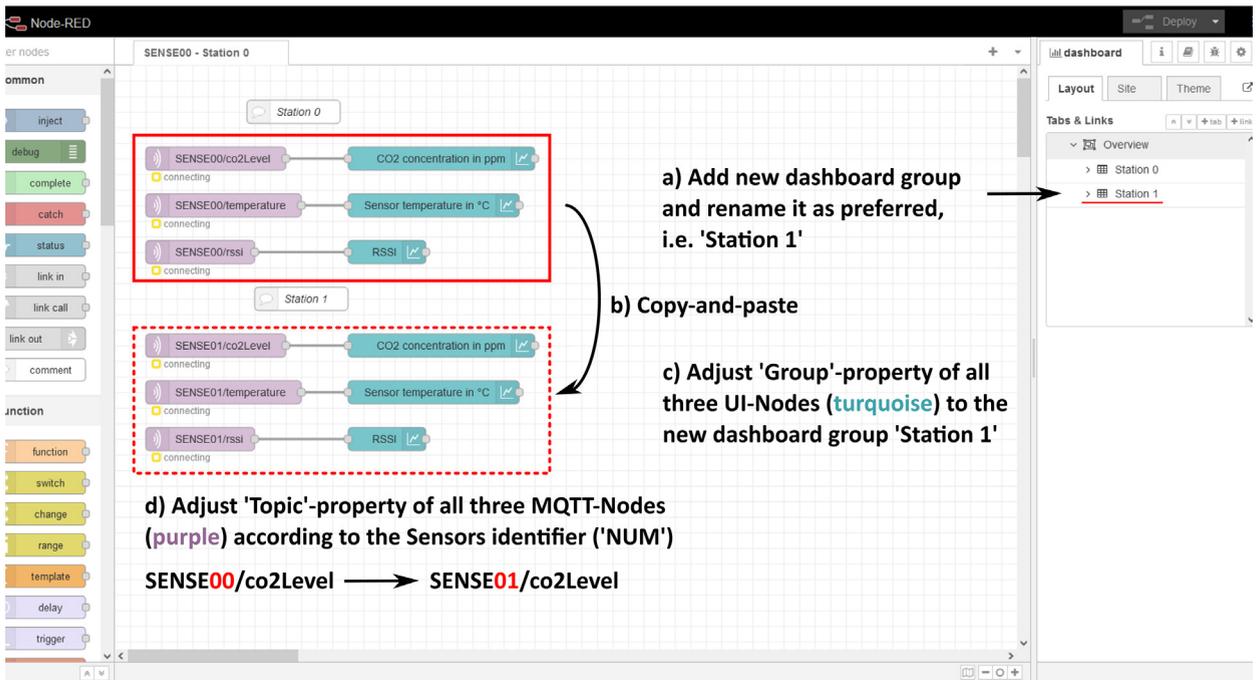
Fig. 2. 4-step instruction on how to duplicate the provided Node-RED flow **CO2-Monitor-Station.json** to accommodate the user interface to the required amount of CO_2 traffic lights.
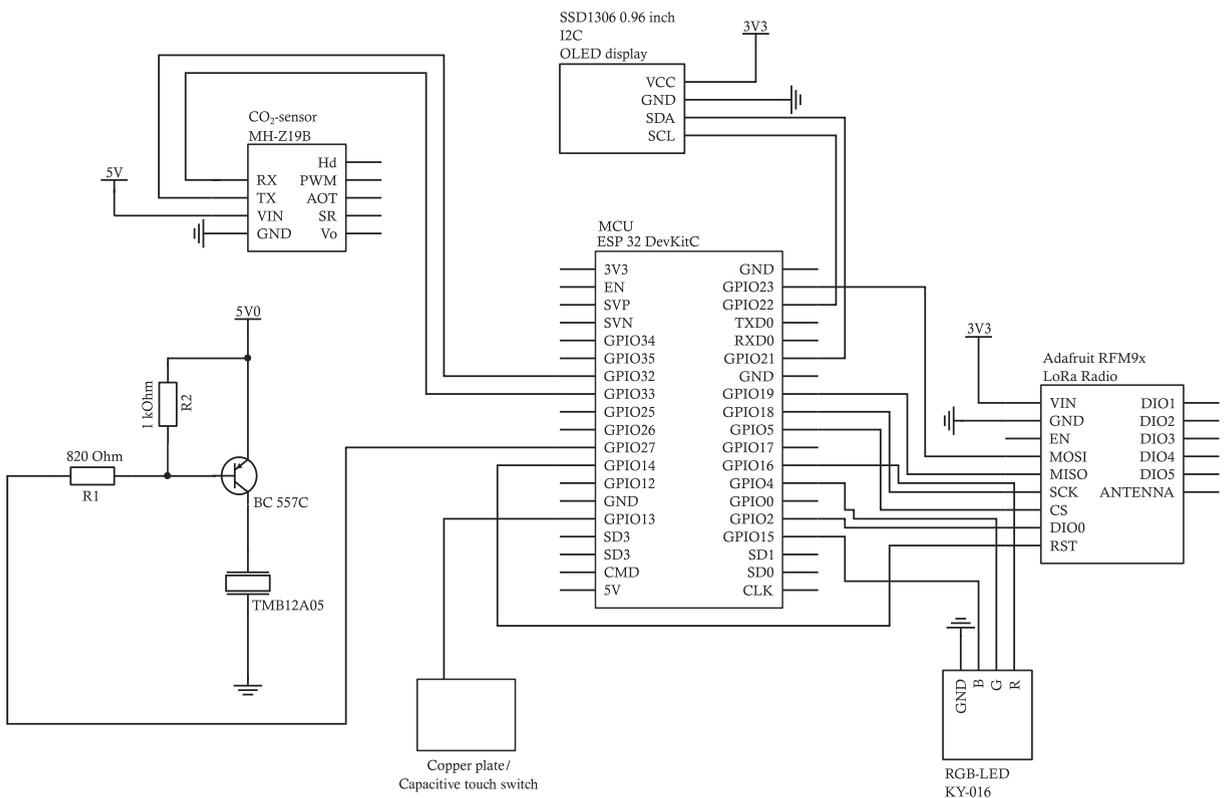
Fig. 3. Wiring diagram of the CO_2 monitor.
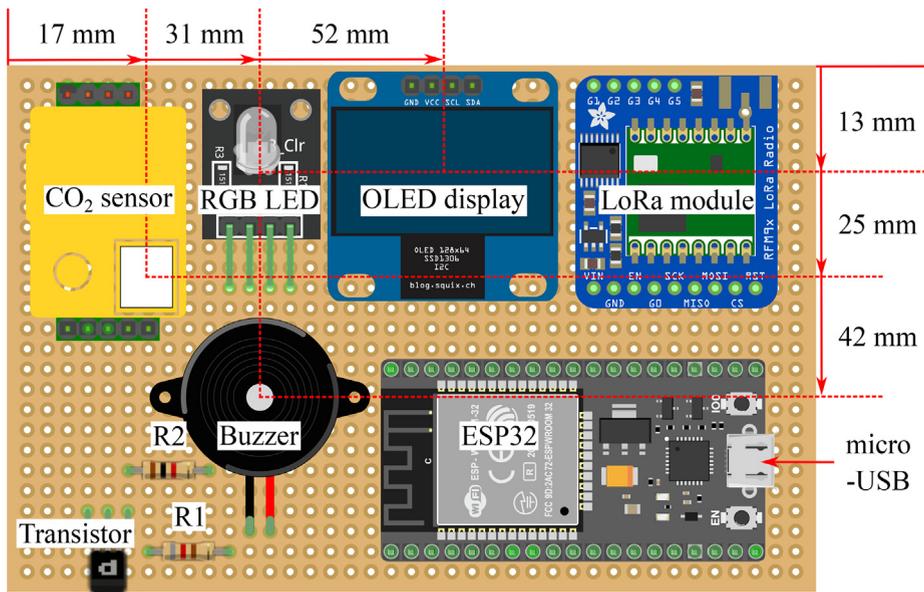
Fig. 4. Crucial dimensions when wiring the components onto the DOT PCB. The dimensions of the shown PCB are 100 mm × 65 mm (h × w).
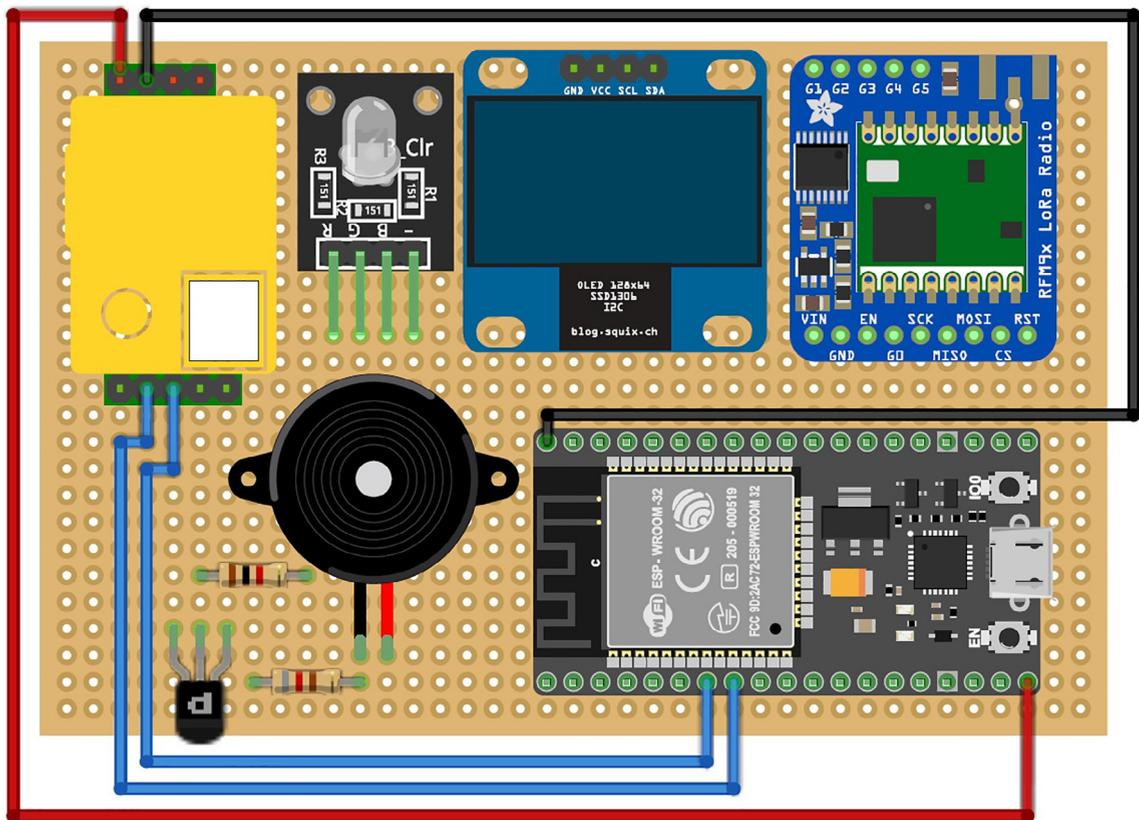
Fig. 5. Step-by-step wiring: connecting the CO_2 sensor.

(g) To connect the 'LoRa module' (RFM9X) wire GPIO2 with **DIO0**, GPIO5 with **CS**, GPIO14 with **RST**, GPIO18 with **SCK**, GPIO19 with **MISO** and GPIO23 with **MOSI** as shown in Fig. 7. For the power supply, wire the 3V3 to **VIN** and GND to **GND** or a common ground.
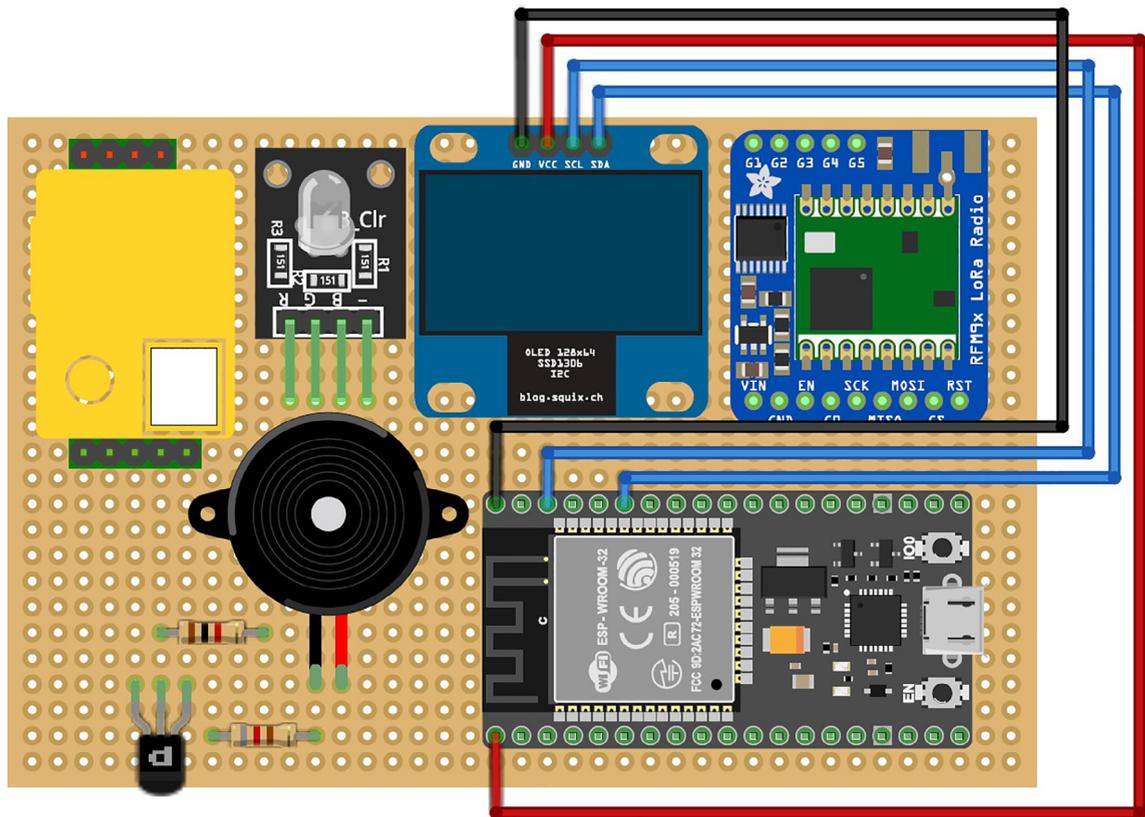
Fig. 6. Step-by-step wiring: connecting the OLED display.

(h) To connect the 'RGB led' (KY-016) wire GPIO4 with **G**, GPIO15 with **B**, GPIO15 with **R** and GND to **GND** or a common ground as shown in Fig. 8.

(i) To connect the 'Buzzer' (TMB12A05) wire GPIO27 with **R1**. Connect **R1** directly to **R2** and the **base** of the transistor. Wire the other end of **R2** and the **emitter** to 3V3. Finally connect the **collector** with the 'Buzzer' and itself to **GND**.

(j) To connect the 'Touch plate' wire GPIO13 directly to the copper plate after the cable has passed through the 'casing (front)'. To join the housing together afterwards, a cable length of 10 cm is recommended.

(k) The copperplate which functions as a capacitive touch switch is intended to be glued down by some adhesive into the according slot of the 'casing (front)'.

(l) Once every component is correctly wired press the assembled DOT PCB (Fig. 9a)) with a small amount of force into the 'casing (back)' (Fig. 9b)). The dimensions are designed to be press-fitted. In the case of too wide tolerances, i.e. the DOT PCB has slack inside the housing, apply some hot-glue to keep the DOT PCB in place within 'casing (back)'.

(m) To assemble the whole CO_2 traffic light, press the 'casing (front)' (Fig. 9c)) directly onto the prior assembled 'casing (back)'. The dimensions of both parts are designed to be press-fitted. Should the two casing parts exhibit too wide tolerances, one can easily apply some electricians tape to fill the gap and thus insure a removable press-fit. The utilization of super-glue is fine (avoid contaminating display or sensor), however, disassembly of a glued casing is most likely destructive and will require printing a new casing. The final assembly is shown in Fig. 9d).

Uploading the firmware to the ESP32

This section covers the upload of the firmware to the ESP32 and the required settings in the software file **CO2-Monitor_v7f.ino**. A basic distinction is made between the regular CO_2 traffic light and the connection station, a software modification of the CO_2 traffic light, which additionally transmits the data collected from every other traffic light via LoRa to the Raspberry Pi via MQTT.

(a) The software designated for the ESP32 is the **CO2-Monitor_v7f.ino**. To upload this software the integrated development environment of Arduino is used (Arduino IDE).
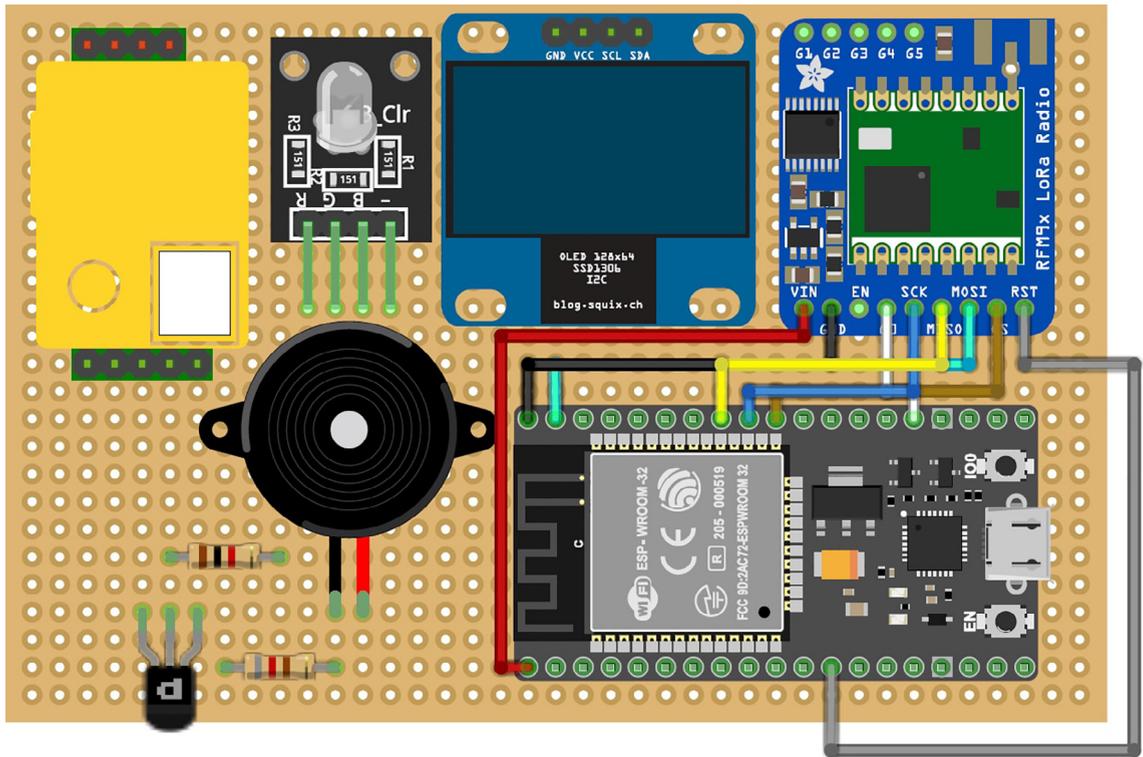
Fig. 7. Step-by-step wiring: Connecting the LoRa modul.
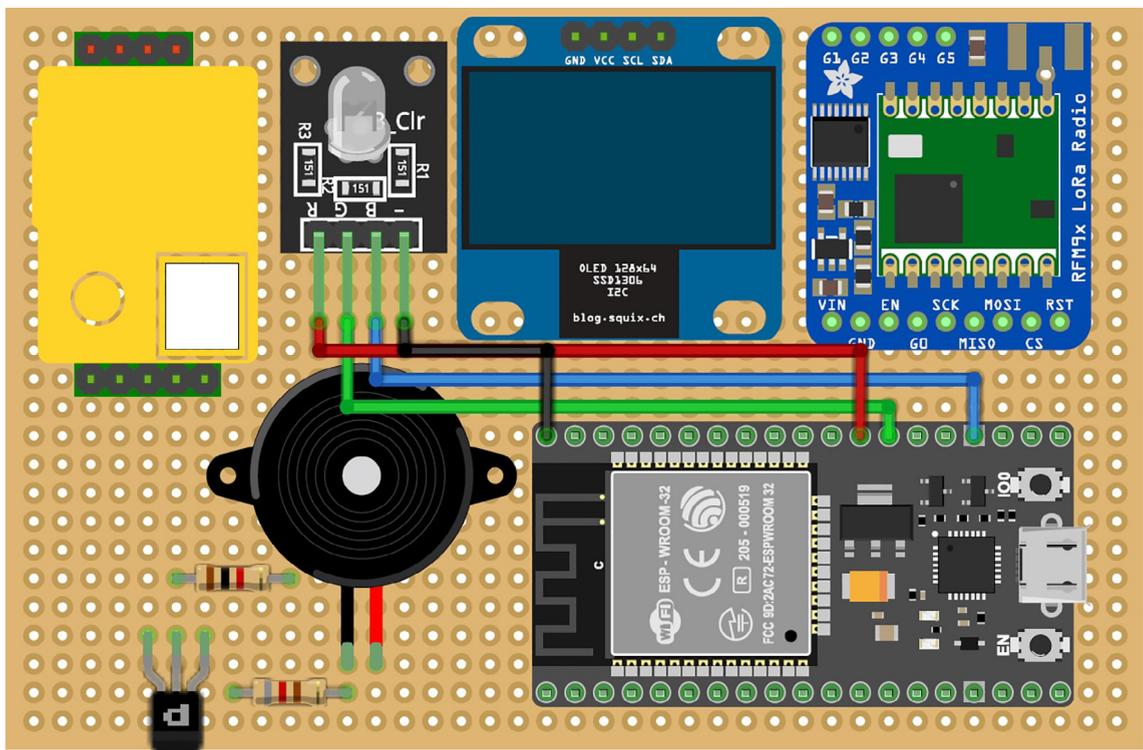
Fig. 8. Step-by-step wiring: connecting the RGB LED.
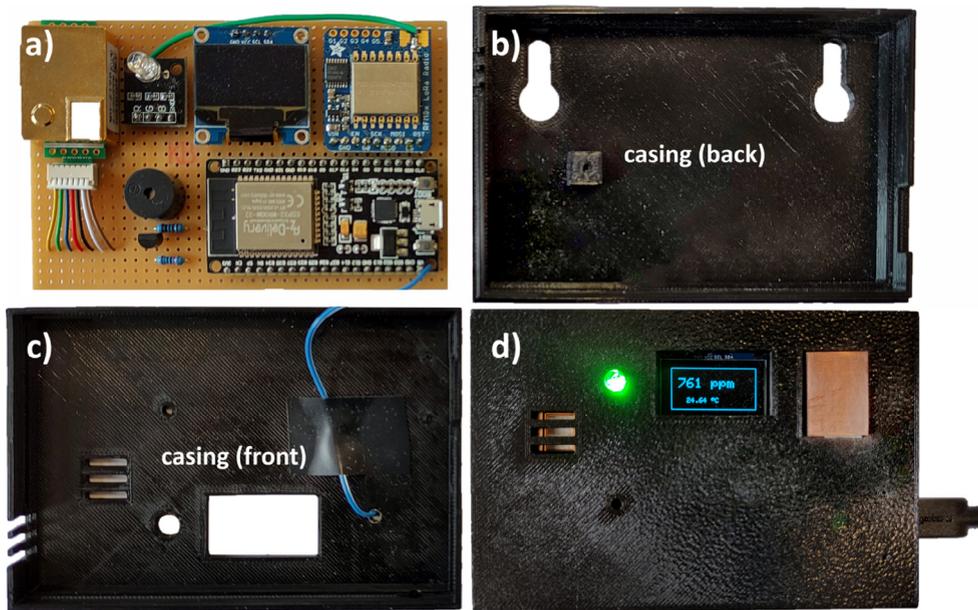
Fig. 9. Photograph of a) the assembled DOT PCB, b) the empty 'casing (back)', c) the 'casing (front)' with the 'Touch plate' wire visible and d) the completely assembled CO_2 traffic light.

(b) The first step is to add the ESP32 as a board. In your Arduino IDE, navigate to **File → Preferences** and add **https://dl.espressif.com/dl/package_esp32_index.json** into the 'Additional Board Manager URLs' field.

(c) The **requirements.txt** file contains an overview of the required libraries, which can be downloaded either directly from the repository or from the Arduino IDE package manager.

(d) Immediately before uploading the software to the ESP32, the correct board (ESP32 Dev Module) must be selected under **Tools** and configured if necessary.

(e) The following constants and variables must be set before the upload according to the desired configuration.
- **NUM** is a unique hexadecimal number between 0 and 255 (0x00 to 0xFF) which must be different for each CO_2 traffic light.
- **SETUP_STARTUP_TIME** is 3 min if a CO_2 sensor is installed.
- **SENSOR_MODULE** is true (CO_2 traffic light) or false (only connection station without CO_2 sensor)
- **MQTT_MODULE** is false (CO_2 traffic light) or true (connection station)
- **PERIPHERY_MODULE** is true (CO_2 traffic light) or false (without the OLED display etc.)
- int **stage1** = 800; lower CO_2 threshold in ppm
  int **stage2** = 1000; upper CO_2 threshold in ppm
- const char* **ssid** = "*RaspiAP*"; your ssid of the Raspberry Pi AP
- const char* **password** = "*12345678*"; your password of the Raspberry Pi AP, change at your earliest convenience, but do note it somewhere
- const char* **mqtt_server** = "*192.168.178.11*"; your IP of the Node-RED server change to your liking

(f) After all constants and variables have been set to the desired value, the **CO2-Monitor_v7f.ino** file can be uploaded to the ESP32.

Design decisions and possible alternatives

The choice of the MH-Z19B CO_2 sensor is due to its good availability at the time of writing. In addition to a sufficient measuring range from 0 ppm to 5000 ppm, this particular sensor has a self-calibration function. It should be noted that there are also cheaper air quality sensors, but these are usually not CO_2 specific, resulting in potentially faulty readings due to cross-sensitivity to other gases. Another positive point is the easy integration with the Arduino. Possible alternatives are the somewhat more expensive SCD30 CO_2 sensor from *Sensirion* or the direct successor model, the MH-Z19C.

The used ESP32 NodeMCU DevKit C V4 was chosen especially because of its programmability in Arduino and its integrated WLAN and Bluetooth functions. Compared to its direct predecessor, the ESP8266, the ESP32 has a 240 MHz dual core

processor and a 4 Mbyte flash memory, making it the modern and more powerful choice. This together results in a large and helpful online community, making development very beginner-friendly. Again, it should be noted that the specific choice of this ESP32 module is related to availability at the time of writing. Alternatively, any other available ESP32 module can be used. Only the software has to be adapted accordingly and sometimes not even that, if a pin-compatible replacement has been chosen.

The RFM9X LoRa Packet Radio, along with the CO_2 sensor used, is at the heart of the hardware presented here. By additionally using a Raspberry PI as WLAN access point and MQTT broker, the RFM9X module allows to monitor entire building complexes and facilities centrally via LoRa at 868 MHz. The obvious advantage is the low cost (approx. 90 €) of the individual CO_2 traffic lights without requiring an already existing or area-wide WLAN. In order to remain compliant with the legal framework regarding the bandwidth used and to avoid possible transmission collisions, the measured values are transmitted approx. every 2.5 minutes with a random jitter of 60 seconds.

Operation instructions

The following instructions deal with the operation of the distributed CO_2 monitoring network. They cover the operation of the individual CO_2 traffic lights as well as the entire network. The installation as described in chapter 5 is mandatory and presumed.

CO_2 traffic light operation instructions

- Place or mount the CO_2 traffic light in a location of your choice using the integrated keyhole mounting. Keep in mind that the positioning has an influence on the measured CO_2 concentration and it is therefore recommended to mount the CO_2 traffic light at chest/head height.
- Connect the CO_2 traffic light using a micro USB cable and an appropriate USB power adapter (5 V, 1 A) with the power outlet. Alternatively, a power bank can be employed for mobile use. The consumption of the CO_2 traffic light is about 550 mW.
- Immediately after start-up, the CO_2 traffic light displays its previously set unique number **NUM** as 'Sense **NUM**' followed by the message 'Sensor Warm-Up'.
- The warm-up time of the sensor is 3 min according to the manufacturer's specifications and can be edited in the code. After this time, the CO_2 traffic light is ready for use and displays the CO_2 content in ppm and the room temperature in °C.
- The RGB LED indicates an exceeding of the previously set thresholds by a change in color from green (everything is alright) to orange (it should be ventilated soon) and finally to red (ventilation is now required). At the same time the respective thresholds are linked to an acoustic warning signal.
- To mute the acoustic warning signal of the CO_2 traffic light, touch the copper, touch-sensitive switch. The muting of acoustic warning signals is toggled back to active by the CO_2 reading falling below the predetermined threshold.
- Transmission of the current CO_2 concentration via LoRa to the connection station is done automatically and does not require any further steps besides the correct configuration of the CO_2 traffic light.

Centralized monitoring network operation instructions

- In order to use the LoRa based CO_2 monitoring system, one of the CO_2 traffic lights must be set up as a connection station as described in chapter 5. The basic concept is to use exactly one connection station in combination with a Raspberry Pi based access point and any number of additional ordinary CO_2 traffic lights.
- The connection station must first be installed in the WLAN range of the Raspberry Pi access point used. The CO_2 traffic lights connected via LoRa have a range of several hundred meters due to the use of typical radio frequencies. The absolute range depends primarily on the combination of distance and obstacles (walls/buildings) and cannot be generalized.
- To use the monitoring capabilities an additional device like a tablet or laptop is advised. With said device connect via WLAN to the access point of the Raspberry Pi and navigate to the browser-based Node-RED UI ('http://**IP-address**:1880/ui').
- A brief explanation on the setup is provided within Section 5.1. The above used **IP-address** is the one of the Raspberry Pi running the Node-RED service.
- From the browser-based Node-RED UI the real-time CO_2 concentration, room temperature and received signal strength indicator (RSSI) can be monitored as shown in Fig. 10. The data gets updated approximately every 2.5 min.
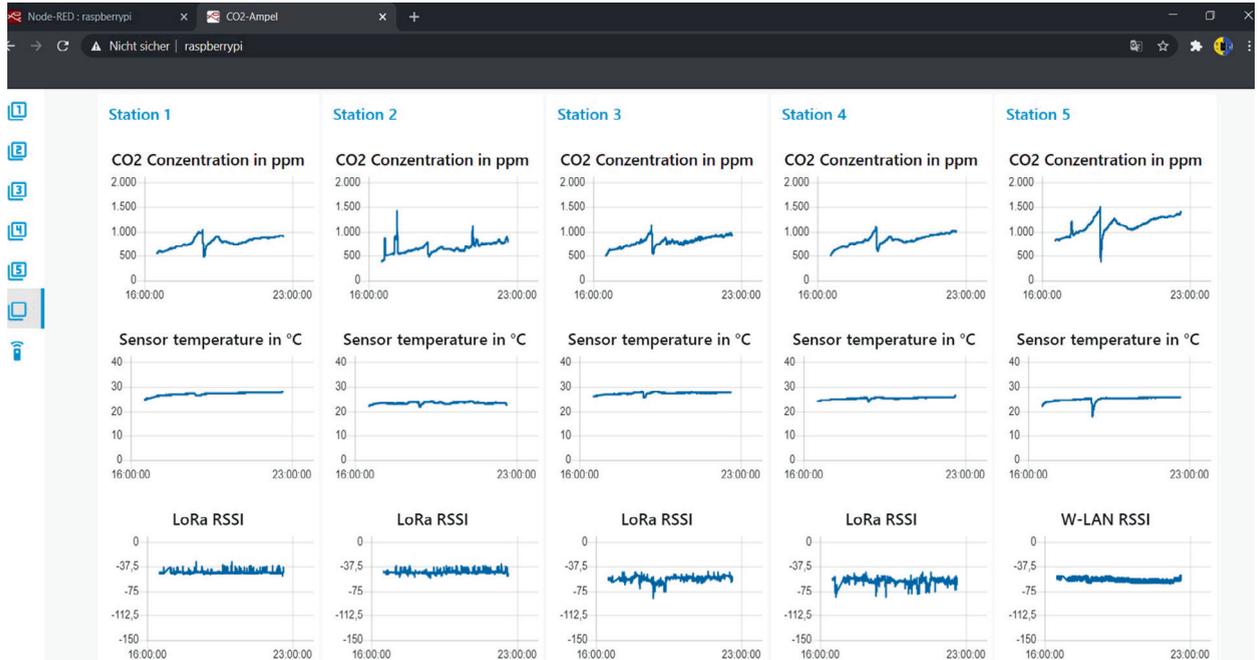
Fig. 10. The presented CO_2 monitor allows simultaneous monitoring of several rooms at the same time as shown in the screenshot above. Here the CO_2 concentration, the room temperature and the received signal strength indicator of the LoRa modul are displayed i.e. for system debugging during installation.

Validation and characterization

In this chapter, two types of measurements are presented to validate the individual CO_2 traffic light and the entire monitoring network from a practical point of view. In order to reliably comply with the set concentration thresholds, one traffic light was examined with regard to its CO_2 concentration measurement capability. Furthermore, the validation of the hardware regarding its everyday use takes place in a volunteering school.

CO_2 concentration measurement validation

For validation of the CO_2 concentration measurements, four predefined gas mixtures (1000 ppm, 2000 ppm, 3000 ppm and 4000 ppm) were prepared and used to measure different concentration levels by means of an exemplary CO_2 traffic light. The measurements were carried out with the kind support of 'ecom GmbH'.

The process of producing the gas mixtures is described in the following paragraph. For mixing, a bottle of 20 % CO_2 ('Westfalen AG', type: carbon dioxide 3.0) and a bottle of pure N_2 ('Westfalen AG', type: nitrogen 5.0) are used. Each one of the bottles is connected to a separate gas flow controller (CO_2, 'Vögtlin Instruments GmbH', type: GSC-B9TS-DD23 calibrated to 2 bar; N_2, 'Vögtlin Instruments GmbH', type: GSC-B4TS-DD23 calibrated to 3 bar) and the corresponding normal flow rates (CO_2, 2.0 l/min; N_2, 0.4 l/min) are set. A commercial gas bag ('Westfalen AG', type: Alumini 1 (15 l)) is used as a vessel for mixing, which is completely evacuated before the mixing process. Then, using a stopwatch and the gas meter, the two gases are filled one after the other into the gas sack by means of a hose with a quick-release coupling (PFA 4 × 6 mm, various Rectus products with material 1.4305). When the previously calculated duration is reached and the gas meter indicates the required amount, the quick-release coupling is disconnected. The gas volumes used are shown in Table 1. The calculated concentration is shown in the column 'reference CO_2 conc. (ppm)'.

For the validation process, the warm-up phase of the CO_2 traffic light takes place directly at the open window. Afterwards, the CO_2 traffic light is placed in an airtight lockable box (approx. volume: 2l) with a fixed inlet and outlet (6 mm holes). To power the hardware a power bank is used. The previously filled gas bag is weighted with a simple 1 kg weight to create a constant pressure. The gas bag is then connected to the box with the CO_2 traffic light by means of a hose with a quick-release coupling. To maintain a constant gas flow, the weight must be repositioned approximately every 5 min. This ensures that the box is continuously purged with the previously prepared gas mixture. After approximately 25 min, the final static value is read from the CO_2 traffic light. The results of the validation measurement are shown in Fig. 11.

Table 1
Experimental CO_2 validation.

Gas products	volume (l)	reference CO_2 conc. (ppm)	measured CO_2 conc. (ppm)
CO_2 20.1%	0.05	1000 ± 134	878 ± 93
N_2 99.999 %	9.95		
CO_2 20.1%	0.10	2000 ± 138	2126 ± 156
N_2 99.999 %	9.90		
CO_2 20.1%	0.15	3000 ± 140	2864 ± 193
N_2 99.999 %	9.85		
CO_2 20.1%	0.20	4000 ± 142	3873 ± 244
N_2 99.999 %	9.80		
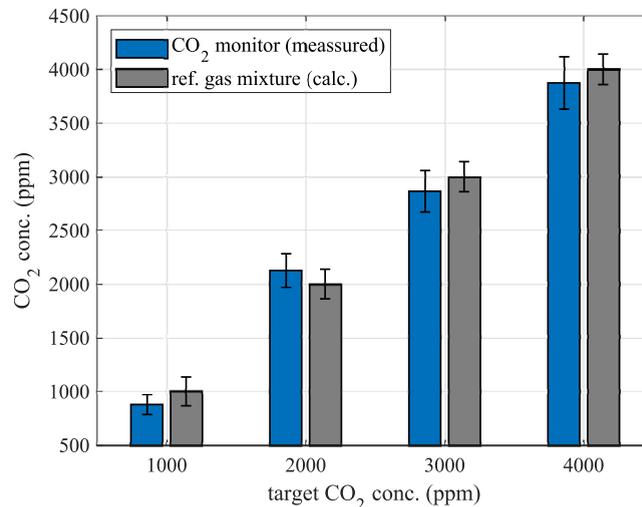
Fig. 11. Validation of the CO_2 concentration measurement capability of the presented hardware. A total of four predefined gas mixtures were prepared. The measured static concentrations (blue) were taken after the sensor had been flushed for approx. 25 min. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Within the limits of their errors, the measurements show an excellent agreement between the CO_2 concentration measured by the CO_2 traffic light (MH-Z19B) and the beforehand prepared CO_2 concentration of the gas mixture. We conclude that the CO_2 traffic light is suitable to provide accurate CO_2-measurements and thus valuable information of the viral load within its error margin. In addition, the predefined threshold of 800 ppm is a useful first indicator of when ventilation is recommended. According to the manufacturer's data sheet, the measurement error at a read concentration of 1000 ppm is ± 100 ppm. Accordingly, the upper threshold of 1000 ppm is undercut with a high probability assuring maximal safety.

School measurement validation

For the validation of the CO_2 monitoring network from a practical point of view (central monitoring, LoRa functionality and deployment under real conditions), the system presented in this paper was deployed in the 'Evangelisches Gymnasium Nordhorn' and subjected to a field test. For this purpose, the system was used in a total of two classrooms as shown in Fig. 12 in addition to the locally applicable regulations for ventilation. The classrooms were ventilated approximately every 20 min for a period of 5 min (according to the specifications of the head of school), irrespective of the actual CO_2 concentration. If the previously set threshold of 800 ppm is exceeded, additional ventilation takes place. Fig. 13 shows the measured course of CO_2 concentration over a total of six school hours from 07:45 a.m. till 12:15 a.m. with two 20 min breaks.

The gathered data was sent via LoRa from the classroom to the connection station approximately every 2.5 minutes (including a random delay for collision avoidance) and stored via Node-RED. The course of the data suggests that the selected sampling rate is sufficient to represent the rather slow variation in CO_2 concentration with sufficient detail.

It can be clearly seen that after a short time delay after opening the windows for ventilation, the CO_2 concentration decreases. This delay is most likely due to the initial mixing of the stale and fresh air, so that the CO_2 concentration does not drop instantaneously when opening the windows. Besides prolonged ventilation periods like from 11:15 a.m. till 12:00 a.m. due to high temperatures above 31.0 °C a direct decrease in concentration is achievable when necessary. It should be emphasized at this point that at two points in time, despite the ventilation regulations already in place, the threshold of 1000 ppm was exceeded, which underlines the usefulness of the presented CO_2 monitoring network.
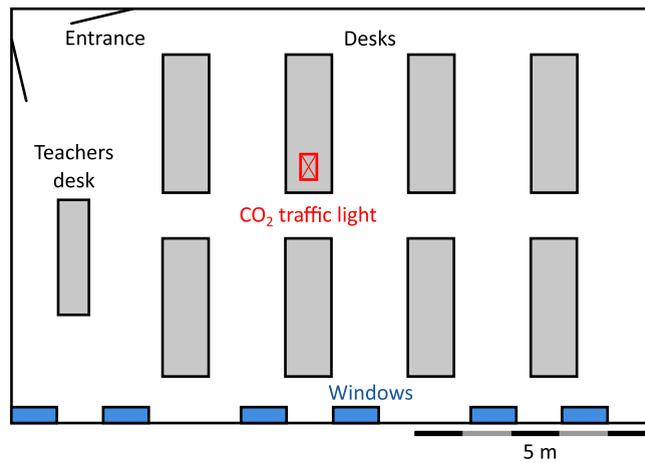
Fig. 12. Validation of the CO_2 monitoring network through a field test in a school. Shown is a sketch of the classroom's layout and the relative position between CO_2 traffic light in red and windows in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
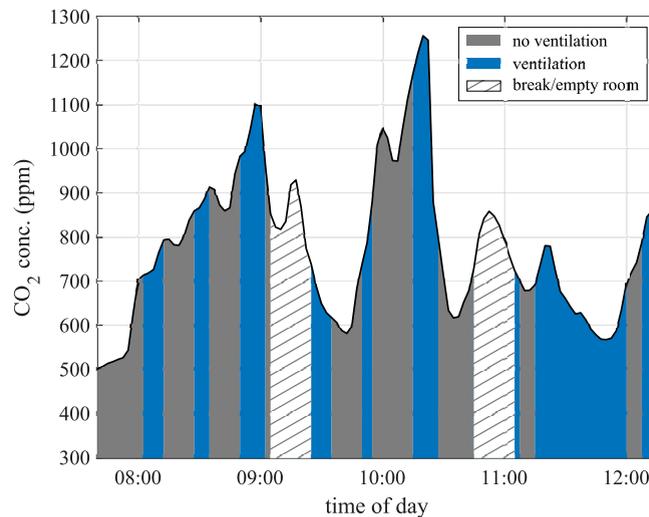
Fig. 13. Validation of the CO_2 monitoring network through a field test in a school. Shown is the measured course of CO_2 concentration over 6 school hours (07:45–12:15). A gray shading corresponds to no ventilation, during a blue one there is ventilation and in the dashed areas the classroom was empty. A ventilation-dependent decrease in CO_2 concentration with an expected delay after opening the windows can be clearly seen. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

LoRa range validation

To validate the CO_2 monitoring network's LoRa range, the system presented in this paper was tested thoroughly at the 'Evangelisches Gymnasium Nordhorn'. In particular, the potential range of this system was analyzed in two scenarios, one indoors and one outdoors. It is important to emphasize that accurate validation of LoRa range depends on a variety of different parameters, such as distance, shielding by walls and ceilings or background noise. Since these parameters can only be controlled to a limited extent, the validation performed serves more as a proof of concept instead of an exact measurement of the achievable range.

For the indoor validation the CO_2 traffic light used as receiver (connection station) was placed at a fixed position inside the school's building while the transmitting CO_2 traffic light was moved to ten different rooms and locations for validation of the received signal strength indicator (RSSI). Fig. 14 shows a sketched layout of the school building. The red dot represents the position of the fixed receiver (connection station). The blue dots numbered from 0 to 9 show the relative positions of the transmitter. Differences in height are omitted for sake of simplicity. The measured RSSI, including a short description of involved obstructions and an estimate of the distance are shown in Table 2. The data obtained clearly indicates a sufficient signal strength for an obstruction of up to five walls (#5) at a distance of approx. 43 m. Only through eight walls (#6) at a
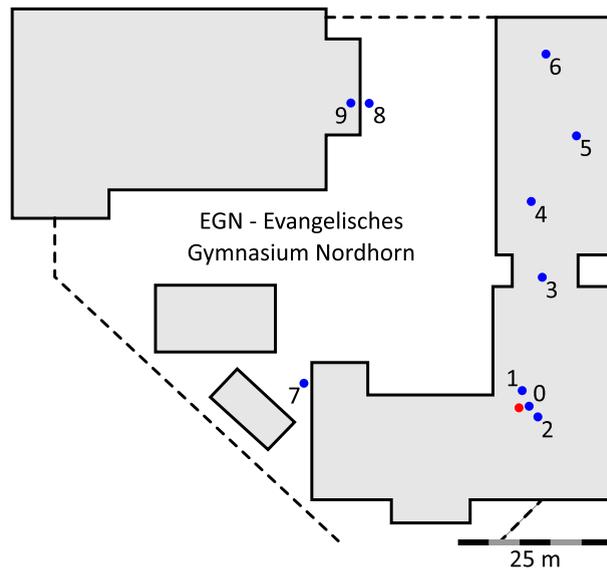
Fig. 14. Validation of the CO_2 monitoring network's LoRa capabilities according to Table 2 using a sketched layout of the school building. The red dot represents the position of the fixed receiver (connection station). The numbered blue dots show the relative positions of the transmitter (CO_2 traffic light). Distances used are estimated and differences in height are not shown in this sketch. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Indoor LoRa distance validation.

Number	Obstruction	Distance (m)	RSSI (dB)
0	no wall	0.2	−16
1	one wall	3	−68
2	one ceiling	3	−68
3	three walls	21	−75
4	four walls	32	−106
5	five walls	43	−107
6	eight walls	57	no signal
7	one ceiling + two walls	33	−108
8	one wall	54	−104
9	one wall + glass pane	54	−105

Table 3
Outdoor LoRa distance validation.

Distance (m)	100	200	300	400	500	600	700	800	900	1000
RSSI (dB)	−88	−90	−97	−102	−104	−107	−108	−108	−108	−109

distance of approx. 57 m no signal was received, which does not represent the most realistic use case since the CO_2 traffic light used as receiver would be planted in a more central position.

Furthermore, Table 3 shows the measured RSSI in an outdoor scenario from 100 m to 1000 m with an unobstructed view realized on a field trail. This data also indicates a sufficient signal strength even at the maximal distance of 1000 m. Any further distances were neglected due to the unrealistic use case. Both measurements combined conclude, that the number of obstructions play by far a more crucial role as the absolute distance and the use of one CO_2 traffic light configured as connection station is sufficient in most cases.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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