CO2 Meter: A do-it-yourself carbon dioxide measuring device for the classroom

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ABSTRACT

In this paper we report on CO2 Meter, a do-it-yourself carbon dioxide measuring device for the classroom. Part of the current measures for dealing with the SARS-CoV-2 pandemic is proper ventilation in indoor settings. This is especially important in schools with students coming back to the classroom even with high incidents rates. Static ventilation patterns do not consider the individual situation for a particular class. Influencing factors like the type of activity, the physical structure or the room occupancy are not incorporated. Also, existing devices are rather expensive and often provide only limited information and only locally without any networking. This leaves the potential of analysing the situation across different settings untapped. Carbon dioxide level can be used as an indicator of air quality, in general, and of aerosol load in particular. Since, according to the latest findings, SARS-CoV-2 can be transmitted primarily in the form of aerosols, carbon dioxide may be used as a proxy for the risk of a virus infection. Hence, schools could improve the indoor air quality and potentially reduce the infection risk if they actually had measuring devices available in the classroom. Our device supports schools in ventilation and it allows for collecting data over the Internet to enable a detailed data analysis and model generation. First deployments in schools at different levels were received very positively. A pilot installation with a larger data collection and analysis is underway.

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CCS CONCEPTS

• **Information systems → Information systems applications**; **Sensor networks**; • **Computer systems organization → Sensor networks**; **Firmware**; • **Hardware →** *Sensor applications and deployments*; *Sensor devices and platforms*; *Wireless devices.*

KEYWORDS

embedded hardware, sensor networks, information systems, education, do-it-yourself

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1 INTRODUCTION

Even after more than a year into the Corona pandemic, large parts of the world are struggling between lockdown and recurring infection waves. One of the most important rules to avoid a Corona infection these days is to keep social distancing and, where this is not possible to wear medical face masks. So, many states in Europe and the rest of the world are trying to stop the spread of the disease by more or less hard lockdown measures, by avoiding contacts and by working from home. While many efforts are being made to control the spread of infections, new and even more infectious viral mutations threaten to undo these efforts.

A group that is particularly suffering from the pandemic situation are pupils who have to undergo distance learning [12]. This often causes difficult situations for the learners and their families [17]. It is common sense that the social, but also skill-wise impacts of learning without social contacts is not unproblematic for the development of the learners. Therefore, distance learning is not an approach for longer terms, for example, since it changes social practices [16] and because it pronounces social inequalities [4]. The personal contact between teachers and pupils must somehow be achieved, following highest possible safety measures. Counter measures despite the ongoing infections need to be taken, such as ventilation plans and intensive Corona testing for pupils and teachers. This is the reason why in many states, schools open up again despite still too high infection rates throughout the respective country.

We have also learnt that staying in small rooms with other human beings increases the risk of infections as transmissions take place via aerosols emitted from human breathing. Therefore, one measure particularly in schools is to ventilate the classroom well. Before the winter break this meant that many pupils had to sit in class with their jackets and wool hats on while the window was open all the time with temperatures outside being around freezing point. There are some air cleaners available that kill the aerosols and clean the air. However, these devices are expensive and they are therefore deployed very scarcely and their use is refused for other reasons such as noise as well. Instead, the dominant approach taken is to open the classroom windows often and long enough to reduce the amount of aerosol in the air.

In this paper, we report on our project to equip schools with very accurate but low-cost CO_2 measuring devices to support schools in controlling the air quality in the classroom. While many projects similar to ours even with nearly the same hardware setup exist in the Arduino and makerspace forums throughout the world, we are particularly interested in tracking the CO_2 emission data from classrooms over longer times and correlate them with infection rates in the class.

Our approach to the hardware design is not unique, there are many similar approaches around in the web and also a number of different DIY solutions exists. Some examples in the literature are [2, 9, 15, 23]. Also commercial products are available on the market usually ranging from about one hundred Euros to several hundred Euros.[1] Most of these products also use a solution that is technically similar to ours. Our kit ranges at the lower end of the market prices (cf. also http://makerspace-ac.de/co2meter).

What is possibly novel with our approach, though, is that we want to track ventilation behaviours for a large number of classrooms over a longer period of time. Then, we try and learn if some correlation with the rate of respiratory diseases can be identified. Moreover, good ventilation in the classroom is possibly not only an important building block in reducing transmission of respiratory diseases, it also helps that the student may be more concentrated in the classroom [26, 30]. Hence, our device may be a useful addition to the classroom even after the pandemic.

The rest of the paper is organised as follows. In the next section, we examine the background of indoor air quality, CO_2 monitoring and ventilation schemes and we review related work. In Section 3, we give an overview of the hardware design of the device, its software system and the server infrastructure for tracking CO_2 values in the classroom. Section 4 gives an overview of the current role-out of the device and deployment numbers planned in the very near future. We conclude with a discussion in Section 5.

[1] See, for instance, https://blog.denninger.at/2020/compile-own-tasmota-firmware-on/, https://www.elektormagazine.com/news/sensirion-inside-co2-traffic-lights-rely-on-sensirion-s-co2-sensor-technology, https://www.renz-germany.de/produkte/protection/air2color/.

2 BACKGROUND AND RELATED WORK

The effectiveness of the common Corona precaution measures like avoiding close contact, increased hygiene, and covering mouth and nose (abbreviated as “hands, face, space” in English or AHA in German) has been discussed and proven, for example, in [10], [25], or [33]. As an additional means, regular ventilation measures are important. This is also reflected in country guidelines such as those issued by the German Federal Ministry for the Environment [27, 28]. It is recommended to ventilate the class-room when concentrations higher than 1000 ppm are measured. With CO_2 concentrations rising higher than 2000 ppm an immediate ventilation is recommended. Studies such as [24] highlight the correlation between air quality in classrooms and the risk for respiratory diseases. Therefore, monitoring air quality is very useful, especially in classrooms. CO_2 is a good indicator for indoor air quality [6]. An overview of ways to monitor air quality in naturally ventilated classrooms is also given in [7].

An overview of CO_2-based determination of ventilation rates is given e.g. in [1]. [13] propose a framework for CO_2-based ventilation control with the goal of reducing the risk of infection with COVID-19. The ventilation recommendations are based on the fact that the air in a room needs to be exchanged regularly because the air contains aerosols which in turn may contain viruses. Studies suggest that SARS-CoV-2 is also transmitted via aerosols [8, 14].

There is a direct correlation between the amount of aerosol in the air and the level of CO_2. In human-built environments the only source for additional CO_2 are human beings. In the literature, some work establish mathematical models to predict the level of CO_2 when humans meet each other in confined indoor spaces (e.g. [18, 19]). These works also try and predict the transmission of respiratory diseases such as measles and others. For other diseases such as measles there are models to compute the infection risk under a number of assumptions like constant air exchange rate or viral load. A general model for the transmission of respiratory diseases is described in [18]. The infection risk is given by $P = \frac{D}{S} = 1 - \exp\left(\frac{Ipqt}{Q}\right)$, where D is the number of infected persons, S is the number of persons in a room, I the number of potentially infectious persons, p the rate of inhalation in m^3/s, q the viral load measured in quanta per second, and Q the fresh air supply rate in m^3/s. The model assumes well-mixed air and a stable state. [19] extend this model to the case where the state is not stable and there is no constant supply of fresh air. An estimate of the viral load q in the above model for COVID-19 is reported on in [3]. Many factors, of course, influence the direct transmission, but, with CO_2 as a convincing marker for human exhaling and by that the possibilities to infect other humans, constantly measuring the level of CO_2 can give an indication of possible transmission ways.

Many of the current recommendations for ventilation of classrooms only give rules with fixed time intervals. This, however, neglects individual environmental factors and circumstances that also influence air quality and air exchange such as the size and shape of the room, number of present people or the current weather conditions and the activity being conducted. As an example, air exchange happens more quickly if the difference in temperature between indoor and outdoor is high. Also, the level of CO_2 at the start of ventilation is obviously significant for how long it takes to bring back the CO_2 level to below 1000 ppm as recommended. The type of ventilation has an influence as well. Opening several windows to allow for vertical transverse flow is more effective than only opening a single window just a little. Effective ventilation (in terms of reducing the aerosol load) thus depends on being able to monitor the CO_2 level.

This is where our work comes in. We aim at providing schools and other educational institutions with simple and low-cost devices for monitoring CO_2 levels. The information should ideally be available not only to the persons in a particular room but they should be collected for as many places and situations as possible. That is why we also integrate means to send measurements of our sensor box to a central data server via the telemetry protocol MQTT [5]. MQTT is a publisher/subscriber communication protocol that was specifically designed for wireless sensor networks. The idea to use a sensor network for monitoring indoor air quality has already been proposed and executed previously, e.g. in [22].

3 THE CO2 METER

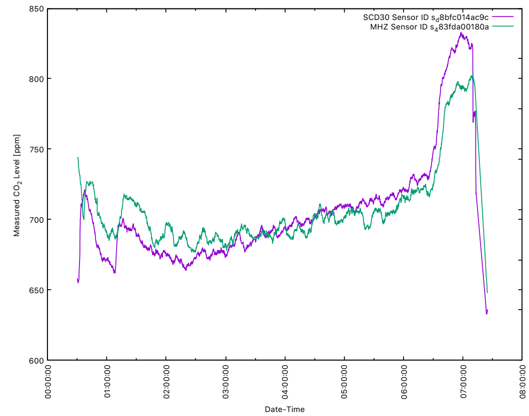
In this section, we present the CO2 Meter, our approach to measuring CO_2 in the classroom. We discuss different sensing techniques and our decision for deploying the Sensirion SCD-30 in Section 3.1. Section 3.2 gives an overview of the overall hardware design before we present the device's user interface in Section 3.3. Then, we introduce the software design in Section 3.4.

3.1 Selecting the right sensor

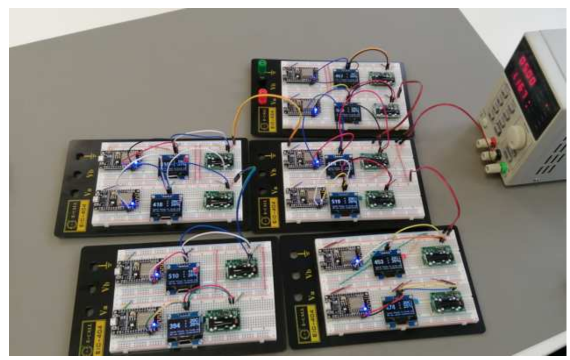
For measuring the air quality, a number of sensors are available on the market. The available sensors basically all follow one out of two measurement principles: (a) VOC and (b) NDIR. VOC stands for Volatile Organic Compounds and measures the air quality as gases such as carbon monoxide, carbon dioxide or benzene change the conductivity of the sensor. The other principle stands for Non-Dispersive InfraRed (NDIR) and, roughly, the carbon dioxide concentration in a measuring tube is estimated by the amount of infrared light that is reflected by the gas mix in the tube.

Capabilities and limitations of CO_2 sensors are investigated in [11]. We tested a number of sensors of both classes. Right in the beginning of our experiments it became obvious that VOC sensors are not suited well for the deployment in the classroom. They give a rough indication about the air quality, but we wanted to give as exact concentrations as possible to give an advice about the ventilation of a classroom. Furthermore, we want to compare the results from different rooms in order to draw conclusions. Inaccurate measurements could lead to wrong conclusions.

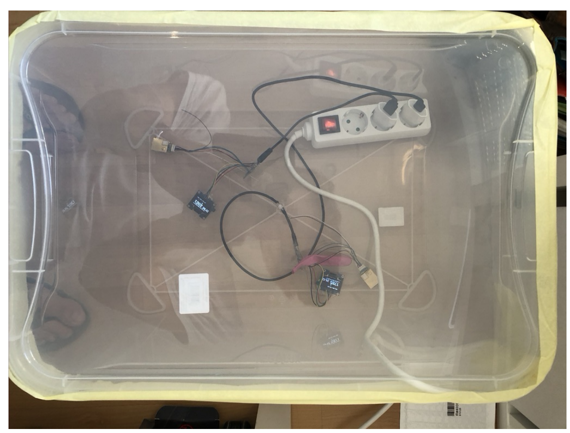
Our CO2 Meter device uses a non-dispersive infrared (NDIR) sensor. A comparison of NDIR sensors can be found, for example, in [32]. We also compared a number of different NDIR sensors that are available on the market. In particular, we made experiments with the Winsen MHZ-19B [31], the Sensair S8 [20] and the Sensirion SCD-30 [21]. We wanted to get an impression how accurate and stable the different NDIR sensors would measure and also how big the deviations from different lots of the same sensors are. Figure 1a shows a comparison between an MHZ-19 and an SCD-30 in a real-world scenario. It shows that qualitatively both sensors measure the same CO_2 concentration in this scenario. Figure 1b shows how a number of SCD-30 sensors are being calibrated against 400 ppm (fresh air), while Figure 1c shows an accuracy test of two MHZ-19 sensors in a defined volume under a defined CO_2 concentration. Also the deviations among the sensors of this type were in an acceptable range. Having this said, we only took samples and we



(a) Comparison between two different NDIR sensors.

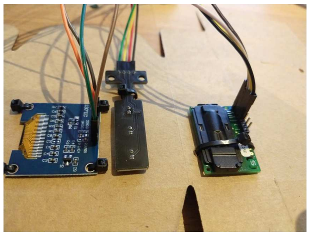


(b) Testing and calibrating the Sensirion sensors

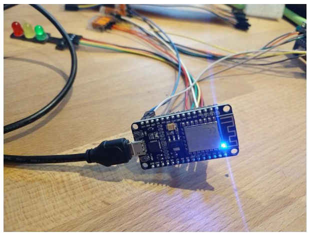


(c) Testing the sensors in a defined CO_2 concentration.

Figure 1: Testing and calibrating the different sensors.



(a) Wiring



(b) Micro controller

(c) CO_2 sensor

(d) Final device

Figure 2: CO2 Meter kit components and its assembled version.

are far away from making statements about systematic and larger-scale tests. In the end, taking also the live span of the sensor into account, we decided to deploy the Sensirion SCD-30 in our devices.

3.2 The CO2 Meter Kit for precise CO_2 measuring

In this section, we detail the design of our CO_2 measuring kit. The main components of our CO2 Meter kit are as follows:

- **CO2 Sensor** Sensirion SCD30
- **Microcontroller** NodeMCU ESP8266-12F
- **Display** 1,3 inch OLED I2C 128 x 64 pixels (SH1106 controller, I2C)
- **Traffic Light** LED Traffic Light Module for 3,3V - 5V
- **Real-time Clock** DS3231 real-time clock
- **Clamps** Wago 413 Compact Splicing Connector, 3 conductor with levers 0,2-4 qmm
- **Power Supply** USB Wall power supply with minimum 1A output current
- **Cable** USB Cable with Micro-USB connector
- **Wiring** Jumper Wire Female-Female, Jumper Wire Female-Male

We decided to provide a kit that requires no soldering to keep the entry level as low as possible. This way, not tools other than a cutter knife is needed to complete the device from the kit. Also, even primary school students can successfully assemble it. In a later version, we might even provide a custom-designed PCB where the single components only need to be placed in the right spots. Figure 2d shows the build up and the final device.

3.3 User interface

With people becoming more aware of the importance to check air quality inside buildings and especially to measure CO_2, numerous new products were introduced on the market. Recently, the German consumer test magazine "Stiftung Warentest" tested a number of products that are available on the consumer market [29]. While the test design that has been conducted by the magazine is debatable since it does not explain or distinguish different CO_2 sensing methods (cf. Section 3.1), it gives a good overview of the different user interfaces coming along with most of the devices and rating of their usability. Some of the devices only show the CO_2 values by a traffic light system, some have displays, some allow for configuring the measurement ranges at which CO_2 concentrations "green", "yellow", or "red" is shown, some don't. Some allow to access and configure the device via Wi-Fi or Bluetooth, some devices do not allow for any configuration at all. As for the usability of the user interface, in a nutshell, transparency of the measuring result was preferred.

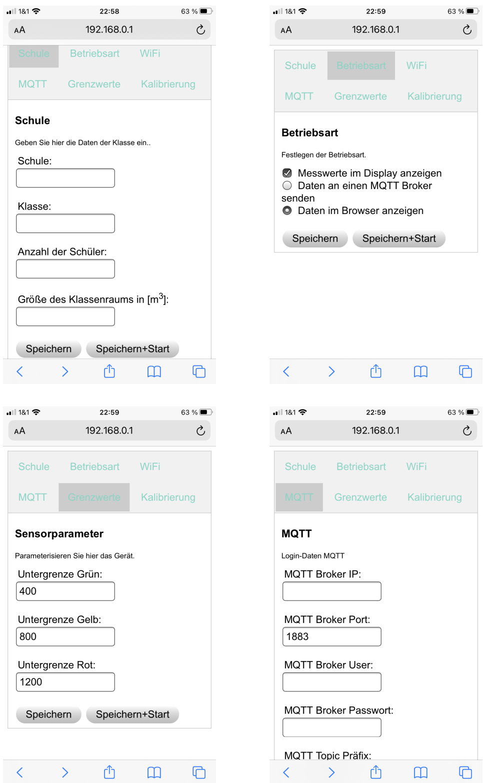
Our device has the following interfaces: (a) a Wi-Fi/Webinterface, (b) an OLED display, and (c) a three-colour LED traffic light. Figure 2d shows the final device with the LED traffic light. Figure 3 shows the device's web user interfaces. The wireless engine of the CO2 Meter supports three different modes: (1) *Access-Point mode*, where the device opens up a Wi-Fi accespoint to which other devices can connect to. A webserver offers a website with the current CO_2 data and a history of data points of the last hour; (2) *Wi-Fi mode*, where the device logs into an existing Wi-Fi network to display the live data; (3) *MQTT mode*, where in addition to the Wi-Fi mode also MQTT messages to a specified server are being sent.

To configure the respective data like Wi-Fi accesspoint or MQTT server, the user can access a web config where all these data can be entered. Besides the operation modes, the Wi-Fi and MQTT servers, also threshold values for displaying the CO_2 values with the traffic light can be configured via the web config.

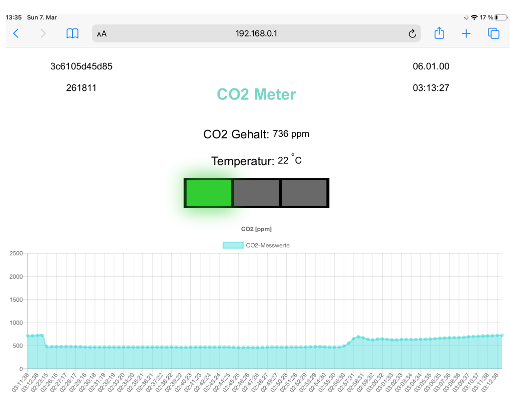
3.4 Software Architecture

The lifecycle of the device's software system foresees a startup phase, where the user can configure the device, a network startup, where network settings are applied if necessary, and a measuring phase where CO_2 concentrations are perceived and displayed.

In the startup phase after a device initialisation, the device opens up an accesspoint which allows users to connect to the device and configure it. The user then can access the device via a Web browser and change a number of configuration settings, such as the device mode, the Wi-Fi and MQTT settings, setup the internal clock or start the sensor calibration (see Figure 3a). Settings are stored persistently on the device's flash drive. If no user connects to the device in this phase, after a threshold of about 30 seconds, the device moves to the measuring phase (see Figure 3b). Depending on the device mode, the device connects to an external Wi-Fi accesspoint or connects to the specified MQTT server. The different connection options of the CO2 Meter are shown in Figure 4. The measuring interval of the device is 5 seconds, each new data point is being displayed on the devices' OLED display, the respective light of the traffic light LED is set, and the devices' data webpage is updated. The sensor, the display and the built-in real-time clock communicate via I^2C. With offering an MQTT interface it is particularly easy to further process the data such as storing it to a database, displaying the data with tools such as Node Red, or even using cloud services such



(a) CO2 Meter configuration on a mobile device.



(b) Displaying the data on a mobile device via webinterface.

Figure 3: CO2 Meter's user interfaces.

as Grafana for this purpose. At the time of publishing this article the sources of the control software but also Node Red flows for displaying the data will be available on Github.

3.5 Server infrastructure

As mentioned earlier, we designed the CO2 Meter with the option to report data to a central server via MQTT. To this end, we set up and maintain a server that collects data for every device that has been deployed and that is in MQTT mode. We use a unique device ID to distinguish data.

With a sampling rate of $\leq 5s$ the sensor records the CO_2 level. This results in 17,280 samples per room per day. For a year, this accounts to $6,3072 \cdot 10^6$ samples. If we assume a total target amount of 1000 devices to be deployed in the longer term, this amounts to $6,3072 \cdot 10^9$ samples. While the storage capacity needed is rather low, the number of data sets that are touched in aggregating analysis operations is still complex. However, The FH Aachen University of Applied Sciences provides a Big Data Cluster capable of performing the computations accordingly.

4 DEPLOYMENT AND WORKSHOPS

Our CO2 Meter device was very well received so far and created quite some interest. We have already deployed almost 350 devices, however, not all of them are using MQTT and are continuously reporting their data to our server. On the other hand, we are currently applying for additional funding to equip many more schools and we hope to be able to reach out more intensively and broadly. The goal is to place devices in 1000 classroom across different types of schools and for all age groups. One of the aims that we have for CO2 Meter is to enable a larger collection of data about ventilation schemes and infection risks for and transmission of respiratory diseases, in particular in the Corona pandemic.

As we have already mentioned in previous sections, the CO2 Meter can be run in a mode that sends measurement data to a server. The primary data that we are collecting is, of course, CO_2 level, but also temperature and relative humidity. In terms of background knowledge, we know what type of room a sensor is installed in. This primary data and static background data can then be combined with additional information. For instance, we collect class schedules from schools and can therefore relate CO_2 levels over time with certain types of activity and with the age structure of classes. Ideally, we would also receive anonymous feedback from schools about the number of pupils with sickness absences or even the occurrence of respiratory diseases.

This data can then be fed into some appropriate learning algorithm to develop models about the behaviour of CO_2 levels in the classroom and to potentially make predictions about the risk of infections with respiratory diseases. At least the data should be sufficient to develop more fine grained and more tailored ventilation schemes for schools that do not have CO_2 measurement equipment installed.

For data analysis we plan to use well-established data analysis algorithms. While we really do not have the capacity nor the expertise to conduct a clinical study with our CO2 Meter, we contribute to enabling such studies or at least tosh some light into the correlation between indoor air quality and respiratory diseases in the current pandemic.

Even after the acute Corona situation the devices can help to increase air quality in the classroom but also as a practical element to convey technical content with hands-on applications in schools.

To ease the assembly of the kit we provide all the information on our web page at maskor.fh-aachen.de/co2meter. We give the list of parts and detailed assembly instructions as PDF files. A series of YouTube videos show the unboxing of the kit, the assembly of the

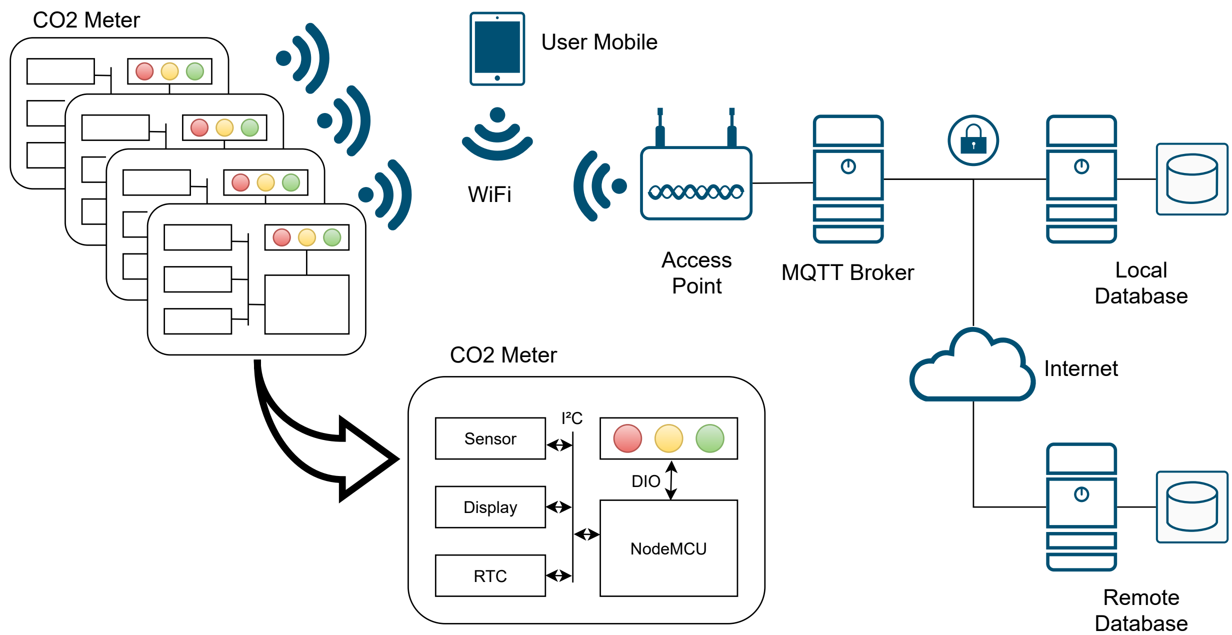


Figure 4: CO2 Meter's architecture and network connectivity.

electronics and how to build the case, respectively. Figure 5c gives an impression of these videos.

Many of the deployments of the CO2 Meter were accompanied with workshops on how to build up and use the devices. What is more, students and teacher were very interested to learn about the underlying principles, too. Some schools feature the devices in their handicraft courses or for extracurricular activities. This is beneficial for several reasons. For one, building the devices on their own creates a stronger relationship and commonly results in students caring more for the hardware. Also, being able to actually see the effects in actions of what was being explained in class, for example, in terms of physics principles allows for a deeper understanding.

5 DISCUSSION

In this paper we presented CO2 Meter, a low-cost do-it-yourself carbon dioxide measuring device for the classroom. It was designed and developed to help schools with coping with the current pandemic situation. Using the actual carbon dioxide level as an indicator for indoor air quality and the potential risk of virus infection support ventilation strategies that respect local settings and circumstances. With reporting the CO_2 data along with additional background information like class schedule or even weather information over the Internet, we can perform data analysis to discover patterns or to generate models of useful ventilation schemes. While we have deployed a number of devices already, data are still too sparse to make any meaningful interpretation of it yet.

It is quite easy to reproduce CO2 Meter devices within school workshops and attach them to every classroom of schools, universities and other public buildings because the sensor is easy and cheap to build. The design of the CO_2 sensor can also be modified to different requirements to increase its acceptance. Also, an extension of the CO2 Meter design can be anticipated to evolve towards a building automation system. There are other measures available to help keeping CO_2 levels low, but the cost and availability is limited because of the pandemic situation. To this end, the proposed CO_2 sensor is a simple and effective concept for alerting humans within buildings who might be exposed to critical CO_2 levels. At the end of the day, this might help to prevent people from being infected by SARS-CoV-2. Of course it should be emphasised that the CO2 Meter devices are meant to provide a supplemental level of safety within public areas and are in no way meant to replace, bypass or modify any of the existing pandemic rules.

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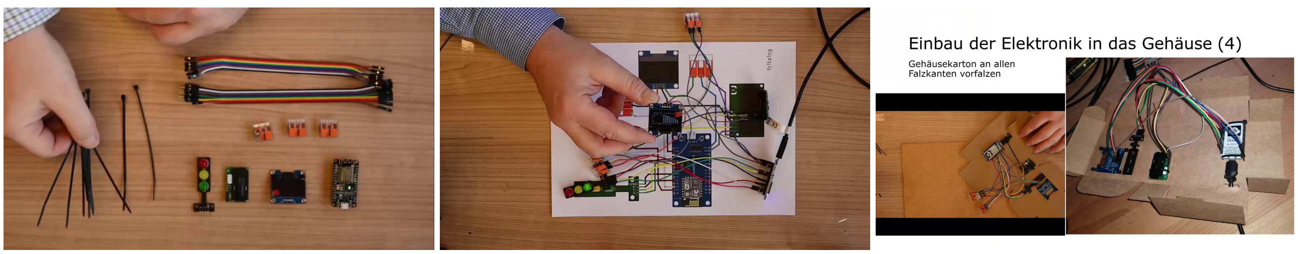
(a) CO2 Meter device in a local newspaper

(b) Impression from a device building workshop in a classroom



(c) YouTube videos on how to assemble the CO2 Meter kit

Figure 5: Media and workshop impressions.

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