

Design of a low-cost wireless emission monitoring system for solid-fuel heat sources

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Abstract

INTRODUCTION: The study presents a conceptual and detailed design methodology overview of a wireless sensor network (WSN) aimed to evaluate the SmartCity air quality in real-time. The aim of the article is to provide low-cost, reliable, and accurate emission data at remote locations, assisting the 2050 Climate-Neutral target set by the European Commission. The sensor devices shall monitor emission parameters such as ozone, carbon dioxide concentration and particle concentrations, specifically concentrations $PM_{2.5}$ and PM_{10} .

OBJECTIVES: The overall objective of the article is to demonstrate the use of a modern home-made air quality device within the market of boilers, fireplaces or other heating devices.

METHODS: The methodology consists of reverse engineering of used professional portable emission analyzers, determining the detailed parts, building a model of how the device's internal systems operate. The paper later explains a series of future experiments including the setup, the necessary components and specific aim. Two numerical models shall be constructed in MATLAB Simscape and Simulink, specifically a telecommunication model, assisting the design of the telecommunication module, and thermal numerical model, that aids in verifying the system temperature and cooling.

RESULTS: The study presents a large potential in increasing the accuracy and spectrum of modern air quality data and decreasing emission levels.

CONCLUSION: In the conclusion of the paper, the functional requirements of the data processing are stated, along with schematic illustration of the user interface of measured emissions.

Keywords: wireless sensor network, emission monitoring system, prototyping, graphical interface, Arduino

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1. Introduction

The concept of a SmartCity is to use resources efficiently and implement innovation and new emerging technologies to provide its residents with a high standard of living [1]. Wireless sensors technologies are no new topic to this concept, as they allow to objectively evaluate problem in real-time at any place, at any time, regardless of the location and distance. The European Commission had set the “2030 Climate Target Plan”, in which a European target

has been set to decrease the greenhouse gas emissions by at least 55 % below the 1990 levels [2]. The EU also aims a revolutionary goal to become a climate-neutral culture by 2050, in which a net-zero greenhouse gas emission economy exists [3]. This goal strongly correlates with one of the main SmartCity initiatives. To create and maintain a safe and healthy environment for its residents.

All domestic heating devices, such as boilers, fireplaces, or stoves, create heat at cost of releasing emissions such as CO, NOx (gas emissions), particulate matter (particle emissions) such as $PM_{2.5}$ or PM_{10} . This is of course not desirable and is often overlooked. According to [4], the

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average age of solid-fuel boilers in Slovakia is 12 years, and for fireplace stoves up to 21 years. Additionally, over 57 percent of citizens use outdated heating systems. Neglected maintenance increases fuel waste, specifically over 25% [5]. To counter this, the new EU regulation n. 2015/1189 endorses the Ecodesign Directive [6]. The directive defines minimum mandatory requirements regarding to emission and energy efficiencies of boilers and classifies boilers into five distinct classes, “class 1” up to “class 5”, based on emission and efficiency measurements [7]. From 1.1.2022 for instance, the operation and production of boilers of emission class 1 or 2 shall be legally banned.

Wireless low-cost air quality devices are readily available with demonstrated functioning and accuracy implementing graphical user interfaces in mobile phones or laptops. These devices however were only used in indoor environments, where the temperatures range from 10 - 25 degrees [8]. The environment within the exhaust from boilers, fireplaces or stoves is significantly more volatile, the temperatures range between 180 – 200 degrees, which simply is technically not compatible.

This article presents a conceptual design and a detailed design methodology overview of a low-cost portable wireless sensor network that monitors the air-quality throughout a city. The aim is to detect critical "black" city districts, streets, making large health risks in the smog and dust situations visible. The system shall measure both gas, particulate emissions, flue gas estimate boiler efficiency and present the data in a graphical-interface. The results shall drive data-based countermeasures to be taken within the SmartCity, maintaining a healthy, safe, and sustainable climate for the residents and future generations to come.

2. Related Works

[9] demonstrated the use of a wireless sensor network (WSN) in the early detection of forest fires. The system nodes were placed throughout a remote forest, where a base station collected all measured data. The position of every node was localized via GPS connection. The diagnosis divided the monitored areas based on predicted fire risk: High Active (HA), Medium Active (MA), and Low Active (LA). This allowed the data to be transmitted and modulated based on the likelihood of a forest fire taking place. [10] remotely monitored a landslide prone zone within a hilly mountain demographic using sensors specially designed to detect landslide activity. Establishing a network connection in real-time deals with specific challenges such as weather signal fluctuations, inadequate solar panel power or insufficient transmission signal strength. The landslide sensor system connects a few nodes relay nodes connecting the wireless sensor network (WSN) using a IoT (Internet of Things) gateway. Figure 1. presents a schematic overview of the landslide monitoring system.

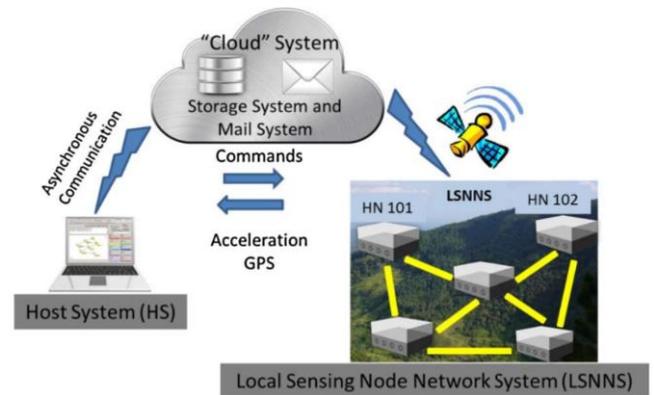


Figure 1. Landslide Monitoring System [10]

One of the critical characteristics of any wireless system is energy expenditure. In specific, the total amount of electrical power required for all the electric appliances to properly function. Historically systems often relied on finite energy sources, such as fuel cells or batteries. With today's modern technology however, it is possible to produce energy continuously and more ecologically via the concept of energy harvesting (EH). Energy is gathered from the environment via either solar, wind, thermal, or mechanical means. In aims of minimizing required energy, a network may use node clustering. Clusters represent a set of nodes in which where a single node collects data from the cluster and sends the entire data itself it to the communication base. The benefits include scalability, energy-efficiency, and routing delay reduction [11]. It is interesting to note however that very few scientific papers, if any at all, provide explicit analysis regarding to its actual effectiveness of node clustering in WSNs and/or manage to prove its actual effectiveness. [12].

[13] demonstrates an application of ecological SmartCity initiatives in China. The extent to which a given city incorporates SmartCity initiatives is denoted by the Comprehensive Smart City Index (CSCI) [14]. The results showed an increase in city smartness led to a reduction of approximately 20.7 % in industrial exhaust gas emissions and 12.2 % wastewater determined via a difference-in-differences analysis.

3. Conceptual Design

The measurement unit must be able to sample flue gas escaping chimneys, analyse, and successfully transmit the collected data wirelessly. The design must be removable in a relatively simple manner to allow for quick inspections and system checks and operate during harsh weather conditions, such as winter snowstorms or heavy rainfalls, as at this time residents tend to heat up homes the most. Sufficient transmission power is needed to counter all cable, air, weather, and antenna losses in the transmission

process. All outdoor air quality sensors available on the market operate with a temperature range of between -10 to 50 degrees, which is significantly lower than the temperature of the flue gas in the chimney that reaches 180-200 degrees [15]. Therefore, the system must be able to cool down the gas prior to analysis. All electrical components must be protected from the hot flue gases. According to all mentioned requirements, a conceptual design may be made, illustrated in figure 2.

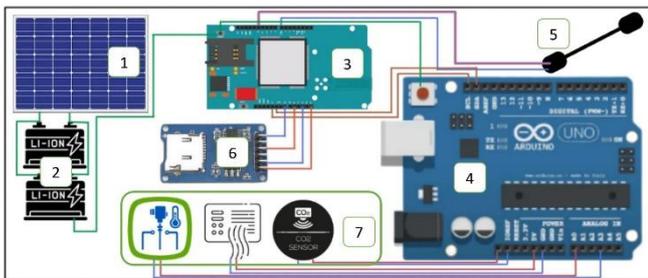


Figure 2. Schematic representation of the monitoring device and its components

- Energy Harvesting System
- Energy Storage System – Li-ion battery pack
- 2G/3G SIM card transmission module - Arduino-based “GPRS-GSM Shield SIM900”
- System controller / Minicomputer- Arduino UNO unit
- Transmission Antenna – Unidirectional antenna
- SD card module
- Sensors
- Emission concentrations, flue gas temperatures
- Condensation system} – Condensate tank to collect water from the cooled flue gas

The process begins as the probe creates a sample of the exhaust flue gas. The hot gas condenses within the pipeline and cools, the condensate is gathered in a condensation tank and the cooled gas travel to the flue gas analysis system. The individual sensors measure emission concentrations of the sample such as particulate matter concentrations (PM), carbon monoxide (CO), carbon dioxide (CO₂), volatile organic compounds (VOC) or ozone (O₃). Table 1. presents a list of market-available gas sensors compatible with the Arduino computer. Please take note, the PMS5003 has a very impressive counting efficiency of above 98 % for all particles larger than 0,5 μm [16]. After analysis, the gas is then expelled via a gas nozzle outlet.

Table 1. Emission sensors: market price

Emissions	Available sensors on market		
	Model name	Range (ppm)	Unit Price (€)
CO ₂	MH-Z19	0 – 5 000	17,72
VOC	MP503	10 – 1 000	1,11
O ₃	MQ-131	10 - 1 000	11,97
PM	PMS5003	0 – 1 000	14,97

The telecommunication system shall consist of a GSM module unit that sends the data wirelessly connected to a local SIM card. This configuration allows a completely independent telecommunication connection as local Wi-Fi connection is not needed. The system shall be powered by li-ion battery storage and recharged by either solar or thermal energy harvesting (i.e., Solar panels). The measurement device shall be placed within the chimney. The sampling probe is placed in the center of the chimney to ensure maximum flue gas mass flow. The sensor shall be held by a heat-resistant clamping stand that it adjustable based on the chimney shape and dimensions, illustrated in figures 3. and 4.

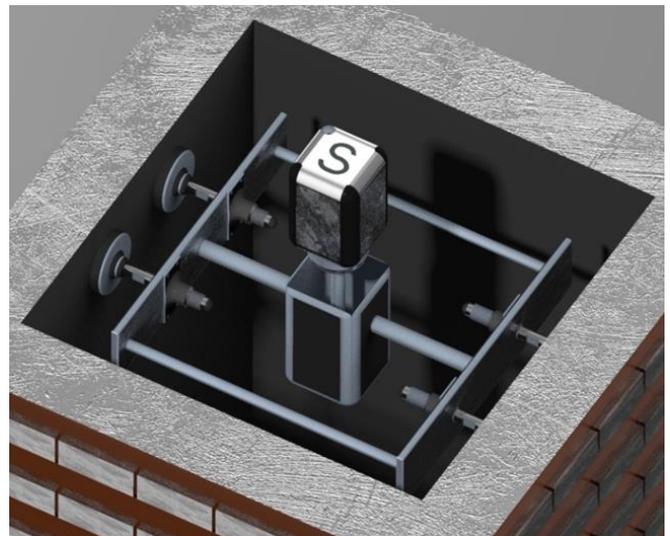


Figure 3. Design 1 - Rectangular chimney

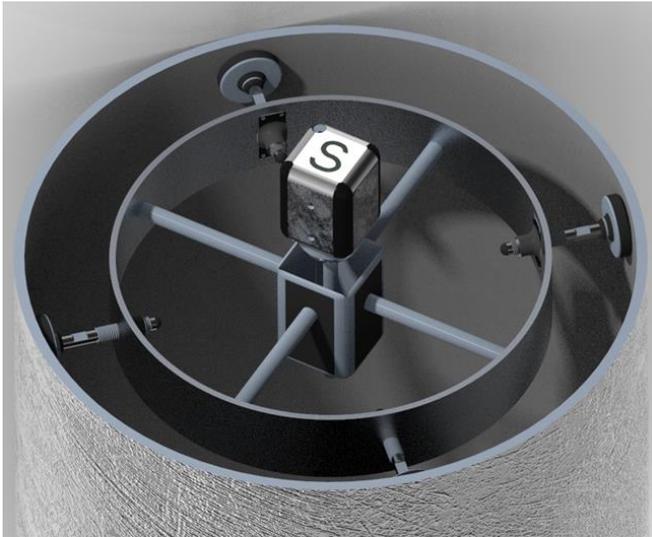


Figure 4. Design 2 - Circular chimney

4. Numerical models

As already mentioned, the aim of the project is to develop a solution to monitoring emissions remotely that would be financially scalable, accurate and most importantly functional. To achieve this, many system parameters must be traded-off to come to the most-desired design. Two numerical models will simulate the device performance and environment behaviour using the telecommunication, antenna design and thermal toolbox in MATLAB.

4.1. Telecommunication model

The telecommunication toolbox within MATLAB shall be used to simulate key parameters of the wireless sensor network and perform end-to-end simulations. Parameters such as Bit-Error-Rate (BER), Signal-to-Noise-Ratio (SNR), Block-Error-Rate (BLER) shall be determined. Link budget shall also be simulated, which is critical to ensure a stable wireless network. A link budget calculation is illustrated in equation 1. [17]. During the design process, trade-offs will be compared including a sensitivity analysis to come to a correct system design. MATLAB also provides an antenna catalogue in which is possible to select antennas such as cavity, cone, dipole or helix shaped antennas.

$$P_{TX} + G_{TXant} + G_{RXant} - L_{FSPL} - L_{TXcable} - FM - RSRX > 0 \quad (1)$$

- P_{TX} = Power of the transmission radio
- G_{TXant} = Gain of the transmitting antenna
- G_{RXant} = Gain of the receiving antenna
- L_{FSPL} = Loss due to Free Space Path Loss
- $L_{RXcable}$ = Loss associated with any cable on the receiving side

- $L_{TXcable}$ = Loss associated with any cable on the transmitting side
- FM = Fade Margin
- $RSRX$ = Receive sensitivity on the receive side.

4.2. Thermal model

The measurement device shall be installed within the chimney. Therefore, it is very important to know the temperatures of chimneys based on the boiler output power. This will allow to compare the system efficiencies based on the flue gas temperature that enter the system. Experiments shall be aimed to validate the numerical model. The thermal model will be made using the MATLAB interface Simscape, in which thermal elements, sensors, sources and systems can be defined, in which a numerical model of a solid-fuel boiler may be built.

5. Conceptual Design

The design process will begin from a feasibility prototype, proving the basic concepts of the system. Follow up experiments shall add complexity at every stage.

5.1. Reverse Engineering

Official documents as to how modern sampling and condensation work are kept secret from the world by large companies. Portable measurement devices that are to be commissioned soon out of service shall be disassembled to its basic components. By reverse engineering, basic information such as component size, shape, or material, or a system flow chart can be made. During the process, the following research questions shall be addressed:

- What kind of control mechanism do modern portable emission analyzers use to sample flue gas?
- In what way is the internal air within the sensor recycled and cleaned / expelled from the system?
- How does the condensate from the cooling process exit the system into the condensation tank?
- How does the device regulate the temperature of the sampled gas before analysis?

5.2. Feasibility prototype – Wireless Dust particle measurement via Wi-Fi

The first prototype shall replicate an existing DIY project that consists of an Wemos minicomputer that shall send measured dust concentrations, specifically PM_{2.5}, via a dust particle measurement sensor. The software interface “Tasmota” shall be installed into the minicomputer using the Tasmotizer compiler. Tasmota is an open-source firmware aimed for home system automation. Only two hardware components are needed [18]:

- Plantower PMS5003 particular matter sensor
- Wemos D1 Mini with ESP8266
- Tasmotizer
- Tasmota
- 3D-printed enclosure

The Wemos shall be connected via three cables, specifically ground (GND), power source (VCC - 5V), and to the measured data (T - 3.3V). The emission probe trigger will be connected to the control unit. This is illustrated in figures 5. and 6. The program will turn on and turn off the sampling procedure. Once the flow has stabilized, the sensors begin measuring. The components shall be inserted into a heat resistant casing along with the emission probe.

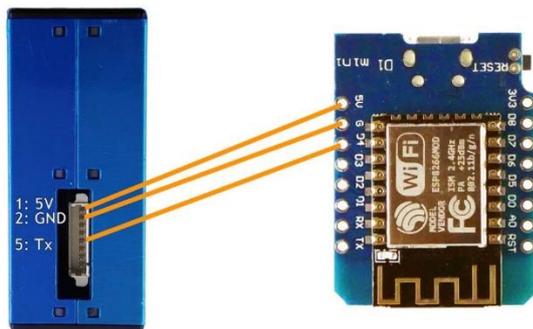


Figure 5. Connection between the WEMOS and the PM5003 sensor

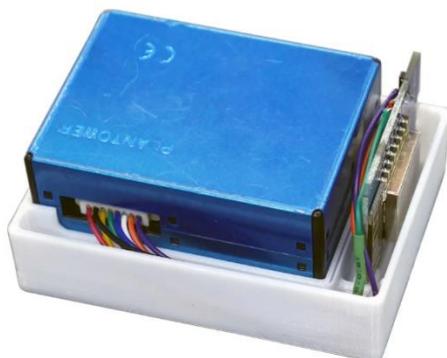


Figure 6. Assembly of the basic dust air quality device

The aim of the experiment is to:

- Quantify the influence of the sampling probe – Accuracy of the measured PM concentrations
- Demonstrate the functionality of the Wi-Fi module within the heat resistance casing.

A solid-fuel pellet boiler shall operate at 20%, 40%, 60% and 80% maximum nominal power output for a period of 15 minutes. The device shall be secured 20 cm from the chimney ending. The device shall take measure the particular matter concentration PM_{2.5} every 30 seconds. The measured data shall be displayed in real time on an external device using the Tasmota Data module. This experiment shall be conducted a total of three times for both reference and prototype measuring devices. The aim of the experiment is to evaluate influence of the sampling and cooling system in the particulate matter concentration measurements. Additionally, the experiment will also test the sampling frequency, varying the sampling frequency of 1 second (identical rate achieved by the indoor air quality sensors), 10 seconds, 30 seconds and 1 minute. This experiment will also shed light to the amount of condensate produced for the given power settings.

5.2. Preliminary prototype - Arduino Pro Mini air quality sensor

The second experiment shall consist of an Arduino computer that is connected to four unique emission sensors. The internal setup is built according to the [8]. The following components are necessary:

- PMS5003 PM Sensor
- MH-Z19 CO₂ Sensor
- MQ-131 Ozone Sensor
- MP503 VOC Sensor DS3231 RTC
- Arduino Pro Mini
- Capacitors values: 0.1uF ceramic and 10uF electrolytic

- Transistors – 2N3904
- 2 Positions switch

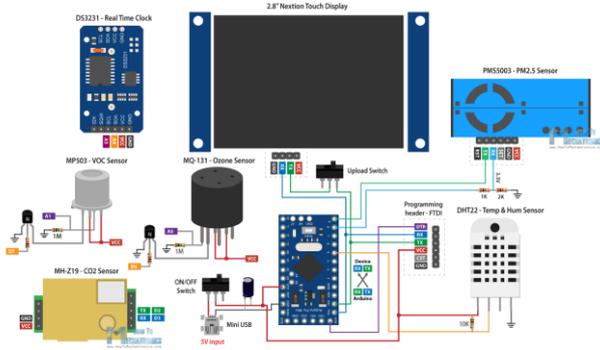


Figure 7. Schematic overview of component assembly of the air quality device using the Arduino Mini Pro [8]

The original assembly is present in Figure 7. The data shall be sent via a Arduino Wi-Fi module. The experiment will demonstrate functionality of a multi-sensor system and evaluate the accuracy of individual sensor measurements compared to a reference measurement.

5.3. Pre-production prototype – 2G SIM card air quality sensor

The third prototype will follow the exact steps as the second, the data however, will be transferred via a GSM module, sending the data via the SIM900 GSM module via the 900MHz band. An interesting point is the simple three cable connection between any Arduino and GSM module. This is depicted in figure 8. [19]:

- GSM transmission output (**Tx**) → Arduino receiver input (**Rx**)
- GSM receiver output (**Rx**) → Arduino transmission output (**Tx**)
- Ground pin connection

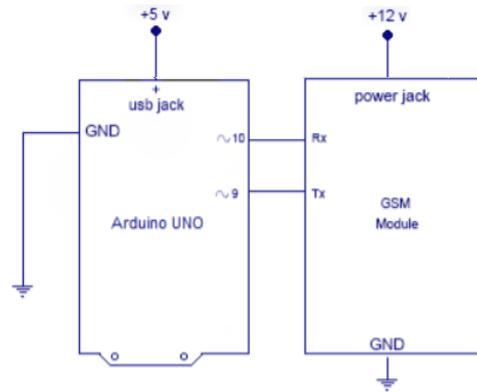


Figure 8. GSM connection to Arduino unit

The experimental setup is identical to the earlier mentioned setups; however, the receiver (computer) shall be located at a distance from the measurement device. The results will be compared to data acquired via Wi-Fi. The aim of the experiment is to objectively determine key telecommunication characteristics and their trade-offs. The experiment will aim to find statistical correlations between the minimum transmission power at a given distance during bad weather or the battery life per an average number of measurements. Once this prototype is optimized both numerically and validated by experimental data, the network data processing must take place.

5. Data Application and Representation

The data from a single unit will consist of emission concentrations and boiler efficiency readings. The challenge is in combining hundreds of system nodes to create valuable data and conclusions to the users. Maximum or minimum values, estimated boiler efficiencies within each city district or a plot diagram showing if emissions how fast or slow emissions are growing or declining, to name a few. Without the data, governmental officers and environmental representatives have no choice but to rely on check-ups that, as stated, take place extremely seldom. Producing more emissions, larger health risks and cost. One example of the data representation is shown in figure 9. in form of a color map. Each color representing the severity of contamination.

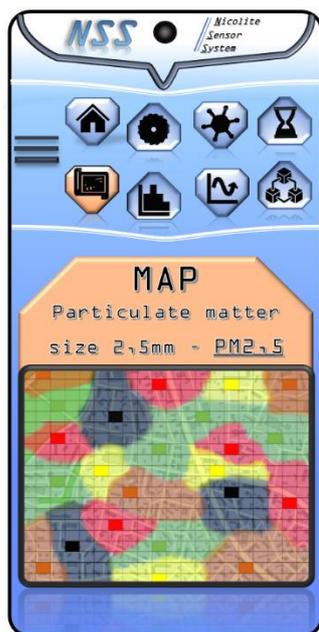


Figure 9. Schematic representation of the data processing application - Displaying a color plot of the measured particulate matter PM_{2.5}

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