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A Novel IoT-based Plug-and-Play Multi-Gas Sensor for Environmental Monitoring

João Bernardo Alves Gomes

Agosto - 2019

A Novel IoT-based Plug-and-Play Multi-Gas Sensor for Environmental Monitoring

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Dissertação apresentada ao Instituto Nacional de Telecomunicações (INATEL), como parte dos requisitos para obtenção do Título de Mestre em Telecomunicações.

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“Simplicity is the ultimate sophistication”.

Leonardo DaVinci

Dedication

To God that gave me life.

To my family that always supported me.

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LIST OF ABBREVIATIONS AND ACRONYMS

6LoWPAN	-IPv6 over Low Power Wireless Personal Area Networks
App	-Mobile application
ARM	-Advanced RISC Machine
C_2H_4	-Ethylene
C_3H_8	-Propane
C_6H_6	-Benzene
CaF_2	-Calcium Fluorite
CFCs	-Chlorofluorocarbons
CH_4	-Methane
Cl_2	-Chlorine
CMOS	-Complementary Metal Oxide Semiconductors
CNTs	-Carbon Nanotubes
CO	-Carbon Monoxide
CO_2	-Carbon Dioxide
CoAP	-Constrained Application Protocol
DSP	-Digital Signal Processing
FPGA	-Field Programmable Gate Array
GPRS	-General Packet Radio System
GPS	-Global Positioning System
GSM	-Global System for Mobile Communication
GWP	-Gross World Product
H_2S	-Hydrogen Sulphide
HCFCs	-Hydroclorofluorocarbons
He	-Helium
HFCs	-Hydro-fluorocarbons
HITRAN	-High-Resolution Transmission Molecular Absorption

HTTP	-Hypertext Transfer Protocol
HTTPS	-Hypertext Transfer Protocol Secure
HVAC	-Heating Ventilation and Air Conditioning
I2C	-Inter-Integrated Circuit
ILO	-International Labor Organization
IoT	-Internet of Things
IP	-Internet Protocol
IP68	-Ingress Protection Against Dust and Water
IPv4	-Internet Protocol version 4
IPv6	-Internet Protocol version 6
IR	-Infrared
JSON	-JavaScript Object Notation
LoRaWAN	-Long Range Wild Area Networks
LPG	-Liquefied Petroleum Gas
LTE-M	-Long Term Evolutoin for Machines
M2M	-Machine-to-Machine
MAC	-Medium Access Control
MCU	-Microcontroller Unit
MDF	-Medium Density Fiberboard
MEMS	-Microelectromechanical Systems
MOS	-Metal Oxide Semiconductors
MQTT	-Message Queuing Telemetry Transport
mW	-Miliwatt
MWCNTs	-Multi-Walled Carbon Nanotubes
N_2	-Nitrogen
NB-IoT	-Narrowband IoT
NH_3	-Ammonia
NO	-Nitric Oxide
NO_2	-Nitric Dioxide
O_2	-Oxygen

O_3	-Ozone
OS	-Operating System
OTDR	-Optical Time Domain Reflectometry
PCBs	-Printed Circuit Boards
PnP	-Plug-and-Play
ppb	-Parts per Billion
ppm	-Parts per Million
QoS	-Quality of Service
Ra	-Radium
REST	-Representational State Transfer
RISC	-Reduced Instruction Set Computer
RJ	-Registered Jack
Rn	-Radon
SD	-Secure Digital
SF_6	-Sulfur Hexafluoride
SnO_2	-Tin Dioxide
SPI	-Serial Peripheral Interface
SSID	-Service Set Identifier
SWCNTs	-Single-Walled Carbon Nanotubes
TDLAS	-Tunable Diode Laser Absorption Spectroscopy
TDMA	-Time Division Multiple Access
TI	-Texas Instruments
TiO_2	-Titanium Dioxide
U	-Uranium
UART	-Universal Asynchronous Receiver/Transmitter
USA	-United States of America
USB	-Universal Serial Bus
USCI	-Universal Serial Communication Interface
USD	-United States Dollar
UV	-Ultra Violet

V	-Volts
VOCs	-Volatile Organic Compounds
WASN	-Wireless Sensor and Actuator Networks
Wi-Fi	-Wireless Fidelity
WO_3	-Tungsten Trioxide
WSN	-Wireless Sensor Networks
ZnO	-Zinc Oxide

RESUMO

A detecção e a medição de gases ambientais tornaram-se essenciais em diversos campos e aplicações, desde a prevenção de acidentes, até avisos de poluição do ar, e garantindo a mistura correta de gases para pacientes em hospitais. Vazamentos de gases podem atingir grandes proporções, afetando bairros ou até mesmo cidades, causando enormes impactos ambientais. A integração de sensores de gases ambientais por meio do paradigma da Internet das Coisas (do Inglês, *Internet of Things* – IoT) deve facilitar os processos de coleta e compartilhamento de dados, proporcionando melhores experiências aos usuários e evitando grandes perdas e despesas. Com esta integração, os usuários finais devem ser capazes de operar esses dispositivos sem prévio conhecimento tecnológico, portanto, a proposta de sensores e atuadores *Plug-and-Play* (PnP) deve ser considerada. Esta dissertação explora uma revisão e avaliação das tecnologias de detecção de gases, os sensores de gás com conexão sem fio propostos na literatura e as abordagens PnP para dispositivos habilitados para IoT. Após a revisão da literatura, uma solução integrada baseada em IoT para detecção de gases ambientais sob uma nova abordagem PnP é proposta, combinando as integrações de hardware e software para uma melhor experiência do usuário. Nesta proposta, é definida uma interface *Plug-and-Play*, utilizando-se a interface de comunicação serial universal (do Inglês, *Universal Serial Communication Interface* – USCI) para microcontroladores (do Inglês, *Microcontroller Units* – MCUs) através do protocolo universal assíncrono receptor e transmissor (do Inglês, *Universal Asynchronous Receiver/Transmitter* – UART), explorado através do múltiplo acesso por divisão de tempo (do inglês, *Time Division Multiple Access* – TDMA), permitindo que mais de dois MCUs se comuniquem no mesmo barramento. A comunicação sem fio é feita através dos padrões IEEE 802.15.4 e IEEE 802.11 (Wi-Fi), e as unidades de detecção são compostas por um MCU de baixa potência e um transdutor de gás. Nesta proposta, as tecnologias para sensoriamento de gases eletroquímico e semicondutor de óxido de metal (do Inglês, *Metal Oxide Semiconductors* – MOS) foram escolhidas devido à sua fácil implementação. Finalmente, foi feita a integração do sistema proposto com um Middleware para IoT, um software que recebe os dados detectados, armazena-os e os encaminha para outros dispositivos inteligentes no mesmo contexto. Foi desenvolvido um aplicativo móvel para Android, a fim de alertar os usuários sobre as concentrações de gases ambientais foi desenvolvido através da plataforma Android Studio. A solução proposta foi experimentada, demonstrada, validada e está pronta para uso.

Palavras chave

Internet das Coisas, IoT, Sensores Inteligentes, Plug-and-Play, Monitoramento Ambiental, Sensoriamento de Gases.

ABSTRACT

Ambient gas detection and measurement is essential in diverse fields and applications, from preventing accidents, to air pollution warnings, and granting the correct gas mixture to patients in hospitals. Gas leakage can reach large proportions, affecting entire neighborhoods or even cities, causing enormous environmental impacts. The integration of gas sensors through the Internet of Things (IoT) paradigm should ease the information collecting and sharing processes, granting better experiences to users, and avoiding major losses and expenses. With this integration, final users must be capable of operating these gadgets without previous technological knowledge, thus, the proposal of Plug-and-Play (PnP) sensors and actuators should be considered. This dissertation explores a review and evaluation of the gas sensing technologies, the connected gas sensors proposed on the literature, and the PnP approaches for IoT-enabled devices. Following the literature review, an integrated IoT-based solution for sensing environmental gases preceding a PnP approach is proposed, combining the hardware and software integrations for a better user experience. In this proposal, the Plug-and-Play interface is defined, using the universal serial communication interface (USCI) for microcontroller units (MCUs) through the universal asynchronous receiver/transmitter (UART) protocol, explored through the time division multiple access (TDMA), allowing more than two MCUs to communicate on the same bus. The wireless communication is made through the IEEE 802.15.4 and IEEE 802.11 (Wi-Fi) standards, and the sensing units are composed by a low-power MCU and a gas transducer; in this proposal, the electrochemical and metal oxide semiconductor (MOS) sensing technologies were chosen due to their easy implementation. Finally, the proposed system was integrated with a Middleware for IoT, a software that receives the sensed data, stores, and forwards them to other smart devices on the same context. An Android-based mobile application to warn users regarding the environmental gases concentrations was developed through the Android Studio platform. The proposed solution is experimented, demonstrated, validated, and it is ready for use.

Keywords

Internet of Things, IoT, Smart Sensors, Plug-and-Play, Environmental Monitoring, Gas Sensing.

Chapter 1: Introduction

Sensors have been employed to collect signals from the environment, providing data to control systems for over 2,300 years, when the first noted system have been developed by the Greeks to control the level of liquids using a floater, similar to the ones that are used today in water boxes to keep a water container in a constant level. With that it was possible to create a precise water clock, where the time was measured by the constant dripping from the water from the first container to another one, where the level changed proportionally to the water flow [1].

Control systems use sensors to collect data from the environment where they are installed, actuators to react to the environmental changes until the system achieves the expected state, and a controller responsible to process the data collected by sensors, to adjust the response on the actuators and to inform the users regarding the system's status; as simple examples, it is possible to highlight the temperature control system on air conditioners and showers. The loop between the controller and the plant can be performed through a dedicated network, or through the Internet, although the last option cannot provide the best quality of service (QoS) [1], [2].

Wireless sensors networks (WSN) have been developed to enhance data collection from the environment and transferring process to databases, allowing remote monitoring of areas of interest and difficult access, for instance. Moreover, wireless actuators were also placed into the networks known as Wireless Sensors and Actuators Networks (WSAN), working on a collaborative way to ensure the automatic and intelligent decision making on certain events, reacting with environmental changes to provide the best user experience, without needing users' interference [3]–[7].

Currently, control systems have reached to complex levels where buildings are being automated to make the best decision for users, self-driving cars and autonomous planes are being experimented, relying on autonomous decisions based on data provided by numerous sensors placed on vehicles. Hereafter, these data will be provided not only by the embedded sensors on devices to be controlled, but also by data collected on other devices and even in other networks. These significant data will be shared among the devices on the same context by the Internet, through the Internet of Things (IoT) paradigm, permitting even more crucial precise decisions [8]–[14].

Mechanisms of sensing gases have been studied since the 19th Century when the first method to notice the presence of unwanted gases at underground mines was performed by using canaries and observing their states. The presence of toxic gases is deathly for the birds and the workers would have enough time to leave the place with no harm [15]. More recently, the detection of other gases have been studied with the purpose to avoid incidents and accidents, as fires and explosions involving flammable gas leakages as well as to provide better results from industrial processes involving chemical reactions [16]–[19].

1.1. Motivation

Environmental gas detection and measurement had become essential in diverse fields and applications, from preventing accidents (including life-saving), avoiding equipment malfunctions, warning about air pollution, and granting the correct oxygen (O_2) concentration patients on a hospital must breath [17], [18], [20]–[22]. Moreover, the supervision of mines is essential to avoid explosions due to methane (CH_4) escape and intoxication from carbon monoxide (CO) and carbon dioxide (CO_2) leakages. The consequences of gas escapes are expensive varying from explosions to intoxication and deaths [17], [19], [20], [23], [24].

Considering these scenarios, the development of a sensor capable to attend these demands being able to collect information about numerous gases is crucial to avoid all the losses caused by unwanted gases.

The costs attributable to gas leakage are enormous: from the loss of production at the food industry, to reconstruction of buildings caused by flammable gas leakage followed by explosions, and the healthcare expenses to treat patients who suffered injuries by gas poisoning [17], [18], [20]–[22]. Only in the United States of America (USA), the annual costs linked to carbon monoxide intoxication is over $1.3 billion, and the deaths as a consequence of this gas leakage is over 2000 per year [19], [21].

Other gases represent an imminent risk to the population and to the environment, being linked to cancer, cardiovascular diseases, cognitive disabilities and respiratory failure [19], [25]–[33]. Gas leakage can reach large proportions, affecting entire neighborhoods, or even cities. The magnitude of the environmental impact of such an incident can be catastrophic in terms of deaths and evaded area [17], [18], [22],

[26].

It was estimated by the International Labor Organization (ILO) that 4% of the Gross World Product (GWP) is expended with labor accidents and the percentage is higher when taking in account the work-related health problems [16]. Another study has shown that, in a period of 40 years, accidents caused by gas leakage, fires, and explosions on oil sub-products storage tanks represented 90% of the accidents in this field, and human error were linked with 30% of all kind of incidents in the same industry. The same study showed that the average cost per casualty of the 10 most devastating incidents on this industry was around $114 million, reaching $330 million on the most expensive disaster until the study publication [22].

The detection of gas leakage can be crucial to avoid all the health and environmental problems, not only by alerting people about the incident, giving time to evade the area, but also by providing information to actuators that can act in order to stop the leakage and mitigate the consequences [17]–[21], [36], [39], [83]–[86], [92], [93].

Together with the development of a multi-gas sensor, the information collected by these devices should be easy available to the users and to other devices that could use the provided data to contribute with the best experience to the users of this system, as well as to decrease avoidable costs, making possible investments on demanding areas [7], [10], [13], [36].

The concept of connected devices uniquely identified, known as the Internet of Things (IoT), allows the generation of precious information, which permits the intelligent automatic control of entire environments, as smart homes and smart cities, granting better experiences to the users. All smart objects on an environment, as smart coffee machines, connected windows and curtains are fed with data collected by the smart sensors, enabling decisions to be taken based on these data, preventing accidents, increasing the thermal comfort, and reducing energy consumption [11], [14], [36].

With the IoT paradigm, it is expected the number of connected devices reach a number of 50 billion by 2025 with an estimated increase of $1 to 2.5 trillion USD on the GWP by the same year [11], [13], [36]. Connected gas sensors would be able to avoid the major problems related with gas escape, as other smart devices as windows, gas valves, and alarms would be aware of the leakages and act in order to control it.

1.2. Problem definition

Environmental gas monitoring is essential in various fields, as industry, medicine, environmental and enclosed spaces supervision. The automobile industry has been deploying gas sensors on the engines for over 40 years, to promote better performances, ensuring that correct concentration of fuel-air mixture is injected on the engine, granting lower levels of pollution and greenhouse gas emissions.

In medicine, it is necessary that patients in a hospital have the appropriate concentration of oxygen to breath and recover from their illness. Furthermore, it is essential monitoring underground mines, ensuring that people in these environments have air with good quality to breath, avoiding intoxication by gas leakage or by the lack of O_2 [23], [37]–[40].

Gas leakages can affect entire cities, causing devastating effects in terms of lost lives, building destruction, and health care, due to explosions and large fires [17], [18]. Only in North America 70,000 visits to the emergency room are caused by gas leakages, and more than 2,000 people die every year in the USA from carbon monoxide intoxication [19]–[21].

To avoid the problems listed above, the development of multi-gas sensors for ambient monitoring is crucial, allowing people on these environments to be alerted towards gas leakages, and to warn authorities, when the risks of great disasters involving gas escapes are increased. The information collected by these devices should be easy available to the users and to other devices that could use the provided data to contribute with the best experience to the users of this system, as well as to decrease avoidable costs, making possible investments on demanding areas [7], [10], [13], [36].

The Internet of Things paradigm allows the diverse smart objects on the environment to communicate among each other, including sensors and actuators [11], [14], [36]. Data generated by the sensors can be used for autonomous decisions, permitting smart windows to open, exhaust systems to start, and alarm systems to warn users regarding the leakages. The sectors (IoT verticals) where new technologies will be introduced with a positive impact and the use of a multi-gas smart sensor will also avoid major losses can be seen on Figure 1.

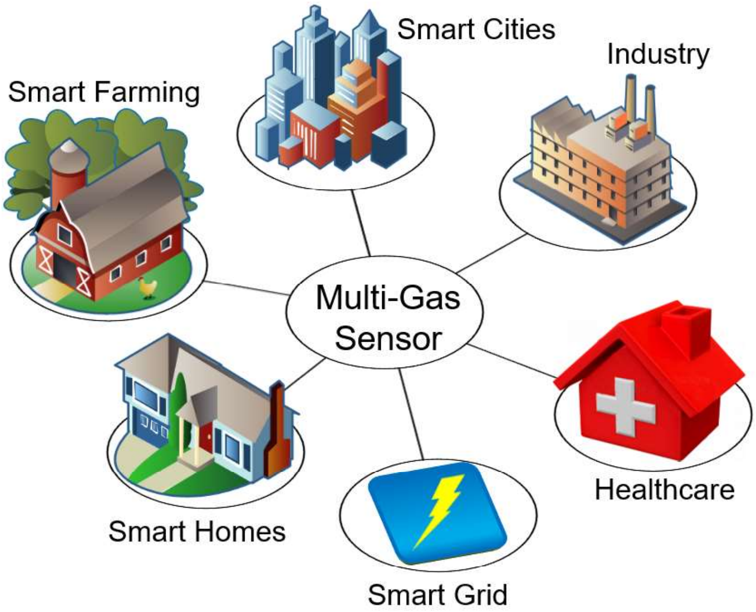


Figure 1 – *Illustration of Internet of Things verticals and market opportunities for multi-gas smart sensors: Smart Homes, Agriculture, Smart Cities, Industry, Healthcare, and Smart Grid.*

A multi-gas sensor together with other devices integrated over IoT networks will have a positive impact on the sectors (IoT verticals) previously shown, allowing new investments by governments, companies, and people in sectors that might demand more attention. The number of accidents related with the presence of determined substances should decrease reducing the risks of specific activities, causing a positive effect on the costs to avoid, and repair the damages caused by such incidents [19]–[21], [28].

1.3. Research objectives

The main objective of this dissertation is to present a novel multi-gas sensor with the Plug-and-Play (PnP) feature support following an Internet of Things approach. The solution should be capable to feed other smart solutions with crucial data on environmental gases, enabling smart decisions autonomously.

Based on studies of wireless gas sensors and Plug-and-Play technologies for low-power smart devices, this work presents a prototype to sense multiple environmental gases and it is ready for use. The study will also act as a guideline for future researches involving low-power Plug-and-Play interfaces and smart gas sensors. To attain this main objective, the following partial objectives were defined:

- Review of the literature towards gas sensing technologies and their applications on IoT solutions;
- Review of the literature on Plug-and-play technologies for solutions based on Internet of Things;
- Identification of the requirements for IoT-enabled gas sensors;
- Proposal and construction of prototypes (hardware and embedded software) to offer a complete solution to sense gases on smart environments, with the Plug-and-Play feature;
- Performance evaluation, demonstration, and validation of the new solution in a real environment.

1.4. Main Contributions

The first contribution is a deep review of the state-of-the-art of the environmental gas sensing technologies and their applications on the Internet of Things, presented in chapter 2. This literature review brings the characteristics of the most relevant sensing technologies, the main requirements for sensing gases on smart environments, as well as the comparison of the main approaches for remotely sensing gases. This survey was submitted to an international journal (June 2019).

The second contribution is the construction of the first prototype to sense gases on smart environments, presented in Chapters 3 and 4. This contribution presents the key requirements of sensing gases on smart environments and compares the main wireless protocols for short range communications. This contribution was published in [41].

The third contribution is the final prototype of an IoT-ready plug-and-play multi-gas sensor, and its performance analysis. The presented prototype was designed to detect smoke and 9 environmental gases, although it is capable of measuring up to 16 simultaneous channels. This prototype is ready for use, and it is presented in Chapters 3 and 4. This work was submitted to an international journal (July 2019).

1.5. Publications

During this research work, three scientific papers were prepared.

a) **João B. A. Gomes**, Joel J. P. C. Rodrigues, Jalal Al-Muhtadi, Arunkumar N, Ricardo A. L. Rabêlo, Vasco Furtado, "An IoT-based Smart Solution for Preventing Domestic CO and LPG Gas Accidents," *IEEE 10th Latin-American Conference on Communications* (IEEE LATINCOM 2018), Guadalajara, Mexico, 14-16 November, 2018.
b) **João B. A. Gomes**, Joel J. P. C. Rodrigues, Ricardo A. L. Rabêlo, Neeraj Kumar, "IoT-Enabled Gas Sensors: Technologies, Applications, and Opportunities," (submitted for publication in an International Journal).
c) **João B. A. Gomes**, Joel J. P. C. Rodrigues, Ricardo A. L. Rabêlo, Neeraj Kumar, Sergey Kozlov, "A Novel IoT-based plug-and-play multi-gas sensor for environmental monitoring," (submitted for publication in an International Journal).

1.6. Thesis statement

The choice of an IoT-based gas sensor is crucial for the safety of smart environments, as it can prevent the intoxication of people in these ambient and major losses from leakages. These devices must be simple operated, as final costumers with or without technological knowledge will manage it. The proposal of a novel IoT-ready Plug-and-Play solution for sensing environmental gases, its construction, and evaluation in real situations can contribute with this characteristic of simple devices for general costumers.

The study focuses on enhancing life quality, public health, as well as reducing accidents from gas leakages. It also might increase the awareness towards environmental pollution since people will be well informed on ambient gas levels.

1.7. Document organization

The remainder of this dissertation is organized as follows. Chapter 2 provides a literature review on gas sensing technologies, the main wireless gas sensors proposed on the literature, the low-power Plug-and-Play interfaces proposed on the literature, and the discussion among these topics. The proposal of a novel solution to sense multiple ambient gases in smart environments is presented on Chapter 3. Chapter 4 presents the evaluation of the proposed solution for sensing multiple environmental gases, and its Plug-and-Play feature. Finally, Chapter 5 concludes this dissertation, reporting the lessons learned during this work, the main conclusions, and the suggestions for future studies.

Chapter 2: Gas Sensing Technologies

2.1. Background on environmental gases

Some gases are the key to ensure the functionality of systems and entire industries, as well as the presence of other gases can be a problem to other fields, causing the loss of entire production lines, as in the food industry, or even cause the loss of lives and explosions. In this section, the most important gases in terms of pollution monitoring and control, health issues, and accident preventing are listed with their main characteristics.

Oxygen (O_2) is the most important gas to life, and is crucial in numerous fields. Patients under anesthesia, or recovering from surgery and from certain diseases need controlled O_2 doses to keep them alive and fully recovered. The decrease of oxygen levels in enclosed spaces can be related with other gases leakage, which would lead people inside these spaces to asphyxia, leading to unconscious state, or even to death [42]. Numerous industrial processes rely on the correct concentration of this gas to achieve the best results, mainly chemical and combustion, which without the correct percentages will not grant the best accomplishments of the systems. Engine control systems depend on the correct mixture to achieve the expected performances, weather it is lower fuel consumption or power and speed [39], [40], [42], [43].

Carbon Dioxide (CO) is a colorless, odorless gas, generated by the oxidation and combustion of hydrocarbon, as well as by living beings on the respiration process. It is a key gas on greenhouse effect, and the increase of its levels, in the presence of other gases, it is related with atmospheric pollution. It is also the key gas on the oxygen production by the photosynthesis process. The accumulation of this gas in enclosed spaces can be responsible to suffocation; it can be deathly when the concentration of CO_2 reaches levels above 3% [44]–[46].

Carbon Monoxide (CO_2) is a result of the incomplete combustion of hydrocarbon fuels, due to the lack of oxygen or insufficient temperature. It is an odorless, colorless gas, mainly originated on enclosed or semi-enclosed spaces, such as closed parking garages, home heaters and fireplaces. It is well known that this gas has around 200 times more affinity to hemoglobin than the oxygen, making the protein unable of carrying the second gas to the body cells, leading to a hypoxia state, causing damages to body tissue, the poisoning symptoms are easily mistaken with fatigue. Depending on the exposition time and concentrations of this gas, it can be lethal or reduce lifetime, causing cardiovascular diseases and brain damage [19]–[21], [46]–[48].

Volatile Organic Compounds (VOCs) are carbon-based organic compounds, in a vapor state at room temperature, generated by the combustion of fossil fuels, or natural emissions. Some of these compounds are toxic, affecting human health by causing the irritation of the respiratory system and eyes, diseases as cardiovascular and respiratory malfunctions, or even cancer. As examples, it can be listed as VOCs methane, benzene (C_6H_6), propane (C_3H_8), and alcohol vapor [24], [26], [27], [49], [50].

Liquefied Petroleum Gas (LPG) is a fossil fuel, composed of a mixture of hydrocarbon gases, used in domestic and industry, to generate electricity, power heating systems, vehicular combustible and cooking. It is a highly flammable gas, capable of severe damage, if a leakage is followed by an ignition; major explosions and fire incidents were reported on the literature, due to its gas leakage, in numerous countries, such as the 2011 Karakopru incident, where an entity plant was destroyed due to an explosion. The leakage of this gas can lead to great expenses and to the loss of many lives [17], [18].

Ozone (O_3) is present at the atmosphere, in high altitudes, where it is fundamental to maintain life on Earth, acting as a natural filter to ultra violet (UV) light emitted by the Sun, avoiding skin cancer on humans and allowing the agriculture, by filtering the UVc light. The increase of this gas in lower atmosphere layers is an indicator of air pollution and bad air quality, being one of the causes of lung dysfunctions, worsen respiratory diseases [51]–[54].

Sulfur Hexafluoride (SF_6) is an odorless, colorless, chemically stable, non-flammable gas used as electrical isolator on the electrical power industry, due to its capability of extinguishes electrical arcs in high tension. It is a non-toxic greenhouse gas, and it is not a risk if inhaled in proportions under 20%. The detection of this gas leakage is essential to prevent damage to high power electrical equipment, and with that, avoiding failures on power distribution; the detection can be done by the SF_6 itself or their sub-products, generated by electrical discharges [55]–[63].

Radon (Rn) is a colorless, odorless, radioactive gas that can be emitted from soil and rocks like granite and its long-term exposition is related with lung cancer. It can be generated from the decay of Radium (Ra) and Uranium (U), and it has a half-life from approximately 3.8 days. Rn can be transported through water, or carrier gases such as CO_2, methane, Helium (*He*), and other gases. As this gas represent half of the radiation exposure to human beings, the detection of this gas is crucial to avoid long term exposition, being a key factor on the lung cancer prevention, mainly in underground miners, that suffer more contact with this radioactive gas [28], [44], [64]–[68].

Ammonia (NH_3) is an irritant, corrosive, colorless gas, with a strong odor, employed on the production of fertilizers and explosives, as well as in the textile industry. It can be found as a refrigerant gas and in hygienic products. Its leakage can cause atmosphere, soil and water pollution, and severe damages to the eyes and respiratory system, causing even the death of people directly affected by the gas escape [47], [49], [69]–[72].

Nitric Oxide (*NO*) is a colorless gas that can be lethal if its concentrations reach certain levels on the ambient. In the atmosphere, it is one of the compounds responsible to the smog pollution, causing irritation to the exposed people. It is employed on the semiconductor industry, as well as on medicine, as muscular relaxant and in the treatment of hypertension, due to its vasodilation property. This gas can be one of the sub-products of fossil fuel combustion, and it is also produced naturally, at the human body, being an important signaler of inflammation, if its concentration on the human breath reaches levels above 50 parts per billion (ppb); it is used to monitor the inflammation conditions of asthma patients' lungs. The oxidation of *NO* results in nitrogen dioxide (NO_2) [73], [74].

Nitrogen Dioxide (NO_2) is a result of the combustion process of fossil fuels, as well as the oxidation of nitrogen. It is one of the pollutants responsible for the formation of acid rain, and it is toxic at low levels, 1 part per million (ppm) is the maximum recommended contact volume; its exposure is related with respiratory diseases, pulmonary malfunction and death. NO_2 can be found in highway surroundings, as well as dense traffic areas; it can also be found indoors, as a result of the combustion on generators and heaters [26], [75]–[78].

Hydrogen Sulphide (H_2S) is a colorless, flammable, corrosive and toxic gas, which is poisonous even in low concentrations. The exposure to this gas can lead to damages on the human nervous system. Its generation can be either natural, from volcanic activities or from the decomposition of organic compounds, or due to the combustion of fossil fuels or from sewage. This gas can be found on coal mines, petroleum exploration and in diverse industrial processes [79]–[81].

Chlorine (Cl_2) is broadly used on chemical and pharmaceutical industries, water treatment and in domestic cleaning products. With a strong odor, in the gaseous state, it is extremely toxic; the exposure limit in workplaces are around 30 ppb. The inhalation of low concentration levels (50 ppm) of Cl_2 can cause severe damage to the respiratory system and levels of 1000 ppm is enough to be fatal to humans. Numerous accidents involving transportation and industrial leakages have been reported over the years. Moreover, it has been used as chemical warfare agent from the First World War, to the Syrian Civil War on the present days [82]–[85].

Refrigerant Gases: Temperature control is vital in certain areas, like food industry, hospitals and data centers. Refrigerators and air conditioning systems rely on refrigerant gases to accelerate the thermal exchange and keep the ambient on the adequate temperature [86]–[88]. Not only the malfunctioning of entire systems can be caused by the leakage of refrigerant gases, but the increase of atmospheric pollution, greenhouse effect and the destruction of the ozone layer. The first generation of refrigerant gases was composed of toxic and flammable gases, endangering workers that could be exposed to leakages. After that, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) were introduced; the last do not affect the ozone layer, different from the two first [89], [90].

Monitoring and controlling the level of these gases can grant better work conditions, reduce pollution levels, enhance life quality, decrease health disorders and death in the limit, and prevent equipment malfunction on industry. This section presented a background on the most relevant gases that are considered in the study.

2.2. Evolution of gas sensing technologies

The attempt of sensing gases had become necessary when several pitmen lost their lives during underground mine exploration due to the lack of O_2 or to the leakage and accumulation of other colorless, odorless gases, mainly CO_2, CO and CH_4. During the 19^{th} century explorations, miners used to have canaries with them while working in the mines to signalize the presence of unwanted gases. While the birds were at their pits, there were enough oxygen for them to breath; in contrast, if the canaries had succumbed or passed out, the quality of the air was not good enough for the people inside to breath, and they should leave the mine immediately [15], [30], [38].

Much have evolved in the last century, and gas sensing has become a key feature in numerous activities, such as medicine, sports, the industrial field, environmental monitoring and pollution control [23], [39], [40], [45], [46], [91]. Oxygen sensors were the first to be developed: in 1956, Leland C. Clark developed the first electrochemical oxygen sensor, known as Clark Cell [39], [92], [93]; in 1961, Peters and Mobius developed the Lambda probe to perform oxygen measurements in vehicle engines, helping with the admission control and fuel mixture to achieve the best performance, in terms of fuel consumption or in terms of power [39], [94], and it has been produced by Bosch since 1976. Both developed sensors are consumable, reacting with the oxygen, in order to provide an output value representing the gas concentration on the environment [37], [95]. After the development of these expensive, and not so accurate sensors, the research for new technologies capable to grant more accurate measurements and more durable devices to this field have been taking advantage on many characteristics of the sensed gases; as an example, oxygen have magnetic characteristics, consequently, it can be measured by the attraction to a magnetic field. Other gases can be measured taking advantage on their ultrasonic properties or by optical spectrometry [23], [39], [94].

Gas sensors rely on a physical or chemical reaction with the gas that is trying to sense to generate a response, proportional to the concentration of the gas, thus the speed of the reaction. Some of the sensors have a reversible reaction, while other have irreversible, the last being expendable with 2 to 5 years of lifetime. The response generated by the presence of the target gas is either linear or non-linear, depending on the materials and target gases [23], [37], [95]. It is fundamental to grant the quality of the air patients are breathing at a hospital, as well as to provide the correct mixture to divers, in particular to deep divings, where the gas mixture the diver must breathe is different according with the time and depth of the activity. Not only to grant the quality of air, but also to avoid gas leakage and its consequences such as poisoning or explosions, sensing gases is of great importance at the industry [17], [20], [21], [40].

Over time, other sensing methods were developed, exploring the propagation characteristics of the gases to perform measurements, and comparing with a reference to determine which gas is being sensed. The analyzed characteristics vary from signal attenuation, frequency shifting, propagation time, among others, and are performed by acoustic or optical sensors [23], [37], [39], [92], [95]–[99]. Moreover, the miniaturization of gas transducers have taken place on the research topics [25], [47], [100], [101], as well as the development of wireless gas sensors, to monitor remote areas, easily collect and analyze data from the environment [34], [35], [95], [105]–[114].

With the IoT paradigm, gas sensors are becoming key devices to measure ambient gases, generate warnings related to the presence of unwanted gases and allowing other systems, as smart windows, smart curtains, automated exhaust systems, and automated heating ventilation and air conditioning (HVAC) systems to automatically act in order to avoid damages from the leakages [11], [12].

2.3. Gas sensing technologies

The methods to sense gases lean on the change of physical or chemical properties of a given material or property on the presence of the target gas, compared to an ideal environment. Some of the sensing methods use the reaction between the sensing element with the target gas to determine this gas concentration; other methods are based on the comparison of physical properties such as speed velocity and wave propagation between an ideal mean and the one with the gas being sensed.

2.3.1 Electrochemical

Electrochemical gas sensors were the first gas sensors to be created, starting with the Clark Cell in 1956, to sense levels of oxygen. In 1976, the Lambda probe was developed to sense oxygen in combustion engines, constructed with a solid electrolyte Yttria-Stabilized Zirconia, requiring high temperatures to function properly; the working temperature is variable, and depends on the chosen electrolyte, which can be liquid or solid, the last one allows the miniaturization of the sensors [24], [112].

These sensors benefit from chemical reactions to sense a target gas where the product of the reaction and its speed is proportional to the gas target concentration. The materials used to compose these sensors have different target gases, depending on the temperature of the reaction. These sensors are basically composed by a membrane that separates the ambient gases from the electrolyte solution, the electrolyte, which is mainly composed by a liquid compound of acids or bases, and the electrodes that are consumed by the electrochemical reaction. The polarization of the electrodes and measurement of the variation of the output parameter is dependent on the sensing approaches, which could be potentiometric, voltametric, conductimetric, or amperometric. A filter, between the membrane and the environment gases, can be used to limit the contact with unwanted gases, improving accuracy and sensitivity on these devices [34], [38], [39], [113]–[115]. The representation of an amperometric electrochemical gas sensor is shown on Figure 2.

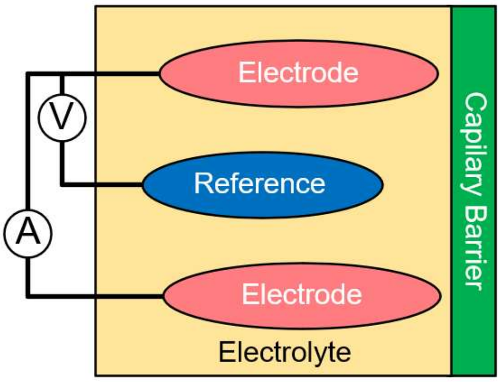


Figure 2 – *Schematics of an amperometric electrochemical gas sensor.*

Electrochemical transducers are easily miniaturized, being able to reach the order of a few millimeters, which is beneficial to embed the sensors in printed circuit boards (PCBs). All subtypes of electrochemical sensors rely on the reduction of the cathode to hydroxyl ions; when the anode material is completely oxidized, the sensor have reached the final of its lifetime and must be changed [39], [40]. Electroanalytical measurements can be executed with four different sensing approaches, in where each sensing technique will better fit a different necessity of sensing gases: Potentiometric, Voltametric, Conductimetric and Amperometric [34], [38], [115].

Potentiometric Sensors: they have as an output the electrical tension proportional to the equilibrium potential of an indicator electrode, in where the absence of the target gas results on the output of 0 Volts (V). This measurement method results in high selective transducers, which are able to measure only low concentrations of the target gases [34], [38], [115]. This technology is important for the measurement of highly toxic gases, as the chlorine gas, which is toxic above 30 ppb.

Voltametric Sensors: they have the output current as a function of the concentration of the target gas and the applied potential, generating measurements of low gas concentration; it allows the measurement of more than one gas, with the variation of the input electrical potential. The applied potential, as well as the choice of the electrodes can result in a highly selective transducer [34], [38], [115].

Conductimetric Sensors: they are mostly used by detecting the presence of the target gas after a determined threshold; it relies on the measurement of the resistance of the solution, which means that these sensors are not selective and more than one gas can change its resistance [34], [38], [115].

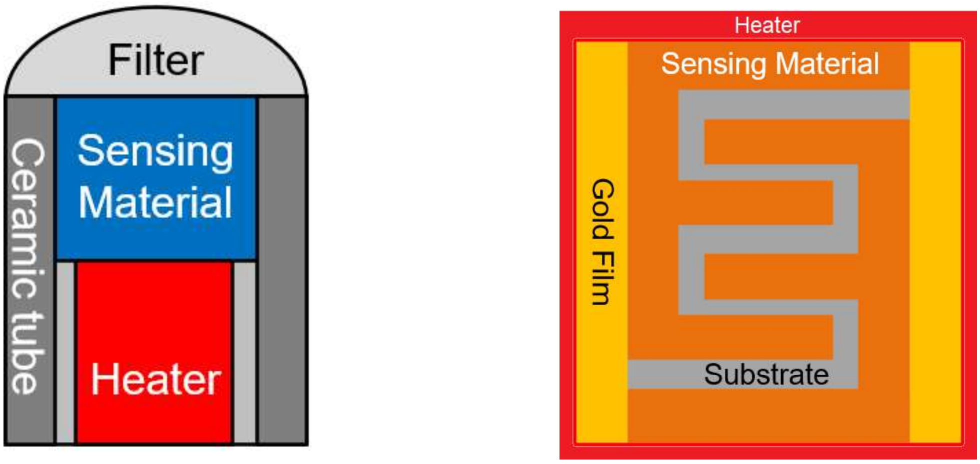
Amperometric Sensors: have the variation of the electrical current as a sensing parameter, where the reduction of the cathode to hydroxyl ions generate a current, proportional to the concentration of the target gas. The cathode and anode must be linked with a resistor, in where the variation of the current on the load resistor can be measured as a tension value [32], [93], [120], [121].

2.3.2 Metal Oxide Semiconductors

Metal Oxide Semiconductors (MOS) gas sensors are broadly used in hospitals to grant the correct mixture of O_2 and Nitrogen (N_2) to patients as well as at the industry to avoid toxic gas leakages. These sensors are simple to fabricate, easy to reproduce, and present a low cost, compared to other technologies. The sensors can be fabricated using commercial Complementary Metal Oxide Semiconductor (CMOS) processes, which means the easy fabrication of numerous components, with low cost, and identical characteristics [116].

These sensors operate at high temperatures, the reaction with the target gas generates a variation on its internal resistance and the sensor responds with a proportional output tension, according to the concentration of the gas it is sensing; the sensors are normally designed within a heater. The transducers are sensible to more than one gas and the temperature of operation is a key to determine the gas that will be sensed [23], [42], [48], [116], [117].

MOS sensors are usually constructed with a ceramic tube in where the heater is placed in contact with the electrode; the sensing layer is made with the metal oxide semiconductor, placed in between the electrode and a heater; the sensor could also be printed in a ceramic wafer [43], [100], [118]. Figure 3 shows both MOS sensors, where (a) represents the tubular gas sensor and (b) the wafer gas sensor.



(a) - Tubular MOS sensor. *(b) - Wafer MOS sensor.*

Figure 3 – Illustration of metal oxide semiconductor gas sensors.

These sensors can be easily miniaturized, including the use of nanomaterials to develop the sensing elements, which have demonstrated an increased performance on these transducers; the use of external stimulus, as UV light, have shown better efficiency on measurements at room temperature [116], [117]. The most common materials used on these transducers are the Tin Oxide (SnO_2), Zinc Oxide (ZnO), Tungsten Trioxide (WO_3) and Titanium Dioxide (TiO_2). The transducers need to be heated to achieve the sensing point, and are consumed with the reaction with the gas it is sensing, making necessary a periodic calibration and limiting the lifetime of these devices. The heating process must be adequate to the target gas, as the sensor will respond to different gases if the temperature is not the suitable for the gas of interest. A physical gas filter, to eliminate interference from other gases can be added to the sensing element, upgrading the performance of the measurements [23], [48], [116], [119].

These sensors, in contact with the target gas and elevated temperature, have their internal resistance altered, which also vary the output tension; the variation of the internal resistance is determined by the concentration of the target gas and the semiconductor that composes the transducer. The concentration of the target gas (R) is calculated as a relation between the internal resistance on the presence of the target gas (R_s) by the output resistance at the presence of a reference gas (R_o), as shown in Equation (1) [78].

$$R = {}^{R_S}\!/_{R_O} \tag{1}$$

There are two types of MOS sensors, the n-type, where there are more electrons than protons, and the p-type, where the number of electrons is inferior, and the electricity flows through the positive holes. The n-type sensor have the internal resistance decreased by reducing gases, and increased by the oxidizing gases, whereas the p-type presents the opposite effect [23], [120], [121]. The use of UV light within the sensing element allows a lower sensing temperature, produces lower internal resistances, as electrons are inducted to pair, and the resistance of the sensing material will increase, proportionally to the increase of the target gas [42].

Over the past 10 years, the use of nanostructures as metal oxide semiconductors to sense gases have become a topic of interest of some research groups, with reports of ameliorated sensing characteristics [73], [74], [100], [118], [119]. Response time and energy consumption are also topics of research, where the most part of commercial solutions have response times of a some seconds, sometimes reaching a few minutes; the energy consumption of these devices can reach the order of 500 milliwatts (mW) or even higher, due to the necessity of the heater. As the miniaturization of the devices has shown better response times, of the order of seconds to milliseconds, and power consumption of 80 mW, as reported by the Stratulat *et al.* [122], it has a good potential to be used integrated in an IoT solution. Although no commercial solution were found employing nanomaterials or Microelectromechanical Systems (MEMS), it has shown to be a promising technology to future products, allowing the development of embedded systems to measure gas concentrations in diverse scenarios, with lower power consumption than the traditional MOS transducers [123].

2.3.3 Catalytic

Catalytic gas sensors are used to detect combustible gases in environments with concentrations of at least 15% of O_2. These sensors perform the detection by measuring the variation on the internal resistance, which occurs when combustible gases are present on the ambient. The process of detecting gas on this type of sensor consists on the chemical reaction between the catalytic element and the combustible gases on the environment, generating an elevation on the temperature on the sensor, which causes the variation on its resistance [124]–[126].

These sensors have been reported to present fast response time, although it is not accurate on determining the concentration of the gas; it only detects combustible gases and respond with the change on its resistance [124]–[126]. These sensors can be deployed on environments with humidity and temperature variations, without losing its capacity of detecting the target gases.

The lifetime of these sensors will depend on the concentration of the target gas on the environment it has been deployed, being operative for 10 years on normal conditions; the presence of corrosive gases and exposure of the sensor to the target gases in concentration levels above the recommended can limit the lifetime to months of operation [124]–[126].

Catalytic gas sensors are composed by two semiconductor elements: a passive element, used as reference, and one active element, that reacts with the target gas, generating an elevation on the temperature and, thus, generating a variation on the internal resistance. The reaction between the target gas and the catalytic element is responsible for the consumption of these kind of gas sensor, and the exposure of catalytic gas sensors to concentrations above the upper flammable limit will deteriorate the catalytic element, therefore, the sensor will lose its capacity of detecting the target gas, providing invalid results [124]–[126]. As an example, if a catalytic gas sensor targeting hydrogen with an upper concentration limit of 14000 ppm (1.4%) is exposed to the target gas at concentrations of 10%, it will no longer provide valid concentrations for the measurements. Figure 4 shows the concept of the catalytic gas sensors.

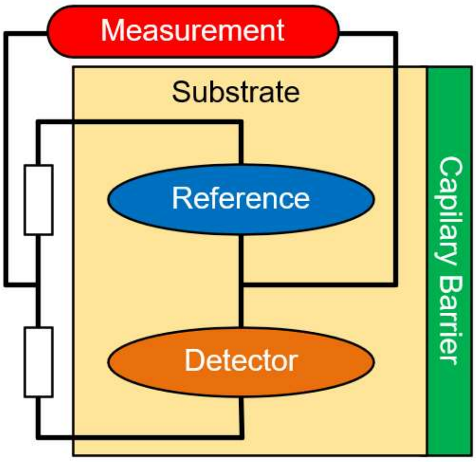


Figure 4 – *Representation of catalytic gas sensor.*

2.3.4 Polymers

Volatile organic compounds can be toxic above certain concentrations, causing harmful health effects, as cancer, are difficult to be detected by the electrochemical transducers. The polymer transducers used to detect gas are useful to sense these common organic compounds, present at the industry and household, in everyday use products [25]–[27], [72].

Doping polymers by redox reactions, which is a reversible process, generate conductors or semiconductors, which can be used to sense gases by the variation of these materials' conductivity. The doping level can be changed by the reaction between the polymer and the sensed gas, turning the sensing process effective. The conductivity variation is affected by the exposition of these compounds to certain gases, proportionally to the target gases concentration on the ambient. Thus this variation, it is possible to calculate the concentration of the gases, with a short response time and, depending on the sensing material and target gas, high accuracy. These materials can also sense inorganic gases, however the sensibility and accuracy can be compromised, as the main target gases to these compounds are the VOCs [23], [127]–[129].

The electrical conductivity of polymers alone is extremely low, making the use of these compounds alone unpractical to sense gases; the conductive polymers were reported to be used in biosensors, generating electric signals from biological data. Non-conducting polymers can be used with other sensing techniques to improve sensibility, accuracy and response time. Researches have demonstrated the use of these compounds with capacitive, mass sensitive, calorimetric and wave-dependent sensors [23], [129], [130].

Gas sensors based on polymers are used for over 35 years, with good accuracy and response time dependent on the chosen materials, reaching 11 minutes and recovery time of a few minutes; these sensors also present low stability, in some cases after one month of operation [124]. They run at room temperature, with low energy demand, while they can be easily affected by environmental changes, present inadequate selectivity, and they are consumable, with a lifetime of approximately 6 months. The sensors can be easily reproduced in large scale, into portable devices, with low fabrication costs, although more researches on these compounds should be conducted to achieve better reliability levels. These transducers can be used with other sensing techniques, to achieve greater sensing properties [23], [124], [127], [128].

2.3.5 Carbon Nanotubes

Carbon Nanotubes (CNTs) were first observed in 1991, and have been investigated for over 20 years as gas sensors, and became the assured materials in terms of sensing characteristics to low gas concentrations at room temperature, lower response times and good corrosion resistance. These transducers can respond physically or chemically to different gases; to O_2 and CO_2 the response is reversible and linear, whereas to other gases, irreversible chemical reactions may happen. It also has higher costs due to the difficulty in fabrication and reproduction. The use of CNTs to sense gases can be set as individual CNTs, or arrays, where multiple units of these transducers are placed to make the measurements [23], [131].

The fabrication process of these devices generate impurities, that are inserted to the nanotubes, and must be cleaned, in order to generate precise measurements; the cleaning process is of a key importance on making the CNTs to work properly, what impacts negatively on producing these transducers in large scale [135]. CNTs are constructed from graphene sheets, which are rolled, in order to produce these transducers. The angle and the radius in which the sheets are rolled determine whether the carbon nanotube will be metallic or semiconductor. The rolling process also determine if the CNT will be single-walled or multi-walled [23], [101], [132], [133].

Single-Walled Carbon Nanotubes (SWCNTs) are constructed from a single graphene sheet. The use of a single SWCNT presents worse sensing characteristics than using a single MWCNT; although the use of a network of SWCNTs have been reported by Wang *et al.* [134] to present better sensing characteristics and mechanical resistance, as well as faster response and recovery times [47], [77], [101], [131]–[134].

Multi-Walled Carbon Nanotubes (MWCNTs) are com- posed of two or more graphene sheets, displayed concentrically, and supported by Van der Waals forces. The chemical bonds, similar to the ones found on graphite, provide unique mechanical characteristics to the MWCNTs. The use of more than one graphene sheet provides better sensing characteristics to these transducers [47], [101].

The sensing mechanisms of CNTs are described as the variation of conductivity or electrical resistance, due to direct contact with the target gas; the variations of the electrical characteristics are proportional to the concentration of the gas [132]. As no commercial solutions were found, the developed sensors should be analyzed with known concentrations of the target gas, to ensure the correct calibration and analysis of the gases. No reports on the linearity of these transducers were found.

One of the drawbacks of using CNTs is the recovery time; when the target gas is in contact with the transducer, the gas penetrates the nanotubes, as the material absorbs the gas, the time that is necessary for the CNT recover from this contact is higher than other sensors, what can lead to inaccurate readings, conducting to malfunction of the systems dependents from the measurements [131]. The combination of CNTs with other sensing techniques have been reported to reduce the recovery time, as well as improve sensing and mechanical characteristics, as in the combination of CNTs and polymers to sense environmental gases [47], [130].

2.3.6 Acoustic

Sound propagates differently depending on the propagation medium: in gases, the ultrasonic speed is a function of the temperature, pressure, humidity and the gas mixture properties. Taking advantage of these characteristics, acoustic waves can be used to determine whether a gas is present on the ambient or not. The analysis of the gases can be performed by the speed of the sound, by the attenuation of the signal, the acoustic impedance, or the combination these characteristics [23], [39], [96], [135]. Figure 5 shows the schematic used on the acoustic gas sensing approaches.

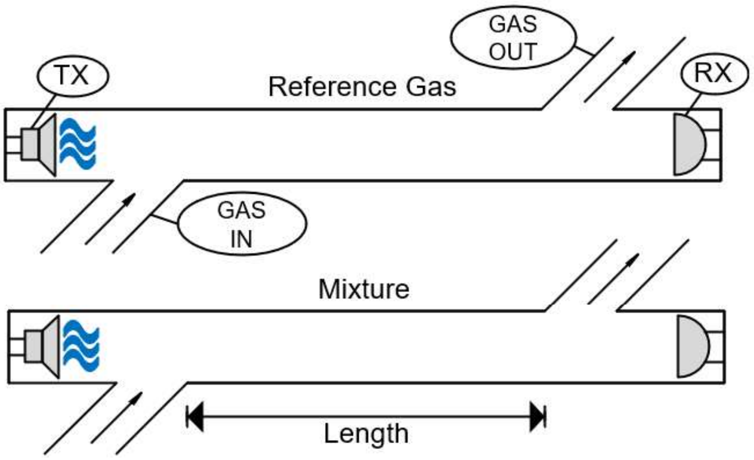


Figure 5 – *Ultrasonic speed-based gas sensor.*

The most used and studied technique is based on the difference of sonic speed in different propagation medium, using the propagation time in a fixed distance to determine the composition of a given gas mixture. Equation (2) shows the dependency of the sound speed in relation to the gaseous propagation medium [97].

$$c = \sqrt{\mathrm{kRT}/M}\,, \tag{2}$$

Where c is the speed of the sound, in meters per second; k is the average specific heat ratio; R is the gas constant; T is the temperature, in Kelvin; and M is the average molecular weight [97]. The approach is efficient by measuring concentrations in binary gases, in other words, it is useful to measure gas concentrations in systems where there is only the possibility of having two types of gases. When more gases are added to the system, the detection can present a false positive to a given gas, due to the presence of another gas in the proportions that would generate the same sound speed in the propagation medium [98]. Moreover, the temperature variations can influence on the sensing process; the calibration must take in consideration the working temperature of the system where the sensor will function, and analyze the possible moisture in these temperatures. A sensor using this technology, combined with another sensing technique can refine the sensing accuracy, as well as the selectivity. Prototypes using this technology have been proposed by Minglei *et al.* [98], and Sonoyama *et al.* [97].

The attenuation of the acoustic signal is a reference to the scattered energy in a defined propagation distance. When a signal propagates through a gaseous medium, the equilibrium of the gases is broken and the molecules exchange energy through collisions, generating thermal energy. The energy generated is proportional to the energy consumed by the gaseous molecules creating the movement that lead to the collisions. It is said that the acoustic energy is absorbed by the system, and the level of absorption is proportional to the concentration of the gases that compose the propagation medium [23], [96], [99]. Prototypes of acoustic attenuation gas sensing were developed by Perculescu *et al.*, to sense CH_4, CO_2, N_2, ethylene (C_2H_4) and air [99]; and by Shengying and Minglei to sense SF_6 [96]. The attenuation of the signal is calculated using Equation (3) [96].

$$P = P_O * e^{-\alpha X} \quad (3)$$

Where P_o and P are the acoustic pressure in two different points, α is the attenuation coefficient and X is the distance from P_o to P [96].

Acoustic impedance analysis is less studied technique to sense gases, and no commercial uses of this technique have been identified. The gas is sensed through its density, by Equation (4) [135].

$$Z = \rho c , \quad (4)$$

Where Z is the acoustic impedance, ρ is the gas density, and c is the sonic speed. This technique can generate detection errors, as a given gas mixture can be mistaken to another, as they can present the same density. It also could be used within another detection technique [135].

The use of only one duct, considering the theoretical measurements of the ultrasonic speed, acoustic impedance and attenuation in air or other gases could decrease the energy consumption of the sensors based on this technique, as well as be more precise, considering the fact that the reference chamber could suffer variations, different from the environmental changes the ambient where the system is installed. The gas that should be detected can penetrate the reference tube, or temperature changes could easily be different from the ones on the second tube

2.3.7 Optic

It is well known that specific gases absorb different wavelengths, and every gas has its peculiar absorption property to different wavelengths; the wavelengths and the target gases are listed on the High-Resolution Transmission Molecular Absorption (HITRAN) database [136]. Many techniques explore these optical characteristics to measure gas concentrations on the environment, and other rely on adding materials that react with gases in the presence of light, reflecting, absorbing or shifting wavelength from the emitted beam to fiber optics, in other words, these materials react with the target gas in the presence of determined wavelength, emitting a different wavelength, absorbing or reflecting the emitted light. The materials used to produce these effects are normally nanomaterials, employing polymers or metals [23], [37].

The fluorescence quenching sensors are normally composed by a matrix of nanomaterials, permissible and sensitive to the target gas, mainly composed by polymers and in some cases metals, attached to the tip of a fiber optic, with a 50:50 Y-type optical coupler. On the one tip of the coupler, a light source is attached, and an optical spectrometer is installed on the other. The polymer matrix, with the target gas and adequate wavelength and energy, will react and emit a different wavelength, where the intensity of the light is proportional to the gas concentration. The response time is variable, being approximately a few seconds, depending on the chosen materials, intensity of the light source and target gas concentrations [23], [37], [92], [113]. Figure 6 illustrates this technique of sensing gases.

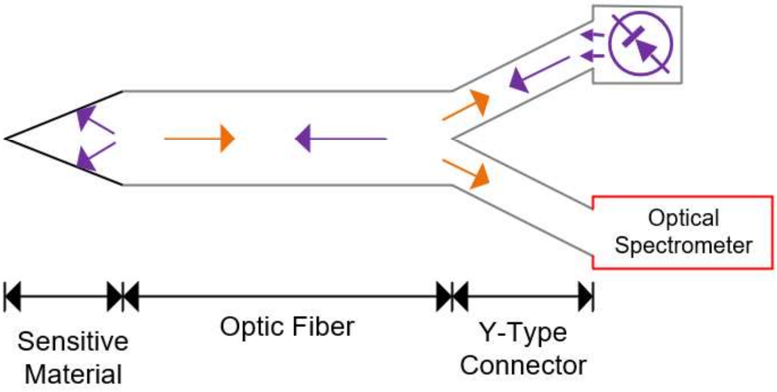


Figure 6 – *The fluorescent quenching effect gas detector.*

The absorption spectroscopy techniques, such as the Tunable Diode Laser Absorption Spectroscopy (TDLAS) consists on the emission of a modulated wavelength at a determined frequency and amplitude trough a fixed length with the presence of the gas; part of the light is absorbed, and then the light beam is detected by a photo-diode. On the TDLAS technique, the gas is sensed by the analysis of the harmonics of the signal, making use of the Beer-Lambert law [23], [39], [95]. Shao *et al.* [137] had discussed integration between the optical spectrometry and electrochemistry to sense NH_3, without any calibration. Iwata *et al.* [138] presented another sensor, using the UV absorption spectroscopy with a calcium fluorite (CaF_2) window to analyze breath moisture in parts per billion levels.

Optical Time Domain Reflectometry (OTDR) is a common technique used in optical networks, and had been studied to sense chemicals, using the reflected light signal as a measurement parameter. The signal is attenuated and scattered by the optical fiber, depending on the length and specifications of the fiber; part of the scattered signal returns to the source, being able to measure the level of the signal and compare with the expected returning signal in normal operation conditions, with the absence of the target gas [114].

Infrared (IR) based gas sensors use the target gas absorption of IR light to determine which gas is present on the environment, and it is possible to determine its concentration by the level of attenuation on the signal. The light beam is emitted by a diode and received by a photo-detector, analyzed by a Micro Controller Unit (MCU) and displayed on a screen or shared with other devices [28]. CO_2 sensors based on IR light have been developed over the past 4 years, researchers focused on meliorate characteristics of these sensors, weather it was the response time, sensitivity, accuracy and selectivity of the devices [2], [139]–[142]. Figure 7 shows a representation of an optical gas sensor, coupled on a duct.

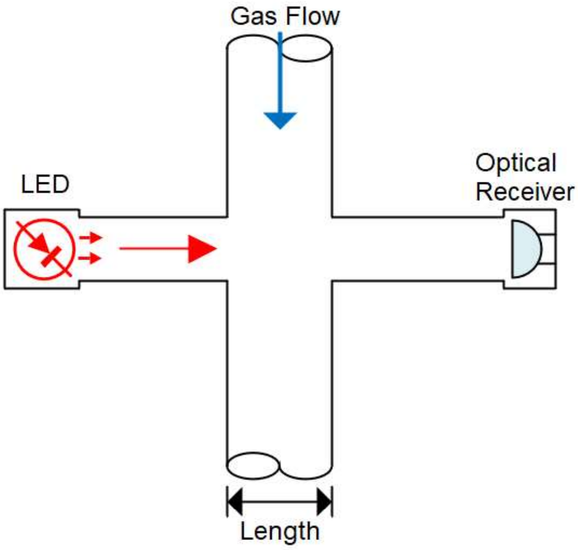


Figure 7 – *Optical gas sensor coupled on a duct with gas flow.*

2.4. Wireless gas sensors

Over the last 20 years, the research and development of smart sensors for different purposes have become essential in many areas, such as environmental monitoring and pollution control, residential and industrial automation, protective equipment and assisted living devices [3], [6], [7], [143]. The necessity of remote monitoring of numerous parameters lead to the development of wireless sensors in numerous fields. Moreover, wireless sensors and the construction of WSANs facilitated the automation process, data collection, transfer, processing, and storage. More recently, these smart sensors have acquired the capacity of performing Machine-to-Machine (M2M) communications, simplifying the communication and inter-operation between devices, granting numerous possibilities in control systems and automation [11], [12].

Many authors have focused on proposal and creation of gas sensors to attend a specific target gases, in particular conditions [40], [45], [102], [107], [109]. As examples, Sieber *et al.* [32] proposed an oxygen gas sensor for personal protective equipment without wireless transmissions; in [34] the authors have developed a CO_2 gas sensor for remotely monitoring the levels of this gas, transferring the data through General Packet Radio System (GPRS).

Recently, systems for indoor air quality monitoring and even to control gas leakages based on the data collected by smart sensors have been proposed [91], [102], [103], [107]. They present different characteristics weather it is on the sensing mechanism or the implemented communication protocols. Many contributions towards wireless gas sensors and IoT-enabled gas sensors are only published on proceedings, and to the best of authors knowledge, no commercial solution is available on the market. In this section, the main characteristics and requirements of IoT-enabled gas sensors and the most relevant smart gas sensors proposed in the literature will be reviewed, emphasizing the main characteristics of the proposals.

2.4.1 Standard protocols for connected gas sensors

The demand on IoT environments might change in compliance with the applications and their specifications. In general, IoT networks are known to their low energy consumption, low power transmissions, and reduced number of data transfer through the network. Besides, it is essential that the devices on the network can operate for long periods, generate precise data and communicate with other devices on the network. Other applications may demand for real-time data acquisition, exhibition of the collected information to users, long range communications and battery-based devices [11], [12].

To attend these characteristics, it is essential to choose correctly the sensing technology for these applications, as well as the network characteristics, in order to avoid energy loss with poorly selected protocols on the communication stack, starting with the Layer 2 protocols, attending the communication requirements in terms of mobility, security, area of coverage, and energy consumption.

2.4.1.1 Long-range communications

For long-range communications, protocols such as Long Range Wide Area Network (LoRaWAN), SigFox, Narrowband IoT (NB-IoT), GPRS, and Long Term Evolution for Machines (LTE-M) have been proposed in scenarios with low power consumption, some of those for low data transfer and other attending more frequent transmissions in short periods. These protocols are compatible with Internet Protocol (IP) networks, which allow M2M communications through high layers protocols.

Most part of the protocols above mentioned are provided as a service by network operators, as the SigFox, NB-IoT, GPRS, and LTE-M, therefore, users must pay for the use of the provided wireless network. The LoRaWAN protocol is not provided by a telecommunications operator, thus the infrastructure must be implemented before choosing this communication technology [11], [14].

2.4.1.2 Short-range communications

For short-range communications, Bluetooth, Wireless Fidelity (Wi-Fi) and ZigBee are the most common technologies proposed for sensors; energy consumption may limit the usage of some of these protocols in terms of IoT-enabled devices, as some devices should be able to operate on batteries for several years. Following the TCP/IP stack, the network layer protocol is dependent on the layer 2 protocol; in some cases, as the IEEE 802.15.4, it is necessary an adaptation protocol in between the layers 2 and 3. The Internet Protocol version 6 (IPv6) over Low Power Wireless Personal Area Networks (6LowPAN) is a protocol that ensures the IPv6 addressing on low power networks using the IEEE 802.15.4 as a medium access protocol [11], [13], [14].

The ZigBee protocol operates through the MAC ad physical layers defined by the IEEE 802.15.4 standard, with proprietary superior layer protocols. This standard has a proprietary addressing method, using 16 bits, as a short address, or 64 bits as a long address, thus, it does not support any IP addressing. Through the 6LoWPAN adaptation layer, it is possible to communicate through the IEEE 802.15.4 standard with an IPv6 addressing [11], [13], [14].

Bluetooth is a low-power protocol, known as Bluetooth Smart in its version 4, and with theoretical IPv6 addressing, through the 6LoWPAN adaptation layer, in its 5th version. This protocol allows piconets with limited number of devices, reaching a maximum number of 8 connected devices on its version 4. The communication through this protocol is under a master-slave architecture, and it can use gateways, as a smartphone, to reach the internet [11], [13], [14].

Wi-Fi is a widely spread protocol for wireless communications, which is used to connect multiple devices with the internet. It follows the TCP/IP stack, allowing an IPv4 or IPv6 addressing on the network. Data transmission has a higher hate, and the energy consumption is also higher, compared with the previously mentioned protocols for short-range [11], [13], [14].

2.4.1.3 Application layer protocols

The communication between devices with different layer medium access protocols must happen on WSN and IoT environments. It can easily be performed through the application layer protocol. The Hypertext Transfer Protocol (HTTP) and the Hypertext Transfer Protocol Secure (HTTPS) can be modified to perform this bridge between lower protocols, although they were not developed to perform this kind of functionalities. Other protocols as the Constrained Application Protocol (CoAP) and the Message Queuing Telemetry Transport (MQTT) were designed to allow M2M in different scenarios, as the first implements a request/respond scenario and the last attends a publish/subscribe scenario. Transport layer protocols are dependent on the application protocols [11], [13].

2.4.2 Gas sensing solutions for IoT and WSANs

During the past two decades, authors have focused on proposing and developing wireless gas sensors, for diverse applications. The primary approaches on wireless gas sensors were made for monitoring large areas with no specific wireless protocol implemented. Sensors were able to transmit the sensed information through satellite networks or the ISM bands through simple modulation techniques [2], [144], [145]. Later, systems to transfer sensed data through other technologies have been proposed, using cellular networks for long range [45], [104], [108], [109]. Bluetooth, ZigBee and Wi-Fi have been used to short range communications [103], [106], [107].

Recently, other systems have been proposed to attend the demand of remotely sensing gases in different ambiences, as industrial, domestic or even outdoor remote areas [45], [104], [108]–[110]. As new communication protocols are emerging, they are being used to cover wireless sensors networks, when the characteristics of these networks correspond to the ones of these protocols. Some authors have proposed sensors with more than one wireless protocol [103], [109], and different cellular networks have been used to perform the transmission, from the GPRS to the LTE [45], [104], [108], [109].

To attend the demand for gas sensing on smart cities and remote area monitoring, sensors with different characteristics on the sensing elements, data transfer and energy consumption have been proposed, as in these scenarios, energy supply from power lines may not be available and batteries will not keep sensors functioning for long periods. A CO sensor using electrochemical transducers, employing techniques to reduce energy consumption or to grant the necessary power supply by alternative means, as solar panels and aeolic generators, was proposed by Baranov *et al.* [110] to monitor urban areas with ZigBee, although no middleware integration nor online website was reported to have data exhibition to the users.

Based on the second generation of mobile communications, different researchers have proposed gas sensors to attend the remote area monitoring perspective. The GPRS technology was used on [45] and [108]. The first presented a CO_2 sensor for monitoring this gas concentration in remote areas with an optic sensing element and a Global Positioning System (GPS) module; the collected data is stored on a database, as well as on a secure digital (SD) card and exhibit on a web page. The second, authors have proposed a VOC, NO_2 and O_3 sensor with MOS transducers to collect information on urban air pollution, where data is stored on an online database. Based on the Global System for Mobile Communication (GSM), Sun *et al.* [104] proposed and developed a CO and NO_2 sensor with electrochemical elements to monitor air quality on urban areas, collecting data mainly during the 2015 Hong Kong marathon.

Dong *et al.* [109] proposed a natural gas wireless sensor with a MOS transducer, with deployments in different networks, allowing the easy adaptation to divergent scenarios, through the GPRS, 3G, 4G, LoRaWAN and Bluetooth networks. Although this work was focused on environmental monitoring and automation, the sensor was not integrated on a middleware with a dashboard, to facilitate the visualization of the collected data.

The research focused on gas sensors for indoor monitoring have started with the development of new devices with the capacity of sensing at least one target gas with good precision and alert the users by enabling an alarm, which become a commercial product, installed in many houses, apartments and offices.

Wireless gas sensors focused on indoor monitoring were proposed on the literature by some authors, with different characteristics. Peng *et al.* [146] presented a ZigBee-based optical gas sensor to monitor VOCs in enclosed environments, displaying the collected information in real-time in an online dashboard. A system to detect and withhold CH_4 leakages on industrial environments was proposed by Somov *et al.* [107], based on catalytic gas sensors and with the ZigBee stack to perform the system's communication.

Focusing on indoor environmental quality control, a photo- acoustic based CO_2 sensor was proposed by [102], employing a Z-Wave transceiver to make the communication with a gateway, responsible to transfer data to an online dashboard with periodic data collection and transmission. Suh *et al.* [103] presented a portable dual gas detector for H_2S and CO based on Wi-Fi and Bluetooth, operating with MOS transducers and communicating with smartphones; the sensed data in transferred to an online spreadsheet.

Jelicic *et al.* [91], Kumar *et al.* [106] and Choi *et al.* [111] have proposed multi-gas wireless sensors based on ZigBee. The first proposed a sensor to detect and VOC with MOS transducers deploying a solution that is capable for detecting people on the environment to perform the gas sensing, which helps to decrease energy consumption. The second presented a SO_2, NO_2, CO, CO_2, and O_2 sensor with electrochemical transducers with periodic calibration, to monitor greenhouse gases. The last developed a CO, CO_2, NO_2, and CH_4 sensor operating with MOS, electrochemical and optical transducers, to monitor air pollution in diverse environments.

2.5. Plug-and-Play technologies

With the popularization of the Internet of Things, sensors and actuators should be able to be connected with low effort by the users, who not always have the necessary knowledge to perform complex configurations. Most part of the users just want to acquire a new device, turn it on, and have all the functionalities with no difficulty, in terms of hardware and network [11], [14].

In terms of the network, servers are used to provide the IP address to devices that request a new connection, allowing cellphones, tablets, computers, and other devices to be connected with the internet without any effort and knowledge by the users, being necessary only to set the service set identifier (SSID) and password in wireless networks [147].

The term Plug-and-Play refers to hardware devices that are automatically configured without human intervention, as computer peripheral connected through Universal Serial Bus (USB) interfaces [148]. Its development become with the popularization of electronic devices and computers, as consumers should not have previous knowledge to install, configure, and use of certain basic devices, as mouse and keyboards.

2.5.1 Serial communication protocols for microcontroller units

There are three main serial protocols for interconnecting low-power microcontroller units, the Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI), and the Universal Asynchronous Receiver/Transmitter (UART). These protocols are described on the next paragraphs.

The I2C is a synchronous serial communication protocol, introduced by Philips Semiconductors, designed to connect devices on a Master-Slave architecture, where the Master allows the slaves to transmit or receive data through the I2C-bus. All devices connected on the bus have a unique 7-bit address, allowing a theoretical number of 128 devices to be connected through the bus. The connection between devices is made by two lines: one providing the clock generated by the Master, and the other to transfer data [149].

The SPI is a synchronous serial communication protocol, designed by Motorola, to support full-duplex communications under a Master-Slave architecture, using four lines to perform the communication; the Master device is responsible to provide the clock for the Slaves devices. The weakness of the SPI compared to the I2C is the fact that the first is not a fixed standard, allowing numerous variations of this protocol [149].

The UART is an asynchronous protocol designed to interconnect only two devices through a two-line bus, where the receiver channel from the first device must be connected on the transmitter channel from the second, and vice-versa. Both devices must have the same transmission rate set to communicate [149]. Although this approach aims the connection of only two devices, it is possible to overcome the limitation of this protocol and interconnect numerous devices on the same line.

2.5.2 Plug-and-play solutions for IoT-ready devices

Few authors have studied and proposed models of IoT-enabled plug-and-play sensors and actuators [150]–[152], although most part of the proposals on the literature are complex, involving three or more communication protocols between the devices that must be easily interconnected. In all studied approaches, batteries, wireless communication modules, memories, sensors, and actuators are treated as peripherals.

Mikhaylov and Petajajarvi [150] have proposed a modular PnP solution, where the main board was designed with a STM32F207 MCU, and the modules were deployed with a MSP430G2553 in each. The communication interface was made through an 8-line bus, with the UART, I2C, and SPI communication protocols. This approach allows any sensor or actuator to be connected with the main board, although the energy consumption could increase.

Weddell *et al.* [151] proposed a modular plug-and-play solution, using the One-Wire protocol to connect sensors and actuators to the main board. Authors have used a multiplexer to determine which module is transmitting to the main board. The integration between the main board and the peripheral boards is made through the Registered Jack 45 (RJ-45) connectors. In [152], a modular PnP solution based on field programmable gate array (FPGA) and digital signal processing (DSP) was proposed and demonstrated, making use of the UART, SPI, and I2C communication protocols, and with ADC and digital connectors. A multiplexer was used to select the communication protocol used between the modules.

2.6. Discussion and open issues

This section brings the discussion towards the best solutions studied on this chapter, and the open issues regarding these topics.

2.6.1 Sensing Technologies

Table 1 brings the main characteristics on the sensing technologies reviewed on this survey paper. To the best of authors' knowledge, until the date of this publication, no authors have reported the approximately lifetime of carbon nanotubes transducers for sensing gases.

The studied solutions for gas monitoring on connected environments mostly apply the most antique technologies to sense gases, as the electrochemical, MOS and catalytic, as these technologies are the most available on the market. These technologies also consume less energy than acoustic and optic gas sensors, which is not the best option for battery-based sensors. Polymers present short lifetime and carbon nanotubes were not found on commercial solutions, being unviable for IoT-based solutions.

Despite of the possibility of interference from other gases and environmental factors, as temperature and humidity, sensors based on chemical reactions can have their precision and accuracy increased with the employment of recalibration processes along with filters for other gases.

Table 1 – *Main Gas Sensing Technologies available for IoT-Enabled Gas Sensors.*

Technology	Description	Lifetime	Strengths	Weaknesses
Electro-chemical	Composed by a membrane, an electrolyte, and electrodes. Reacts with the target gases, generating a variation on the output signal	2-5 years	• Low cost • Easily miniaturized • Filters can improve sensitivity	• Interference from other gases and environmental factors • Low sensitivity and selectivity • High response time • Periodical calibration is necessary
MOS	Consists on a metal oxide semiconductor connected through a wire, involved on a ceramic structure, where it is heated	2-5 years	• Low cost • Easily miniaturized • Filters can improve sensitivity	• Need of heaters • Interference from other gases • Low sensitivity and selectivity • Periodical calibration s necessary

Technology	Description	Lifetime	Strengths	Weaknesses
Catalytic	Consists of two elements dispersed on a substrate. The active element reacts with the target gases, generating a variation on its resistance	Up to 10 years	• Low cost • Long lifetime • Easy fabrication and replication • Low response time • Low environmental interference	• Consumable • Can be compromised by other gases • Need of oxygen to perform gas detection • Reacts with more than one target gas • Periodical calibration s necessary
Polymers	Reacts with the target gases, generating an output signal variation according with the concentration of the target gas; the materials are consumed by the reaction, presenting low lifetime	< 6 months	• Low cost • High sensitivity • Low response time • Easily miniaturized	• Instability • Long response and recovery times • Consumable • Periodical calibration s necessary • Low lifetime
Carbon Nanotubes	The interaction between the nanotubes and gas molecules changes the electron configuration of these nanostructures, allowing the measurement of differences on the output current or tension.	n/a[1]	• Great sensitivity and selectivity • Low response time • Small weight and size	• Difficulty in fabrication and replication • High costs • No commercial solutions available • Response time can be affected by gas molecules stocked into the nanostructures
Acoustic	Relies on sound propagation characteristics to determine the gases on the sensor. Can be used to measure gas flow in pipes.	5-10 years	• Ideal for dual gas mixtures • Low environmental interference • Low response time • Log lifetime	• Reference gas needed • Difficulty in miniaturization • Low sensitivity in 3+ gas mixture • High cost
Optic	Relies on wavelength propagation characteristics to determine the gases in the mixture. It can be used to determine more than one gas	5-10 years	• High sensitivity and selectivity • No environmental interference • Low response time • No periodical calibration needed • Long lifetime	• Difficulty in miniaturization • High cost

[1] No contributions on the literature have reported the lifetime of carbon nanotubes based gas sensors.

2.6.2 Wireless gas sensors

Table 2 summarizes the main aspects of the most promising systems, in terms of sensing technologies, wireless protocols, and their focus. It includes a brief description of each proposal highlighting their strengths and weakness.

Table 2 – *Comparison among the studied approaches for remotely sensing gases.*

Ref.	Description	Target Gases	Sensing Technology	Wireless Protocol	Strengths	Weaknesses
[45]	Remote gas monitoring system. Data collected are transferred to a database and displayed on a webpage.	CO_2	NDIR (Optic)	GPRS	• Measurement of other environmental parameters • GPS module • Has a LCD display • Information displayed on a webpage	• Only one target gas • Periodic data transfer • No M2M • No IoT platform integration
[91]	Energy efficient gas sensor for indoor air quality. Nodes exchange information in order to save energy	VOC CO	MOS	ZigBee	• Low power • Sensor is awaken by people's presence • Supports M2M	• Periodic data transfer • Only battery based • No online dashboard, nor IoT platform integration
[109]	Describes the deployment of the sensor in various networks, although no data transfer to online dashboards was reported, nor application layer protocols were described	Natural Gas	MOS	GPRS 3G/4G LoRaWAN Bluetooth	• Deployed in various networks • Monitoring of diverse environmental parameters	• Only one target gas • Periodic data transfer • No M2M communication were reported or tested • No IoT platform integration presented • No transport nor application layer protocols were described on the publication
[110]	Presents the development of a CO wireless sensor with hybrid power supply to monitor outdoor areas, focusing on energy efficiency	CO	Electrochemical	ZigBee	• Hybrid power supply • Only transmits relevant data	• Only one target gas • Periodic data transfer • No M2M • No IoT platform integration • No application layer protocol presented
[111]	Multi-gas wireless sensor using one MCU to collect the data from the transducers and another to transfer the information to the network	CO CO_2 NO_2 CH_4	Optic Electrochemical MOS	ZigBee	• Multi-gas • Measures other environmental parameters • Hybrid power supply • Small size	• No M2M • No application layer protocol presented
[102]	Sensor collects environmental data and transfers it to an online dashboard through a gateway	CO_2	Photoacoustic	Z-Wave	• Thermal compensation • No reference channel needed	• Only one target gas • Periodic data transfer • No application layer protocol presented
[103]	Portable multi-gas sensor that uses a smartphone as a gateway. Data available on Google spreadsheet	H_2S CO	MOS	Wi-Fi Bluetooth	• Hybrid power supply • Small size • Low power consumption	• No M2M • Uses HTTPS as application layer protocol
[106]	A multi-gas sensor with automatic periodic calibration	SO_2 NO_2 CO CO_2 O_2	Electrochemical	ZigBee	• Automatic periodic recalibration • Measures other environmental parameters	• No M2M • No IoT platform integration

Ref.	Description	Target Gases	Sensing Technology	Wireless Protocol	Strengths	Weaknesses
[107]	Gas sensor to identify gas leakages on industrial environments and gas distribution systems, integrated with an actuator to immediately interrupt the detected leakage	CH_4	Catalytic	ZigBee	• Low power consumption • Reduction of irrelevant data transmission	• Only one target gas • Periodic data transfer • No IoT platform integration • No M2M
[108]	Presents a WSN to collect data on gaseous air pollutants on urban areas. Sensed information is stored on a database	O_3 NO_2 VOC	MOS	GPRS	• Real evaluation in urban areas • Highlights the need of periodic calibration	• Periodic data transfer • No IoT platform integration • No M2M
[146]	Energy efficient indoor gas sensor with M2M communication data displayed on an online dashboard. The collected data is stored on a local database	VOC	Photoionization detectors (Optic)	ZigBee	• Low power consumption • Sensor and actuator • M2M communications	• Only one target gas • Periodic data transfer • No IoT platform integration • Powered only by batteries

In terms of wireless transmission protocols, in short range communication, the ZigBee protocol is the most applied to the studied proposals. This protocol uses the IEEE 802.15.4 physical and medium access control (MAC) layers, although it does not allow the use of IPv6 on the final devices, as the pure IEEE 802.15.4 deployed with the 6LoWPAN adaptation layer. As this protocol can be used in mesh networks, the energy consumption and communication range on the network can be greater than Wi-Fi applications with one single access point, which is more suitable for IoT applications.

Regarding long-range communications, cellular technologies were more explored on wireless gas sensors. The second generation of mobile communications was applied in four solutions, as these networks are still operating and the cost to use these networks is small, compared to the costs of deploying a new network to operate wireless devices, as the LoRaWAN. The monitoring process of remote areas, such as big farms, where the coverage of legacy mobile networks are pour, protocols as LoRaWAN may be more suitable for these scenarios.

Most part of the studied solutions does not support M2M communications, which is an important feature on smart environments and IoT-ready solutions. This aspect allows devices to act in favor of users in determined situations, as stopping gas leakages, opening windows to help with the ventilation, or even warning users with alarms. This can be achieved through IoT platforms, that store and forward data to other devices with the same context of the sensors. Moreover, these platforms can also exhibit the collected information for the final users.

2.6.3 Plug-and-Play technologies

Table 3 summarizes the main aspects of the most promising Plug-and-Play solutions for low-power smart devices, in terms of communication protocols, interfaces, and their focus. It includes a brief description of each proposal highlighting their strengths and weakness.

The proposals for plug-and-play solutions found on the literature followed a modular approach, in which the main board is composed by a MCU and the modules to be attached to this board also contain a MCU. All three solutions found on the literature approached the wireless communication as a peripheral of the proposed main boards. The solutions were not integrated with any IoT platform, and no M2M communications were reported or experimented by the authors.

Table 3 – *Comparison among the studied approaches for IoT-based Plug-and-Play solutions.*

Ref.	Description	Communication Protocol	Interface	Strengths	Weaknesses
[150]	Modular PnP solution, made with UART, I2C, and SPI.	UART I2C SPI	8-Line Bus	• Low-Power MCUs	• Multi-protocol approach • The main board must know the addresses of some of the connected boards • Wireless communication is considered as a peripheral
[151]	Modular PnP solution with a single protocol. The main board needs to know the addresses of the peripherals.	One-Wire	RJ-45	• Single-protocol	• The main board must know the addresses previously • Limited number of devices • Wireless communication is considered as a peripheral
[152]	Complex PnP solution made with FPGA and DSP. UART, I2C, and SPI are used for the communication between the main board and the modules.	UART I2C SPI	RJ-45	• FPGA and DSP-Based	• Multi-protocol approach • Wireless communication is considered as a peripheral • Complex and higher power consumption

In terms of communication protocols for microcontroller units, most part of the proposals have implemented more than one, although this approach is more complex. The I2C and One-Wire protocols require an addressing system, where the main board need to know the addresses of the peripherals that will be connected to the board. This approach requires a major adaptation for the development of solutions for these PnP systems, and limits the number of connected devices. Moreover, the solutions that have implemented the UART communication, only allow one peripheral device with this protocol. The number of SPI devices is also limited.

2.6.4 Open issues

In the sequence of the presented discussion, the following open issues are identified and proposed for further research studies:

- Gas sensing could provide valuable data to diverse applications, using the IoT paradigm, offering important data for decisions taken by smart devices. They can provide better experiences to users.
- The improvement of sensing characteristics, miniaturization of transducers and combination of sensing technologies are topics with great potential of research.
- Creation of customized multi-gas smart sensor since, to the best of the authors' knowledge, there are no these kind of solutions in the literature.
- Proposals following a Plug-and-Play approach based on IoT focusing on the end-user empowerment to properly configure these devices according to their needs.
- The lack of plug-and-play proposals on the literature demonstrates the need of new approaches for this feature in IoT-ready low-power devices.

Based on the literature review and the analysis of the most promising solutions presented in this chapter, the proposal of a novel IoT-ready plug-and-play solution for sensing multiple environmental gases will be presented on the next Chapters of this dissertation.

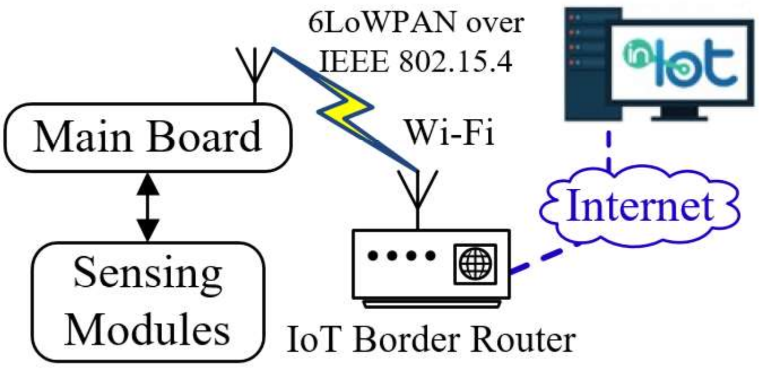
Chapter 3: Proposal of a novel Plug-and-Play Gas Sensor

3.1. Introduction

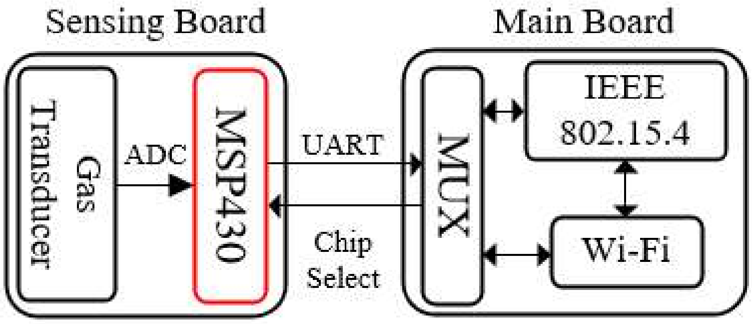
To attend the demand of gas sensing on smart environments, a novel multi-gas smart sensor is proposed in this document, with plug-and-play features, where the users can easily customize the sensor according with the needs of the environment to be sensed. The proposed solution for the ambient gas detection can be deployed in both indoor and outdoor environments. The proposed sensor is IoT-ready, allowing users to verify the sensed information through the Internet and through a mobile application (App). Moreover, the solution allows other devices on the same context to be aware of the concentration of the sensed gases on the environment, permitting actions to be taken if the levels of overcome the ideal for not putting users at risk.

The proposed system was designed to facilitate the installation by the users: with one single sensor, it is possible to measure the levels of numerous gases and other parameters, using the same structure. The sensor was divided in two parts, one being responsible for the sensing and the other for collecting the data and transferring it to an IoT Middleware. The IoT Middleware allows an easy integration among connected devices, independently from the wireless protocol, which reduces the complexity on sensors and actuators [13], [36]. In this proposal, the authors have chosen to publish the data on the *In.IoT* Middleware [153], as it is the best option to display the information for the users and due to the easy deployment of mobile applications with this specific middleware.

The proposed sensor considers two different tiers: the transmission tier, named as main board, and the sensing tier. The transmission tier is the sensor's core, responsible to transfer the sensed information to the network. For this proposal, two of the main wireless short-range protocols were deployed: the 6LoWPAN over the IEEE 802.15.4 and the IEEE 802.11, although the sensor is capable of being deployed with any available communication protocol, with minor changes on the main board. Figure 8 shows the block diagram of the proposed sensor, where (a) is the proposed system, and (b) is the detailed diagram of the proposed sensor. Although the sensor supports up to 16 sensing boards, there was constructed 10 different sensors, to validate the plug-and-play and multi-gas sensing features.



(a) Block diagram of the proposed sensor.



(b) Detailed diagram of the proposed sensor, highlighting the sensing board and the main board.

Figure 8 – *Schematics of the proposed plug-and-play multi-gas sensor, where (a) is the block diagram of the pr0posed sensor, and (b) is the detailed diagram of the proposed sensor, highlighting the sensing board and the main board.*

3.2. Plug-and-Play interface

The expression ‘Plug-and-Play’ indicates the ability of a device to be automatically configured when attached to another hardware, without or with little human intervention. Most part of these peripherals are connected to the main hardware through USB interface. The main disadvantage on this approach, in terms of IoT-enabled devices, is the high energy consumption, memory usage, and processing power by the nodes with this approach [152]. Other protocols, designed to interconnect microcontrollers, as the universal serial communication interface (USCI), which supports multiple serial communication modules on the same hardware, as the I2C, SPI, and UART can be explored, to achieve the Plug-and-Play feature for IoT-ready devices [150]–[152].

The plug-and-play interface proposed on this paper uses the UART protocol to transfer the information from the sensing boards to the main board. To grant the operability of the protocol with more than two devices on the same line, a multiplexer was used, performing a time division multiple access (TDMA) on the UART channel, where each sensor has the full access to the communication channel in determined periods. As the sensors transmit a few bytes, the process is fast, allowing the connection of numerous devices, with no performance degradation [154]. Other approaches, as random access using Aloha and Slotted Aloha have been investigated without success for the application of the UART protocol. The USB connector was chosen, as it represents the main plug-and-play peripheral devices for computers, and it is simple for users without technological knowledge to properly configure the proposed device.

3.3. Wireless communication

Considering a short-range Smart Environment scenario where numerous devices will be connected to the Internet, it is necessary to integrate and exchange data among them and the possibility to identify remotely every device inside this environment by their IP addresses. As the number of connected devices is increasing every year, the 128-bit IPv6 address is the most adequate for this scenario. The low power networks are a requirement in terms of energy saving, frame size of the MAC layer protocol, and complexity of the devices, which leads to the use of the 6LoWPAN. With these characteristics, it is possible to nominate and compare the MAC Layer protocols, to select the most suitable for each sensor.

The comparison among MAC layer protocols to local and personal area networks is displayed on Table 4. To the best of authors' knowledge, until the publication date, no Bluetooth® 5 devices support IPv6 connections, which limits the usability of these communication modules on IoT applications and smart devices communications. The comparison between these protocols were made using the characteristics of the available modules to construct the proposed sensor, which are the CC2650 (supporting IEEE 802.15.4), the CC2640R2 (Bluetooth® 5 module), both from Texas Instruments, and the NodeMCU, which is a low-cost MCU with a built-in Wi-Fi module, the ESP8266.

Table 4 – *Comparison between MAC layer protocols for Wireless Sensor Networks.*

IEEE Standard	**802.15.4 [1]**	**802.15.1 [2] (Bluetooth 5)**	**802.11 [3] (Wi-Fi)**
Device	**TI CC2650**	**TI CC2640R2**	**ESP8266**
IP Addressing	IPv6 [4]	n/a	IPv4/IPv6
Medium Access	CSMA-CA	TDMA/FDMA	CSMA-CA
Topology	STAR/MESH	STAR/MESH	STAR
Modulation	O-QPSK	GFSK	ADAPTATIVE
Spread Spectrum	DSSS	HSSS	OFDM
Security	AES 128 b	AES 128 b	WPA2-PSK
Power Consumption	LOW	MEDIUM	HIGH
Max. TX Power	+5 dBm	+5 dBm	+20.5 dBm
Max. Data Rate [5]	250 kbps	2 Mbps	16 Mbps

The comparison was performed between transmission modules available on the market, where [1] us the CC2650, [2] is the CC2640R2, both form Texas Instruments, and [3] is the NodeMCU (with an ESP8266 Wi-Fi module). [4] IPv6 addressing through the 6LoWPAN adaptation layer. [5] The maximum data rate is varies with the number of devices and their distance between each other and from the border router or access point.

The transmission tier also called main board, supports up to 16 sensing boards simultaneously. It is responsible for the data transfer to the *In.IoT* [153] middleware platform. In this board two MCUs where chosen to perform the wireless communication, each supporting one different MAC Layer protocol, the nodeMCU (Wi-Fi) and the TI CC2650 (IEEE 802.15.4). As both wireless protocols use the 2.4 GHz channels, a switch is responsible to define which protocol is being used at the moment. Although only these two protocols have been implemented, any other wireless protocol can be easily deployed on the proposed sensor, with minor modifications on the main board layout.

The first is a low-cost MCU with a built-in Wi-Fi module (the ESP8266), under a 32-bit reduced instruction set computer (RISC) architecture. This MCU allows the extension of the Wi-Fi coverage, as it can operate as a Wi-Fi repeater. The second is a low-power microcontroller that supports the 6LoWPAN over the IEEE 802.15.4, which counts with an advanced RISC machine (ARM) cortex-M3 processor, supporting an embedded operating system (OS). In this proposal, the Contiki OS was chosen for the CC2650 MCU.

For the IEEE 802.15.4, a multi-protocol border router was designed with another CC2650 operating with a Qualcomm DragonBoard model 410c. The DragonBoard operates with the Linaro 96 Boards IoT Edition. The border router supports the IEEE 802.15.4, the IEEE 802.15.1 (Bluetooth 5), IEEE 802.11 (Wi-Fi), and the IEEE 802.3 (Ethernet) to perform the connection with the information to the Internet. It is responsible for publishing the sensed data on the middleware, to receive the information from other topics and forward it to other smart devices on the network.

The proposed sensor has an IPv6 address for the IEEE 802.15.4 and an IPv4 address for the Wi-Fi. Both addressing mechanisms allow the connection with the Internet, making the sensor reachable from external networks. On the application layer, the MQTT protocol was chosen. Different from other protocols on the same layer, this protocol works on a publish/subscribe scenario, sending the sensed data to other devices on the same context of the gas sensor. Other application protocols, such as the CoAP, requires that other devices request the data from the topics of interest, which can generate more transmissions on the network and increase the energy consumption on the smart devices [36].

3.4. Sensing module

The proposed sensing board counts with a MCU, the Texas Instruments (TI) MSP430G2553, a low-power 16-bit RISC microcontroller, with 512B of RAM, 16 kB of flash memory, and maximum clock rate of 16 MHz, which will be referred as MSP430 [149]. This board is responsible to collect environmental data and transfer it to the transmission tier. It must be capable to be connected in any USB port of the main board and function properly.

In the proposed prototype, electrochemical and MOS gas sensors were chosen, due to its easy implementation, although the sensing tier can support any available technology for sensing gases and for other environmental analysis, with minor modifications on its layout. The chosen transducers, from Seeed Studio, need to be pre-heated, and to grant this process, a switch was added to change the operation mode between sensing and pre-heating. Figure 9 shows the chosen gas transducers, where A. is the methane transducer; B. is the carbon monoxide transducer; C. is the oxygen transducer; D. is the benzene transducer; and finally, E. is the adaptation board where the transducers are assembled.

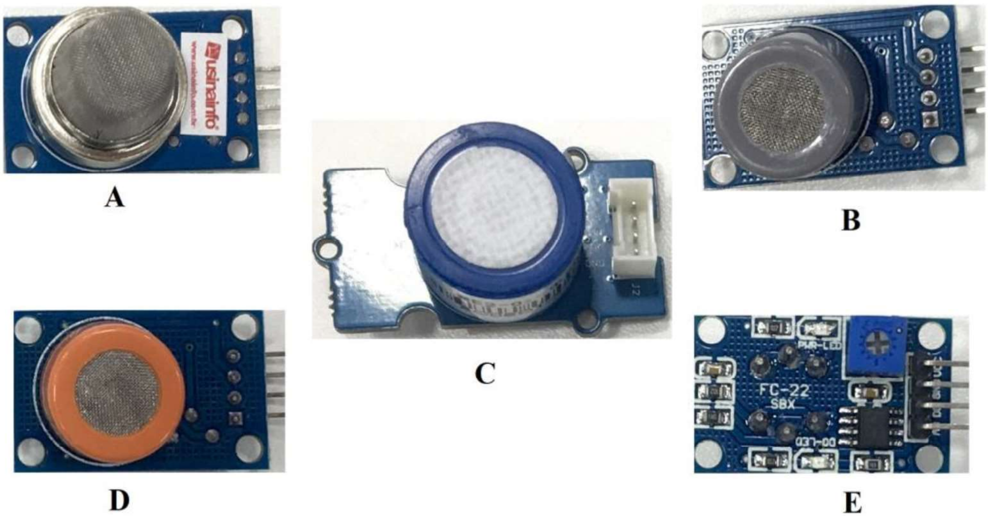


Figure 9 – *Gas transducers. As it is seen: A. is the methane MOS transducer; B. is the carbon monoxide MOS transducer; C. is the oxygen electrochemical transducer; D. is the benzene MOS transducer; and finally, E. is the adaptation board where the transducers are assembled.*

The chosen transducers were calibrated according with the manufacturer information, provided on the datasheet. The measurement equations were also retrieved from the charts, provided on these documents. The provided graphs were linearized, and an equation for each transducer was obtained through regression process, by the graphic analysis appliance on the Microsoft Excel. Table *5* brings the retrieved equations for each transducer (Equations 5 to 14), along with the R-squared coefficient for each obtained equation. This coefficient measures the goodness of fit for equations obtained by linear and nonlinear regression, varying from 0 to 1, where 1 represents the most accuracy equation obtained by the regression process [155].

The sensing tier was modeled to accept any sensing technology with minor modifications. It uses the UART communication protocol to send the sensed data to the main board, responsible for the communication. It was used an USB connector to link both structures, and the sensors can be connected in any of the USB ports on the main board.

Table 5 – *Gas transducers' equations, and their R-squared coefficient.*

Transducer	Sensing Technology	Target Gas	Regression Method	Equation*		R^2 coefficient
MQ-2	MOS	C_3H_8	Power	$C = 42.527*R^{-1.754}$	(5)	0.9977
MQ-3	MOS	C_6H_6	Power	$C = 4811.9*R^{-2.687}$	(6)	0.9977
MQ-4	MOS	Smoke	Exponential	$C = 10^{7} e^{-2.699*R}$	(7)	0.9963
MQ-5	MOS	CH_4	Power	$C = 180.42*R^{-2.588}$	(8)	0.9991
MQ-6	MOS	Alcohol vapor	Power	$C = 5*10^{7}*R^{-5.973}$	(9)	0.996
MQ-7	MOS	CO	Power	$C = 102.14*R^{-1.521}$	(10)	0.9974
MQ-8	MOS	H_2	Power	$C = 978{,}18*R^{-0.69}$	(11)	0.9973
MQ-9	MOS	LPG	Power	$C = 1051*R^{-2.07}$	(12)	0.9981
MQ-135	MOS	NH_3	Power	$C = 107.23*R^{-2.481}$	(13)	0.9969
ME2-O2	Electrochemical	O_2	Linear	$C = 16.667*V$	(14)	1

* R is the relation between the measured resistance on the presence of the target gases and the internal resistance, according with on equation (1), and V is the measured tension.

3.4.1 Firmware

The sensor was designed to be easily handled by final users, so the calibration process is performed automatically when the sensor bards are plugged into the main board. As the sensors must be calibrated with fresh air, the first step of the operation mode is the calibration, which can be performed periodically by only unplugging the gas sensor from the main board and plugging it again, or by pressing the reset button. After the calibration, the sensor starts to measure the concentration of its target gas on the environment. This information is stored on the MCU, compared with the previous sensed information, and if it is relevant, the collected data is transferred to the main board on the correct time-slot. The simplified flowchart of the sensing boards is represented on Figure 10.

The comparison among the sensed data with its previous value decreases the number of transmissions. As the wireless network and the number of wireless transmission are the main energy consumers of the system, only transferring relevant information will decrease the energy consumption by the proposed sensor.

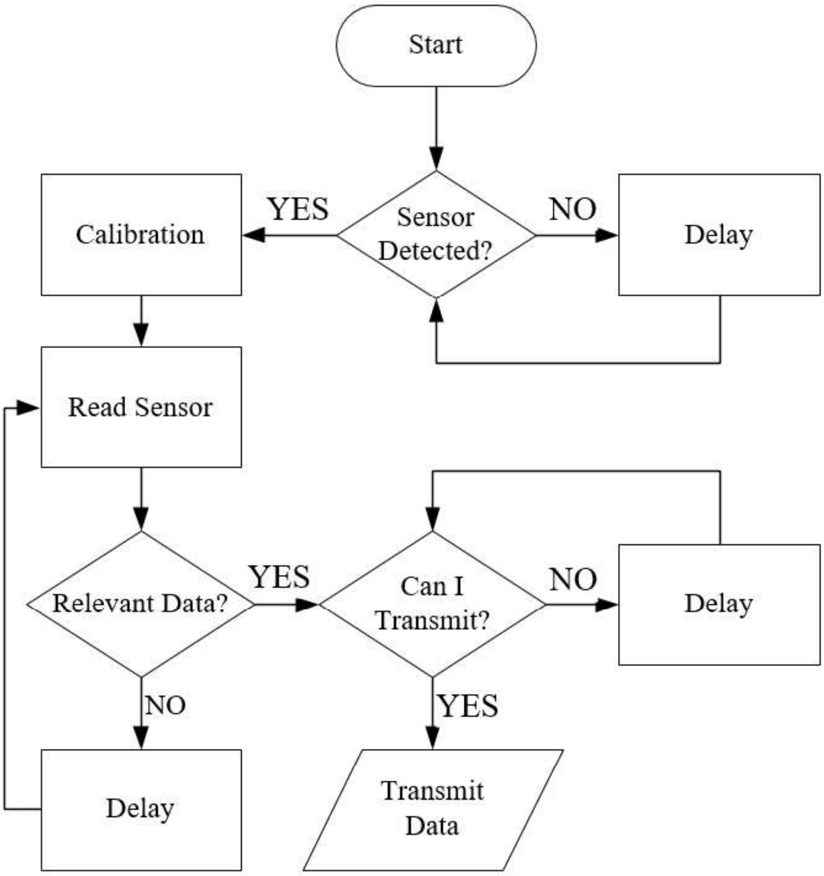


Figure 10 – *Simplified flowchart of the sensing board firmware.*

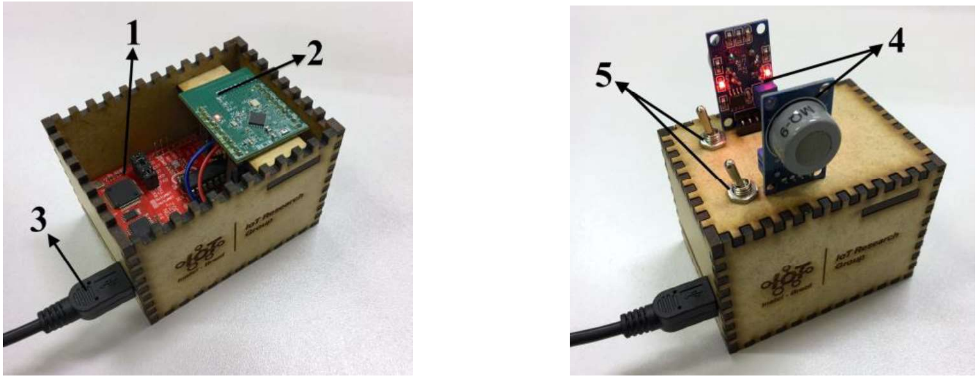
One of the most energy consumption processes on IoT-based systems is the wireless transmissions. By comparing the sensed value with the previous sensed value, and only transmitting it if it is a relevant information, the number of wireless transmissions is reduced, impacting positively on the energy consumption of the proposed system. It also decreases the traffic on the local and wide networks, increasing the QoS.

Chapter 4: Performance evaluation, demonstration, and validation

The construction of the proposed sensor was divided into two prototypes, where the first was used to validate the IEEE 802.15.4 wireless communication, the use of the MQTT protocol, and the firmware of the sensing tier. The second prototype validates the plug-and-play interface and the deployment of two short-range wireless protocols, the IEEE 802.15.4 and the Wi-Fi. This chapter will present these prototypes and the evaluation of them.

4.1. Solution validation

To validate the proposed solution, a first prototype was developed, to validate the wireless communication through the IEEE 802.15.4 protocol, the sensing tier firmware, and the chosen transducers. This first proposal counts with two transducers, for measuring levels of *CO* and LPG. It was hosted on a medium density fiberboard (MDF), although any other material could be used for the case. The firmware on this prototype follows the flowchart previously presented, on Chapter 3. Figure 11 shows this first prototype, deployed to sense carbon monoxide and liquefied petroleum gas. As it can be seen, in A) 1. is the MSP430 launchpad; 2. is the CC2650 communication mote, and 3. is the energy supply cable. In B), 4. shows the transducers and 5. the switches responsible to define the sensing mode and calibration mode.



(A) **(B)**

Figure 11 – *First sensor prototype assembly for the validation, where A) highlights the MCUS, showing 1. the MSP430 launchpad; 2. the CC2650 communication mote, and 3. the energy supply cable. B) brings the gas transducers for CO and LPG in 4., and 5. The switches, responsible to set the calibration or sensing modes.*

The validation of the IEEE 802.15.4 was made through a local MQTT broker to simplify the data transferring process. 'The Mosquitto^{TM}' broker was chosen to perform these experiments, as it is an open source message broker, well-known, and validated solution in the community, and it can operate in low-power computers [156]. The sensor's IPv6 address and the published data is shown in Figure 12. As it may be seen, (a) brings the sensor and border router IPv6 addresses. The network characteristics are presented in (b). Finally, (c) brings the sensed data from the experiments, published on the MQTT broker.

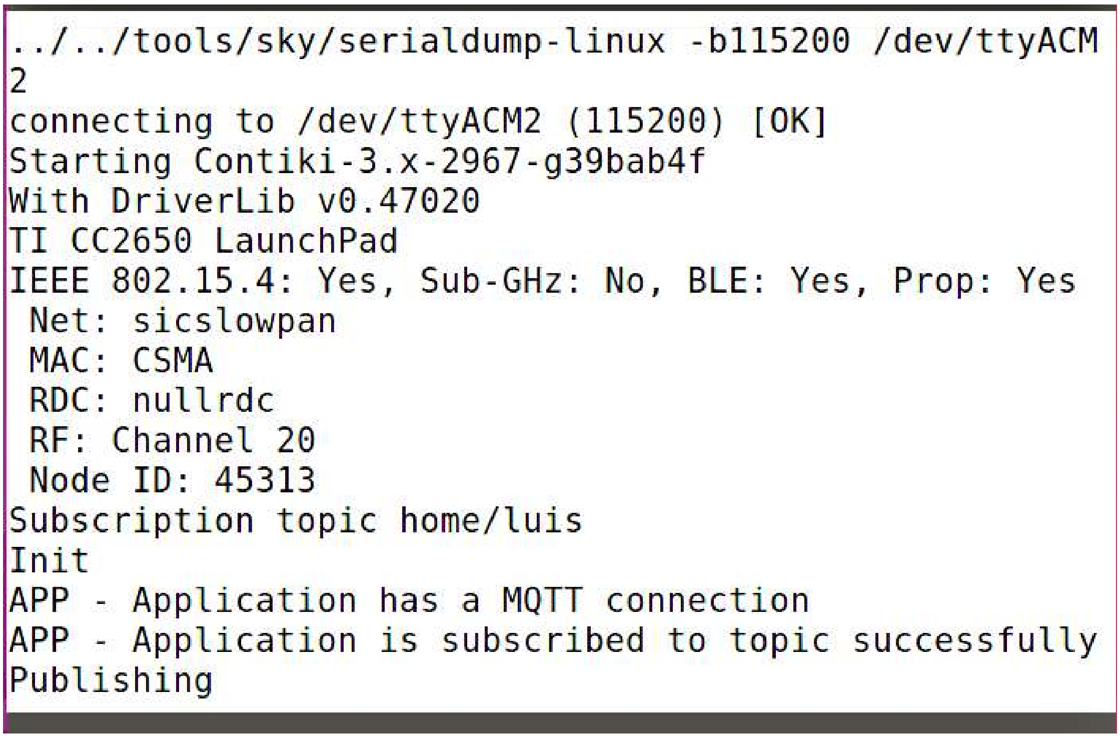
Neighbors

```
fe80::212:4b00:791:b101
```

Routes

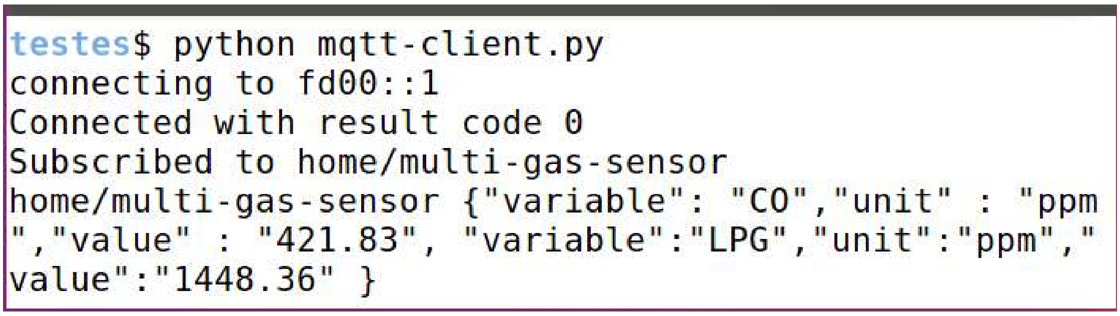
```
fd00::212:4b00:791:b101/128 (via fe80::212:4b00:791:b101) 1026s
```

(a) Sensor and Border-Router IP addresses.



```
../../tools/sky/serialdump-linux -b115200 /dev/ttyACM
2
connecting to /dev/ttyACM2 (115200) [OK]
Starting Contiki-3.x-2967-g39bab4f
With DriverLib v0.47020
TI CC2650 LaunchPad
IEEE 802.15.4: Yes, Sub-GHz: No, BLE: Yes, Prop: Yes
 Net: sicslowpan
 MAC: CSMA
 RDC: nullrdc
 RF: Channel 20
 Node ID: 45313
Subscription topic home/luis
Init
APP - Application has a MQTT connection
APP - Application is subscribed to topic successfully
Publishing
```

(b) Network characteristics.



```
testes$ python mqtt-client.py
connecting to fd00::1
Connected with result code 0
Subscribed to home/multi-gas-sensor
home/multi-gas-sensor {"variable": "CO","unit" : "ppm
","value" : "421.83", "variable":"LPG","unit":"ppm","
value":"1448.36" }
```

(c) Mosquitto^{TM} local MQTT broker with the published data.

Figure 12 – *Data published on the local MQTT broker, where (a) is the sensor and boarder router IPv6 addresses; (b) presents the networks characteristics; and (c) the Mosquitto^{TM} local MQTT broker with the published data.*

4.2. Prototype demonstration

After the solution validation by the initial experiments, the final prototype was developed, to be able to detect up to 16 environmental gases simultaneously. The prototype was deployed with 10 sensing boards, which validates the PnP feature. The interface was submitted to experiments, in which the sensing boards were connected, disconnected, and connected in another place. The interface supported all the boards simultaneously, with no decrease on the measurement intervals. The sensing units were also submitted to experiments, which will be described on the 'Validation Experiments' section, further in this chapter. The sensing boards are presented on Figure 13, as it follows, A. is the USB connector; B. is the MSP430 MCU; C. is the gas transducer connector; and finally, D. is the sensing board with a gas transducer assembled.

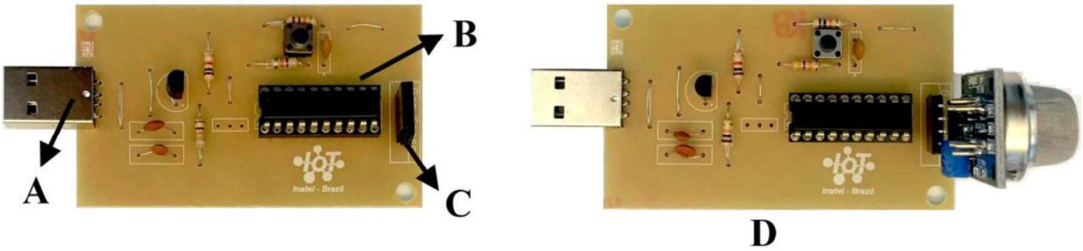


Figure 13 - *Sensing Boards, where A. is the USB connector; B. is the MSP430 low-power MCU; C. is the gas transducer connector; and D. is one of the sensing boards assembled with the methane transducer.*

As the sensor was proposed for ambient monitoring in both indoor and outdoor environments, the main board and the sensing board were protected with a MDF case, analogous as the first prototype, although other materials can be applied, so the proposed sensor can be deployed on outdoor environments without problems. The Ingress Protection against dust and water exposure for long periods (IP-68) should be applied for these scenarios. Figure 14 presents the Main Board, where A. is the multiplexer, responsible for the sensed data receiving; B. is the NodeMCU, responsible for the Wi-Fi communication; and C. is one of the USB connectors. The CC2650 is assembled on the bottom of the main board.

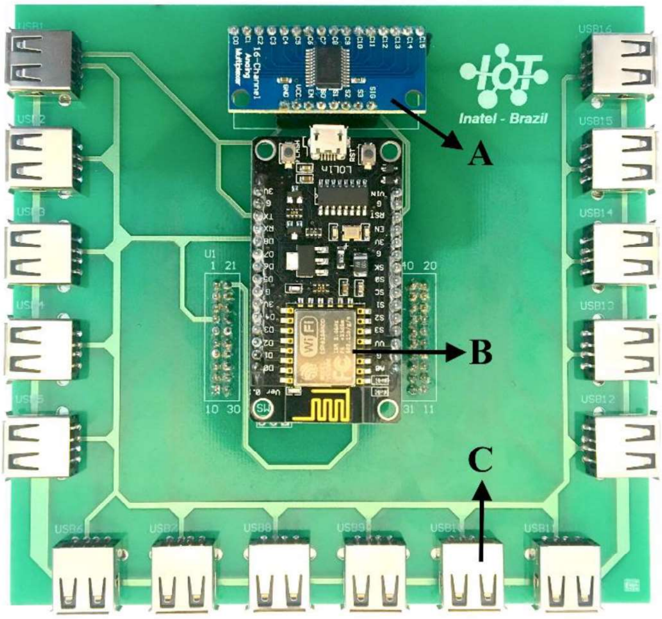


Figure 14 – *The Main board, responsible for the wireless communication, where: A. is the multiplexer, responsible for the sensed data receiving; B. is the NodeMCU, responsible for the Wi-Fi communication; and C. is one of the USB connectors. The CC2650 is assembled on the bottom of the main board.*

4.2.1 Middleware integration

Middleware is a mediator software, used to connect systems with different architectures and protocols. This software acts as a “translator” between the incompatible systems, receiving the information and forwarding it in a comprehensive structure for the final destinations [13].

The *In.IoT* middleware solution [153] is an open source, scalable solution to connect devices through the MQTT, CoAP, and Representational State Transfer

(REST) application protocols. It can be locally installed or deployed on a cloud service. For the proposed sensor, a cloud version of the *In.IoT* is being used.

The integration with the chosen middleware was made through the Internet, as it is deployed on a web server. Sensed data is transferred through the MQTT protocol, on a simplified JavaScript Object Notation (JSON) format, including only the variable name and its value. The *In.IoT* middleware recognizes the received variable and value, exhibits them on a dashboard for the users, and forward it for other devices subscribed on the same topics as it was published.

The sensed data is transferred and stored on the *In.IoT* middleware [153], as it is the best option for the scenario, allowing other devices, as actuators, to subscribe to the same topics of the sensors, permitting smart actions to be taken by these devices, which does not have to be on the same wireless network as the proposed sensor [36]. As a practical example, a smart window, subscribed to the same topic of the gas sensor could be opened if the levels of hazard gases reach critical levels in an indoor environment, avoiding accidents and explosions, and the users could be informed by smart alarms and evacuate the location.

The sensed data is available to the users through a dashboard, which can be public or private. Figure 15 illustrates the integration of the proposed multi-gas sensor with the *In.IoT* middleware platform, during the validation experiments.

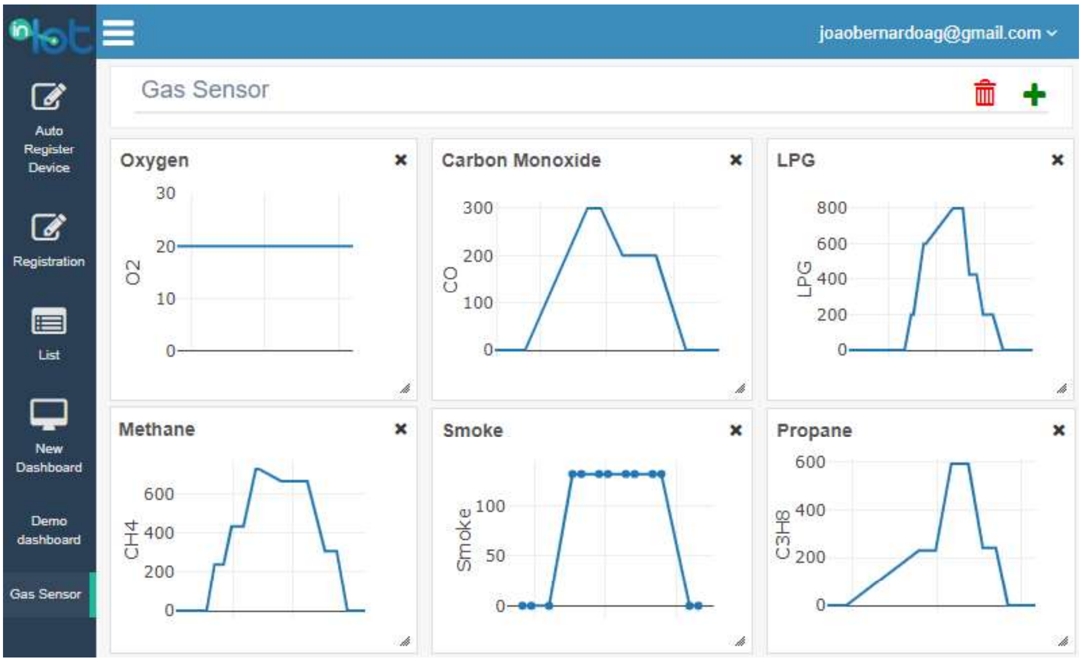
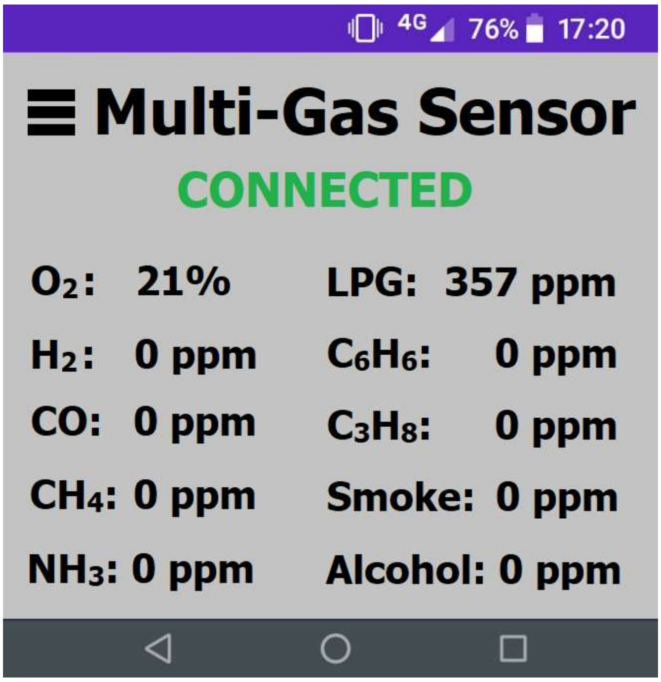


Figure 15 – *Screenshot from the In.IoT middleware platform, with the concentration of different gases during the validation experiments.*

4.2.2 Mobile application

The chosen middleware platform allows an easy integration between the proposed gas sensor and a mobile application. For this prototype, an Android based application was developed with the Android Studio platform, enabling users to be informed regarding the concentration of the sensed gases. The proposed App compares the concentration of the sensed gases with acceptable concentrations on the environment the proposed sensor is installed (indoor or outdoor), generating an alarm if the concentrations exceed these values. The screenshot form the mobile application, during one of the validation experiments is displayed on Figure 16.



Multi-Gas Sensor

CONNECTED

O_2: 21%
LPG: 357 ppm
H_2: 0 ppm
C_6H_6: 0 ppm
CO: 0 ppm
C_3H_8: 0 ppm
CH_4: 0 ppm
Smoke: 0 ppm
NH_3: 0 ppm
Alcohol: 0 ppm

Figure 16 – *Screenshot of the Android-based mobile application, during one of the validation experiments.*

4.3. Validation experiments

The sensing boards were submitted to diverse experiments in 5 different scenarios. During these experiments, the variation of environmental gases were collected and forwarded to the *In.IoT* middleware. The experiments will be described in this section.

The proposed sensor was installed in a domestic kitchen, above the stove, where controlled leakages were deployed, allowing the evaluation of the response time of the proposed sensor. The experiment have demonstrated the capacity of detecting the gas leakage with fast response time (less than 5 seconds from the start of the leakage). Figure 17 shows the collected data on a domestic kitchen.

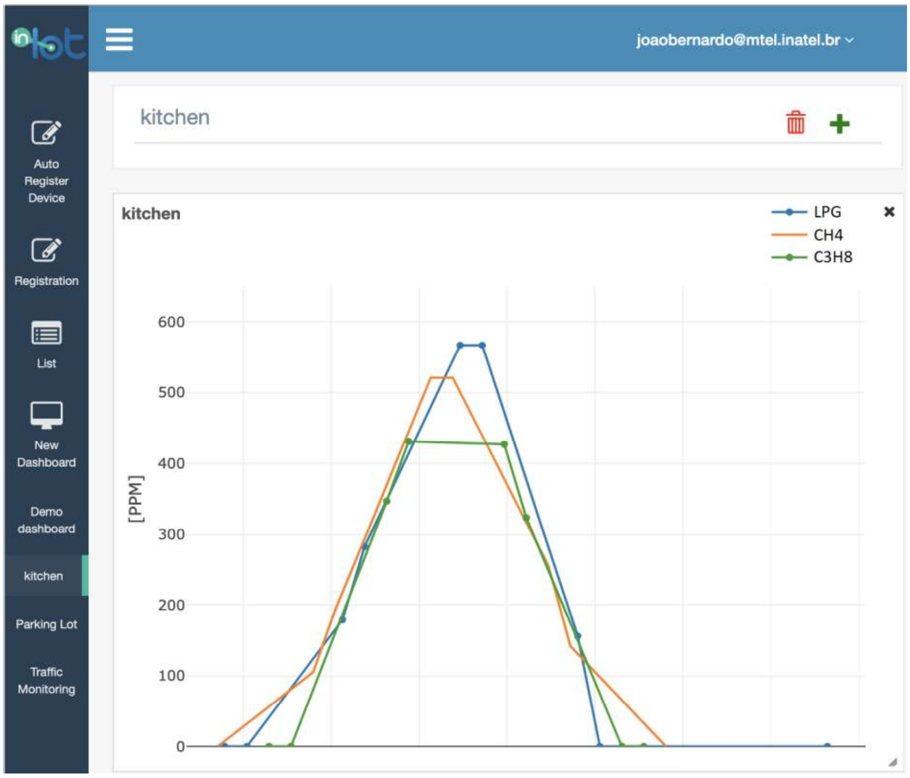
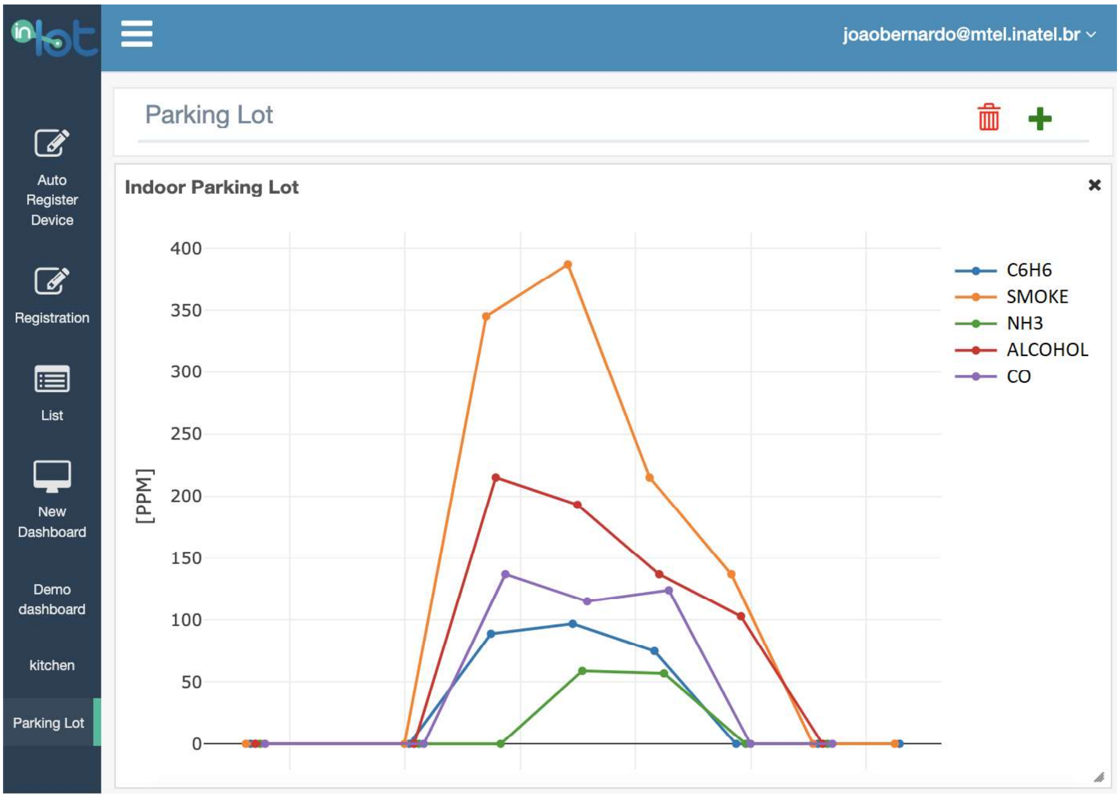


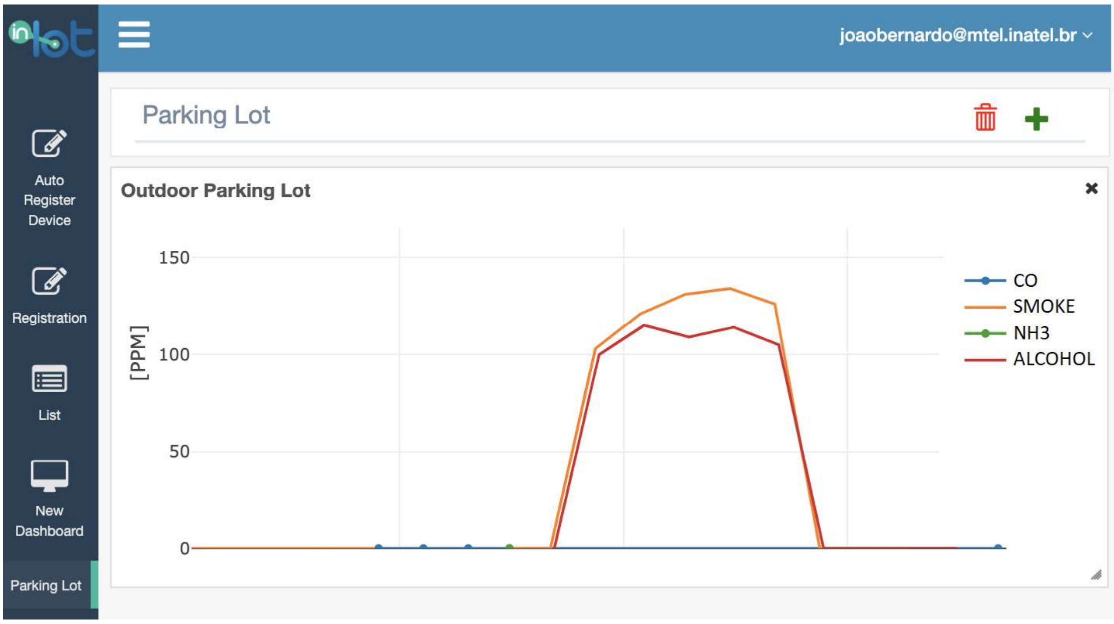
Figure 17 – *Gas monitoring on a domestic kitchen, with controlled gas leakages of LPG,* CH_4, *and* C_3H_8.

The sensors was also evaluated on indoor and outdoor parking lots, where it was installed near the parking spots, measuring the environmental gases and the pollution from the vehicles. On an enclosed space, the detection process was faster presenting higher levels of pollutants than on open spaces, as the gases were concentrated. The sensed data from the indoor and outdoor parking lots are displayed on Figure 18, where (a) displays the environmental gases on an indoor parking lot, and (b) shows the environmental gases on an outdoor parking lot.

The monitoring of environmental gases on an indoor parking lot have demonstrated the capacity of the proposed sensor in detecting pollutants in enclosed spaces. The device was placed close to the cars, and some toxic gases, as CO, C_6H_6, and NH_3 were detected. Moreover, alcohol vapor from the incomplete combustion of ethanol, and smoke were also detected.



(a)



(b)

Figure 18 – *Data collected from indoor and outdoor parking lots, where* ***(a)*** *represents the gases on an indoor parking lot, and* ***(b)*** *represents the gases from an outdoor parking lot.*

For indoor environments, the proposed sensor was also installed on the IoT Research Group laboratory, at Inatel, for environmental gases monitoring and for experiments with controlled gas leakages, through lighters. Moreover, smoke and *CO* were detected by burning paper in a closed recipient; alcohol vapor was exposed to the sensor through isopropyl alcohol, which is commonly used for PCB cleaning, and it easily evaporates at room temperature. Figure 19 demonstrates the proposed Plug-and-Play multi-gas sensor integrated with the In.IoT middleware, where A. is the proposed sensor with 9 sensing boards, and B. is the In.IoT screen, with the dashboards with the concentration of the environmental gases.

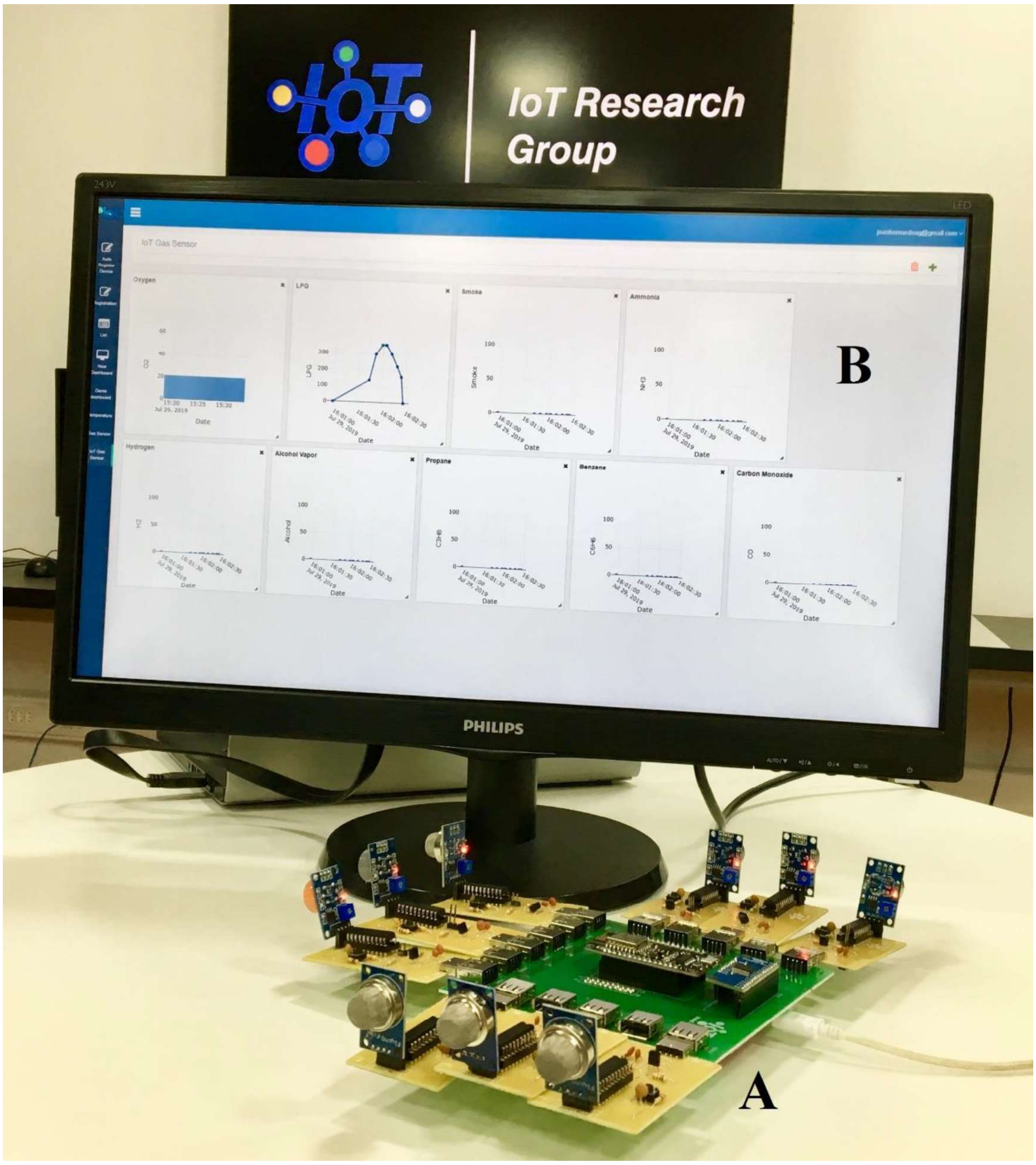


Figure 19 – *Demonstration of the proposed sensor. Highlights: A. The proposed sensor with 9 sensing boards and B. the In.IoT screen with the dashboards referred to the sensing boards.*

Finally, the proposed sensor was deployed for measuring environmental gases during traffic jams. The sensor was capable of detecting smoke and alcohol vapor, from the cars' exhaust system, in the same way as the monitoring of an outdoor parking lot. The collected data, published on the *In.IoT* middleware are shown in Figure 20.

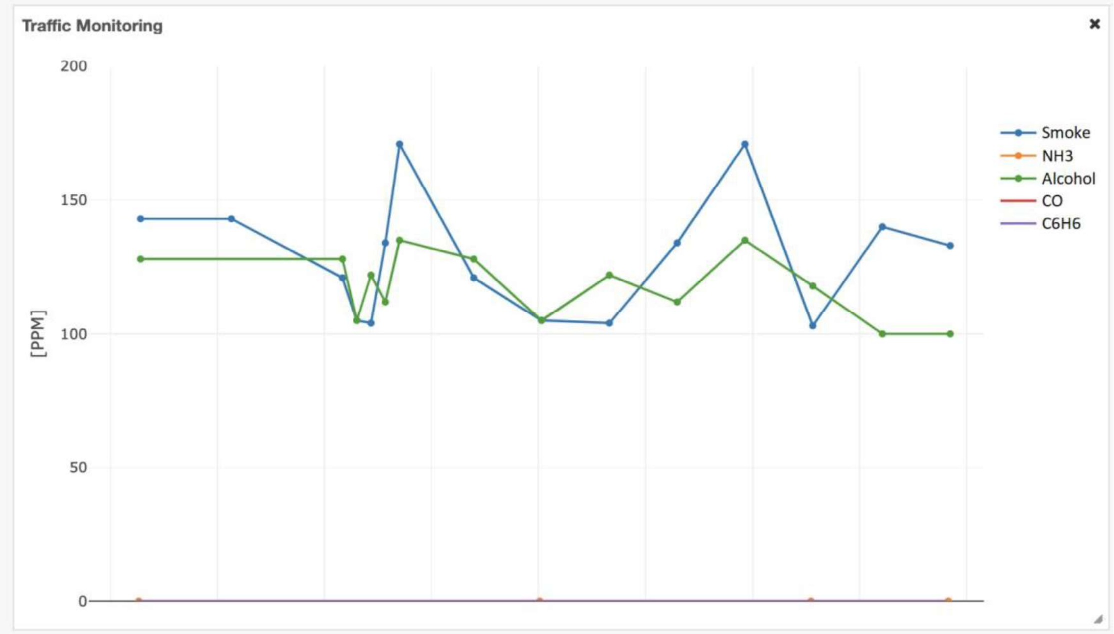


Figure 20 **–** *Data collected from environmental monitoring of traffic congestion, through the proposed smart gas sensor.*

Chapter 5: Conclusion and future work

5.1. Learned lessons

Through this research study, valuable lessons were learned, which can benefit future researchers interested in gas sensing technologies, IoT-based gas sensors, and Plug-and-Play technologies for smart devices, as developers working on these solutions.

Many researchers mistaken Metal Oxide Semiconductors with Electrochemical and Catalytic sensors; the principle of operation and their sensing characteristics are similar, although the fabrication techniques, sensing methods, as well as the types of materials to construct the transducers differ in quite a few aspects.

Despite the potential of some sensing techniques, no further investigation on these topics were found. Commercial solutions are more focused on using the most researched and antique technologies, as the metal oxide semiconductors and electrochemical transducers, even knowing that these sensors can lead to mistakes due to interference from other gases. Decreasing final prices of these transducers could help to make gas sensors ubiquitous systems.

As presented on Chapter 2, ZigBee is chosen by many authors due to its easy deployment characteristics and lower power consumption, compared to Wi-Fi and Bluetooth. Nevertheless, the standard IEEE 802.15.4 with the 6LoWPAN should be considered as a relevant alternative in future solutions given its promising characteristics. The Wi-Fi protocol should be also considered in solutions where energy consumption is not an issue, as it is a pervasive technology.

The deployment of smart gas sensors alone does not solve the gas leakages problems, as it would be necessary applications to warn the users on these leakages. Other smart devices should also be deployed on the same smart environment, decreasing the response time in terms of mitigating the gas discharge consequences, as smart windows would automatically open to ventilate the environment, while connected gas valves would act to stop the leakage. People on this environment could be warned through the smartphones or by IoT-based alarm systems.

5.2. Main Conclusions

Throughout this dissertation, an up-to-date study regarding IoT-enabled gas sensors and Plug-and-Play technologies for smart devices was presented, along with the proposal, construction, and evaluation of an IoT-ready Plug-and-Play multi-gas sensor prototype was presented.

The dissertation first introduced the motivation and delimited the research topic, describing the objectives and displaying its main contributions. In chapter 2, an up-to-date study regarding gas sensing technologies, IoT-based gas sensors, and Plug-and-Play technologies for the Internet of things was presented. This chapter began with the evolution of the sensing technologies for environmental gases, providing the first uses, and the technological evolution of these sensors. It also reviews the most promising technologies for sensing environmental gases, and the main wireless gas sensors proposed on the recent literature. Later, the plug-and-play technologies and proposals to interconnect low-power smart devices are reviewed. Then, this chapter brings the discussion among the best studied solutions, in order to evaluate the best characteristics for the proposal of a novel IoT-ready environmental gas sensor with the plug-and-play feature.

Chapter 3 introduced the proposal of the novel smart sensor for environment gas detection and the block diagrams of the proposed system. The main characteristics of the plug-and-play interface are presented, along with the characteristics of wireless communication and the main board, which is responsible for this feature. Moreover, the sensing modules are displayed with their calibration process and firmware.

In chapter 4, the proposed solution is presented, demonstrated, and validated through experiments. The proposed counts with independent sensing units that are interconnected with the main board through USB connectors. The main board is responsible for the wireless communication, counting with independent wireless modules for Wi-Fi (the ESP 8266) and for IEEE 802.15.4 (the TI CC2650), and a multiplexer, which facilitates the data reception by the proposed Plug-and-Play interface. A gas transducer and a low-power MCU, the TI MSP430G2553, compose the sensing unit. This chapter also addressed the evaluation process through the development until the final proposal, the middleware integration, and the experiments to validate the final prototype.

The evaluation experiments have demonstrated the capacity of simultaneously gathering data from different environmental gases. The sensor's response time is compatible with those reported on the reviewed literature on the sensing technologies applied to this solution.

The integration of sensors and actuators through the Internet of Things paradigm allows autonomous decisions according with the sensed data, decreasing the response time of various systems, increasing the positive experience of users on the smart environments. The proposal, development, and demonstration of IoT-ready plug-and-play sensors is indispensable for these environments, and it is crucial for various fields, including the surveillance of environmental gases, which will prevent numerous accidents related with gas leakage.

5.3. Future work

As future work, it would be interesting to compare the efficiency of the gas measurement technologies in real environments. The combination of more than one technology could result in better sensing characteristics, mitigating the drawbacks from the isolated sensing techniques.

Regarding the Plug-and-Play interface, it should be extended to actuators on the same board. An autonomous decision between the available wireless technologies should be proposed, developed, experimented, and validated in future studies. Another study that would be relevant is the comparison among the proposed Plug-and-Play interface with other approaches proposed on the literature. This study would grant the best performance of the Plug-and-Play feature for smart objects and IoT-enabled devices.

The proposed sensor could also be improved with a local alarm system, to analyze the sensed data and warn the users even though a network failure occurs. The sensor could also count with displays to show the sensed data and the air quality.

Regarding the mobile application, the development of more sophisticated applications, including other mobile operating systems, as the iOS, should be considered as a future work. The integration of other modules, as GPS, should be considered, as it would facilitate the precise localization of the sensors. The reduction of the sensing boards should also be evaluated for future deployments. The proposal of a software to warn the public emergency services regarding gas leakages and the GPS coordinates would decrease the response time from these calls, increasing the chances of avoiding major losses as consequences of these leakages.

Finally, the comparison of the measured values with known concentrations of the target gases should be performed, to ensure the precise calibration of the proposed sensor, and to evaluate the sensor’s lifetime.

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