An IoT framework for the pervasive monitoring of chemical emissions in industrial plants

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***Abstract*—In this work an IoT framework for the monitoring of chemical emissions in industrial plants is presented. The proposed system can embed different sensors. In particular, each sensor node manages a humidity sensor and an array of temperature and electrochemical gas sensors for the detection of CO, NO_x and O_2. Moreover it exploits some dedicated processing algorithms to compensate the dependence of the sensor response on temperature. The sensor node is provided with LoRa LPWAN connectivity that allows Wide Area data transmission: tests carried out in urban areas proved that a 3km communication range is achievable in noisy environments. A network architecture and a data acquisition and management structure is then presented for an application scenario in a Smart Industry context. A multilayer, modular topology is presented, combining the features of LoRa technology with shorter and larger range telecommunication channels, to develop an IoT framework that can be customized according to the physical and technical features of the deployment environment.**

***Index Terms*—IoT, Chemical sensors, industrial monitoring, WSN, LoRa, ZigBee**

I. Introduction

It is now apparent that the man-made pollution of the atmosphere can have dramatic consequences, so the monitoring of the air quality is of the utmost importance. Among other pollutants, CO and NO_x, which are byproducts of the combustion, are very armful and dangerous even if very diluted in the atmosphere and appearing in very low concentrations (also below $1\,ppm$) [1]. For this reason, toxic gas monitoring in ambient-air is a difficult task: the required measurement accuracy and resolution are challenging [2]–[4]. It is obviously convenient to monitor the sources of toxic gas emissions also from the point of view of a policy of emission abatement. In this context, there is a great interest in developing systems able to continuously monitor the combustion processes that are a certain sources of air pollutants.

Moreover, the monitoring of combustion products allows also to optimize combustor operations and to alleviate instabilities of combustions and their severe consequences [5].

There are different technologies and instrumentation that can be used to measure gaseous emission of combustion processes, but usually they are expensive, complex and require frequent, cumbersome and time consuming calibration procedures. In the practice, gaseous emissions in industrial plants are rarely continuously monitored, even if the advantages of such a measurement are apparent.

In this work an IoT framework for the continuous monitoring of chemical emissions in industrial plants is presented. The proposed system can embed different sensor systems based on a simplified version of a measurement device developed and tested as a stand-alone instrument [6]. The sensor node manages an array of electrochemical gas sensors of CO, NO_x and O_2 and exploits some processing algorithms designed ad hoc to compensate sensor drift and dependence of the sensor response on temperature and humidity. In fact, it is well known that electrochemical sensors response is influenced by temperature: e.g., for the proposed CO sensor the variation of the response to $2\,ppm$ CO can vary up to 20% in a a 30 degree range [7].

The sensor node has been studied not only to measure the required parameters, but also to remotely transfer, in real-time, the collected data, based on previously developed pervasive environmental monitoring architectures [8]–[10]. In particular, different architectures have been studied for the communication module of the node, ranging from Local Area (ZigBee) to Wide Area (LoRa) and global connectivity (Internet). While all these solutions have proved to be employable, suggesting their use for a modular, multi-layer network topology, the final sensor node prototype has been provided with LoRa connectivity. Indeed, the LoRa technology has proven to be the most flexible one, allowing the deployment of both local and city scale networks. In the context of industrial monitoring, this turns in the chance to deploy wireless monitoring infrastructures for both small and large scale industrial plants, as well as multi-plant networks.

II. IoT framework architecture

As anticipated in the previous section, an ad-hoc multi-layer IoT network architecture has been studied and designed to fit different industrial environments, according to different levels of capillarity. The overall network architecture is based on a cluster-tree topology, where each level of the tree corresponds to a different communication technology. The three communication layers of the proposed architecture are shown in Table I, while the network topology can be seen in Fig. 1.

TABLE I
Communication technology layers

Layer	*Communication technology*	*Transmission range*
Bottom Layer	ZigBee	$< 100m$
Middle Layer	LoRa	$100m - 3km$
Upper Layer	Ethernet-GPRS/UMTS	$> 3km$

According to the three layers, three sensor node and three cross-layer gateway typologies have been designed. In order to test the functionalities of the monitoring infrastructure, one sensor node and one cross-layer gateway have been fully developed.

The lower level of the network structure is composed of the clusters of ZigBee-connected nodes arranged in mesh sub-networks. Due to the limited communication range, these networks are thought to be employed for the monitoring of single rooms or for deployment of sensor arrays positioned at limited distances. Each node integrates a ZigBee radio module which is able to collect data from one or more sensors.

The ZigBee nodes represent the lower level of the network architecture, acting either as ZigBee End Devices or ZigBee Routers according to their function in the mesh network. They are designed to be as simpler as possible, optimized in terms of power consumption by enabling duty-cycling and characterized by a low data-rate since only numerical values acquired by the sensors need to be transmitted. The ZigBee nodes interface with the upper levels exploits two possible cross-layer gateways: the ZigBee-Internet gateways and the ZigBee-LoRa gateways.

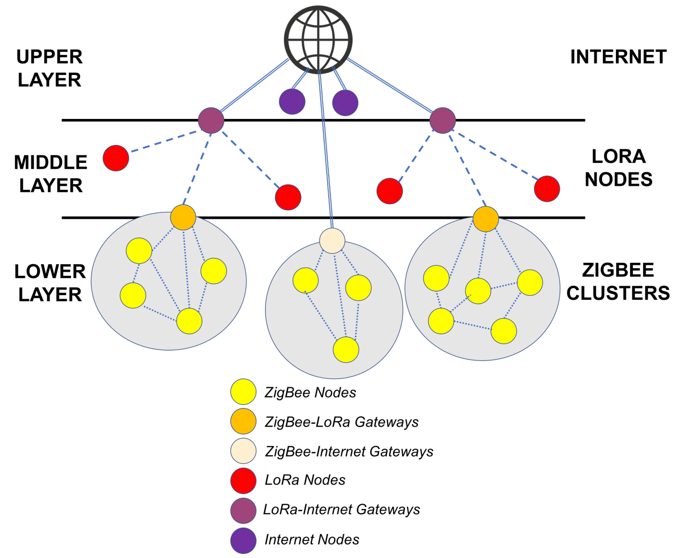

Fig. 1. Multi-layer network architecture.

The ZigBee-Internet gateways can be based on both wired and wireless connection. The wired ones are designed to integrate on a single microcontroller-driven board a ZigBee radio module, acting as a ZigBee coordinator, and an Ethernet module. The wireless ones can be based either on a WiFi module or a SIM-based GPRS/UMTS connection. The ZigBee-LoRa gateways are based on a multi-protocol board that re-routes the ZigBee data packets to the middle layer. Since these nodes present an ad-hoc microcontroller for the packet management, they can also be in charge of data filtering. Indeed, a first check, based for example on threshold values, can be performed directly on the gateways through ad-hoc data check protocols. The needless packets will be then discarded and then only a sub-set of them will be forwarded to the LoRa network , with a notable reduction in the overall network traffic.

The middle layer of the IoT framework is represented by the LoRa infrastructure. This is basically a tree network that can be employed to cover larger areas than the ZigBee one: in particular, with an adequate positioning of the LoRa gateway nodes, 3km transmission ranges can be achieved. Since the main task of the LoRa nodes is to collect the sensor data and to transmit them, their structure is very simple. Indeed, their architecture integrates only the microcontroller units in charge of data acquisition and transmission, the sensors and the LoRa radio module. LoRa modules are developed to reduce as much as possible power consumption, and LoRa protocol is more energy efficient than the ZigBee one due to the lack of routing algorithms required to implement multi-hop. These nodes are then expected to be the most energy efficient ones, even if less fault-tolerant due to their intrinsic network architecture.

The middle layer is provided with two cross-layer gateways: the already mentioned ZigBee-LoRa gateway and the

LoRa-Internet gateway. This second gateway is similar to the ZigBee-Internet one even if, due to the larger transmission ranges, the ideal configuration is the wired one. Indeed, in large industrial plants Ethernet connectivity will be surely available in several locations. The wired connection is intrinsically more fault-tolerant than the wireless one and the gateway could be powered through PoE technology.

The upper level is represented by the Internet backbone. In this context, Internet-connected nodes have been designed, allowing to collect sensor data and forward them directly to the Internet through wired (Ethernet) or wireless (GPRS/UMTS or WiFi) connection. These nodes are obviously more complex and power hungry then the previous ones due to the need to implement the TCP-IP protocol stack. However, the advantages achievable in terms of data rate and efficiency are not fully exploited due to the limited amount of data to be transferred. This suggests their use only in presence of a power source, otherwise other solutions should be preferred. The cross-layer gateways interfacing with this layer are the ones described earlier, i.e. the ZigBee-Internet and the LoRa-Internet ones.

While the whole infrastructure could be set up in case of large and articulate monitoring architectures, the minimal autonomous subset is represented by a sensor node and an Internet-enabled gateway. The modules developed as a proof-of-concept in this research satisfy this requirement being them a LoRa node and a LoRa-Internet gateway.

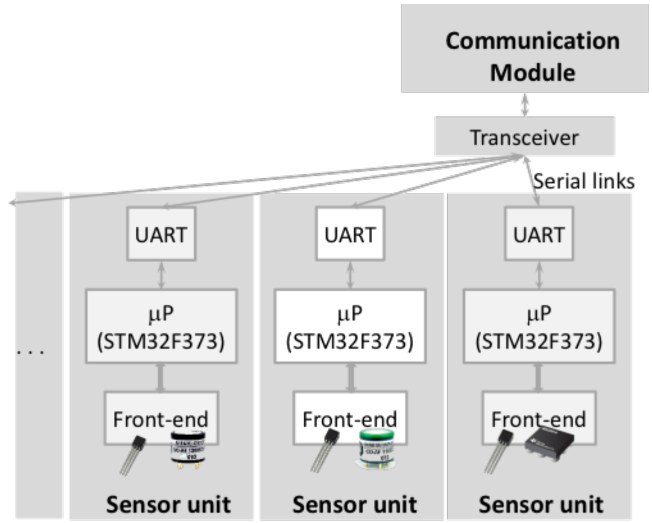

Fig. 2. Sensor node structure.

TABLE II
SENSORS USED IN THE PROPOSED SYSTEM

Electrochemical sensors [1]	***Humidity sensor***	***Temperature sensor***
Alphasense CO-A4 Alphasense NO_2-A43F Alphasense NO-A4 Alphasesne O_2-A1	Honeywell HIH4000 [4]	National Semicond LM 32 [5]

III. SENSOR NODE

The proposed measurement system must be connected to a sampling and cooling apparatus (chiller), usually present in the industrial plants. The system has a modular architecture and is composed of a network of sensor nodes. Each node, shown in Fig.2, consists of a communication module connected to a series of different sensor units. A sensor unit manages one of the electrochemical sensors listed in table II or a humidity sensor coupled with a sensor for the measurement of the local temperature. All sensors are placed in a special measurement chamber [6].

A. Sensor unit architecture

Each sensor unit contains: an electrochemical (or humidity sensor) and a temperature sensor, the dedicated front-end electronics (whose architecture for the electrochemical sensors is shown in Fig. 3) and a microprocessor (STM32F373) that controls the measurement process.

In particular, the microprocessor can bias the sensors generating via the DAC (12 bit) an appropriate voltage V_{bias}, it acquires the chemical and the temperature sensor outputs via a 16 bit $\Sigma - \Delta$ ADC, finally it manages a serial interface that allows for easy connection with the communication module (via a transceiver). Each sensor-unit accepts configuration data (e.g. the value of V_{bias}) and delivers digital processed data providing the local temperature measurements in °C and the estimation of the target gas concentration in ppm, corrected in terms of temperature effect using the specific calibration data.

The front-end electronics has the structure shown in fig. 3 where, as an example, the CO sensor is considered. For this sensor, as shown in the figure, the front end consists of an I-V converter and of a biasing circuit. The I-V converter is used to convert the current flowing through the sensor across the Working Electrode (WE) and the Counter Electrode (CE) into an analogue voltage, which is then A/D converted. This current is caused by the electrochemical reaction (sketched in figure 3 for the CO sensor) and is theoretically proportional to the target gas concentration. The biasing circuit assures a constant voltage across the WE-electrolyte interface, irrespective from the current flowing through the sensor, by a feedback loop that sets the CE voltage on the basis of the comparison of the Reference Electrode (RE) voltage with the voltage V_{bias}.

Being the reaction at the WE highly influenced by the voltage at the WE-electrolyte interface, this control circuit highly improves the sensor output stability.

The accuracy of the current measurements is $\sim 1.5\mu A$, corresponding to an accuracy $< 3ppm$ in terms of target gas concentration for all the adopted sensors.

B. Communication Modules Architecture

The prototypal data transmission architecture is based on the two devices proposed in section II, i.e. the LoRa node and the LoRa-Internet gateway.

The LoRa node is in charge of receiving the data measured by the sensor units and forward them to the LoRa-Internet

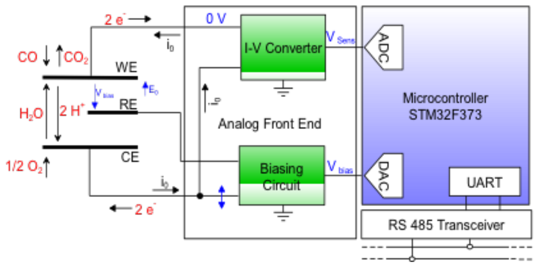

Fig. 3. Electrochemical front end structure.

gateway that will make them available for storage on a cloud platform. It is basically composed of a microcontroller which acts as a transceiver, identifying and managing all the packets coming from the sensor units, and a LoRa radio module for data transmission. The prototype has been developed using an ATMega328 microcontroller managing the serial connections with the sensor units, and a Libelium 868MHz SX1272 LoRa module. The prototype foresees the use of a dedicated serial connection for each sensor unit: this solution allows the overall architecture to be more fault tolerant because each sensor unit is totally autonomous with respect to the others. Otherwise, a solution exploiting a single serial bus, connected to all the sensor units, managing the data packets through an anti-collision policy could be set up: nevertheless, this solution is less fault tolerant because a malfunctioning in the serial bus would prevent from receiving data from all the sensor units.

The LoRa-Internet gateway receives all the packets transmitted by the node and through an ad-hoc API transfers them to a cloud infrastructure in charge of storing them into a MySQL database. The prototype of the gateway has been realized exploiting an Arduino MKR1000 WiFi board connected to a Libelium 868MHz, SX1272 LoRa module. While this prototype is based on WiFi connection, alternative solutions could have been set up by using either wired Ethernet connection or Wireless GPRS/UMTS connection, by simply using dedicate transmission modules.

IV. Test and validation

The tests on the operation of the sensor node have focused on both the sensor uint and the communication module. Regarding the sensor unit, in Fig.4 characterization data obtained in laboratory with the proposed system are presented. These measurements are obtained by analyzing test gases obtained by means of a characterization system, which allows to generate reference mixtures of air and CO, NO or NO_2 with known compositions, starting from reference gas cylinders and using mass-flow controllers Bronkhorst (accuracy 1% of the full scale). The total flow during a measurement is constant (in the results reported in this paper equal to $200mL/min$), whereas its composition can change, dynamically, during a measurement. The gas humidity is set by means of a bubbler containing ultrapure water, kept at known temperature in which the dry air is saturated; the desired RH value is obtained by mixing the flow from the bubbler with a dry gas. The electrochemical sensors exhibit in general a linear dependence of the output current on the gas concentration, and the measurements can be effectively corrected for the effect of temperature. In Fig. 5 an example of data coming from the monitoring of a combustion process in-field are shown.

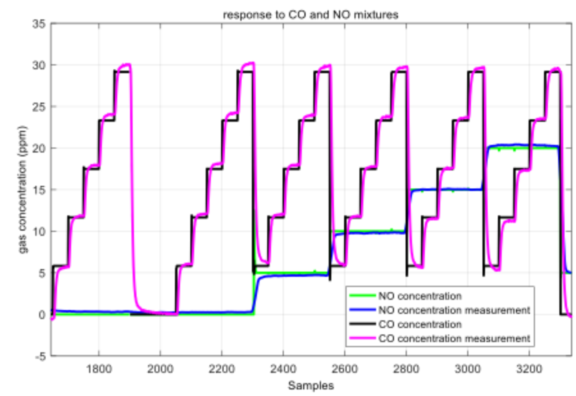

Fig. 4. CO and NO measurements obtained with NO and CO mixtures in air (RH = 50%, flow rate $200mL/min$). The true concentration of the two gases are indicated with green and black lines.

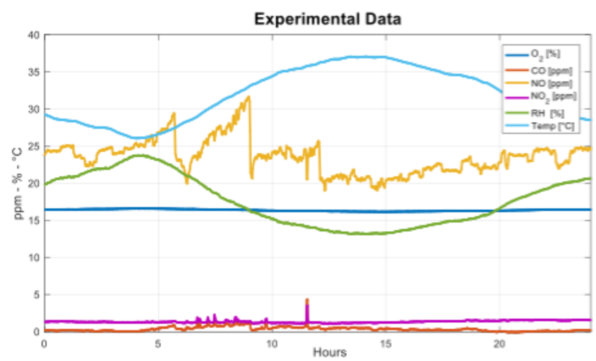

Fig. 5. Example of data obtained from the monitoring of a combustion process.

Following the tests on the sensor unit, the overall sensor node architecture has been tested, focusing on the reliability of the LoRa minimal communication infrastructure described in section III-B. Data transmission has been validated with indoor tests, performed in the main building of the Department of Information Engineering and Mathematical Sciences of the University of Siena (See figure 6). This structure has been identified as suitable for the tests due ti its size and features that make it similar to a real deployment scenario.Indeed, the building has a 80 x 100 m rectangular shape, with a total surface of around 7.000 m^2. The long sides are roughly oriented north-south, while the short ones are oriented east-west. It is structured on five floors subdivided in a large number of rooms separated by large concrete walls that in some cases reach a 1 m width. The rooms host scientific laboratories where electromagnetic instrumentation is used: moreover, the whole structure is covered with WiFi connection. The level of electromagnetic noise is then very high.

Fig. 6. Aerial view of the main building of the Department of Information Engineering and Mathematical Sciences of the University of Siena, acting as a test site for the LoRa network.

In order to test the reliability of the communication channel the sensor sampling rate was set at 6 samples per minute, i.e. 1 sample each 10 seconds. Table III shows the radio settings for the LoRa modules, chosen to maximize the reading range according to the networking guide [11]. The packet loss rate was calculated by counting the number of packet losses across a 4 minutes time span. The gateway node was placed inside a room positioned in the south-western corner of the third floor of the building, in order to test the functioning in a worst case scenario: indeed, in a real deployment the ideal positioning would have been in the centre of the building. The data loss rate was checked across all the five floors, by checking the received packet rate in ten different spots: 4 at the corners of the building, 4 in the intermediate points of the long sides and 2 in the intermediate points of the short sides. A 0% data loss rate was achieved on all the floors for the tests achieved in 8 out of 10 spots: the only two points where data losses occurred were the north-eastern corner (the farthest from the gateway) and the adjacent point on the northern side. The data loss rates for the two spots are shown in table IV.

V. Conclusion

The aim of this paper was to propose and test an IoT infrastructure for the monitoring of chemical emissions in industrial plants. The architecture described in this paper is expected to be seen as a general-puropose framework to be shaped on different scenarios, ranging from small dimension industrial plants to large production areas. Tests were performed to demonstrate the effectiveness of the proposed solution: while they were focused on a small sub-set of the proposed infrastructure, it is expected that they can easily be extended to a larger scale scenario.

TABLE III
Data loss rates for the test points.

Channel number	CH_13_868
Center frequency	866.10 MHz
Bandwidth	125 KHz
Coding Rate	4/5
Spreading factor	12
Output power	14 dB

TABLE IV
Data loss rates for the test points.

Test Point	1-8	9 (northern side)	10 (north-eastern corner)
First Floor	0%	25%	Not achievable
Second Floor	0%	12.5%	87.5%
Third Floor	0%	12.5%	41.7%
Fourth Floor	0%	29.8%	50%
Fifth Floor	0%	50%	100%

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