Adopting Smart Metering RF Networks for particulate matter distributed measurements

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Abstract— **Pollution represents one of the major problems of modern cities. Typical indices of extent of this unhealthy phenomenon are the concentration of oxides and particulate matters in the air. Namely Particulate Matter (PM) is responsible for breathing problems and even lung diseases. As a consequence, numerous suitable solutions have been thought in the fields of sensing devices and wireless networks. In the paper, a solution is proposed which aims to use for pollution monitoring the same Advanced Metering Infrastructure (AMI) that is the backbone of smart city projects where measurements of private consumption or public services are called to be smart. In particular in those urban areas where smart meters, concentrators and central access systems come to life, suitable PM sensors based devices can be added to either water or gas smart meters, in order to exploit their widespread deployment. The main issues and experimental results regarding the inclusion of some smart PM sensors in a 169 MHz network based on wM-Bus for data collection from smart meters and sensors are discussed in terms of battery energy saving and data storage.**

Index Terms— **PM, WSN; smart meter; radio communication protocol; pollution.**

I. INTRODUCTION

The Smart City paradigm has been declined, according to several principles, all aimed to make more and more livable cities for residents, hospitable for businesses and greener for the global environment [1]-[2]. The common factor of all declinations is the use of smart meters and communication networks. Smart meter technology lies at the foundation of smart city networks and provides the basic information upon which services for people can be developed. This is the reason why metering systems (state-of-the-art electronic/digital hardware and software [3]-[5], which combine interval data measurement with continuously available remote communications) are being more and more widespread. Communication networks allow the information flow produced by meters to get to the place where information must be stored, processed and made available for services. The monitoring of pollution level in urban areas must be considered one of the most important services for the collectivity, stated that high levels of pollutants are a major cause of respiratory illnesses such as asthma, bronchitis and

chronic obstructive pulmonary disease [6]-[7]. Particulate Matter (PM) are suspended particles or droplets that can be found in the air alone or in combination with other pollutants. PMs are classified in terms of diameter, i.e. PM10 have a 10 microns diameter or less. Both PM2.5 and PM10 particles contain nonvolatile components such as sulfur, heavy metals and elemental carbon. Primary outdoor sources of PM are burnt fuel from automobiles, construction equipment and power plants.

Air pollution was traditionally monitored thanks to conventional inflexible, expensive and time consuming measuring stations equipped with multiple sensors. The most current solutions involve the use of wireless sensor networks (WSNs) whose low cost nodes can measure information from the environment, process and relay them to a base station. The use of WSN is having a greater and greater interest which can be mainly ascribed to the cost reduction, the node autonomy, the fine spatial and temporal granularity they allow without heavy infrastructure [8].

The topic is widely discussed in scientific literature, mainly as for the infrastructure which must be able to gather information produced by sensors and store it in a data base accessible from everywhere by citizens, multiservice companies, and so on.

A whole infrastructure for environment monitoring which comprises devices, back-end infrastructure and client applications (web and mobile) is described in [9]. It represents a class of solutions where all sensor nodes are featured with GPS and GPRS antennas. These kind of nodes cannot be battery powered and require each one a sim card. This implies that their number is limited and the desired spatial resolution can be obtained only through a suitable statistical method aimed to reduce the number of actual nodes [9,10,11]. The problem of optimal deployment of wireless sensors still remains on the research field and solutions are usually searched for among artificial intelligence techniques [8,10].

At the same time, great efforts have been made to experiment ad hoc designed WSNs [12,13]. Battery powered sensor nodes equipped with short range radio module are installed within the coverage range of a dedicated gateway, which is able to gather information and redirect it on the Internet. Based on Xbee and ZigBee 2,4 GHz radio modules mesh network architectures are usually adopted, in order to increase the coverage range of gateways and thus the number of nodes connected. A suitable routing protocol has to be implemented in each sensor node to manage multi hop

communication among nodes. Large scale networks can be suitably deployed but battery consumption cannot be uniform among nodes (the farer node to gateway the higher power consumption) unless complex routing control techniques be implemented to make the mesh more efficient [13].

Advanced Metering Infrastructures (AMIs) are intended as full-scale bi-directional data communication channels enabling measurements and in general time-based information to be frequently collected and transmitted to various subjects. Typically AMI includes gas, water or electric meters at customer site, communication networks between customers and service providers and data reception and management systems that make information available to all the actors.

The most of water and gas meters are outdoor devices and are widespread in urban areas with very high density. In this paper the authors, on the basis of their previous experiences in the field [14,15], propose suitable PM sensors based devices that can be added to either water or gas smart meters, in order to exploit their widespread deployment. The inclusion of some prototypes of PM sensors in a urban area based on wM-Bus 169 MHz network for data collection from water and gas smart meters and other sensors is presented in the paper. At first some details about the AMI are given, then the radio module of the PM sensor node is described. Finally the first experimental results are discussed in terms of battery energy saving and data storage.

II. ADVANCED METERING INFRASTRUCTURE

AMI is a network that automatically provides utility companies with real-time data about consumptions that come from smart meters.

Based on different physical channels and available to various type of utilities (water, electric power, gas) AMIs have been proposed during last years [16], [17].

Thanks to OPEN Meter project [18], whose recommendations were accepted by many national regulations, a complete set of open and public standards for AMIs is today available for developers and utilities. Among these the 169 MHz wM-Bus has been being the most adopted solution for gas and water smart meters. Due to the hundreds of meter range of 169MHz radio modules, the network infrastructure is made of suitable gateways, called "concentrators", which interface smart meters with a central unit through the GSM-GPRS network. The DLMS-COSEM [19] has been accepted by the most of the stack holders among the suggested protocols for communication between smart meters and central unit, via concentrators. Typically water and gas meters are widespread in urban areas with high density and different heights of installation, depending on how tall buildings are. This means that if particulate matter sensors were included in water or gas meters, they could provide a very dense tridimensional map of particulate concentration in urban areas. Spatial density of measurements can be managed by properly choosing the sensor installations among all the available ones. In order to experience this kind of solution to particulate
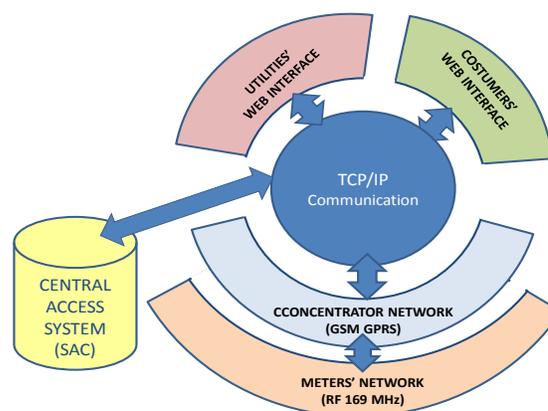

Fig. 1 Block scheme of the AMI

matter distributed measurements the authors have chosen an AMI which is designed to serve water and gas utilities in the city of Salerno (Italy) and neighborhood.

The communication architecture topology is hierarchical (**Fig. 1**): a set of wireless sensor nodes (leaf nodes) are connected to the master node, the Data Concentrator Unit (DCU/GW), which in turn forwards information to the Central Access System (SAC) where data are processed and stored. The leaf node battery powered hardware is featured only with a 169 MHz wM-bus radio module, whilst master node hardware is provided also with long-range transmission capacity (GSM/GPRS antenna) to get to the SAC via cellular network. DCUs are either AC powered or solar cell recharged battery powered, it depends on the installation. Both leaf node – master node communications and master node – SAC communications are based on DLMS/COSEM protocol. Each master node is responsible for the concentration and management of data generated from a number of leaf nodes, which are to be sent to the SAC.

A. Radio Frequency (RF) 169 MHz Smart Meters

The *wireless M-Bus* [20] represents a good tradeoff between coverage range that allows to reduce the number of DCUs, and power consumption due to radio transmission. wM-Bus transceivers require low energy thanks to a low-overhead protocol, transmission-only modes (which do not need an idle receive phase) and long-range sub-GHz transmission bands (GFSK, GMSK and 4-GFSK modulations, with lower data rates (up to 19.2 kbit/s). The transmission mode over 169 MHz frequency band allows extended transmission range due to the inherently lower path losses, while the reduced data rates permit higher sensitivity for the receiver, with a consequently reduction of the transmission power at the transmitter or a longer transmission range using the same transmission power [21]. The leaf node always starts the transmission first to the concentrator, while the latter is always in reception. The concentrator is not able to start the transmission session, indeed, the meters for most of the time remain in sleep mode to save battery life; only after the transmission of the first packet by the meter, the concentrator can send commands or requests in a small reception window.

B. Data Concentrator Unit

The use of gateways prevents all meters from connecting directly to the central access system. This is usually impractical given the high cost and the number of transactions required. Data collected from smart meters, indeed, must be gathered by the control system for billing and quality of service. Conversely, the central system sends commands, firmware upgrades and billing methods to smart meters. Concentrators reduce the number of long range connections with a factor depending on the concentration factor, that is the number of meters connected to the same concentrator.

The DCU hardware architecture includes: *i)* a main board able to processing information at application level (DCU functionalities); *ii)* as many RF 169 MHz microcontrolled radio modules as the different services (gas, electricity, water, pollution, etc..) are intended to be simultaneously managed by the concentrator; *iii)* a GSM/GPRS modem.

At DLMS/COSEM level, DCU behaviors both as a client (with respect to the smart meters) and server (with respect to the central access system), also providing a transparent end-to-end communication. These functionalities of the concentrators are implemented at the meter network side by the RF 169 MHz modules, whereas, at the other side, the DLMS/COSEM communication profile over TCP/IP (developed for GPRS transmission within a Public Network) is implemented by the main board. Considering that in Salerno city application the mean number of meters for each concentrator is 250, the characteristic of the 169 MHz radio-network have required a time division scheme in order to avoid the packet collision (multiple channel access). Each meter has the real time clock (RTC) and it is possible to program an awake time for each meter.

C. Central Access System

The function of the Central Access System in the remote reading system is the networking management: all subjects interested in data coming from any kind of meter must access to the SAC, that is element of the AMI designed to allow this.

The Central Access System thought for the application consists of three software modules: i) a JAVA module implementing the communication with concentrators using DLMS-COSEM protocol and mobile (GPRS/UMTS) network; ii) a web application that allows users and utilities to send commands to the meters and access the stored data; iii) a relational database that records all data uploaded by all kind of meters. The commands coming from the utility (such as orders for Tariff Plan changing, new metering point associations, meter valve closing) are transmitted through the DLMS/COSEM messaging. Analogously, customers and/or other authorized subjects may access their measurement data by a suitable web interface, where security mechanisms for authentication allow the access to the concentrators and utilities.

Fig. 2 The particulate matter sensor GP2Y1010AU0F

D. Particulate Matter Sensor

The PM sensor used to measure the outdoor PM level is the GP2Y1010AU0F model manufactured by Sharp and reported in Fig.2. To achieve the measure, the adopted sensor is based on an optical sensing system which exploits the light reflection (thanks to the inclusion of a suitable infrared light emitter). When the light hits the particulate matter, a phototransistor discloses the presence: the corresponding measure comes out as a voltage signal in the (expected) range 0.9 to 3.4 Volt.

In the following, the experimental results are reported about both the metrological characterization and the energy requirements of the PM sensor in order to evaluate the actual feasibility of:

i) integration of the PM sensor into a remote node of short range Wireless Sensor Network.;

ii) development of a distributed (low-cost) application for air pollution monitoring according to the national and European legislation.

III. EXPERIMENTAL RESULTS

The visual water meter add-on introduced in [15] and reported in Fig. 3 has been provided with the GP2Y1010AU0F sensor in order to verify the duration of the battery life and the correct detection of the particulate matter. In details, the visual add-on to be adopted within WSN based on wM-Bus include the following 4 main devices:

i) the high performance ARM®Cortex™-M3 32-bit RISC core as Microcontroller;

ii) a color camera sensor;

iii) the Texas Instruments CC1120 chip as RF Transceiver;

iv) the SKY65367-11chip as RF front-end module.

The data provided by the PM sensor is collected by the visual add-on, which is responsible for the analog voltage sampling: an external conditioning circuit has been developed to allow the correct operation. In details, the circuit drives the PM sensor infrared diode according to the pulse-driven waveform suggested by the manufacturer: a PWM is adopted with a period T of 10 ms and a T_{on}/T_{off} interval respectively equal to 0.32 ms and 9.68 ms.

By taking into account the sensor (operating) range (0÷5 V) and adopting the internal 12-bit ADC converter of the ARM Microcontroller, the single measured value (as 8-bit word) is obtained by averaging 64 consecutive readings within 1
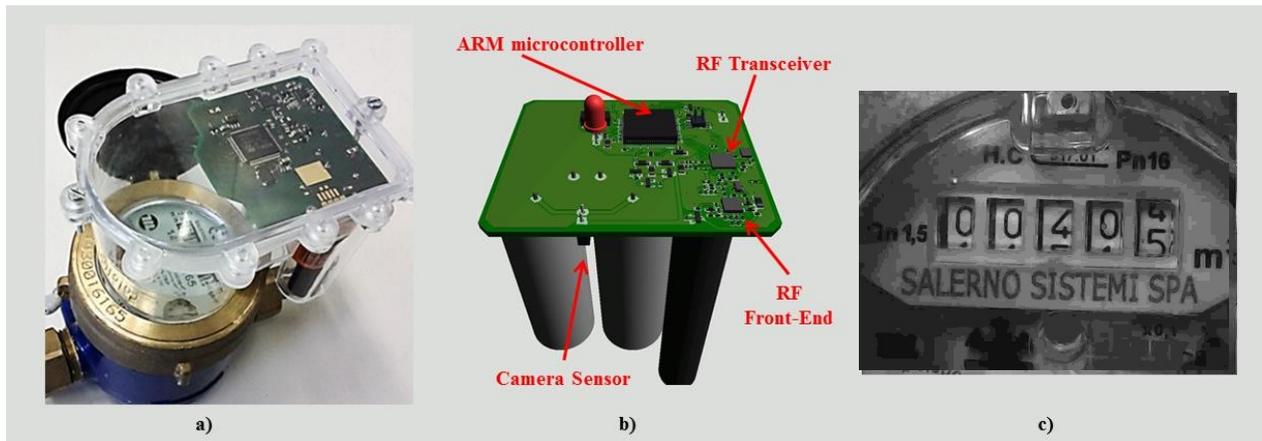
Fig. 3 Water Smart Meter with 169 MHz RF wM-Bus communication module

second. About the power consumed, a very little quantity of current is needed for the measurement operation. Indeed, the mean consumption is around 11 mA with a maximum consumption in the worst case of 20 mA.

In order to estimate the metrological performance of the developed digital sensor, the calibration of 30 PM sensors has been performed according to the procedure suggested in [12] by adopting the highly accurate Dylos Pro-1100 device (as reference instrument) and the corresponding calibration curve obtained in [21].

More in details, the PM sensors and the reference instrument were placed inside a hardboard box (internal volume = 1 m^3). A cigarette (kept at the middle of the box) was used as PM source for calibration, whereas the sensors (previously synchronized with time resolution of 1 second) were collecting samples at one minute intervals. After lighting the cigarettes, the box was closed and left for a total of 300 minutes. After a sharp increasing in the corresponding readings, the PM sensors remained saturated until the 150th minute, and then gradually decreased. By adopting the cubic polynomial fitting suggested in [12], the calibration curve has been computed for each PM sensor. The results are shown in **Fig. 4** in terms of mean value and standard deviation within the output range of interest (0÷500 µg/m^3).
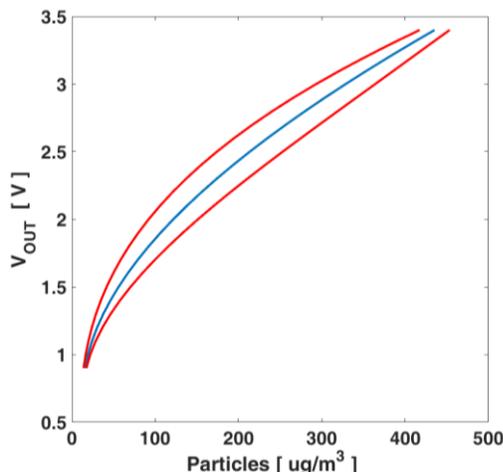

Fig. 4 Calibration curve (blue line)of the PM sensor and corresponding uncertainty interval

Although the measurement uncertainty exhibited by the developed PM sensor seems to be (as expected) poor (ranging from 5% to 25% of the corresponding reading), the metrological performance still remain feasible for the implementation of a microscale model to be adopted for PM10 monitoring (as integration of the fixed stations).

According to European and national directive of air quality evaluation [22], the daily PM10 concentration should be estimated on hour basis with high-cost instrumentation able to assure data coverage (not lower than 75%, equal to 18 daily measurement results) and data uncertainty (with 95% confidence level) not greater than 25% of the limit value for preserving the public health, that is equal to 50 µg/m^3 (against which the dally mean value has to be compared). In other words, the width of each (1-hour) measurement result (expressed as 95% Confidence Interval) should lower than 25 µg/m^3 .

Thus, in order to adopt the PM sensor, the corresponding metrological performance has to be compensated through the averaging operation by exploiting the data availability from spatially distributed sensors within the WSN. In detail, the comparison between the worst case for the estimated measurement uncertainty (80 µg/m^3 at PM concentration equal to 230 µg/m^3) and the prescribed data quality (12.5 µg/m^3) leads to a requirement for the concentration ratio, which should be assured by the distributed WSN, as detailed in the following scenario, where the wM-Bus protocol limitations are considered.

According to national regulation for AMI [23] (UNI-TS 11291) a smart meter with short range radio capability is allowed to send 4 wM-Bus frames (maximum length equal to 255 byte) a day, by adopting the N2-a channel (featured by 12.5 kHz bandwidth centered at 169MHz, GFSK modulation and transmission rate equal to 4.8 kbit/s). Each one of the four transmission start times is randomly selected by the autonomous smart meter within the corresponding 6-hour window (6:00:00 is considered as the conventional daily starting time, when the software routine for the random selection is executed). Thus, the smart (gas/water) meter equipped with the PM sensor may be programmed to run the PM measurement once an hour in order to include the available 1 byte PM readings (stored in the volatile memory)
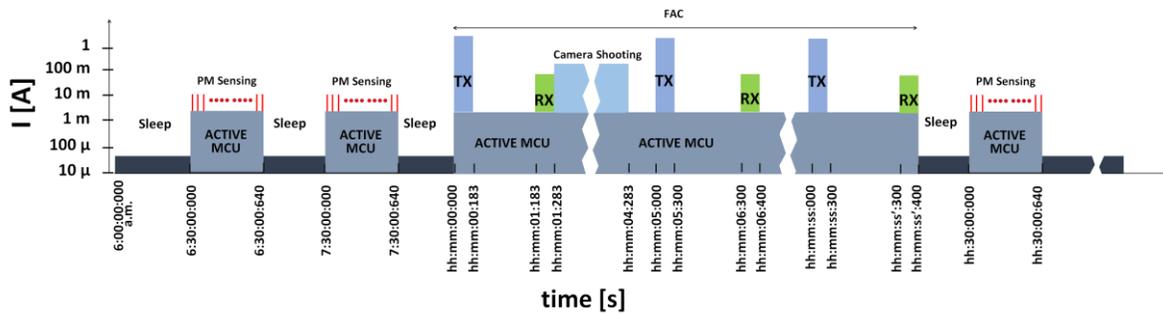
Fig.5 Electrical current absoprtion of the smart meter equipped with the PM sensor.

into the data field of the next wM-Bus frame (whose typical length ranges from 70 to 120 byte for spontaneous upward transmission from gas and water meters compliance with DLMS/COSEM).

The proposed scenario is depicted in the scheme of Fig. 5, where the overall electrical current absorption by the visual smart meter including the PM sensor is reported about the different operating states (sleeping mode, PM sensing, camera snapchat, radio transmission and receiving).

By taking into account a successful communication rate (of the uplink transmission) not lower than 75% (which is commonly achieved by various AMI Pilot Projects) and the prescribed minimum data coverage previously mentioned, the 1-hour PM measurements should be available at level of Central Access System (as average of the corresponding readings from the smart meters) when the minimum concentration ratio of 1 DCU/GW to 100 remote nodes is considered. The requirement is typically fulfill by the smart meter planning in urban area, where each DCU/GW is able to effectively manage the bidirectional short-range communication with hundreds of sensor nodes located until to 300 m.

About the battery life of the developed visual add-on equipped with the PM sensor, by considering the introduced measurement of the task energy and the following application options:

i) microcontroller operating at 3.0 V;
ii) the CC1120 transceiver operating in wM-Bus N2a mode at maximum transfer power;
iii) 4 daily random push sessions including hour readings by the PM sensor (data rate = 4.8 kbs and wM-Bus mean frame length = 110 byte);
iv) a monthly image acquisition for the front panel of the water meter (typically a .jpg file with size = 12 kB) and corresponding radio transmission (through the mechanism of FAC session including a mean value of 100 wM-Bus frames);
v) 2 lithium batteries for a total capacity equal to 7000mAh (3.6 V);

the expected battery discharge reveals to be greater than 12 years, with a contribution by the activities carried out for the PM monitoring and PM readings transmissions estimated equal lower than 1 %.

IV. CONCLUSIONS

The original adoption of Advanced Metering Infrastructure based on short-range communication (wM-Bus) is proposed for the continuous monitoring of Particulate Matter within urban areas. A prototype of a visual water meter equipped with a low cost off-the shelf PM sensor has been developed as remote node to be adopted in the radio Local Area network. Result of the metrological characterization against the quality requirements of the PM measurement according to European regulations as well as the measured energy consumptions of the prototype confirm the feasibility of the proposed AMI for an effective adoption within urban areas. Further research will be addressed to the pilot project including the installation of hundreds of smart sensors in order to compare the resulting microscale distributed model for the PM monitoring against the reference data by monitoring station (fixed measurement).

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