Wireless Sensor Network for Low-cost Air Quality Measurement

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Abstract. The original proposal of Advanced Metering Infrastructure (AMI) based on short-range communication (wM-Bus) is suggested for the continuous monitoring of Particulate Matter within Smart Cities. A prototype of 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. The simulation of a Smart Metering scenario based both on the result of the metrological characterization of the PM sensor (against the quality requirements of the PM measurement according to European regulations) and on the typical communication performance of the wM-Bus confirm the feasibility of the proposed AMI for the continuous analysis of the air pollution exposure within urban areas.

1. Introduction

The monitoring of pollution level in urban areas must be considered one of the most important services for the citizens, indeed, the presence of high levels of pollutants are correlated with respiratory illnesses such as bronchitis, asthma, and chronic obstructive pulmonary disease that represent the cause of death for 12 million of peoples according to the World Health Organization [1]. Typically the air pollution is monitored by expensive station, usually equipped with multiple instruments (worth more than 30,000 €) and located in fixed point in an urban areas. Moreover, complex and repetitive calibration and maintenance operations are requested in order to obtain highly accurate measurements. Thus, few points of measurements are often available, not ensuring the awareness of the air quality in places not close to the measurement station. In order to obtain a distributed information on air pollution some solutions are adopted such as the use of air-quality mobile stations, passive samplers or models. In the first case, mobile stations are also very expansive as fixed stations and in most cases they do not guarantee to reach a sufficient level of information to make a good density of spatial sampling. The passive samplers are less expensive than fixed and mobile stations, nevertheless they are not able to appreciate episodes of pollution with a high dynamics. Finally, the adoption of models requires a high level of knowledge and data that are not easily available in the most cases [2].

Recent technological advances in the field of embedded electronic and IoT communication lead to the development and proposal of low-cost sensors (~15€) for pollution monitoring and wireless/wired interfaces (GPRS, Wi-Fi, LAN), enabling people [3]-[4] to share information about the urban air quality.

Following the Smart City paradigm, the authors intend to perform the air pollution monitoring through the Advanced Metering Infrastructure (AMI) that is the backbone of pilot projects where
measurements of private (gas, water, electricity) consumption or public services are already remotely managed [5].

Two advantages are expected: i) the (zero-cost) sharing of an existing network infrastructure currently used by the smart meter to delivery information to the end users, and ii) the high spatial density of the measurement points guaranteed by the pervasive meter installation which may be exploited to achieve a three-dimensional air pollution map.

2. The System under Test
AMI is a network that automatically provides utility companies with real-time data about consumptions that come from smart meters according to the hierarchical topology schemed in Figure 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 battery powered hardware of the leaf node is featured with a 169 MHz wM-Bus [6] radio module, whilst the master node hardware is also provided with long-range transmission capacity (GSM/GPRS antenna) to get to the SAC via cellular network. Both the leaf node – master node communications and the master node – SAC communications are based on DLMS/COSEM protocol [7]. Each master node is responsible for the concentration and management of data generated from a number of leaf nodes (constituting a Radio Local Network), which are to be sent to the SAC.

The adoption of Advanced Metering Infrastructure (AMI) based on short-range communication (wM-Bus) is proposed for the continuous monitoring of Particulate Matter within urban areas in order to exploit the widespread deployment of gas and water meters: a prototype of smart 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.

In detail, the GP2Y1010AU0F sensor manufactured by Sharp (see Figure 2) was previously proposed to measure the outdoor PM level [8] and integrated into the visual water meter described in [9]: in order to estimate the metrological performance of the developed digital sensor, the calibration of 30 PM sensors was performed by adopting the highly accurate Dylos Pro-1100 device (as reference instrument, [10]) and obtaining the calibration curve reported in Fig 3. More in details, the PM sensors and the reference instrument were placed inside a hardboard box (internal volume = 1 m³). 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 [11], the calibration curve has been computed for each PM sensor. The results are shown in Figure 3 in terms of mean value and standard deviation within the output range of interest (0÷500 µg/m$^3$). As expected the measurement uncertainty exhibited by the developed PM sensor is quite poor (ranging from 5% to 25% of the corresponding reading) if compared with the data quality assured by fixed measurement stations.

3. The feasibility study
Result of the previous metrological characterization has been the basis of the present feasibility study about a microscale model to be adopted for PM10 monitoring (as integration of the fixed stations), which takes into account the quality requirements of the PM measurement according to European directive [12] about the air quality evaluation. Indeed, the daily PM10 concentration should be estimated on hour basis with 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 daily limit for preserving the public health, that is equal to 50 µg/m$^3$ (against which the daily 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 effectively adopt the proposed Wireless Network, the corresponding metrological performance of the corresponding PM sensors 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 the 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. Indeed, according to national regulation for natural gas AMI (UNI-TS 11291, [13]) 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 should be 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 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) 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 in compliance with DLMS/COSEM protocol).

Figure 2. The Particulate Matter sensor GP2Y1010AU0F.

Figure 3. Calibration curve (blue line) of the PM sensor and corresponding uncertainty interval (red lines)
Numerical simulation of the micro-scale model has been carried out by considering for each node of the proposed WSN a corresponding measurement equal to the random variable which takes into account the probability distribution of the outputs from a fixed measurement station and the low-cost PM sensors. In detail, the former distribution has been estimated by averaging the 1-hour measurement results recorded during 1 month by a fixed air quality station placed in Salerno, Italy, whereas, the latter (uniform) distribution of the PM sensor output takes into account the calibration results. Finally, different values (in the range 75%-95%) have been considered for the successful communication rate of the uplink transmission from WSN nodes to DCU/GW.

As main result of the simulation, the necessary 1-hour PM measurements about the micro-scale (with the prescribed data quality) are always 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 (population density > 6000 inhabitants/km²), where each DCU/GW is able to effectively manage the bidirectional short-range communication with hundreds of sensor nodes located until to 300 m.

4. References

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