Characterization for an Industrial Wireless Network in a Gas Sensing Scenario

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Abstract

Employing wireless communications in gas sensing and air quality monitoring is essential in many industrial scenarios where wired networks cannot perform the task safely and effectively. In industrial environments, deploying wireless gas sensing networks becomes a major safety requirement. Hence, we consider the use of wireless networking in safety gas sensing applications. At the National Institute of Standards and Technology (NIST), we have developed a wireless network characterization method to measure latency and reliability of the deployed network without accessing network-level metrics. In this work, we use our characterization method to study the performance of a gas sensing wireless network operating over industrial wireless channels. We have built the gas sensing scenario using the NIST industrial wireless testbed which includes ISA100.11a wireless devices, a channel emulator, and a high performance programmable logic controller (PLC), where the physical process is simulated. We use the channel emulator to replicate the path loss and multipath of the industrial environment while the signal injected into the emulator comes from ISA100.11a wireless devices. Moreover, we inject 4 mA-20 mA gas sensing signals into the wireless devices. In this work, we test various network parameters over the described setup.

Index Terms

Wireless gas sensing, Industrial wireless, ISA100.11a, Confined spaces, Cyber-physical systems, Safety, Channel models.

I. Introduction

Gas sensing has become a typical component in many industrial systems because of its broad usage in many industrial areas, such as manufacturing, automotive, and medical industries. Specifically, gas leaks monitoring is employed for safety purposes in scenarios when leaks can result in human fatalities. Moreover, distributed gas sensing networks are widely deployed because of different gas densities at different locations and heights. Hence, wiring of these distributed networks represents a major concern in implementation because of the cost and complexity of wiring in some environments. As a result, wireless gas sensing networks provide a more flexible and suitable solution for continuous distributed gas sensing applications.

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Moreover, confined space monitoring plays an important role in reducing injury that may happen due to gas accumulations. Entering a confined space for performing a maintenance task requires following a proper safety protocol. The major requirements of safety protocols typically include checking air quality before entering and having a portable gas sensor for continuous gas level monitoring while inside. Hence, technologies of gas monitoring equipment are being advanced to achieve these requirements. Wireless communication is used to connect distributed gas monitoring sensors to various control and alarming units allowing continuous monitoring even for closed confined spaces and more reliable measurements from portable devices [1].

A. Research Purpose and Approach

In this work, we test the applicability of using wireless sensing in gas level detection in confined spaces. We focus on the use of ISA100.11a nodes to transmit a typical accumulating carbon monoxide (CO) gas density signal. We characterize the performance of the deployed wireless system through calculating the end-to-end delay and error in the transmitted signals. We also use a channel emulator to generate confined space wireless channel effects on the signals. We study the effects of various system parameters on the performance where we evaluate the use of wireless communications in confined spaces for gas monitoring.

B. Related Work

In [2]–[6], the use of wireless gas sensing is introduced in various scenarios. In [2], the notion of smart sensors is introduced and their requirements and characteristics are discussed. A wireless gas sensor is introduced as an example of the smart sensing applications where the sensor is able to sense various types of gases, store data, and generate alarms through the integration of a microprocessor. In [3], a long-term air quality monitoring testbed is built and evaluated. A wireless IEEE 802.15.4 based node was continuously being operated and it is compared to a standard non-wireless air quality monitoring system. In [4], an experimental setup of a sensor-actuator system for gas detection and control is introduced. The system uses wireless sensors and actuators that deploy the ZigBee standard with the BACnet building automation protocol. In [5], the use of wireless gas sensing is discussed in industrial environments. The authors have justified the importance of wireless gas sensing networks due to the ease of installation and the low cost of maintenance. Finally, in [6], the use of wireless gas sensing is proposed for underground gold and platinum mines. The existence of methane gas in these mines can cause fires and toxicity. Hence, wireless communications can be used in order to improve gas detection capabilities underground.

C. Paper Organization

The remainder of the paper is organized as follows. The gas sensing application and the test setup are discussed in Section II. Numerical results are shown and discussed in Section III. Finally, the paper is concluded in Section IV.

II. Gas Sensing Monitoring System

A. Application

In this paper, we consider the case of welding a tank where the welding process produces gases in rates which are generally non-hazardous. In confined spaces, gas accumulations may lead to an increased density level of these gases which may lead to high risk situations [7], [8]. Specifically, the welding smoke can be extremely toxic as it contains many substances, such as chromium, nickel, arsenic, asbestos, manganese, silica, beryllium, cadmium, nitrogen oxides, phosgene, acrolein, fluorine compounds, carbon monoxide, cobalt, copper, lead, ozone, selenium, and zinc. An example of a case study in which CO became dangerous and life-threatening was discussed in [9].

The existence of CO at high density can lead to poisoning of humans and increased risk of fire and explosion. For a gas to lead to a fire or an explosion, it has to be in the range between the lower explosive limit (LEL) and the upper explosive limit (UEL) which are 12.5 parts per million (ppm) and 74 ppm, respectively, for CO. Moreover, the permissible exposure limit (PEL) of CO is 25 ppm which defines a threshold for alarming a worker to vacate from the confined space.

The considered scenario is shown in Fig. 1. Two ISA100.11a wireless nodes exist inside the tank and the wireless access point is located directly at the opening of the tank. One of the sensors is close to the welding location while the other sensor is on the other side of the tank.

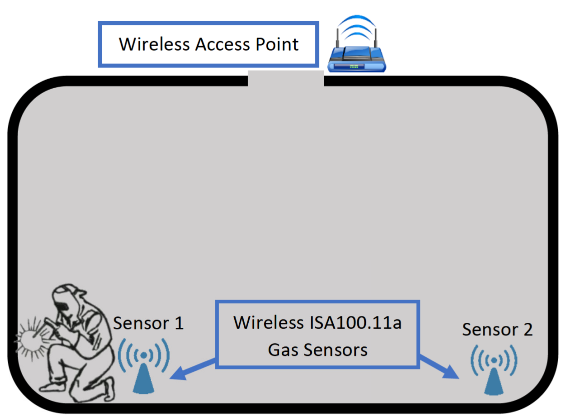

Fig. 1. Wireless System Model.

B. Test Setup

The testbed includes a high-performance programmable logic controller (PLC) equipped with 16-bit digital-to-analog (D/A) conversion modules which convert digital stimuli to $0V$-$10V$ analog signals. The wireless network is composed of the wireless sensors and a wireless gateway for infrastructure connectivity between nodes. Moreover, the testbed includes a radio frequency channel emulator capable of replicating the multi-path and path loss environments for a mesh network of up to 8 physical nodes and 56 half-duplex emulated links between those nodes. The channel emulator supports an instantaneous bandwidth of 250 MHz for each emulated channel with an effective dynamic range of 73 dB. The emulator is controlled by a nearby computer which loads the path loss and channel impulse response models for each link.

In the testbed, we have employed the channel emulator in order to include industrial confined space environment effects on the wireless transmissions. We consider the confined space channel model in [10]. This channel model is a generic simulated channel model in a confined space with different numbers of absorbers to represent the existence of workers in the space and/or approximate the effect of the confined space wall material reflectivity on the performance.

The primary objective of this testing is to evaluate the performance of a wireless network deployed in a confined industrial space. We employ a two-stage method for assessing the performance of an industrial wireless network. The method calls for estimation of network delay using maximal length pseudo-random binary sequence correlation followed by estimation of the signal errors through the network adjusted by the delay estimates.

We exploit the conventional general cross correlation (GCC) method for delay estimation [11]. In order to obtain a good delay estimation using the GCC method, we choose an input signal with no repeating patterns within the window of delay estimation. Thus, we use a maximal length binary sequence generated by a linear feedback shift register (LFSR).

In order to quantify the error effect on the performance of an industrial network, an arbitrary input signal is injected at the transmitting node. The injected signal is selected to be similar to practical signals of the sensing node, for example, being a linear signal with certain slope, or a signal with a charging behavior to represent gas accumulations. The received signal is distorted and delayed.

III. Results

We employ the wireless system model shown in Figure 1 where the distance between sensor 1, near the welding point, and the access point is fixed at 17.5 meters. Sensor 2 takes two locations at 10 meters and 20 meters away from sensor 1. The distance between sensor 2 to the access point is 17.5 meters when it is 10 meters from sensor 1. The wireless nodes used follow the ISA100.11a standard, but their topology is not enforced. The channel power delay profile is obtained from [10] for four different cases with 0, 1, 3 , and 7 absorbers. The increase in number of absorbers may reflect an increase in number of workers inside the confined space which reduces the reverberation within the confined space. An increase in the number of absorbers may also reflect a decrease in reflectivity of the walls. The test of each case has been run for 15 minutes.

First, we measure the average delay for each of the sensors by inserting a maximal length sequence and computing the delay using the GCC method. The time resolution of the obtained delay is 0.5 second. The results are shown in Table I. The delays are not much affected by the sensors locations and hence the major source of this delay is not packet losses and retransmissions. Instead, the major source of delay is the polling by the PLC of the Modbus transmission control protocol (TCP) server which is located within the ISA100 gateway. The Modbus is a serial communications protocol widely used in industrial applications. Using this testing method, we ascertain the total system delay which includes all sources of delay from data acquisition to PLC computation. The obtained values are generally satisfactory for gas sensing applications due to the slow rate of accumulations.

TABLE I
TABLE OF THE DELAY VALUE IN SECONDS FOR THE TWO GAS SENSORS AGAINST THE DISTANCE FOR VARIOUS CHANNEL MODELS.

Channel/Sensor(Distance)	Sensor 1(10m)	Sensor 1(20m)	Sensor 2(10m)	Sensor 2(20m)
No Absorbers	2.5	2.5	3.0	3.0
1 Absorber	2.5	2.5	4.0	3.5
3 Absorbers	2.5	2.0	4.0	3.5
7 Absorbers	2.5	2.5	4.0	4.0

Then, we evaluate the average root mean square (RMS) error in the received signal compared to the transmitted signal after being aligned using the calculated delay. We first consider a ramp signal where the density of the CO increases with a fixed rate over time. The slope of the ramp signal at sensor 1 is 5 ppm/minute and at sensor 2 is 1 ppm/minute because sensor 2 is located away from the welding point. The obtained errors are shown in Table II. The obtained RMS errors compared to signal magnitude are very low, and hence the sensors have a satisfactory performance. The errors are smaller at sensor 2 because of the smaller magnitude of the transmitted signal. Moreover, the error is not highly affected by the nodes locations, and hence, the major source of error is signal acquisition which may include quantization errors and biases.

TABLE II
TABLE OF ERROR VALUES FOR A RAMP SIGNAL FOR THE TWO GAS SENSORS AGAINST THE DISTANCE FOR VARIOUS CHANNEL MODELS.

Channel/Sensor(Distance)	Sensor 1(10m)	Sensor 1(20m)	Sensor 2(10m)	Sensor 2(20m)
No Absorbers	0.0633	0.0654	0.0258	0.0300
1 Absorber	0.0593	0.0599	0.0193	0.0210
3 Absorbers	0.0743	0.0614	0.0167	0.0182
7 Absorbers	0.0669	0.0699	0.0279	0.0259

Then, we consider a charge signal to represent the effect of the gas accumulations in a confined space where the density of the CO increases with a time constant of 1.67 minutes for sensor 1 and 8.33 minutes for sensor 2. The time constant is smaller, and hence, the accumulation of the gas is faster at sensor 1, because sensor 1 is located close to the welding point. The obtained errors are shown in Table III. The charge signal errors have a similar trend to the ramp signal. The average RMS is relatively higher in this case because quantization errors are larger in the charge signal compared to the ramp signal.

TABLE III

TABLE OF ERROR VALUES FOR A CHARGE SIGNAL FOR THE TWO GAS SENSORS AGAINST THE DISTANCE FOR VARIOUS CHANNEL MODELS.

Channel/Sensor(Distance)	Sensor 1(10m)	Sensor 1(20m)	Sensor 2(10m)	Sensor 2(20m)
No Absorbers	0.1741	0.1634	0.0709	0.0681
1 Absorber	0.1588	0.1739	0.1211	0.0878
3 Absorbers	0.1612	0.1840	0.0582	0.0868
7 Absorbers	0.1599	0.1827	0.1253	0.1257

IV. CONCLUSIONS

In this work, we have tested the performance of two ISA100.11a wireless gas sensors operating in a simulated welding process within a confined space. The sensors transmit the CO level produced by a welding process close to one of the sensors. We have employed the NIST wireless testbed to replicate the confined space wireless channel effects on the performance of the wireless nodes. In the current setup with the existence of a line of sight (LOS) and having the typically slow gas accumulations, the measured performance is considered satisfactory for gas safety applications. The measured delays and errors are mainly produced by Modbus polling and data acquisition errors. Hence, more improvement still can be obtained while deploying wireless for confined space communications by reducing Modbus publication and polling delays. Indeed, many ISA100.11a gateways have Modbus servers that refresh at a much slower rate than the fastest allowable sensor update rates. This can mask or exacerbate delay issues of the wireless network. Improvements to the standards to address storage and publication rates of sensor data by the gateway are needed. However, the current ISA100.11a standard supports gas sensing and alarming for single-chamber confined spaces as demonstrated by this study. Confined spaces with multiple chambers will be addressed in a later study.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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