

# Automatic Reaction to a Chemical Event Detected by a Low-cost Wireless Chemical Sensing Network

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**Abstract**—A test-scale wireless chemical sensor network (WCSN) has been deployed within a controlled Environmental Chamber (EC). The combined signals from the WCSN were used to initiate a controllable response to the detected chemical event. When a particular sensor response pattern was obtained, a purging cycle was initiated. Sensor data were continuously checked against user-defined action limits, to determine if a chemical event had occurred. An acidic contaminant was used to demonstrate the response of the sensor network. Once the acid plume was simultaneously detected by a number of wireless chemical sensor nodes, an automatic response action, which was the purging of the EC with clean air, was initiated and maintained for a period of time until the WCSN indicated that normal status had been re-established.

## I. INTRODUCTION

There is a public expectation of protection from extraordinary incidents within the built environment [1]. However, in their current state of development, built environments lack the ability to detect hazardous chemical components in indoor air [2]. Without active chemical sensor networks coupled to building management systems it is not possible to provide warning of an event or to automatically react to an event as it occurs. Wireless sensing platforms show potential for use in this space due to the ease of component installation, the huge reduction in required hard wiring and the flexibility in positioning of small lightweight sensor nodes [3-5]. Due to the advances in WSN hardware, research in the development of low-cost, low-power sensing methods that are suitable for integration with wireless sensing platforms have become very active recently [6].

A path of research within the CLARITY group is the development of low-cost sensors that, when deployed in numbers over a distributed area, will provide greater spatial and temporal resolution of contaminant concentration measurements than is achievable with conventional single point measurement methods. Research by Lau *et al.* [7] and later by Shepherd *et al.* [8] built on a low-power reverse-

biased LED light detection method employed by Deitz *et al.* [9] to construct low-cost optical chemical sensors. Trials of the resultant LED-based chemical sensors have previously been conducted by our group for the detection of contaminants in liquid [10] and gaseous environments [8]. These LED-sensors have also been incorporated onto wireless communications platforms and the resulting sensor ‘nodes’ used to form demonstration WCSNs [11, 12]. Results have shown that even these relatively simple WCSNs can detect chemical contaminant plumes, and report on plume dynamics and its possible source, information that cannot be obtained from solitary sophisticated sensors [12]. To expand the functionality of the passive WCSN monitoring system, we now demonstrate that the WCSN can be used as an input to a control loop to initiate a real-time response to a detected chemical event. The developed real-time system, detailed in this paper, is termed a Wireless Chemical Sensor Actuator Network (WCSAN).

## II. WIRELESS CHEMICAL SENSOR NODE

### A. Chemical Sensor Operation

The paired emitter-detector chemical sensor configuration used in the developed wireless chemical sensor node has been described in detail in previous publications and was based on the paired emitter-detector LED arrangement described previously [7, 8]. Further information with regards to the sensors construction and optimization for a target acidic species can be found by referring to [8, 11, 12]. Therefore, only a brief overview of the sensors construction and operation relevant to the study described in this paper are provided here.

The colorimetric polymer based sensing layer operates in the following manner. In the presence of an acidic vapor, the sensor membrane color shifts from the blue alkaline state towards the yellow acidic state. Removal of the acidic species allows the colorimetric polymer to recover to the initial alkaline blue state. This stable and reversible sensor

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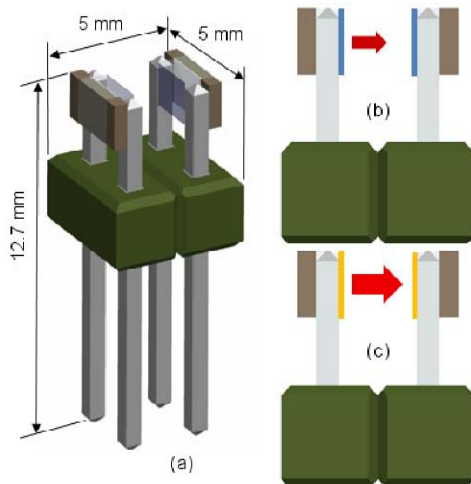


Figure 1. Paired emitter and detector LEDs (a) overall physical dimensions (b) red emitted light filtered by polymer layer in blue alkaline state (c) higher red light transmission when polymer is in yellow acidic state.

can be used to monitor the environmental change for a long period of time, *i.e.*, it is not a “single shot” device. Optimal sensitivity in measuring the color change was achieved by matching the spectral absorbance band (blue,  $\lambda_{\max} \cong 590$  nm) of the pH indicator dye encapsulated within the membrane, with the emission band of the red LED light ( $\lambda_{\max} \cong 600$  nm) source (emitter) [11]. Application of the polymer membrane onto the LED surface modulates the light intensity that passes from the emitter onto the detector, much like a filter. The sensor components are depicted in Fig. 1. In Fig. 1(a) the overall dimensions of the sensor, along with an indication of the colorimetric reagent coating, are shown. The filtering operation of the reagent coating is shown in Fig. 1(b) and Fig. 1(c). When in the alkaline state (blue), *i.e.*, no acidic species present, the red emitted light is filtered by the reagent



Figure 2. Constructed wireless chemical sensing node, detailing physical size and component layout

coating, Fig. 1(b). However, in the presence of an acidic vapor, less of the red emitted light is filtered by the reagent layer (yellow) and thus increases the light intensity falling on the detector LED, affecting a change in the detector LEDs response.

### B. Sensor Node Hardware and Operation

The operation of the sensor is reliant on a microcontroller. In general commercial wireless sensor nodes utilize microcontrollers coupled with separate radio transceivers. This provides a convenient platform for integrating this form of sensor to result in a wireless chemical sensor node. In this body of research MPR500 Mica2Dot motes ([www.xbow.com](http://www.xbow.com)) with radios operating at 868 MHz were equipped with the developed component based chemical sensor interfaced to each mote using MTS510A prototyping boards. During these laboratory studies, sensor nodes were operated at a sensing rate of 0.5 Hz and powered by 2 AA 1.5 V cells (2600 mAh). The completed sensor node was packaged in a custom protective enclosure, see Fig. 2. An opaque cover, with two openings to allow free movement of vapors across the sensing surfaces, was placed over the sensor at the top of the completed enclosure. The function of this cover was to reduce interference effects from fluctuating ambient light. Sensed data were transmitted directly after each measurement, providing real-time environmental monitoring.

The procedure for performing measurement with the sensor can be found in our previous publication [12]. In short the output of the sensor is an integer value in the range of 0 to 4000. The sensor response is dependent on the light intensity reaching the detector LED [9] and thus is a measurement of the blue color intensity of the pH sensitive colorimetric layer on the LED surfaces. The measured response of the sensor to the presence of an acidic stimulus was a reduction in the sensor output value resulting from a decrease in blue color.

### III. DATA CAPTURE AND SYSTEM CONTROL SOFTWARE

VB MoteGate, a programme for receiving, decoding and logging of mote data packets, was obtained under a GPL license from SourceForge under the TinyOS project [13]. This software was used as a basis upon which a custom data acquisition and output control interface was built. Previous calibration studies were conducted through incremental contaminant concentration increases of 0.1 mg/L. The results of these studies found that the response of the sensor was none linear, but could be approximated over a range of 0-1 mg/L by a third order polynomial equation. Real-time conversion of received raw sensor values to concentration units was conducted at the basestation PC based on this equation. While data acquisition and visualization were the primary role of the developed interface, it was possible to adapt the software to facilitate logic output control of the basestation PCs parallel port. This resulted in a feedback loop where chemical sensor data acted as an input to the ECs gas extraction control system.

The concept of the WCSAN was to examine the colour state of a number of nodes within the WCSN to determine when an event was occurring. Confirmation of an event was achieved by a number of nodes simultaneously detecting a chemical contaminant. Therefore, for these studies, the specific concentration of the contaminant was not of immediate concern. The first concern was whether or not a contaminant was present within a node's local environment. This was achieved by attributing a binary chemical contaminant state (No Event / Event) to the real-time data returned by deployed sensor nodes. The sensor threshold of detection (TOD) (0.03 mg/l) [12] was set to define the state switching threshold. The binary states corresponded to no detected contaminant, *i.e.*, a sensor response value less than the TOD, or to a detected contaminant, *i.e.*, a sensor response value greater than the TOD. Upon detection of a contaminant, the status of the affected sensor node was changed to "Event". To confirm the chemical species detection, the surrounding sensor nodes were examined to determine if they had also detected the contaminant. In this laboratory trial, the criterion to confirm a chemical event, and thus initiate a reactive response was, the event states of three nodes, within the five node network, simultaneously indicating the presence of a contaminant species. Fulfillment of this criterion resulted in the activation of the gas extraction components of the EC, via the basestation PCs parallel port, until all deployed sensors had returned to a state of "No Event".

#### IV. EXPERIMENTAL ARRANGEMENT

The design and construction of a 2 m<sup>3</sup> Environmental Chamber (EC) for the evaluation of various sensor devices and sensor networks was documented previously [11]. The arrangement of the EC for these trials is presented in Fig. 3. Acidic plumes were generated and entered the EC at point A

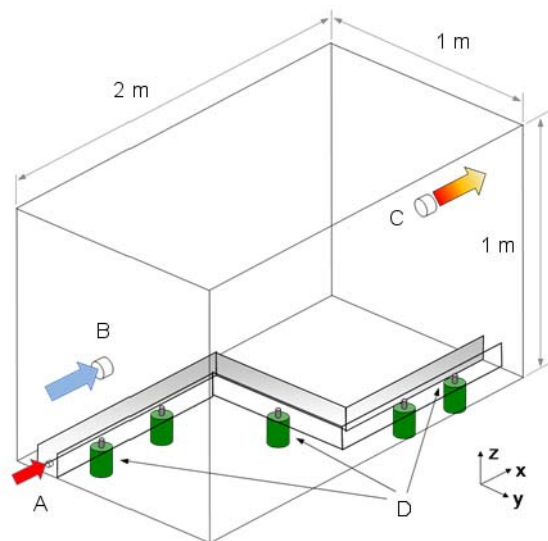


Figure 3. Environmental Chamber (EC) with volume of 2m<sup>3</sup>, (A) Contaminant vapor inlet point, (B) Fresh air inlet, (C) Contaminant extraction point, (D) Deployed wireless chemical sensor nodes reporting to automated chamber control interface.

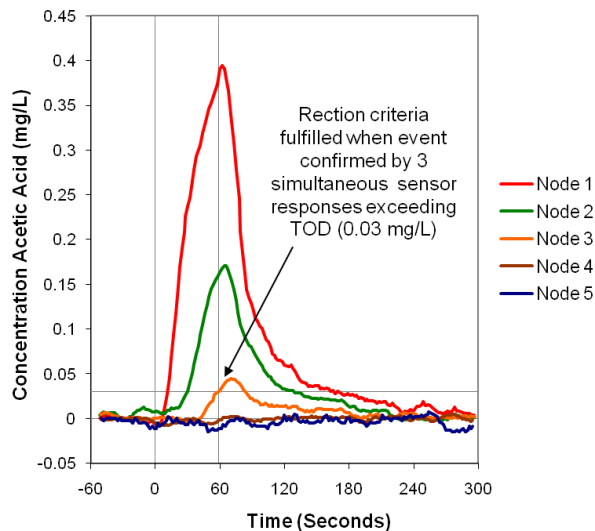


Figure 4. Real-time data where the presence of a contaminant was detected by individual sensor nodes. A chemical event was confirmed by simultaneous response of a subgroup of nodes, initiating an automatic extraction response.

by applying clean dry air (CDA) at a rate of 300 mL/min to a bubbler unit containing an 80 mL of diluted acetic acid in the ratio of two parts water to one part pure acetic acid (Fluka, Ireland, no. 45727). Purging of the chamber was achieved by opening a fresh air inlet via a pneumatic actuator (point B) and activation of an extraction fan (point C). Dispersion of the denser than air contaminant from the chamber base was achieved by a CDA agitation supply, also located at point A, which dispersed stagnant denser than air contaminant vapor from the chamber base. A total of five sensor nodes were mounted within a channel on the chamber base in numerical sequence, with node 1 positioned closest to the contaminant inlet and node 5 at the far end below the extraction point.

#### V. EVENT DETECTION AND AUTOMATIC REACTION RESULTS

The resultant data for a conducted trial of the WCSAN is presented in Fig. 4. Sensor devices were operated in uncontaminated air for a period of 60 s to establish baseline response values ( $t = -60$  s to  $t = 0$  s). At  $t = 0$  s the contaminant plume was activated through the control interface. From the response data it can be seen that the initial detection of the contaminant was recorded by node 1 and occurred at  $t = 13$  s. At  $t = 30$  s, node 2 reported the presence of a contaminant. Confirmation of an event, as per the outlined event criterion occurred at  $t = 59$  s when three separate sensor nodes (nodes 1, 2, and 3) simultaneously reported a contaminant presence at their locations.

The automatic response to the detected chemical contaminant event was to stop the contaminant supply and activation of the purge system. Initiation of the reactive response is visible at  $t = 59$  s, as a marginal increase in the concentration level recorded by node 1. The peak concentration recorded by node 1 occurred 3 s later at  $t = 62$

s. The reason for the short delay in the recovery of this sensor node and the marginal contaminant concentration spike before beginning to recover towards a negligible contaminant concentration level was the activation of the CDA agitation input. The same delay effect is also evident in the responses of nodes 2 and 3. Maximum concentration levels were recorded by nodes 2 and 3 at  $t = 66$  s and  $t = 72$  s respectively. The sequence of recovery of nodes 1-3 shows that the denser than air contaminant vapor was forced across these sensor nodes by the applied CDA before it was purged from the environment.

Removal of the contaminant from the immediate environments of the sensor nodes is shown through the reduction in their recorded concentration levels. Sensor node 3, because of the smaller concentration to which it was exposed in comparison with nodes 1 and 2, was first to recover to a concentration level below the TOD. This occurred at  $t = 84$  s. At  $t = 128$  s the concentration recorded by node 2 had also been reduced to a value less than the TOD. At  $t = 171$  s, node 1 recovered to below the 0.03 mg/l TOD. At  $t = 235$  s all sensor nodes recorded a negligible contaminant concentration level and the purge response was automatically stopped.

In this example it is clear that an inherent tradeoff exists between the time required to obtain confirmation of an event (*i.e.*, to exclude the possibility of false positives) and the minimum system reaction time.

Initiation of a reactive response, in this case a purge operation, based on sensed values from a single solitary sensor would not be acceptable. There are many reasons to justify this, but two important examples are as follows. The sensor response could be a false positive due to an interference effect, or the sensor response could be accurate but the detected contaminant could be stationary (non-dispersive). In the first example it would be unnecessary to activate a purge response. In the second case, data from a single sensor would not provide additional information with regard to the movement of the contaminant. Activation of a local environment purge could lead to further dispersion of the contaminant within the environment. Additional data from neighboring nodes would confirm the occurrence of an event, and more importantly, provide information with regard to the dynamics of the contaminant. This information would better inform any decision making system as to how to react to the contaminant. For instance, in the case of the described laboratory trial, a more effective way of limiting the impact of the contaminant within the environmental chamber, would have been to purge the volume from an exit point close to the contaminant source, reducing the extent of the contaminant dispersion.

## VI. CONCLUSIONS

The developed WCSAN has shown the integration of real-time data from a group of low-cost wireless chemical sensors with a controlled response system. The developed system is capable of detecting an acidic contaminant vapor. Confirmation of the contaminant detection is achieved by a number of nodes simultaneously indicating a contaminant's presence. Once an event is confirmed, the reactive response is activated until the contaminant is removed from the environment (again verified by the network of low cost sensors). Removal of the contaminant is verified when all nodes deployed in the monitored area have returned to below the TOD level. This proposed WSN system is envisaged to be applicable in the detection and effect limitation of hazardous gas leaks within built environments.

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