Chemical Event Tracking using a Low-cost Wireless Chemical Sensing Network

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Abstract—**A recently developed low-cost light emitting diode (LED) chemical sensing technique is integrated with a Mica2Dot wireless communications platform to form a deployable wireless chemical event indicator network. The operation of the colorimetric sensing node has been evaluated to determine its reproducibility and limit of detection for an acidic airborne contaminant. A test-scale network of five similar chemical sensing nodes is deployed in a star communication topology at fixed points within a custom built Environmental Sensing Chamber (ESC). Presented data sets collected from the deployed wireless chemical sensor network (WCSN) show that during an acidic event scenario it is possible to track the plume speed and direction, and estimate the concentration of chemical plume by examining the collective sensor data relative to individual sensor node location within the monitored environment.**

I. Introduction

The majority of published research in the area of Wireless Sensor Networks (WSN) focuses on the monitoring of physical parameters such as temperature, humidity and light, with the main research concerns being scale of deployment, data communication protocols and node operating longevity [1-4]. Current deployments have identified that the ability to detect chemical vapours, measure gas concentrations and pH would augment the measurement capabilities of currently available physical sensors [2]. Therefore, 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 [5]. Merging of low cost chemical sensing methods with deployable WSNs is an attractive concept, and if realised, distributed ubiquitous real-time monitoring of important chemical species will become possible without the physical, temporal and cost restrictions of sophisticated laboratory measurement equipment. It was envisaged that such devices should also be simple, small and perform only basic detection function which would form the lowest level of chemical monitoring in a sensor network hierarchy [6]. These devices will therefore have the responsibility to be the first line of detection of the presence of a chemical contaminant and to report the event detection to the next level of responsibility in their respective network hierarchy. However, documented low-power wireless chemical sensing platforms and their application within a sensing network is scarce in the literatures, as opposed to the more regularly investigated physical sensor networks. Some published examples include a single RF wireless chemical sensor node which used a magnetoelastic sensor array to measure pH in an aquatic environment [7]. Chavali *et al.* presented results from a single electro-chemical sensor operating on a Mica2Dot mote platform for the detection of a volatile anesthetic agent [8].

Recent research by Deitz *et al.* [9] saw the use of light emitting diodes as light detectors in the development of a low-power, low-cost, optical communication platform. The subsequent application of chemical reagents to the surfaces of light measuring LEDs by Lau *et al.* [10] and Shepherd *et al.* [11] has led to the development of, low-cost, optical chemical detectors. Integration of this form of chemical detector with a wireless communications platform and its deployment as a Wireless Chemical Sensor Network (WCSN) has shown the potential of these devices in passive real-time monitoring of a chemical plume [12]. The body of work described in this paper is the development of WCSN using a calibrated wireless optical chemical sensor.

II. Wireless Chemical Sensor Node

A. Component Chemical Sensor Construction

A low-cost chemical sensor was constructed using a paired emitter and detector LED arrangement, as described by Shepherd *et al.* [11]. Super bright orange 610 nm 1206 format surface mount LEDs (Kingbright, KP-3216SEC, 3.2 x 1.6 mm) soldered to a 2.54 mm pitch header pin formed the low-cost optical sensor. Addition of a colorimetric chemically sensitive coating to the LED surfaces allows the simple light detector to function as a simple chemically selective optical sensor that detects acidic vapors and is shown in Fig. 1.

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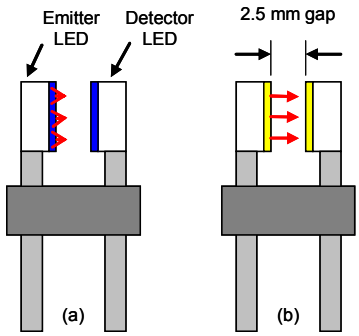

Figure 1. Paired emitter and detector LED with acid responsive chemical sensor.

Optimal sensitivity was achieved by matching the absorbance spectra of the selected colorimetric receptor, in this case a pH indicator dye, and the emission spectrum of the LED light source. For further detail with regard to this process please refer to [12]. The sensor formulation was prepared by dissolving the pH indicator bromophenol blue (BPB), which changes from blue to yellow in the presence of an acid, with a solution of ethyl cellulose in ethanol. In order to prepare an acidic responsive sensing polymer, the indicator was stabilized in the blue alkaline form by adding the salt tetrahexylammonium bromide (THABr), which acted as a solid-state pH buffer. A small volume of the formulation was manually applied to the surface of both LEDs and allowed to dry in the dark for a period of 24 hours, ensuring adherence of the polymer layer to the LED surface, before use.

B. *Sensor Operation*

The sensors operation is controlled by a microcontroller. To perform a measurement, the detector LED is first charged by setting the digital I/O pin connected to its cathode to logic high, i.e., reverse bias. Subsequently, the emitter LED in series with a 1 kΩ current limiting resistor is activated to act as a consistent light source over repeated sample measurements. In a simultaneous operation the state of the pin connected to the cathode of the detector LED is reversed, allowing the capacitance to discharge into a microcontroller at a rate dependent on the light intensity reaching the LED [8]. The logic state of the discharging pin is checked for a fixed number of microcontroller processor counts (4000). The sensor response is the quantity of processor counts for which the logic state of the detector voltage remains above logic zero (high state) resulting in an integer value ranging from 0 to 4000. In short, strong light intensity will result in a low count value and vice versa. This is because strong light produces higher photocurrent to discharge the reverse biased detector LED.

Fig. 1 depicts the constructed sensor in both alkaline and acidic states. In Fig. 1(a) a large portion of the red emitted light is filtered by the dark blue chemically sensitive layer. A change in color of the sensing layer from blue to yellow induced by the presence of acidic vapor in the immediate environment of the sensor, as indicated in Fig. 1(b), allows for a greater proportion of the emitted light to pass through the responsive layer onto the detector LED. The measured response of the sensor to the presence of a chemical stimulus was an increase in light, represented by a reduction in the number of processor counts.

C. *Wireless Sensor Node Hardware and Programming*

MPR500 Mica2Dot motes (www.xbow.com) with radios operating at 868 MHz were equipped with component based chemical sensors interfaced to each mote using MTS510A prototyping boards. An alternative, higher capacity power source of 2 AA 1.5V cells (2600 mAh) was incorporated into each sensing node to account for the high resolution sensing rate of 0.5 Hz employed during laboratory trial studies. As part of a power management scheme, the size of the data packet payload was reduced from the standard 20 bytes to 4 bytes (2 bytes for sensor value and 2 bytes for battery voltage level). For this work, the role of the sensor platform is purely data acquisition and transmission. Data were managed so that sensor values are transmitted directly after each measurement is completed, i.e., real-time transmission of all updating sensor values. Data processing is the responsibility of conditioning software at the host PC which accesses sensor data from the network basestation comprising of a MPR400 MICA2 mote mated to a MIB510CA serial interface board.

D. *Node Enclosure*

The completed sensor node packaging design is shown in Fig. 2. The package is a circular cone enclosure that encapsulates and protects the electronics from the hazardous environment. It was designed and fabricated in-house using a 3D rapid prototyping system (Dimension SST 768 3D printer). An opaque cover for the sensor with two openings

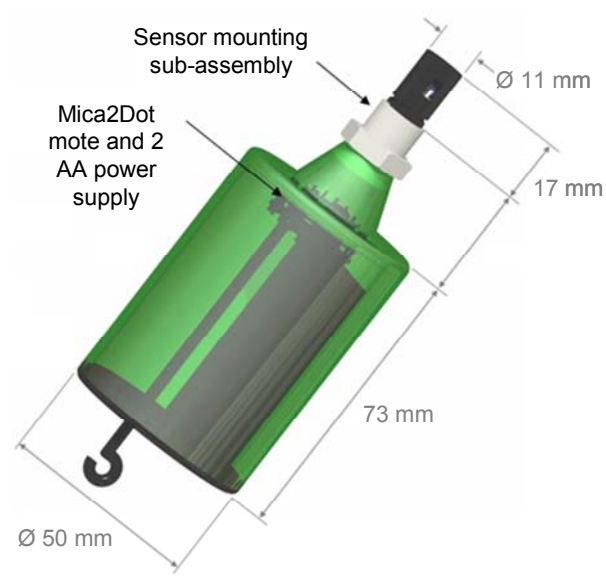

Figure 2. Constructed wireless chemical sensing node, detailing physical size and component layout.

to allow free movement of vapors across the sensing surfaces was designed to reduce the interfering effects from ambient light which is a common problem with optical chemical sensors.

III. Conditioning Software

Data acquisition and visualisation software provided by Crossbow was not suitable for the real-time contaminant monitoring application under investigation. Alternative software, VB MoteGate, 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 interface was built. The modified software accommodates extraction of data from the minimised payload packet structure. Received chemical sensor data were processed in real-time within the interface to give the chemical concentration. Conversion of raw sensor values to concentration units is based on user defined conversion equations developed through calibration studies.

IV. Environmental Sensing Chamber Arrangement

The design and construction of a 2 m^3 Environmental Sensing Chamber (ESC) for the evaluation of various sensor devices and sensor networks was documented in [12]. Acidic plumes were generated by applying clean dry air (CDA) at a rate of 300 mL/min to a bubbler unit containing an 80 mL dilution of acetic acid in the ratio of two parts water to one part pure acetic acid (Fluka, Ireland, no. 45727). Applying the accumulating headspace of acidic air to an inlet point on the chamber via diameter 6 mm tubing allowed for the contaminant vapor to enter the chamber volume as a plume with an inlet velocity of 0.4 m/s. Purging of the chamber was achieved by activation of an extraction fan in conjunction with CDA agitation supplies which dispersed the denser than air contaminant plume from the chamber base. Sensor nodes were mounted onto the chamber by inserting (screwing) the sensor head into the through holes so that only the sensor is inside the chamber with the main body remaining outside. Nodes 1-4 were positioned within a channel on the chamber base to track plume dispersion. Node 5 was located outside of the channel so that a breach of the channel wall by the contaminant plume would be recorded. The arrangement of deployed chemical sensor nodes within the chamber, the contaminant source and initial inlet flow direction are depicted in Fig. 3.

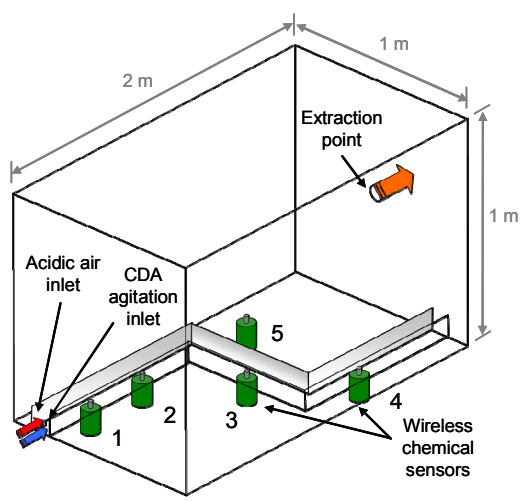

Figure 3. Physical layout of deployed sensors within ESC, with reference to physical dimensions of environment, contaminant course CDA inlet and contaminant extraction point

V. Results

A. Sensor Response Results

The sensor's response time was measured through exposure of a sensor node to an environment seeded with a 1 ppm concentration of acetic acid vapour. The recorded data indicate a response time of 51 s. The reproducibility of the sensor node's response was examined over three consecutive exposure periods. The trial resulted in a relative standard deviation over the three exposure periods of 1.67 %. Calibration of the device was conducted through incremental contaminant concentration increases of 0.1 ppm. The response of the sensor was non-linear, but has been approximated over the range 0 - 1 ppm by a third order polynomial equation. Calibration of multiple nodes resulted in a unique data conversion for each device because of the non-uniform coating layer thicknesses generated from the presently employed fabrication process. The limit of detection (LOD) was calculated as 3 x standard deviation of the baseline level and was found to be 0.03 ppm.

B. Plume Development Tracking Results

Sensor devices were operated in uncontaminated air for a period of 120 s to establish baseline response values. Subsequently, a continuous chemical plume was applied to the chamber for 180 s. At the end of the exposure period the purge system was activated to remove the contaminated air from the environment. Contaminant concentration levels recorded by nodes over the 600 s trial period are presented in Fig. 4. Sensor activation times are defined as the time interval between activation of the contaminant source and recorded sensor concentration exceeding the 0.03 ppm LOD (indicated in Fig. 4). A summary of the node activation times, estimated vapor concentration levels at the end of the exposure period (t = 180 s) and distance from plume source are presented in Table 1. Using these data, very rich information can be inferred regarding the plume dynamics and dispersion of concentration.

The plume flow path is described by the sequence of sensor activation times. The sequential response of nodes to the stimulus was interrupted by the reaction of node 5 prior to node 4. The plume development and direction of movement is tracked through the channel path by nodes 1-4. A split in the plume flow is recorded by node 5, positioned

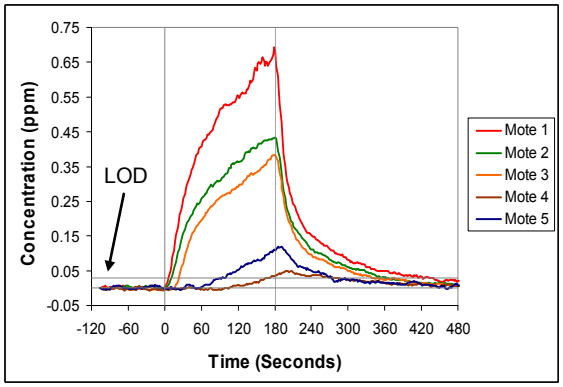

Figure 4. Typical real-time plume tracking data recorded by the deployed network of 5 calibratied wireless chemical sensor nodes over a 180 s continuous exposure period

outside of the channel. The breach of the channel wall resulted in a significantly lower concentration being observed by node 4 with respect to nodes 1-3 located closer to the plume source. The contaminant dispersion rate is determined from the difference between neighboring sensor node activation times. The rate of plume dispersion between sensor nodes 1 and 2 is, therefore, 0.07 m/s. The dispersion rate is affected by the geometry of the chamber, as found through the flow rate between nodes 2 and 3, which are separated by a right-angled turn in the channel path, being at a reduced level of 0.04 m/s.

Examining the recorded data without prior knowledge of the plume source identifies the location of node 1 as nearest to the contaminant source because this node consistently reported the highest chemical species concentration. The results obtained from the deployed wireless chemical sensor network (WCSN) show that during an acidic event scenario it is possible to track the plume speed and direction, and estimate the concentration of chemical plume by examining the collective sensor data relative to individual sensor node location within the monitored environment. This proposed WSN system is envisaged to be applicable in hazardous gas detection in field (e.g. gas leak) environments.

TABLE I. SENSOR RESPONSE AND LOCATION DATA

Node	Activation time (s)	Concentration at t = 180 s (ppm)	Distance from plume source (mm)
1	7	0.69	333
2	12	0.43	666
3	25	0.38	1246
4	169	0.04	1826
5	90	0.11	1333 [a]

a. Obstructed by 100 mm channel wall

VI. CONCLUSIONS

Preliminary trials of the developed low cost wireless chemical sensor node resulted in a stable platform that returned calibrated data over a concentration range of 0 – 1 ppm acetic acid. The developed optical chemical sensor node displayed good reproducibility and was found to have a LOD of 0.03 ppm. When replicated and deployed as a network of monitoring devices it was possible to explore the plume tracking and contaminant localization capabilities that would be provided by such a network. Trial study results, which focused on the contaminant concentration levels recorded by individual nodes, showed that it was possible to identify the area of contaminant origin and track the development of an acidic chemical plume applied to the monitoring environment through a point source.

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