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Abstract
Previous research by our team to develop a wireless hydrogen sulfide (H2S) detection system for use in swine housing indicate a multi-point detection system is needed to characterize in-house H2S concentrations both spatially and temporally during slurry agitation. Pulsed fluorescence H2S analyzers, while highly accurate at H2S concentrations less than 20 ppm, require asynchronous sampling to accommodate multiple measurement points with a single analyzer. Additionally, pulsed fluorescence H2S analyzers are not designed to measure the high H2S concentrations associated with burst releases during deep-pit swine manure agitation. The dynamic nature of the environment necessitates simultaneous sampling of multiple points with a sensor that can respond to very high (100 – 500 ppm) H2S concentrations. This can be accomplished through the use of electrochemical sensors that have demonstrated the ability to perform similarly to pulsed fluorescence at high concentrations. The objective of this project was to develop a wireless H2S sensor network that can be used to characterize the spatial distribution of H2S that workers and swine in pork production facilities are exposed to in different facility types during different operating conditions. The wireless H2S sensor network developed in this project was designed to meet the following operational criteria: a) less than 5% sensor drift per 1000 ppm-hours, b) up to 50 m range, c) data collection interval less than 90 seconds, and e) H2S detection range of 0-500 ppm.

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Abstract. *Previous research by our team to develop a wireless hydrogen sulfide (H_2S) detection system for use in swine housing indicate a multi-point detection system is needed to characterize in-house H_2S concentrations both spatially and temporally during slurry agitation. Pulsed fluorescence H_2S analyzers, while highly accurate at H_2S concentrations less than 20 ppm, require asynchronous sampling to accommodate multiple measurement points with a single analyzer. Additionally, pulsed fluorescence H_2S analyzers are not designed to measure the high H_2S concentrations associated with burst releases during deep-pit swine manure agitation. The dynamic nature of the environment necessitates simultaneous sampling of multiple points with a sensor that can respond to very high (100 – 500 ppm) H_2S concentrations. This can be accomplished through the use of electrochemical sensors that have demonstrated the ability to perform similarly to pulsed fluorescence at high concentrations. The objective of this project was to develop a wireless H_2S sensor network that can be used to characterize the spatial distribution of H_2S that workers and swine in pork production facilities are exposed to in different facility types during different operating conditions. The wireless H_2S sensor network developed in this project was designed to meet the following operational criteria: a) less than 5% sensor drift per 1000 ppm-hours, b) up to 50 m range, c) data collection interval less than 90 seconds, and e) H_2S detection range of 0-500 ppm.*

The developed wireless H_2S sensor network will be utilized in deep pit swine facilities during normal operating conditions, as well as during pit agitation and removal events to monitor H_2S concentration and spatial distribution.

Keywords. Wireless sensor network, WSN, hydrogen sulfide, spatial and temporal H_2S distribution, swine manure agitation, mesh network, Zigbee

Introduction

Hazardous high concentration hydrogen sulfide (H_2S) burst releases can occur during swine manure slurry agitation. Manure slurry is commonly land applied as a fertilizer for crop production. Slurry agitation is needed to suspend the settled solids for removal from storage and land application to crop production fields. One swine confinement design is a deep-pit building with the animal occupied zone (AOZ) separated from the manure slurry storage area by a slotted floor.

Humans frequent the AOZ as caretakers of the swine. During slurry agitation dangerous conditions can exist in the AOZ caused by H_2S gas escaping the manure slurry storage area through the slotted floor into the animal area. While it is never recommended a human enter a swine house during slurry agitation, entries still occur.

Repeated exposure to H_2S can cause respiratory problems and other illnesses in humans; exposure to high H_2S concentrations possible during slurry agitation and removal events can lead to death (Donham 1990; Donham and Gustafson 2004). Hydrogen sulfide poisoning also occurs in swine. Swine losses to H_2S poisoning can still occur when precautions are taken to avoid swine loss (Puck, 2008). Custom manure applicators report that when loss is randomly scattered throughout the building the swine succumb to H_2S poisoning were most likely lying on the slotted floor nearest the pit headspace. Other times when swine loss is localized to an area, insufficient ventilation (natural or mechanical) or unfavorable airflow patterns to prevent accumulation of H_2S is suspected to be the cause. This observation demonstrates the need to investigate H_2S temporal and spatial distribution (horizontal and vertical) within swine housing during manure slurry agitation and removal events.

Muhlbauer et al (2008) collected high frequency (less than 1 minute sampling interval) H_2S concentration data at two points within the same confinement simultaneously and concluded considerable spatial variation in H_2S concentration can exist in a swine confinement during slurry agitation. More sampling points are necessary to characterize the distribution of H_2S within a swine confinement. Greater spatial resolution would provide an enhanced representation of the environment. An assessment of the conditions within the swine confinement will have greater value with an enhanced representation.

The burst characteristic of H_2S gas releases make it dangerous. Studies have shown that H_2S levels can change rapidly reaching lethal concentrations during agitation of manure in sub-floor pits (Ni et al, 2000; Muhlbauer et al 2008; Patni and Clarke 2003). Although a mobile lab containing gas analysis equipment is highly accurate (Hoff et al 2006; Ni et al, 2000; Ni et al, 2002), it has several limitations including: installation time, low mobility of sampling locations, and asynchronous sampling. Short duration bursts could be concealed due to the time interval and stabilization period associated with asynchronous sampling of multiple locations utilizing a mobile lab (Ni et al 2000). Due to the dynamics of the environment multiple locations need to be sampled at high frequency simultaneously to capture the distribution of H_2S bursts. This can be accomplished through the use of an array of electrochemical sensors which have demonstrated the ability to perform similarly to a pulsed fluorescence analyzer during swine slurry agitation (Muhlbauer et al, 2008). Electrochemical sensors interfaced with a wireless data network allow high frequency transmission of concentration data from multiple sample locations. This paper discusses the development of a wireless H_2S sensor network to quantify H_2S concentration data within deep-pit swine housing.

Safety Emphasis

The wireless H_2S sensor network will be used to collect concentration data in deep-pit swine buildings before, during, and after manure slurry agitation and removal events. Entry into a swine facility during slurry agitation and removal is never recommended. The H_2S data collected using this wireless sensor network will be compared to current suggested worker exposure levels to assess the risk associated with entry before, during, and after manure slurry agitation and removal events. H_2S distribution maps will be developed to suggest management practices to better safeguard animals during these events.

Materials and Methods

The wireless H_2S sensor network was designed to measure H_2S concentrations in multiple locations within a swine facility and transmit the data to an outside location where an operator can monitor the conditions real-time. Multiple H_2S gas sensors measure gas concentrations within the swine production facility, and a wireless data communications network transmits gas sensor data to a central location for remote monitoring, analysis, and storage. The network will be installed in a swine facility and collect data before, during, and after a slurry agitation and removal event. After data collection the network will be removed, disinfected, and reinstalled at another swine facility.

Hydrogen Sulfide Gas Measurement

Previously, Muhlbauer et al (2008) tested multiple commercially available H_2S sensors for response time, accuracy, and repeatability in a controlled laboratory environment. A H_2S sensor (PT-295 HEC H2S, Pem-Tech Inc) performed very well in comparison to a lab grade H_2S analyzer (Model 45C, Thermo Environment Instruments) in both controlled lab and sub-floor slurry storage swine house environments. The sensor has demonstrated excellent durability in the detection system during its use by multiple slurry applicators since October 2007. The electrochemical sensor has a 0 to 500 ppm range to capture potential high concentration bursts during slurry agitation and removal events from sub-floor swine slurry storages. The project team selected the Pem-Tech PT-295 HEC H_2S sensor for use in this project because of its familiarity, performance, and durability.

To determine if continuous exposure to H_2S would degrade the sensor reading, the sensor was exposed to H_2S for an extended period. Gradual signal degradation leading to unrepresentative sensor readings is called sensor drift. The sensor was tested for drift in a controlled environment within a fume hood at the Iowa State University Agricultural and Biosystems Engineering Department Agricultural Waste Management Laboratory.

To evaluate sensor performance 97 ppm (certified +/- 2%) (Matheson Tri-Gas, Joliet, IL) H_2S gas was used for drift testing. The test circuit used by Muhlbauer et al (2008) was employed to further evaluate the Pem-Tech PT-295 HEC. Figure 1 is a schematic of the test circuit. A digital dilutor controlling a zero air generator (produces clean, dry air free of SO_2, NO, NO_2, O_3, H_2S) was used to expose the sensor to a continuous airstream of 0 ppm (herein referred to as zero air). The test circuit consisted of Teflon® tubing and Teflon® coated electric solenoids. A switch controlled the solenoids to switch between zero air and 97 ppm H_2S. An in-line humidifier was installed to maintain procedure continuity. The sensor output was recorded using a Campbell Scientific CR10X data logger (Campbell Scientific Inc., Logan, UT).

During testing the sensor was initially calibrated to measure 97 ppm H_2S cylinder gas as 100 ppm H_2S. The sensor was allowed to warm up for over two hours before testing commenced. Initially the sensor was exposed to zero air to track the baseline output. The sensor was then

introduced to continuous H_2S cylinder gas for 10 hours. After 10 hours the sensor was exposed to zero air for a period of hours (overnight) to allow the sensor to stabilize. After stabilization the sensor was challenged to a 5 minute burst of H_2S, this challenge was repeated in triplicate. The H_2S sensor was then recalibrated and again triplicate challenged to 5 minute bursts of H_2S.
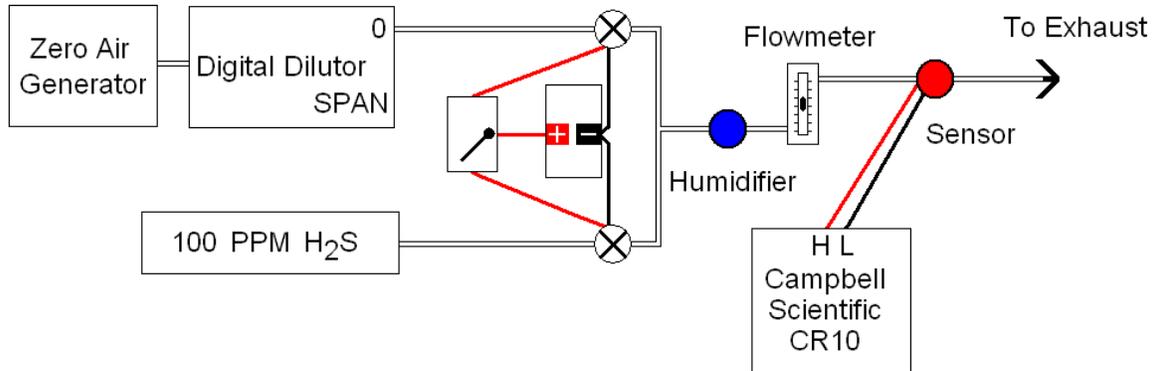

Figure 1. Lab test circuit for H_2S drift test.

Wireless Data Transmission Network

In the interest of mobilizing data collection quickly, the project team selected to purchase an out-of-the-box ready wireless network system. A SensiNet Wireless Networking System (SensiCast Systems, Needham, MA) was purchased to interface with the H_2S sensors. The SensiNet system is a turnkey wireless network system ready for installation out-of-the-box. The SensiNet wireless network system follows a star or multipoint to point network topology, shown in Figure 2 where wireless sensor nodes communicate directly with the gateway or network coordinator. While the range of this network is limited by the distance to the most distant node, the range can be extended with a SensiNet mesh router. The router acts as a hopping device where data to and from the nodes can pass through the router.
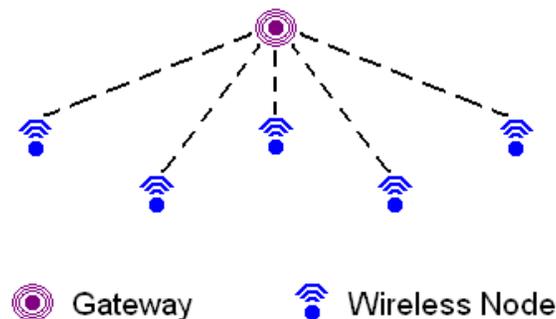

Figure 2. A schematic of multipoint to point (star) network topology.

To connect the H_2S sensor to the wireless node, the analog output of the H_2S sensor is tied to one of the two input ports of a current sensor node (CURR-1022, SensiCast Systems). Upon power-up the sensor self identifies into the network and transmits data to the central gateway. The SensiNet gateway (GWAY-1020, SensiCast Systems) is the hardware device that nodes report to and users can configure and manage the network through this gateway. The gateway has internal storage which can be configured to automatically upload to a computer via file transfer protocol (FTP), hypertext terminal protocol (HTTP), Modbus, and Open Database

Connectivity (ODBC). The system also boasts a host of connectivity options to automation software applications such as *LabView*, *Microsoft Excel*, among others. To access the network management options and view a graph of recent data using the built-in graphic user interface (GUI), a local area network (LAN) is established connecting the gateway and a computer using an Ethernet router. Figure 3 shows the components of the planned wireless sensor network.
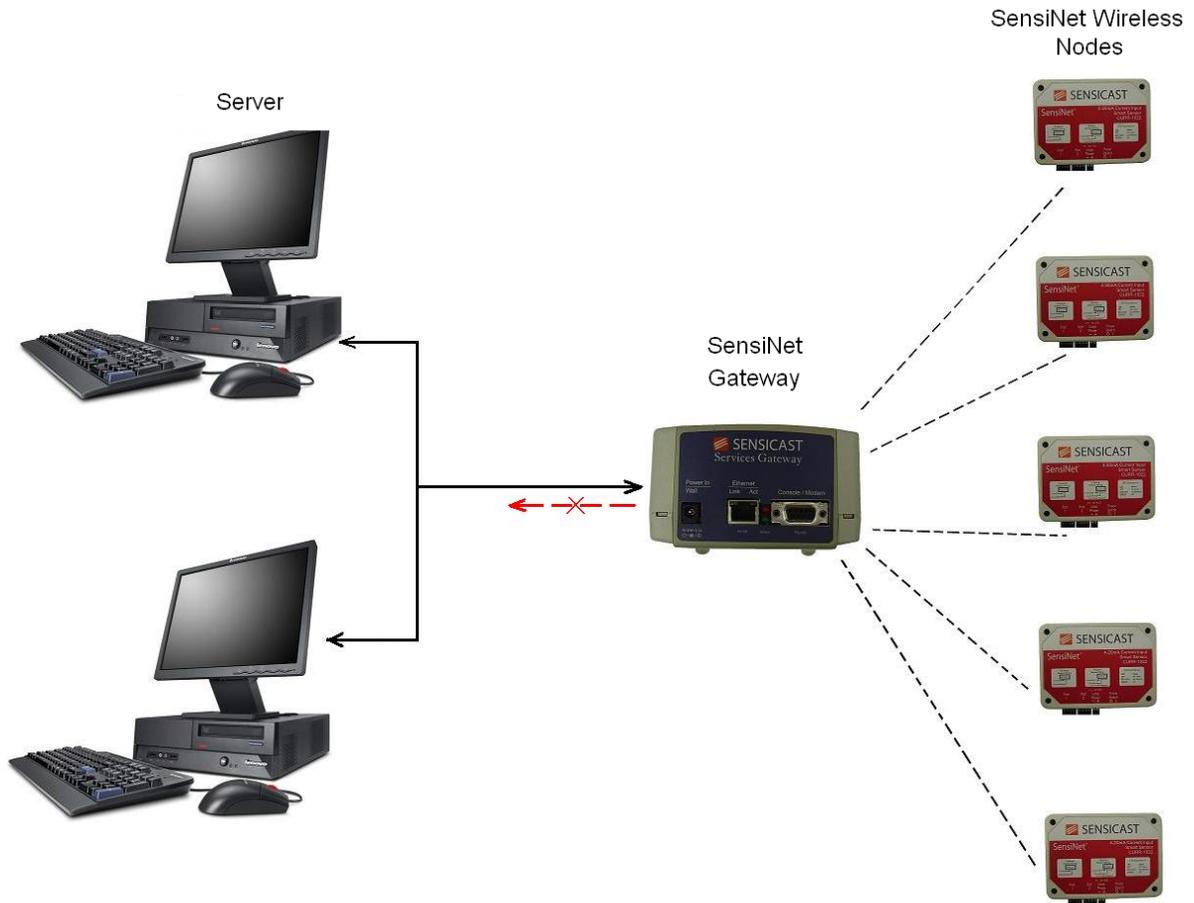

Figure 3. The SensiNet wireless network was intended to transmit the H_2S sensor output through the gateway to the computer. The red dashed arrow indicates the SensiNet gateway would not transmit data to the LAN thus proving to be an inoperable system.

A range test was performed on the SensiNet wireless network to determine the maximum transmission distance. Initially, multiple wireless nodes were powered and placed near the gateway (less than 3 m separation distance) with a clear line of sight between the gateway and nodes to achieve maximum potential connectivity. To test the range of the wireless network, the gateway GUI was monitored while the wireless node was carried a distance until the node lost connection with the gateway. The test was performed multiple times with different nodes. A mesh router was not utilized to extend the range of the nodes.

The inoperability of the SensiNet wireless network caused the team to search for other wireless network technology to implement in this research. Recent advances in mesh networking technology have led to their implementation in agricultural environments (Darr and Zhao, 2008; Coates and Delwiche, 2008). In a mesh network topology, nodes can act as routing hops to transmit data from other nodes to the data sink as shown in Figure 4. The data sink node is the final destination for the data where the nodes can be monitored via connection to a computer.

The sink functions similarly to the previously described central gateway of the SensiNet wireless system, acting as the coordinator for the personal area network (PAN).
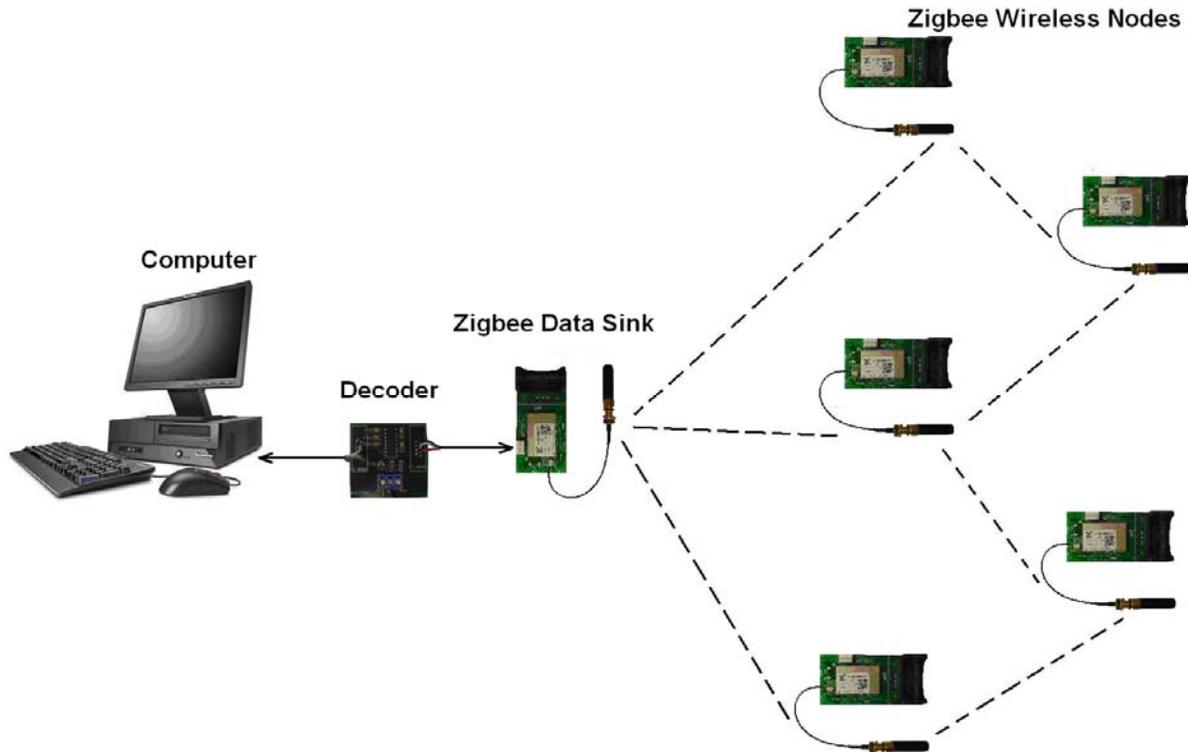

Figure 4. Zigbee nodes operate as a mesh (peer-to-peer) network to transmit data to the sink. The nodes can be monitored using a decoder and a RS232 connection to a computer.

Previous researchers (Hebel, 2006; Hebel et al, 2007; Darr and Zhao, 2008) utilized wireless network systems employing the Zigbee standard. Zigbee was developed under the IEEE 802.15.4 communication protocol (IEEE, 2003) and was designed for long battery life, low data rate, and low cost applications. Two network topologies can be defined for wireless modules utilizing the Zigbee protocol (multipoint to point or mesh). The advantage of a mesh network is range and reliability can be increased with the addition of nodes within range of one another to route data to the sink.

Results

Hydrogen Sulfide Sensor Drift Test

The H_2S sensor performed well during drift testing. During continuous long duration exposure the maximum error experienced was 6%. Minimal signal degradation occurred due to continuous exposure to H_2S. The results shown below illustrate sensor performance.

Figure 5 shows the performance of the H_2S sensor during continuous exposure to H_2S for 10 hours. The sensor was calibrated to measure 97 ppm H_2S as 100 ppm prior to test start up. The maximum error during this test was 6%, experienced during the first 10 minutes of the test. For the majority of the test the sensor output was 99 ppm, a 1% error from the sensor's calibrated value. Interestingly, the sensor registered 1 ppm within 1 minute of applying zero air, but returned to 15 ppm; gradually decreasing to zero output after 1.25 hours. H_2S flow was

interrupted for approximately 1.5 minutes near the 5.5 hour mark to refill the in-line humidifier. Once flow was restored the sensor returned to 99 ppm.
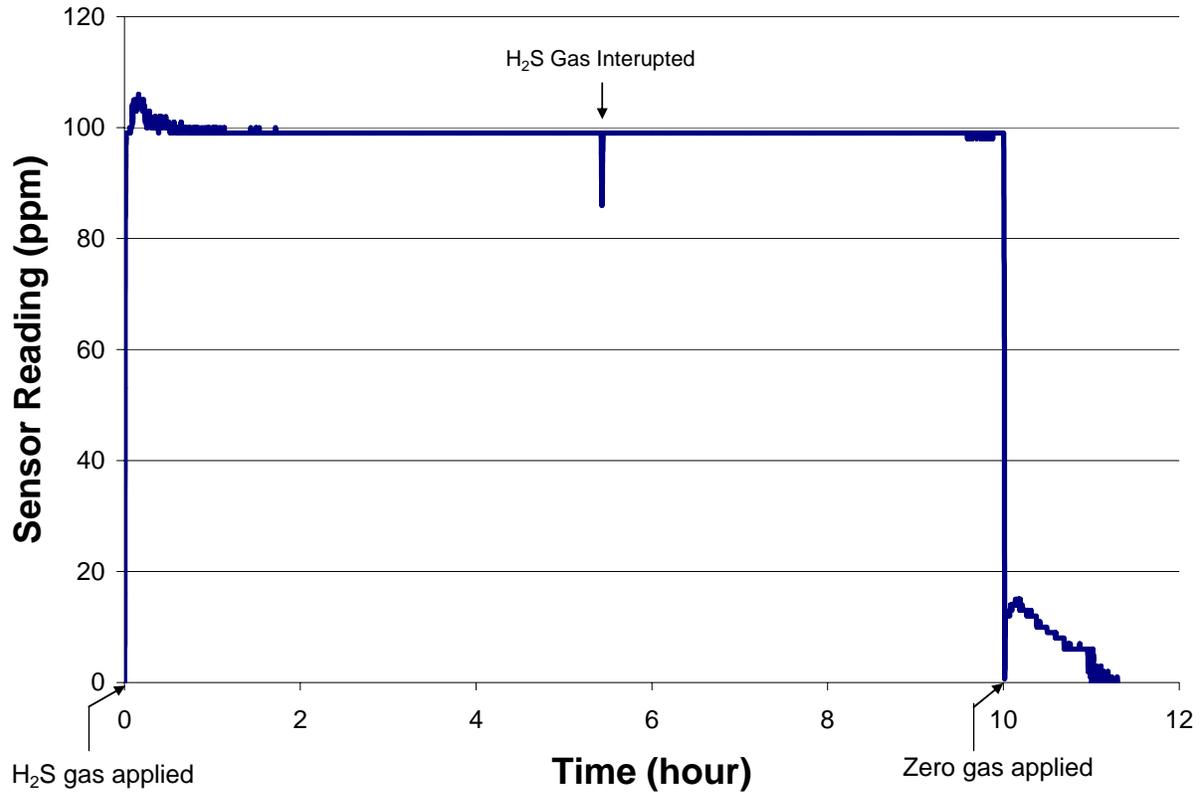

Figure 5. Graph of continuous long duration exposure to 100 ppm H_2S. H_2S gas applied at t = 0 and zero air at t = 10 hr. Measurements were taken in 10 second intervals.

After the sensor was drift tested its output during burst challenges was compared to burst challenges after recalibration. Figure 6 shows the average of each triplicate burst challenge before and after recalibration. The sensor demonstrates similar performance before and after recalibration. The sensor reached 90% of the applied concentration (T_{90}), at approximately 1 minute for both scenarios and returned to zero with minimal hysteresis.
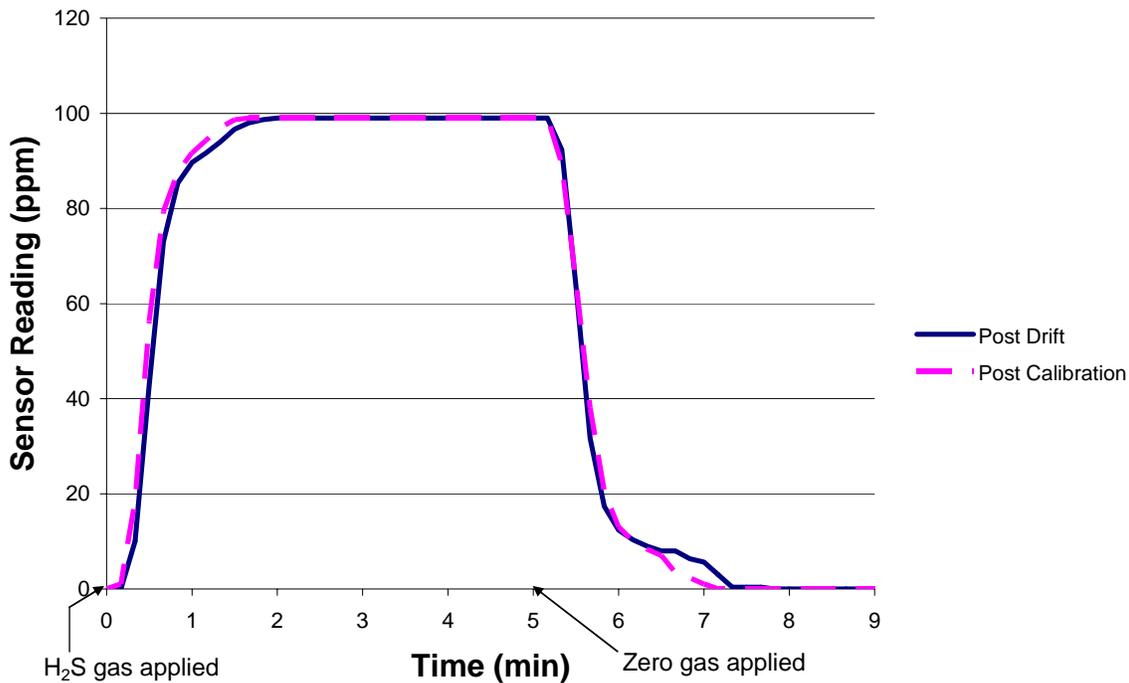
Figure 6. Comparison of H_2S sensor reading to 100 ppm burst after drift test and after recalibration. H_2S burst initiated at t = 0 and zero air at t = 5 min. Measurements were taken in 10 second intervals.

Upon completion of the drift test the sensor had been exposed to 970 ppm-hours of operation without recalibration. During subsequent burst challenges the sensor reached over 1100 ppm-hours of operation until a recalibration was performed. The sensor outputs during the 100 ppm burst challenges before and after recalibration were very similar.

SensiNet Wireless Network Performance

A LAN was established connecting the gateway and two computers using an Ethernet router. When configuring the gateway to upload to the connected computer via FTP or HTTP, issues arose with no data transferred to the computer. The LAN was monitored using a network protocol analyzer (Wireshark, Wireshark Foundation) for data packet transmission between devices within the LAN. Data packet transmission was verified between two computers within the LAN; this verified the address of the server computer was correct. When the SensiNet gateway was configured to upload to the server on the computer, no data packets were transmitted by the gateway. The gateway should send a data packet requesting access to the specified server address even if the server address is incorrect. Thus the gateway was incapable of automatic transmission to a host computer using the manufacturer network management options. This led the team to diagnose the automatic data transmission function of the gateway to be defective.

A range test of the wireless nodes was attempted, but reliability issues led to inconclusive results. Ten sensor nodes were powered up and placed within 3 m of the gateway. When near the gateway the wireless nodes would unexpectedly drop from the network and report no

8

network available. After a period of time some nodes would rejoin while others would not. This would repeat unexpectedly and without reason. Of those nodes connected to the gateway, data could at times be displayed graphically using the provided software interface. When this data was manually exported from internal storage to the connected computer, the file would display no data.

SensiCast Systems provided no customer support and remained unreachable for a warranty claim. The proprietary architecture of the network along with inoperable equipment required complete replacement of the system.

Zigbee Wireless Network Implementation

Through collaboration with Dr. Matthew Darr[1] and Dr. Lingying Zhao[2] ([1]Iowa State University, [2]The Ohio State University), the team was able to utilize a wireless data acquisition system developed by Darr and Zhao, described in Darr and Zhao, 2008. The system required configuration for utilization in this project. First, the current output of the H_2S sensor required conversion to a voltage signal (Figure 7) to utilize an available analog-to-digital (A/D) channel on the wireless sensor node. The A/D channel is a maximum 1.2 VDC and has a programmable 5 to 12 bit resolution.
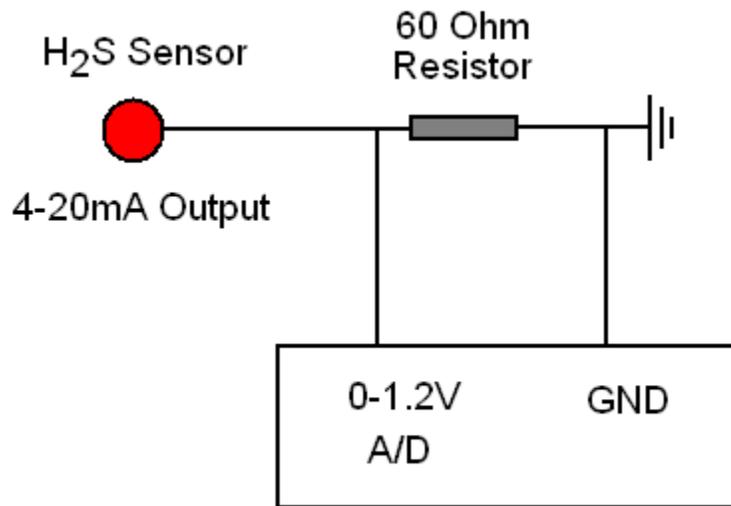

Figure 7. Circuit to convert 4-20mA H_2S sensor output to max 1.2V signal for A/D channel on wireless sensor nodes.

Using the manufacturer supplied software and the Ohio State University supplied configuration files, the wireless nodes and sink were configured to identify into the same channel on the same PAN allowing communication to begin upon startup. The Zigbee protocol automatically finds the route nodes utilized to transmit data to the sink, routing messages through another node if the sink is out of range. The data transmission interval is user-programmable and is currently set to 1 minute. The transmission interval can be decreased in the event finer temporal resolution is desired. Battery life is not expected to be an issue as monitoring events are expected to be 72 hours or less and power is supplied by a DC/DC (12 to 3) voltage converter connected to a 9Ah 12VDC sealed lead acid battery. This battery also provides power to the H_2S sensor via an additional DC/DC (12 to 24) voltage converter.

Conclusion

The H$_2$S sensor demonstrated excellent performance during drift testing and burst challenges. Although the maximum sensor error during drift testing was 6%, the signal degradation due to continuous exposure was minimal. A wireless H$_2$S sensor network utilizing this sensor as the gas measurement interface will suitably characterize high concentration H$_2$S in swine housing before, during, and after slurry agitation and removal events.

Due to the combination of defective equipment and poor customer service with the SensiNet wireless network from SensiCast Systems, the project team has collaborated with Darr and Zhao to utilize a wireless data acquisition system which has demonstrated success in a swine finisher where temperatures have been monitored for over 2 years. The system is configured to identify into the same channel on the same PAN upon startup and transmit data from sensor nodes to the data sink every 60 seconds. At the time of paper submission, the system is undergoing testing to confirm reliability and transmission capabilities and interfacing with the H$_2$S sensors.

The wireless H$_2$S sensor network will be deployed in a two-level matrix style grid within the AOZ of a deep-pit swine house prior to slurry agitation as shown in Figures 8a and b. Multiple locations will capture H$_2$S concentration data from sensors located at slat level and approximately 1.5 m above the slats. The data will then be used to characterize the spatial (horizontal and vertical) and temporal distribution of H$_2$S before, during, and after manure slurry agitation.
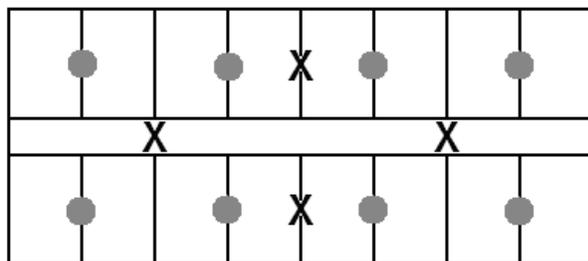
Figure 8a. Conceptual horizontal layout of wireless H$_2$S sensor nodes and fluorescence sample ports.
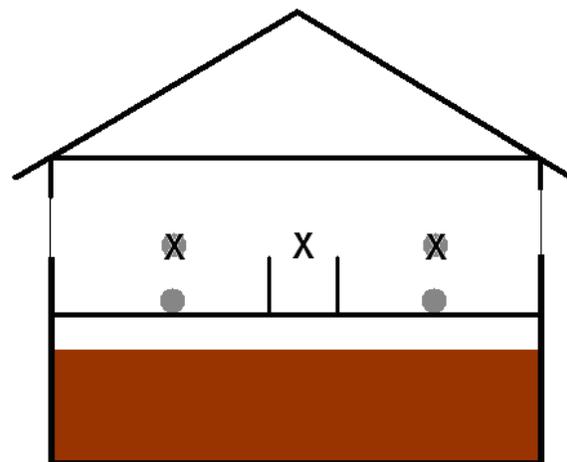
Figure 8b. Conceptual vertical layout of wireless H$_2$S sensor nodes and fluorescence sample ports.

H$_2$S concentrations are anticipated to be low (<10 ppm) during normal operational periods. A mobile lab with a fluorescence H$_2$S analyzer (Advanced Pollution Instrumentation Model 101E) with four sample locations (Figures 8a and b) within the animal area of the deep-pit swine house will also be installed to characterize low concentrations (<10 ppm).

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