Design, Development and Field Deployment of a Low-cost Distributed Wireless Sensor Network System for Real-time Hydraulic Fracturing Monitoring in Mines

Amirali Soroush, Wen Shen (Vincent) Mow
Onshore Gas Program, Energy
Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Melbourne, Australia
e-mails: amirali.soroush@csiro.au, vincent.mow@csiro.au

***Abstract* — A low-cost Distributed Wireless Sensor Network (DWSN) system designed and developed for real-time monitoring and diagnostics of hydraulic fracturing activities applicable to mine preconditioning operations is introduced in this paper. Built on open-source electronics platforms, as well as XBee wireless transceiver modules, and powered by solar energy, the system was deployed during the preconditioning operation in Whitehaven's Narrabri mine (New South Wales (NSW), Australia) and Luossavaara-Kiirunavaara Aktiebolag's (LKAB) Malmberget iron ore mine (Norrbotten County, Sweden). Over a period of two years, the system successfully monitored the placement of more than 2000 hydraulically-induced fractures in real-time, while providing an average packet delivery success rate of more than 99.995%.**

Keywords - Tiltmeter Monitoring; Surface Deformation Monitoring; Mine Preconditioning; Hydraulic Fracturing Monitoring and Diagnostics; Distributed Wireless Sensor Network Systems.

I. INTRODUCTION

DWSN systems are growing rapidly and being used extensively in various domains, such as environmental monitoring [1][2], agriculture [3][4], urban monitoring [5] and structural health monitoring [6] as a viable solution for monitoring various parameters of interest, such as pressure, temperature, humidity, strain, and acceleration in real-time and for long periods. The evolution of open source platforms for hardware and software development, along with the commercialization of modular low-cost and low-power electronics for data logging, processing, and wireless communication has provided developers with the opportunity for rapid prototyping and implementation of DWSNs for scientific, industrial and commercial applications.

Hydraulic fracturing refers to the process of injecting pressurized fluid into a wellbore with the intention to create new fractures in the deep rock formations and/or increase the size, extent, and connectivity of existing fractures. The process can be applied in the mining industry, particularly to the underground long-wall and block-cave mines, to induce predictable rock caving within excavation cavities. Hydraulic fracturing treatments are usually applied to the undisturbed rock or ore-body in advance of the mining operation as a method to pre-weaken or pre-condition the rock for improved operation productivity and safety during resource extraction [7]–[9].

To ensure the effectiveness of a hydraulic fracturing treatment, an array of high-resolution tiltmeters is placed beneath the ground in concentric circles surrounding the injection hole to measure the displacement gradient induced by the injected fluid and hence, map the fracture propagation process [10]. Flowmeters can also be used at the observation boreholes around the injection hole to determine any fracture connectivity between the injection hole and monitoring holes by measuring and confirming potential fluid return. The data recorded by tiltmeters and flowmeters provide helpful guidance for the operators to control the injection fluid, thus optimizing the fracturing treatment and ensuring its effectiveness where required, therefore reducing the operational costs [11].

In this paper, we introduce a novel DWSN system as a low-cost and flexible solution for real-time monitoring of hydraulic fracturing activities during the preconditioning operation on mine sites. The system, built on the Arduino open-source platform and XBee wireless transceiver modules, aims at providing sensory information for the operators in real-time while allowing for remote management and control of the sensor array over the Internet.

This paper is organized as follows. The overall architecture of the system is introduced in Section II. The design and development of various hardware and software components of the DWSN system is then detailed in Section III. Section IV elaborates the system optimizations in terms of total power consumption. Finally, the results of the field deployment of the system are illustrated in Section V, before drawing the conclusion and providing the outline for future work.

II. SYSTEM ARCHITECTURE

The overall architecture of a DWSN system designed and developed for monitoring preconditioning operations is illustrated in Figure 1. The system comprises a number of surface nodes interfaced with a sensor of interest (tiltmeter and/or flowmeter). The sensor array is usually scattered across a 1000 [m] × 1000 [m] area, and the average distance between sensor nodes is typically 50 to 100 meters. The ground surface is covered by vegetation and tall trees, so line of sight is not

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-744-3

necessarily available between sensor nodes for wireless communication.

Each sensor node is equipped with an XBee radio transceiver, as well as a microcontroller unit interfacing various modules, such as Global Positioning System (GPS), micro Secure Digital (microSD) card, voltage scaler and serial-to-TTL (transistor-transistor logic) converter for integrating multiple sensors with analog or digital output to the system. The base station also consists of an XBee transceiver, connected to a laptop using an XBee Universal Serial Bus (USB) shield. The XBee transceivers (sensor nodes and the base station) form a mesh network using DigiMesh communication protocol. DigiMesh is a proprietary wireless mesh networking topology which allows for time synchronized sleeping nodes and low-power operation [12].

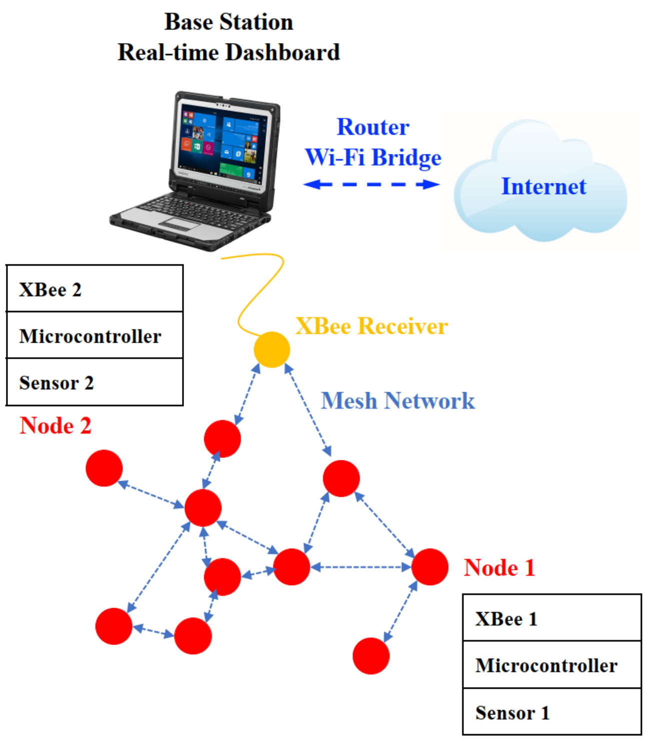

Figure 1. Overall system architecture.

The main advantage of the DigiMesh protocol is that all devices on a network are configured the same. Therefore, no complex architecture is required to define different nodes on the network as end-nodes, routers, coordinators, border routers, etc. Every device is the same, and capable of routing, sleeping for power optimization, and communicating via a mesh network [12].

The base station is connected to the Internet via a Wi-Fi bridge allowing for direct access to the nearest mobile tower. The real-time dashboard on the base station laptop serves as an interface to control the DWSN system, monitor sensor health, record sensor data, and synchronize data with CSIRO's online cloud servers in real-time. The dashboard can be accessed by authorized staff both on-site and off-site using third-party remote desktop connection software.

III. Design and Development

A. Sensor Node

The sensor node is developed around the Atmel SAM3X8E 32-bit Advanced RISC Machine (ARM) core microcontroller on the Arduino Due framework. Arduino is an open-source electronics platform integrating commonly-used flexible and low-cost hardware and software for rapid-prototyping of science and engineering projects [13]. The Arduino Due prototyping board offers 54 digital input/output pins, 12 analog inputs, 4 Universal Asynchronous Receiver-Transmitter (UART) ports, an 84 MHz clock, a 12-bit analog-to-digital converter (ADC), and a Serial Peripheral Interface (SPI).

The Lily self-leveling borehole tiltmeter is the instrument used for surface deformation monitoring. The dual-axis tiltmeter senses the displacement gradient induced by the underground fluid injection in two orthogonal vertical axes using precision electrolytic tilt sensors with nano-radian resolution. The instrument's on-board electronics samples the analog tilt signal and then, outputs a data string containing the X and Y tilts, azimuth (sensor heading with respect to magnetic north), temperature, power supply voltage and the instrument's serial number over RS-232 or RS-485 serial communication protocol [14]. This output is interfaced with the Arduino microcontroller using a MAX485 chip on a UART-to-RS485 converter module and a MAX3232 on a transceiver breakout module.

A u-blox NEO-M8M Global Navigation Satellite System (GNSS) module interfaced to each sensor node facilitates global geo-spatial positioning and time synchronization, provided antenna reception to sufficient satellites. Major GNSS, such as GPS, Galileo, and Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) are supported, and data is outputted in standard National Marine Electronics Association (NMEA) string format [15]. The tilt-sensing application involves immobile assets, so geospatial data is not time-critical and only require a single update in most cases. The location and time data are used as a redundancy in tiltmeter installation information and also clock synchronization of data between various sensors. On-site operators can access these visualized data via the real-time dashboard.

The wireless network is designed and developed based on a mesh topology using XBee-PRO 900HP embedded modules from Digi International. This radio transceiver utilizes the Australian Industrial, Scientific and Medical (ISM) 918-926 MHz frequency band and offers up to 200 Kbps data transfer rate at maximum transmit power. It is capable of outdoor communication of up to 6.5 kilometers line of sight range using 2.1 dBi dipole antennas, and up to 28 kilometers line of sight range using high gain antennas [12]. XBee-PRO 900HP modules utilize DigiMesh networking protocol, an innovative mesh protocol developed by Digi International specifically for power-sensitive applications relying solely on batteries. DigiMesh is built on the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 technical standard, which specifies the Physical (Binary Phase Shift Keying (BPSK) modulation at the 900MHz band) and Media Access Control

Copyright (c) IARIA, 2019.

TABLE I. HEXADECIMAL BYTE OUTLINE OF AN EXAMPLE FRAME TO BE PASSED TO THE XBEE TRANSCEIVER VIA UART FOR RADIO TRANSMISSION OF THE DATA PAYLOAD.

Start Delimiter	Frame Length	Frame Type	Frame ID	64-bit Dest. Address	16-bit Dest. Address	Broadcast Radius	Options	Payload (shown in ASCII text)		Checksum
								Tilt-data	GNSS-data	
7E	00 7C	10	00	01 3A A2 00 41 5B 7E 79	FF FE	00	00	$ 13.232, -25.221,239.83, 21.71,10/12/18 16:32:49,13.07,N7928	,12/10/2018,06:33:46,-30.5055199,+149.85530093	87

(MAC) layer protocols. DigiMesh offers a wide range of advantages, such as added network stability through self-healing, self-discovering, and dense network operation. At the user-level, only the destination module serial address, preamble ID, and network ID are required for one-to-one transmission. Data transmitted are packed into frames in the XBee API2 format [16]. Reserved characters for frame formatting and an integrated checksum byte improve the reliability of the received data, at the cost of using more bandwidth. The current average size of the frames per transfer is approximately 127 total bytes (example shown in Table I). Data acknowledgments and failure retries are disabled to decrease network bandwidth, reduce energy consumption, and enforce sleep mode. Data encryption is also an available feature, but is currently disabled.

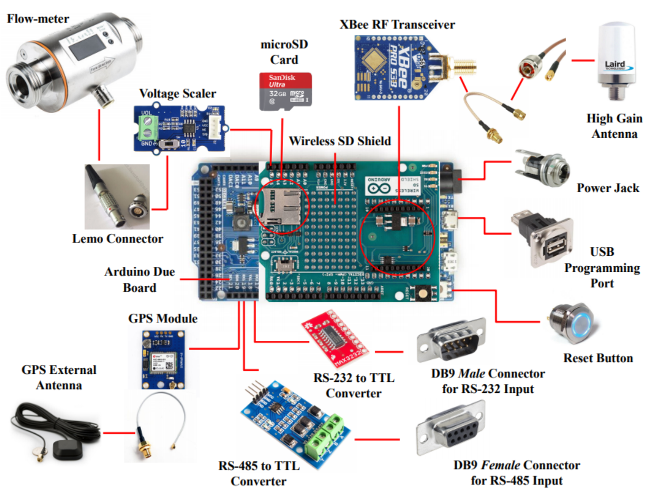

Figure 2. Electronics layout for the sensor node.

An Arduino Wireless SD shield is used to interface the XBee transceivers with the Arduino Due board. Communication between the microcontroller and the XBee, as well as microSD card is via UART and SPI, respectively. Each XBee transceiver is equipped with a Laird 3 dBi outdoor omni-directional antenna to enhance the communication range. The microcontroller firmware is developed in C/C++ and has the primary function of relaying the tiltmeter output data-string to the XBee module for wireless data transfer to the base station. Secondarily, it integrates all other additional peripherals, such as the microSD card and GPS module. Lastly, it performs additional housekeeping, including implementing a watchdog for potential software hang-ups, node health reporting, GNSS data refresh, and modification of communication parameters. Other features of the firmware are over-the-radio firmware updates and reset. The set-up and calibration commands designated for the tiltmeter are relayed across to the instrument, and node-specific commands are intercepted by the firmware.

Over-the-radio firmware updating is achieved without the need for any additional electronics due to the dual partition memory capability of the Atmel SAM3X8E microcontroller. The binary file of the firmware update is transmitted, checksum verified, and flashed into the adjacent memory bank before a software reset into the correct memory boot location. The sensing instrument and the sensor node are powered indefinitely using solar power and an Absorbent Glass Mat (AGM) battery. The electronics layout for the sensor node is well illustrated in Figure 2.

B. Base Station

The base station consists of an XBee transceiver interfaced with a Panasonic Toughbook via an XBee Explorer USB module (USB to UART). The XBee module baud-rate at the base station is set to 230,400 bps to take advantage of the maximum bandwidth allowed by the XBee-PRO 900HP transceiver. The XBee receiver is equipped with an omni-directional antenna. The electronics layout for the XBee receiver at the base station is shown in Figure 3.

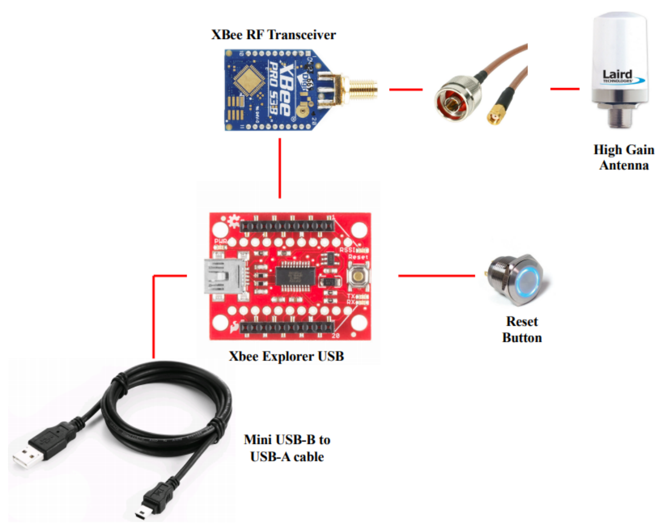

Figure 3. Electronics layout for the XBee receiver at the base station.

A real-time dashboard developed in the LabVIEW environment is used for recording and visualizing the measurements. The application is hosted on a Windows-based laptop at the base station on-site, and receives the data from the XBee receiver via a USB port. The objective of the software is to consolidate the data collection process, the diagnostics needed by the on-site operators to maintain system health, and interaction with the instruments' core firmware into a single intuitive platform. High-level functionalities,

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-744-3

such as data quality control, preliminary processing, data visualization, command generation, issue reporting, and alarms are examples of the features implemented in the dashboard. The recorded data are instantly synced with CSIRO's online cloud service, so off-site engineers and scientists have real-time access to the data as required. An example of the application interface is shown in Figure 4.

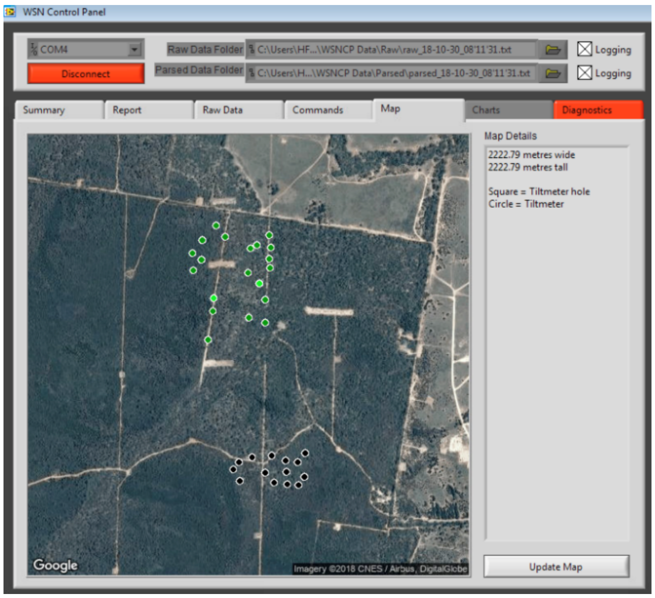

Figure 4. Real-time Dashboard for monitoring the tiltmeter array during preconditioning Long Wall 108 at Narrabri mine, NSW, Australia.

Data arriving into the dashboard is checksum verified for quality control, before being sorted and logged according to date-time and the instrument's serial number. Charted tiltmeter data, mapped locations, color-coded alarms, and tabulated tiltmeter health allow for quick system health verification at a glance. Operators can use the commands' panel to access the tiltmeter core utilities, such as instrument calibration, by sending the commands over the radio. Command transfer can be instrument specific or broadcasted to the entire array. Some special commands are reserved to be intercepted by the sensor node microcontrollers for radio module functionality, such as firmware reset and radio communication parameter changes.

IV. Power Optimization

As a preliminary prototype, the sensor node components were selected based on high-level compatibility and availability. Upon successful field demonstration, the sensor node firmware was revised to reduce average power consumption, with the hardware remaining mostly unchanged. Improvements to the microcontroller firmware include putting the SAM3X8E microcontroller into 'Backup' (i.e., deep sleep) mode between the sampling intervals. In this state, the microcontroller's internal core voltage regulator and memory peripherals are powered down. The still-running internal real-time timer is synced to the tiltmeter output rate and provides the trigger to restart the microcontroller, effectively implementing a 20% duty cycle on-time. A relatively-large buffer period (approximately 15% duty cycle) is used due to slow startup, non-constant XBee transmission time, and for a command reception window. The GNSS is configured to run on low-power, which involves a slower satellite scanning rate. The microcontroller disables the GNSS upon the registry of valid geo-location and time data. The XBee module is placed in sleep mode at the same duty cycle as the microcontroller.

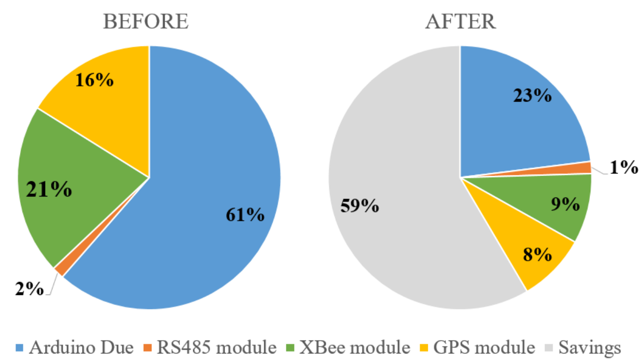

Figure 5. Sensor node power consumption before and after optimization.

The power consumption of the sensor node before and after the firmware revision is shown in Figure 5. The revised firmware includes algorithms that disable unused peripherals and enable periodic system sleep in-between sensor data sample. The average power consumption of the sensor node (at 0.1 Hz sample transmission) was reduced by 58.5% to approximately 500 mW through firmware optimization. At the moment, the majority of power is consumed to transmit the radio signal and store the data into the microSD card.

V. Field Deployment

A total of fifty sensor nodes (radio modules) and six receivers were developed as part of the DWSN system introduced in this paper. The total cost of each sensor node was approximately A$250, which is low relative to similar products currently available on the market. An example of the developed sensor node is shown in Figure 6.

Figure 6. Example of developed radio module enclosure or sensor node.

The DWSN system was first deployed in April 2017 during the preconditioning operation of Long Wall 107 in Narrabri mine located in NSW, Australia. Up to 34 tiltmeters were used throughout the preconditioning operation, and the real-time dashboard was deployed on-site in 2018. The DWSN system introduced in this paper has been operating in Narrabri mine 24/7 ever since, and has successfully monitored the propagation of more than 2000 hydraulically induced fractures placed in ~500 boreholes during the preconditioning operation of three long-walls (LW107, LW108 and LW109) from April 2017 to June 2019.

In 2017, the DWSN system was also deployed at the Malmberget iron ore mine in Sweden for the purpose of monitoring the preconditioning operation for mitigating the seismic hazards in the underground mine [17]–[19]. The deployment included 15 tiltmeters buried underground, each connected to a sensor node on the surface and a base station with a receiver for logging the data in real-time, as shown in Figure 7.

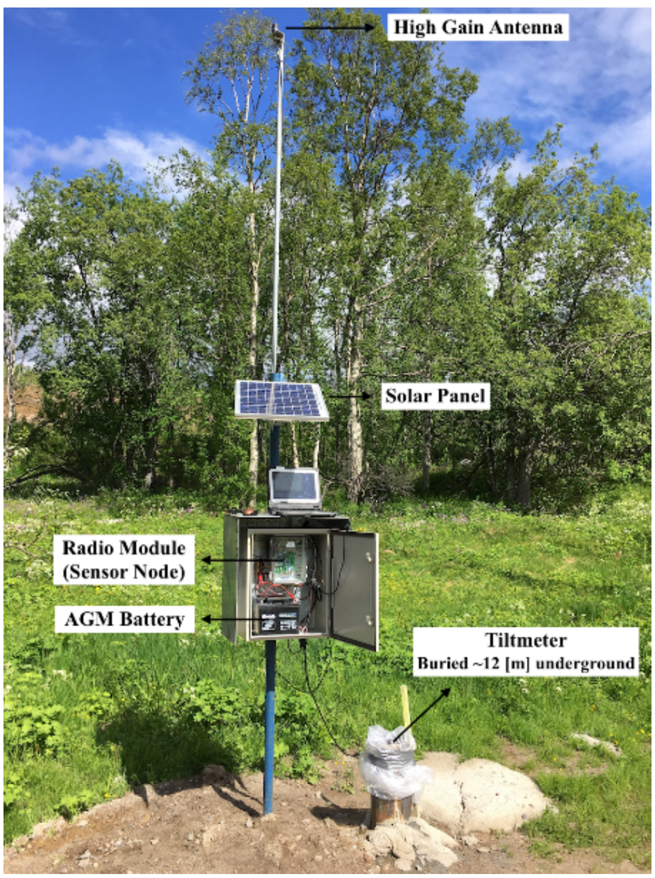

Figure 7. DWSN system sensor node surface setup. Monitoring preconditioning in LKAB's Malmberget iron ore mine, Sweden, July 2017.

Overall, the DWSN system improved the quality of the recorded tilt data significantly by minimizing data loss across the network and removing data access latency problems by supplying the recorded data to the CSIRO's cloud service in real-time. The system proved robust and reliable by providing an average packet delivery success rate of more than 99.995%.

VI. Conclusion and Future Work

In this paper, the design, development, and deployment of a low-cost DWSN system for real-time monitoring of the hydraulic fracturing operations in mines is introduced. The system is built on the Arduino open-source platform and XBee wireless transceiver modules. The sensor nodes are scattered around the injection borehole in a 1000 [m] × 1000 [m] area with ~50-100 meters spacing, and interfaced with tiltmeters buried underground.

Over the course of two years, the DWSN system deployed in Narrabri (Australia) and Malmberget (Sweden) mines successfully monitored the preconditioning operation with real-time data delivery success rate of more than 99.995%. The system deployment showed great potential in automating the tilt monitoring operation for the purpose of fracture monitoring, system diagnostics, and reducing the time required for sensor calibration from days to minutes. The system has also improved the quality of the recorded tilt data significantly by minimizing data loss across the network and removing data access latency limitations by pushing the recorded data to the CSIRO's cloud service in real-time.

The successful deployment of the DWSN system demonstrates the advantage of developing in-house low-cost and low-power data collection system using open-source electronics platforms with modular components as compared to commercially available solutions which are often limited in offering long term reliability, flexibility, and scalability across various scenarios. The system has proven easy to implement, cheap to maintain, and simple to modify when future adjustments and upgrades were required.

Future works include reducing the system bandwidth (a potential 70% reduction) by replacing the system data encoding format with binary. This, along with the second revision of hardware and electronics, will drastically reduce system power consumption, as well as physical dimensions of the radio module unit. Transitioning the final product away from the prototyping platform to fully-integrated printed circuit boards and electronics at scale can reduce the per-unit cost to below A$100. Furthermore, the implementation of the lower-power Long Range (LoRa) radio technology to replace the existing radio system can unlock the capability for the DWSN system to be deployed in no-recharge scenarios, such as in underground mines.

Acknowledgment

The authors would like to thank CSIRO Energy for granting permission to publish this work.

References

[1] P. Corke, T. Wark, R. Jurdak, W. Hu, P. Valencia, and D. Moore, "Environmental Wireless Sensor Networks," *Proc. IEEE*, vol. 98, no. 11, pp. 1903–1917, 2010.

[2] S. Ferdoush and X. Li, "Wireless Sensor Network System Design Using Raspberry Pi and Arduino for Environmental Monitoring Applications," *Procedia Comput. Sci.*, vol. 34, pp. 103–110, 2014.

[3] J. Gutiérrez, J. F. Villa-Medina, A. Nieto-Garibay, and M. Á.

Porta-Gándara, "Automated Irrigation System Using a Wireless Sensor Network and GPRS Module," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 1, pp. 166–176, 2014.

[4] J. Polo, G. Hornero, C. Duijneveld, A. García, and O. Casas, "Design of a low-cost Wireless Sensor Network with UAV mobile node for agricultural applications," *Comput. Electron. Agric.*, vol. 119, pp. 19–32, 2015.

[5] J. Lee, Z. Zhong, B. Du, S. Gutesa, and K. Kim, "Low-Cost and Energy-Saving Wireless Sensor Network for Real-Time Urban Mobility Monitoring System," *J. Sensors*, vol. 2015, p. 8, 2015.

[6] T. Torfs *et al.*, "Low Power Wireless Sensor Network for Building Monitoring," *IEEE Sens. J.*, vol. 13, no. 3, pp. 909–915, 2013.

[7] A. van As and R. G. Jeffrey, "Caving Induced by Hydraulic Fracturing at Northparkes Mines," *4th North American Rock Mechanics Symposium*. American Rock Mechanics Association, Seattle, Washington, p. 8, 2000.

[8] R. G. Jeffrey and K. W. Mills, "Hydraulic Fracturing Applied to Inducing Longwall Coal Mine Goaf Falls," *4th North American Rock Mechanics Symposium*. American Rock Mechanics Association, Seattle, Washington, p. 8, 2000.

[9] R. G. Jeffrey, X. Zhang, A. Settari, K. W. Mills, and E. Detournay, "Hydraulic fracturing to induce caving: fracture model development and comparison to field data," *DC Rocks 2001, The 38th U.S. Symposium on Rock Mechanics (USRMS)*. American Rock Mechanics Association, Washington, D.C., p. 10, 2001.

[10] R. G. Jeffrey, Z. Chen, K. W. Mills, and S. Pegg, "Monitoring and Measuring Hydraulic Fracturing Growth During Preconditioning of a Roof Rock over a Coal Longwall Panel," *ISRM International Conference for Effective and Sustainable Hydraulic Fracturing*. International Society for Rock Mechanics and Rock Engineering, Brisbane, Australia, p. 22, 2013.

[11] V. Pandurangan, Z. Chen, and R. G. Jeffrey, "Mapping hydraulic fractures from tiltmeter data using the ensemble Kalman filter," *Int. J. Numer. Anal. Methods Geomech.*, vol. 40, no. 4, pp. 546–567, 2016.

[12] "XBee-PRO 900 DigiMesh RF Module User Guide." [Online]. Available: https://www.digi.com. [Accessed: 23-Sep-2019].

[13] "Arduino Due." [Online]. Available: https://www.arduino.cc/en/Guide/ArduinoDue. [Accessed: 23-Sep-2019].

[14] "LILY Self-Leveling Borehole Tiltmeter User Manual." [Online]. Available: http://www.jewellinstruments.com. [Accessed: 23-Sep-2019].

[15] "ublox NEO-M8 series." [Online]. Available: https://www.u-blox.com/en/product/neo-m8-series. [Accessed: 23-Sep-2019].

[16] "API Mode for XBee Modules." [Online]. Available: https://www.digi.com/resources/documentation/Digidocs/90001942-13/concepts/c_api_escaped_operating_mode.htm?TocPath=XBee API mode%7COperating mode configuration%7C_____1. [Accessed: 23-Sep-2019].

[17] R. Jeffrey, D. Kasperczyk, K. Quinlan, R. Pandurangan, and A. Soroush, "Hydraulic fracturing trial in Malmberget Printzsköld crown pillar." Confidential Report, 2017.

[18] P. K. Boeg-Jensen, K. Jonsson, and R. G. Jeffrey, "Hydraulic Fracturing Trial Layout and Approach to Mitigate the Seismic Hazard at LKAB ' s Mines in Kiruna and Malmberget," *9th International Symposium on Rockburts and Seismicity in Mines*. Santiago, Chile, pp. 1–6, 2017.

[19] K. Jonsson and J. Martinsson, "Evaluating the effect on seismicity of a hydraulic fracturing trial using Bayesian data analysis," *Fourth International Symposium on Block and Sublevel Caving*. Australian Centre for Geomechanics PP - Perth, Perth, pp. 451–658, 2018.

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-744-3