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ARG-US Wireless Sensor Network for Critical Facilities

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ABSTRACT

ARG-US (meaning "Watchful Guardian") Remote Area Modular Monitoring (RAMM) is a remote, "unattended" monitoring system with a two-layered architecture: a wired Ethernet base layer and a wireless sensor network (WSN) overlay. Each RAMM unit is equipped with a suite of sensors that can be customized for the application environment, and multiple communication modules. The wired network, which provides normal, baseline data collection and communication, also keeps the batteries in the RAMM units charged via power over Ethernet. The RAMM units, each with its unique sensory and communication provisions, form a WSN using the wireless transceivers in the RAMM units. In this paper, we focus on testing of two RAMM systems deployed in a radiological facility and an office building at Argonne National Laboratory. Together, these two RAMM systems provided a testbed operating environment for studying the behavior and performance of the WSN, including its formation and transmission of selected sensor data across the WSN.

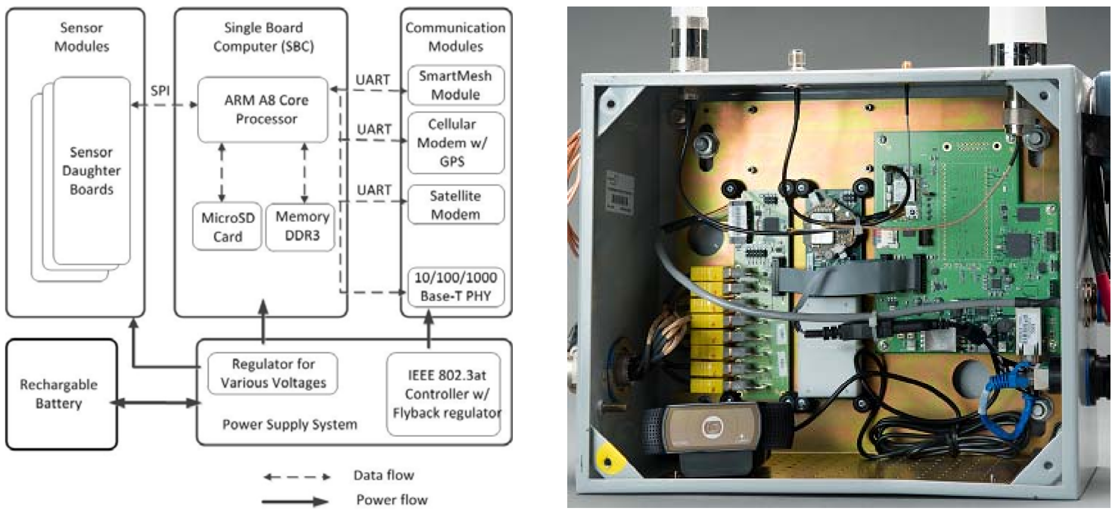
INTRODUCTION

ARG-US (meaning "Watchful Guardian") Remote Area Modular Monitoring (RAMM) is designed to mitigate the deficiencies in situational awareness noted after the Japanese Fukushima accident when landline-based surveillance assets were lost. [1-6] By leveraging the patented ARG-US radiofrequency identification (RFID) sensor technology, Argonne researchers designed RAMM with a two-layered architecture: a wired Ethernet base layer and a wireless sensor network (WSN) overlay. The WSN links multiple RAMM units, each with its unique sensory and communication provisions in the application environment. Overlaying the wired network is a WSN formed by the wireless transceivers in the RAMM units. The wired network, which provides normal, baseline data collection and communication, also keeps the RAMM batteries charged via power over Ethernet (PoE). Each RAMM unit carries a suite of sensors that can be customized for the application environment, and multiple communication modules that are also functionally dependent; for example, cellular and satellite modems are installed only in those RAMM units that are gateways to the outside world.

A RAMM system is scalable—the monitoring area and communication distance of the system can be extended by adding more RAMM units (called Motes)—a feature that is often described as multi-hop "self-forming," or "self-healing," because a RAMM unit will find its neighbors in the WSN to relay data communication to the gateway RAMM (called Manager). Development and testing of a WSN of multiple RAMM units has begun in a radiological facility and an office building at Argonne National Laboratory. Together, these RAMM systems provided testbeds for studying the behavior and performance of WSNs in the facility's operating environment, including self-forming, or self-healing, and transmission of temperature sensor data across the WSN. In this paper, we will also briefly discuss the limitations and challenges of the current RAMM systems.

MONITORING PLATFORM

The RAMM has been designed with modularity to allow for flexibility and easy expansion. Each RAMM unit is equipped with a suite of sensors that include a 3-axis accelerometer, a thermistor and other customized specialty sensors such as thermocouples, a gamma dosimeter and a neutron detector, an electronic loop seal; and a USB connection for the support of a digital camera [5]. Figure 1 shows the block diagram of a RAMM unit (a), and its prototype embodiment incorporating a digital camera and other sensors (b). [6]



(a) (b)

Figure 1. Block diagram of a RAMM unit (a), and its prototype embodiment incorporating a digital camera and other sensors inside the lunch-box-sized unit (b).

Along with the sensor modules, the RAMM units have multiple communication modules and a redundant power supply, as shown in Fig. 1(a). The primary method of communication is over Ethernet. The unit is also primarily powered by PoE. Backup communication modules include a WSN module for Motes, and cellular and satellite modems for the Manager gateway. When Ethernet communication fails, the RAMM units will switch over to the WSN for communication, and over to a battery backup for power supply. Information is transmitted from the Motes to the WSN Manager gateway, which then forwards the information to the data collection point via cellular modem or satellite.

RADIOLOGICAL FACILITY

During 2018, three RAMM units equipped with digital cameras were installed in Argonne's Alpha Gamma Hot Cell Facility (AGHCF), which is a Category III radiological facility that has been undergoing decommissioning and decontamination since 2011. Figure 2(a) shows three RAMM units (#1101, #1102 and #1114) with digital cameras in the AGHCF, which cover nearly 100% of the accessible areas on the first floor of the AGHCF. (The coverage of each digital camera is indicated by the shaded areas.) Figures 2(b) and 2(c) show camera images acquired by RAMM Units #1101 and #1102, respectively: #1101 monitors the front entry of the AGHCF; #1102 monitors the Clean Transfer Area (CTA) where packaging and off-loading of radioactive wastes is performed routinely during normal operation. RAMM Unit #1114 monitors the glovebox and connecting pathway between AGHCF's radiation buffer area and radiation controlled area. RAMM Unit #1114 was the first unit introduced into the AGHCF for motion detection. In

(a) (b) (c)

Figure 2. RAMM units with digital cameras in the AGHCF: (a) accessible areas shaded to show coverage by Units #1101, #1102 and #1114; (b) camera image of front entry taken by Unit #1101; and (c) camera image of CTA taken by Unit #1102.

addition to the digital camera, all three RAMM units are also equipped with other sensors for temperature and radiation (gamma and neutron), which allow corroboration of camera image data with the sensor data collected by the distributed ARG-US RFID surveillance tags in the facility. Corroboration of image data acquired by RAMM and sensor data acquired by the RFID surveillance tags has been shown to enhance facility safety and security in the AGHCF [6], and that discussion will not be repeated here.

OFFICE BUILDING

Multiple RAMM units were deployed in an office building at Argonne to study the behavior of a WSN in an environment simulating daily operation of a facility. Figure 3 shows the layout of the first floor of the building and locations of the RAMM units. Six of them are Motes: #1108 and #1109 to the north; #1110 in the northeast corner; #1105 and #1106 to the south; and #1107 in the southeast corner. RAMM Units #2104

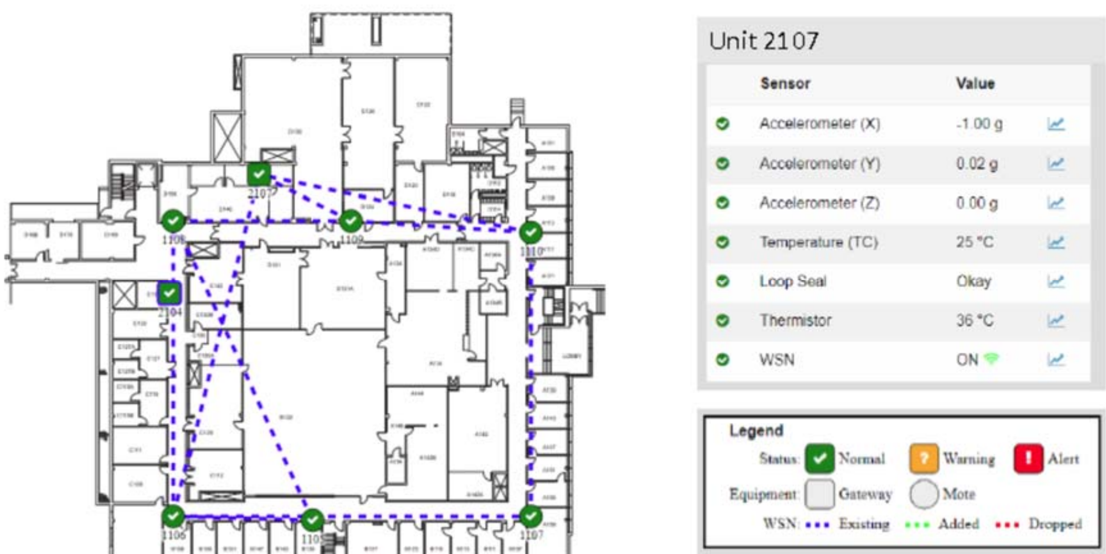


Figure 3. RAMM units deployed on the first floor of an office building: six Motes and two Managers (only #2107 was enabled; #2104 is a standby) on 10 May 2019, 21:27:25 GMT.

and #2107 are “Managers,” but only one (#2107) was enabled for the WSN, whereas the other (#2104) is a standby, or vice versa. In addition to managing Motes, Unit #2107 has the same suite of sensors as the Motes: this suite includes a 3-axis accelerometer, a thermocouple, an electronic loop seal, and a thermistor, with their current values displayed in Fig. 3. The sensor values of Motes #1105, #1106 and #1107 located in the southeast corner of the building (see Fig. 3) are displayed in Fig. 4, and are generally consistent among themselves and with those of Manager #2107 (Fig. 3), as expected, given that all RAMM units are indoors and the building has central air control.

Unit: 1105

Sensor	Value
Accelerometer (X)	-1.04 g
Accelerometer (Y)	0.01 g
Accelerometer (Z)	-0.01 g
Temperature (TC)	24 °C
Loop Seal	Okay
Thermistor	37 °C
WSN	ON

Unit: 1106

Sensor	Value
Accelerometer (X)	-1.03 g
Accelerometer (Y)	0.01 g
Accelerometer (Z)	-0.03 g
Temperature (TC)	24 °C
Loop Seal	Okay
Thermistor	35 °C
WSN	ON

Unit: 1107

Sensor	Value
Accelerometer (X)	-1.02 g
Accelerometer (Y)	0.01 g
Accelerometer (Z)	0.00 g
Temperature (TC)	23 °C
Loop Seal	Okay
Thermistor	35 °C
WSN	ON

Figure 4. Sensor values for Motes: Units #1105, #1106 and #1107 on 10 May, 2019, 21:27:25 GMT.

Self-Forming WSN of RAMM Units

Self-forming (or self-healing) is a key feature of WSNs of RAMM units. Any of the existing Motes in a WSN can "fail," as can the Manager, whose failure is even more critical and detrimental to sustaining the WSN. (Note: The cause of failure of a RAMM unit could be physical and/or intentional.) We began our study of a simulated Manager failure by switching #2107 and #2104 and observing the subsequent self-forming behavior of a WSN of Motes. Figure 5(a) shows that all radio links (colored red) between Manager #2107 and the Motes were dropped on 02 Jul 2019, 17:01:32 GMT; Fig. 5(b) shows that the first radio link (colored green) between Manager #2104 and Mote #1106 was added on 02 Jul 2019, 17:04:32 GMT.

(a) (b)

Figure 5. Switching between Managers (gateways) #2107 (a) and #2104 (b) for a WSN of RAMM units. Radio links (red) between Manager #2107 and the Motes were dropped in (a), whereas the first radio link (green) between Manager #2104 and Mote #1106 was added in (b).

Figure 6 shows the self-forming sequence of the WSN of RAMM units shortly after switching to Manager #2104, from 17:05:32 GMT (a) to 18:16:35 GMT (i). During the first two minutes after switching, as shown in Fig. 6(a), a new radio link (colored green) was added between Motes #1106 and #1107, whereas the

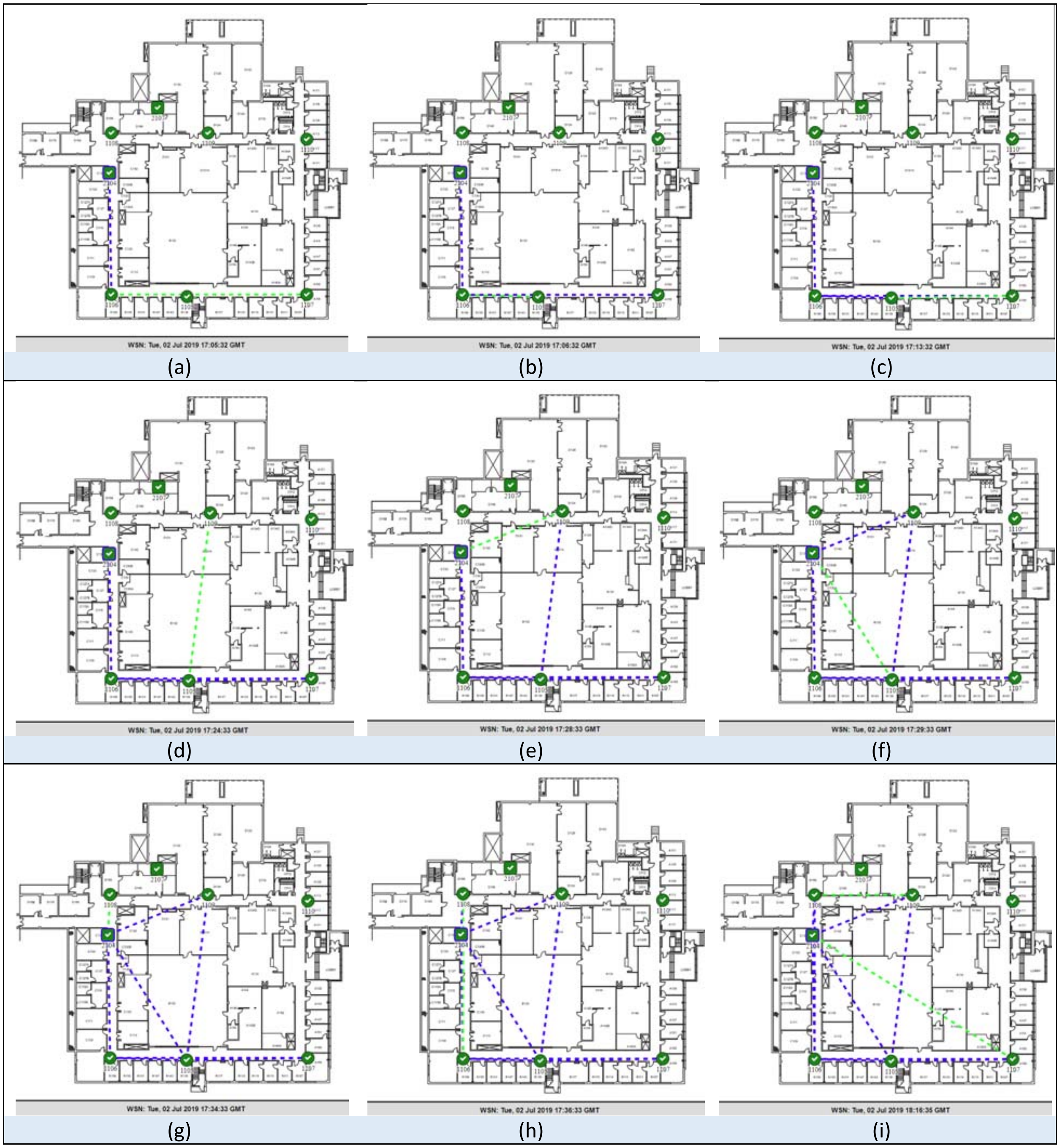


Figure 6. Self-forming sequence (a) to (i) of WSN of RAMM units (Motes) following switch to Manager #2104.

existing radio link between Manager #2104 and Mote #1106 changed color from green [Fig. 5(b)] to purple, denoting an existing link. A minute later, Fig. 6(b) shows that the added radio link (green) in Fig. 6(a) between Motes #1106 and #1107 changed to purple, whereas another link (green) was added between Motes

#1105 and #1106. This process of adding radio links between Manager #2104 and Motes and between Motes themselves continued until the last direct link between Manager #2104 and Mote #1107 was added at 18:16:36 GMT [Fig. 6(i)], about one hour and 12 minutes after the Manager was switched to #2104. While these radio links are shown as straight paths in the figures, they are simplified representations of radio waves traveling through air that were affected by any media encountered along the paths, such as walls, ceilings, and the ambient environment.

The WSN of RAMM units evolved as additions and drops of radio links among Motes continued. Table 1 shows a summary of the number of changes of radio links among the RAMM units each day over a seven-day period that included a holiday (July 4) and weekend (July 6 and 7), during which few occupants were in the building, as was the case during all non-office hours (before 8 am and after 6 pm). Table 1 also shows the time (GMT/CDT) when the first and the last change of radio links occurred each day. From the empirical observations of the behavior of radio links among the RAMM units over time, we can only make conjectures but offer no exact explanations for, e.g., why the number of changes differed significantly each day (except for July 2 during and after the WSN Manager switch), or the time (first and last) when a radio link among the Motes was added or dropped each day. Continuing study of the WSN beyond July 9 may determine whether a pattern emerges over time.

Table 1. Summary of changes of WSN radio links each day over a seven-day period

Date	No. of Changes	First (GMT/CDT)	Last (GMT/CDT)
July 2 (Tu)	20	17:02:32/12:02:32	23:16:48/18:16:48
July 3 (W)	8	14:16:25/09:16:25	23:16:50/18:16:50
July 4 (Th)	16	00:16:52/19:16:52	23:16:51/18:16:51
July 5 (F)	9	04:17:04/23:17:04	23:16:52/18:16:52
July 6 (Sat)	6	04:17:05/23:17:05	11:16:22/06:16:22
July 7 (Sun)	16	00:16:56/19:16:56	19:16:42/14:16:42
July 8 (M)	12	04:17:06/23:17:06	23:16:54/18:16:54
July 9 (Tu)	8	02:17:01/21:17:01	11:56:23/06:51:23

Sensor Data Communication during Normal Operation

The RAMM units (Manager and Motes) are connected to the building's IT system via PoE. All sensor data are collected and sent to the server at regular intervals. Figure 7 shows the temperature (TC) histories for Manager #2104 and Motes #1106, #1105, #1107, #1108 and #1109 over a 24-hour period. These temperature sensor data were logged at 2-minute intervals and they are within one to two degrees Celsius of each other at 2 am, July 16, 2019. The temperatures on weekdays during office hours (8 am to 6 pm) are generally lower by two degrees Celsius than those overnight because of the building's central air control schedule.

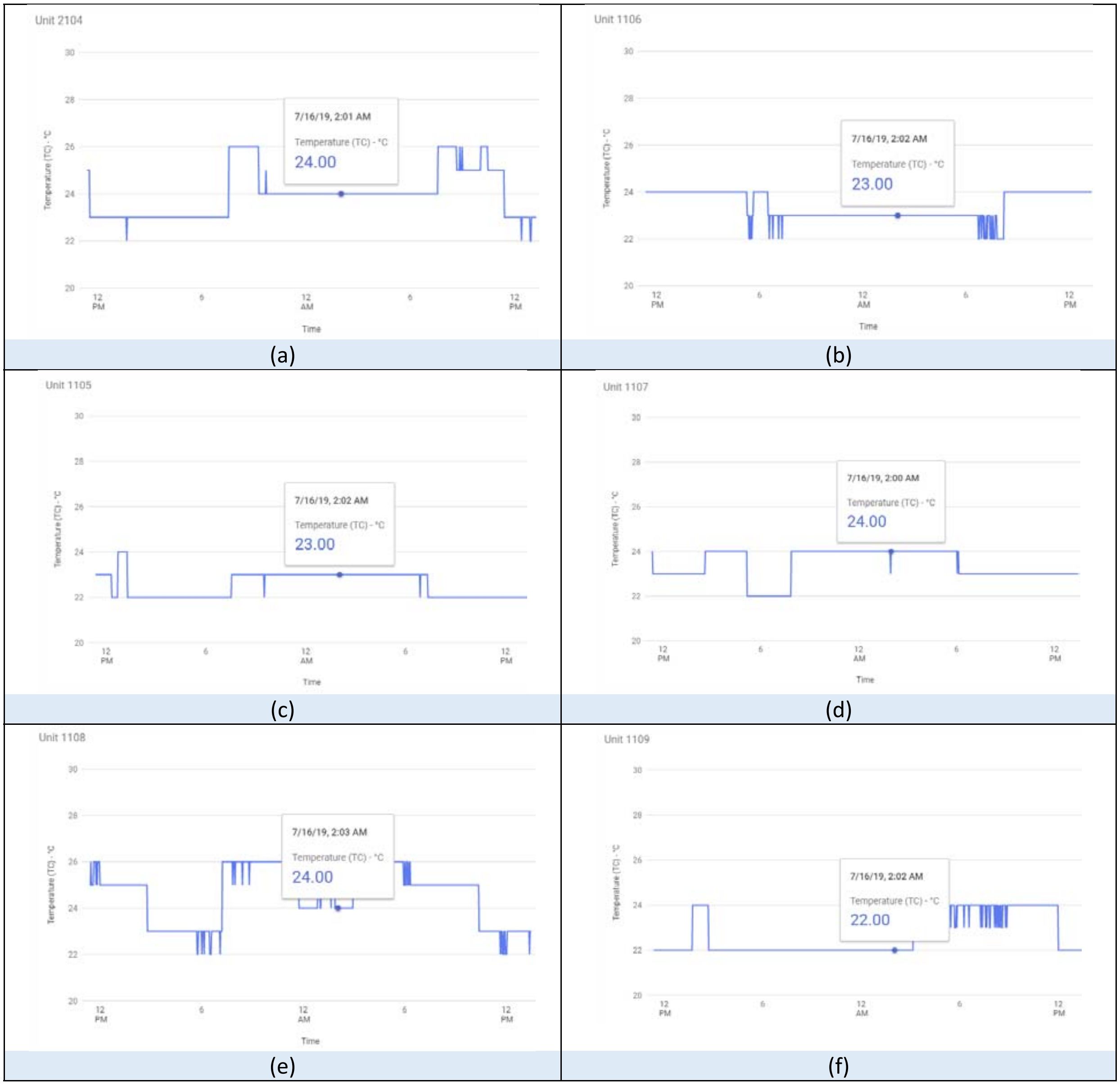


Figure 7. Temperature histories for (a) Manager #2104 and Motes (b) #1106, (c) #1105, (d) #1107, (e) #1108, and (f) #1109 over a 24- hour period.

WSN Sensors Data Communication

Utilizing the established WSN, a Mote will fail over to wireless transmission of sensor data if it is unable to send data over wired Ethernet. The WSN uses a time-sharing schema to manage data transmission across the network. After wired communication is lost, a Mote will request bandwidth from the Manager. When the Mote has been allocated a time slot for transmission, the Mote will transmit sensor information across the WSN. The information transmitted must be broken down into very small data packets for wireless transmission. A typical message transmitted over wired communication contains about 1,500 bytes. The WSN, however, only supports packets of up to 64 bytes. This constraint requires the Mote to reduce the amount of information contained in the message. The data are usually converted from a user-friendly, Javascript Object Notation (JSON) format into a pure binary format before transmitting the message to the

Manager over the WSN. Upon receipt, the Manager unpacks the sensor information and recreates the JSON-formatted message to relay and forward to the central servers. Once the message has been transmitted, the Mote will release the requested bandwidth to free up resources on the WSN. For typical Mote sensor information, such as temperature, transmission over a WSN is adequate. The WSN also allows for transmission of images over the network; however, owing to the limited packet size, the throughput of the current system is severely restricted to a few frames an hour.

Another way to study the WSN sensor data communication during a "simulated" incident or accident is by introducing a Mote that is not connected to the building IT system via PoE, but has a battery power supply. Mote #1110, shown in Fig. 3 at the northeast corner of the building, was disconnected from the building IT system and fitted with a battery power supply, and thus became a mobile Mote in May 2019. We have moved Mote #1110 inside the building to various locations in the proximity to other Motes (and Manager) and observed formation of radio links and verified temperature sensor data transmission. We have also moved Mote #1110 into an adjacent building until it was out of radio range to the existing Motes and Manager. The distance between Manager #2104 and Mote #1110 in the neighboring building was about 100 m, including a heavy fire door between the two buildings. Mote #1108, which is near Manager #2104, did not form a radio link with Mote #1110.

SUMMARY AND DISCUSSION

Two ARG-US RAMM systems, each consisting of multiple RAMM prototype units with customized sensors, have been deployed in a radiological facility and an office building at Argonne National Laboratory. Together, these two RAMM systems provided a testbed operating environment in facilities for studying the behavior and performance of wired and wireless sensor networks, including self-forming and/or self-healing of a WSN of RAMM units and transmission of sensor data across the WSN. On the basis of the testing results obtained to date, the performance of the RAMM systems has been judged to meet the original, overall design objective of the system, i.e., monitoring critical facilities during normal operation and providing situational awareness during and after disruptive incidents/accidents for emergency response and management.

More work remains to evolve the RAMM prototype systems for practical applications in critical facilities such as fuel enrichment and manufacturing plants, radiological facilities, nuclear power plants, spent-fuel storage installations, and geological repositories. Among the areas identified for near-term future development, power supply, sensor modules and communication are all under consideration, especially for the digital video camera in the RAMM prototypes. Adopting embedded devices, developing embedded control software and advanced algorithms (including artificial intelligence), and harnessing the power of edge computing, when successfully implemented and coupled with 4G-LTE cellular communication, are expected to yield orders-of-magnitudes enhancement of system performance of RAMM within the next 2–5 years.

ACKNOWLEDGMENT

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