Wireless Sensor Network Technologies for Applications in Nuclear Power Plants

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***Abstract*—There are several distinctive considerations when deploying wireless technologies inside a nuclear power plant. They include: (1) potential interference with existing highly sensitive safety systems through electromagnetic (EM) radiation; (2) ionizing radiation in nuclear power plant may cause damages to electronic components on the wireless sensor boards in particular in an event of an accident; and (3) efficient and effective ways for data transmission and relaying over long distance in confined spaces within a nuclear power plant. This paper will consider the above issues and discuss some potential solutions. The first part will focus on wireless technologies suitable for deployment in nuclear power plants during normal operation, while the second part will focus on wireless technologies for situations under severe accident conditions. Finally, some of the latest wireless communication technologies based on distributed antennas for wireless data transfer are discussed.**

Keywords*— Wireless sensor networks, indoor data transmission, EM interference, deployment under severe accident conditions

I. Introduction

Wireless technologies have proliferated in many domains of applications in the past decade. They offer unique advantages over existing wired technologies for communications and information transfers. In industrial applications, these technologies have revolutionized the way that measurement data are transmitted within confined spaces, and provided flexibilities and reduced cost especially for non-permanent installations. These technologies have enabled implementation of advanced monitoring schemes on targeted plant systems to make preventive maintenance feasible, and hence, to improve plant operational safety. Despite of initial hesitation in nuclear power industries, wireless technologies have now been adopted widely in nuclear industries.

There are many standards and application guidelines for wireless sensor networks. Each standard is tailored to specific applications. In the domain of automation, the major ones are ZigBee, WirelessHART, ISA100.11a, and WIA-PA. These standards are discussed in [1] to examine the similarities and differences among them. All these standards have been used to develop commercial products, which are available on the market.

Back in 2002, Electric Power Research Institute (EPRI) published two volume “Guidelines for Wireless Technology in Power Plants” [2] and [3]. The first volume covers basic wireless local area networking technologies, and provides some guidelines, as well as examples as how to such technologies should be used in power plants (including nuclear plants). The second volume provides some information on specific implementation aspects. The materials are presented a high level in both volumes. Even though some of the materials on wireless parts are now dated, however, the requirements on the plant sides, as well as some of the key considerations for wireless systems are still very much relevant today.

Back in 2004, Oak Ridge National Lab undertook a study for the US NRC to consider various wireless technologies, including wireless sensor networks for deployment in nuclear facilities. The outcome of this project was a published report as NUREG/CR-6882 [4]. This document contains essential elements to be considered when introducing wireless technologies into nuclear facilities, including available technologies at the time, interference and coexistence issues among different devices, advantages and disadvantages of different network configurations, as well as network security issues, in case a perpetrator has managed to gain access to the network via wireless means. Many of the issues discussed in this report are still relevant even today.

A review paper has been written with special focus on issues for deploying wireless sensor networks inside nuclear power plants [5]. The paper considered issues, such as EMI/RFI, network reliability with respect to deployment strategies, and tools to assist in the deployment process. It indicates that WSNs are particularly useful for condition-monitoring of equipment in the plant, or to be used to transfer data from personal radiation dosimeters to a central location for radiation exposure monitoring. Because it is a review paper, it does not provide any solutions, but does draw attention to many important issues when considering WSNs in nuclear facilities as well as the perspectives that this new technology can potentially offer.

Findings from an IAEA sponsored Coordinated Research Project (CRP) entitled “Application of wireless technologies in nuclear power plant instrumentation and control systems," have been documented in a technical report [6] recently. It contains the latest research results and new technologies for wireless applications in nuclear power plants. These include, but not limited to: (1) the latest codes, standards and regulatory guides; (2) different wireless technologies suitable for nuclear applications; (3) past practice, experience and lessons learned; (4) potential promising applications; and (5) emerging technologies and existing challenges.

II. Wireless systems for normal conditions

An EPRI report on a demonstration project of using wireless technologies for equipment condition assessment is published as [7]. It details the results of a pilot project to use wireless technologies (WLAN) in Comanche Peak energy production facility. The pilot project has three clearly defined goals:

- To prove the effectiveness of wireless equipment sensors in an energy generation environment,
- To prove the productive coexistence of wireless equipment sensors with other WLAN uses in a complex energy generation environment, and
- To increase the ability of Comanche Peak's Systems Engineering staff to prevent equipment failure through more frequent monitoring of critical plant equipment.

The report contains detailed planning and execution phases with clearly identified equipment being monitored and measurement variables to be acquired. The goals of the monitoring system are defined and the technical requirements are specified with cost-benefit analysis. Subsequently, the report proceeds to design and installation phase of such systems. Description of software interface developments are provided to support data collection and analysis. Finally, some technical and non-technical lessons learned are discussed on applications of wireless technologies for equipment condition monitoring in nuclear power plant environments.

The pilot project proved that wireless sensors can operate successfully in a typical energy production environment. The wireless sensors can be easily adapted to a wide variety of plant equipment and they are proven to have a negligible impact on the existing WLAN infrastructures.

A subsequent EPRI report [8] provides a guideline for wireless sensor applications in the area of condition-based maintenance (CBM). It helps nuclear facilities to determine the best approach for implementing wireless technologies to achieve efficient transmission of data for CBM or real-time transmission of dosimeters and radiation sensors data to reduce personnel exposure. The report covers well-known wireless protocols, such as Bluetooth, Wireless Ethernet as well as 802.11b. It also addresses specifics about using wireless sensors for condition-based monitoring, such as different types of wireless sensors available on the market, and strategies for their deployment in a specific plant environment to form a wireless sensor network. The report also includes several practical application examples of using WSN systems in nuclear facilities and other industry environments for condition monitoring tasks.

A technical survey has been complied [9] to discuss some of the key issues of wireless sensor networks for nuclear power plant applications. It examines the state of the art of wireless sensor networks in relation to their applications in such environments. The topics discussed include: (1) potential interaction of wireless sensor networks with the sensitive plant protection equipment, (2) radiation damage to the electronics on board sensor nodes, (3) optimal placement of relay nodes that collect and forward data in the network, and (4) possible applications, such as radiation dose and level monitoring, and equipment condition monitoring. Different aspects of deployment of such wireless sensor networks have also been examined. Industrial standards and guidelines for deployment of WSNs in NPPs are also been considered.

The EPRI has been in the forefront of applications of wireless technologies in nuclear power plants. An EPRI report [10] presents some additional application examples of wireless technologies in nuclear facilities. It provides some good practice in terms of equipment installed and data observed during these trial deployment.

Four applications have been carried out and documented in [11]: The first is to use wireless vibration sensors for monitoring the condition of refuel floor overhead crane wheel bearings while under actual load conditions. The second is to monitor critical plant parameters during the decommissioning activities in a nuclear facility. The third monitors the temperature variations of several circulating water pump motors. Finally, voice communications over wireless channels within a nuclear facility have been examined.

III. Wireless systems for accident conditions

One of the lessons learned from the Fukushima Daiichi nuclear disaster is the difficulty of obtaining up-to-date status information on the plant after the accident, such as water levels in spent fuel bays, hydrogen concentration in reactor buildings, and temperatures in heat transport systems, due to the lack of operational monitoring instruments [12]. As an integral part of accident management systems, regulatory bodies for operating nuclear power plants (NPPs) now require plants to have some form of monitoring system available on-site for accident conditions [13,14]. Considering various potential scenarios during a severe accident in a nuclear power plant, a potential approach to deal with such situations is to use wireless technologies to implement a post-accident monitoring system (PAMS) which can provide much needed information about the plant conditions, reactor integrity, and environment in the vicinity of the nuclear power plant without relying on likely damaged communication infrastructures [15].

Typically, a wireless sensor node consists of several electronic based elements: i.e. a processing unit, a communication unit, and a sensor unit [16]. When they are used in severe accident monitoring applications, these units will undoubtedly be exposed to a strong radiation environment. The damaging effects of ionizing radiation on electronic devices can generally be categorized into three types: (1) Displacement damage, which is caused by long-term nonionizing effects [17]; (2) Total ionizing dose, which accounts for the total amount of energy deposited by the particles on the semiconductor materials, causing malfunctions of the devices [18]; and (3) Single event effects, which are primarily caused by single particle ionization and/or secondary particle formation [19].

Six different wireless sensor nodes and networks under a radiation environment with a dose rate of 20 K Rad (Si)/h have been examined experimentally [20]. The wireless nodes evaluated are ZigBee, WirelessHART, ISA 100.11a, LoRa, and 433/915 MHz point-to-point devices made from commercial off-the-shelf (COTS) components. The experiments were carried out using a ^{60}Co gamma source, while the devices are at on-power operating states, and their operating statuses have been continuously monitored to determine the first instance of radiation induced failure and the rate of gradual degradation in terms of communication channel performance and quality of the wireless signals.

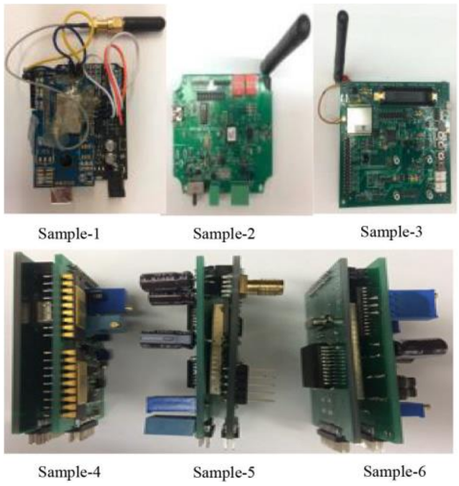

Fig. 1 Six sample wireless transceivers used in the radiation tests [20].

IV. DISTRIBUTED ANTENNAS FOR NPP DEPLOYMENT

Since a nuclear power plant is a large facility with many different equipment scattered in a large area, there is a need to develop a centralized data collection and transmission system to concentrate the measurement data to a central location for processing. To gather real-time measurements from distributed wireless sensor networks (WSNs) and to the data to a gateway for further processing [6], an array of antenna systems must be located throughout the plant to form a communication network. This can be done through so-called Distributed Antenna Systems (DASs) [21].

Even though those communication technologies have enjoyed a lot of success in many domain of applications, however, one has encountered a major hurdle when deploying within a nuclear power plant. The main reason is that nuclear power plants are constructed with thick concrete structures within which embedded tons of reinforcing bars (rebars). These concrete steel enforced walls and big heavy (often airtight) steel doors create a perfect Faraday cage to confine electromagnetic signals (i.e. wireless signals) within a local region.

Depending on the requirements in specific applications, DASs can be classified into three major types: (1) Passive DAS; (2) Active DAS, and (3) Radiating cables. Specific properties of them are summarized as follows:

(1) Passive DAS: The network with passive DAS is composed of only passive elements, such as coaxial cable, splitters, and diplexers for signal distributions. Typically, passive systems are not suited for large facilities, as the strength of wireless signals diminishes quickly as distance increases between the transmitter and the receiver. Furthermore, one cannot monitor the performance of individual node on the network easily. This type of networks is only suited for small and localized deployment.

(2) Active DAS: An active DAS makes use of electronic amplifiers to increase the signal strength along transmission paths to provide consistent strong reception for reliable communication. Often, they use fiber optic cables to connect a centralized signal source and antennas at edges of the network around the facility to be deployed. Therefore, active DAS is more suitable for large facilities, such as a nuclear power plant. In practice, it is also possible to mix active and passive DAS, where the active DAS cover a large general area, while passive DAS is deployed in a small local area. The resulting network is often called "hybrid" DAS.

(3) Radiating Cables (also known as Leaky Cables): In applications where the physical area to be covered is in the form of a long tunnel, cylindrical area, or only along a corridor, rather than an area, radiating cables can be used as a simple antenna. It is in fact a particular form of passive DAS. An illustrative diagram of such cable can be shown in Fig. 2.

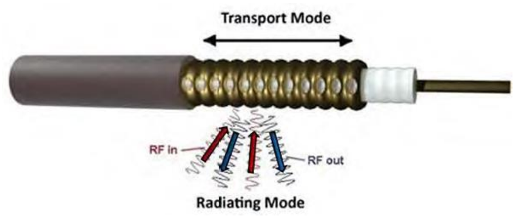

Fig. 2 A section of a radiating cable.

The cable can be laid to run along the intended corridor used as an extended antenna for transmitting and receiving wireless signals. A case study of using such radiating cables in a nuclear facility has been conducted as part of an EPRI research project [22]. In this project, radiating-cable based DAS has been investigated extensively in Crystal River NPP in Florida (Fig. 3).

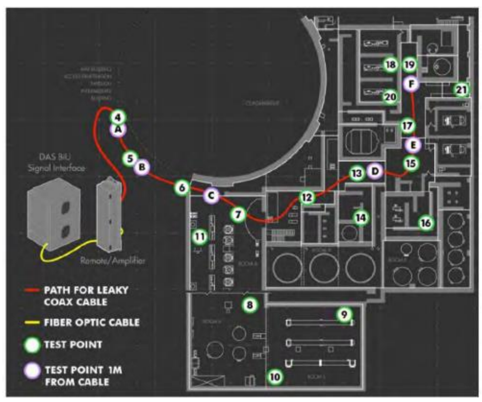

Fig. 3 Layout of leaky cables for DAS experiments in Crystal River NPP in Florida [22].

Such antenna systems have widely been used in subways [23], as well as inside commercial buildings [24] to support communication systems. It is promising technology for wireless systems in nuclear power plants as well.

V. Conclusions

Being an enabling technology, wireless sensor networks can be used to collect measurement data throughout a nuclear power plant in a flexible and economical way, especially for retrofitting installations. Once the measurements are collected, the information can be extracted through appropriate data processing techniques to assist in decision-making.

Even through wireless technologies are still developing rapidly, the present devices and systems have reached a technical level that can be reliably deployed in real industrial settings. Furthermore, several industry standards and guidelines for wireless sensor applications have been developed and a number of high-quality industry-grade systems are commercially available. Hence, the technology is sufficiently mature to be considered for meaningful deployment in practice.

In the event of a nuclear accident, wireless sensor networks can provide a convenient way to relay critical plant information to first responders. However, due to potential exposure to ionizing radiation, electronics used in these wireless devices should be hardened through fault-tolerant design, diversified component selection, and adequate radiation protection.

To provide wireless coverage over a large area or a long tunnel structure, distributed antenna systems can be an effective solution. However, the complex of a nuclear power plant configuration and multiple barriers to meet separation requirement for safety consideration may pose considerable challenges at the deployment phase. For example, there are multiple airlocks in a nuclear power plant, transmitting a measured signal from one side of an airlock to the other side while keeping the pressure boundary intact requires further investigation.

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References

[1] Q. Wang, and J. Jiang, “Comparative Examination on Architecture and Protocol of Industrial Wireless Sensor Network Standards,” IEEE Communications Surveys and Tutorials, Vol 18, No. 3, pp. 2197 - 2219, 2016.

[2] EPRI, Guidelines for Wireless Technology in Power Plants Volume 1: Benefits and Considerations, Electric Power Research Institute (EPRI), 2002.

[3] EPRI, Guidelines for Wireless Technology in Power Plants Volume 1: Benefits and Considerations, Electric Power Research Institute (EPRI), 2002.

[4] USNRC, Assessment of Wireless Technologies and Their Application at Nuclear Facilities, U.S. Nuclear Regulatory Commission, 2006.

[5] A. Bari and J. Jiang, A Review of Wireless Sensor Networks for Nuclear Power Plant Applications, Nuclear Safety and Simulation, Vol. 6, Number 1, pp. 53-67, 2015.

[6] IAEA, Application of Wireless Technologies in Nuclear Power Plant Instrumentation and Control Systems, IAEA Nuclear Energy Series NR-T-3.29, 2020.

[7] EPRI, Demonstration of Wireless Technology for Equipment Condition Assessment- Application at TXU Comanche Peak Steam Electric Stations, Electric Power Research Institute (EPRI), 2005.

[8] EPRI, Wireless Sensor Application Guideline, Electric Power Research Institute (EPRI), 2008.

[9] J. Jiang, D. Y. Chen, A. Bari, and Hash M. Hashemian, "Technical Survey on Applications of Wireless Sensor Networks in Nuclear Power Plants." Proceedings of ISOFIC/ISSNP 2014, Jeju, Korea, August 24~28, 2014.

[10] EPRI, Wireless Technology Power Plant Applications, Electric Power Research Institute (EPRI), 2003.

[11] EPRI, Revised Guidelines for Wireless Technology in Power Plants Volume 1: Benefits and Considerations, Electric Power Research Institute (EPRI), 2006.

[12] K. Nagatani, S. Kiribayashi, Y. Okada, ‘Emergency response to the nuclear accident at the Fukushima Daiichi nuclear power plants using mobile rescue robots’. J. Field Robot, 30, (1), pp. 44–63, 2013.

[13] USNRC ‘Instrumentation of Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident’. U. S. Nuclear Regulatory Commission, Regulatory Guide 1.97, Rev. 03, 1983.

[14] IEEE, ‘Standard Criteria for Accident Monitoring Instrumentation for Nuclear Power Generating Stations’ The Institute of Electrical and Electronics Engineers (IEEE), Std. 487. 2016.

[15] K.S. Son, C.H. Kim, and H.G. Kang: “Conceptual Design of Emergency Communication System to Cope With Severe Accidents in NPPs and its Performance Evaluation,” Ann. Nucl. Energy, 76, pp. 367–377, 2015.

[16] F. Karray, M.W. Jmal, A. Garcia-Ortiz, ‘A comprehensive survey on wireless sensor node hardware platforms’, Comput. Netw. V.144, pp. 89–110, 2018.

[17] J.R. Srour, and J.W. Palko "Displacement damage effects in irradiated semiconductor devices," IEEE Trans. Nucl. Sci., Vol. 60, pp. 1740–1766, 2013.

[18] D. M. Fleetwood, "Total ionizing dose effects in MOS and low-dose-rate sensitive linear-bipolar devices," IEEE Trans. Nucl. Sci., 60, pp. 1706–1730, 2013.

[19] V. Ferlet-Cavrois, L. W. Massengill, and P. Gouker, "Single Event Transients in Digital CMOS – A Review," IEEE Trans. Nucl. Sci., 60, pp. 1767–1790, 2013.

[20] Q. Huang, J. Jiang, and Y. Q. Deng, "Comparative Evaluation of Six Wireless Sensor Devices in a High Ionizing Radiation Environment," IET, Wireless Sensor Systems, Vol. 10, pp. 276-282, 2020.

[21] H. L. Hu, Y. Zhang, and J.J. Luo (Edited) Distributed Antenna Systems – Open Architecture for Future Wireless Communications, Auerbach Publications, 2007.

[22] EPRI, Use of LTE Cellular Network and Distributed Antenna Systems to Improve Connectivity and Increase Data Transfer A Plant Monitoring Initiative,, Electric Power Research Institute (EPRI), 2017.

[23] L. L. Feng, X. D., and Z. Wang, "Application of Leaky Coaxial Cable in Subway Mobile Communication System," Proc of 2011 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference, 2011.

[24] S. Baasan, DAS 101 Distributed Antenna System: A Basic Guide to In-Building Wireless Infrastructure, 2014.