A review of wireless sensor networks for nuclear power plant applications

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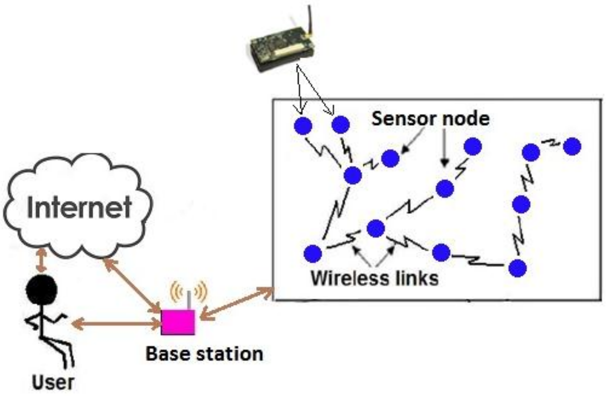
Abstract: Wireless sensor network (WSN) has attracted a lot of attention recently in nuclear power plants (NPPs) due to its potential to bring tremendous benefits to the plant and environment monitoring applications. Although there is no general consensus on using wireless technologies in NPPs yet; however, nuclear regulatory bodies and relevant organizations have undertaken efforts to provide guidelines for the requirements of wireless devices and systems in NPPs. Several applications of WSNs in NPPs have also been investigated, most noticeable of those include radiation level and dose monitoring, and equipment condition monitoring. Moreover, deployment of wireless systems in a NPP also faces unique challenges, which include i) absolute requirement to ensure that electromagnetic interference from a wireless system do not interfere with the functionality of existing safety system instruments in a plant, ii) robust device and system design to deliver reliable WSN performance in harsh NPP environments, and iii) strict compliance with the nuclear regulatory guidelines. This paper gives the reviews on the state of the art of WSNs in NPPs.

Keyword: nuclear power plant; equipment monitoring; wireless sensor networks

1 Introduction

With the advancement and maturity of wireless communication technologies, wireless systems are now widely used in homes and offices. Recent research and development (R&D) activities have also made wireless communication systems feasible for industrial applications. In addition to voice communications (*e.g.*, with walkie-talkies), wireless technologies have also been considered for plant and process monitoring and control applications, in particular, using wireless sensor networks (WSNs).

A WSN is a network of low-powered wireless devices, known as sensor nodes. Each node is generally composed of a micro controller, memory, a wireless transceiver and sensor(s) for measuring certain physical attributes from a given piece of equipment or an environment [1]. A sensor node can communicate sensor measurements without wire to a central receiver, often called a base station. This information then can be further accessed, even over the Internet, for analysis, decision-making and/or back-up storage [1]. Data from a WSN can also be made accessible though mobile devices to interact directly from a handheld device. A conceptual illustration of a WSN is shown in Fig. 1. WSNs have now been used in many civil, military and health-care applications.



Fig, 1 A conceptual illustration of a WSN.

For industrial applications, in addition to process monitoring and control, WSNs have also been considered for equipment condition monitoring, predictive maintenance, remote diagnostics, safety shutdown, and post-accident monitoring [2]. Due to the growing interest among industry operators, several industrial sensor manufacturers have even collaborated with wireless device suppliers to provide integrated WSN systems for industrial applications [2]. A number of international standards and protocols

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have also been developed specifically for industrial applications of WSNs that include ZigBee, WirelessHART and ISA 100.11a [3].

Operators of safety-critical industries, such as nuclear power plants (NPPs) are also showing significant interest in using WSNs in their plants. In a survey conducted on 33 NPPs in the USA, nearly 80% of the respondents indicated that they are interested in using WSNs, in particular, to extend existing plant monitoring activities [4]. Similar enthusiasm can be found among the NPP operators around the world. The urge to implement wireless technologies in NPPs has been amplified manifold recently, after the accident at Fukushima NPP, as the only way to get information out in this situation is probably through wireless communication. In response to the increasing interest, International Atomic Energy Agency (IAEA) has recently launched a coordinated research project (CRP) to investigate different aspects of implementing wireless technologies in NPPs [5]. Furthermore, several nuclear regulatory bodies and relevant organizations, such as the U.S. Nuclear Regulatory Commission (NRC) and the International Electrotechnical Commission (IEC), have also undertaken substantial efforts to provide guidance with respect to the selection and use of wireless devices in NPPs [6].

Using WSNs, the safety, reliability and efficiency of a NPP can be improved, as WSNs can effectively monitor radiation levels and doses, plant environments, as well as equipment and process conditions. In particular, a WSN can become a convenient and cost-effective option to extend existing plant monitoring activities by acquiring additional measurements, which is very useful for safety critical industries [2]. It may be noted that such functions can also be achieved through wired sensors in some cases. However, by using a WSN, sensors can be deployed and signals can be acquired without the cost and time associated with evaluating, installing, and managing the wiring and conduit that are essential for wired sensors [7]. Installing and maintaining wires in NPPs can be significantly more expensive [8]. Wires are also difficult to install, especially in existing and/or refurbished NPPs, which, ironically, may need additional monitoring due to aging.

The significance of the benefits that a WSN can bring to the monitoring of a NPP is understood; however, as with the implementation of any new technology, nuclear industries are relatively slower than other industries in accepting wireless systems into the plants [2]. Such a pace is justified as a nuclear industry needs to deal with increased safety, regulatory and licensing requirements, and also needs to examine all possible impacts before adopting any new technologies. This is important as the outcome of any technological uncertainties in a nuclear industry can be extremely costly, or even catastrophic in some cases [2].

Moreover, deployment of WSNs in NPPs also comes with unique challenges, due to the complex geometry of a typical NPP, harsh operating environments, and extremely high standards in terms of safety related requirements. Some of the major issues that need to be addressed before a WSN can be effectively deployed in a NPP include:

i) Electromagnetic interference (EMI) / radio frequency interference (RFI): a NPP usually houses a large number of sensitive instruments in its safety systems, which can be vulnerable to the EMI/RFI from the wireless transceivers. It is imperative that any WSN device deployed in a NPP does not interfere with the functionality of the instruments in the existing safety and protection systems of the plant [8].

ii) Reliable performance of a WSN in harsh NPP environments: the deployment area of a WSN in a NPP is usually complex, as it is packed with cable trays, piping, valves, pumps, motors, and concrete and steel structures [9]. The electromagnetic (EM) environment is also very harsh due to EM interferences from other plant devices, such as relays and motor driven pumps. These factors may severely affect wireless communications. Furthermore, ionizing radiation sources in a NPP may also cause damage to the electronic components of a WSN device. A WSN stem, when deployed in an NPP, must be able to perform reliably under NPP environments.

iii) Compliance with regulatory guidelines: nuclear regulatory bodies specify requirements for all devices and systems that can be used in a NPP. These requirements are usually very strict as these guidelines are prepared while putting utmost importance on the safety of the plant and people. A WSN system in an NPP must strictly comply with nuclear regulatory guidelines.

Furthermore, issues associated with cyber security risks, network coverage and integration with existing data networks need to be addressed as well [2][10][11][12]. In fact, these concerns are somewhat hindering widespread adoption of wireless systems in existing plants. However, WSNs may be incorporated in plant designs of the next generation NPPs [13].

To address these issues and concerns, research initiatives have been undertaken by several groups and organizations around the world. Among them, the US Department of Energy (DOE) and the Electric Power Research Institute (EPRI) have launched several research projects in the USA focusing on the development of WSN systems that can meet the requirements of NPP applications [9]. A number of WSNs have also been deployed in some operational NPPs in the USA on experimental basis [7][14].

In this paper, an attempt has been made to provide a state of the art review of WSNs in NPPs. The rest of this paper is organized as follows. In **2**, some issues associated with the deployment of WSNs in NPPs are briefly reviewed, along with some discussions on some of the research done to address those issues. In **3**, several potential applications of WSNs in NPPs are presented. Some open research issues are discussed in **4**. Finally, conclusions are drawn in 5.

2 Issues with WSN systems in NPPs

In this section, some issues associated with the deployment of WSNs in NPPs are reviewed.

2.1 Electromagnetic interference

One of the major concerns with wireless systems in NPPs is EMI/RFI. The EMI/RFI is a phenomenon where electromagnetic energy emitted from a wireless device interferes with surrounding electrical/electronic devices [15]. An NPP typically implements several safety and protection systems in the plant, such as reactor protection systems, emergency core cooling systems, shutdown systems, and emergency power supply systems. The performance of these safety systems largely depends on the effective functioning of some highly sensitive instruments used in their respective control systems (*e.g.*, criticality and airborne contamination systems, and flux detectors). The EMI/RFI produced by the wireless transmitters can adversely affect the functionality of these instruments and can lead an NPP to an inadvertent state. Due to this concern, US NRC standards has prohibited the use of wireless technologies on the critical digital assets, effectively banning wireless devices in the protection or the control functions in the safety systems [13].

In fact, concern with EMI/RFI among NPP operators is one of the reasons that wireless technologies have not been adopted widely in any NPPs [2]. This concern is partially influenced by their experience with walkie-talkie radios, which, when used within the plant, have inadvertently effected plant safety systems [2]. EMI/RFI concerns are legitimate as the long-standing experience of military organizations, and equipment history of power industries have also raised this concern. Furthermore, research studies by the Oak Ridge National Laboratory (ORNL) in the USA and several other organizations have concluded that EMI/RFI is an environmental condition that can adversely affect the performance of electronic equipment [16]. The US NRC - Regulatory Guide 1.180 clearly specifies that: “Electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges have been identified as environmental conditions that can affect the performance of safety-related electrical equipment” [17][18]. Introduction of digital technologies in the advanced safety and protection systems in NPPs has further amplified this concern, as digital instruments can be more susceptible to the effect of EMI/RFI compared to their analog count-parts [16][19]. The concerns with EMI/RFI even led to the establishment of EM exclusion zones inside NPPs to safeguard the sensitive and critical equipment from interference.

Use of wireless devices is strictly prohibited inside of an EM exclusion zone. Furthermore, strict limits on the maximum transmitting power level of wireless transceivers have also been imposed by many NPPs [13]. Here, it may be noted that the intensity of EMI/RFI produced by a wireless transmitting device also depends on the transmit power level of the device.

Recently, EMI/RFI effects on safety related instrument and control (I&C) systems have been investigated by several nuclear regulatory bodies, as well as a number of research and utility organizations including U.S. NRC, US DOE and EPRI [9][11][12]. The focus of these studies have been to identify wireless system specifications that, when used in a NPP, will not adversely affect its safety systems. For example, the Regulatory Guide 1.180 has identified all portable and fixed wireless devices as EMI/RFI sources that can potentially affect safety-related electrical equipment [17][18]; however, the same guide has also specified safe EM operating envelopes for safety related I&C systems. Therefore, based on this guide, a wireless system can be deployed in a NPP; if the EMI/RFI produced by the wireless devices remains within the recommended levels.

The regulatory agencies have provided general guidelines for the use of wireless technologies in NPPs, while taking into consideration different safety aspects of the people and plants. Based on these guidelines, state-of-the-art wireless devices have strong potential for safe deployments in NPPs. To illustrate, consider a modern WSN device. It is well known that the EMI/RFI impacts largely depend upon the transmit power level. Operating frequencies of a wireless device can also have an impact. Modern WSN devices can operate at very low levels of transmit power, and at higher frequency bands. These can certainly reduce the level of EMI/RFI. For a comparative example, consider a walkie-talkie device that typically operates with 3W transmit power at a frequency band of several hundred MHz. Safety-system instruments can be more vulnerable to the effects of EMI/RFI from such a device. In contrast, most modern WSN devices operate at much lower power levels (e.g., 100mW or less) at a frequency band of several GHz. Different methodologies can also be used in the lower layers of the networking stack to further mitigate the interference. Therefore, significantly less EMI/RFI effects can be experienced from modern WSN devices, which can alleviate the concerns of NPP operators.

The EMI/RFI issue has been further investigated in several research studies recently. AMS Corporation in the USA has surveyed the EM environments in Comanche Peak NPP to assess possible impacts of EMI/RFI on the safety related I&C instruments [4]. The survey has helped to understand existing EMI from various sources in the plant, to determine EM interaction among the plant environment and wireless systems, and to identify equipment that are more susceptible to EMI. In a case study, a WiFi-based wireless sensor system has been deployed to monitor the condition of pump motors at a research reactor facility in the USA, which has an environment similar to that of a commercial NPP [13]. Another case study has used a WiFi-based sensor system at Arkansas Nuclear One NPP to monitor the vibration level of containment cooling fans [14]. These case studies reported no issues with EMI/RFI from the wireless modules on the safety system instruments.

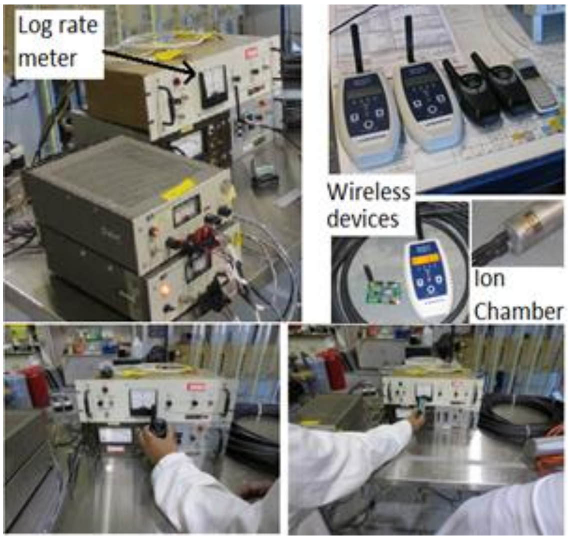

Fig 2 Instruments, equipment and wireless devices used for EMI/RFI test at AECL-CRL [20].

The potential EMI levels from some WSN devices have been quantitatively measured recently in an experimental study [20]. The study has used a piece of sensitive instrument, referred to as 'Log rate meter', from the plant safety systems in ZED-2 reactor, which is located at Atomic Energy of Canada Limited (AECL) - Chalk River Lab [20]. For the purpose of the tests, the log rate meter has been subjected to the EMI produced by several different wireless devices including walkie-talkies, and cellphones, as well as a number of modern WSN devices (based on IEEE802.15.4 transceivers). Instruments, equipment and wireless devices used in these tests are shown in Fig. 2. The test results have found that walkie-talkies and cellphones (*i.e.*, higher powered, lower frequency wireless devices) produced much higher levels of EMI, which significantly affected the functionality of the log rate meter. However, none of the WSN devices used in the study have exhibited any measurable EMI impacts on this instrument.

The risk of EMI from wireless technologies is also evaluated at Diablo Canyon NPP recently [15]. At first, installation of sensitive/critical equipment throughout the plant are evaluated to assess their vulnerabilities to EMI from wireless devices. Evaluations are done for grounding, shielding, use of conduit and cable trays, exposed signal leads, and plant equipment. After identifying equipment potentially susceptible to wireless signals, EM emission measurements are taken to characterize EM environments. This is done to identify areas where either plant equipment may interfere with wireless communications, or where wireless devices may cause interference with plant equipment. Finally, targeted radiated immunity tests have been performed with selected pieces of plant equipment. From the test results, it was concluded that a majority of the equipment is immune to the injected wireless signals, except for some pressure transmitters and radiation monitors. Based on the test results, Diablo Canyon has implemented administrative procedures to limit the effect of EMI, and also has developed EMI shielding using RF cloth material to protect the sensitive devices [15].

The preliminary results from those case studies mentioned above have clearly increased the potential for safe deployment of state-of-the-art WSN devices in NPPs. However, EMI/RFI issues in NPPs are not yet clearly known, and hence, further investigations are still necessary in this regard.

2.2 Reliability of WSNs in NPPs

It is important that a WSN performs reliably when deployed in a NPP. The reliability of WSNs in NPPs may be investigated for several aspects, as discussed in this subsection.

2.2.1 Reliability in network communication

NPPs traditionally rely on data communications network for effective plant operation and monitoring [10]. Entities in the network receive information in an electronic format, and forward it to a final destination [10]. Wires are usually used as a communication media. Communication errors can occur in several ways in such a networked system. Signals can get corrupted at the source, transmitter, transmission media, or at the receiver, resulting in communication failures [10]. In a WSN, the probability of communication errors can be higher due to the unpredictable nature of the wireless transmission media. Wireless communication can also be affected by the presence of obstacles between the wireless transmitter and the receiver, as well as by the changes in the surrounding EM environments [10]. These issues can become much more challenging for a WSN in a NPP. To illustrate, the EM environment of a NPP can be very harsh due to the EMI coming from devices like relays and motor driven pumps. Such EMI in a plant environment may severely affect wireless communications. Furthermore, a typical NPP plant layout is complex as it is packed with cable trays, piping, valves, pumps, motors, and concrete and steel structures. This introduces obstacles, and also reduces line of sight (LOS) ranges. This also raises other issues including multipath fading, which is a result of self-interference arising from radio waves reflecting off obstacles in the environment [10].

The performance of a WSN may be affected by several factors occurring at different layers of the network protocol stack [10]. Corrective measures may also need to be taken into account at different layers [10]. In modern WSN systems, several techniques are employed in different layers of the network stack to resolve the issues with wireless communications. To suppress or cancel EMI at the physical layer, the spread spectrum (SS) technique, where the transmission bandwidth of the signal is made much wider than the information bandwidth, is used in many modern WSN systems [10]. The most common SS techniques include direct sequence spread spectrum (DSSS), frequency-hopping spread spectrum (FHSS) and chirp spread spectrum (CSS). In DSSS, a signature sequence waveform is multiplied to each user's data signal to achieve resistance to multipath fading, low-power spectral densities, and higher capacities. A DSSS system can be suitable for safety-related applications since it is resistant to detection and interception due to its noise-like power spectral density [10]. In a FHSS system, narrow-band message signals are transmitted at successively different carrier frequencies to achieve spectral spreading [10]. The carrier frequency is changed according to a pseudo-noise sequence. FHSS offers frequency diversity, and improved resistance to frequency-selective fading and narrow-band jamming [10]. In a CSS system, the carrier frequency is swept over a wide frequency band. During each bit interval, the spectrum is spread by a linearly swept frequency between predefined lower and upper frequency range [8]. CSS signals can provide anti-eavesdropping capabilities and low-Doppler sensitivities [8].

Path-loss, shadowing and multipath fading are among other phenomena that may introduce serious impairments to the wireless communications [10]. Path loss is a term used to express the attenuation of the power level of the received signal as a function of the distance. The most common path loss model used to predict signal-strength is the log-distance model [10]. Although many studies have been done for commercial cellular network environments, very little is known about this in NPP environments, and hence, needs to be carefully investigated. Due to a multi-paths effect, signal components may be constructively or destructively added to form a received signal with random amplitude and phase [10]. Multi-path effects can be handled using coding, equalization, diversity and frequency hopping [10].

Reliability of data communication also needs to be addressed in the higher layers of the network stack. The network layer performance is usually measured in terms of the number of packets transmitted, the number of packets received correctly, the number of packets received erroneously, and the number of packets dropped [10]. The network layer performance can be influenced by the packet size, traffic load, selection of routing strategy, and network topology [10]. Furthermore, network traffic pattern may also have an impact on the interference [10].

2.2.2 Reliability in network deployment strategy

When a WSN is deployed inside a NPP containment, all sensor measurements should be forwarded to a central wireless receiver, which should also be located within the containment as radio signals cannot pass through the containment wall. The central receiver can forward the data to the main control room or to the maintenance crew through dedicated penetration channels. The central receiver should be located near the penetration, while sensors should be attached to the equipment whose attributes are being measured. A conceptual illustration of deployment of a WSN in NPP containment is shown in Fig. 3.

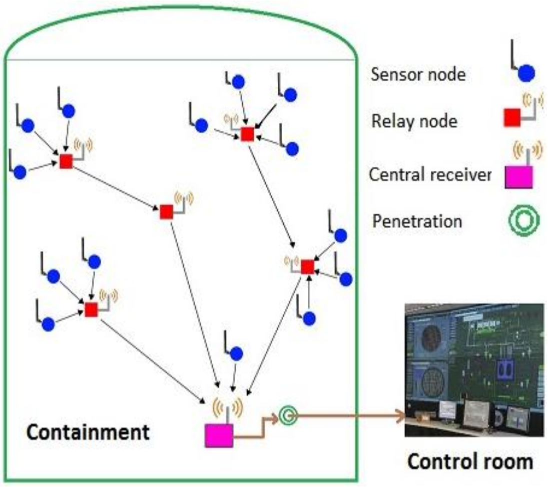

Fig. 3 A conceptual illustration of WSN in NPP containment.

In such a WSN deployment, each sensor node will not be able to pass its measurements directly to the central receiver, due to obstacles, interferences and/or the central receiver being out of range of a sensor node. In a WSN in a NPP, the transmission range of each sensor node can be small, as each node must use a very low level transmitting power to comply with the regulatory guidelines. The transmission range can be further compounded by the cramped and complex geometry of a typical NPP containment. Therefore, it is feasible to deploy some additional nodes to perform the networking tasks. These additional nodes, often referred to as the relay nodes, need to form a connected network to forward measurements from other sensors to the central receiver.

To achieve reliable WSN performance, it is extremely important to consider the placement of these relay nodes in the network based on the plant layout. Node placement should be such that each sensor node can find a relay node to pass its data, and the relay nodes can find a path to forward data to the central receiver. Furthermore, relay nodes can only be placed where it is physically possible, and no relay node should be overloaded as a relay node may need to forward data from multiple other nodes. Therefore, it is useful to develop a node placement strategy that ensures effective deployment of a WSN in a NPP, to reduce any uncertainties and trial-and-error based works during the actual deployment phase.

The importance of node placement in industrial WSN has been investigated recently. An optimal strategy for node placement, based on a variant of the Swarm Optimization algorithm, has been proposed [21]. The joint problem of the relay node placement and network routing that also incorporates fault tolerance has been addressed [1]. A WSN deployment strategy for 3D NPP containment space has been investigated [22]. The proposed approach takes into consideration containment geometric constraints, impact of EM environments, and obstacles on the individual radio link, and finds the locations for a minimal number of relay nodes while ensuring a certain level of reliability in the communication channels.

2.2.3 Reliability under high radiation environment

A higher level of radiation can be expected in some areas of a NPP during normal operating conditions. In an accident condition, the radiation levels can become extremely high, and can encompass a wider area around the plant. WSN devices are composed of semiconductor based components, which can be temporarily or permanently damaged when exposed to a high level of radiation. For example, neutrons may physically damage a semiconductor crystal [23], and gamma rays can knock electrons off atoms in an insulator of a metal-oxide semiconductor device [23]. To ensure reliable performance of a WSN in a NPP, it is important to consider the effect of radiation on the electronic components on board sensor nodes when designing the network.

The mitigation approaches to the effect of radiation on microelectronics are mainly based on radiation hardened microelectronics design and radiation shielding. The use of radiation hardened components can be a feasible but expensive option for a WSN in a NPP. An electronic device can also be protected from radiation damages by enclosing it with radiation shielding. Lead and Cadmium can be used as shielding materials to protect electronics against gamma-ray and neutron damages, respectively.

To design a WSN for a NPP, the expected radiation environment of the intended application needs to be examined carefully. A WSN intended to survive a severe accident condition must employ a robust design using radiation hardened components and/or appropriate radiation shielding. However, for a WSN intended for normal operating conditions, requirement for radiation protection may be relaxed to a certain degree. Several locations in a NPP may maintain a tolerable level of radiation under normal operating conditions. If a WSN is deployed in one of those locations, commercial electronics with little or no protection may be used, as most commercial electronics can handling 500 to 1000 rads of radiation levels in silicon [23].

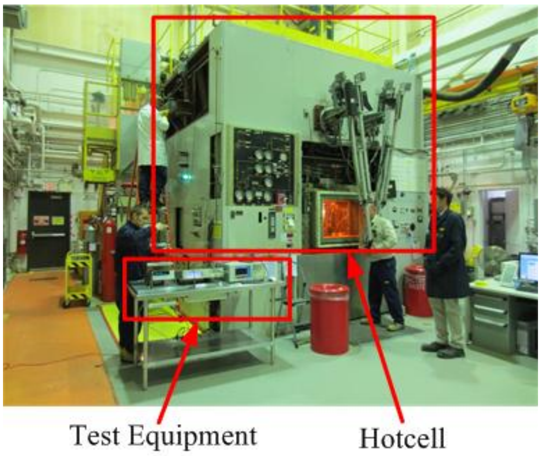

Fig.4 Overview of tests in hot cell at AECL-CRL [24].

Furthermore, the effect of ionizing radiation on electromagnetic wave propagation also needs to be investigated, in particular for a WSN intended for accident condition monitoring. As of now, very little work has been done in this regard. In one of these works, the results of some preliminary tests are presented to investigate the effect of radiation on radio wave propagation.[24]. The tests were carried out in a hot cell (at AECL-CRL [24]), which has a very high level of radiation environment. Both transmitting and receiving antennas were deployed inside of the hot cell. A signal generator was used at the transmitter, and signals were received and analyzed with a spectrum analyzer. The test setup in the hot cell of AECL-CRL is shown in Fig. 4. These tests have found some effects in terms of frequency shifts and receiver power level fluctuations [24]. Furthermore, similar effect has also been detected in another study carried out at Westinghouse research center [25].

The results from the tests mentioned above may not be conclusive. Further investigations are required and any arising issues need to be properly considered when designing a WSN system that is expected to perform reliably under high levels of radiation, such as in accident condition.

2.3 Regulatory and other guidelines

Over the past few years, different nuclear regulatory bodies and other relevant organizations have worked diligently to identify safety related issues associated with the use of wireless technologies in NPPs. They have considered several potential adverse impacts that a wireless system may induce on the safety systems of a NPP, the most important of which is the EMI/RFI. Since all portable and fixed wireless devices are identified as EMI sources, and the fact that EMI/RFI can adversely affect the functionality of sensitive instruments in the safety and protection systems, it became important for the regulatory bodies to assess the EMI/RFI impacts on safety systems, and to provide some guidelines on the allowable levels of EM emissions from the wireless devices when used in a NPP.

The U.S. NRC Office of Nuclear Regulatory Research in partnership with ORNL have undertaken significant efforts to develop EM standards, and to recommend a safe EMI/RFI operating envelope for safety-related I&C systems in NPPs. Based on these guidelines, a safety system should be able to function properly with a high degree of confidence, and without experiencing any upset or malfunction, if it remains within the level of interference specified in the recommended envelope.

To develop the specifications of the envelope, the U.S. NRC has worked with ORNL to take extensive measurements from eight nuclear units in the USA for a period of fourteen months to characterize expected levels of EMI and RFI in typical NPP environments [26]. Based on the results of this study, Regulatory Guide 1.180 [17], has recommended EM operating envelopes for I&C systems in NPPs as “For the radiated electric field operating envelope of 10 V/m (140 dB μV/m), the size of the exclusion zone should be set such that the radiated electric fields emanating from the portable EMI/RFI emitters are limited to 4 V/m (132 dB μV/m) in the vicinity of safety-related I&C systems.” [17][18].

Recently, the International Electrotechnical Commission (IEC) has also undertaken an effort to provide guidance for the selection and use of wireless devices in nuclear power plants [6]. A detailed report has been published in July of 2014 (IEC/TR 62918 ed 1.0). This report has focused on non-safety applications, with a discussion on future work and investigations required to overcome the barriers of using wireless for control and safety applications [6]. The report discusses mainly the following issues [6].

- Fundamental requirements of a digital system that can be installed in a NPP, and how it applies to a wireless system.
- Wireless applications in NPPs and associated requirements, which include a plant-wide network for voice and data communications, and small footprint network for equipment condition monitoring.
- Specific considerations and requirements of the wireless communication protocols, which include network, timing, bandwidth, radio coverage, power supply, security, availability, and failure management.
- System qualification for environmental, electromagnetic compatibility (EMC), and radiation requirements.

It is important to understand the guidelines set by all these agencies and relevant guidelines available from other sources, *e.g.*, the EPRI [4]. However, it may be noted that these guidelines are not necessarily based on the use of any particular wireless technology [4].

For example, the NRC [16] and EPRI [27] provide guidance on establishing EM exclusion zones, and determining the minimum distance of the wireless devices from sensitive instruments [4]. However, these guideline documents also indicate that the emission limits do not apply to wireless transmitters [4]. Moreover, most modern WSN devices operate at a much lower power level, which reduces the intensity of EMI to a very low level. For example, following the regulatory guidelines, a 5W walkie-talkie device needs to be placed 17ft away from any sensitive instruments to ensure an acceptable electric field strengths [4]. In comparison, a WSN device needs to be kept only a few inches away from the instrument to achieve the same acceptable level of electric field strengths. Therefore, how these guidelines apply to the modern WSN devices should be carefully investigated.

3 Prospects of WSNs in NPPs

WSNs have been investigated for several applications in NPPs, most importantly, for radiation doses and levels monitoring, and for equipment and process condition monitoring.

3.1 Radiation doses and levels monitoring

Use of WSNs has been considered for continuously monitoring the radiation dose that a person is receiving, while he/she intervenes in a radioactive zone. Several studies have been done in this regard. In one of these studies, a tele-dosimetry sensor can report without wire the level of radioactivity periodically by attaching each person in a group of people while they intervene in a radioactive zone [28]. To achieve continuous monitoring, each person’s received radiation dose is reported to the team leader, while simultaneously being forwarded to a control station over a WSN for further analysis. The study is based on the ZigBee [3] devices which uses IEEE 802.15.4 standard in the physical layer. The advantages of using a WSN for continuous radiation dose monitoring is clearly demonstrated in this study, even when people are moving around within the radiation risk zone. To achieve this goal, the entire zone has been covered by relay nodes, which communicate with tele-dosimetry sensors, and forward data to the team leader and to the control station.

A wireless radiation detection system with a high sensitivity to the radiation levels has been developed for gamma ray dose monitoring [29]. The system is able to collect radiation doses reliably, and to transmit data without wire to the control center. In another study, a WSN system architecture has been proposed which consists of a nuclear radiation dose monitoring terminal, a wireless transmission system, and a monitoring data processing center[30]. The radiation doses are collected by the monitoring terminal, and then transmitted without wire to the monitoring terminal. A CDMA Virtual Private Dialup Network is used to transfer the measurements to the monitoring terminal through the Internet communication program.

A WSN system, combined with a Mobile Ad-hoc Wireless Network (MANET) has been investigated to monitor radiation levels inside and around a NPP [31]. In this study, radiation sensors are mounted on WSN nodes, which are then distributed throughout a plant. Plant workers, equipped with Personal Digital Assistants *(*PDAs), have acted as mobile elements. The PDAs without wire receive radiation level readings from the sensors, and can communicate among themselves (which constitutes a part of MANET). The proposed system enables the workers to monitor plant conditions remotely. It can become an effective radiation level monitoring tool, which is particularly useful during plant shut down inspections.

Several other works which have been done in this regard include a wireless data acquisition system to monitor the condition of the nuclear waste in a sealed underground nuclear repository[32]. The main discussions are on the cumulative radiation effect on the electronics, and on the energy supply unit, as the system is expected to work for a hundred years after its installation. A multi-functional radiation detection system with network capabilities has been developed, which can detect and store gamma ray and neutron data, and also can send forward them without wire to a remote central facility that can be viewed on a PDA [33]. A WSN system has been designed and a prototype wireless sensor node equipped with a radiation sensor has been developed for real time monitoring of radiation levels at nuclear facilities [34].

The radiation sensor is based on Geiger Muller tube (GMT) and the wireless system is based on ZigBee technology and Arduino platform. The WSN allows recording the radiation levels from the environment and can provide warning in case of an early detection of radiation release. Continuous monitoring and archiving of background radiation levels in and around a nuclear facility is also proposed, in particular, for logging time correlated environmental gamma dose rate [35]. The system is based on portable Geiger Muller detector, and can be provided with wireless communication capabilities.

The wireless radiation dose and level monitoring systems have been widely investigated. Many commercial products are available off-the-shelf that can be used to deploy wireless radiation dose monitoring systems. Moreover, many nuclear facilities are now working with commercial vendors to acquire integrated wireless systems for continuous monitoring of the radiation levels in and around the plant. However, many commercial off-the-shelf systems may not work properly in an accident condition when the radiation level can be extremely high. Monitoring in an accident condition is still an open issue, and much more investigation has yet to be done before an effective solution can be found.

3.2 Condition monitoring

Recent studies have indicated a huge prospect for the application of WSNs for equipment and process condition monitoring in industrial facilities [2-4][14]. Sensors in a WSN are capable of measuring temperature, pressure, vibration, humidity, and some other parameters of interest, and can become a tool for more effective industrial monitoring. Wireless allows access to remote devices and opens up blind spots in a plant where measurements cannot be taken as often, and hence, provides convenient access to information previously unattainable. This information can be used to improve plant safety, reliability and efficiency.

WSNs can provide support in both primary and secondary systems, and can be used to facilitate extended monitoring of equipment conditions in a NPP. With WSNs, additional sensor measurements can be acquired in an easy and cost-effective way to achieve measurement redundancy and/or diversity through the use of more sensing points without compromising plant safety[13]. This measure can serve as an important defense mechanism against mishaps in a monitoring system. This wireless sensor channel can serve as a back-up unit of a wired sensor, which can be used to validate the wired sensors readings, and also to obtain measurement information if and when the wired sensor fails [13].

Furthermore, many rotating machinery in a NPP are maintained either on a periodic schedule basis, or run-to-failure, and then replaced or repaired [13]. This approach may be costly as failure of a piece of degraded machinery can cause an unplanned shut down and/or a longer down time of a plant [2]. A rotating machinery usually degrades over a period of time before it fails, and an unexpected total-failure can be avoided if its condition can be continuously monitored using some wireless sensors[13]. Plant operators can be made aware of any potential problems beforehand so that they can streamline the maintenance schedule. This will help reduce plant down time and save man power, which in turn can improve plant economy, safety and availability [13].

Several industries and organizations have launched collaborative research projects for equipment condition monitoring with WSNs in NPPs. The Comanche Peak nuclear power station in Texas, together with EPRI, has deployed a 802.11b based wireless network infrastructure that also incorporates about one hundred wireless sensors for equipment condition monitoring and diagnostics [2]. The wireless coverage has been limited to a selected number of non-safety related systems in this deployment.

As a part of a US DOE funded project that has focused on investigating applications of WSNs to facilitate predictive maintenance in NPPs through equipment health and condition monitoring, a WSN has been deployed in the containment of Arkansas Nuclear One (ANO) power generating station in the USA[14]. ANO is a two-unit NPP that uses containment cooling fans inside the containment structures. ANO manually collects vibration readings monthly from these fans, which is in line with its predictive maintenance program. This may raise the risk of excessive personnel radiation dose levels. AMS Corporation has installed wireless vibration sensors to monitor the condition of these fans. The installed wireless system communicates vibration measurements once a day, and remains in power-saving mode for the rest of time. The battery pack is expected to last for 18 months of operation, which coincides with the regular plant refuel cycle. In another work, a WSN system has been developed (also by AMS Corporation) that can monitor the amount of oil present in the oil collection tanks in the containment of ANO[7]. The oil collection tanks is a vital component of the oil collection system, and ANO has an interest to monitor the oil level in the tank to provide an early warning of tank overflows, and to verify the volume of oil in the lubrication system. The developed wireless system is currently undergoing test at AMS Electromagnetic Compatibility (EMC) laboratory, prior to its deployment in the ANO.

A pilot WSN system has been developed and deployed to monitor sodium leaks at a nuclear research facility in Indira Gandhi Centre for Atomic Research[36]. This facility is constructed to test the influence of sodium on the mechanical properties of component materials of a fast breeder reactor that uses sodium as a coolant. In this facility, sodium leak is normally detected by about 140 sodium leak detectors that are wired to the control room. However, a prototype WSN system has also been introduced to investigate its performance so that WSN systems can be used with wired sensor network in parallel to achieve measurement redundancy. It has been reported that the WSN system has run without any problem for over 18 months.

Furthermore, a WSN, based on IEEE 802.15.4 standard and ZigBee protocol has been developed, for monitoring water pressure and temperature using a new class of pulsating sensors[37]. The performance of a ZigBee based WSN system under different configurations has been analyzed through experimental deployments, prior to its final deployments in a nuclear facility[38]. Another WSN has been experimentally deployed to monitor the temperature and humidity continuously at the inlet and outlet of the chimney of a scaled down model of safety grade decay heat removal (SGDHR) system [39]. The SGDHR has been commissioned at a research facility in Indira Gandhi Centre for Atomic Research to study the thermal hydraulic behavior of SGDHR system of a prototype fast breeder reactor. The WSN system has employed five nodes between the open terrace and control room. The system has been successful in processing and transmitting measurement signals to the control room.

Another application of WSNs has focused on distributed process condition monitoring and fault diagnostics in NPPs[36]. Since wireless sensors can be used conveniently to acquire additional information related to a specific part of a process, this information can be utilized to obtain more accurate diagnosis. The concept has been demonstrated through the deployment of a prototype WSN system on a physical NPP simulator, as shown in Fig. 5. A Naive Bayes based decision-making scheme has been implemented onboard wireless sensor nodes to perform local diagnosis by carrying out real-time signal processing. To evaluate the performance of the system, various faults are physically simulated in the simulator, and the WSN is then used to diagnose the faults. The test results demonstrated the system.

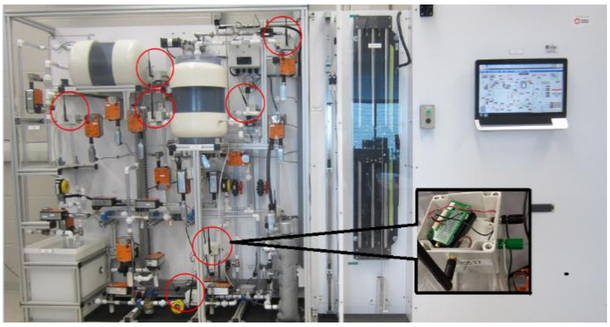

Fig. 5 Deployment of a WSN on the physical NPP control system simulator for fault diagnosis [40].

Application of WSNs has also been considered for post-accident monitoring in NPPs, which has attracted renewed attention after the Fukushima incident. In the event of a severe accident, it is extremely important to monitor several critical parameters of reactor, containment, and spent fuel pool; as well as onsite and offsite radiation levels so that emergency response personnel can effectively manage accident conditions. The existing wired I&C system may fail during an accident, due to physical damages and/or due to unavailability of line power. For example, it was difficult to obtain credible information during the first few weeks of the situation at Fukushima, as the emergency power supply system had failed. This has certainly highlighted the need for a monitoring system independent from the conventional I&C system. A self-powered WSN can potentially be such a system. In this regard, Korea Atomic Energy Research Institute (KAERI) has investigated a monitoring system that consists of hardened monitoring equipment (that consumes low power and survives extreme environments, *e.g.*, high temperature and radiation), a mobile control room (that can be installed on a truck), and wireless communication over satellite. The proposed system is capable of monitoring several important accident signals including reactor temperature and pressure, coolant flow, and radioactivity.

4 Open research issues

Several open research issues will be discussed in this section associated with the deployment of wireless systems in NPPs [5].

4.1 Integration with existing I&C systems

In order to integrate new wireless I&C systems into the existing wired systems, it is imperative that the minimum required performance is maintained, and that the complete I&C system performs adequately. There are specific requirements for the reliability and performance of I&C systems in NPPs in terms of, *e.g.*, capacity, reliability, availability, coexistence and timeliness that wireless systems must satisfy.

4.2 Deployment environment

The equipment in a NPP may be exposed to two types of radiation: electromagnetic radiation (emitted from devices such as relays and motor driven pumps), and ionizing radiation. Both can pose challenges to a wireless system. In a NPP, most electromagnetic interference will result from intermittent bursts of narrow-band signals and random electromagnetic interference (*e.g.* background noise), which may disrupt communication. Moreover, high levels of radiation may also cause functional failure and/or physical damages to wireless devices. Furthermore, wireless devices operate on the principle of electromagnetic radiation for transferring information through a medium (*i.e.* air). If the air is ionized by the 'ionizing radiation', its propagation property may change. The effects of ionizing radiation on transmitted signals are not well understood today and have to be further investigated. This is particularly important in dealing with beyond design basis accidents, where the ionization levels may be significantly higher.

4.3 Interference and coexistence

The impact of EMI/RFI from the plant equipment on the WSN system performance (and *vice versa*), as well as issues with the coexistence of multiple wireless system also need to be investigated for NPP environments. For example, any newly installed wireless device must not generate EM radiation above allowable limits, and also must be electromagnetically compatible with the existing I&C systems of the plant. Also, one WSN system should not interfere with other wireless systems (*e.g.*, other WSN systems, wireless routers, pagers, and voice communication system).

4.4Wireless network architectures

The deployment environment of a WSN a NPP is harsh with complex geometry. Intentional or unintentional addition or removal of sensor nodes will also cause dynamic changes of network topology. It is important to investigate an appropriate network architecture that can be reconfigured dynamically, and also capable of self-healing. The design of the network architecture should also consider acceptable network performance, in terms of, *e.g.*, latency, throughput, and packet loss.

4.5 Signal propagation

The compact layout of typical NPP, large metal and concrete structures, and harsh EM environment may severely affect wireless signal propagation due to, *e.g.*, fading, shadowing and multi-path interference. It is important to carry out studies to characterize wireless signal propagation in NPP environment. Furthermore, use of antennas to mitigate some of these effects can also be investigated.

4.6 Development of deployment tools

The propagation behavior of the electromagnetic waves needs to be characterized for a NPP environment, while considering the geometry and material composition of the objects within the deployment environment. Furthermore, an effective deployment strategy need to be developed that can account for issues such as blind-spots, multi-path effects and obstacles. These issues can be studied through appropriate software simulation tools, which can facilitate investigation of 'what-if' scenarios or optimization of performance of the overall system through routing planning.

4.7 Security

The security must be ensured for widespread adoption of wireless systems in NPPs. A WSN system can be passive (*e.g.*, monitoring), or active (*e.g.*, control). In either cases, it is imperative to enforce that the wireless system is accessible to authorized personnel only. Insider attacks should also be considered. Although secure digital communications is quite common in many industries, this issue need to be further investigated due to the extremely sensitive nature of nuclear industries.

4.8 Energy sources

Energy source is also a concern for reliable operation of a WSN. Typical energy sources include line power, battery power, and energy harvesting. If line power is feasible, then the system can operate effectively, even with a high data rate application (*e.g.*, vibration monitoring). However, line power may not be an option for all applications, *e.g.*, post-accident monitoring. Battery power can be used for some low-powered, low data rate applications; however, batteries have limited life and must be replaced/recharged periodically. The most effective option can be energy harvesting, mostly based on solar, thermal and vibration harvesters. However, their performance in NPP environment (*e.g.*, under radiation) needs to be investigated.

Further issues include analysis of standards, regulatory requirements, guidance and practices, communication through the containment walls, and Small modular reactor (SMR) considerations.

5 Conclusions

Application of WSNs in NPPs has attracted significant interest recently as it can potentially bring tremendous benefits to the monitoring activities of a plant. However, several challenges unique to NPP environments remained to be addressed before WSN systems can be widely accepted in NPPs. Different research organizations and nuclear regulatory agencies have undertaken initiatives to resolve these issues, and to provide guidelines on the specification of wireless systems for NPPs. It is concluded that wireless systems have a strong potential for monitoring applications in NPPs. However, some issues are yet to be resolved for widespread adoption of WSNs in NPPs.

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