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APPLICATION OF WIRELESS TECHNOLOGIES IN NUCLEAR POWER PLANT INSTRUMENTATION AND CONTROL SYSTEMS

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IAEA NUCLEAR ENERGY SERIES No. NR-T-3.29

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INTERNATIONAL ATOMIC ENERGY AGENCY
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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the Agency is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

Various industries have adopted wireless signal transmission technology, primarily for diagnostics and process monitoring, and many organizations have published standards for wireless communication. Wireless applications have demonstrated benefits in terms of reduced wire installation time and costs as well as increased flexibility of process instrumentation and control.

The rapid advancement and deployment of wireless technologies in other industries has created a unique opportunity to implement tried and tested technologies in the world's nuclear fleet to improve communication reliability and enhance productivity. Wireless technologies offer a way to provide the backbone infrastructure and monitoring, diagnostics and modelling capabilities with reduced operation and maintenance costs.

However, owing to challenges such as computer security, electromagnetic and radiofrequency interference and coexistence, power source/battery use, and response time issues, the nuclear industry still has not adopted this technology widely. There may be potential to increase the reliability and safety of nuclear energy if wireless technologies can be expanded to a larger percentage of the existing fleet and new build initiatives.

Recognizing the relevance of these issues and the rapid development of wireless technologies, the Technical Working Group on Nuclear Power Plant Instrumentation and Control recommended to the IAEA that it initiate relevant activities to address these problems in the nuclear power engineering field. In response, the IAEA conducted a coordinated research project (CRP) on the Application of Wireless Technologies in Nuclear Power Plant Instrumentation and Control Systems.

The CRP addressed key issues associated with wireless communication through coordinating and conducting research under the auspices of the IAEA. The project facilitated the collaboration of the participating international institutes and subject matter experts. The overall objective was to develop and demonstrate techniques of advanced wireless communication in the instrumentation and control systems of nuclear power plants that could be used for transferring process and diagnostic information, offering an alternative to wired solutions. Another objective was to strengthen Member States' capability to optimize nuclear power plant performance by means of an improved understanding of wireless technologies.

This publication was produced by a diverse group of international experts (the chief scientific investigators and observers) from 2015 to 2017 and documents the work of the CRP. It focuses on wireless sensor and network technology applications in the instrumentation and control systems of nuclear power plants, drawing on the latest tools, algorithms and techniques. The information in the main body was developed from the results of each research group for its respective subject area; the annexes include supporting information and selected details of the research performed.

The publication was written for all those who are involved in the nuclear industry, for example regulators, utility engineers and managers, and executives making decisions on the implementation of wireless technologies in nuclear power plants.

The IAEA wishes to acknowledge the valuable assistance provided by the CRP participants, especially those who attended the research coordination meetings, wrote or reviewed the material contained here, or provided data. Their names are listed at the end of this publication. Special thanks go to R. Shankar (United States of America) as the chair of the CRP.

The IAEA officer responsible for this publication was J. Eiler of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Wireless technologies are among the fastest growing technologies today. The exponential growth of these technologies has created numerous applications across diverse industries. Over the last decade, these technologies have become increasingly pervasive in everyday life.

Adoption of wireless technologies has proven beneficial in many industries owing to their potential to reduce cable installation time and costs and to increase flexibility in terms of the acquisition of process information and condition monitoring data through temporary sensor deployment. The nuclear industry could also benefit from the adoption of advanced wireless technologies, but issues, including rapidly developing standardization, unique environmental conditions, computer security concerns, electromagnetic interference/radiofrequency interference (EMI/RFI) concerns and a more conservative view towards adopting new technologies, have limited their deployment to date.

As wireless communication standards became more common and mature in the early 2000s, the Electric Power Research Institute (EPRI) launched several parallel efforts to explore potential uses for wireless technologies. First, a number of applications of wireless sensing were demonstrated and documented at nuclear power plants (NPPs) in the United States of America. These were all confined to balance of plant systems [1]. The operating plants were satisfied with not only the results, but also the ability to perform on-demand monitoring when required, and saw a potential for significant operations and maintenance cost savings. A few years later, Luminant Energy (then called TXU) embarked on a comprehensive project to develop and test wireless sensing of a flow loop in the balance of plant at its Comanche Peak NPP [2]. EPRI formalized these early demonstrations and lessons learned into guideline documents to assist its members (mostly in North America) in implementing wireless technologies for their specific applications [3].

Wireless technologies might become an attractive alternative to wired technologies in NPPs worldwide. An important factor when deciding whether to implement wireless technologies is the savings in installation and maintenance costs. Installing cables in an NPP environment can be one of the largest costs involved in upgrading existing facilities.

Potential cost savings provided by wireless technologies may also enhance plant operations, as a large number of wireless sensors can be deployed economically. The data derived from these plant sensors could provide a more in-depth understanding of the area or process being monitored [4].

Recognizing the relevance of these issues, in 2014 the IAEA initiated a coordinated research project (CRP) on the application of wireless technologies in NPPs. Sixteen institutes signed research agreements with the IAEA to conduct the required activities. The research project was implemented over three years from 2015 to 2017.

The CRP addressed five key areas: (1) relevant codes, standards and regulatory guides; (2) technological concepts associated with wireless communication for nuclear applications; (3) current practices, operating experience and lessons learned; (4) potential wireless applications and (5) emerging wireless technologies.

Three research coordination meetings were held during the course of the project, in which information was exchanged between the participating institutes. The reports on the results of the research by the participating organizations were collected and compiled into this publication. The results of this work can be used to assist instrumentation and control (I&C) experts and decision makers at nuclear utilities, licensing authorities, research organizations and vendors in assessing the potential challenges and operational benefits for NPPs that can be obtained through the deployment of wireless technologies.

1.2. OBJECTIVE

The overall objective of the CRP was to develop and demonstrate advanced wireless communication techniques for potential implementation within the I&C systems of NPPs, so that these can be used for transferring process and diagnostic information, offering an alternative to wired solutions. This publication summarizes the results of the CRP and provides an overview of the current knowledge, existing practices, operating experiences and benefits and challenges related to the use of wireless technologies in the I&C architecture of an NPP. The publication is intended to strengthen Member States' capabilities to support the design, development, implementation, operation and, as necessary, licensing of wireless technologies in NPPs.

It is anticipated that the main beneficiaries of this publication will be nuclear utilities. The outcomes of the CRP, as summarized here, may contribute to the more widespread adoption of wireless communication in existing and future NPPs by providing guidance on the deployment of the technology.

It needs to be noted that in cases where wireless technologies are being considered for potential use at NPPs, a safety and security assessment needs to be performed to determine the extent to which challenges have been addressed, together with any operational and cost benefits that may be obtained, before determining whether wireless communication is the preferred option.

1.3. SCOPE

The scope of this publication is identical to that of the research conducted for the CRP, and follows the five main research areas. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3.1. Codes, standards and regulatory guides

The publication provides an overview of the various industry standards and guidance documents that were available as of the time of concluding the CRP and are applicable to the implementation of wireless technologies. This includes the numerous standards and protocols for wireless communication that have a potential use in the nuclear industry, as well as the existing guidance from the IAEA, the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE) and other organizations that was developed for or that may relate to the deployment of wireless technologies.

1.3.2. Wireless technologies for nuclear applications

An overview of wireless technology concepts such as network topology, signal propagation, EMI/RFI and energy source considerations is presented, along with related concerns or limitations in an NPP environment. Ionizing radiation and extensive metallic structures are additional limitations specific to the nuclear industry and are addressed in the publication.

1.3.3. Practices, experience and lessons learned

Operating experience, which encompasses the existing successful implementations of wireless technologies in NPPs throughout the world, is summarized as part of this publication. Various case studies are provided for equipment condition monitoring, process measurements and radiation monitoring. Simulation tools that can be used to assess the performance of wireless technologies prior to their installation to optimize their location and transmission characteristics are also addressed. In addition, aspects of a wireless robotic system are covered. The publication outlines the applications, technologies and challenges that were faced during implementation. This information provides a valuable reference as Member States look to develop individual, country specific guidance for wireless implementation and deploy these technologies.

1.3.4. Potential wireless applications

Potential applications for wireless technologies in, for example, post-accident monitoring (PAM) are outlined in this publication. These are applications where there is an existing gap that wireless technologies can fill or where the benefits of wireless technologies can be exploited to improve upon the reliability, resilience and robustness of the application. For instance, in NPP fault scenarios where PAM might be necessary, existing power and instrumentation cabling infrastructure may have been compromised, and battery operated or locally powered wireless sensors could potentially continue to transmit information from specific areas of the plant.

1.3.5. Emerging technologies and challenges

The publication also outlines emerging technologies such as ray tracing methods and optimum polarization wireless communication as part of the analysis of the propagation of signals within an NPP environment. Wireless communication through existing apertures in metallic and concrete structures at NPPs is also addressed in this part.

1.4. STRUCTURE

This CRP report is organized into two parts. The first part provides guidance on the implementation of wireless technologies and is contained within the main body of the publication. This part has seven main sections — an introduction, one section for each of the five CRP research areas and a section containing the final conclusions. The second part of the report is a more detailed description of the specific research conducted by selected organizations and is included in the ten annexes.

2. CODES, STANDARDS AND REGULATORY GUIDES

2.1. INTRODUCTION TO WIRELESS TECHNOLOGIES AND PROTOCOLS

Wireless communication is an evolving technology, and many protocols have been developed for various applications, including voice communications, Internet connectivity and home automation. Several protocols have been or are being developed by different organizations. The main wireless communication protocols that are available at the time of writing this report and are applicable to industrial applications are given in Table 1.

TABLE 1. LIST OF WIRELESS TECHNOLOGIES USED IN INDUSTRY

Technology	Document describing the technology
802.11a/b/g/n/ /ac/ad/h/i (Wi-Fi)	IEEE 802.11-2016, IEEE Standard for Information Technology — Telecommunications and Information Exchange Between Systems — Local and Metropolitan Area Networks — Specific Requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications [5]
802.15.1 (Bluetooth)	IEEE 802.15.1-2005, IEEE Standard for Information Technology — Local and Metropolitan Area Networks — Specific Requirements — Part 15.1a: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPAN) [6]
802.15.3 (UWB WiMedia)	IEEE 802.15.3-2016, IEEE Standard for High Data Rate Wireless Multi-Media Networks [7]
802.15.4	IEEE 802.15.4-2015, IEEE Standard for Low-Rate Wireless Networks [8]
ZigBee	ZigBee Document 05-3474-21: ZigBee Specification [9]
WirelessHART	IEC 62591:2016, Industrial Networks — Wireless Communication Network and Communication Profiles — WirelessHART [10]
ISA-100	International Society of Automation (ISA) ISA-100.11a, Wireless Systems for Industrial Automation: Process Control and Related Applications [11]

TABLE 1. LIST OF WIRELESS TECHNOLOGIES USED IN INDUSTRY (cont.)

Technology	Document describing the technology
ISA-100	IEC 62734:2014, Industrial Networks — Wireless Communication Network and Communication Profiles — ISA 100.11a [12]
802.16 (WiMAX)	IEEE 802.16-2012, IEEE Standard for Air Interface for Broadband Wireless Access Systems [13]

The requirements within an NPP differ significantly from those within other industrial environments, particularly in terms of safety and security, and specific national and international standards and guidance may apply in these fields. Therefore, the various industrial wireless communication protocols may not be suitable for use in all NPP applications. This section considers the issues related to the use of wireless technologies for data communications (sensors and instrumentation) in NPPs based on the typical requirements found in relevant standards and guidance.

As shown in Table 1, the IEEE 802 family of technologies falls into several different categories depending on the application. Table 2 indicates the overall features of the most commonly adopted technologies for wireless personal area networks (WPANs), wireless local area networks (WLANs) and wireless metropolitan area networks.

WLANs in the 802.11 technology are marketed under the brand name Wireless Fidelity (Wi-Fi). The most notable 802.11 versions are 802.11a, 802.11b, 802.11g, 802.11n and 802.11ac. The frequency bands for Wi-Fi are the 2.4 GHz industrial, scientific and medical (ISM) band used by 802.11b and 802.11g and the 5 GHz band used by 802.11a and 802.11ac. The 802.11n standard can use either the 2.4 GHz or the 5 GHz band. WLANs are most appropriate for high bandwidth applications where devices can be line powered, such as video monitoring and continuous vibration spectrum monitoring.

WPANs are low rate, low cost, short range wireless networks and are covered in the IEEE 802.15.4 standard [8]. Several wireless protocols have been developed based upon the 802.15.4 technology, including ZigBee, WirelessHART, ISA-100.11a and 6LoWPAN. WPAN devices can operate in three different frequency bands, as follows:

— The 868 MHz band is only available in the European Union and has a single, 600 kHz wide channel.
— The 915 MHz ISM band, only available in the United States of America, has ten channels spaced 2 MHz apart.
— The 2.4 GHz ISM band has 16 channels with 5 MHz spacing between them.

TABLE 2. COMPARISON OF IEEE 802 WIRELESS NETWORK TECHNOLOGIES

IEEE standard	Industry name	Operational frequency	Characteristics	Common application
802.11 [5]	Wi-Fi	2.4 GHz, 5.7 GHz	High data rate, local area network	Network/Internet connectivity
802.15.1 [6]	Bluetooth	2.4 GHz	Low data rate, personal area network	Peripheral wireless devices
802.15.3 [7]	UWB WiMedia	~5 GHz	High data rate, personal area network	Video transmission
802.15.4 [8]	ZigBee, WirelessHART and ISA-100.11a	868/915 MHz, 2.4 GHz	Low data rate, personal area network	Sensor networks
802.16 [13]	WiMAX	2–11 GHz, 10–60 GHz	High data rate, metropolitan area network	Broadband wireless access

WPANs are suited for monitoring conditions that do not change rapidly or do not require the transmission of large amounts of data. These could include process measurements (temperature, pressure, level, flow), environmental monitoring and infrequent vibration monitoring. Although in some instances it could be more frequent, these processes typically require monitoring conditions with a frequency of the order of once an hour or once a day.

2.2. CURRENT STATUS OF STANDARDIZATION FOR NUCLEAR POWER PLANT APPLICATIONS

At the time this CRP was conducted, there were no international standards for the application of wireless technologies in NPPs; however, IEC TR 62918 [14] had been published as a technical report for NPPs on the selection and use of wireless devices to be integrated in systems important to safety. After the completion of the CRP, the IEC 62988 [15] standard was published to address the selection and use of wireless devices in NPPs. There are other IEC standards that have been developed for the use of wireless technologies in industrial environments that may be applicable to NPPs (see Refs [16, 17]).

There are several standards that describe the general requirements for I&C systems in NPPs and, in particular, for data transmission. Following is a list of standards that contain requirements or are relevant to the requirements for data transmission and communications in I&C systems in NPPs:

- IEC 61226, Nuclear Power Plants — Instrumentation, Control and Electrical Power Systems Important to Safety — Categorization of Functions and Classification of Systems [18];
- IEC 61513, Nuclear Power Plants — Instrumentation and Control Important to Safety — General Requirements for Systems [19];
- IEC 60880, Nuclear Power Plants — Instrumentation and Control Systems Important to Safety — Software Aspects for Computer-Based Systems Performing Category A Functions [20];
- IEC 62138, Nuclear Power Plants — Instrumentation and Control Systems Important to Safety — Software Aspects for Computer-Based Systems Performing Category B or C Functions [21];
- IEC 60987, Nuclear Power Plants — Instrumentation and Control Important to Safety — Hardware Design Requirements for Computer-Based Systems [22];
- IEC 61500, Nuclear Power Plants — Instrumentation and Control Systems Important to Safety — Data Communication in Systems Performing Category A Functions [23];
- IEC 60964, Nuclear Power Plants — Control Rooms — Design [24];
- IEC 60965, Nuclear Power Plants — Control Rooms — Supplementary Control Room for Reactor Shutdown Without Access to the Main Control Room [25];
- IAEA Safety Standards Series No. SSG-39, Design of Instrumentation and Control Systems for Nuclear Power Plants [26];
- IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [27];
- European Utility Requirements for LWR Nuclear Power Plants, Vol. 2: Generic Nuclear Island Requirements, Ch. 10: Instrumentation & Control and Human–Machine Interface [28];
- NUREG/CR-6082, Data Communications [29];
- STUK Guide YVL A.12, Information Security Management of a Nuclear Facility [30];
- Multinational Design Evaluation Programme, DICWG No. 4, Common Position on Principle on Data Communication Independence [31];
- NRC DI&C-ISG-04 (Rev. 1), Highly-Integrated Control Rooms — Communications Issues [32].

The requirements for computer security are addressed in Section 2.4.3 of this publication.

2.3. WIRELESS COMMUNICATION AND THE CONCEPT OF DEFENCE IN DEPTH

It is common practice to use the principle of defence in depth (DID) to divide NPP subsystems into groups for the purpose of distributing functional requirements between specific levels [33]. In accordance with this DID concept, all control systems can be distributed between the following five independent levels:

— Normal operation I&C systems (Level 1): The operational I&C systems at DID Level 1 are designed to prevent normal operation disturbances and failures of components important for operation. Such components include the I&C of the reactor (nuclear) and turbine islands, turbine generator, fire protection and radioactive water treatment.
— Abnormal operation I&C systems (Level 2): For the detection and monitoring of normal operation disturbances and prevention of situations leading to accidents, DID Level 2 I&C systems are used, which in the majority of control system designs are implemented by means of preventive protection or limiting systems.
— Accident I&C systems (Level 3): I&C systems and equipment at DID Level 3 ensure safety in the case of postulated initiating events that may lead to radioactive emission and core damage. This equipment includes the reactor protection system, diverse protection systems and the engineered safety features actuation system.
— Severe accident I&C systems (Level 4): I&C systems and equipment at DID Level 4 are designed to mitigate the consequences of accidents that were not prevented by the Level 3 equipment. The main task is the localization of radioactive emissions. Level 4 I&C includes PAM systems and emergency control systems (including transportable systems).
— Emergency I&C systems (Level 5): The purpose of DID Level 5 is to mitigate the radiological impact of radioactive emissions. This purpose is achieved by implementing emergency response plans on and off the site. Level 5 I&C systems collect information from the surviving systems and sensors and transmit it to the emergency response centre.

The independence of defence levels must be implemented to as high a degree as is feasible [27]. Therefore, signal transmission should not occur, so far as reasonably practicable, between I&C systems of different DID levels.

A theoretical overall architecture of an NPP I&C system in accordance with the control hierarchy is shown in Fig. 1 and comprises the following five control layers [34]:

— Technical information/management system;
— Supervisory control and information system;
— Process control system;
— Field control devices;
— Sensors and actuators.

Each layer of the control hierarchy model consists of a functional and a network sublayer. The functional sublayer is designed to perform control functions and operations via the technical means of the respective layer and the network sublayer is meant to exchange information between layers.

The required connections between the subsystems are indicated in Fig. 1 by the solid lines and the possible connections are indicated by the dashed lines. Cloud elements are representative of potential wireless connections.

The field control devices network sublayer provides the interaction between the corresponding functional sublayer and the process control system layer. The following wireless network protocols could typically be used at this layer: ZigBee, WirelessHART, 6LoWPAN and ISA-100. These protocols were developed to transmit data from sensors to programmable logic controllers at a relatively low speed over short distances to reduce the power consumption of wireless transmitters.

The process control system network sublayer provides interconnections between the corresponding functional sublayer and the supervisory control and information system layer, which in turn exchanges the data with the technical information/management system layer via a network sublayer. Wi-Fi and WiMAX wireless network protocols could typically be used to transmit the data here. They can provide high speed data transmission over distances from several tens of metres up to several kilometres.

There are some restrictions on wireless data transmission for subsystems and systems that implement safety functions in accordance with IEC 62988 [15] and IEC 61226 [18].

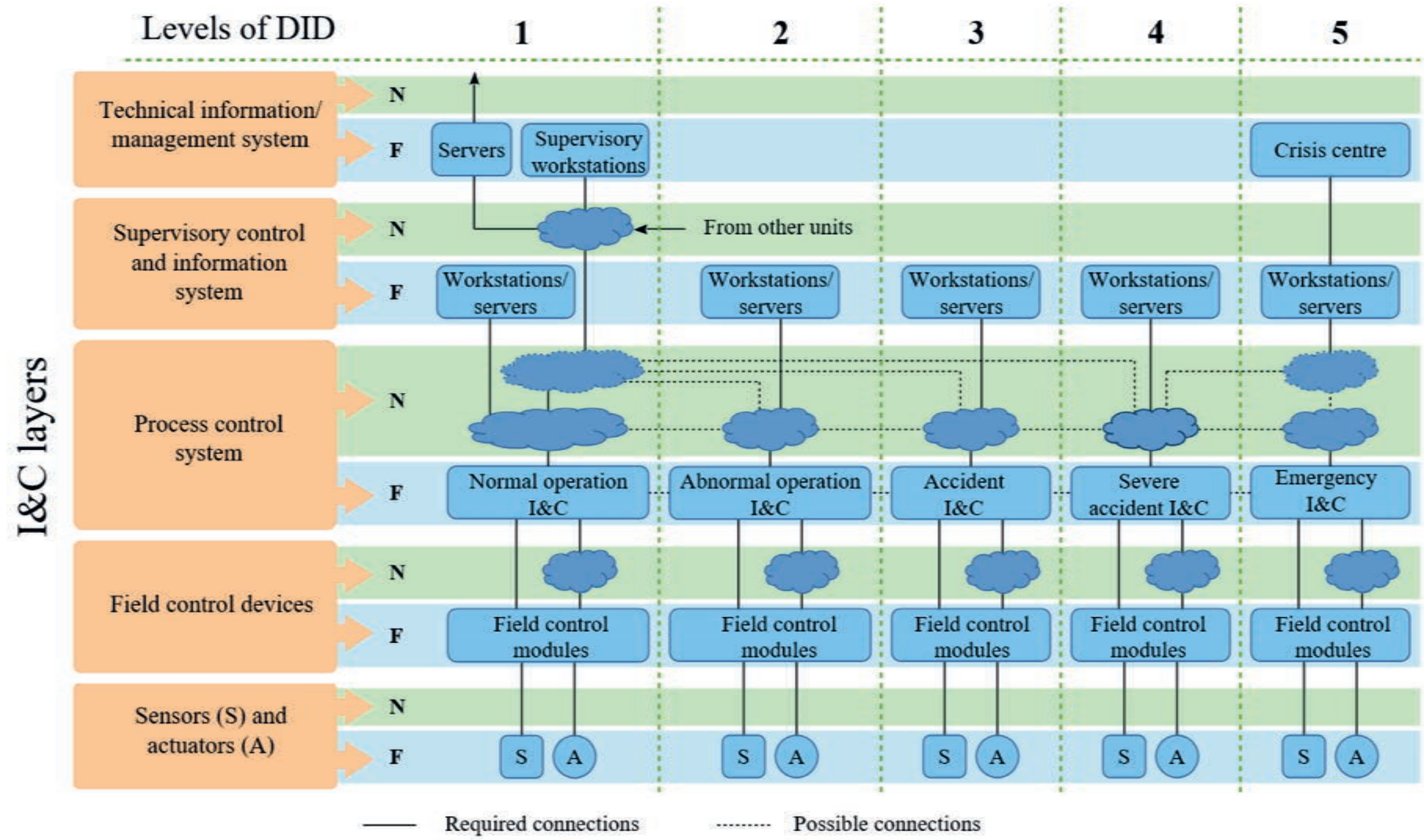

FIG. 1. *A theoretical overall instrumentation and control architecture diagram of a nuclear power plant. F — functional sublayer; N — network sublayer.*

2.4. GENERAL REQUIREMENTS FOR WIRELESS COMMUNICATION

The following sections describe general information and requirements for wireless communication technologies related to frequency, transmission power, computer security, electromagnetic compatibility (EMC), wireless coexistence and the establishment of exclusion zones.

2.4.1. Member State governmental frequency control considerations

Wireless transmission in specific frequency bands may be subject to government regulations in Member States. For example, the Federal Communications Commission in the United States of America and the European Telecommunications Standards Institute in Europe are responsible for governing the use of licensed and unlicensed devices in the ISM band. The user will have to verify that the frequency of a selected wireless device can be used within a given Member State and within the selected NPP.

2.4.2. Maximum transmission power

Each standard has restrictions on the maximum power output for a given device. These restrictions are included in power regulations covering power output, antenna gain and cable loss (i.e. effective isotropic radiated power limits).

The maximum output transmission power limit for 2.4 GHz devices is typically 1 W in the United States of America and Asia, 100 mW in Europe and 10 mW/MHz in Japan. The maximum transmission power levels in different geographical regions and different frequency ranges are shown in Table 3.

TABLE 3. MAXIMUM TRANSMISSION POWER LEVELS

Frequency band	Geographical region	Maximum conductive power/radiated field limit
2400 MHz	Japan	10 mW/MHz
	Europe (except Spain and France)	100 mW EIRP[a] or 10 mW/MHz peak power density
	United States of America	1000 mW
	Canada	1000 mW (with some limitations on installation location)
902–928 MHz	United States of America	1000 mW
868 MHz	Europe	25 mW

[a] EIRP — effective isotropic radiated power.

2.4.3. Computer security

Communicating through the air can leave wireless networks prone to cyberattacks. Protective measures have to be defined based on a systematic approach for I&C system protection. Currently, there are a number of standards that address computer security, including the following:

- IAEA Nuclear Security Series No. 17, Computer Security at Nuclear Facilities [35];
- IEC 62859, Nuclear Power Plants — Instrumentation and Control Systems — Requirements for Coordinating Safety and Cybersecurity [36];
- IEC 62645, Nuclear Power Plants — Instrumentation, Control and Electrical Power Systems — Cybersecurity Requirements [37];
- ISO/IEC 27001, Information Technology — Security Techniques — Information Security Management Systems — Requirements [38];
- Multinational Design Evaluation Programme, DICWG No. 8, Common Position on the Impact of Cyber Security Features on Digital I&C Safety Systems [39];
- NEI 08-09 (Rev. 6), Cyber Security Plan for Nuclear Power Reactors [40];
- NRC 10 CFR 73.54, Protection of Digital Computer and Communication Systems and Networks [41];
- NRC RG 5.71, Cyber Security Programs for Nuclear Facilities [42];
- IAEA Nuclear Security Series No. 33-T, Computer Security of Instrumentation and Control Systems at Nuclear Facilities [43].

Most wireless communication protocols include considerations that provide some protection against computer security vulnerabilities. These are addressed in Section 3.3.3.

2.4.4. Electromagnetic compatibility

EMC in the nuclear industry is addressed by several national and international standards and guidance documents, including the following:

- IEC 62003, Nuclear Power Plants — Instrumentation, Control and Electrical Power Systems — Requirements for Electromagnetic Compatibility Testing [44];
- NRC RG 1.180 (Rev. 1), Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems [45];
- EPRI TR-102323 (Rev. 4), Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment [46].

Wireless devices to be deployed in an NPP environment are subject to EMC qualification tests. These EMC test methods are categorized as: conducted emission, radiated emission, conducted immunity, radiated immunity and surge withstand capability. The documents listed above specify the EMC qualification tests, both emissions and immunity, according to certain EMC test methods given in IEC 61000 [47].

2.4.5. Wireless coexistence

Wireless networks operating on the same frequency bands can interfere with each other's operations. For example, IEEE 802.11, IEEE 802.15.4 and Bluetooth devices operate in the same 2.4 GHz ISM band. This unlicensed band is used by a variety of devices. At the time of concluding the CRP, NUREG/CR-6939 [48] was the only source of guidance available for the coexistence of wireless networks in NPPs. IEC 62657 Part 2 [17] has been developed to address coexistence of industrial wireless networks. The American National Standards Institute C63.27 [49] standard defines the coexistence test guidelines for medical equipment. IEEE 802.15.2-2003 [50] addresses the problem caused by interference due to various competing wireless technologies in the same band and recommends general practices to combat interference problems.

2.4.6. Exclusion zone development

EMI/RFI between coexisting wireless networks of different I&C systems can occur. For example, IEEE 802.15.4 devices operate at 2.4 GHz with other ISM technologies such as Wi-Fi, cordless phones and Bluetooth. Simultaneous operation of these networks may result in repeated retransmissions that could affect packet latency and device power consumption.

Additionally, in accordance with SSG-39 [26] and SSR 2/1 (Rev. 1) [27], the following considerations may also need to be taken into account:

- Interference between safety systems or between redundant elements of a system has to be prevented by means such as physical separation, electrical isolation, functional independence and independence of communication (data transfer), as appropriate.
- The design needs to ensure that any interference between items important to safety will be prevented, and in particular that any failure of items important to safety in a system in a lower safety class will not propagate to a system in a higher safety class.
- Physical separation may be used to protect against: (i) common cause failure in normal, abnormal or accident conditions; (ii) the effects of accidents (including all design basis accidents); or (iii) the effects of internal and external hazards. (Examples include space to attenuate the effects of EMI and separation between systems and components qualified to different levels.)

One approach to deal with EMI/RFI from wireless devices is to establish exclusion zones by physically separating sensitive I&C equipment from EMI/RFI sources (see para. 6.125 of SSG-39 [26]). The size of the exclusion zone(s) depends on the effective radiated power and antenna gain of the wireless transmitters used within an NPP and the permitted electric field strength. To define the size of an exclusion zone, an 8 dB difference between the equipment susceptibility limit and the permitted electric field strength is recommended by the United States Nuclear Regulatory Commission (NRC) [45] and EPRI [46]. For the recommended equipment susceptibility limit of 10 V/m (140 dBμV/m), the size of the exclusion zones has to be set such that the electric field strength of the wireless transmitters is limited to 4 V/m (132 dBμV/m) in the vicinity of sensitive I&C equipment [46].

Exclusion zones are enforced by administrative controls (among other controls) whereby it is normally prohibited to activate wireless devices (walkie-talkies, cell phones, welders, etc.) within the exclusion zone of safety related I&C equipment during its operation [45]. Effective EMI/RFI protection of sensitive I&C equipment may require exclusion zones to be applied in combination with other strategies (e.g. radiofrequency shielding and barriers).

An exclusion zone strategy can have several advantages. Exclusion zones:

- Are established and controlled by each NPP;
- Are independent of equipment suppliers;
- Can be adjusted depending on the safety classification of the equipment;
- May not require any I&C system or equipment design modifications.

However, there can be significant disadvantages, including the following:

- Implementation and enforcement of exclusion zones can be problematic because of their large size (in some cases in excess of 4 m) or the location of physical barriers.
- Enforcement of exclusion zones implies a prohibition on the use of wireless devices (e.g. walkie-talkies) in the vicinity of sensitive I&C equipment during activities such as maintenance and repair work.

All these aspects need to be considered when deciding on the assignment of exclusion zones.

3. WIRELESS TECHNOLOGIES FOR NUCLEAR APPLICATIONS

3.1. INTRODUCTION

This section focuses on wireless sensor related applications of devices for process, environmental and equipment condition monitoring. It addresses the current state of the art in wireless technologies and outlines the main considerations that may need to be taken into account when implementing these devices at an NPP. As new wireless technologies emerge in the future, considerations similar to those presented in this section may be used to evaluate the suitability of the technology for use in an NPP environment.

When evaluating the deployment of wireless equipment in a nuclear facility, designers and decision makers will have to consider the following technology differentiators:

— Use of licensed versus unlicensed frequencies;
— Power considerations;
— Network topologies and medium access control;
— Network size and range;
— Focused versus omnidirectional antennas;
— Open standard versus proprietary products.

Most of these aspects are addressed in the following subsections.

3.2. COMPONENTS OF A WIRELESS SENSOR

As shown in Fig. 2, a wireless sensor node has the following four basic components:

— Sensing unit: This consists of sensors for measuring different physical parameters and analogue to digital converters.
— Processing unit: This reads sensor data, processes them and communicates with other sensor nodes. It is usually connected with a small storage unit for data processing.
— Transceiver unit: This connects the sensor node with other nodes in the network using one of a selection of physical communication media, typically radiofrequency.
— Power source: This powers the components of the node for the time required.

The type of sensing unit in a wireless sensor is based on the physical parameters to be measured, such as vibration, position, temperature, pressure, light, radiation or humidity. Table 4 shows some environmental physical properties and the related sensors that are used to detect the physical properties.

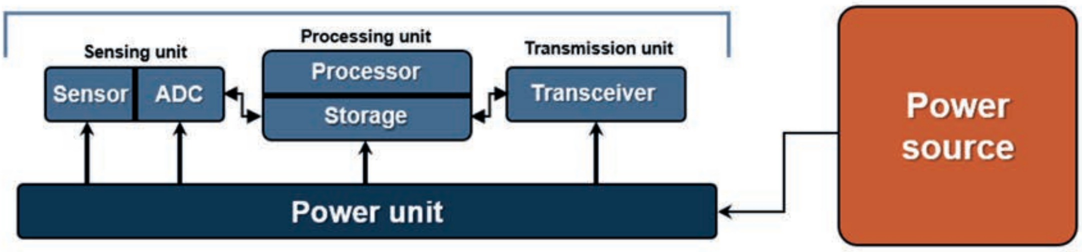

FIG. 2. Components of a wireless sensor.

TABLE 4. EXAMPLE OF SENSORS

Physical properties	Examples of sensors
Pressure	Pressure gauges, barometers
Temperature	Thermistors, thermocouples
Optical	Photodiodes, phototransistors
Acoustic	Piezoelectric resonators, microphones
Flow	Mass air/liquid flow sensors
Motion	Accelerometers
Position	Global positioning system
Chemical	pH sensors
Radiation	Geiger–Müller counters, ion chambers
Humidity	Capacitive and resistive sensors

There are many schemes that can be used to collect data from the sensor nodes. One scheme would be to acquire data according to an event driven scheme, such as radiation detection, with nodes only sending their gathered information when events of interest occur. In time driven applications, such as a physical parameter monitoring scheme, nodes send their gathered sensor data periodically to a gateway device. Finally, in query driven (sometimes called 'on-demand') applications, operators can request sensed data through a gateway device that is responsible for requesting data from sensor nodes when needed.

3.3. RADIOFREQUENCY COMMUNICATION CONSIDERATIONS

3.3.1. Wireless network topology

Wireless sensor networks (WSNs) consist of devices of several different types, such as sensor nodes, repeaters and gateways. The sensor node is a device that measures the desired parameter. A repeater device extends the coverage of a network by receiving the signal from one device and transmitting it to another device. Repeater devices might not be present in some network topologies. A repeater device can also sometimes serve as a sensor node. The gateway device receives all data and serves as the end device of a network. The gateway device will typically interface with another network or provide a user interface for the sensor data.

There are two main topologies that are used in wireless networks: the star and the mesh network. In a star network, each sensor node communicates directly with the gateway device, meaning there is one path (or hop) to the gateway. In a mesh network, sensor nodes can communicate with other sensor nodes (or repeater devices) or the gateway itself, and there can be numerous paths or hops between a sensor node and the gateway. Figure 3 displays a graphical representation of star and mesh network topologies.

There are advantages and disadvantages to each topology. Star networks are more common, tend to be simpler to set up and maintain and have a more deterministic latency (latency being the delay between when the message is sent from a sensor node and when it is received by the gateway). However, the maximum range of the network is limited by the effective communication distance between a sensor node and the gateway. A mesh network can have a significantly wider footprint because it allows for signal hopping among the various devices in a network, thereby extending the effective communication range of the network. Another benefit of a mesh network is the possibility for redundant paths to exist between a sensor node and gateway device. If a repeater node malfunctions, the system

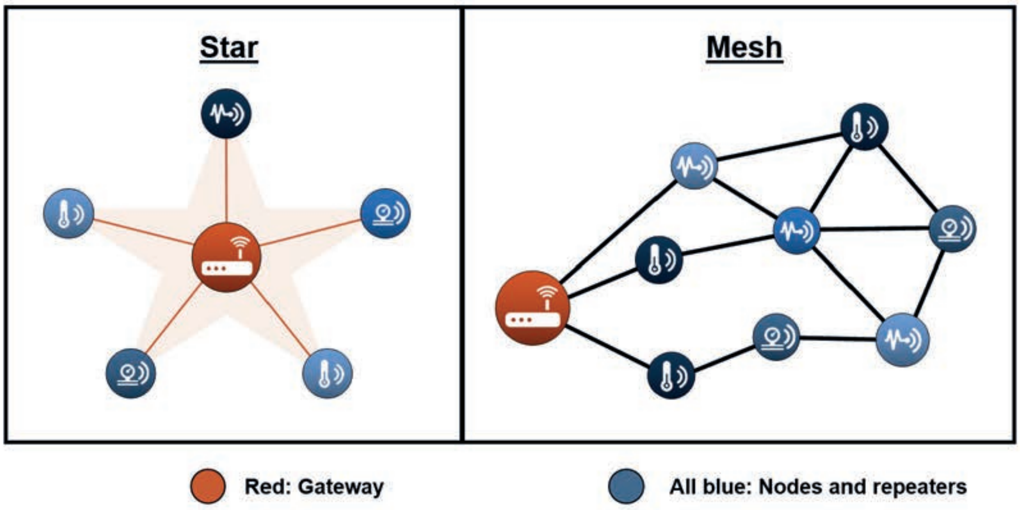

FIG. 3. Main wireless network topologies.

could establish a new path around that repeater node and still communicate the data to the gateway. However, this increase in range may come at a cost of increased and less deterministic latency, since it is not known with certainty how many hops the data will take to get from the sensor node to the gateway. For monitoring applications in NPPs, however, latency may not be an issue.

One method for extending the coverage of a gateway device is to use a distributed antenna system. Such a system can consist of a network of antennas or a radiating coaxial cable connected to a gateway. A radiating ‘leaky coaxial’ cable is a cable with a discontinuous shield designed to transmit and receive a wide frequency range of wireless signals along its entire length. The antennas or radiating cable can extend the coverage area of a single gateway by several hundred metres. The benefits of a distributed antenna system are ease and cost of implementation, ability to efficiently propagate a wide range of frequencies over a long distance and simplification of network upgrades [51].

Research on more reliable network configurations utilizing dual route redundant wireless networks is described in Annex I.

3.3.2. Wireless network standards and protocols

A number of proprietary and standards based industrial wireless products exist. It is recognized that products implemented using or based upon open standards are preferable to products using or based upon proprietary standards, owing to the following facts:

— Open standards (and products based on these standards) are generally easy to acquire and often inexpensive.
— The non-disclosure of technical details of proprietary standards limits the assessment of their dependability.
— The security of proprietary systems may rely upon elements that are unknown to the user; hence, these systems are often deployed without comprehensive testing to identify potential vulnerabilities or particular weaknesses.

Detailed information on the current standards and protocols can be found in Sections 2.1 and 2.2.

3.3.3. Computer security

Computer security requirements imposed by the regulator or the operator of the NPP will generally limit the application of wireless communication. For example, IEC standards 62988 [15] and 62645 [37] do not allow for the use of wireless communication in security degree 1 or security degree 2 systems.

Owing to their use of air as a transmission medium, wireless networks are naturally prone to eavesdropping and malicious traffic injection. The general requirement for a WSN application is to provide end to end and single hop security.

The IEEE 802.15.4 [8] standard uses the advanced encryption standard, counter with cipher block chaining message (AES-CCM) specification for security. This security specification supports encryption, authorization, integrity of data packets and authorization for IEEE 802.15.4 devices. IEEE 802.15.4 defines only the link layer security procedures. Other application standards define the upper layer security mechanisms and other essential security mechanisms not defined by IEEE 802.15.4. For example, key distribution is the responsibility of upper layer application standards. Key management throughout the lifetime of a system is an important consideration when deploying wireless communication that requires encryption to meet security requirements.

Wi-Fi uses various types of security standards such as wired equivalent privacy (WEP)[1], Wi-Fi protected access (WPA) and Wi-Fi protected access version 2 (WPA2). These security standards define the different security mechanisms to prevent unauthorized access to 802.11 networks.

Bluetooth implements security attributes such as confidentiality, authentication and key derivation based on the secure and fast encryption routine (SAFER) block cipher. Bluetooth standards define security mechanisms during different processes such as pairing, device discovery and data transfer. For potential NPP applications, it is advisable to have end to end encryption since there is no requirement to open the packets in each router level. The security of the wireless network will have to be verified against each site's requirements to ensure that it adequately addresses security concerns.

It needs to be noted that sensor nodes typically used for low rate WPAN deployment contain low power microcontrollers, which may also be limited in processing power. Hence, the security techniques used in traditional wired and WLAN protocols cannot be directly used with these devices.

Security techniques could take advantage of the physical layer using specific implementations of low density parity check codes and error correcting codes, as well as additional techniques such as the frequency hopping spread spectrum and direct sequence spread spectrum methods. A further example of a security approach for the network layer is the use of a spontaneous watchdog with a low energy adaptive clustering hierarchal algorithm type of routing protocol.

3.3.4. Signal propagation and range of coverage

The four main types of wireless network are described in Table 5. These networks are divided based on their typical coverage range. Most of the applications in an NPP environment will be confined to local and personal area networks with distances of less than 100 m.

Table 6 provides a comparison of the range of coverage for IEEE 802.15.1, IEEE 802.15.4 and IEEE 802.11 wireless technologies. The range of wireless communication mainly depends on the modulation scheme, receiver sensitivity and maximum transmission power. Modulation schemes have a significant effect on the range of coverage of wireless devices because of the corresponding signal to noise ratio (SNR). The energy per bit varies with different modulation schemes. Another important factor is the output power of the transmitter. For instance, an IEEE 802.15.4 [8] compliant device will typically be battery operated and will, therefore, have to optimize the maximum transmission power while extending battery life. IEEE 802.15.4 states that the transceiver should be capable of transmitting at a power level of at least −3 dBm. Generally, these devices are envisioned to operate with maximum output power of 0 dBm. Commercially available IEEE 802.15.4 compliant transceivers can transmit from −17 dBm to +7 dBm. The typical range of these devices is 30–100 m.

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[1] WEP and WPA are not to be used in any system where security is required. WPA2 is the current recommended security standard for 802.11 networks.

TABLE 5. APPROXIMATE COVERAGE RANGE FOR DIFFERENT TYPES OF WIRELESS NETWORK

Name	Range
Wireless personal area network (WPAN)	Devices operating in short range (~10 m)
Wireless local area network (WLAN)	Wireless networks in a range of ~100 m
Wireless metropolitan area network	Wireless networks covering cities and metropolitan areas
Wireless wide area network	Large-scale geographic areas

TABLE 6. COMPARISON OF RANGE OF COVERAGE OF WIRELESS TECHNOLOGIES

Technology	Range of commercially available transceivers		
	Power class…	Maximum transmission power…	Corresponding range…
IEEE 802.15.1	1	100 mW (20 dBm)	~100 m
	2	2.5 mW (4 dBm)	~10 m
	3	1 mW (0 dBm)	<10 m
IEEE 802.15.4	30–100 m (−17 dBm to +3 dBm) 1.6 km (+18 dBm)		
IEEE 802.11	100–250 m (for point to multipoint links) >1.6 km (for long range Wi-Fi point to point links, with use of directional antennas)		

3.3.5. Interference and coexistence

There are three different aspects of interference that must be considered when evaluating wireless technologies:

(i) The interference of wireless devices with existing plant equipment.
(ii) The interference of wireless devices with one another (coexistence).
(iii) The interference (intentional or unintentional) of other equipment with wireless devices. Intentional interference would include jamming devices.

Preventing interference with plant equipment (item (i) above) has traditionally been addressed using exclusion zones to maintain separation between wireless devices and sensitive plant equipment. Exclusion zones are discussed in detail in Section 2.4.6. However, the issue with this approach is that the immunity of plant equipment is typically unknown; therefore, the calculated exclusion zone may be overly conservative or inadequate. In addition, the exclusion zones that result from the calculations often limit the use of wireless technologies. To address these concerns, in situ immunity testing of plant equipment can be performed to objectively determine the exclusion distance for a particular piece of plant equipment. Special consideration needs to be given to planning, performing and interpreting the test results for in situ immunity testing. Combined with engineering evaluations, these test results can be used as objective evidence for establishing appropriate exclusion distances. Annex II includes a case study where an NPP was able to reduce the size of exclusion zones through in situ immunity testing.

Coexistence testing (item (ii) above) is the determination of how wireless devices can coexist with one another. Coexistence is mainly a concern for devices that operate in the same frequency band (e.g. in the 2.4 GHz ISM band). If two devices have sufficient frequency separation, there should be no interference. For two wireless devices communicating using the same wireless protocol, this is also not a concern because the protocol should handle coexistence through interoperability, channel access and other channel sharing techniques. Some protocols even use these same techniques to coexist with other protocols. When two different wireless protocols occupying the same frequency band operate in proximity to one another, there is the potential for interference. Organizations operating NPPs need to employ a spectrum management programme to understand the frequency usage in their plants and manage any coexistence concerns.

Radio interference or jamming attacks (item (iii) above) can seriously interfere with the normal operation of wireless networks and can affect their performance. Radio interference is one of the main factors that can affect the routing decision and employed routing protocols in WSNs. The ability to detect radio interference attacks is important because it is the main basis for building a secure and dependable WSN (see Annex III for more information). Several parameters are monitored to detect jamming, such as signal strength, carrier sensing time and packet delivery ratio. Proven countermeasures against jamming include spread spectrum and frequency hopping techniques [52].

3.4. ENERGY SOURCE CONSIDERATIONS

Wireless sensor nodes can be line powered by either alternating current or direct current power sources. In some cases where sensor node physical access is restricted or where it is not possible to provide power cabling to the sensor node, batteries or power harvesting techniques (i.e. solar, thermal or vibration) are possible solutions to provide energy to the node. In these cases, the power usage has to be limited to conserve power. Different power saving policies such as dynamic power management and dynamic voltage scaling may be used for power conservation. For most nuclear applications, a battery would be expected to provide power for several years, assuming low data transmission rates (e.g. transmission once per hour).

3.4.1. Power consumption

The main contributors to the power consumption of a wireless sensor node are sensing, data processing and radiofrequency communications. The radiofrequency transceiver is the most energy intensive subsystem, and optimizing the operation of the radio unit can lead to a significant reduction in the total power consumption of the device. Generally, the radio unit operates in three different modes: transmit, receive and sleep. The power consumed in receive mode can be equal to or half of the power consumed in transmit mode. Power consumption in these modes is typically of the order of milliwatts. The devices may have the ability to enter a sleep mode when there are no data to transmit or receive. The sleep mode power consumption is usually much lower and can be of the order of microwatts.

There are various energy consumption models that relate energy consumption to data rate and transmission range. The classical energy consumption model states how energy consumption increases with an increase in data rate and distance [53]. Actual energy consumption can vary based on hardware; but in general, it will increase with an increase in data rate or coverage range. Table 7 provides a comparison of the power consumption in various modes of operation for several commercially available transceivers.

3.4.2. Network throughput

The amount of data transmitted over a predefined amount of time from a sensor node to the receiving system is an important consideration when designing the network architecture. The network throughput determines the amount of data that can successfully travel through a channel. Network throughput varies for each application based on the duty cycle and signal processing requirements. Table 8 lists network throughput values for the most common communication standards.

As a rule of thumb, the higher the network throughput, the higher the power consumption will be for a sensor.

TABLE 7. COMPARISON OF POWER CONSUMPTION OF COMMERCIALLY AVAILABLE TRANSCEIVERS

Technology	Details			
	Transceiver	Tx[a] current (mA)/max power (dBm)	Rx[b] current (mA)	Sleep current (μA)
ZigBee	Xbee	40/3	38	1
	Xbee-Pro (S2B)	117/18	45	3.5
	ETRX35x-LRS	140/20	31.5	1
	ProFLEX01-R2	149/20	30	<3
	Transceiver	Active Tx[a] (mW)	Low power idle (mW)	
Bluetooth	BlueCore 3	81	5.8	
Wi-Fi	Cisco PCM-350	1600	390	
	Netgear MA701	990	264	
	Linksys WC12	890	256	

[a] Tx: transmit.
[b] Rx: receive.

TABLE 8. NETWORK THROUGHPUT

Standard	Network throughput
802.15.4/ZigBee	250 kbps
Bluetooth	1–3 Mbps
802.11/Wi-Fi	11 Mbps (802.11b)–6.75 Gbps (802.11ad)

3.4.3. Power harvesting

The power source of wireless sensors is an important consideration, and self-contained solutions can avoid the need for significant power cabling and for long life batteries. Two of the most common self-contained solutions are thermal energy harvesting by utilizing thermoelectric generator technology [54] and vibration energy harvesting. Recent developments appear to show that thermoelectric generator technology is more widely applied.

For post-accident conditions, when common power sources such as power cables, batteries or energy harvesting may no longer be available, alternative energy supply methods for critical I&C equipment exist. These are described in Section 6.5 and Annex X.

3.5. NUCLEAR SPECIFIC CONSIDERATIONS

3.5.1. Environment and radiation effects

NPP structures contain metallic and concrete materials that can impact the propagation of wireless signals by reflecting or absorbing the radiofrequency signals, creating multipath fading. This phenomenon can degrade the quality and reliability of wireless communication, and the coverage can be limited in the harsh reflective environment. Therefore, the effects of multipath fading have to be considered while planning and designing the wireless network.

Wireless technologies could also be susceptible to the EMI and RFI noise specific to an NPP. Hence, the frequency band and type of communication have to be chosen carefully to minimize unwanted effects. Enclosures and electronic components have to be designed to withstand changing temperatures, vibration and other environmental phenomena.

Electronic equipment installed inside the containment building of an operating NPP may also have to contend with the harsh radiation environment (primarily characterized by gamma radiation) to which it will be exposed. Ultimately, the device's continued operation and functionality depends on its tolerance to the total integrated gamma dose received over its expected operating life.

Gamma rays are a type of ionizing radiation characterized by very high penetrating power, range and penetrating distance, dependent on the material composition. Radiation shielding is only possible with the use of very dense materials such as lead, concrete or steel. Radiation damage, such as lattice displacement associated with the ionizing effects of gamma particles in silicon based electronic devices, is often initially manifested as random, temporary errors, such as single event upsets, but eventually results in failure of the device. Research has shown that in addition to metal oxide semiconductor field-effect transistor components, digital to analogue converters, voltage regulators and voltage references, microcontrollers within wireless sensor devices are the components most vulnerable to the effects of radiation. The radiofrequency components are normally more resistant to these effects.

WSNs operate on the principle of electromagnetic radiation for transferring information through the medium (i.e. air). If the air is ionized, its propagation properties may change. The effects of radiation on the electromagnetic wave propagation need to be considered when designing a wireless system for NPP applications under high levels of radiation. This is particularly important in dealing with beyond design basis accidents, where the ionization levels may be very high. These disturbances can pose significant challenges for the reliable operation of wireless systems.

Preliminary research results have indicated that the wireless communication channel is not blocked by high levels of gamma radiation; however, the radiation environment may have some effects on electromagnetic wave propagation in terms of frequency shifts and receiver power level fluctuations.

Annexes IV and V describe research under this CRP that is specifically related to this topic.

3.5.2. Electromagnetic compatibility

Section 2.4.4 discusses EMC, and information on exclusion zones can be found in Section 2.4.6.

3.5.3. Integration with existing I&C systems and components

Commercial off the shelf wireless sensors and transmitters that can be installed onto existing NPP equipment, such as pumps, pipes and valves, are commonly available. In addition to meeting the environmental and security requirements discussed throughout this publication, selection of commercial off the shelf wireless sensors and transmitters needs to consider requirements for interfacing with existing equipment, including duty cycle, frequency of transmission, transmission distance and the presence of metallic obstacles. Another important consideration is the requirements for interfacing with existing wired or wireless networks.

The structural make-up of containment walls (rebar reinforced concrete, steel liner) does not allow the transmission of high frequency wireless signals through this barrier. Currently, the most reliable method for transmitting data outside of the containment is to place a gateway (wireless receiver) unit inside of the containment to establish the wireless network in the area and then use a cable to pass the data through the containment wall. This has successfully been established using existing spare cables, fibre optic cables and telephone lines (establishing a network line on the existing telephone line without affecting the phone performance). A typical configuration of the above arrangement is shown in Fig. 4.

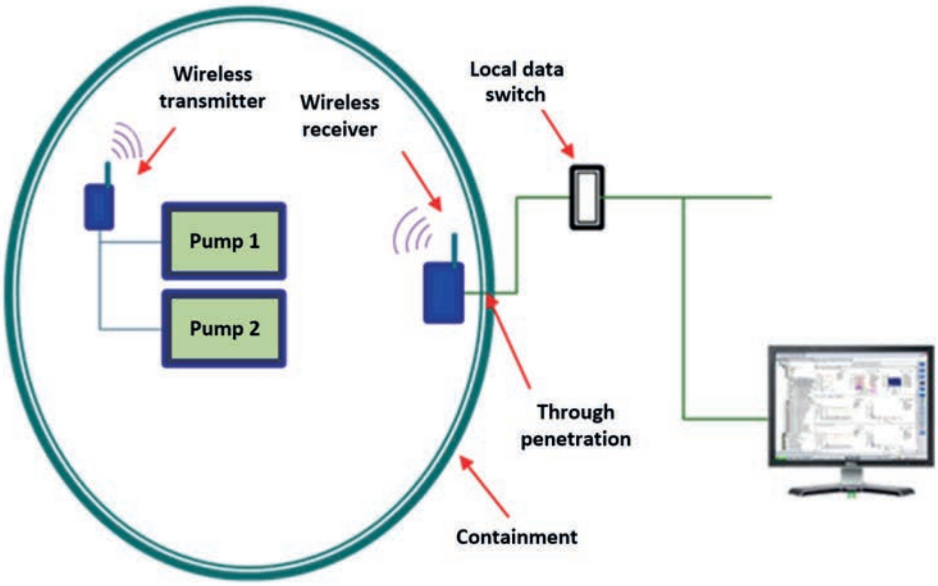

FIG. 4. General configuration for in-containment wireless data transfer and connection to wired systems.

Data communication links established between wireless networks and existing plant I&C systems have to conform to a site's computer security requirements. Section 2.4.3 contains more information on the applicable computer security standards.

It is often not necessary that a given wireless application interface with the plant's overall I&C system; however, even in these cases it may be beneficial to provide the wireless sensor data to the plant historian for easy retrieval for plant engineers.

It needs to be noted that communication technologies are being developed that can potentially communicate through barriers formed by heavy structures and components. More information on this can be found in Annex VI.

4. PRACTICES, EXPERIENCE AND LESSONS LEARNED

4.1. INTRODUCTION

Recent advances in wireless communication technology have increased the use of wireless networks in industrial applications. This includes applications such as process monitoring, preventive maintenance, and process quality and dynamic performance evaluation, in which wireless technology is used with or without traditional wired networks. Wireless field devices are used in several industrial sectors to augment the scope and benefits of automation.

At present, the development of wireless based I&C systems for NPPs is in the initial phase. Various stages of qualification are ongoing in order to demonstrate that they are suitable for more widespread deployment.

This section reviews and summarizes the prominent wireless technologies addressed during the course of the CRP. It also describes some of the past experience with wireless sensor technologies in NPP environments. The application areas described in this section vary from process data monitoring to condition monitoring systems and tools for simulating wireless signal propagation. The wireless technologies used in these deployments include Wi-Fi, WiMAX, Bluetooth, ZigBee and others.

This section may also help in identifying a framework to facilitate the use of wireless technologies in NPPs in future projects.

4.2. CASE STUDIES ON PROCESS MONITORING

4.2.1. Deployment of a wireless sensor network for process measurement in the Fast Breeder Test Reactor at the Indira Gandhi Centre for Atomic Research, India

The Fast Breeder Test Reactor is a 40 MW(th) sodium cooled fast reactor built at the Indira Gandhi Centre for Atomic Research, in Kalpakkam, India. In the reactor, WSNs have been deployed to test the feasibility of such networks in industrial and nuclear installations.

During initial deployment in 2010, eight temperature sensors and three vibration sensors were connected to WSN nodes. These sensors were distributed outside the reactor containment building, the turbine building, the secondary sodium loop area, the sodium flooding area and a speed control system and blower cabin in the filter room. Three router nodes were used to route these signals towards the base station placed in the control room.

To ensure continuous availability of all the nodes in the network, battery backup has been provided. Diverse process signals (such as temperature, flow, level and vibration), sometimes grouped together in a nearby location, have to be monitored. Different types of sensor acquisition boards, capable of handling multiple input channels, have been designed and developed.

As of 2017, the Fast Breeder Test Reactor WSN is functioning satisfactorily with 37 nodes. It monitors 14 thermocouples, six flow sensors, two level sensors, five vibration sensors and two vibration based condition monitoring systems. To administer and manage the WSN, an efficient graphical user interface wireless network management station has been developed. Figure 5 shows the deployed WSN at the Fast Breeder Test Reactor.

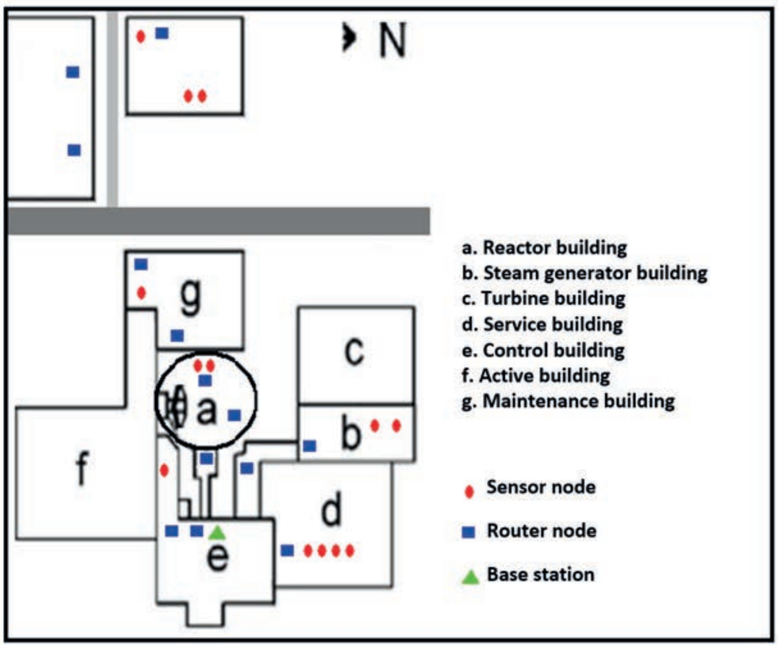

FIG. 5. Deployed wireless sensor network at the Fast Breeder Test Reactor.

4.2.2. Deployment of wireless sensor network for the measurement of sodium leak detection at the In Sodium Test Facility, Indira Gandhi Centre for Atomic Research, India

The In Sodium Test Facility was constructed at the Indira Gandhi Centre for Atomic Research to test the mechanical properties of fast reactor components under the influence of sodium. Molten sodium is circulated in the heat transport circuits of the fast breeder reactors and experimental sodium loops at the centre. The material used for these sodium circuits is austenitic stainless steel with a welded construction. The possibility of a leak cannot be completely ruled out, even though all possible measures are taken to prevent sodium leaks by adequate design, fabrication, quality assurance, operation and maintenance. Wire type leak detectors and spark plug type leak detectors are used as the primary leak detection method in single wall pipelines of secondary sodium circuits and experimental loops. The wire type and spark plug type leak detectors are connected to programmable logic controllers to process the signal from the detectors.

In order to reduce the complexity involved in cable routing and to test the performance of the leak detector wireless connectivity, 50 leak detectors from the In Sodium Test Facility fatigue loop were connected as a redundant system in parallel mode to a WSN developed in house. The data were communicated to a base station located in the control room to display the status of the leak detectors.

Prior to deployment, interference effect studies were performed using a spectrum analyser to identify any sources of interference. Typical WSN sensor node installations are shown in Fig. 6.

The network was distributed across three floors of the building, covering a nearly 80 m^2 area. Three router nodes were placed on each floor to provide a redundant path. The base station was connected to a personal computer and received the field data from the sensor nodes. The statuses of the leak detectors were displayed on the computer. An actuator node for a buzzer alarm in case of sodium leak was installed in the control room.

4.2.3. Deployment of wireless sensor network for the measurement of temperature and humidity at the Safety Grade Decay Heat Removal Loop in Natrium, Indira Gandhi Centre for Atomic Research, India

The Safety Grade Decay Heat Removal Loop in Natrium facility at the Indira Gandhi Centre for Atomic Research is a 335 kW sodium test facility used to study the safety grade decay heat removal of the Prototype Fast Breeder Reactor. A ventilation stack 20 m in height provides the air flow required to transfer the heat from the secondary sodium circuit to the atmosphere through an air heat exchanger.

When the loop is in operation, it is necessary to continuously monitor the temperature and humidity at the stack inlet and outlet from the control room. Wiring the facility over a long distance was considered cumbersome

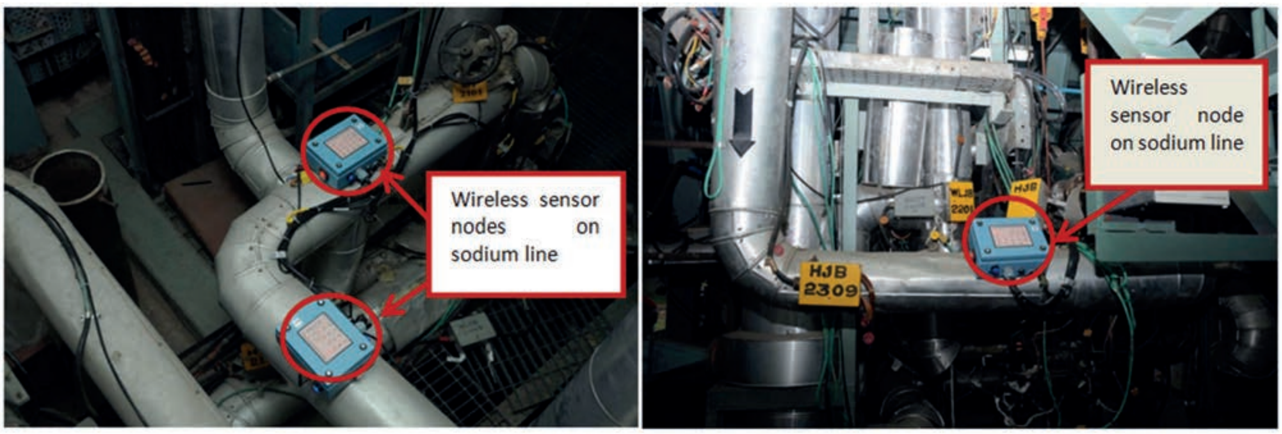

FIG. 6. Deployed wireless sensor nodes at In Sodium Test Facility.

and a WSN based solution was determined to be the most appropriate. The links were established for continuous data monitoring at 1 min intervals at 2.4 GHz.

The WSN was deployed using five nodes between an open terrace and the control room, as shown in Fig. 7. The parameters from the ventilation stack inlet and outlet were acquired, processed and transmitted successfully to the control room. The connection status of two temperature and two humidity sensors to the WSN nodes was verified on a regular basis.

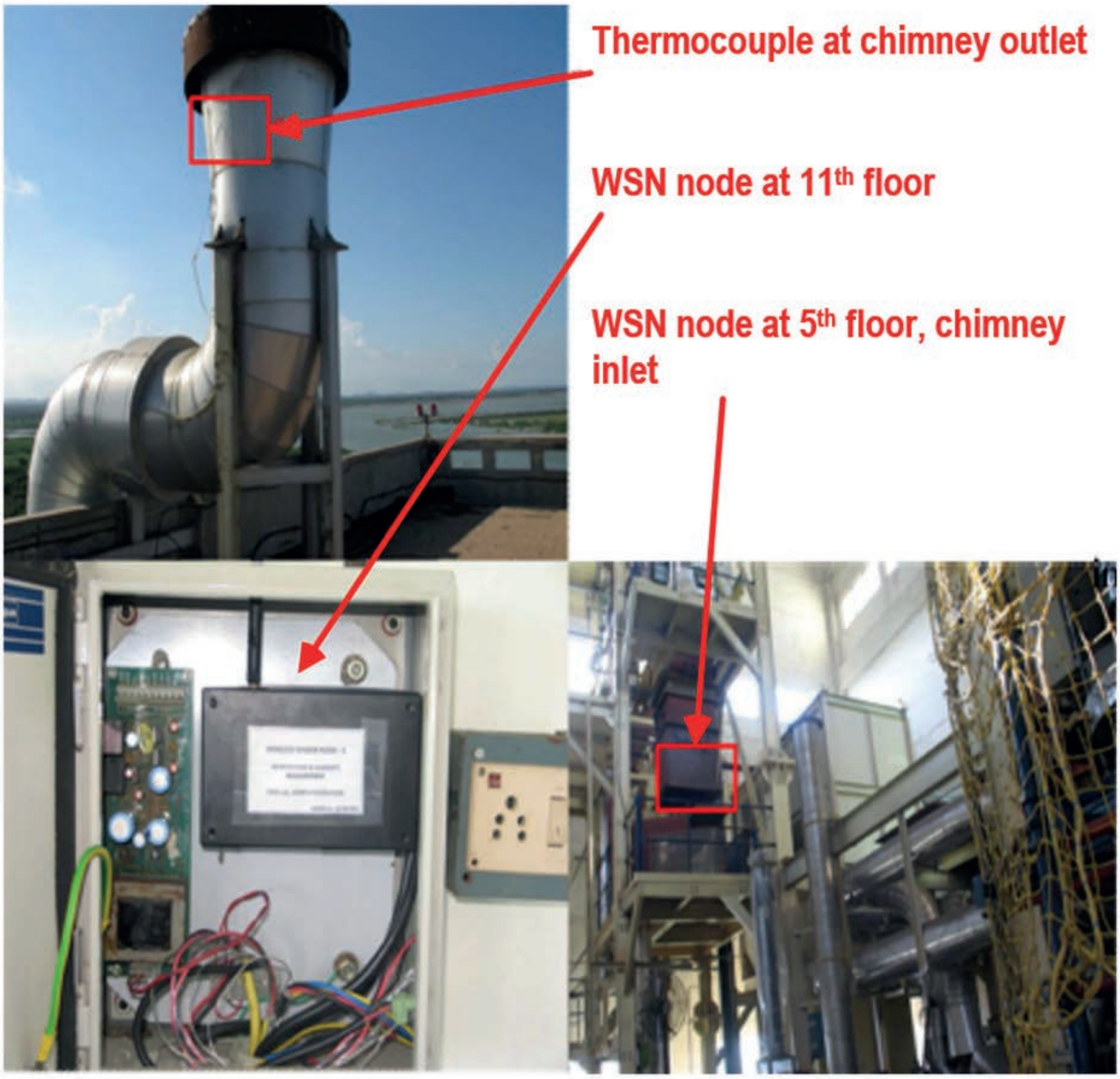

FIG. 7. Wireless sensor network (WSN) deployed at the Safety Grade Decay Heat Removal Loop in Natrium facility.

4.3. CASE STUDIES ON EQUIPMENT MONITORING

4.3.1. Wireless conditioning monitoring at Luminant’s Comanche Peak plant, United States of America

Wireless technologies were first introduced at Comanche Peak more than a decade ago and are now a crucial element in its strategy because they can reduce the cost of operation and improve reliability.

Figure 8 shows the flow loop at the plant, indicating the equipment that is wirelessly monitored. The loop includes several major systems in the balance of plant and a total of 40 sensors monitoring process and equipment condition. The wireless infrastructure at Comanche Peak consists of a redundant fibre optic backbone connecting wireless access points deployed throughout the plant. The infrastructure and mobile devices conform to IEEE 802.11 [5] standards. The same infrastructure also accommodates wired LAN connectivity throughout the plant for both voice and data applications as well as remote video monitoring and control.

The utility applies wireless technologies to help it integrate work order management and scheduling, electronic procedures, clearance and tagging, operator logs, equipment monitoring, electronic messaging, plant drawings, phonebooks, equipment references and locations and selected Internet/intranet access. Utility applications include radiation monitoring, equipment condition monitoring, process monitoring and video conferencing. As an example of the benefits, an employee reported that wireless sensors have saved him up to 4 hours per day by enabling him to sit at his computer and analyse data rather than needing to be out in the plant manually collecting that same data [3].

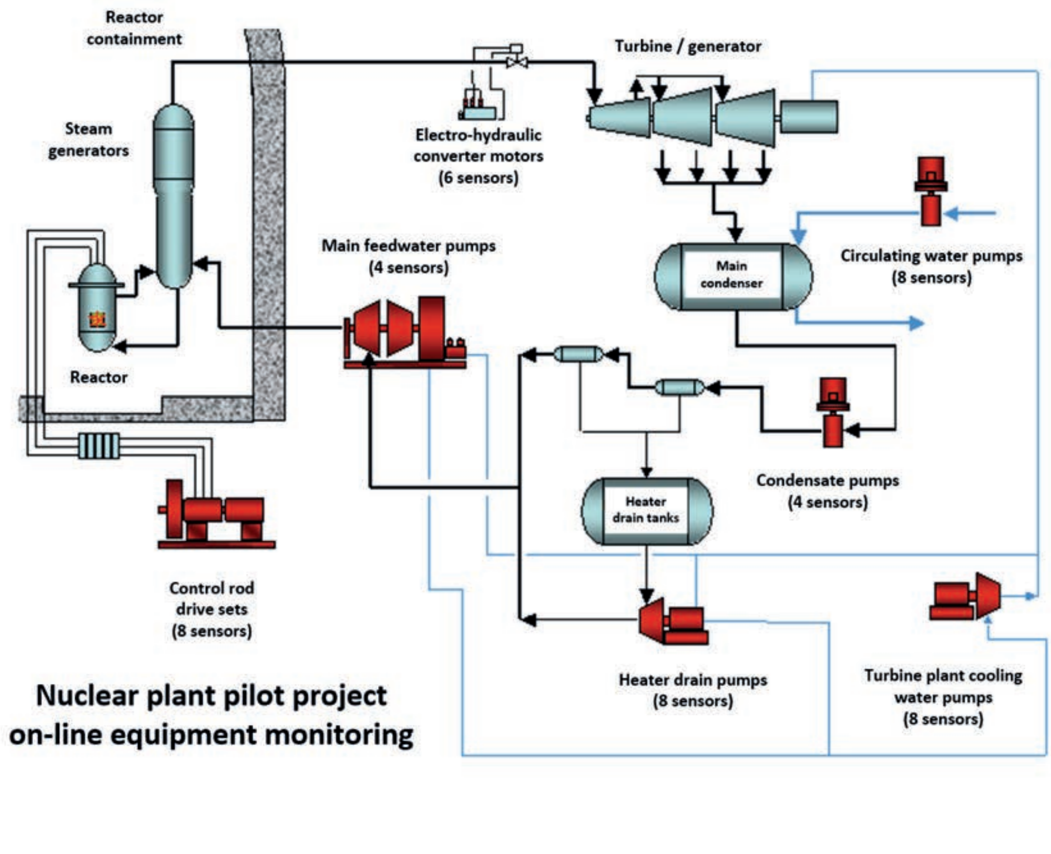

FIG. 8. Luminant’s Comanche Peak plant flow loop, which is wirelessly monitored. (Reproduced courtesy of EPRI.)

4.3.2. Containment cooling fan on-line monitoring at the Arkansas One plant, United States of America

The Entergy Arkansas One site has an installed Wi-Fi network similar to Comanche Peak’s that is used for voice and data communications, as shown in Fig. 9. The plant’s wireless network also provides workers with on-line access to plant documents when performing in-field procedures (e.g. equipment calibration). In 2011, the plant collaborated with a wireless equipment supplier on an R&D effort to extend the use of wireless technologies inside its containment building. The plant installed several wireless vibration monitoring systems and a Wi-Fi access point inside the containment building. The system transmits vibration data for the four containment cooling fans twice a day to an engineering workstation. The system has been extended into the containment building of both units and also monitors the vibration of the four control element drive mechanism cooling fans. With the new wireless monitoring systems, maintenance personnel can more effectively monitor the condition of the equipment, providing them with sufficient time to detect any impending failure and plan for maintenance activity.

4.3.3. Cooling tower fan motor monitoring at the High Flux Isotope Reactor at the Oak Ridge National Laboratory, United States of America

An R&D programme was successfully completed to develop and deploy an integrated condition monitoring system utilizing wireless data delivery for the predictive maintenance of rotating equipment at the High Flux Isotope Reactor at the Oak Ridge National Laboratory, as depicted in Fig. 10. In particular, the completed R&D has successfully implemented a unified approach to the collection, analysis and interpretation of equipment performance data using a combination of traditional accelerometers and ultrasonic sensors with wireless signal transfer from multiple data collection systems to a secure server managed by the High Flux Isotope Reactor. Real time signal analysis algorithms are utilized to provide automated analysis of trends in machinery operating parameters and to display the status of the machinery to plant operators as well as system engineers.

The results of this effort have applications not only at research reactors such as the High Flux Isotope Reactor, but also at the Advanced Test Reactor located at the Idaho National Laboratory and at the Spallation Neutron Source located at the Oak Ridge National Laboratory. It is anticipated that nuclear power reactors, fuel fabrication facilities and spent fuel storage installations will also benefit.

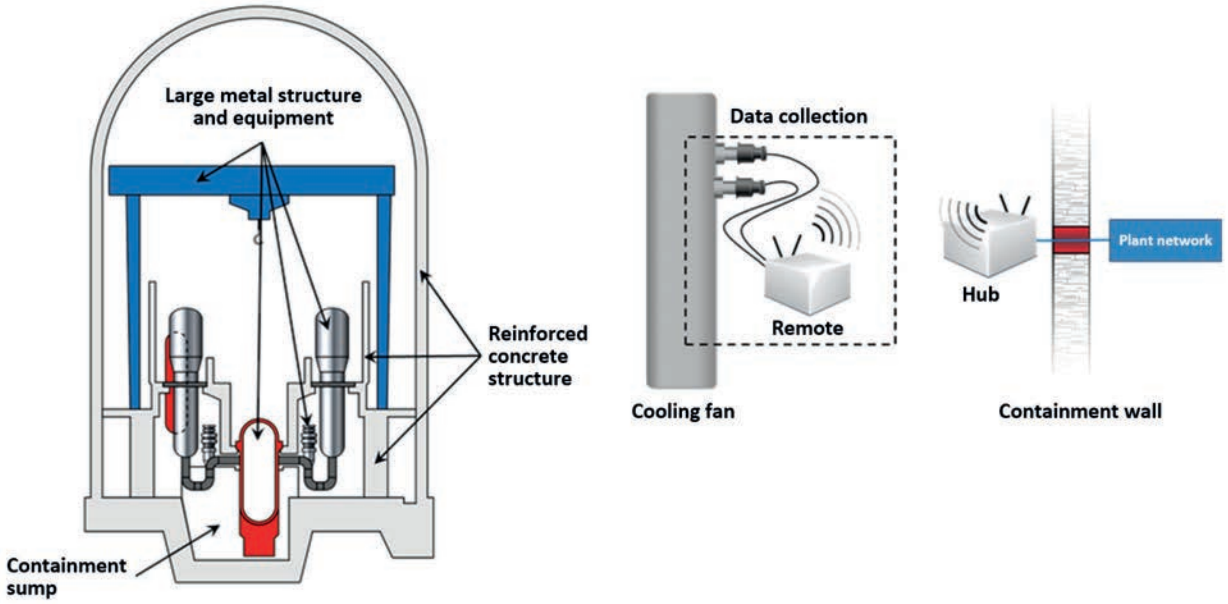

FIG. 9. Entergy Arkansas One Wi-Fi network. (Reproduced courtesy of AMS.)

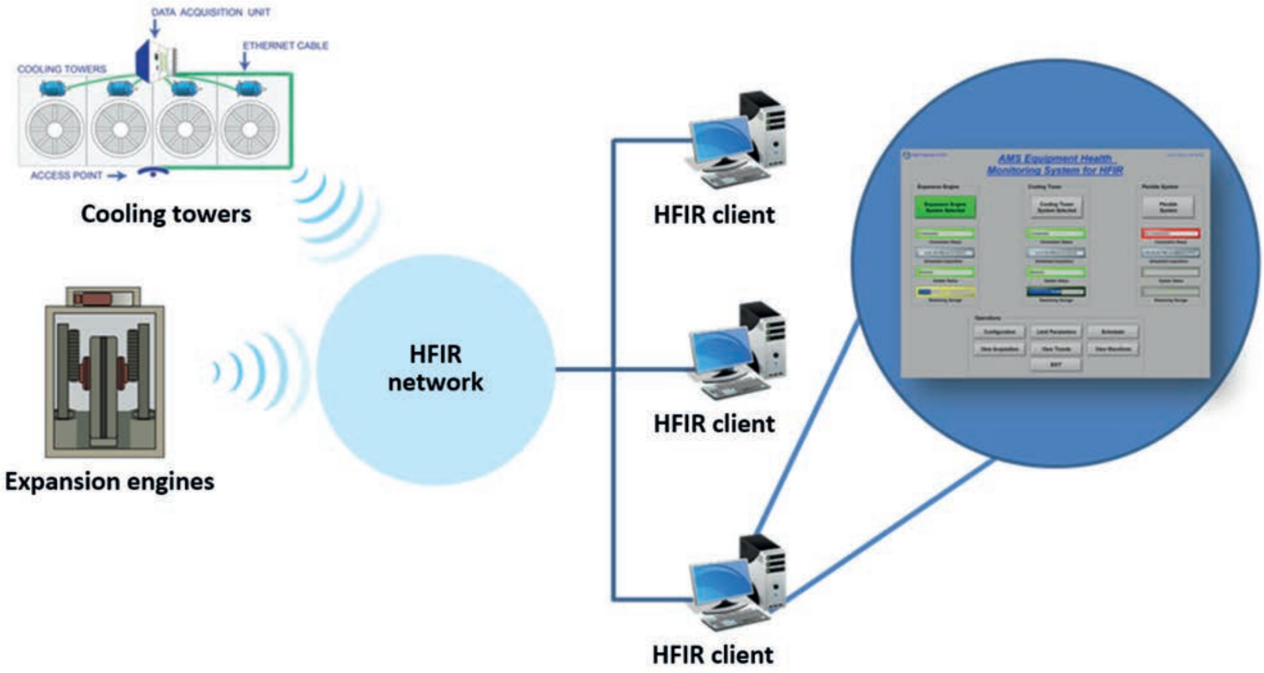

FIG. 10. Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR) Wi-Fi network. (Reproduced courtesy of AMS.)

4.3.4. Vibration and temperature monitoring for fan motor at Exelon's Limerick plant, United States of America

The Limerick plant experienced maintenance problems with its turbine enclosure exhaust fans, which were used to remove heat from turbine building equipment. These fans were nicknamed 'fan-in-a-can' as they were typically mounted inside cylindrical ducts and the fans and motors were inaccessible to technicians during plant operation. It was not feasible to gather condition assessment data for the fans while the plant was on-line. This problem was resolved by deploying wireless based vibration and temperature sensors to the fan motor within the duct. The implementation of wireless technologies helped the plant technicians acquire condition assessment data during plant operation, thus improving reliability and reducing down time.

4.3.5. Motor health monitoring at Southern California Edison's San Onofre plant, United States of America

A study was conducted to implement a wireless technology based condition monitoring system for the plant motors (1860 kW installed capacity) at the San Onofre Nuclear Generating Station. Any failure of one of these motors would reduce the plant capacity by 20% for a number of days. In order to improve the capacity factor, it was necessary to collect and analyse real time temperature data from the motors to avoid catastrophic failure.

An IEEE 802.15.4 wireless mesh network was selected for the collection and analysis of motor temperature data in real time. The selected system enabled the plant engineers to take timely action. This system was chosen to avoid adding new cables, which helped in reducing the installation expenses with improved plant life cycle.

4.4. CASE STUDIES ON RADIATION MONITORING IN NUCLEAR POWER PLANTS

4.4.1. Radiation monitoring at the Indira Gandhi Centre for Atomic Research, India

Radiation monitoring systems are essential in and around any nuclear facility. To monitor radioactive material movements at the Kalpakkam nuclear complex, area gamma monitors with local alarm facilities were placed at various entry/exit points. A WSN was deployed to provide a centralized overview of the radiation situation and to have a record of events for future analysis. The WSN nodes were designed to be protected from rain without compromising the radiofrequency transmitting and receiving power for outdoor deployment. Efficient powering options were provided to the nodes from solar panels with battery backup for 48 h.

Before deploying these nodes, a site survey was carried out using different networking tools (for example, Wi-Spy and ZigBee Sniffer) developed in house. This process was used to find the different sources of radiofrequency interference and to identify the optimal number and locations of router nodes for proper operation. The router nodes were deployed with redundancy after a careful examination of the link quality between the nodes, especially where dense trees, metallic structures or bends in roads causing loss of line of sight were present, and as necessary to work under the worst environmental conditions that could reduce the link quality between nodes.

Post-deployment network data were observed at different points. Based on these observations, the locations of router nodes were changed for optimal network architecture. Some additional router nodes (with/without a solar panel) were added to increase the overall network reliability. The routing algorithm was modified to increase the packet delivery ratio. Clustering was introduced at source locations to reduce data traffic and congestion in the network. A dedicated wireless network management station was developed to display the radiation dose and health status of individual nodes in the network.

As of 2017, the WSN for radiation monitoring was functioning successfully with 90 nodes. It collects data from 34 area gamma monitors using 55 router nodes to transmit the dose information with high reliability to the base station, which is kept at the health physics room of the Fast Breeder Test Reactor and is staffed continuously. At four different locations, redundant cluster heads were configured to aggregate the area gamma monitor data. For better correlation of the performance of this wide area network with the environmental conditions, a WSN node for environmental monitoring was also added that logs temperature, humidity and the presence/absence of rain.

4.4.2. Radiation monitoring at the Paks nuclear power plant, Hungary

The environmental and radiation monitoring system of the Paks NPP (see Fig. 11) contains multiple types of wired and wireless sensors. These sensors monitor the radionuclide concentration in the air. The sensor types are as follows:

— Type A stations (see Fig. 12 for their positions) monitor the radiation situation around the plant. These stations have both wired and wireless connections to the central station. Their functions include the following:
  - Gamma radiation dose rate measurement;
  - Total beta activity concentration measurement of aerosols;
  - Phase measurement of radioiodine;
  - Aerosol and iodine sample collection for laboratory measurements;
  - Data collection, processing and transmission to the central supervisory control and data acquisition system.

— Type B stations monitor the same parameters as type A stations without wired connections, and are located 30 km from the plant. Data transmission is done wirelessly or via media devices (e.g. a USB drive). In case of a loss of power failure, type A and B stations are powered from uninterruptible power supplies. These power supplies are expected to provide power for at least 24 h in the event of a power failure.

— Type G stations have the same type of gamma radiation sensors as type A stations, but these are solar powered and connected only wirelessly to the central station.

— Type U stations have gamma dose rate sensors (10 nSv/h–10 Sv/h) and are located in the courtyard of the power plant.

There is a low speed, 450 MHz ultra-high frequency network transferring data between the stations and the headquarters with a minimum 1200 bit/s bandwidth and a high speed microwave network between the headquarters and the emergency response centre with a minimum rate of 11 Mbit/s bandwidth. The ultra-high frequency system operates 24 hours a day with two transceivers placed on the top of the second and third units. They receive data transmitted by the surrounding monitoring stations. If the ultra-high frequency communication is not working properly, the system automatically switches to wired mode except in the case of the G stations, where transmission is through radio communication only.

The high speed microwave transmission to the emergency response centre is done in the frequency range of 2400–2483.5 MHz with encrypted data using a 128 bit key. The encryption adds some overhead to the information being transferred, so the real transmission speed is approximately 8 Mbit/s.

The propagation of microwave signals can be influenced by rain, fog or snow, and the communication can be interrupted in extreme situations. Therefore, it is important to have a margin to compensate for possible signal losses. In case of Paks, a 25 dB fading margin is calculated to compensate for the attenuation caused by rain, fog or snow. According to the ITU-CCIR Report 563-3 [55], the specific attenuation caused by rain is 0.4 dB/km. This value applies to rain at maximum intensity, and was calculated using the Marshall–Palmer distribution at a temperature of 20°C. Dry snow does not cause significant attenuation below 50 GHz, whereas wet snowfall causes almost the same attenuation as rain. When the visibility is 50 m in foggy and cloudy conditions, the attenuation is 0.1 dB/km. The attenuation caused by dust is 0.5–1 dB/km. The calculations above show that the radiofrequency attenuation rate is around 1–2 dB for every 0.5 km. The difference between the fading margin and the attenuation is 23 dB, so there is still some margin left in the system.

In the event of an earthquake, signal attenuation can be caused by the movement of the antennas. Based on preliminary calculations, the buildings have a maximum movement of 0.2–1 m. Such movement, even if it is permanent, cannot cause communication interruptions in the 2.5 GHz band. The −3 dB direction of the antennas

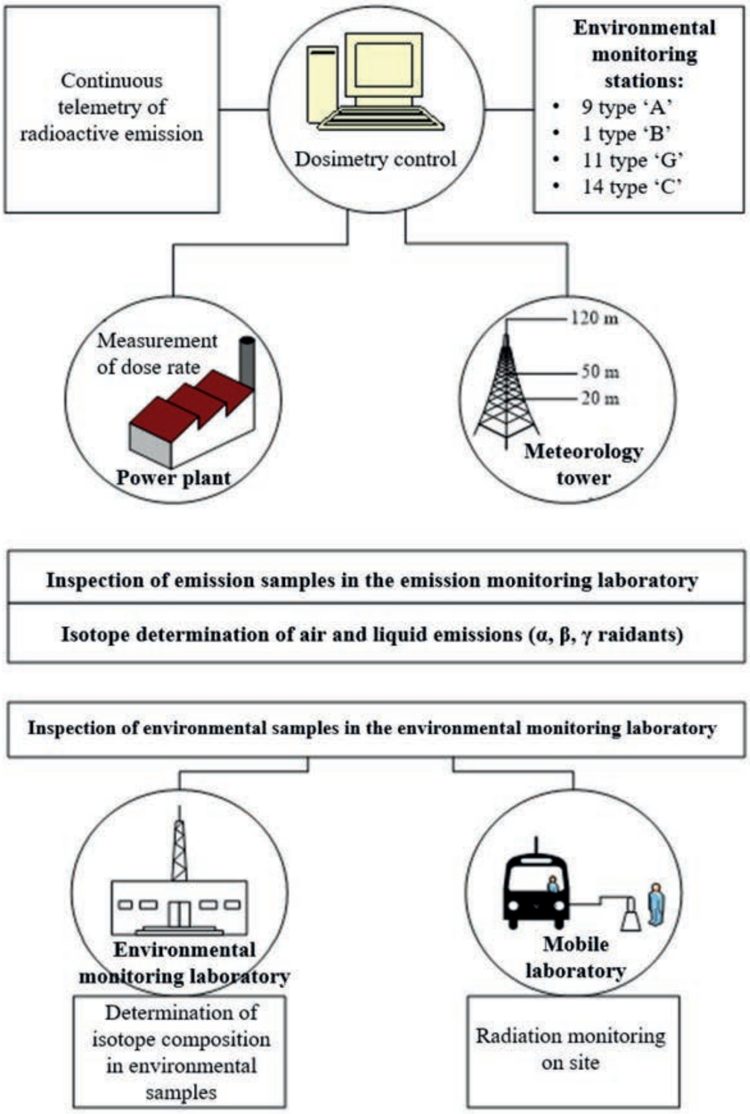

FIG. 11. The structure of the environmental and radiation monitoring system at the Paks nuclear power plant.

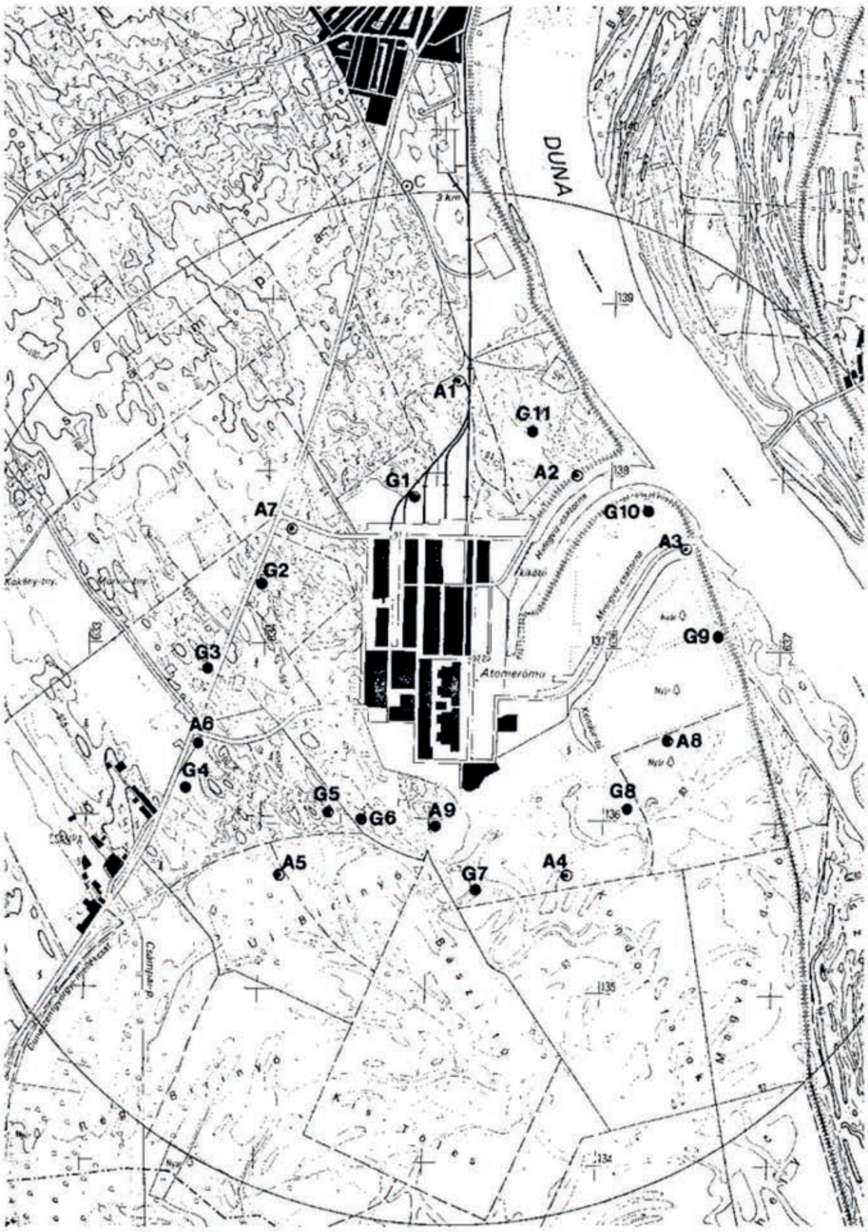

FIG. 12. The positioning of type A and G monitoring stations around the Paks nuclear power plant.

used here is positioned ±15° relative to the main transmitting direction. This means that the receiver site would have to move 134 m in one direction to see a 3 dB reduction in signal strength when transmitting over a 500 m distance. This large movement is not a realistic scenario during an earthquake.

The rotation of the antennas from the main transmitting direction can cause additional signal attenuation, and the previously calculated 25 dB fade margin is available for compensation. After subtracting the 2 dB attenuation that could be caused by weather, the antennas could cause an additional attenuation of 23 dB before the connection is interrupted. A 23 dB signal attenuation would occur if the antennas (the two opposite antennas combined) rotated 40° from one another, which is unlikely as the installation is seismic-proof.

4.5. TOOLS FOR SIMULATING WIRELESS DATA TRANSMISSION

4.5.1. Microwave signal propagation

The design of long distance wireless connections can be supported with the help of wireless simulation tools, for instance with the web application Microwave Link Wizard (see Fig. 13). This tool lets the user set the parameters of the surrounding terrain (e.g. elevation and height data) and parameters for the calculation as follows:

— Antenna manufacturer;
— Bandwidth (typically 300 MHz);
— dBm level, dB attenuation (transmitting level, receiver threshold);
— Climate (rain rate in mm/h, etc.);
— Frequency (8 GHz, 11 GHz, 18 GHz, 23 GHz, etc.);
— Polarity (vertical/horizontal).

A number of environmental variables affect the wireless transmission, causing path loss and performance degradation. For its calculations, the tool uses international telecommunications standards where possible (currently these cover 193 countries). The environmental variables that Microwave Link Wizard takes into account are as follows:

— Interference (the main issue affecting microwave link performance);
— The curvature of the Earth and atmospheric refraction factors;
— Propagation conditions;
— Rainfall;
— Reflection (from the ground and particularly over water);
— Free space path loss (loss of signal as it travels through the air);
— Multipath fading.

4.5.2. Wi-Fi signal propagation

HeatMapper is a free Wi-Fi mapping tool that can be used for short distance IEEE 802.11 wireless connection design. This tool can map already deployed WLAN networks using hardware devices and helps when relocating

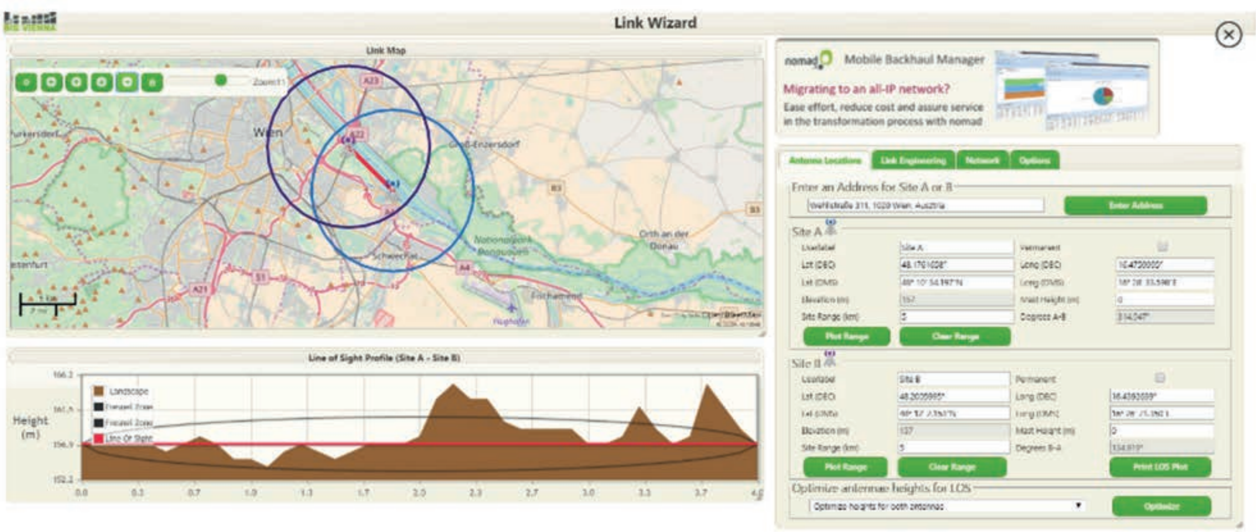

FIG. 13. The user interface of Microwave Link Wizard.

wireless routers or access points. While planning short distance wireless connections, multiple factors that affect signal coverage and strength can be adjusted by measuring the details of the scene, including the following:

— Antenna;
— Distance;
— Frequency;
— Interference;
— Physical obstacles;
— Power supply;
— Security;
— Wireless standard.

TamoGraph Site Survey can be used for planning wireless networks that have not been deployed yet. This type of tool is called ‘predictive’ or ‘virtual’ because Wi-Fi characteristics are predicted for the virtual environment model created by the user. The process of creating and adjusting the virtual environment, the selection and placement of simulated access points and the analysis of the resulting wireless network is commonly referred to as radiofrequency planning. To create a virtual model of the environment, the user needs to specify the position, size and type of the physical objects that affect radio wave propagation. The model uses built in or custom designed walls, floors and attenuation areas; simulated access points; and a large selection of antenna patterns.

FortiPlanner can estimate the number of required wireless access points and recommends their placement on the premises for optimum performance. This application makes it possible to import a building’s floor plan, draw the walls and other obstructions that can impede a wireless signal and place the right number of access points based on the type of wireless application chosen. The output of the tool is a comprehensive report that can be used to set up the right number of access points for optimum performance.

Aerohive’s HiveManager is a cloud based network management solution. The application is capable of planning the location of access points using a floor plan on-line. The application is also available for real time client and event monitoring, simplified troubleshooting and application programming interface integrations.

4.5.3. Simulation

To demonstrate the application of the above mentioned tools, FortiPlanner and HiveManager were used for sample calculations and to compare the differences between the results of two completely different desktop applications. The same scene was set up in both tools using a sample office floor plan. After setting the same scaling, the walls, doors and windows were placed as physical obstacles. The physical obstacles were set with the following attenuation measurements:

— Exterior concrete walls: −12 dB;
— Interior drywalls: −3 dB;
— Windows: −1 dB;
— Interior doors: −2 dB;
— Exterior door: −4 dB.

The same access point was placed on the same spot in both tools. The antenna pattern, coverage zone and transmission power were set to 0°, normal and 17 dB (50.12 mW), respectively, on a frequency of 2.4 GHz as shown in Fig. 14.

Comparing the results provided by the tools, it was found that the estimated signal coverage around the floor was almost the same. Displaying 5 GHz signal levels, the tools also showed the same mapping results using 17 dB of transmission power. The tools used in this simulation only provide estimations; for precise wireless strength mapping, hardware monitoring on site is required.

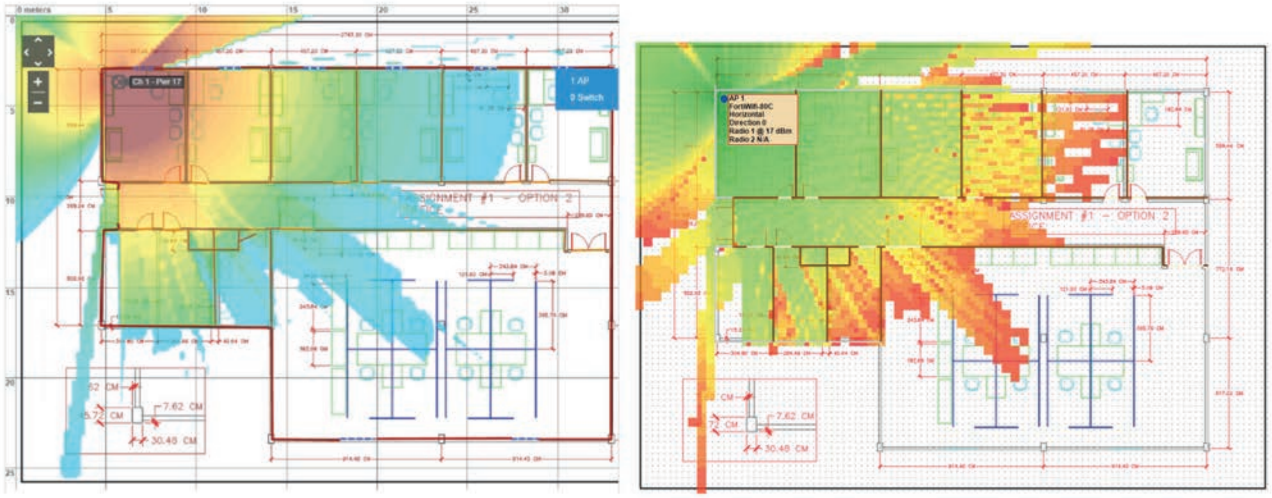

FIG. 14. Maps of the 2.4 GHz signal level transmitted by an access point in HiveManager (left) and FortiPlanner (right).

4.5.4. Network simulators

Network simulation tools can model the behaviour of a network either by calculating the interaction between the different network entities using mathematical formulas or by actually capturing and playing back observations from the network. In simulators, the computer network is typically modelled (with devices, links, applications, etc.) and the performance is analysed. The network simulators can extend the usage of the wireless communication simulators to provide precise information about the predicted network traffic.

Open source network simulators can be reprogrammed to model wireless networks, calculate the measurement of signal fading and use the results obtained from wave propagation tools. Scene editors can be used to create and implement virtual testing environments for wireless network models and emulate physical obstacles, terrain, climate or radiation.

4.6. A WIRELESS ROBOTIC SYSTEM FOR SEVERE ACCIDENT APPLICATIONS IN JAPAN

4.6.1. Application requirements

In severe environments, such as a disaster area, various remote controlled robots will need to be used for accurate situational assessment. To manipulate the robots smoothly, video data and robot control data need to be transmitted reliably and efficiently. However, device faults and cable disconnection can easily occur in severe environments. Communications need to be maintained reliably even under known fault conditions, which may include a physical disconnection, instrument fault or other issues. If a single fault were to occur, the robot is required to maintain communication, detect the fault and, if possible, replace the faulty component.

4.6.2. Wireless system configuration

Figure 15 shows the communication system for remote controlled robots, which was developed as a hybrid system of wired and wireless links. The communication between the robot operation computer and a repeater is provided via a wired network and the communication between the repeater and the robot is done via a wireless network.

Figure 16 shows the abstract structure of the hybrid wired and wireless communication system with single fault tolerance criteria. This system establishes a loop between wired and wireless communication and controls route information by using a rapid spanning tree protocol. Normal communication is established through a wired network. In the case of a cable disconnection, communication is established via the wireless network.

Generally, two network systems are established between the operation terminal and the robot, and these network systems are controlled by using the routing information protocol. In the case of device fault/failure, the system switches

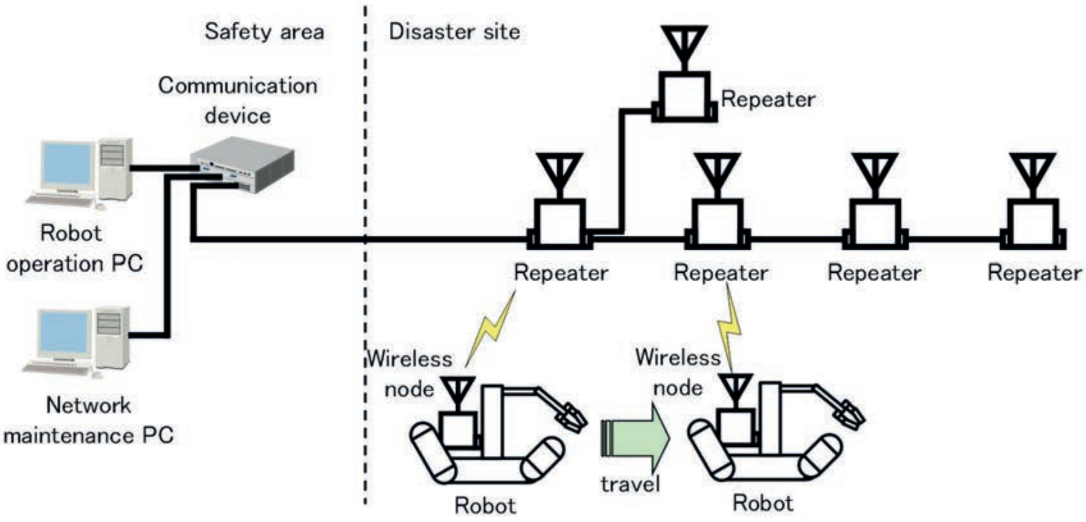

FIG. 15. System overview of the robot communication system.

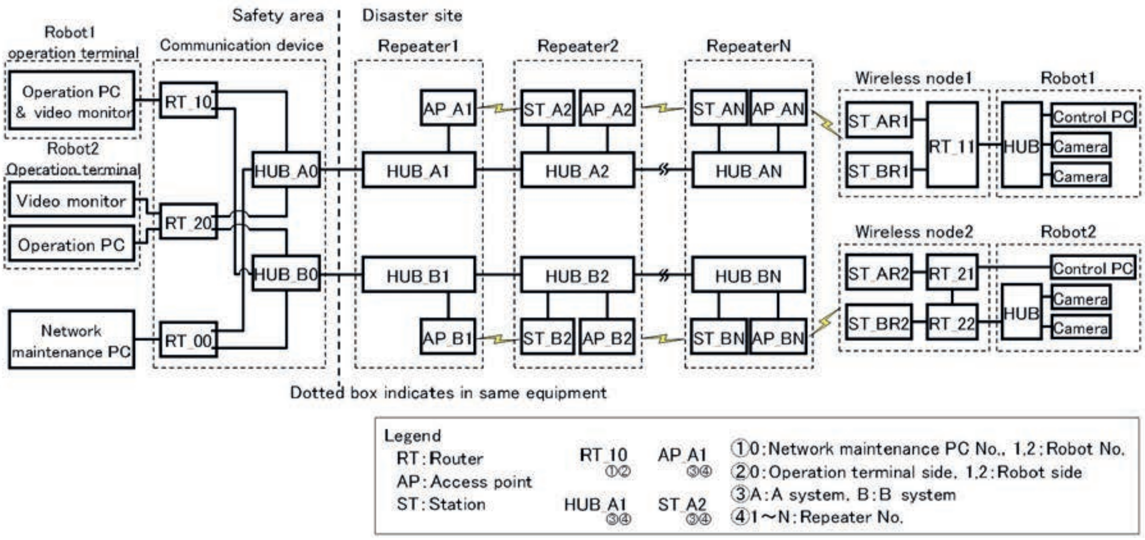

FIG. 16. Block diagram of a wired and wireless hybrid robot communication system.

communication to the other network (the network to which the faulty device is not connected). If wireless interference is encountered, this system has the capability to switch to another frequency. By using these two methods, communication can be maintained even if a cable disconnection or a device fault occurs.

4.6.3. Wireless system prototype

Figure 17 shows overview pictures of the experimental devices. By attaching extension bars, the height of the antenna of the repeater shown in Fig. 17(a) can be adjusted by the robot. For the wireless node on the robot, devices were designed with two different shapes. One is placed vertically (Fig. 17(b)) and the other horizontally (Fig. 17(c)). The required communication throughput of the robot is up to 20 Mbps. In order to avoid traffic congestion in the 2.4 GHz band, two wireless bands are used for communication. One is a 4.9 GHz band that complies with IEEE 802.11j and the other is a 5 GHz band that complies with IEEE 802.11a.

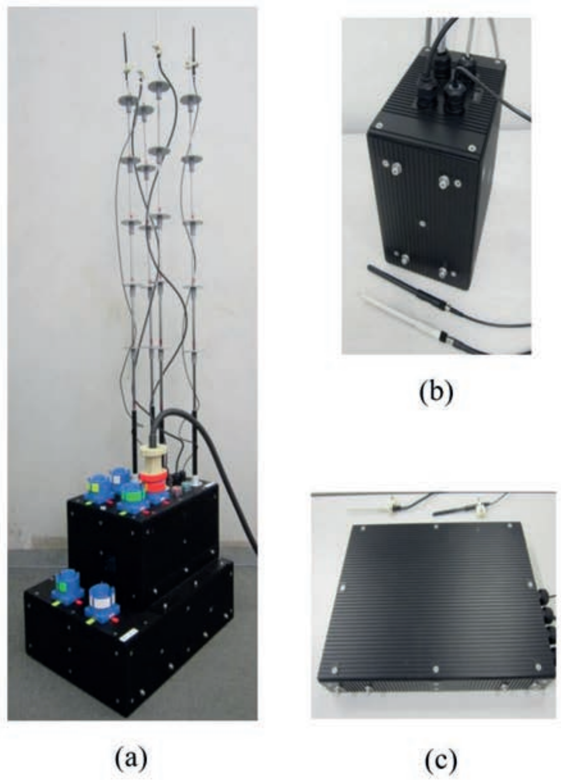

FIG. 17. Overview of the prototype wireless communication terminal. (a) Repeater (with battery); (b) robot wireless node (vertical); (c) robot wireless node (horizontal).

4.6.4. Testing

Tests were conducted based on two types of simulated communication faults: (a) the cable disconnection simulation test and (b) the device fault simulation test. Other tests carried out to check communication performance included throughput and packet loss rate tests. Testing was carried out by simulating the error in the hybrid communication system and observing the performance during a change of robot communication route or system structure as planned. Figure 18 shows the communication error test structure.

4.6.4.1. Cable disconnection simulation test

This test was carried out by simulating the disconnection of cable (2) between the repeaters to confirm the change of the route from wired communication to wireless communication by rapid spanning tree protocol.

4.6.4.2. Device fault simulation test

This test was carried out by simulating the disconnection of cables (1) and (3) of the system alternately to simulate faults in the hubs or the wireless devices, and to confirm the change to the system by the routing information protocol.

The performance of the wireless communication was measured over an area of 40 m × 40 m at an operating NPP. Figure 19 shows the communication performance measurement structure. The communication throughput and the packet loss rate were measured by using the tool 'Iperf'. The test arrangement for measuring the communication performance was as follows:

— The first repeater was placed at the near point of the equipment hatch.

— The communication throughput and the packet loss rate were measured when the received signal strength indicator (RSSI) showed −60 dBm, −70 dBm and −80 dBm, respectively.
— The next repeater was placed at a location confirming a throughput of 20 Mbps and a packet loss rate of about 0%, and the above steps were performed again.
— More repeaters were added as above, and the tests were performed again.

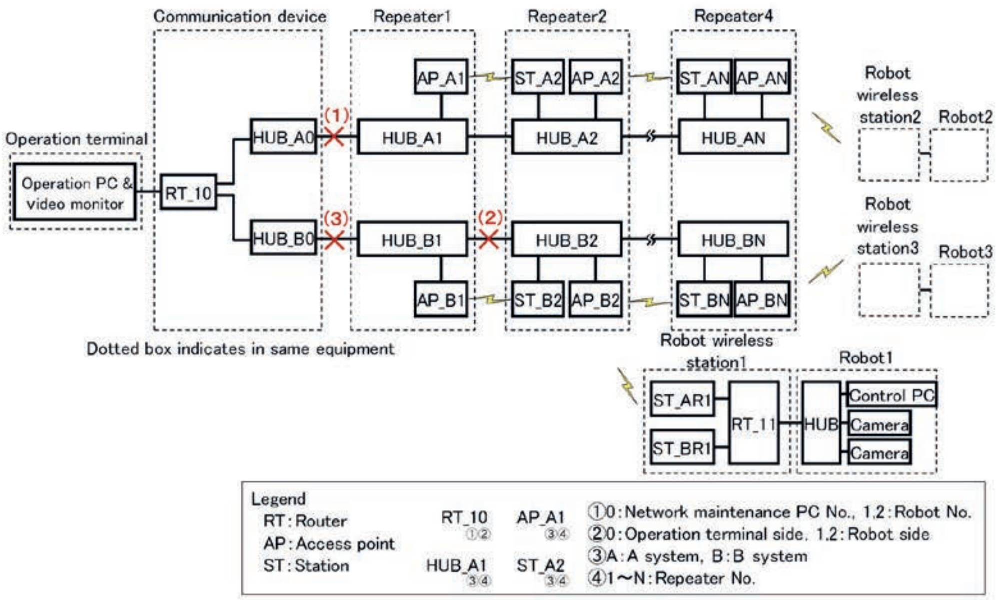

FIG. 18. Communication error test structure.

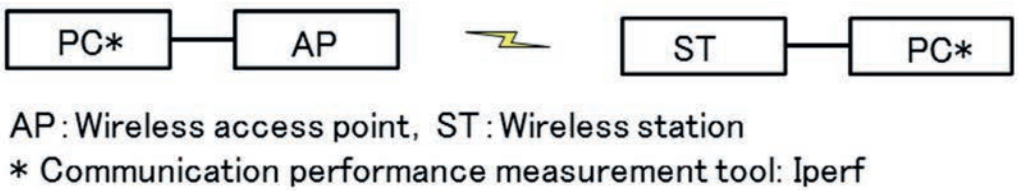

FIG. 19. Communication performance measurement structure.

TABLE 9. RESULTS OF COMMUNICATION FAULT TEST

Test item	Result
Cable disconnection simulation test	The communication was resumed within 1 s after the cable between the repeaters had been disconnected
Device fault simulation test	The communication was resumed within 35 s after the root cable of system A had been removed The communication was not affected after the root cable of system B had been removed

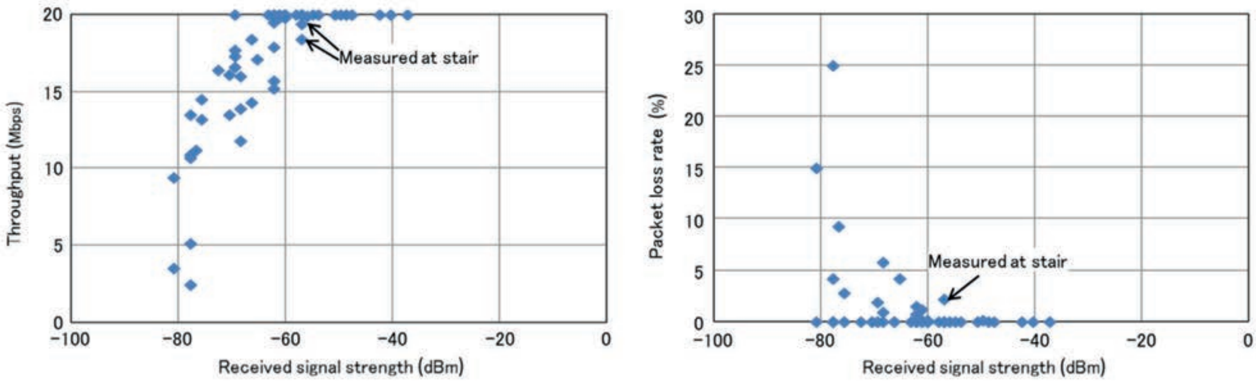

FIG. 20. Relationship between the received signal strength and the communication performance. (Left: throughput; right: packet loss rate.)

Table 9 shows the results of the tests. In each test, it was confirmed that the communication was resumed by changing the communication route and the system.

Figure 20 shows the relationship between RSSI and the communication performance in the plant. It was confirmed in the tests that the throughput is over 18.4 Mbps and the packet loss rate is under 2.2% when the RSSI is over −60 dBm.

The communication performance tests in the NPP indicated the highest performance when the RSSI was above −60 dBm. Therefore, repeaters needed to be placed at the points where they would gain an RSSI of above −60 dBm. Repeaters needed to be positioned closer than this at points where the performance showed low throughput even though the RSSI showed was more than −60 dBm. Such points were often found at the junctions of narrower and broader areas, in corridors with more than two corners and on stairways in enclosed spaces.

5. POTENTIAL APPLICATIONS

5.1. WIRELESS SYSTEMS FOR POST-ACCIDENT MONITORING

During and after NPP accidents, the following two challenges arise (among others): (1) how to obtain accurate plant status information, and (2) how to keep essential equipment in working condition. Equipment and power sources could be either temporarily or permanently damaged. A possible solution for obtaining plant status information can be to use a wireless network interconnected with plant based sensors. This section outlines various considerations in obtaining NPP status information through the use of wireless technologies.

A potential approach is to use wireless sensors to measure and monitor critical parameters continuously throughout accident and post-accident conditions. The measured data are transmitted to emergency response centres wirelessly to enable decisions to be made and actions to be taken in design basis accidents or conditions not expected by plant accident analysis. Figure 21 shows a potential arrangement of such a wireless PAM system.

There can be advantages in using wireless sensors, including ease of construction, lower financial cost and portability. However, there are many other, more important issues that have to be considered when using the technology for PAM.

5.1.1. Requirements for post-accident monitoring

The IEC 61226 [18] and IEEE 497-2002 [56] standards describe the basic requirements that may be applicable to wireless sensing devices used in PAM. The requirements can be summarized as follows:

(i) IEC 61226 [18]: The purpose of IEC 61226 is to categorize and classify I&C systems important to safety depending on their contribution to preventing and mitigating postulated initiating events and to develop requirements that are consistent with their importance to safety. A PAM system can be considered to perform Category B safety functions (see annex A of IEC 61226) and, in this case, the PAM sensors need to be designed accordingly.

(ii) IEEE 497-2002 [56]: The 2002 version of this standard is considered here because it is endorsed by Nuclear Regulatory Commission Regulatory Guide 1.97-2006 [57]. The purpose of IEEE 497-2002 is to assist users in selecting and categorizing PAM variables as well as establishing design and performance requirements. It provides guidance on the use of portable instrumentation.

The latest version of the second standard (IEEE 497-2016 [58]) addresses lessons learned from various industry events regarding instrumentation for severe accident conditions. IEEE 497-2016 covers type testing or survivability analyses that may need to be performed on systems and equipment that is intended to be used in anticipated severe accident conditions.

5.1.2. Important considerations for wireless sensors used in post-accident monitoring applications

5.1.2.1. Single failure

PAM instrumentation (described as Type A, Type B and Type C in IEEE 497-2002 and Category B in IEC 61226) has to be capable of providing the required information to operators in the presence of a single failure. Wireless sensors powered by batteries or other power harvesting devices can be the preferred choice as they do not have wired connections to other equipment, thereby reducing the probability of failure caused by other sensors or equipment. Also, it is possible to satisfy the single failure criterion at the PAM system level by using multiple redundant wireless sensors arranged so that loss of a single sensor does not adversely affect the system's ability to perform its assigned safety function.

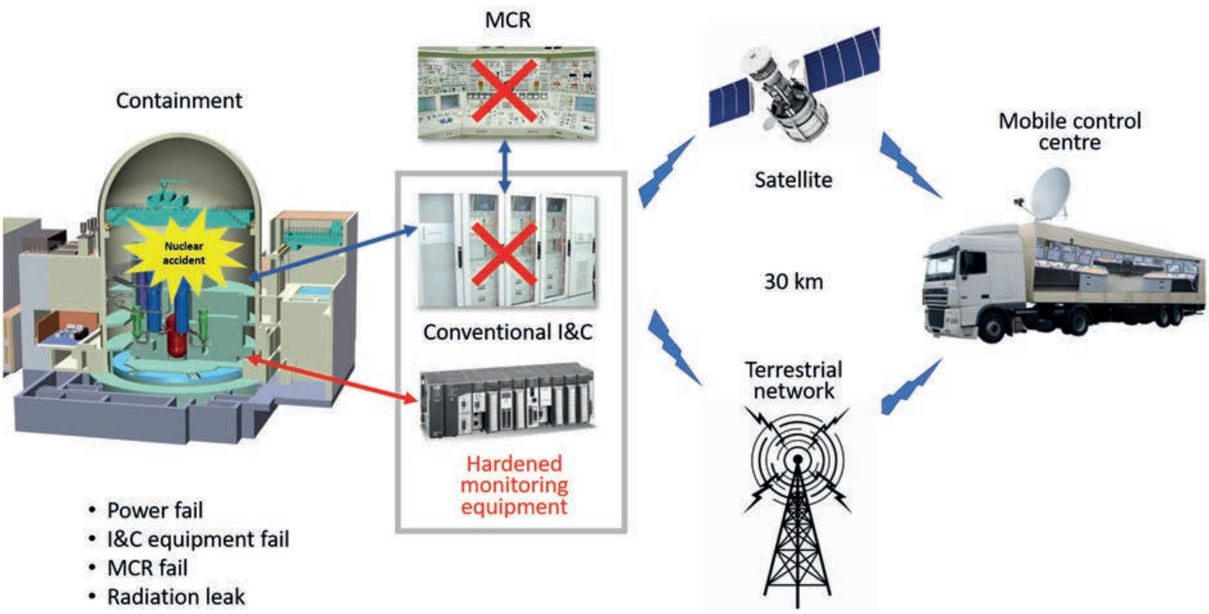

FIG. 21. Wireless sensor based post-accident monitoring system. I&C — instrumentation and control; MCR — main control room.

5.1.2.2. Independence and separation

Wireless sensors can be considered to be independent and electrically isolated as they are typically powered by batteries or power harvesting devices that have little or no wiring to other equipment. The wireless sensors need to be arranged within a PAM system so that they are not affected by failures of other equipment. This characteristic can be a major advantage when compared with wired sensors.

5.1.2.3. Power supply

There are three power supply options for wireless sensors: line power, battery power and energy harvesting (e.g. piezoelectric materials or solar cells). The differences are shown in Table 10.

Battery or energy harvesting powered wireless sensors need to be capable of providing power with the necessary voltage and duration to allow sensors to operate with a specified accuracy and reliability. Sensors built to the IEEE 802.15.4 [8] standard use a low data rate (250 kbps), which gives a longer battery life (from several months to several years) under normal conditions.

Where a wireless sensor is to be used under harsh environmental conditions, the battery or energy harvesting device needs to be qualified accordingly to demonstrate that it can survive for the specified operational lifetime.

5.1.2.4. Access control

In IEEE 497-2002 [56], the PAM wireless sensors are required to be capable of allowing access for maintenance activities such as calibration adjustments, testing at specified points and controls to remove a sensor from service. To alleviate the potential computer security vulnerability of a wireless network, measures such as encryption and network coverage control have to be considered during implementation.

5.1.2.5. Maintenance and repair

Wireless sensors are required to be capable of transmitting diagnostic information to facilitate their maintenance, repair and adjustment.

5.1.2.6. Portable instruments

When required, as part of an emergency operating procedure or an abnormal operating procedure, portable instruments might be used to obtain data. In such cases, wireless sensors can be an effective solution owing to their flexibility and ease of deployment in transmitting data within the coverage area of the wireless network. To ensure reliable transmission, aspects such as the coverage area, network parameters and bandwidth have to be considered at the design stage.

TABLE 10. ADVANTAGES AND DISADVANTAGES OF THREE POWER SUPPLY OPTIONS FOR WIRELESS SENSORS

Option	Advantages	Disadvantages
Line power	Higher data rate No dormant time	Cabling problems Electric wiring with other devices
Battery power	No cabling problems Independence and isolation	Lower data rate Dormant time to prolong battery life
Energy harvesting	No cabling problems Independence and isolation	Lower data rate Dormant time to prolong battery or capacitor life Limits on external power supply

5.1.2.7. Qualification requirements

Wireless PAM equipment and instrumentation have to be qualified to the same degree as their conventional wired equivalents, including seismic, environmental and operational constraints and EMC testing. In addition, PAM wireless equipment and instrumentation have to be qualified with any auxiliary parts, such as power sources, electronic controllers and radiofrequency transmitters. Where PAM equipment is to be used in an environment with potentially high levels of radiation, it needs to be qualified or else protected accordingly.

5.1.3. A potential wireless post-accident monitoring network configuration

The general requirements for the PAM system are to acquire specific plant and environmental attributes that are critical in monitoring a severe post-accident situation and to be able to relay this information to a base station or emergency response centre. Data acquisition and forwarding can be performed by processing and communication modules, commonly referred to as nodes. Each node can either be equipped with or connected to multiple sensors. Sensor readings can be forwarded to a base station using wireless communication channels. Nodes may be capable of forwarding data from other nodes such that the data may be transmitted to the base station through multiple hops or pathways.

In locations where wireless communication is not feasible (e.g. from the inside of a thick concrete enclosure such as a containment building), a wired channel could be used to pass data through a penetration. Devices can also be equipped with acoustic communication channels. This could be useful if a subset of the PAM is required to transmit data under water, for instance, where a containment is to be flooded to mitigate the effects of an accident. A generalized wireless network architecture is illustrated in Fig. 22.

Considering that the relayed data will be utilized in severe accident mitigation efforts, the accuracy and timeliness of the sensor data can be crucial. Therefore, all modules have to provide a high level of availability and reliability. At present, it is difficult to use wireless sensors on safety instrumentation applications because there are few suppliers providing nuclear grade wireless sensors. With the development of the technology, this situation may change in the near future.

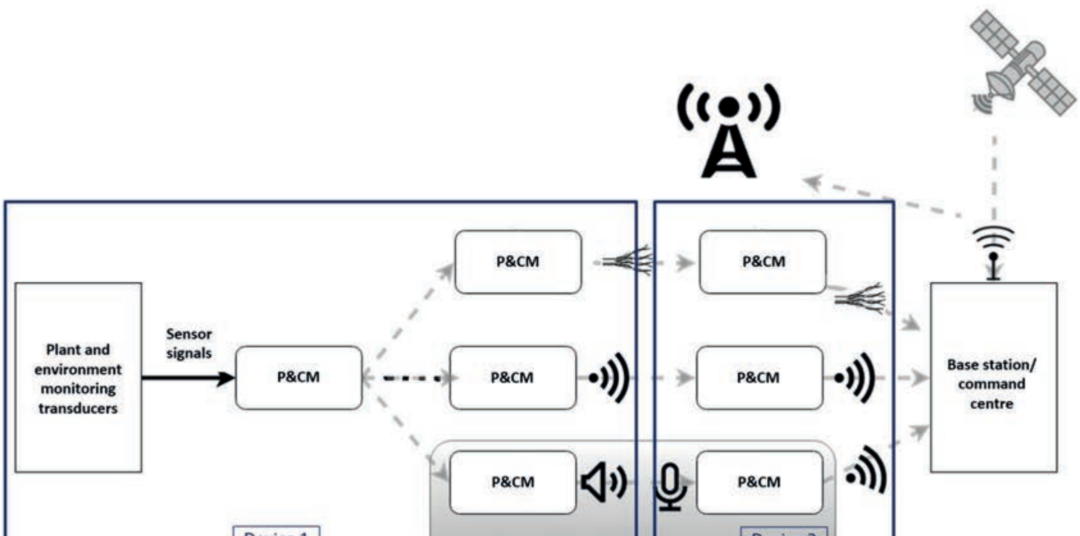

FIG. 22. General communication architecture for post-accident monitoring. P&CM — processing and communication module.

5.2. WIRELESS SPENT FUEL POOL LEVEL INSTRUMENTATION

After the release of new requirements in the wake of the Fukushima Daichi accident, utilities were directed to install reliable, extended range spent fuel pool level instrumentation in their facilities. As an example, the Nuclear Energy Institute (NEI) prepared report NEI 12-02 [59] to provide guidance to utilities in complying with the new requirement.

A spent fuel pool instrumentation system has to provide the capability to reliably monitor the spent fuel pool water level under adverse environmental conditions. This monitoring capability is essential in terms of understanding the water level in the pool and the corresponding prioritization of actions that plant operations staff can take to mitigate water inventory loss.

At many power plants, the extended range spent fuel pool level instrumentation was a subsequent installation that was not included in the original design, and long wired connections might have been difficult to realize. The system can be made partially wireless by using a wireless transmitter located outside the spent fuel pool environment such that tolerance of radiation from postulated accident conditions is not a requirement for the hardware. Power consumption should not be a critical consideration since power may be readily available. Wireless signal repeaters can be located as needed based on the plant layout. Wireless transmitters and repeaters have the capability of encrypting the data. Directional antennas may be used to minimize the potential for EMI/RFI or eavesdropping. A possible architecture of the system is shown in Fig. 23.

Each measurement device consists of a flexible stainless steel cable probe suspended in the spent fuel pool from a seismic Category 1 bracket attached to the operating deck or to the raised kerb at the side of the pool. The cable probe extends to nearly the top of the spent fuel racks. The electronics for the sensor are mounted in an adjacent room so that the instrument is not subjected to the radiation and high temperatures in the spent fuel pool area that could result from a postulated loss of water inventory in the pool.

A sensor electronics module is connected to a battery backed uninterruptible power supply and a wireless transmitter, which sends the value of the pool water level to a remote location where it is displayed.

5.3. IN-CORE RADIATION TOLERANT WIRELESS TRANSMITTER

Sensors and instrumentation that can precisely monitor process variables inside an operating nuclear reactor vessel, while withstanding its harsh environment, are of potential benefit to NPPs given the safety requirements and economic pressures faced by utilities.

Current sensors employed in measuring critical in-core parameters, such as thermocouples, resistance temperature detectors and neutron flux detectors, do not normally contain solid state electronics because of the

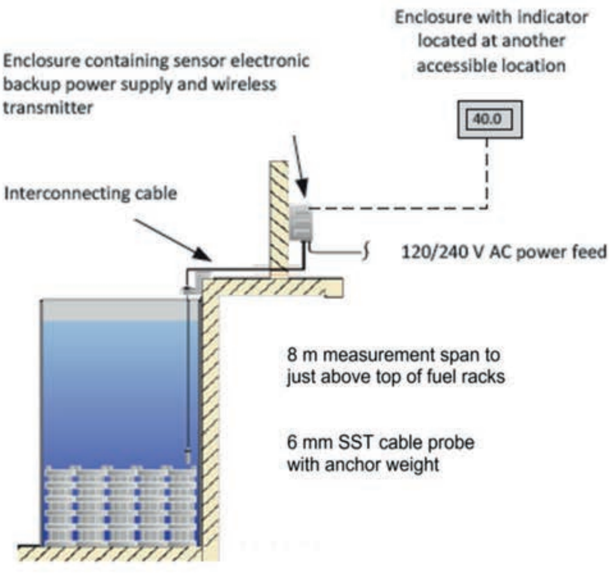

FIG. 23. A possible spent fuel pool instrumentation system architecture. AC — alternating current; SST — stainless steel.

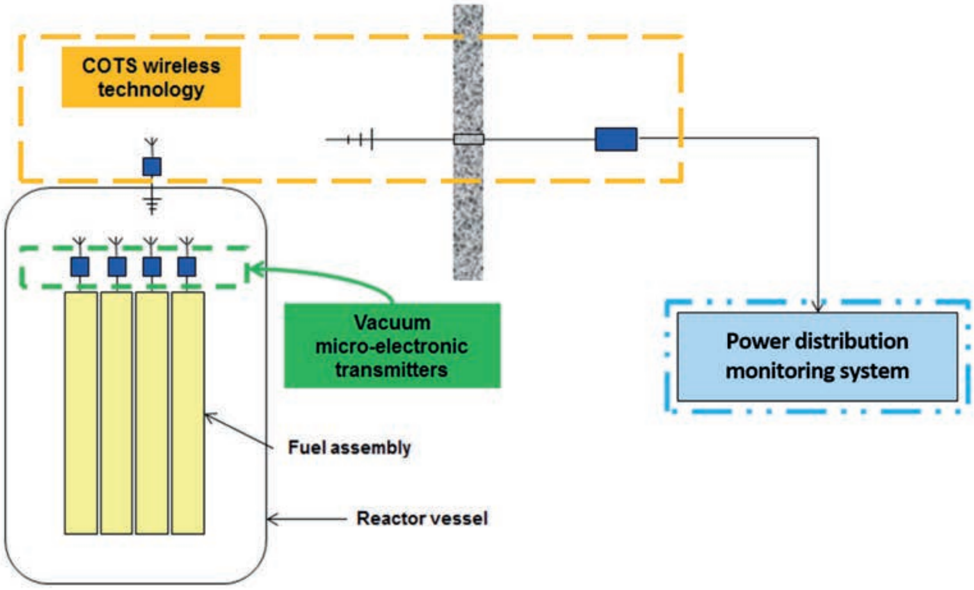

FIG. 24. In-core monitoring system with vacuum microelectronic transmitters. COTS — commercial off the shelf.

harsh environmental conditions. Thermionic vacuum devices, in which charge transport through the vacuum is accomplished by thermionically emitted electrons, are well suited to extreme environments owing to their intrinsic internal high temperature operation and radiation hardness.

Vacuum microelectronic technology is designed to perform like the classical vacuum tube triode or pentode, which are equivalent in functionality to a junction field-effect transistor. These triodes and pentodes can be designed and manufactured as discrete components, then configured in circuits to create electronic switches, operational amplifiers, comparators, high frequency amplifiers and oscillators. They can also be combined to form more complex circuits.

A vacuum microelectronic circuit can be configured as a wireless transmitter capable of continuously transmitting neutron flux data from a self-powered detector operating inside a fuel assembly top nozzle. These devices can be self-powered by harvesting gamma radiation from the reactor fuel. Figure 24 provides a high level depiction of a possible configuration within a plant.

The potential benefits of this application include the following:

— Increase in reactor operating margin owing to measurement density increase: 100% of fuel assemblies can be instrumented in place of only a fraction of them in the current designs.
— Improved reactor power distribution measurement accuracy, which will provide the capability to produce more electricity from the same amount of nuclear fuel or produce the same amount of electricity from less nuclear fuel.
— Reduction of number of reactor vessel penetrations, as well as reduction in mineral insulated cabling and operating costs associated with equipment and penetration inspection.

6. EMERGING TECHNOLOGIES AND CHALLENGES

This section examines emerging wireless technologies that can potentially be applied in NPPs. All these technologies focus on specific difficulties that are caused by the very complex structures of an NPP environment (heavy concrete and metal structures, large objects in the areas, no direct sight between transmission and reception points, etc.). Annexes VI–X provide detailed information on the research done in these subject areas.

6.1. WIRELESS COMMUNICATION THROUGH EXISTING APERTURES IN WALLS AND DOORS

The benefits of through-wall wireless communication are a reduction in construction cost and an increase in equipment placement flexibility. In an NPP, reinforced concrete walls can be more than 1 m thick, with high rebar density. Because the typical transmission loss in such reinforced concrete walls is almost 100 dB/m, communication between areas on either side of reinforced concrete walls (i.e. through the wall) is almost impossible.

However, certain sections of the reinforced concrete wall, such as doorways, are considered as apertures in finite difference time domain calculations. The method, calculations and experiments with aperture structures are introduced in detail in Annex VI. As a result of calculations at 980 MHz, 2400 MHz and 5000 MHz, it was confirmed that transmission around reinforced concrete structures is feasible with frequencies lower than 5000 MHz. See Annex VI for more details on this topic.

6.2. ELECTROMAGNETIC PROPAGATION ESTIMATION USING RAY TRACING METHODS

Electromagnetic propagation is influenced by many factors, including frequency selection, the transmission medium and the physical barriers that could reflect, diffract and attenuate the signal. When designing wireless base station locations for an NPP, consideration of the radio wave propagation caused by electromagnetic wave reflection and the absorption of walls, ceilings or other facilities in the plant is needed. Radio wave propagation prediction simulators are necessary for planning base station locations. For the site specific radio wave propagation estimation, ray tracing methods may be appropriate because of the plant's large space, provided that complex interference effects (e.g. scattering or diffraction effects) from objects in the scenario can be considered negligible.

The ray tracing method approximates electromagnetic waves as optical rays. The paths of rays from a base station to a mobile station are derived by the method. Rays are radiated from the base station in various directions. If a ray collides with an object, it reflects from the object, transmits through or diffracts (see Fig. 25). If the ray from a base station eventually reaches the mobile station, it is considered as received by the mobile station.

A ray consists of reflected, diffracted and transmitted elements. The attenuation coefficients of those elements can be calculated, for example, with Fresnel equations. There are two ways to estimate the total power received by the mobile station. One is to sum up the electromagnetic fields of all the rays (field sum) and the other is to sum up the powers of all the rays (power sum) (see Annex VII for the details). Based on the calculations and previous experiments described in Annex VII, the power sum method appears to be a better method for antenna deployment.

In conclusion, the application of radio propagation estimations by the ray tracing method to optimize generic algorithms is useful for selecting optimal locations that satisfy requirements for a wireless network such as the power level, SNR and throughput.

For more complex cases, other methods such as physical optics or hybrid methods have to be considered. Physical optics is a high frequency approximation, created by using ray optics to estimate the field on a surface and then integrating that field over the surface to calculate the transmitted or scattered field. Therefore, physical optics is able to model several interference effects (e.g. diffraction, scattering and polarization effects), but not the dependence of diffraction on polarization. Physical optics is particularly suited for hybridization with other

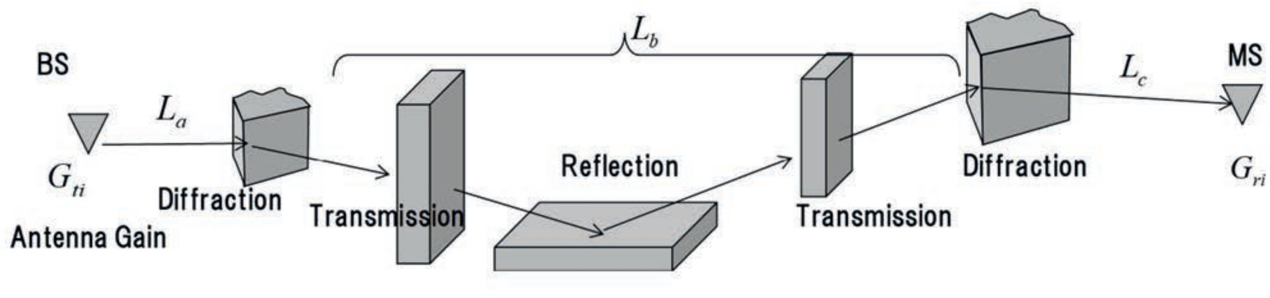

FIG. 25. The path of a ray from a base station (BS) to a mobile station (MS) via a reflection, two diffractions and two transmissions.

electromagnetic methods to simulate complex electromagnetic propagation scenarios, including those involving large structures.

Optimization algorithms are also needed because the base stations' locations may be affected by a wide range of combinations of factors.

6.3. ELECTROMAGNETIC NON-LINE OF SIGHT PROPAGATION

At NPPs, there are many large, medium and small structures and objects that are obstacles to wireless communication. The wireless signal can be blocked by the concrete wall of the containment and by many additional heavy concrete and metal structures. Wireless communication in such areas is referred to as non-line of sight communication. Numeric modelling and electromagnetic simulation in the presence of engineered barriers can be applied to plan this type of communication.

In general, when approaching the electromagnetic design, different mathematical tools are available for evaluating the electromagnetic field in each point of the environment considered.

Given the 'electrical size' of the problem of interest (a typical reactor hall contains structures the dimensions of which are orders of magnitude larger than a 2.4 GHz wavelength), full wave methods can be considered impractical. Hence, the preferred choice for the electromagnetic design may be asymptotic methods, which adopt fundamental, physical approximations of the Maxwell equations.

The simulation environment geometry has to be designed such that both diffraction and reflection are considered, and the line of sight is usually occluded by the presence of conducting walls or concrete barriers. Simulation results obtained under simplified hypotheses show that in such environments the quality of the link greatly depends on the positioning of the transmitter and receiver antennas. A significant improvement can be obtained using directive antennas and employing low noise electronics and wireless reconfigurable mesh networks. A detailed description of the full wave and asymptotic expansion methods can be found in Annex VIII.

6.4. OPTIMUM POLARIZATION WIRELESS COMMUNICATION

Since existing infrastructure systems, including NPPs, have many pieces of equipment that are arranged to maximize area efficiency, all the radio devices that are used to construct a wireless network would ideally be set on the surface of the equipment. These radio devices use reflected waves for wireless communication because there is usually no line of sight propagation path.

The mobile device cannot determine optimum polarization of its antenna because it cannot predict either the true propagation path or the polarization shift occurring at reflecting points on the surfaces of the equipment. Therefore, a radio device that uses a fixed polarized wave may lose communication when the polarization of the arriving wave is spatially perpendicular to the antenna.

A novel wireless system that uses a new mode of electromagnetic waves, called the rotating polarization wave (RPW) technique, to achieve improved communication in the quasi-static radio environment without line of sight paths might be considered to resolve the issue. Wireless communication using RPW achieves good communication quality and maintains it because both the transmitter and receiver use the best polarizations even if the wireless environment surrounding them changes. Additionally, wireless networks that use RPW achieve more stable operation against changes in the surrounding environment, such as changes in equipment layout, than conventional, fixed polarization wave transceivers. A detailed description of this technology can be found in Annex IX.

6.5. WIRELESS POWER TRANSFER

Wireless power transfer of a few watts over distances of several to tens of metres could be a promising solution for battery free wireless sensors in ubiquitous networks and in NPPs, where wireless sensors consist of three major parts: a sensing device, a communication device and an energy source.

Several wireless power transfer methods have been suggested as possible energy sources for use in various wireless sensors. Annex X references the details of the experiments and results achieved with a specific wireless power transfer system.

7. SUMMARY

Wireless technologies provide the ability to economically add instrumentation to improve the monitoring capabilities of NPP equipment, particularly difficult to access equipment. Wireless capable devices can efficiently complement or replace current systems for monitoring plant equipment and parameters. The technology has the potential to eliminate cable installation costs and provide increased flexibility for data acquisition relating to equipment and plant processes to enhance condition monitoring programmes and enable easier access to other plant data that are difficult to attain through conventional methods.

This publication is a summary of the findings of an IAEA CRP and details the current state of the art, based on research and case studies, regarding the deployment of wireless technologies in NPPs. The CRP considered codes and standards governing the use of wireless technologies that have been developed and tested to assure safe and reliable operation. There are numerous standards and guidance documents for the nuclear industry related to I&C systems that include key principles to support their design, implementation and use, notably DID in I&C architectures and measures to protect against cyberattacks, achieve EMC and provide appropriate levels of system and equipment reliability. While these standards and guidance documents were not necessarily developed for wireless technologies, it is apparent that they may be adapted and interpreted to support the application of these technologies.

Attributes of wireless technologies, such as radiofrequency communication protocols, network topology, signal propagation and potential energy sources, are described in this report with an emphasis on their significance in an NPP. Guidance is provided to address NPP specific considerations for wireless devices, such as environmental and radiation effects, EMC and integration with existing I&C systems. One of the biggest challenges with implementing wireless technologies in an NPP is wireless signal propagation and optimizing the location of wireless devices to maximize coverage. This publication outlines methods for resolving the signal propagation concerns using various simulation tools.

Even though there are numerous challenges, wireless technologies have successfully been used in various applications throughout the nuclear industry. The knowledge and lessons learned from these installations can be used by the nuclear industry to further implement wireless technologies for similar applications. The case studies of wireless technologies in NPPs that are documented in this publication include the following:

- Measurement and wireless transmission of process parameters, such as temperature, level, flow, pressure, humidity and leak detection, using wireless sensors that have been developed and deployed in nuclear and other industry sectors (Section 4.2). These sensors can be installed in circumstances where conventional wired solutions may not be practicable due to space or economic considerations.
- Use of wireless sensors on rotating equipment to facilitate predictive maintenance strategies based on fault diagnostics and prognostics for pumps and motors to reduce dependence on routine scheduled maintenance activities (Section 4.3). Wireless sensors can provide convenient and efficient deployment of monitoring systems on critical plant equipment that may not be possible using a wired solution.
- Background radiation and environmental monitoring using wireless radiation monitoring devices that have been developed to allow for centralized monitoring of the radiation environment at an NPP (Section 4.4). These wireless radiation monitoring devices may be deployed outdoors and, as such, signal propagation and attenuation need to be addressed. These sensors and installations could potentially be modified for use in PAM scenarios where monitoring of critical instrumentation is necessary in circumstances when normal sources of power may be temporarily unavailable.
- Remote handling systems that are used in highly radioactive and inaccessible areas due to extreme environmental conditions, where wireless connectivity of these machines has been effective in supporting operations (Section 4.6).

As the range of possible applications for wireless technologies continues to evolve and be considered for wider deployment in NPPs, more specific standards, such as IEC 62988 [15], are being prepared to specifically address the selection and implementation of wireless devices.

Unique challenges encountered in applying wireless technologies in NPPs include computer security, EMI/RFI, signal coverage, device power sources, effects of interference and multipath propagation caused by existing structures, and potential uses during severe accident scenarios considering ionizing radiation and other adverse environmental impacts. The information contained within this CRP report, arising from a substantial research programme, can serve as an initial reference for addressing the above mentioned challenges and for establishing design requirements to ensure reliable wireless communication.

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Annex I

PROPOSED HIGHLY RELIABLE WIRELESS COMMUNICATION TECHNOLOGY

Hitachi, Ltd, Japan

I–1. SELECTION OF A PLANT WIRELESS SYSTEM AND CONSIDERATIONS

I–1.1. Application and wireless system requirements

This annex describes a plant wireless system that can be used to monitor and control instrumentation systems for a wide area, such as a turbine hall and a containment building occupying a 100 m × 100 m × 100 m volume. Figure I–1 shows the layout of the plant wireless system. It assumes that the plant wireless system is created between a gateway device that is connected to a control system and remote terminal blocks, which connect to sensors and actuators. Remote terminal blocks communicate data between field devices and controllers. The target specification of the plant wireless system is shown in Table I–1.

I–1.2. Wireless system configuration

Dual redundant transmission routes and an alternate route are adopted to ensure that high reliability can be achieved from the wireless communication system. The IEEE 802.11a/g [I–1] standard is adopted as the physical layer of this wireless system. A maximum of five signal data hops were selected after consideration of both the

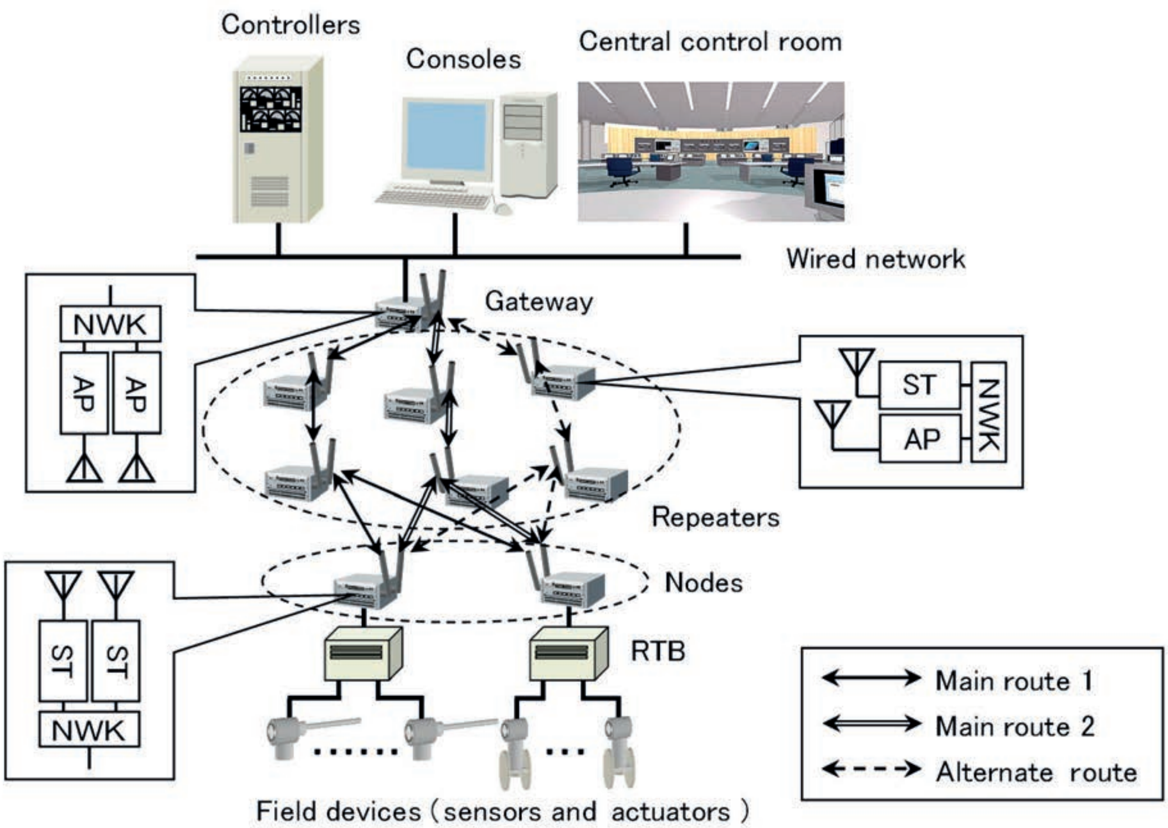

FIG. I–1. Overview of plant wireless system. AP — access point; NWK — network; RTB — remote terminal block; ST — signal transmitter.

TABLE I–1. TARGET SPECIFICATION

Item	Specification
Number of signals	1500 points
Data type	16 bits/point
Communication cycle	100 ms
Communication space	100 m × 100 m × 100 m
Throughput	Over 1 Mbps
Latency time	50 ms or less
Data arrival rate	99.99% or more

communication area and the capability of the IEEE 802.11a/g physical layer. This approach was taken to maintain a specified latency and to account for signal attenuation. Figure I–2 shows an overview of the proposed dual route redundant wireless network.

This illustrates a data packet being transmitted from the gateway to the node. The wireless equipment, such as the gateway or the node, duplicates a data packet coming from the terminal equipment. The wireless equipment assigns an identical sequence number and a network header to the data packet. Each duplicated data packet is transmitted to different routes in accordance with route information. The receiving node checks the sequence number of the received data packet to determine whether the data have already been received or not. When the data packet is the received for the first time, then the packet is retransmitted along the communication route. However, if

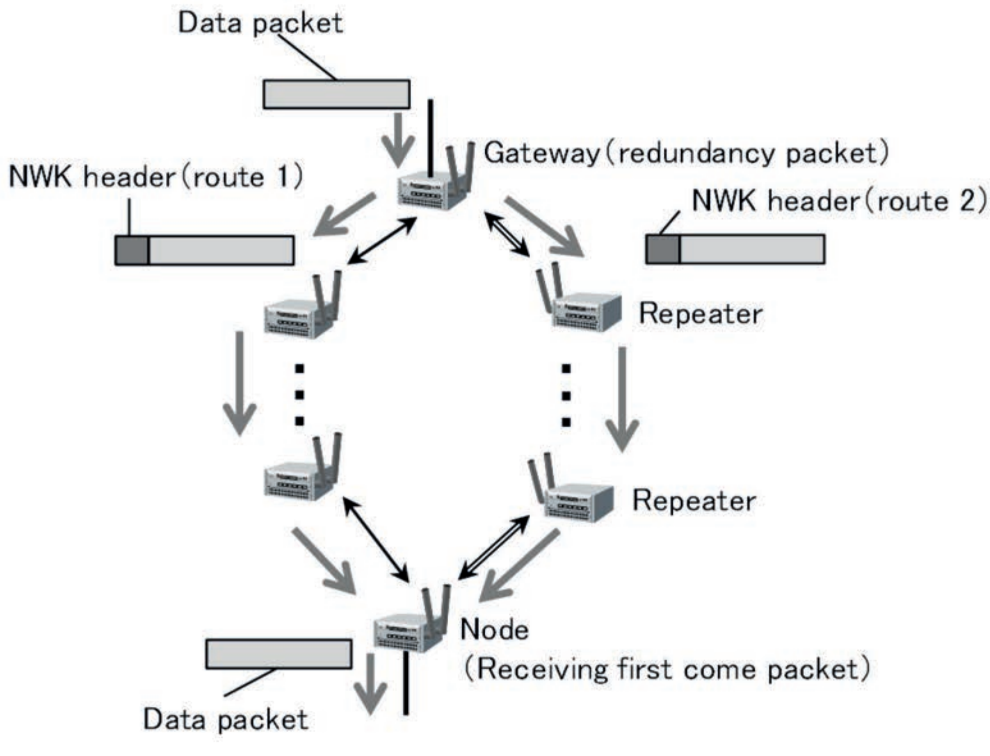

FIG. I–2. Tree topology network with dual parallel paths. NWK — network.

the data packet has already been received, then it is discarded. By sending the same data along different routes, the wireless equipment can potentially receive a data packet with low latency. Compared with single route transmission, the wireless equipment may receive a data packet earlier, thereby reducing the transmission time.

If the wireless equipment detects a communication error on one route, both the gateway and the node can change the route to avoid the error. For example, if the successful data arrival rate on single route transmission is 99% (i.e. the probability of transmission error is 0.01), then the successful data arrival rate on a dual route transmission is 99.99% (i.e. the probability of both channels failing is 0.0001).

I–2. FRAME STRUCTURE FOR WIRELESS SENSOR NETWORKS

I–2.1. Introduction

Figure I–3 shows a frame format of the data block retransmission method and Fig. I–4 shows an example of data block retransmission flow after detecting a transmission error. The data payload in the frame format has some data blocks, error correction codes to detect the communication error and data block numbers. The medium access control (MAC) header has delivery information such as a destination address and a source address. If a communication error occurs in the MAC header, the data payload cannot be received at all. To ensure the data payload is received, the MAC header of this method has error correction codes and is repeated three times.

The receiver checks whether the MAC header of the received packet has an error. If the destination of the data packet is the receiver itself, then the receiver checks each data block. When the receiver detects an error, the receiver requests the data block that has an error and the subsequent data blocks from the transmitter. The transmitter sends or resends the requested data packets. When the receiver has received all correct data blocks, it sends the acknowledgement packet that indicates that the transmission has been successful. The data block retransmission method reduces the retransmission data volume, so the successful data arrival rate can become higher and the latency lower.

I–2.2. Test results

An experimental wireless system was tested in the simulated factory environment shown in Fig. I–5, comprising a 20 m × 24 m site containing a number of metal pipes and operation panels. Since the site was small, the wireless system was configured as two hops. In addition, two Wi-Fi wireless devices were used as an interference source.

Table I–2 shows the communication channel setting and the received signal strength between wireless devices where the communication channels of the Wi-Fi were set to interfere with one hop in each route. Table I–3 shows the experiment’s parameters. The wireless system communicated at 500 kbps in both directions and the successful data arrival rate and transmission latency were measured using a ‘ping’ command.

Table I–4 shows test results for a network configured with two routes and two hops where the data arrival rate is 99.999% and the maximum latency is 29 ms. The results of the experiment were evaluated and estimated for a two-route and five-hop scenario. In this case, the successful arrival rate is calculated to be 99.996% with a maximum latency of 36.25 ms, which meets the target specification.

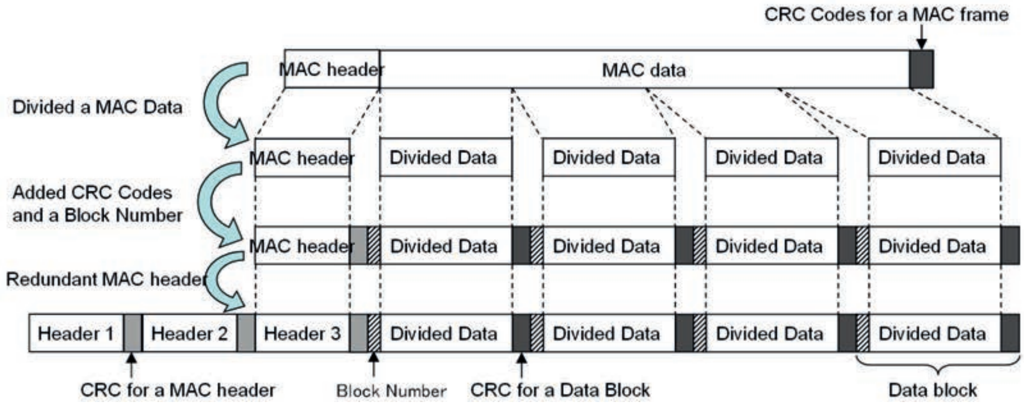

FIG. I–3. Frame structure of the divided data retransmission method. CRC — cyclic redundancy check; MAC — medium access control.

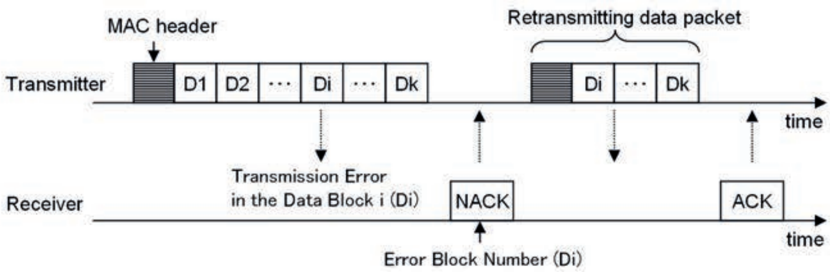

FIG. I–4. Example of retransmission when a communication error has occurred. ACK — acknowledged; MAC — medium access control; NACK — not acknowledged.

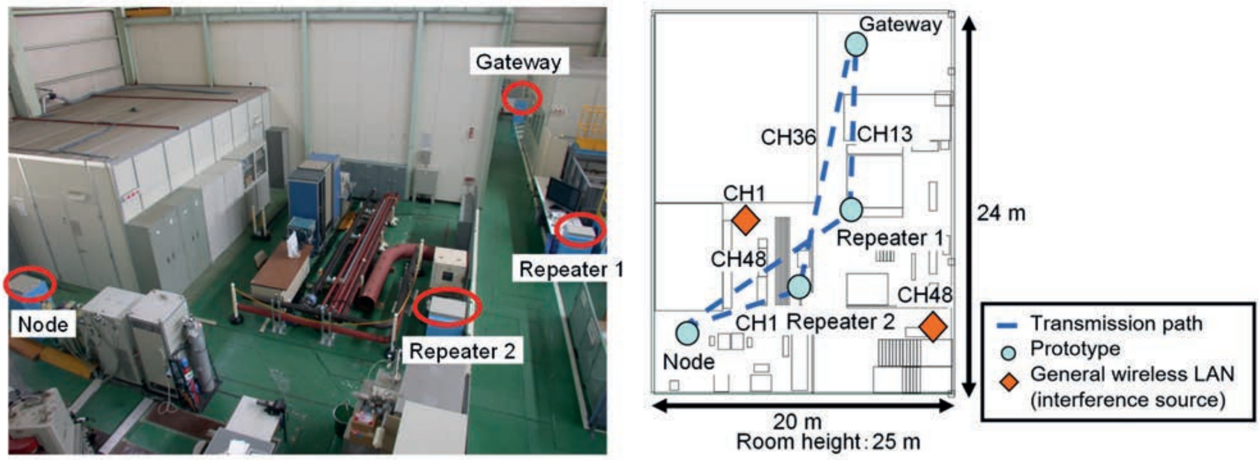

FIG. I–5. Test environment: overview (left); experiment configuration (right); LAN — local area network.

TABLE I–2. CHANNEL SETTING AND RECEIVED SIGNAL STRENGTH BETWEEN WIRELESS DEVICES

Item	Channel (frequency)	Received signal strength
Gateway to repeater 1	13 (2.472 GHz)	−77 dBm
Repeater 1 to node	48 (5.240 GHz)	−73 dBm
Gateway to repeater 2	36 (5.180 GHz)	−76 dBm
Repeater 2 to node	1 (2.412 GHz)	−79 dBm

TABLE I–3. EXPERIMENT PARAMETERS

Item	Parameter
Data length	1024 bytes
Data throughput	1 Mbps
Interference throughput	1 Mbps
Data transmission count	100 000 times

TABLE I–4. TEST RESULTS

Item	Target specification	Test result	Evaluated value
System configuration	Two routes, five hops	Two routes, two hops	Two routes, five hops
One way/round trip	One way	Round trip	One way
Number of tests	—[a]	100 000	—[a]
Packet loss count	—[a]	1	—[a]
Data arrival rate (%)	99.99 or more	99.999	99.996
Latency time (ms)	50 or less	29.0	36.25

[a] —: data not available.

REFERENCE TO ANNEX I

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Annex II

IN SITU ELECTROMAGNETIC INTERFERENCE/RADIOFREQUENCY INTERFERENCE TESTING OF NUCLEAR POWER PLANT EQUIPMENT

Analysis and Measurement Services, United States of America

One of the main concerns regarding wireless technology is the potential for electromagnetic interference/radiofrequency interference (EMI/RFI) with existing nuclear power plant (NPP) equipment. A project was conducted at an NPP to determine the performance of sensitive plant equipment in the presence of cellular phones and other mobile devices [II–1]. The project consisted of three activities: a site walkdown, an EMI/RFI site survey and in situ immunity testing.

II–1. SITE WALKDOWN

A site walkdown was performed to identify plant, equipment and components that may be critical to the safe and reliable operation of the plant. During the walkdown, the installation of the equipment was reviewed to identify potential deficiencies in the routing, shielding and grounding of cables and components. Based upon the results of the walkdown, numerous systems were identified that should be further investigated to determine their vulnerability to EMI/RFI from wireless devices. These included sensitive protection equipment, equipment important to power production and equipment that may be vulnerable to EMI/RFI based upon its installation. In general, good installation practices had been used for sensors and cabinets throughout the turbine building. The amount of exposed cabling was minimized, and the internal wiring of the panels was maintained near their metal structure, which would minimize their reception and radiation of electromagnetic energy. In addition, the conductors within a cable were only separated from one another near the terminal block connection, minimizing the potential for EMI/RFI. Therefore, in general, the panel internals were likely to be immune to EMI/RFI with the panel doors closed, but needed to be tested for immunity with the panel doors open.

Figure II–1 shows photographs taken during the plant walkdown. These photographs show several elements of good installation practice, such as continuous conduit or cable tray bonding to the cabinet to prevent exposed cabling and minimization of conductor separation at the terminal blocks. Also shown are a number of items that should be further explored, including glass windows on cabinet doors, exposed instrumentation and digital displays on panel doors. While the presence of these items does not indicate a susceptibility to wireless signals, it does allow for exposure to wireless signals that may give rise to potential vulnerabilities.

FIG. II–1. Various aspects of plant equipment installation identified during walkdown.

II–2. CHARACTERIZATION OF THE ELECTROMAGNETIC ENVIRONMENT

Site surveys use passive antennas to capture and characterize the electromagnetic environment in a certain area. The two main purposes of characterizing the electromagnetic environment are to identify sources of frequencies that may compete with wireless devices and to indicate potential equipment vulnerabilities [II–2].

At the NPP, nearly 20 different areas throughout the four elevations of the turbine building, including the 4 kV and 12 kV switchrooms, diesel generators and a central control room, were characterized during an emissions site survey. The site survey was performed in the frequency range of 700 MHz to 8 GHz using guidance based upon the RE102 test method of Military Standard MIL-STD 461E [II–3]. The RE102 test method is an electromagnetic compatibility qualification test that measures the high frequency radiated emissions from a piece of equipment. The main sources of emissions were existing site communication devices (cordless phones and Wi-Fi devices) and external cellular signals.

A photograph of the emission site survey testing is provided in Fig. II–2. Figure II–3 contains a sample of results of the emissions testing in the control room. The largest sources of emissions identified were a microwave oven and cordless phone being operated in the control room as well as Wi-Fi access points in the plant.

FIG. II–2. Emissions site survey.

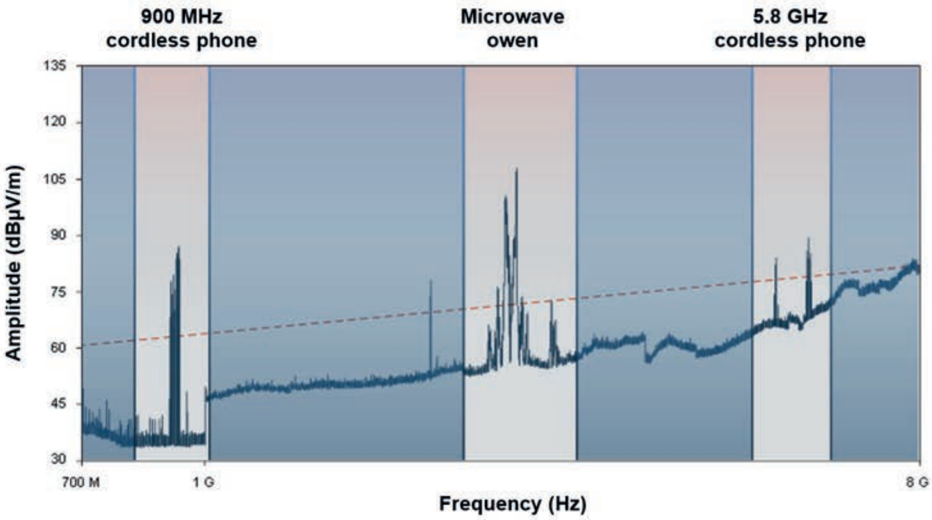


FIG. II–3. Sample results of emissions site survey in the control room.

II–3. IN SITU IMMUNITY TESTING OF NUCLEAR POWER PLANT EQUIPMENT

Once the critical equipment and potential vulnerabilities were identified during the walkdown and site survey testing was completed, the next step was to perform immunity testing of selected plant equipment. Immunity testing can be used to provide objective evidence regarding equipment's susceptibility to signals from wireless devices. This testing was performed while the NPP was shut down for refuelling to minimize the risk to plant operation. In addition, because the NPP's two units share adjacent control rooms and one unit remained operational, sample central control room equipment was tested in the training centre and with development simulators rather than in the control room.

The immunity testing was performed by generating radiofrequency energy at the same frequencies as wireless devices and radiating it onto equipment and cables within the plant. Various frequency bands allotted for cell phones between 700 MHz and 6 GHz were selected such that the electromagnetic field strength at the equipment under test was maintained above 10 V/m. The testing was based on the RS103 high frequency radiated susceptibility test method of MIL-STD 461E [II–3]. The test method is intended to be used when qualifying equipment for electromagnetic compatibility in a laboratory, but was modified for the field testing at the NPP. A block diagram and photograph of the immunity test equipment are provided in Figs II–4 and II–5. The plant equipment that was tested included the following types of equipment:

— Various Barton and Rosemount pressure, level and flow transmitters;
— Various relays and modules associated with the 4160 V vital bus;
— Seismic trigger instrumentation;
— Digital feedwater control system development simulator;
— Turbine control system development simulator;
— Source, intermediate and power range nuclear instrumentation system training drawers;
— Solid state protection system training cabinet;
— Radiation monitor display unit training drawer.

While the frequencies for the wireless devices were being generated, the plant equipment was monitored for degradation. Local and remote indication as well as plant computer data points were used to monitor for degradation. Over 65 different pieces of plant equipment were tested and vulnerabilities were identified in several pressure, level and flow transmitters, radiation monitors and signal conditioning units. The output of the plant process computer for a pressure transmitter during the immunity testing is shown in Fig. II–6. The transmitter showed signs of vulnerability when the transmitting antenna was placed 4.5 m away from the panel housing the transmitter with the panel door open. At a distance of 6 m, the transmitter did not exhibit any vulnerability. When the panel door was closed, the pressure transmitter showed vulnerabilities at a distance of 0.6 m but was immune when

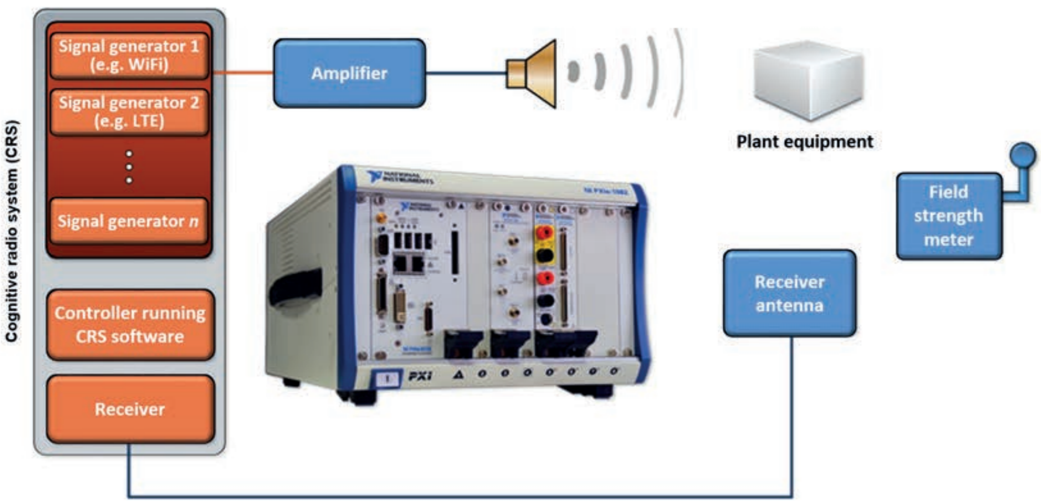


FIG. II–4. Block diagram of the immunity test equipment.

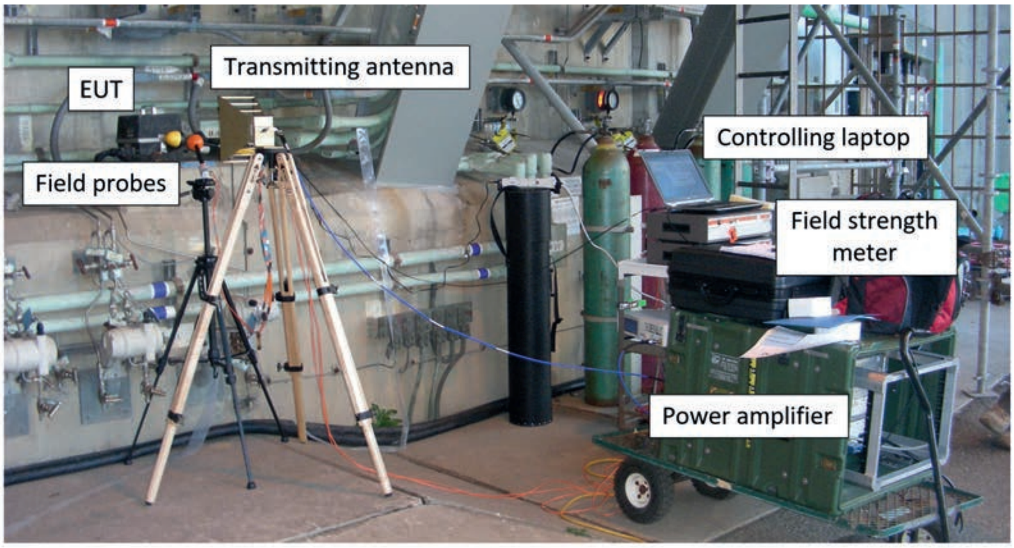


FIG. II–5. Photograph of the immunity test equipment. EUT — equipment under test.

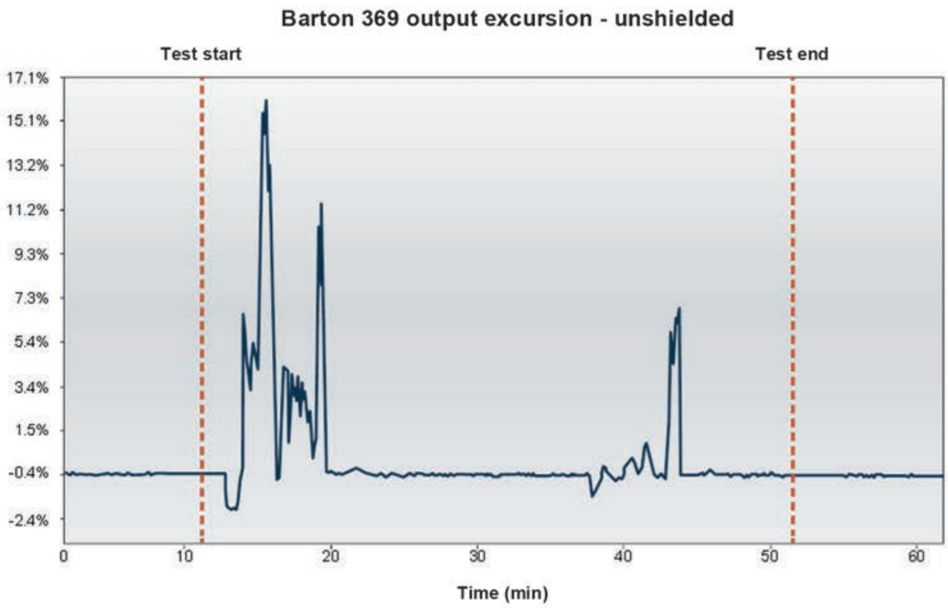


FIG. II–6. Output of pressure transmitter with panel door open and transmitting antenna placed 4.5 m away.

the transmitting antenna was placed 1.2 m away from the panel. With additional shielding material placed over the transmitter and associated cabling within the panel, the pressure transmitter was immune at much closer distances. Similar shielding techniques were applied to the other vulnerable equipment to mitigate any vulnerabilities at distances greater than 0.6 m.

II–4. CONCLUSIONS

Verifying the immunity of an NPP to EMI/RFI from cell phones, Wi-Fi, Bluetooth and other wireless devices is important, as these devices can be used in an NPP. Numerous components were tested in situ in an NPP, as well as in the training centre and development area, for their immunity to signals from wireless devices. In general, a majority of the power plant equipment that was tested (~90%) was immune to the radiofrequency energy. The vulnerabilities that were identified in the remaining plant equipment were mitigated through the use of additional radiofrequency shielding of the components. The information gathered during the testing activities allowed the NPP to establish objective exclusion zones based upon actual system performance in the presence of wireless signals.

REFERENCES TO ANNEX II

[II–1] KIGER, C.J., MOAREFY, A., “Assessing the vulnerability of plant equipment to interference from wireless devices”, Proc. 56th Annual Symp. of the Power Industry Division (POWID) of the International Society of Automation, Orlando, 2013, International Society of Automation, Research Triangle Park, NC (2014).

[II–2] KIGER, C.J., “Empowering the nuclear industry’s mobile workforce: Are exclusion zones enough?”, Proc. American Nuclear Society Annual Meeting, Atlanta, GA, 2013, American Nuclear Society, La Grange Park, IL (2013).

[II–3] DEPARTMENT OF DEFENSE, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, Military Standard MIL-STD-461E, DOD, Washington, DC (1999).

Annex III

INTERFERENCE DETECTION AND MITIGATION

Egyptian Atomic Energy Authority, Egypt

III–1. INTERFERENCE DETECTION USING PACKET DELIVERY RATIO METHOD

In the packet delivery ratio method, the detection of jamming attacks or radiofrequency interference is achieved by exploiting the relationship between received signal strength and packet delivery ratio (PDR) in accordance with the following algorithm:

```
Measure PDR
If PDR < threshold
        Sample signal strength
        If signal strength < threshold 1
             No jamming
        Else report jamming
Else no jamming
```

Under normal conditions, a high signal strength is expected to result in a high PDR as there is no interference, and conversely a low signal strength is consistent with a low PDR measurement. In a case of signal jamming, signal strength can be high while the PDR is low. Therefore, this algorithm checks for low PDR and high signal strength as an indication of a jamming attack. To quantify the impact of the RFI, signal throughput can be used as a metric that defines the amount of data that has been delivered between network nodes.

III–2. INTERFERENCE PREDICTION USING CHANNEL TEMPERATURE

A channel is assumed to be licensed to a primary operator, such as the Global System for Mobile Communications (GSM), with parameters shown in Table III–1. The sensor network acts as a secondary network, which dynamically uses the licensed channel in underlay mode provided that the interference temperature on the channel does not exceed a predefined threshold within the region. In simulations, it is assumed that the time is slotted, and each slot is equal to the time required to transmit a fixed size information packet. Transmissions by sensor nodes on channel C contribute to the interference generated by the secondary sensor network. Although each sensor node needs to locally measure and compute the interference temperature for all the channels, focus is given to one of the designated sensor nodes (referred to as a measurement node), which performs the measurement and computation of the interference temperature of the designated channel C. Similar computations need to be carried out for all the other available channels on all the sensor nodes.

The interference threshold for channel C is assumed to be equal to 10^{-8} W, which is roughly equal to the interference temperature of 362×10^{7} K. In each time slot, if the measurement node senses interference and computes the equivalent temperature as exceeding the above threshold value, it records symbol 1; otherwise, it records symbol 0. A total of L observation symbols is generated, which are divided into (L/T) sequences, each of length T. The first sequence is used as a training sequence, whereas the remaining ones are used as test sequences (see Ref. [III–1]).

Measurement of an observation sequence for initial T time slots for channel C is done. Then, the node predicts the observation sequence for the next T time slots using a trained hidden Markov model (HMM) for the same channel. Accordingly, the channel availability metric (CAM) is calculated. The node selects the channel with the highest CAM to be used for transmission. Hence, a node can select a preferable channel for communication from a minimal interference perspective. Training probabilities for transition and emission matrices are generated from

TABLE III–1. CHANNEL PARAMETERS

Transmission parameter	Value
Carrier frequency	900 MHz
Channel data rate	270 Kbps
Bandwidth	200 kHz
Modulation	BPSK[a]
Transmission power	0.01 W
Packet format	Unformatted
Packet size	2700 bits
Traffic source model	Exponentially distributed on–off model (sensor node)
Mean 'on' sojourn time for sensor nodes	For nodes belonging to red patches: 30 s For nodes belonging to green patches: 15 s
Mean 'off' sojourn time for sensor nodes	For nodes belonging to red patches: 10 s For nodes belonging to green patches: 30 s

Note: The patches of the region where events occur more frequently and for longer durations are referred to as red patches, whereas the patches where events occur relatively less frequently and for shorter durations are referred to as green patches. A set of sensor nodes are randomly selected to belong to red patches, and the remaining nodes belong to green patches. Probability thresholds are assigned to the green patches. These thresholds need to be defined for all the frequencies in various geographical regions.

[a] BPSK: binary phase shift keying.

observations (in this work through biased probability HMM generation) using the default Baum–Welch algorithm of the MATLAB 'hmmtrain' function.

III–3. AN ANTIJAMMING STRATEGY: THE CHANNEL SWITCHING TECHNIQUE

One antijamming strategy is to use a channel switching technique. Typically, when radio nodes communicate, they operate on a single channel. When an interference source comes in range of communication and blocks the use of a specific channel, it is natural to switch to another channel. The expression of channel switching is motivated by a common physical layer technique known as frequency hopping that represents switching from one frequency to another.

In channel switching, nodes that detect themselves to be jammed need to switch immediately to another orthogonal channel to avoid a jamming interference attack and wait for an opportunity to reconnect to the rest of the network. After jammed nodes lose connectivity, their neighbours, referred to as boundary nodes, can discover the disappearance of their jammed neighbour nodes and temporarily switch to the new channel to search for them.

III–4. INTERFERENCE AWARE ROUTING PROTOCOL

Sensor nodes use the trained HMM λ = (initial π, transition A, emission B) to predict the future behaviour of a channel based on an observation sequence and compute the value of the CAM for that channel. This prediction is used to select a preferable channel for communication. Sensor nodes use the CAM value to select a primary channel for transmission. A channel with a higher availability metric value can be selected by the node as the optimal data communication channel. All other sensor nodes will make similar computations for all other available channels. Every sensor node will have the channel with the highest computed CAM as its available data communication channel. The sensor node has to provide its predicted channel behaviour through CAM evaluation to other nodes in the network to establish optimal data communication pathways.

REFERENCE TO ANNEX III

[III–1] SHARMA, M., SAHOO, A., NAYAK, K.D., "Channel modeling based on interference temperature in underlay cognitive wireless networks", Proc. IEEE Int. Symp. on Wireless Communication Systems, Reykjavik, 2008, Institute of Electrical and Electronics Engineers, Piscataway, NJ (2008).

Annex IV

RADIATION EFFECTS ON WIRELESS TECHNOLOGIES[1]

Westinghouse Electric Company, United States of America

IV–1. INTRODUCTION

Point to point, mesh or star configured wireless nodes are commonly used in many industrial applications [IV–1]. From a functional perspective, these types of commercial off the shelf options could be acceptable in a nuclear power plant (NPP). The major problem for use of wireless technology in an NPP can be the harsh environmental conditions in those areas of a plant that can potentially be subject to radiation [IV–2].

A wireless transmitter/receiver was constructed using a system on chip (SOC) integrated circuit as the main processing means and as the radiofrequency (RF) portion. This approach can provide a low power consumption and small footprint with the ability to transmit an encrypted spread spectrum signal. A second wireless transmitter/receiver was developed using discrete components such as junction field-effect transistors (JFETs), metal oxide semiconductor field-effect transistors (MOSFETs), inverters, flip-flops and timer modules. These components were selected as they can often provide a representative sample of components used in transceivers. The following sections describe each of the main components used in each wireless transmitter/receiver and their irradiation test results.

IV–2. SCOPE

IV–2.1. Microcontroller (system on chip) based wireless transmitter

The equipment under test is listed below:

- Transmitter prototype board with signal conditioning circuit;
- Receiver prototype board;
- One lithium–thionyl chloride 3.6 V, 7.7 Ah battery;
- One lithium–thionyl chloride 3.6 V, 16.5 Ah battery.

The transmitter and receiver boards contain an RF integrated circuit transceiver, a current to voltage signal conditioning front end, an analogue to digital converter and supporting circuitry, including two crystal oscillators (reference clocks), a voltage regulator, an SMA connector, resistors, inductors and capacitors.

IV–2.1.1. Transmitter board

Figure IV–1 shows the transmitter board that was tested inside a clean hot cell. As shown in the figure, the AAA batteries were not installed and instead an external power supply was used to power the board. An RF cable was connected to the SMA test point to monitor the amplitude output. The SMA test point was a high isolation coupled output from the main RF output. The input signal was connected to header J12, which is shown on the left side of the figure.

[1] This article was previously published in an earlier form in the conference proceedings of the 10th International Embedded Topical Meeting on Nuclear Plant Instrumentation, Control & Human–Machine Interface Technologies. It is reproduced here with permission.

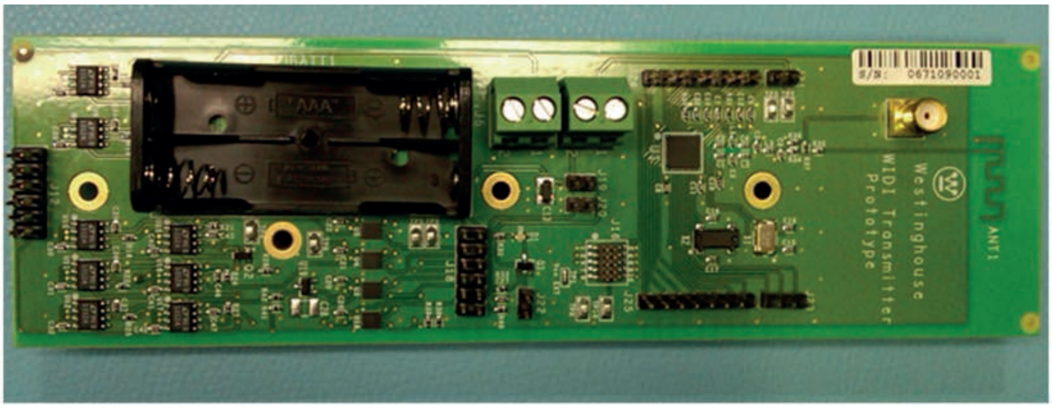


FIG. IV–1. Transmitter board with RF integrated circuit.

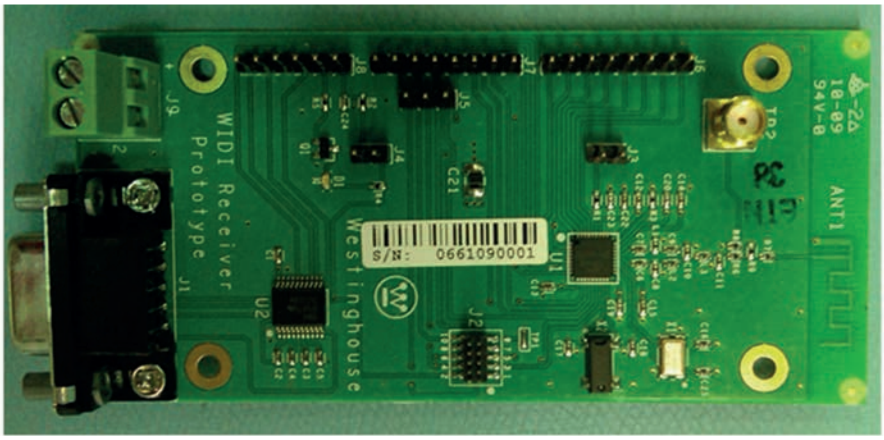


FIG. IV–2. Receiver board with RF integrated circuit.

IV–2.1.2. Receiver board

Figure IV–2 shows the receiver board that was tested inside the clean hot cell. The board was also powered externally through a J9 connector, which is shown on the upper left side of the figure. An RF cable was connected to the SMA test point in a manner similar to that described for the transmitter board. The data received were recorded though an RS-232, J1 connector shown on the lower left side of the figure.

IV–2.1.3. Batteries

Two high density D cell lithium–thionyl chloride batteries were connected to a load resistor in order to draw a current representative of that of the transmitter board current during normal operation. The resistors were located outside of the clean hot cell. The batteries under test were placed in a polycarbonate enclosure as a safety precaution owing to the potential for a radiation induced short circuit to occur. Each battery was configured to draw 22 mA.

IV–2.2. Discrete component based transmitter/receiver board

The equipment under test is listed in Table IV–1 and explained below:

- *Op amp/BJT current sources:* A general purpose operational amplifier (op amp) and common bipolar junction transistor (BJT) were configured as a voltage follower transistor driven output to create a current source to deliver 250 μA through a load resistor. The voltage developed on the load resistor was monitored externally to the unit. Four identical circuits were in place to increase the statistical sample size.
- *Clock oscillator and dividers:* A circuit consisting of high speed complementary metal oxide semiconductor (HCMOS) technology was used to monitor effects of the radiation on a common logic family. The circuit contained an HCMOS clock oscillator module driving an HCMOS flip-flop integrated circuit and two HCMOS decade counters. The outputs of these circuits were 10 kHz clock signals. There were two of these circuits in place to increase the statistical sample size.
- *Transistor amplifiers:* Eight transistor amplifier circuits were included to determine effects of radiation on common amplifier configurations using two types of transistor technologies: JFET and MOSFET. These amplifiers were configured as common source amplifiers and biased for class A operation. The JFETs are common depletion mode N channel devices and were self-biased to provide gain. The MOSFETs are common enhancement mode N channel field-effect transistors and were also biased to provide gain.
- *Power supply:* A direct current (DC) power supply was constructed using half wave rectification and regulation to supply power for the equipment under test. The rail voltages were developed using common linear regulators, which provided +15 V DC, −15 V DC and +5 V DC. Although these outputs were not directly monitored, failure(s) of the power supply would result in the coincident failure of several circuits within the equipment under test.
- *Radiofrequency oscillator:* Two RF crystal oscillators were used to determine the effects of radiation on signal sources. A common JFET was the only active element in the oscillator; no output amplifiers or buffers were used. Commonly available crystals (20 MHz and 20.5 MHz) were provided to control the frequency output.
- *Low frequency oscillator:* Another HCMOS circuit was included to produce a low frequency signal (approx. 100 Hz), which was used to modulate the amplitude of each JFET RF oscillator. The oscillator was constructed using a common unbuffered inverter gate integrated circuit configured as a square wave oscillator.
- *Radiofrequency receiver:* A wideband integrated circuit receiver was used to receive the signal from a JFET and detect the modulated signal imposed on the RF oscillator by the low frequency gate oscillator. Although a frequency modulated (FM) receiver integrated circuit was used, the amplitude modulated (AM) signal was detected on the ‘squelch’ output of the receiver. This signal was derived from the internal limiter action of the integrated circuit, where an output current was developed dependent on the incoming signal strength. This signal was then amplified and detected using a comparator comprising a common operational amplifier to develop a logic level signal relating to the original low frequency signal. The receiver integrated circuit consists of an RF front end amplifier, RF mixer, limiter and quadrature detection circuit. Since the data output signal is derived from the limiter, the quadrature circuit was not involved in the receiver function. However, an internal data comparator was included in the integrated circuit to develop a 5 V logic level output from the previous operational amplifier/comparator stage. Figure IV–3 shows the transmitter and receiver board with discrete components.

TABLE IV–1. TYPES OF FUNCTION AND COMPONENT

Function	Component
Op amp[a]/BJT[b] current sources	Op amp[a] and BJT[b]
Clock oscillator and dividers	HCMOS[c] clock oscillator, flip-flop and decade counter
Transistor amplifiers	JFET[d] and MOSFET[e]

TABLE IV–1. TYPES OF FUNCTION AND COMPONENT (cont.)

Function	Component
Power supply	Linear voltage regulator
RF oscillator	Crystal oscillator and JFET[d]
Low frequency oscillator	HCMOS[c] and JFET[d]
RF receiver	Integrated circuit

[a] Op amp: operational amplifier.
[b] BJT: bipolar junction transistor.
[c] HCMOS: high speed complementary metal oxide semiconductor.
[d] JFET: junction field-effect transistor.
[e] MOSFET: metal oxide semiconductor field-effect transistor.

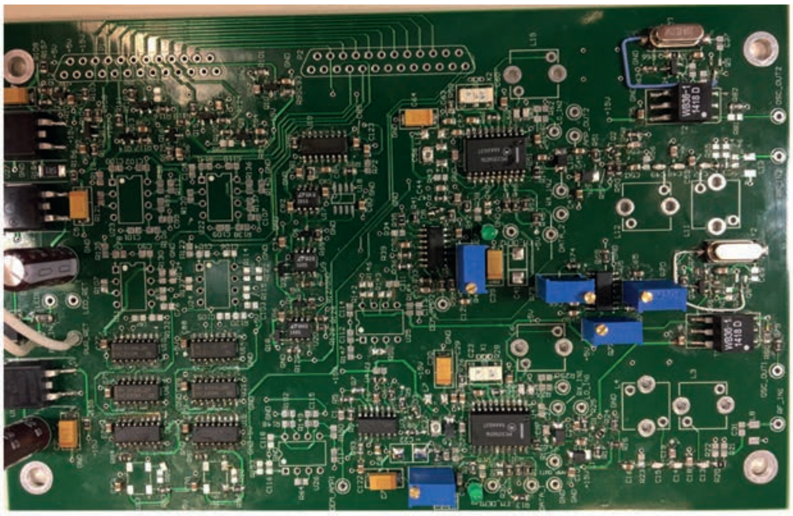


FIG. IV–3. Transmitter and receiver board with discrete components.

IV–3. TEST SET-UP

IV–3.1. Clean hot cell test configuration for the microcontroller based wireless transmitter/receiver

Figure IV–4 depicts the high level schematic of the microcontroller based board. There are two op amp stages that are used to convert a current signal into a suitable voltage for the analogue to digital converter. The analogue to digital converter then sends a serial stream of data to the SOC RF transceiver. The RF transmitter was set up to operate in a continuous mode to transmit a 2.4 GHz signal at 0 dBm. Figure IV–5 shows the test configuration in the clean hot cell.

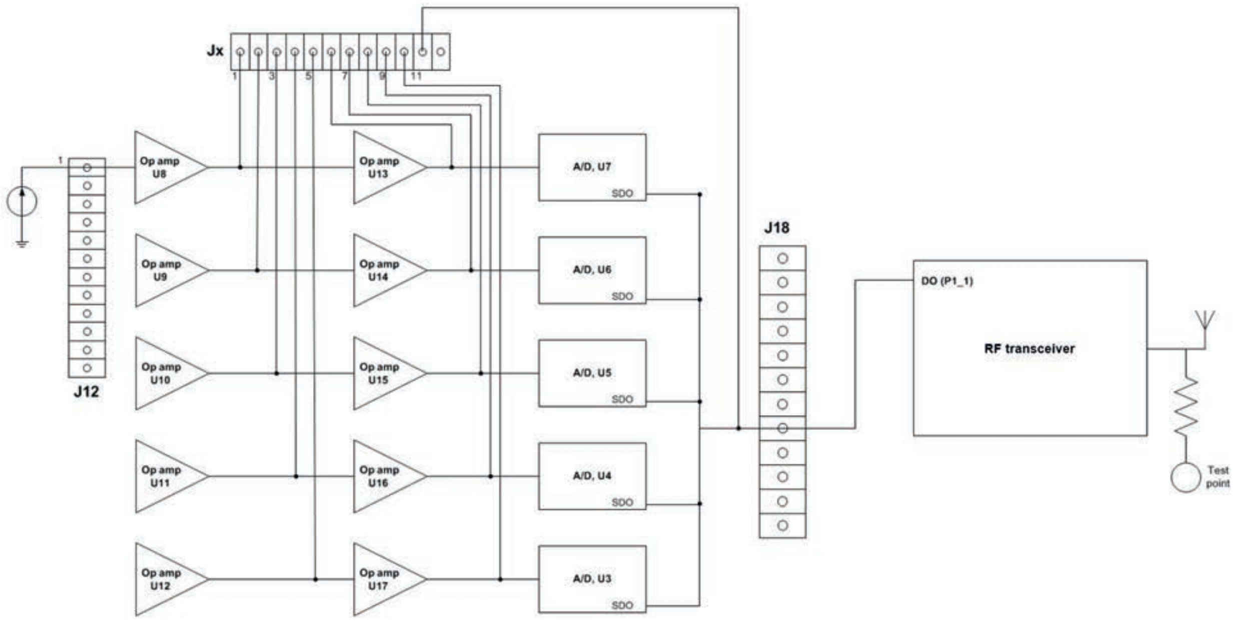


FIG. IV–4. Microcontroller based wireless transmitter and battery test set-up. A/D — analogue to digital converter; op amp — operational amplifier; RF — radiofrequency.

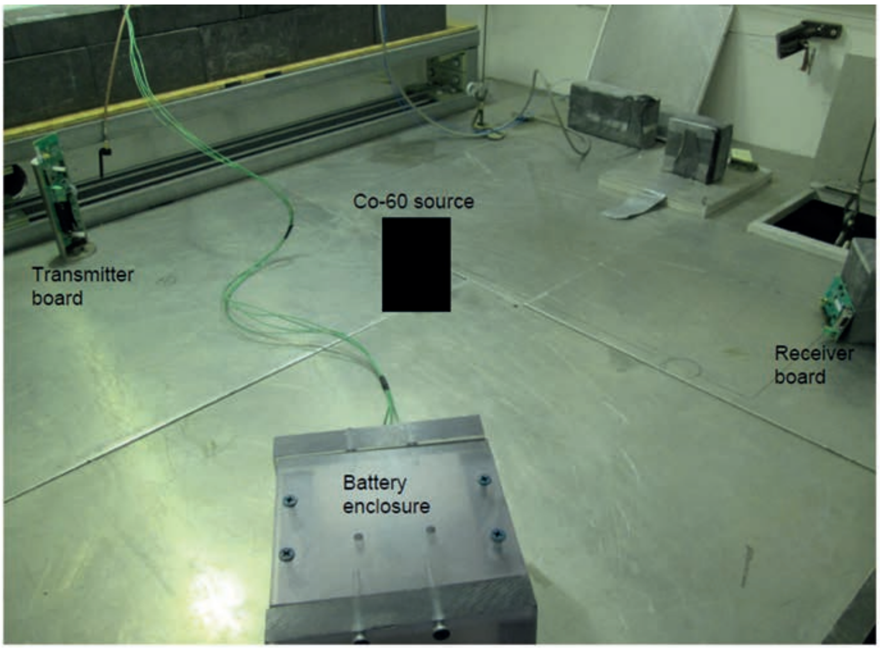


FIG. IV–5. Clean hot cell test set-up for the microcontroller based wireless transmitter and battery.

IV–3.2. Discrete component transmitter/receiver clean hot cell test configuration

Figure IV–6 shows a schematic of a discrete component board that was irradiated. The left side shows a block diagram of the circuits that were irradiated, and the right side shows the signal conditioning circuit used for the monitoring hardware. In order to achieve a required radiation dose of approximately 10 kGy, the cobalt-60 source had to be located in close proximity to the board.

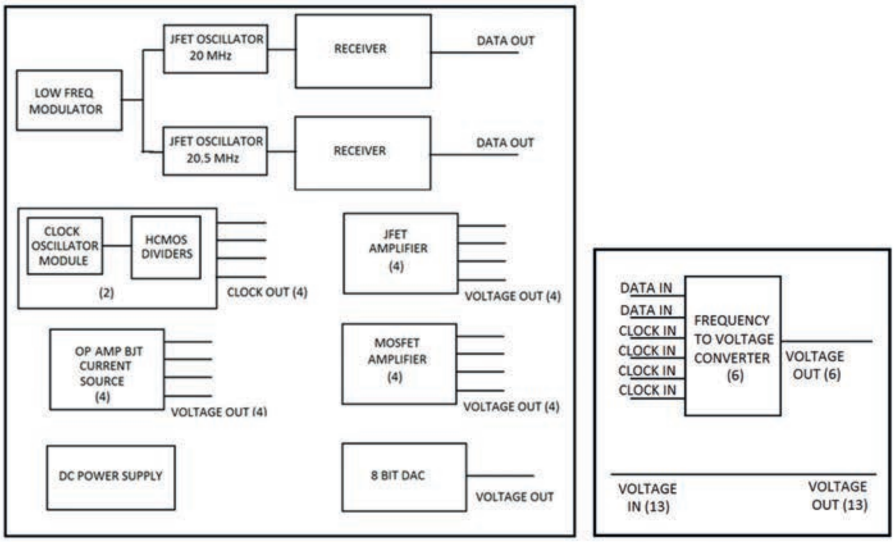


FIG. IV–6. High level schematic of discrete component board tested in clean hot cell (left) and interface board outside clean hot cell (right). BJT — bipolar junction transistor; DAC — digital to analogue converter; HCMOS — high speed complementary metal oxide semiconductor; JFET — junction field-effect transistor; MOSFET — metal oxide semiconductor field-effect transistor; OP AMP — operational amplifier.

IV–4. TEST RESULTS

IV–4.1. Microcontroller based wireless transmitter/receiver and battery irradiation results

IV–4.1.1. Batteries

Battery PN LS26500, with a capacity of 7.7 Ah, survived 1.04 kGy for approximately 258 h, while a different battery with the same characteristics lasted 452 h. It is clear that the exposure to gamma radiation significantly decreased its capacity (nominally 350 h). Battery PN TL-2300, with a capacity of 16.5 Ah, received 3.04 kGy and held its voltage constant at 3.6 V.

IV–4.1.2. Microcontroller based transmitter operational amplifiers

The two operational amplifiers shown in Fig. IV–7, in addition to U12 and U17 from Fig. IV–4, were exposed to 1.83 kGy without any change to their output voltage performance. The test was stopped on these operational amplifiers prior to any performance degradation being detected.

IV–4.1.3. Transmitter and receiver serial data

The wireless transmission from the transmitter board was monitored by extracting the digital data through the universal asynchronous receiver/transmitter port and by a spectrum analyser connected to the SMA test point connector. The wireless data received were also extracted through the universal asynchronous receiver/transmitter port of the receiver board. Each transmitted data package was recorded by the data acquisition software once every second for the transmitter and receiver board. Figure IV–8 shows the transmitted (Tx) and received (Rx) signals tracking each other as the input changes for approximately 6 h. The microcontroller portion that controls the universal asynchronous receiver/transmitter communications started to degrade at approximately 0.46 kGy.

IV–4.2. Discrete component based transmitter/receiver board irradiation results

Some discrete component circuits showed immediate effects after exposure to the radiation (see Fig. IV–9). The MOSFET amplifier bias conditions were immediately affected, with a nearly linear decrease in bias voltage. At approximately 0.22 kGy the decrease ended when the cobalt-60 sources were removed to make alterations to

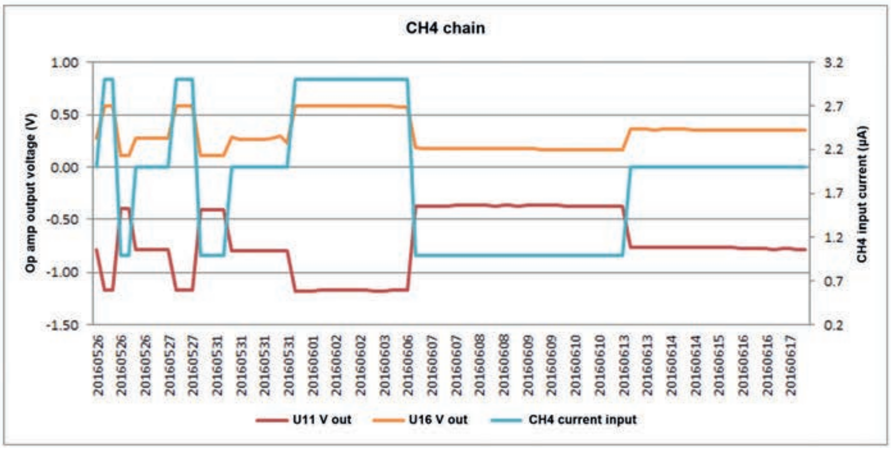


FIG. IV–7. Operational amplifier U11 and U16 voltage output.

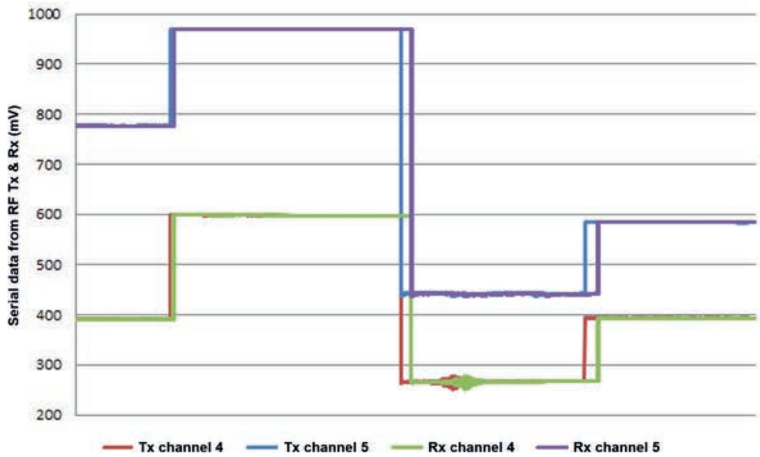


FIG. IV–8. Radiofrequency transmitter and receiver serial data. RF — radiofrequency; Rx — receive; Tx — transmit.

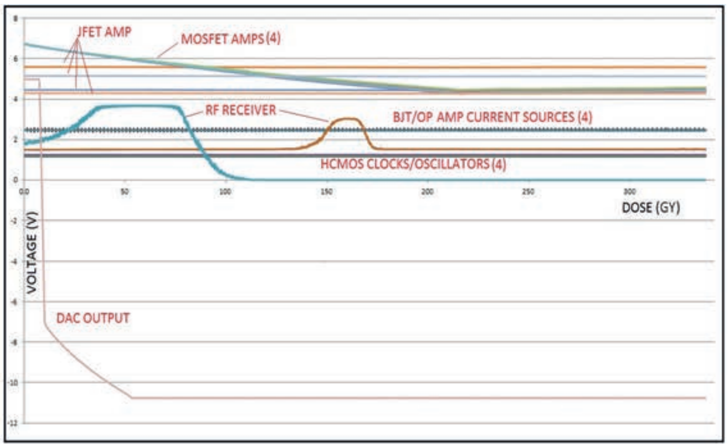


FIG. IV–9. Initial gamma radiation effects of discrete circuit sections. BJT — bipolar junction transistor; DAC — digital to analogue converter; HCMOS — high speed complementary metal oxide semiconductor; JFET — junction field-effect transistor; MOSFET — metal oxide semiconductor field-effect transistor; OP AMP — operational amplifier; RF — radiofrequency.

the test configuration. Early in the test, the digital to analogue converter output voltage dropped to approximately −11 V DC. The RF receiver data showed an increase in voltage, which corresponds to an increase in the output frequency, likely to be due to extraneous pulses, which when processed by the frequency to voltage converters created an increase in output voltage. Other circuits, such as the JFET amplifiers, HCMOS clock oscillators and dividers and the BJT/operational amplifier current sources, showed no signs of degradation.

Long term exposure showed various effects on all circuits in the equipment under test, as shown in Fig. IV–10. In this plot some of the redundant circuit outputs were removed to improve clarity since similar circuit types behaved in the same manner. At approximately 1.5 kGy all circuits showed signs of degradation or failure. At approximately 10.5 kGy all circuits showed a coincident failure, which remained with the exception of a resurgence of circuit activity after exposure to 12 kGy, although proper circuit functions did not return. After 17.5 kGy the total circuit failure returned, and it remained in this state for the remainder of the test.

Following exposure, the unit was removed, and circuit failures were analysed. All power supply rail voltages (+15 V, −15 V and +5 V) were affected. The −15 V rail voltage was at approximately −16.5 V while the +15 V and +5 V outputs were near 0 V. Replacing the +15 V regulator showed the +5 V output to be approximately 4.5 V. After replacing all three regulators, many of the unit's circuit functions were restored to conditions close to those before irradiation occurred. MOSFET amplifier bias voltage deterioration evident during the exposure appeared to be permanent, and the digital to analogue converter failure also matched the failure seen during exposure. All other circuits, including the RF receiver circuits, functioned identically to their original pre-radiation operation.

A more detailed analysis of the circuits showed no degradation in output voltage swing in the HCMOS clock and logic outputs. Nor was any degradation seen in output voltage swings in operational amplifier based circuits, comparators, current sources or the RF receivers. Measurements made within the digital to analogue converter circuit showed that a separate precision reference integrated circuit used to provide the reference voltage was still operable, but the output voltage was reduced by approximately 5%, which is two orders of magnitude larger than that specified by the original manufacturer.

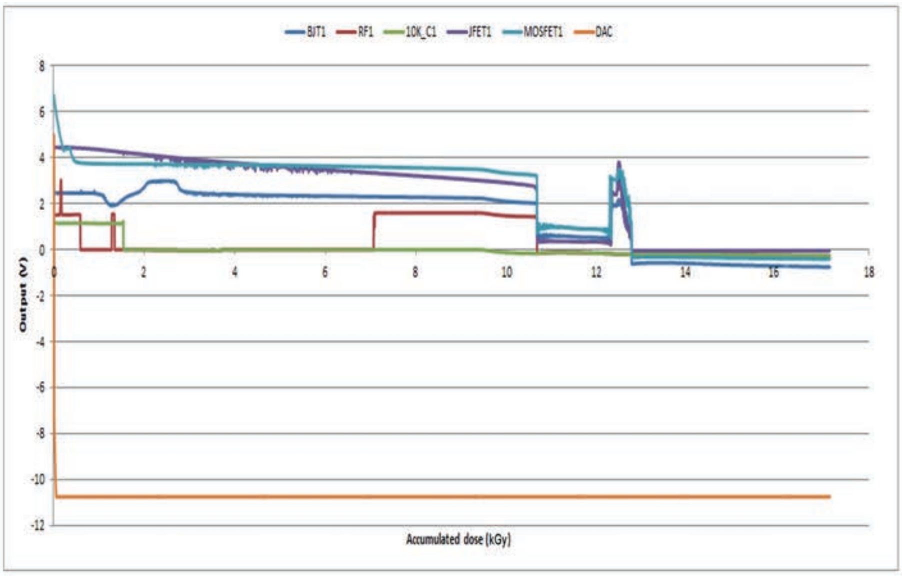


FIG. IV–10. Output voltage variation versus gamma radiation. 10K_C1 — 10 kHz clock signal; BJT — bipolar junction transistor; DAC — digital to analogue converter; JFET — junction field-effect transistor; MOSFET — metal oxide semiconductor field-effect transistor; RF — radiofrequency.

IV–5. CONCLUSIONS

An inexpensive, low power consumption, microcontroller based SOC transceiver board was irradiated and the performance of the signal conditioning operational amplifiers and the SOC was monitored. The commercial off the shelf type operational amplifiers did not exhibit signs of degradation near 1.8 kGy. The SOC, as expected, was much more sensitive to the radiation field and stopped operating at around 0.46 kGy, which was observed by universal asynchronous receiver/transmitter serial data stream corruption. However, the RF portion of the SOC continued to operate until approximately 0.54 kGy.

An alternative to the microcontroller based transceiver, developed using discrete components, was tested in the second part of this research. The discrete component circuits most affected by radiation contained MOSFET components, digital to analogue converters, voltage regulators and voltage references. Linear voltage regulators contain an internal reference, which is likely to be the portion of the regulator that affected the output voltage. Post-exposure analysis of the circuit failures showed that many of the circuit sections were not degraded by the radiation beyond 100 kGy dose. A single point failure of the power supply caused all circuit sections to begin to degrade at over 10 kGy and faulty power supply operation beyond this dose may have caused circuit malfunctions throughout the experiment given that post-radiation analysis showed most circuits were fully operational. The circuits received an additional dose up to approximately 17 kGy but they were not adequately powered after 10.5 kGy (approx.). If the unit had been powered from an external source, it is anticipated that the circuit may have continued operating beyond 10 kGy before severe degradation.

REFERENCES TO ANNEX IV

[IV–1] ELECTRIC POWER RESEARCH INSTITUTE, Automation in Power Plants and Wireless Technology Assessments, Rep. 1010468, EPRI, Palo Alto, CA (2005).

[IV–2] GUIZZO, E., Can Japan send in robots to fix troubled nuclear reactors? IEEE Spectrum (22 Mar. 2011).

Annex V

EFFECTS OF IONIZING RADIATION ON WIRELESS SIGNAL PROPAGATION

University of Western Ontario, Canada

V–1. INTRODUCTION

This annex describes the results of research to evaluate the effect of a radioactive environment on electromagnetic waves, which form the communication media for all wireless systems. This is particularly important if wireless systems are expected to work in a harsh radioactive environment following a severe accident. The experiments involve placing a transmitter antenna and a receiver antenna in a hot cell with radiation of variable strength to determine the attenuation effects on wireless signals.

V–2. EXPERIMENT METHODS

Prior to carrying out experiments to determine the effect of radiation on electromagnetic wave propagation, it is important to establish a baseline for comparison by considering a non-radioactive environment. The experiments were carried out in a radioactive environment, namely a hot cell, using two different radiation levels.

The set-up of the experiment is depicted in Fig. V–1, which shows two antennas, one connected to a signal generator (for transmitting) and the other to a signal analyser (for receiving). These two antennas are supported by acrylic posts for convenient deployment in the radioactive hot cell. Sine waves at different frequencies are generated and transmitted through the first antenna. The other antenna receives the wireless signals and routes them through a cable to the signal analyser. As shown in Fig. V–1, a shielded container with radioactive material inside is placed between two antennas while carrying out the experiment in the hot cell in order to vary the level of radiation between the two antennas.

The power and the frequency of the received signals are determined by the signal analyser, and transmission power loss and frequency shift can be calculated to assess the propagation efficiency of the electromagnetic wave. The effects of radiation on the electromagnetic wave propagation can be assessed by comparing the propagation efficiency of the electromagnetic wave under both radiation and non-radiation environments.

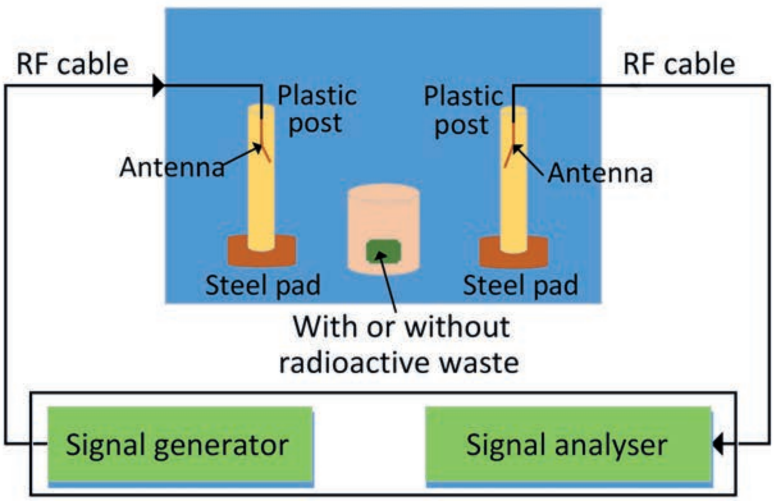


FIG. V–1. A conceptual illustration of the experiment set-up. RF — radiofrequency.

V–3. EXPERIMENTS IN THE LABORATORY ENVIRONMENT

V–3.1. Experiment set-up

An overview of the set-up of the experiment is shown in Fig. V–2. For the experiments, a vector signal generator was used as the transmitter and a signal analyser was used as the receiver. The signal generator was configured to periodically transmit sine waves while the analyser was set on the maximum hold detector to record the received signals.

V–3.2. Experiment results and analysis

During the experiment, the power and frequency shifts in the received signal were recorded. A screenshot of the signal received by the signal analyser is shown in Fig. V–3. The frequency of the transmitted signal was set to 2.46 GHz and the transmission power level was set to +15 dBm so that the maximum power of the received signal was −28.55 dBm, while the frequency at the maximum point was 2.45995 GHz.

The experiments were repeated for several frequencies, from 2.37 GHz to 2.51 GHz, and the transmission power level was fixed at +15 dBm for all frequencies. For each frequency setting, the received signal power loss and the frequency shift were measured. These are provided in Tables V–1 and V–2.

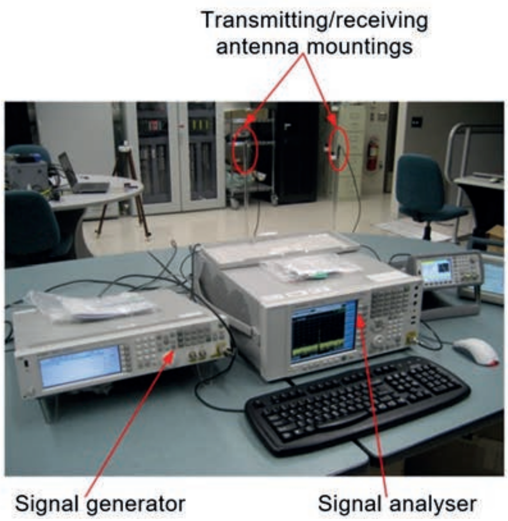


FIG. V–2. Overview of the set-up of the experiment in the laboratory.

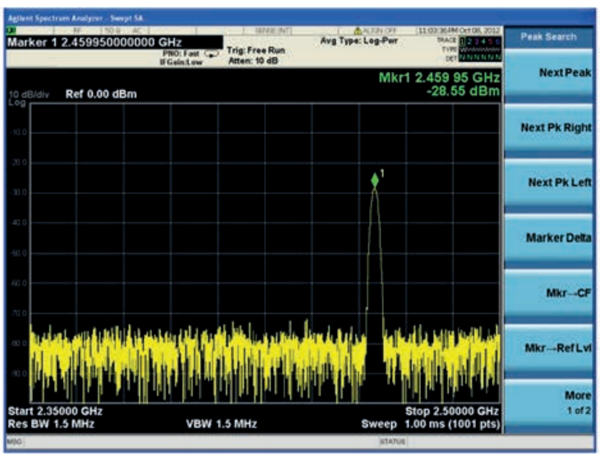


FIG. V–3. Screenshot from the signal analyser when the transmitting signal was set at 2.46 GHz, +15 dBm.

TABLE V–1. SIGNAL POWER LOSS IN THE LABORATORY ENVIRONMENT

Transmitted signal		
Frequency (GHz)	Power (dBm)	Received signal power (dBm)
2.37	+15	−28.07
2.38	+15	−26.94
2.39	+15	−27.53
2.40	+15	−25.99
2.41	+15	−26.88
2.42	+15	−27.92
2.43	+15	−28.75
2.44	+15	−27.16
2.45	+15	−29.63
2.46	+15	−28.55
2.47	+15	−29.34
2.48	+15	−29.13
2.49	+15	−28.05
2.50	+15	−32.73
2.51	+15	−30.03

TABLE V–2. FREQUENCY SHIFT IN THE LABORATORY ENVIRONMENT

Transmitted signal frequency (GHz)	Received signal frequency (GHz)	Frequency shift (kHz)
2.370 0	2.370 0	0
2.380 0	2.380 0	0
2.390 0	2.390 0	0
2.400 0	2.400 0	0
2.410 0	2.410 0	0
2.420 0	2.420 05	+50
2.430 0	2.429 95	−50
2.440 0	2.440 00	0

TABLE V–2. FREQUENCY SHIFT IN THE LABORATORY ENVIRONMENT (cont.)

Transmitted signal frequency (GHz)	Received signal frequency (GHz)	Frequency shift (kHz)
2.450 0	2.450 05	+50
2.460 0	2.469 95	−50
2.470 0	2.470 0	0
2.480 0	2.480 05	+50
2.490 0	2.489 95	−50
2.500 0	2.500 0	0
2.510 0	2.510 0	0

The received signal strength experiences a slight decrease as the frequency increases, as shown in the third column of Table V–1. Table V–2 shows that six out of the 15 tested frequency points experienced frequency shift of either +50 kHz or −50 kHz (e.g. at 2.42 GHz and 2.43 GHz).

V–4. EXPERIMENTS IN THE HOT CELL

V–4.1. Set-up of the experiment

The radiologically hottest spots in a nuclear power plant vault have gamma dose rates over 100 mGy/h. The hot cell used in this experiment has a gamma dose rate that exceeds 100 Gy/h, which is about 1000 times higher than that typically found in a reactor vault. This hot cell is considered to be a suitable platform to study the impact of radiation on electromagnetic wave propagation. The results are considered to be applicable to severe accident scenarios at a nuclear power plant. An overview of the experiment set-up is shown in Fig. V–4. The test equipment is shown in Fig. V–5 and the interior of the hot cell is shown in Fig. V–6.

In these experiments, two different radiation levels were used: one with a gamma dose rate measured as 169 Gy/h, and the other with a higher gamma dose rate measured as 188 Gy/h. The same set of baseline frequencies as in the laboratory experiments was used for generating and transmitting electromagnetic waves. The transmission power level was set at +15 dBm. Two sets of experiments were carried out under the lower and higher radiation field strengths.

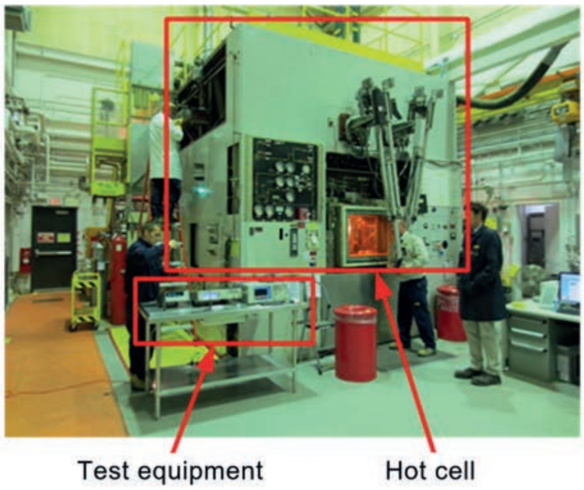


FIG. V–4. Overview of the experiment set-up.

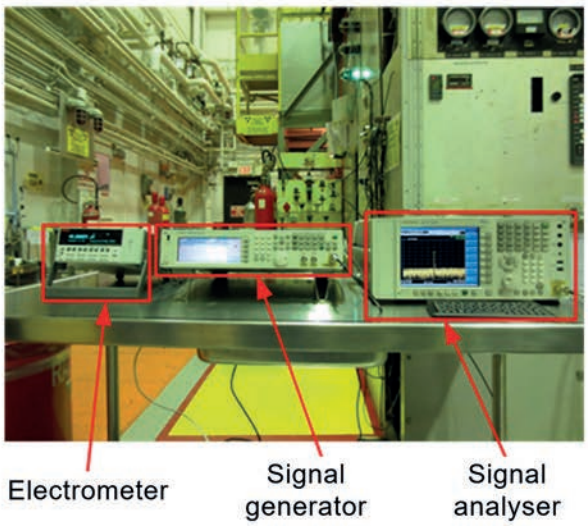


FIG. V–5. Test equipment used in the experiments.

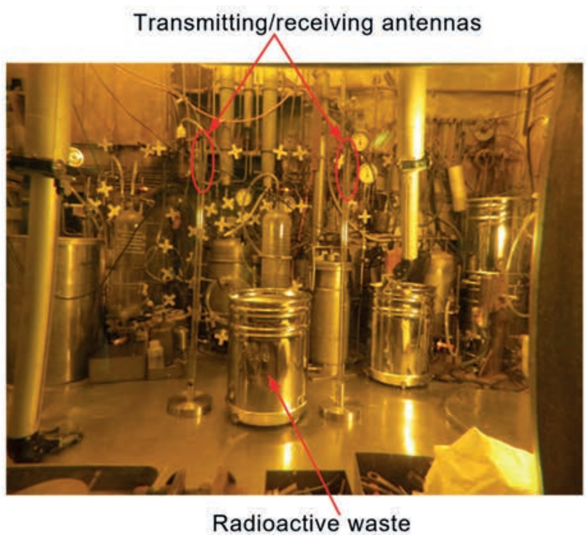


FIG. V–6. Test set-up inside the hot cell.

V–4.2. Experiment results

The signal power losses in electromagnetic waves at different frequencies were recorded during the experiments and are shown in Table V–3. There are some variations on the output power level at different test frequencies, but it is difficult to observe any pattern from the data. The frequency shift of the electromagnetic waves in the hot cell with the lower gamma dose rate is shown in Table V–4. From this table, there appear to be some frequency shifts (e.g. at 2.40 GHz). The frequency shift of the electromagnetic waves in the hot cell with a higher gamma dose rate is shown in Table V–5. Some frequency shifts are noted in these data.

TABLE V–3. SIGNAL LOSS IN THE HOT CELL

Transmitted signal		Received signal		
Frequency (GHz)	Power (dBm)	Low field (dBm)	High field (dBm)	Loss difference (dB)
2.37	+15	−24.85	−25.42	0.57
2.38	+15	−22.72	−26.92	4.20
2.39	+15	−30.46	−25.77	−4.69
2.40	+15	−26.30	−29.13	2.83
2.41	+15	−27.19	−25.03	−2.16
2.42	+15	−28.23	−27.13	−1.10
2.43	+15	−23.46	−21.52	−1.94
2.44	+15	−37.30	−34.61	−2.69
2.45	+15	−33.25	−35.23	1.98
2.46	+15	−26.74	−30.34	3.60
2.47	+15	−34.13	−34.72	0.59
2.48	+15	−21.93	−26.37	4.44
2.49	+15	−27.92	−29.92	2.00
2.50	+15	−30.56	−27.16	−3.40
2.51	+15	−27.13	−26.23	−0.90

TABLE V–4. FREQUENCY SHIFT IN THE HOT CELL WITH THE LOWER GAMMA DOSE RATE

Transmitted frequency (GHz)	Received frequency (GHz)	Frequency shift (kHz)
2.37	2.370 0	0
2.38	2.380 0	0
2.39	2.390 0	0

TABLE V–4. FREQUENCY SHIFT IN THE HOT CELL WITH THE LOWER GAMMA DOSE RATE (cont.)

Transmitted frequency (GHz)	Received frequency (GHz)	Frequency shift (kHz)
2.40	2.400 2	+200
2.41	2.409 95	−50
2.42	2.420 0	0
2.43	2.430 05	+50
2.44	2.440 05	+50
2.45	2.450 0	0
2.46	2.460 0	0
2.47	2.470 0	0
2.48	2.480 0	0
2.49	2.490 0	0
2.50	2.499 95	−50
2.51	2.509 96	−40

TABLE V–5. FREQUENCY SHIFT IN THE HOT CELL WITH THE HIGHER GAMMA DOSE RATE

Transmitted signal frequency (GHz)	Received signal frequency (GHz)	Frequency shift (kHz)
2.37	2.369 95	−50
2.38	2.380 0	0
2.39	2.390 0	0
2.40	2.399 95	−50
2.41	2.409 96	−40
2.42	2.420 4	+400
2.43	2.429 98	−20
2.44	2.439 92	−80
2.45	2.450 0	0
2.46	2.459 94	−60
2.47	2.470 02	+20
2.48	2.479 96	−40

TABLE V–5. FREQUENCY SHIFT IN THE HOT CELL WITH THE HIGHER GAMMA DOSE RATE (cont.)

Transmitted signal frequency (GHz)	Received signal frequency (GHz)	Frequency shift (kHz)
2.49	2.490 04	+40
2.50	2.500 12	+120
2.51	2.510 02	+20

V–5. RESULTS ANALYSIS

The frequency shifts of the electromagnetic waves in both the laboratory environment and the hot cell are compared in Table V–6. This shows that in six out of the 15 test frequencies, there are observed frequency shifts in both the laboratory environment and the hot cell under the lower gamma dose rate. However, in the hot cell under the higher gamma dose rate, there is a frequency shift in 12 out of the 15 frequencies tested. Furthermore, the magnitudes of the frequency shift are larger in the hot cell under the higher gamma dose rate when compared to the results from the other experiments. Therefore, it appears that a high dose rate of gamma radiation may lead to a frequency shift in electromagnetic waves.

As the transmission power was set to +15 dBm, the difference of received signal power may be used to evaluate the effect of radiation on electromagnetic wave power loss. The received signal powers for all three sets of experiments are plotted in Fig. V–7. In this figure, the blue curve represents the received power (in dBm) for those experiments in the laboratory while the red and the green curves represent the hot cell tests at lower and higher radiation levels, respectively. Figure V–7 shows that amplitude fluctuations in both radiation environments are larger than those in non-radiation environments. Therefore, it may be assumed that gamma radiation could have some effect on the received power fluctuation of electromagnetic waves.

TABLE V–6. COMPARISON OF FREQUENCY SHIFTS IN DIFFERENT ENVIRONMENTS

Transmitted frequency (GHz)	Received frequency shift (kHz)		
	Laboratory	Low field	High field
2.37	0	0	−50
2.38	0	0	0
2.39	0	0	0
2.40	0	+200	−50
2.41	0	−50	−40
2.42	+50	0	+400
2.43	−50	+50	−20
2.44	0	+50	−80
2.45	+50	0	0
2.46	−50	0	−60

TABLE V–6. COMPARISON OF FREQUENCY SHIFTS IN DIFFERENT ENVIRONMENTS (cont.)

Transmitted frequency (GHz)	Received frequency shift (kHz)		
	Laboratory	Low field	High field
2.47	0	0	+20
2.48	+50	0	−40
2.49	−50	0	+40
2.50	0	−50	+120
2.51	0	−40	+20

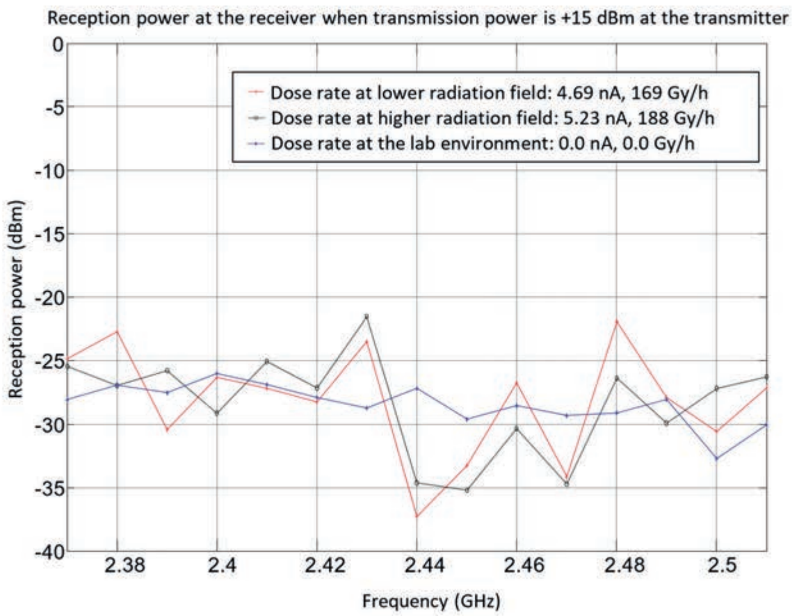


FIG. V–7. Comparison of the received signal strength in different environments.

V–6. CONCLUSIONS

The effect of radiation on electromagnetic wave propagation has been investigated in the framework of a wireless sensor network. The preliminary results appear to indicate that wireless communication channels may not be blocked by high levels of gamma radiation, although it may have some effect on electromagnetic wave propagation such as causing frequency shifts and received power level fluctuations. These may need to be considered when designing a wireless system for nuclear power plant applications under the high level of radiation that could occur in severe accident scenarios.

Annex VI

WIRELESS COMMUNICATION THROUGH EXISTING APERTURES IN WALLS AND DOORS

Hitachi, Ltd, Japan

VI–1. INTRODUCTION

Wireless data transmission without the need to add penetrations or cabling through either a containment building or other structural elements at an NPP could be an important benefit for utilities and others. This annex describes a methodology for wirelessly transmitting data through existing apertures within a containment.

VI–2. TECHNOLOGY

VI–2.1. Finite difference time domain simulation software

To evaluate the transmission loss in reinforced concrete walls with a metal door aperture, a finite difference time domain method was used. Since the distances between the antenna and the reinforced concrete walls were relatively small compared to the wavelength of wireless signals, a near field analysis method was employed.

VI–2.2. Finite difference time domain simulation model

Figure VI–1 shows a finite difference time domain simulation model consisting of reinforced concrete walls and a metal door structure. The thickness of the wall is 1.0 m, the height is 2.5 m and the width is 3.0 m. The wall has an aperture whose height and width are 2.0 m and 1.0 m, respectively. A metal door was placed in an aperture located at the centre of the reinforced concrete wall. The reinforcing rods (38 mm diameter) were placed 200 mm apart within the wall. The door and the reinforcing rods were set to perfect conductivity, the relative permittivity of the concrete was set to 6.9 and the electrical conductivity was set to 0.0096 S/m.

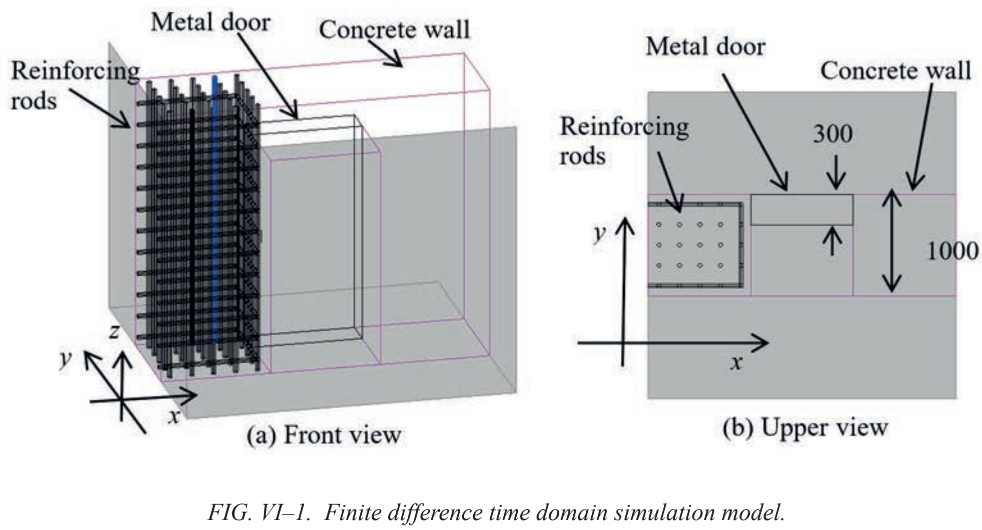


FIG. VI–1. Finite difference time domain simulation model.

VI–2.3. Analysing frequency and mesh size

The following frequencies were used: 980 MHz, 2400 MHz and 5000 MHz. For each frequency, the basic size of the meshes was set to 1/10 of the wavelength. The size of the mesh in the concrete part was set to 1/20 of the wavelength after consideration of the shortening effects. A perfectly matched layer was used as an absorbing boundary condition.

VI–2.4. Antenna placement

Figure VI–2 shows the antenna placement points on the aperture and near the metal door. The circles and triangles are power supply points for the antennas. The circles are centred along the horizontal antenna elements and the triangles are centred along the vertical antenna elements.

VI–2.5. Evaluation

Figure VI–3 shows the antenna position with the evaluation area drawn in blue lines. The electric field strength values in the evaluation area and the transmission losses from the reinforced concrete wall and metal door were calculated.

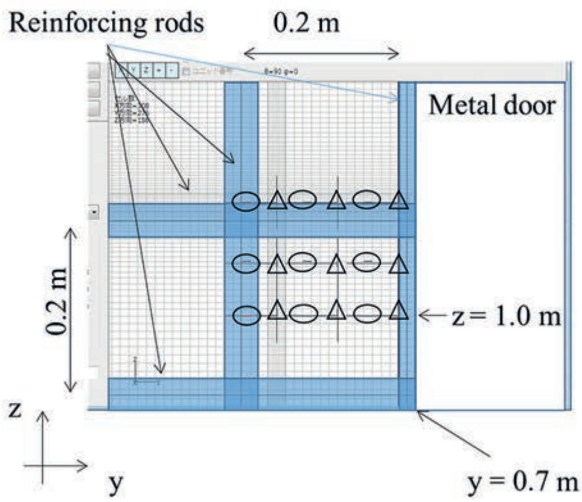


FIG. VI–2. Antenna element placement.

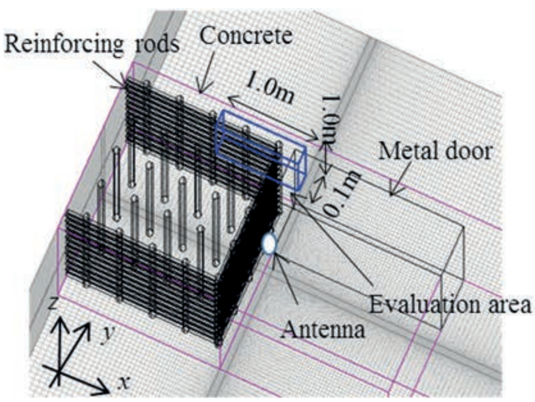


FIG. VI–3. Antenna element and feeding point.

VI–2.6. Simulation results

Figure VI–4 shows examples of the finite difference time domain simulation results for each frequency.

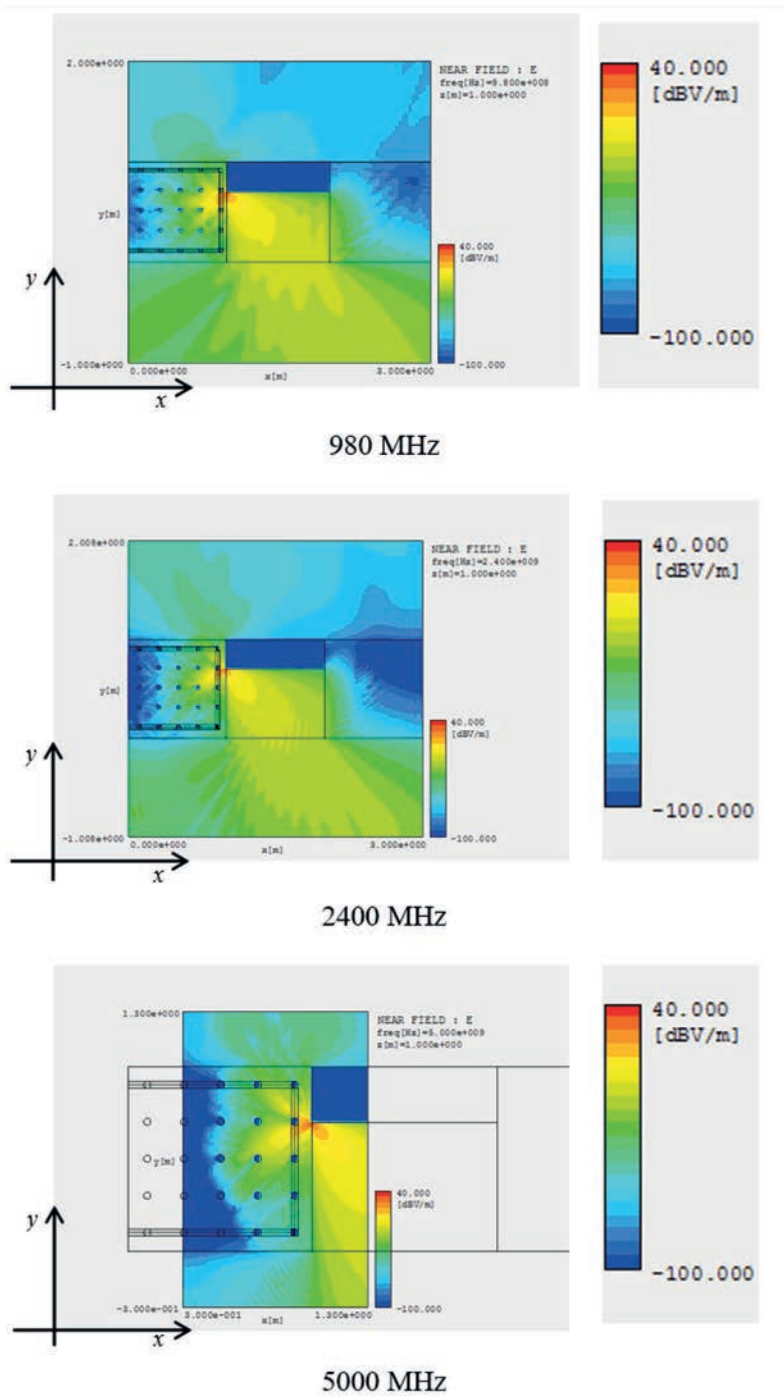


FIG. VI–4. Electric field strength emulation results at different frequencies.

Figure VI–5 shows histograms of the electric field strength in the evaluation area shown in Fig. VI–3. Figures VI–5(a)–(c) show histograms without the reinforced concrete wall and door present, whereas (d)–(f) show histograms with the reinforced concrete wall and door present. The electric field strength falls when the reinforced concrete wall and door are present. The blue bar graph is a histogram of the electric field strength. The red curves show the probability of the electric field strength exceeding the value of the horizontal axis in the evaluation area. The red circles show a probability of 90% for the electric field strength and the arrows show the difference between the red circles with and without the objects (i.e. the reinforced concrete wall and door) present, representing the transmission loss for each frequency. Figure VI–6 shows the differences of electric fields (at 90% probability) with and without objects present. Figure VI–7 shows the electric field strengths of Fig. VI–6 converted to received power levels. In Fig. VI–7, the red dotted line shows the typical sensitivity of a wireless receiver. In this case, communication through the wall may be possible at transmission frequencies of 980 MHz and 2400 MHz, but signal transmission losses may be too large for through-wall communication at 5000 MHz.

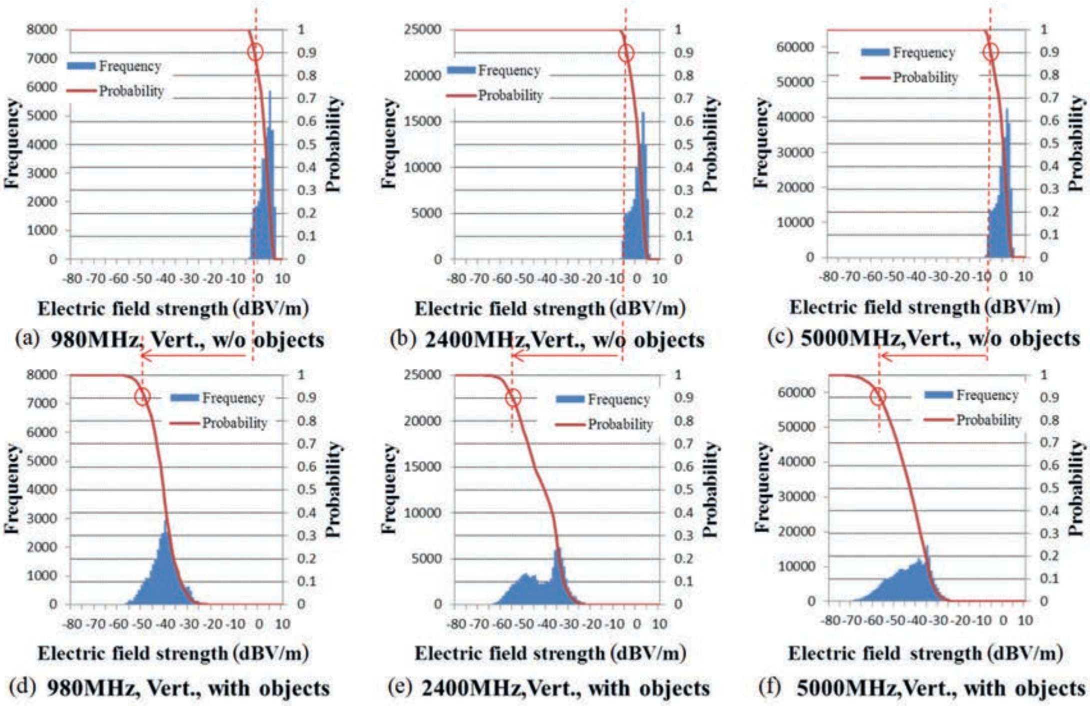


FIG. VI–5. Frequency distribution of field strength and probability.

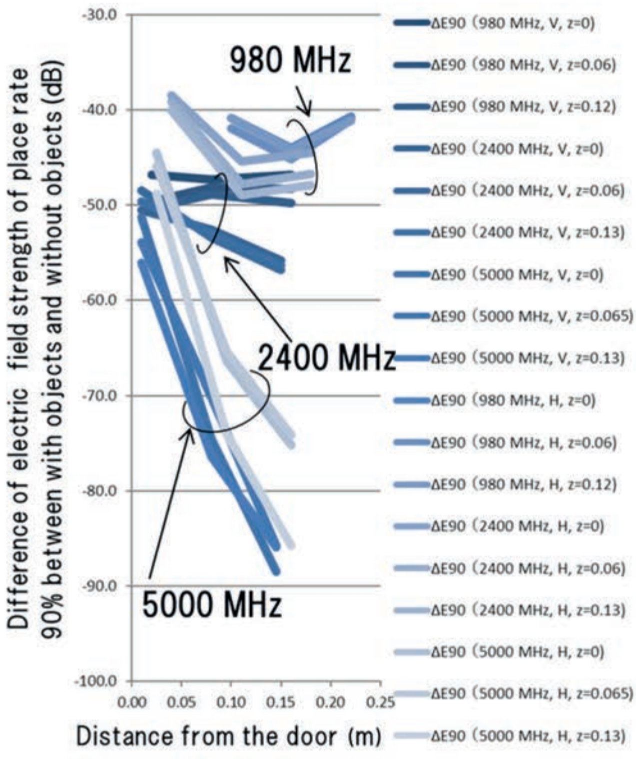


FIG. VI–6. Field strength versus distance at different frequencies. H — horizontal antenna; V — vertical antenna; z — antenna height (above 1 m).

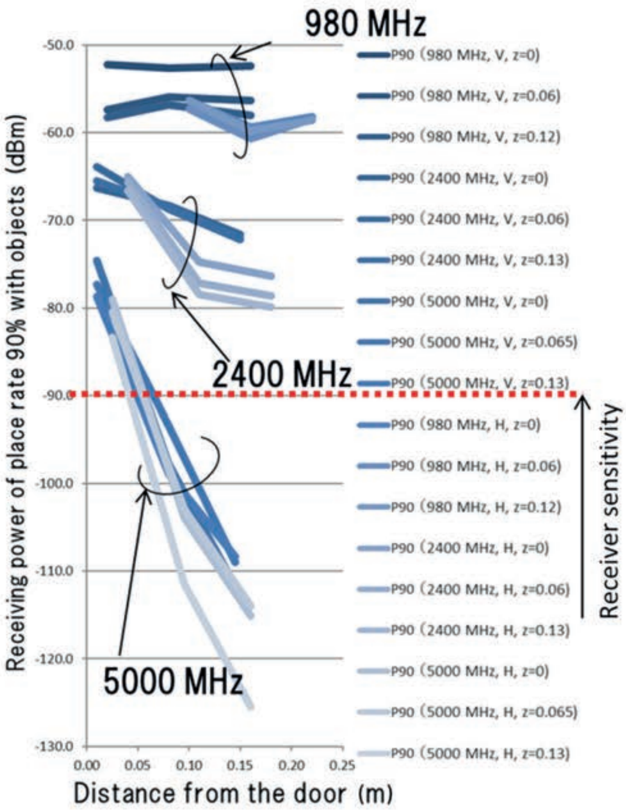


FIG. VI–7. Receiver sensitivity evaluation. H — horizontal antenna; V — vertical antenna; z — antenna height (above 1 m).

VI–3. EXPERIMENT

VI–3.1. Experiment site

Electric field strength measurements were taken of electromagnetic waves through a reinforced concrete wall in a test facility. Figure VI–8 shows the floor plan of the facility where this experiment was conducted.

VI–3.2. Measuring equipment and antenna placement

Two 2400 MHz radios (shown in Fig. VII–1(b)) were used in this experiment. Figure VI–9 shows the placement of the access point and the signal transmitter. As shown in Fig. VI–9 (a), the access point is located on the wall of the corridor side and the signal transmitters are on the reinforced concrete pillar of the front chamber side. The access point is at a height of approximately 1.1 m from the floor and is 0.14 m from the metal door, as shown in Fig. VI–9(c). The signal transmitters are on the far side of the pillar shown in Fig. VI–9(b) and the near side of the pillar shown in Fig. VI–9(d).

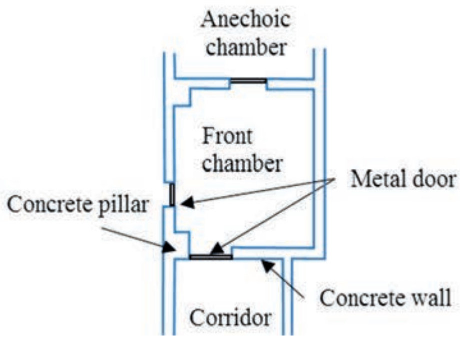


FIG. VI–8. Top view of the floor plan.

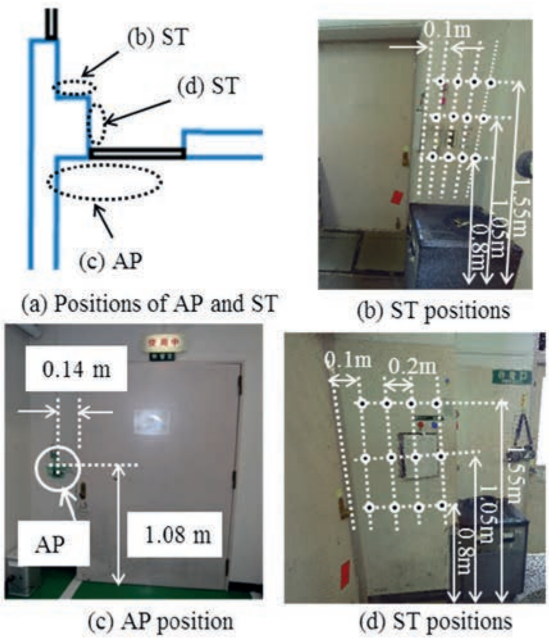


FIG. VI–9. Top view of the anechoic chamber. AP — access point; ST — signal transmitter.

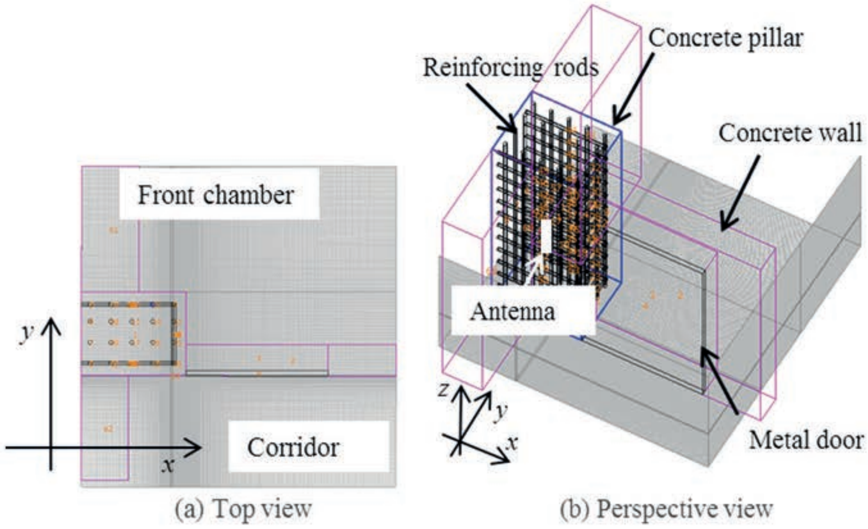


FIG. VI–10. Finite difference time domain simulation model of front chamber.

VI–3.3. Finite difference time domain simulation model

Figure VI–10 shows the finite difference time domain simulation model for this experiment environment. Since the electric conductivity of the concrete was unknown, five values were used, which were considered to be typical of the electric conductivity range of concrete (σ = 0.096, 0.08, 0.05, 0.023 and 0.01 S/m).

VI–4. SIMULATION AND MEASUREMENT RESULTS

Figures VI–11 and VI–12 show the simulated and measured values of electric field strength at the signal transmitter positions. In Fig. VI–11, the signal transmitters were located on the near side of the pillar, while in Fig. VI–12 the signal transmitters were located on the far side of the pillar. The measured values were similar to those simulated using the model for which the conductivity of concrete was set to 0.05 S/m.

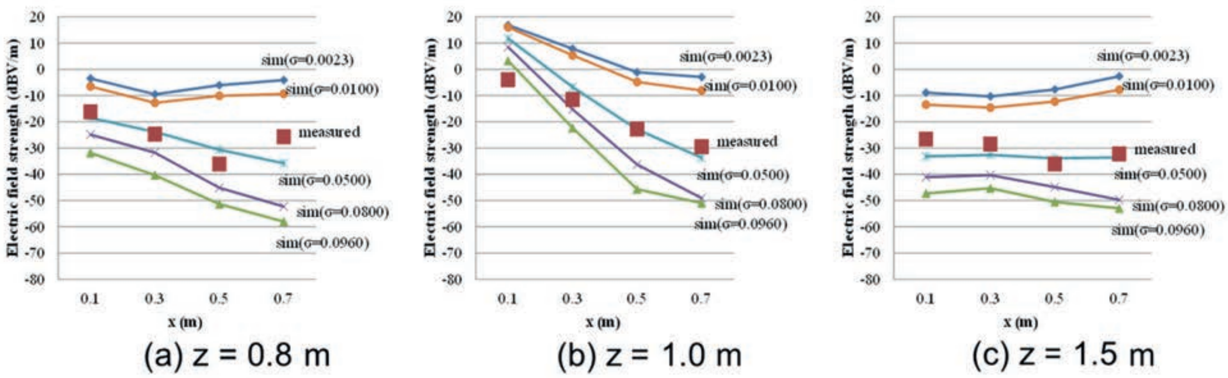


FIG. VI–11. Electric field strength at the signal transmitter positions on the near side of the pillar. z — height of signal transmitter mounting point.

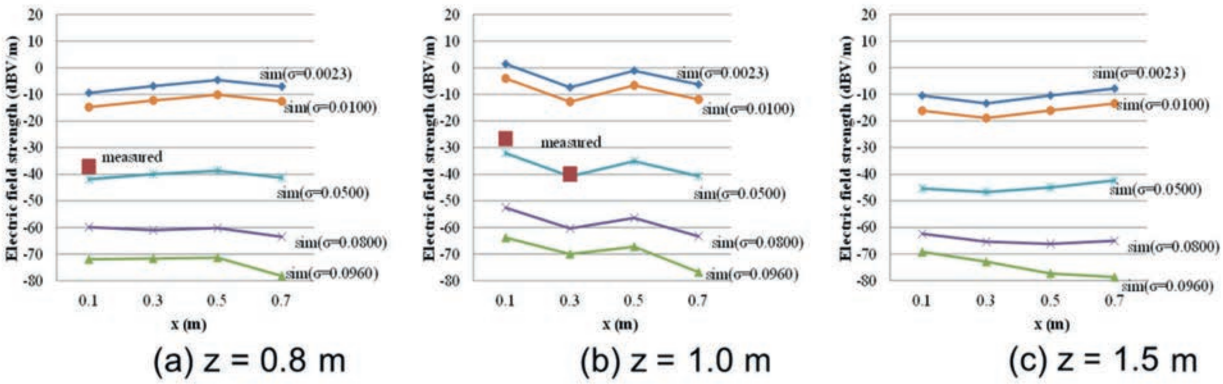


FIG. VI–12. Electrical field strength at the signal transmitter positions on the far side of the pillar. z — height of signal transmitter mounting point.

Annex VII

WIRELESS BASE STATION DEPLOYMENT SIMULATOR USING A RAY TRACING METHOD

Hitachi, Ltd, Japan

Two representative facilities were used to compare theoretical predictions of wireless power levels based on a ray tracing method with actual measured power levels. This annex describes the facilities, the locations of the mobile stations and base station, and the distances between them. An explanation is provided of the results obtained after analysis of the simulated and measured levels.

VII–1. EXPERIMENT SITE

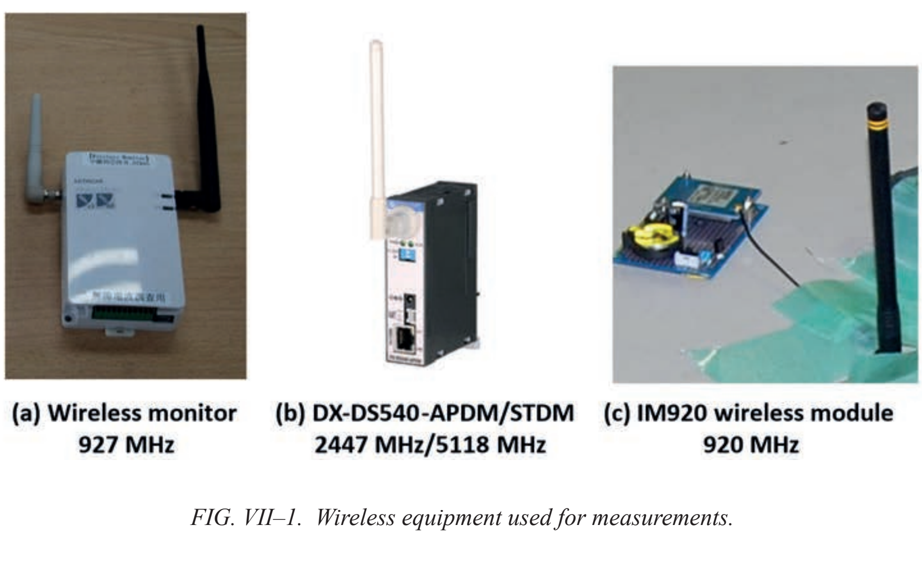
The propagation of radio waves was measured at two experiment facilities considered to be similar to existing nuclear power plants.

VII–2. MEASURING EQUIPMENT

The following commercially available radios were deployed:

- 920 MHz radio (WM-VZEU-D11, ARIB STD-T108);
- 920 MHz radio (IM920, ARIB STD-T108);
- 2.4 GHz/5 GHz radio (DS-540APDM/STDM, IEEE 802.11g/a).

One pair of each type of radio was used, with one radio assigned as the base station in the facility and the other assigned as the mobile station to measure the received power. Figure VII–1 shows the radios, which were set up with a transmitting power of 20 mW/channel and transmission frequencies of 927 MHz, 2447 MHz and 5118 MHz.



(a) Wireless monitor 927 MHz **(b) DX-DS540-APDM/STDM 2447 MHz/5118 MHz** **(c) IM920 wireless module 920 MHz**

FIG. VII–1. Wireless equipment used for measurements.

VII–3. MEASURING PROCEDURE

Figure VII–2 shows a ground plan of one of the two experiment facilities, indicating the location of the base station and the measuring lines of the mobile station indicated by arrows (a) to (e), as well as exterior photographs. Measuring lines (a) and (d) and the base station are in a large experiment room measuring 14 m × 20 m × 10 m, while (e) is in another room partitioned from the large experiment room.

While the mobile station was moved along each arrow, the RSSI from base station to mobile station was recorded. The RSSIs were recorded four or five times per metre. The RSSIs were transformed to received power as dBm and averaged over each 0.4 m distance as measured values.

VII–4. SIMULATION MODEL

Figure VII–3 shows a simulation model of experiment facility No. 1. It covers an area of 40 m × 20 m, is 12 m high and consists of 1561 polygons. The materials used are metal, concrete and glass.

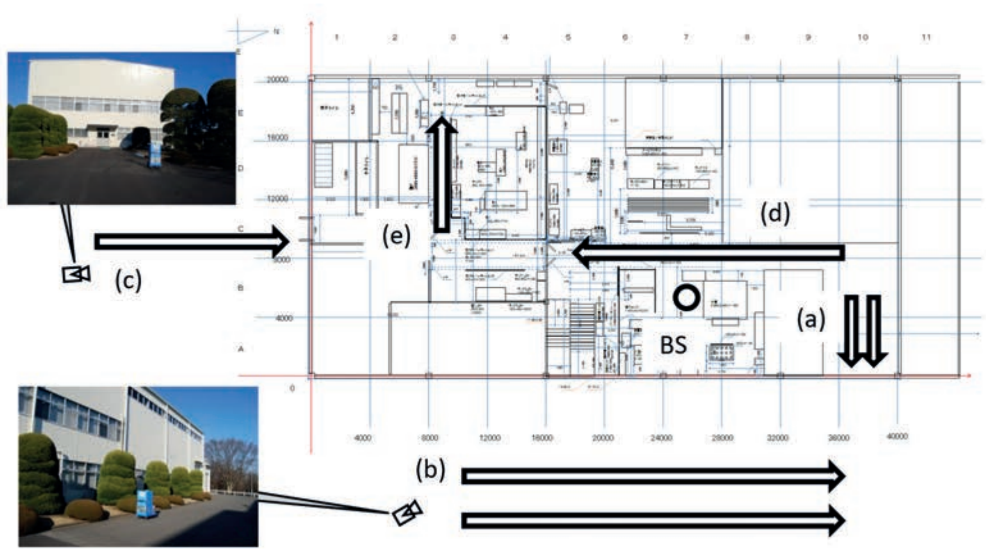


FIG. VII–2. Placement of experiments around experiment facility No. 1.

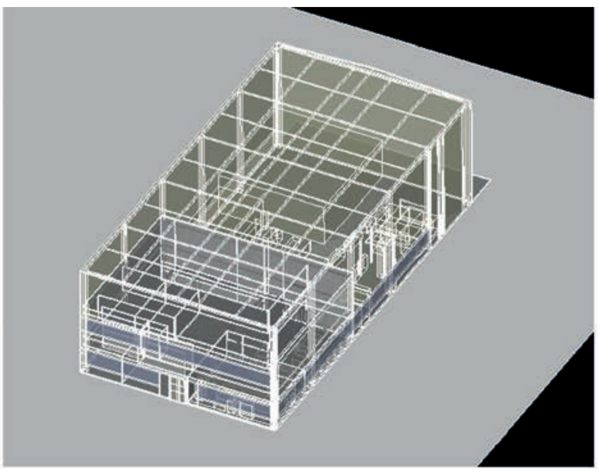


FIG. VII–3. Simulation model of experiment facility No. 1.

Figure VII–4 shows a simulation model of experiment facility No. 2. It covers an area of 300 m × 30 m, is 20 m high and consists of 1632 polygons. The materials are metal, concrete and glass. Facility No. 2 is about 20 times larger than No. 1 and there are many large metal objects representing typical nuclear plant components.

Figure VII–5 shows the results of radio wave propagation prediction for each frequency. The colour contours represent the received power level at 1836 mobile station positions spaced 1 m apart. For each ray tracing calculation, 8 000 000 rays were launched.

Figure VII–6 shows a comparison between the measured power and the calculated field sum or power sum. The horizontal axis represents mobile station points arranged in the measured order. Locations labelled (a) to (e) correspond to the locations shown in Fig. VII–2. The vertical axis represents measured or calculated received power.

Figure VII–7 shows the average differences between the measured and the calculated received power. Average differences are smaller between the power sums and the measured values than between the field sums and the measured values. As a result, the power sums were used for base station deployment.

Figure VII–8 shows a comparison between measured power and the calculated power sum with the horizontal axis representing the mobile station points arranged in order of measurement. Figure VII–9 shows a comparison between the measured power and the calculated power sum with the horizontal axis as the mean distance between the base station and the mobile station. It also shows the received power following a free space loss curve.

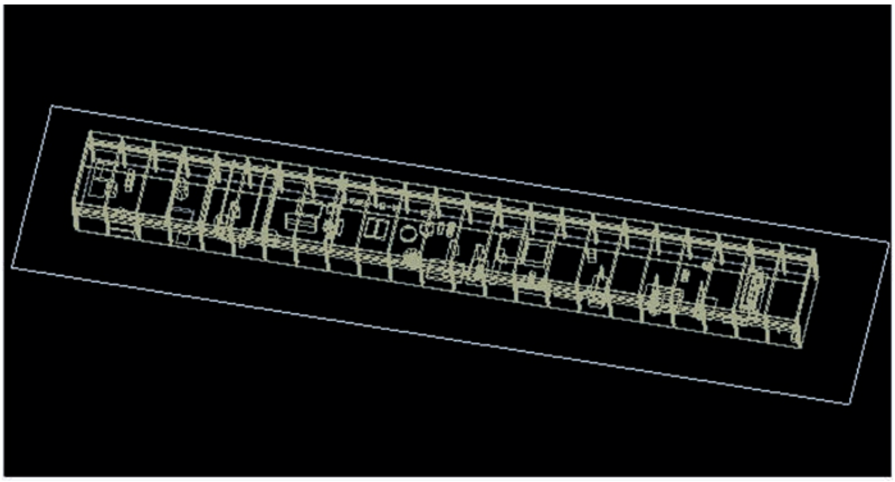


FIG. VII–4. Simulation model of experiment facility No. 2.

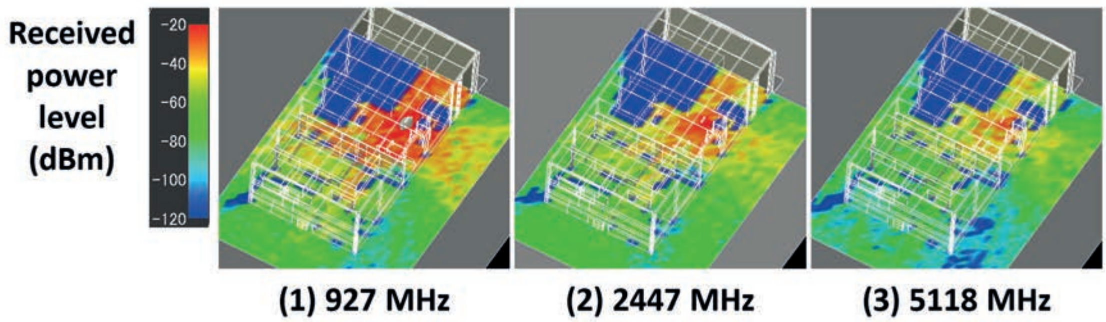


FIG. VII–5. Received power distribution around the experiment facility.

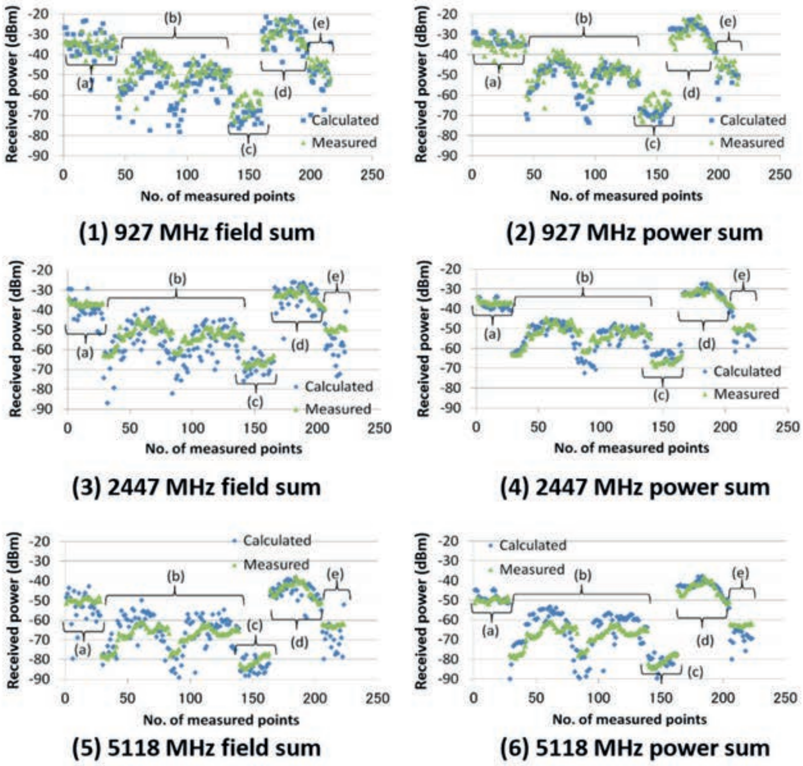


FIG. VII–6. Comparison between measured power and calculated field sum or power sum.

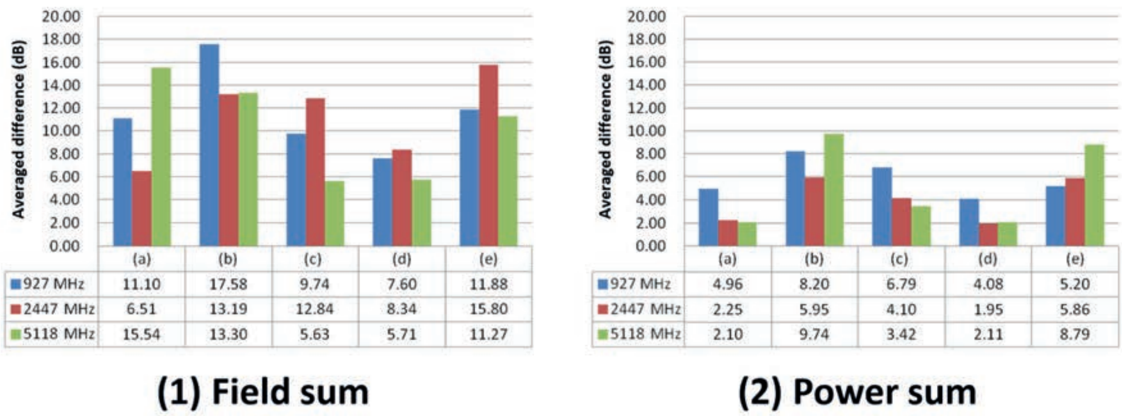


FIG. VII–7. Average difference between calculated and measured received power.

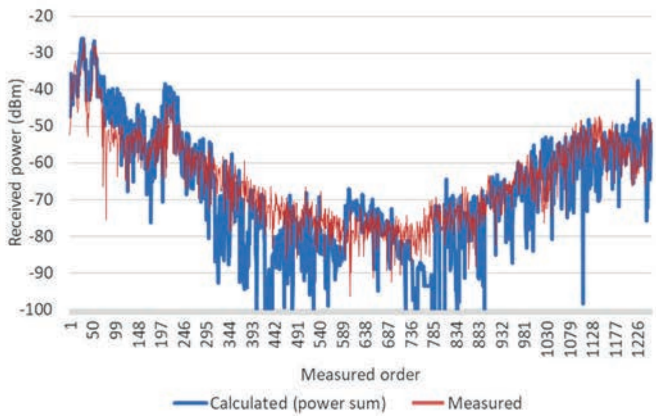


FIG. VII–8. Received power in facility No. 2 (927 MHz).

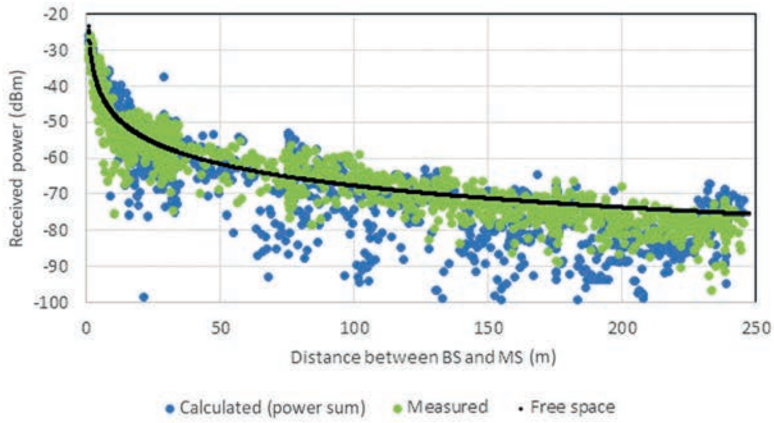


FIG. VII–9. Received power in facility No. 2 (927 MHz). BS — base station; MS — mobile station.

Annex VIII

OVERVIEW OF NUMERICAL MODELLING AND ELECTROMAGNETIC SIMULATION METHODS FOR SIGNAL PROPAGATION IN THE PRESENCE OF PHYSICAL BARRIERS

Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

VIII–1. BACKGROUND

The propagation of electromagnetic fields generated by wireless technologies inside a nuclear facility is complex owing to the presence of physical barriers, which prevent line of sight propagation due to signal reflection.

In this model, two approaches were considered: (1) analytical approximation techniques; and (2) computational electromagnetics. Analytical approximation techniques have several advantages, including ease of manipulation and simplicity of interpretation. However, although they are useful when inferring approximate solutions, analytical approximation techniques typically do not provide a high degree of accuracy.

Computational electromagnetic methods are typically more accurate but more time consuming than analytical approximation techniques. Several computational electromagnetic methods are described in this annex, with brief summaries of their properties when modelling the interaction between the electromagnetic fields generated by wireless technologies and the environment.

VIII–2. FULL WAVE COMPUTATIONAL ELECTROMAGNETIC METHODS

VIII–2.1. Method of moments

Numerical techniques based on the method of weighted residuals are called methods of moments. Most commercial method of moments codes are boundary element codes (i.e. the method of moments is applied to the solution of surface integral equations). However, the method of weighted residuals can be applied to differential equations as well as integral equations. In general, method of moments techniques are well suited to analysing unbounded radiation problems, perfect electric conductor configurations and homogeneous dielectrics. They are not well suited to the analysis of complex inhomogeneous geometries.

VIII–2.2. Finite element method

Finite element methods require the entire volume of the configuration to be meshed, as opposed to surface integral techniques, which only require the surfaces to be meshed. Each mesh element may have completely different material properties from those of neighbouring elements. In general, finite element methods are well suited to modelling complex inhomogeneous configurations. However, they do not model unbounded radiation problems as effectively as methods of moments.

VIII–2.3. Finite difference time domain

Similar to finite element methods, finite difference time domain techniques also require the entire volume to be meshed. Normally, this mesh needs to be uniform, so that the mesh density is determined by the smallest detail of the configuration. Unlike most finite element methods and method of moments techniques, finite difference time domain methods use time domain analysis, making them well suited to transient analysis problems. Similar to finite element methods, finite difference time domain methods can be useful for modelling complex inhomogeneous configurations. Also, many finite difference time domain implementations perform better than finite element methods when modelling unbounded problems. As a result, finite difference time domain techniques are preferred for modelling unbounded complex inhomogeneous geometries.

VIII–2.4. Additional modelling techniques

There are numerous other electromagnetic modelling techniques. Methods such as the transmission line matrix method and generalized multipole technique each have advantages for particular applications.

VIII–3. ASYMPTOTIC EXPANSION METHODS

The demand for computer memory and calculation time increases as more unknowns are added into the equations. This prohibits full wave methods from being applied to high frequency problems where the size of the object is much larger than the wavelength. The methods described in the following subsections are based on asymptotic high frequency expansions of Maxwell's equations. These high frequency methods are only accurate in instances where the dimensions of the objects are large compared to the wavelengths being analysed.

VIII–3.1. Physical optics

The physical optics approximation can be an efficient method for the analysis of large scattering objects. Physical optics reduces the cost of memory and central processing unit time by performing a high frequency approximation. This current based method uses the physical optics approximation to obtain the current density induced on the surface of an object.

The accuracy of the approximation depends on the transverse dimensions of the reflecting surface, the radius of curvature, the location of edges and the angle of the incident field. Generally, physical optics approximation can be used for large, smooth surfaces with low curvature. The implicit assumption for the physical optics approximation is that the incident field is treated locally as a planar wave and that the reflector surface is a perfect conductor.

Physical optics has been shown to provide an accurate prediction of far field radiation patterns for reflected antennas in the main beam region, including several side lobes. One disadvantage of the physical optics method is the potential computational complexity of the integration over the surface of the reflector when the feed is placed off axis or if the feed pattern is asymmetric. Moreover, the radiation integral has to be evaluated each time the observation point is changed.

VIII–3.2. Geometrical optics (ray optics)

Geometrical optics (see Ref. [VIII–1]) or geometrical optics with aperture integration are ray based analysis methods intended for electrically large dielectric structures for applications, such as reflector antennas. Geometrical optics techniques are used to create equivalent currents on an aperture plane, which is normal to the axis of the reflector. The tangential aperture fields are constructed using the Fourier transform to determine the radiated fields. Different formulations are obtained based on the use of aperture electric fields, magnetic fields or a combination of the two. An advantage of the geometrical optics with aperture integration method is that the integration over the aperture plane can be performed efficiently for any feed pattern or feed position.

VIII–3.3. Geometrical theory of diffraction

The approximations in both physical optics and geometrical optics are based on the following assumptions:

- The current density is zero on the shadow side of the reflector;
- The discontinuity of the current density over the rim of the reflector is ignored;
- Direct radiation from the feed and aperture blockage by the feed are ignored.

The physical optics and geometrical optics methods both ignore edge diffractions, which are highly dependent on whether the edges of the reflector are flared, sharp, absorber lined or serrated. Therefore, these techniques cannot accurately predict the far fields' radiation pattern beyond the first few side lobes. To accurately predict the radiation pattern in all regions, geometrical diffraction techniques are recommended.

As an extension of geometrical optics, the geometrical theory of diffraction overcomes the limitations of geometrical optics by using a diffraction mechanism. The diffracted field is determined at the points on the surface where there is a discontinuity in the incident and reflected field. The value of the diffracted field is evaluated at these points using an appropriate diffraction coefficient. The coefficient is typically determined from asymptotic solutions of boundary value problems based on canonical geometries, such as a conducting wedge, cylinder or sphere. Since the solutions of these canonical problems can be determined, the object under investigation can be partitioned into smaller components, such that each component represents a canonical geometry. The ultimate solution for the radiation pattern is a superposition of the contributions from each component as described in Ref. [VIII–2].

Two significant advantages of geometrical theory of diffraction over other high frequency asymptotic techniques are that it provides information on the radiation and scattering mechanisms from the various parts of the structure and it can yield more accurate results. However, geometrical theory of diffraction is inaccurate in the transition region adjacent to the shadow boundary, at caustics (points through which all the rays of a wave pass) or in close proximity to the surface of the scatterer. Ray techniques cannot be used in these regions because the field cannot be treated as a planar wave. A number of alternative approaches have been proposed to address this issue, including uniform solutions, methods for dealing with caustic curves, the physical theory of diffraction and the spectral theory of diffraction.

VIII–3.4. Uniform theory of diffraction

The uniform theory of diffraction is a uniform version of geometrical theory of diffraction meant to address inaccurate results at the shadow boundaries. Uniform theory of diffraction approximates electromagnetic waves in the near field as quasi-optical and uses ray diffraction to determine the diffraction coefficients for each diffracting object–source combination. These coefficients are used to calculate the field strength and phase in all directions from the diffracting point.

VIII–3.5. Conclusion

As addressed in Ref. [VIII–3], modelling the interaction between the electromagnetic fields generated by wireless technologies and a nuclear power plant environment can be difficult because the results are strongly dependent on the particular application (e.g. transmitting frequency, transmission and receiving technology, interfering objects and materials). Full wave analysis techniques are typically exploited for electrically small objects since high accuracy simulation results can be obtained at a low computation complexity. For electrically large objects, asymptotic techniques can be used to approximate results at an acceptable computational cost. Hybrid approaches through a combination of full wave and asymptotic techniques can be implemented to solve large electromagnetic problems with increased simulation accuracy.

An overview of the methods discussed in this annex is shown in Fig. VIII–1, which shows potential computational electromagnetics methods as a function of the electrical size and complexity of the object to be analysed.

Electromagnetic field propagation in the presence of barriers can be modelled such that both diffraction and reflection paths are considered with the line of sight path being obstructed by a perfect electric conductor wall. It is important to choose the proper numerical method for the specific problem in order to come to reasonable, reliable conclusions.

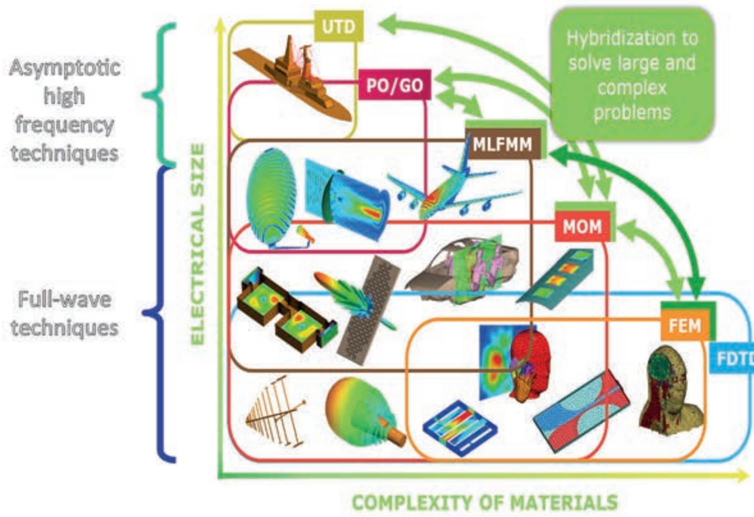


FIG. VIII–1. Different computational electromagnetic methods as a function of the complexity of materials and the electrical size (reproduced courtesy of Altair). FDTD — finite difference time domain; FEM — finite element method; GO — geometrical optics; MLFMM — multilevel fast multipole method; MOM — method of moments; PO — physical optics; UTD — uniform theory of diffraction.

REFERENCES TO ANNEX VIII

[VIII–1] DESCHAMPS, G.A., Ray techniques in electromagnetics, Proc. IEEE **60** 9 (1972) 1022–1035.

[VIII–2] BALANIS, C.A., Antenna Theory Analysis and Design, 3rd edn, John Wiley & Sons, Hoboken, NJ (2005).

[VIII–3] CAPPELLI, M., LOPRESTO, V., CECCHI, R., MARROCCO, G., "Evaluation of electromagnetic fields from wireless technologies in a nuclear plant", Proc. 26th Int. Conf. Nuclear Engineering, London, 2018, American Society of Mechanical Engineers, New York (2018).

Annex IX

ROTATING POLARIZATION WAVE COMMUNICATION TECHNIQUE

Hitachi, Ltd, Japan

IX–1. TECHNOLOGY

The rotating polarization wave (RPW) communication technique uses two different waves that have very closely related carrier frequencies. The sum of these carriers provides a beat wave with an envelope that oscillates at a frequency that is half of the difference of the two carrier frequencies. The RPW consists of the first beat wave transmitted from the first linearly polarized antenna and a second beat wave transmitted with a 90° delay (with respect to the envelope oscillating frequency) from the second linearly polarized antenna, which is spatially perpendicular to the first antenna. The oscillations in the envelopes of these two beat waves have to be synchronous. A mathematical expression of the RPW is as follows:

$$\begin{aligned} V - antenna &: \cos\omega_1 t + \cos\omega_2 t = 2\cos\frac{\omega_1+\omega_2}{2}t \cdot \cos\frac{\omega_1-\omega_2}{2}t \equiv 2\cos\omega_c t \cdot \cos\omega_p t \\ H - antenna &: \sin\omega_1 t - \sin\omega_2 t = 2\cos\frac{\omega_1+\omega_2}{2}t \cdot \sin\frac{\omega_1-\omega_2}{2}t \equiv 2\cos\omega_c t \sin\omega_p t \end{aligned} \tag{IX–1}$$

where

ω_c is the angular frequency of the first oscillator;
ω_p is the angular frequency of the second oscillator;
ω_1 is the angular frequency of the first beat wave;
ω_2 is the angular frequency of the second beat wave;
t is time;
V stands for vertical;

and H stands for horizontal.

This equation indicates that the two circular polarized waves, which have different frequencies and opposite rotating directions, generate the RPW using the two circular polarized wave antennas with perpendicular polarizations.

A digital signal processing device divides the period of the polarization rotation into several durations in which the receiving signal is demodulated. The data rate of information that is transferred from the transmitter to the receiver must be lower than the polarization rotating frequency because the information within one entire period of the polarization rotation must be the same.

The hardware architecture of the RPW transmitter uses two oscillators: $\cos\omega_c t$ and $\cos\omega_p t$. This architecture requires a multiplication process at the carrier frequency ω_c. Since commercial digital signal processing devices cannot perform this multiplication, an analogue mixer can be used in the architecture that can directly change the frequency of the polarization rotation. Since the maximum transfer rate of the information must be much smaller than that of the polarization rotation, this architecture can be useful for selecting the polarizations to use to increase the transfer rate when the frequency of information decreases.

The received RPW signals from the two perpendicular antennas are downconverted and directly sampled at a frequency higher than the inverse of the time duration. Before transmitting data, the RPW transmitter sends a unique bit sequence that is shared by the transmitter and receiver. The data rate of this bit sequence is the same as the frequency of the polarization rotation. The receiver obtains several sequences whose bits are determined by the sampled values in the durations that appear at the polarization rotating frequency. The receiver compares every sequence with the shared sequence. The receiver uses the duration where the received sequence matches the shared sequence to obtain a bit sequence of the transmitted data. The information is modulated using differential binary phase shift keying. The receiver selects the stronger signal among the signals from the two antennas. The difference of the signal strengths in neighbouring durations is compared with a threshold value in the framework of the differential binary phase shift keying demodulation. The block diagrams of the transmitter and receiver are shown in Fig. IX–1.

IX–2. EXPERIMENT RESULTS

The radio transceivers were manufactured for transmission and reception of both RPW and fixed polarization wave communication. A communication test between two RPW transceivers was conducted in a 280 m × 30 m × 20 m factory environment containing large metallic obstacles. The transceiver used four different fixed polarization wave polarizations including 0, 45, 90 and 135 degrees. An illustration of the set-up for this test is shown in Fig. IX–2.

The transceiver transmitted several data packets by using both RPW and fixed polarization wave communication. The packet error rate was determined for thousands of data samples by taking measurements at different positions in the factory, as shown in Fig. IX–2. The packet error rates are shown in Fig. IX–3. The packet error rate for the fixed polarization wave communication varied depending on both position in the factory and polarization. The packet error rate values for the RPW communication were similar for the different positions. In addition, during the testing in the factory, the packet error rate values for RPW communication were lower than those for fixed polarization wave communication.

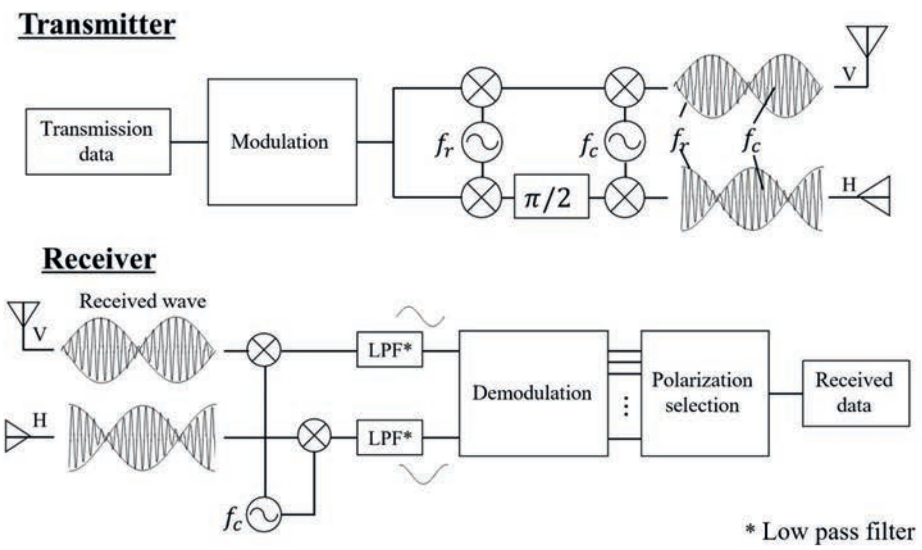


FIG. IX–1. Block diagram of rotating polarization wave transmitter and receiver.

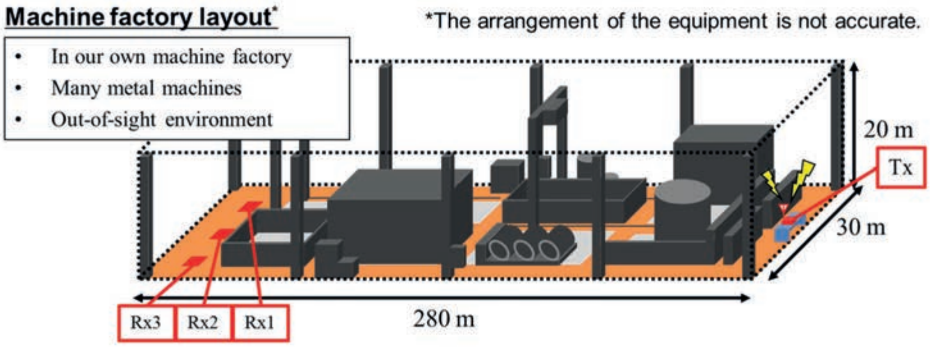


FIG. IX–2. Set-up of communication test in factory.

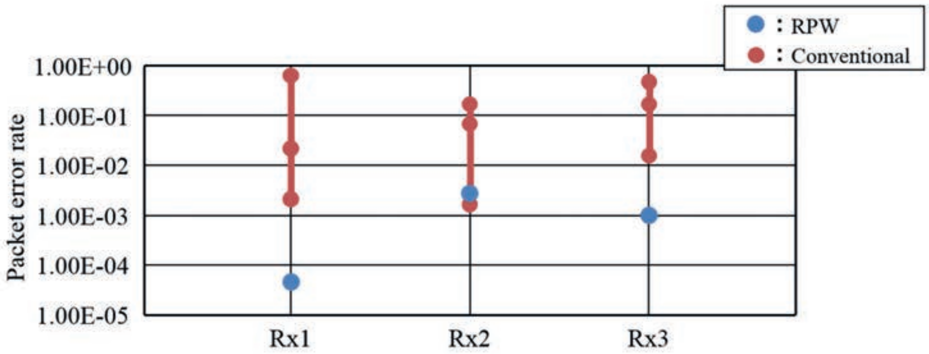


FIG. IX–3. Packet error rate performances at different receiver positions.

Annex X

WIRELESS POWER TRANSFER UNDER SEVERE ACCIDENT SCENARIOS

Gwangju Institute of Science and Technology, Republic of Korea

One of the most challenging problems during severe accident scenarios can be to ensure that power is provided to critical instruments so that plant operators can keep monitoring the plant conditions. Usually this scenario requires systems to be operational when the mains power is unavailable or insufficient. The systems may also need to operate under high radiation and high temperature conditions.

An article by Choi et al. (see Ref. [X–1]) describes a highly reliable power and communication system that guarantees the protection of essential instruments in an NPP under severe accident conditions. Both power and communication lines were established with not only conventional wired channels, but also with wireless channels for emergency reserve. An inductive power transfer system was selected due to its robust power transfer characteristics under high temperature, high pressure and highly humid environments with a large amount of scattered debris after a severe accident. A thermal insulation box and a glass fibre reinforced plastic box were proposed to protect the essential instruments, including vulnerable electronic circuits, from extremely high temperatures. Based on verification test results, the proposed wireless channels and protective boxes can be applied successfully in both currently operating NPPs and new designs.

REFERENCE TO ANNEX X

[X–1] CHOI, B.H., et al., Development of highly reliable power and communication system for essential instruments under severe accidents in NPP, Nucl. Eng. Technol. **48** 5 (2016) 1206–1218.

ABBREVIATIONS

BJT	bipolar junction transistor
CAM	channel availability metric
CRP	coordinated research project
DC	direct current
DICWG	Digital Instrumentation and Control Working Group (Nuclear Energy Agency of the Organisation for Economic Co-operation and Development)
DID	defence in depth
EIRP	effective isotropic radiated power
EMC	electromagnetic compatibility
EMI/RFI	electromagnetic and radiofrequency interference
EPRI	Electric Power Research Institute
FDTD	finite difference time domain
HART	highway addressable remote transducer (protocol)
HCMOS	high speed complementary metal oxide semiconductor
HMM	hidden Markov model
I&C	instrumentation and control
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISA	International Society of Automation
ISM	industrial, scientific and medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JFET	junction field-effect transistor
LAN	local area network
MAC	medium access control
MOSFET	metal oxide semiconductor field-effect transistor
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PAM	post-accident monitoring
PDR	packet delivery ratio
RF	radiofrequency
RPW	rotating polarization wave
RSSI	received signal strength indicator
SNR	signal to noise ratio
WLAN	wireless local area network
WPA	Wi-Fi protected access
WPAN	wireless personal area network
WSN	wireless sensor network

CONTRIBUTORS TO DRAFTING AND REVIEW

Ansari, S.	Pakistan Atomic Energy Commission, Pakistan
Arita, S.	Hitachi-GE Nuclear Energy, Ltd, Japan
Cappelli, M.	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Carvajal, J.	Westinghouse Electric Company, United States of America
Cheng, Xiaolei	North China Electric Power University, China
Chernyaev, A.	Rusatom Automated Control Systems, Russian Federation
Clayton, D.	Oak Ridge National Laboratory, United States of America
Eiler, J.	International Atomic Energy Agency
Frost, S.	Office for Nuclear Regulation, United Kingdom
Hanami, H.	Omika Works, Hitachi, Ltd, Japan
Hazi, G.	Hungarian Academy of Sciences, Centre for Energy Research, Hungary
Jayanthi, T.	Indira Gandhi Centre for Atomic Research, India
Jemimah, E.	Indira Gandhi Centre for Atomic Research, India
Jiang, Jin	University of Western Ontario, Canada
Khan, A.	Pakistan Atomic Energy Commission, Pakistan
Kiger, C.	Analysis and Measurement Services Corporation, United States of America
Kolchev, K.	Rusatom Automated Control Systems, Russian Federation
Li, T.	Shanghai Nuclear Engineering Research and Design Institute, China
Lopresto, V.	Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Mace, J.R.	Framatome, France
Mahmoud, I.	Nuclear Research Centre, Egyptian Atomic Energy Authority, Egypt
Makai, G.	Hungarian Academy of Sciences, Centre for Energy Research, Hungary
Oba, N.	Omika Works, Hitachi, Ltd, Japan
Rim, Chun Taek	Gwangju Institute of Science and Technology, Republic of Korea
Sato, Y.	R&D Group, Hitachi, Ltd, Japan
Satyamurty, S.A.V.	Indira Gandhi Centre for Atomic Research, India
Shankar, R.	Signatech Systems, United States of America

Yamada, T.	Omika Works, Hitachi, Ltd, Japan
Yu, Shuxin	Shanghai Nuclear Engineering Research and Design Institute, China
Zhang, Shuhui	Shanghai Nuclear Engineering Research and Design Institute, China

Research Coordination Meetings

Vienna, Austria: 30 March–2 April 2015
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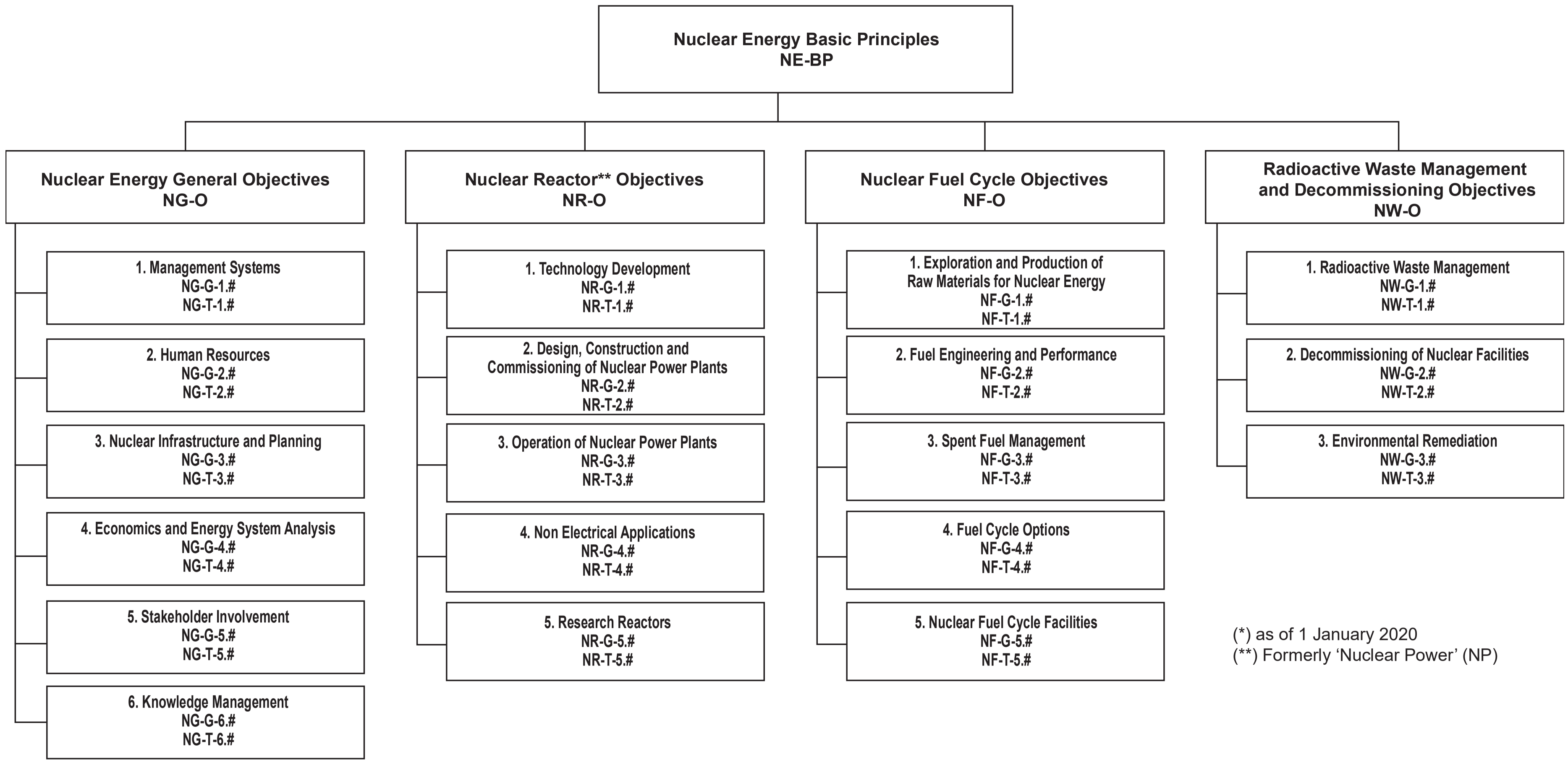

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Key

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