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Protecting People and the Environment

TECHNICAL LETTER REPORT

TLR-RES-DE-2023-007

Determining the Safety of Wireless Technologies at Nuclear Power Plants

Prepared by: Roy Hardin, RES/DE/ICEEB

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Executive Summary

This report documents research performed while conducting Research Assistance Request (RAR) NRR-2021-014, "Criteria for Determining the Safety of Wireless Technologies at Nuclear Power Plants." The report also discusses the companion Oak Ridge National Lab (ORNL)/SPR-2022/2534 report, which was completed as part of this RAR.

The ORNL report focuses on the primary method used to assure that safety systems at nuclear power plants (NPPs) are protected from adverse impacts from wireless sources - the exclusion zone calculation in Regulatory Guide (RG) 1.180, Rev 2, "Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems." Findings reveal that use of this method to estimate the exclusion zone for modern wireless devices may result in increased safety margin (i.e., a larger exclusion zone distance than necessary). The ORNL report correctly points out this method was developed for simple point-source radio-frequency (RF) environments, and that future use cases may benefit from other methodologies that allow for simultaneous modeling of multiple wireless devices emitting at variable frequencies.

This staff report highlights the potential need for continuing research and analysis due to the complex nature of the wireless environment given the potential for multiple fixed and mobile RF sources operating at variable frequencies. It identifies potential areas for future work, such as the use of simulation and modeling techniques and discusses the regulatory considerations. The report also presents additional information not analyzed in the ORNL/SPR-2022/2534 report. Furthermore, this staff report briefly discusses cooperative and synergistic efforts between the staff in RES to investigate the nexus between safety and security analyses associated with wireless devices.

This staff report also discusses the potential for expanding the use of wireless technologies in NPPs as raised in forums like the May 17, 2023, Advisory Committee on Reactor Safeguards (ACRS) meeting on the use of wireless technologies. Based on Department of Energy-Light Water Reactor Sustainability (DOE-LWRS) modernization activities and discussions with advanced reactor vendors, wireless devices may be proposed for use in safety-related or important-to-safety (SR/ITS) functions in the future. This report proposes suggested methods for correlating aspects of wireless to wired systems through wireless reliability. This process would combine electromagnetic compatibility, wireless coexistence, and interoperability into a metric to provide reasonable assurance that a wireless component can perform its intended function.

This staff report concludes with recommendations for future research to prepare the staff to review wireless devices, including sensors, that are characterized for use as SR/ITS components. The report also proposes the NRC consider endorsing national or international codes and standards should wireless devices be considered for use in SR/ITS systems in the future.

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Acronyms

ACRS - Advisory Committee on Reactor Safeguards

ACTWG - Advanced Communications Technology Working Group

AI – Artificial Intelligence

ALARA – As Low As Reasonably Achievable

ARM - Advanced Remote Monitoring

CDA – Critical Digital Asset

CFR – Code of Federal Regulations

CSP – Cybersecurity Plan

DOE – Department of Energy

EMC – Electromagnetic Compatibility

EMI – Electromagnetic Interference

EPRI – Electric Power Research Institute

FCC – Federal Communications Commission

IAEA – International Atomic Energy Administration

ISCP - Interagency Committee on Standards Policy

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronic Engineers

I&C – Instrumentation and Control

LAN – Local Area Network

LWRS – Light Water Reactor Sustainability

ML - Machine Learning

MOU – Memorandum of Understanding

NPP – Nuclear Power Plant

NRC – Nuclear Regulatory Commission

NRR – Office of Nuclear Reactor Regulation

NSIR – Office of Nuclear Security and Incident Response

ORNL – Oak Ridge National Laboratory

RAR – Research Assistance Request

RES – Office of Nuclear Regulatory Research

RF – Radio-Frequency

RFI – Radio-frequency Interference

RG – Regulatory Guide

SR/ITS – Safety Related/Important to Safety

Introduction

The sustained and growing interest in the expanded integration of wireless technologies into NPPs is driven by the potential for improved safety, efficiency, and flexibility these technologies can provide. This integration could pose challenges concerning safety and cybersecurity. This report examines the findings of RAR-NRR-2021-014, a research assistance request tailored specifically to explore the safety-related challenges. Additionally, it illuminates the insights obtained from the ORNL/SPR-2022/2534 report, an integral part of RAR-NRR-2021-014 and discusses the trajectory for future research.

The ACRS expressed concerns regarding the expanded use of wireless technology in NPPs. For instance, the use of power supplies for wireless devices, specifically the use of unique or non-standard batteries, was pointed out as a factor when considering the expanded use of wireless devices. However, it is essential to consider that many wireless devices could harness power from stray RF signals or depend on existing power sources, with batteries acting only as a backup power source. It is clear, therefore, that there remain unanswered questions.

Based on the DOE-ARM and DOE-LWRS modernization activities plus discussions with advanced reactor vendors, wireless devices may be proposed for use in SR/ITS functions in new reactor designs. This report concludes with recommendations for future research to prepare the staff to review potential wireless devices, including sensors, that are characterized for use as SR/ITS components.

Background

Background of the RAR-NRR-2021-014

The implementation of wireless technologies in NPPs has been a topic of discussion for a while. Many nuclear facilities already employ wireless systems in non-critical applications, such as business local area networks. The nuclear industry has demonstrated an interest in expanding the use of these technologies, particularly in contexts more common to industrial control systems and data acquisition monitoring systems. However, the application of wireless technologies in these scenarios can introduce significant safety considerations. For instance, it is vital to ensure that these technologies do not negatively interfere with SR/ITS systems, potentially affecting the plant's safe operation.

Research concerning the cybersecurity issues related to wireless technologies at nuclear facilities has been carried out and continues to progress. One example is technical letter report TLR-RES-DE-2022-007 "Study of Wireless Technology Implementation in Isolated, High Consequence Networks" which was published in July 2022. This report documents the findings of research on the cybersecurity aspects of the use of wireless technologies in other safety-critical industries. While this work connects to the safety aspects of wireless technology, there are distinctive and unique considerations to address to accurately categorize the risk to safety versus the risk to cybersecurity. Much like the division of regulatory responsibility between the office of Nuclear Reactor Regulation (NRR) and Nuclear Security and Incident Response (NSIR) in compliance matters, the review and associated guidance for the use of wireless technologies at NPPs are also divided. In recognition of this division, RAR-NRR-2022-014 was requested by NRR to consider safety aspects relevant to the possible expanded use of wireless technologies.[1]

As for the work identified in this RAR, this research effort offered insights into the expanded use of wireless communication technologies. This work enhances understanding of how such technologies could negatively interact with existing or future SR/ITS systems, and thus potentially compromise the plant's ability to maintain a safe operational state.

Purpose

The purpose of this RAR was to conduct research to identify issues or concerns associated with the expanded safe use of wireless communication technologies (e.g., Wi-Fi, Bluetooth, 5G, Zigbee) implemented at nuclear facilities, the potential adverse impacts on safety, and criteria for safety evaluation. The scope included the use of wireless technologies in or near SR/ITS systems.

The research was intended to benefit Nuclear Regulatory Commission (NRC) staff by:

- Providing licensees and staff with appropriate information on safety hazards and contributors to hazards when using wireless communication technologies in specific

[1] Cybersecurity aspects of SR/ITS wireless use are outside the scope of this RAR and report.

systems at nuclear facilities. It also addresses possible interactions with other plant systems, potential impacts on plant safety, and criteria or conditions for safe use.

- Providing licensees and staff with a clear understanding of the types of wireless technologies that can be or have been used in specific, non-safety-related, applications at NPPs and other nuclear facilities in or near critical functions.
- Acknowledge the inter-relationships between cybersecurity and safety aspects for wireless technology use.

This research also outlined potential next steps for developing guidelines for the safe use of wireless technologies at nuclear facilities.

Regulatory Context

The regulations applicable to this effort were derived from the following:

- The regulatory basis for determining the impacts on safety from the use of wireless technologies includes 10 CFR 50.55a(h). This regulation states that protection systems must meet the requirements of the Institute of Electrical and Electronics Engineers (IEEE) standard (Std.) 603-1991, "Criteria for Safety Systems for Nuclear Power Generating Stations", or IEEE Std. 279-1971, "Criteria for Protection Systems for Nuclear Power Generating Stations". The identified criteria include the range of transient and steady-state environmental conditions during normal, abnormal, and accident conditions under which the equipment must perform its safety functions.
- Furthermore, Criterion III, "Design Control," Criterion XI, "Test Control," and Criterion XVII, "Quality Assurance Records," of Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants" to 10 CFR Part 50 require design control measures to verify design adequacy. These criteria necessitate a test program to ensure that all testing required to demonstrate that structures, systems, and components will perform satisfactorily in service is conducted in accordance with written procedures. These criteria also require the maintenance of sufficient records as evidence of quality assurance activities.

Description of RAR-NRR-2021-014 and its Objectives

The potential integration of wireless technologies into NPPs has been an ongoing topic of discussion. The nuclear industry has expressed an interest in expanding the application of these technologies, especially in areas such as industrial control systems and data acquisition monitoring systems. However, deploying wireless technologies in these contexts brings to light critical safety considerations. For instance, it’s crucial to ensure that these technologies do not negatively interact with wired SR/ITS systems, which could potentially affect the safe operation of the plant.

The nuclear industry has been probing the feasibility of expanding the use of wireless technologies in NPP applications. However, the deployment of these technologies brings potential challenges to the fore, including ensuring safety requirements and managing potential cybersecurity risks. The research conducted under RAR-NRR-2021-014, as well as the findings of the ORNL/SPR-2022/2534 report, provide insights into these issues.

The ORNL/SPR-2022/2534 report indicated that the current RG 1.180 guidance on exclusion zone calculation will result in a safe distance and separation between safety systems and wireless emitters. However, this guidance treats RF sources as nuisances rather than contributors to mission accomplishment, limiting its utility for effective wireless integration into NPP operations. The ORNL report also underscored that the exclusion zone calculation might be overly restrictive for essential wireless use in the nuclear environment and doesn't consider the presence of multiple emitters or the operational effectiveness of wireless systems in that environment.

In conclusion, while the integration of wireless technologies into NPPs offers considerable opportunities for enhanced efficiency and flexibility, it also brings forth important safety and regulatory considerations. The research conducted under RAR-NRR-2021-014, along with the findings of the ORNL/SPR-2022/2534 report, have provided insights into these issues and has set the stage for future inquiries.

Review of RAR-NRR-2021-014 Performance

Overview of RAR-NRR-2021-014

RAR-NRR-2021-014 was initiated with the objective of exploring the safety implications linked to the use of wireless technologies in NPPs. This initiative included a comprehensive examination of wireless methodologies, challenges associated with these technologies, an assessment of the current state of wireless technology utilization in NPPs, and a discussion on potential future applications. The effort also evaluated the relevance of the exclusion zone calculation in ensuring adequate separation between safety systems and wireless sources. While this work didn't directly address all the concerns from the expanded use of wireless in NPPs, it did affirm the effectiveness of RG 1.180 in maintaining a safe distance.

The primary aim of this RAR was to undertake an effort to research potential impacts from the expanded use of wireless technologies. Specifically, the potential wireless effects from modern wireless modalities, such as emissions from cell phones, Bluetooth, and other Wi-Fi devices, on existing safety-related/important-to-safety digital assets. This was accomplished through a collaboration with ORNL, culminating in the ORNL/SPR-2022/2534 report.

The NRC staff, with the assistance of Oak Ridge National Laboratory, undertook an effort to research potential impacts from the expanded use of wireless technologies. Specifically, the potential wireless effects from modern wireless modalities, such as emissions from cell phones, Bluetooth, and other Wi-Fi devices, on existing safety-related/important-to-safety digital assets. In September 2023, the NRC staff issued a Technical Letter Report (ML23222A166) documenting results of this research, including the finding that standoff distances calculated using existing RG 1.180, Rev 2., remain reasonable with modern modalities

As further discussed in this report, there are potential subsequent initiatives aimed at investigating this topic further and providing more definitive solutions to support the implementation of wireless technologies into nuclear power plant systems, particularly those related to safety.

It's important to note that the primary focus of this initiative has been on currently operating NPPs and current designs. However, the potential applicability and support for advanced reactors and new technologies were also considered within the scope of this effort. Components of this effort will be useful for these advanced areas, although further work may be needed. Wireless technologies may play a much greater role in future reactor designs. Thus, the information developed under this RAR provides a useful foundational basis.

The following section breaks down the RAR tasks and their status.

RAR-2021-001Tasks Breakdown

Tasks	Status	Notes
Review literature to assess how the implementation of wireless technologies is done/used in industrial control systems for safety-critical industries. The research should include:	X	
• Identify sources of information regarding the implementation of wireless communication technologies and any potential barriers or challenges associated with their adoption in NPP applications.	X	
• Review the Electric Power Research Institute (EPRI) report on "Wireless Technology Assessment: Analysis of Radiated Emissions from Common Phones, Laptops, and Tablets."	S	Reviewed by staff under EPRI MOU. Not attributable. Information consistent with ORNL effort and testing.
• Review the International Atomic Energy Administration (IAEA) report on "Application of Wireless Technologies in Nuclear Power Plant Instrumentation and Control Systems."	X	
• Review any available research from the national labs on wireless technology application and potential impact to associated systems.	X	

Similar work completed for other Office of Research efforts will be leveraged as possible.	X	
Consider how the expanded use of wireless communication technologies may adversely interact with existing or future SR/ITS systems, and thus challenge the plant's ability to maintain a safe operational state. The areas addressed in this research include:	P	See below.
• Revisit exclusion zone calculations (per RG 1.180).	X	Recommended no change for currently defined wireless use.
• Develop criteria for safely using wireless gauges to reduce operator rounds.	X	Generally applicable information developed suitable for current implementations.
• Identification of safety hazards or contributors and criteria for safety evaluation, e.g.,	P	Impact to other non-wireless systems addressed.
(a) Identify current use cases	X	
(b) Identify potential use cases of interest to facilities	X	Additional potential use cases exist for more integrated wireless implementations such as monitoring.
(c) EMC/EMI/RFI, data fidelity, congestion, reliability, accuracy	P	Examined national/international standards and related information on these areas. Potential items for endorsement based on current and possible future use cases.
(d) Wireless networks within the power block	P	Identified information that may support evaluations of additional relevant use cases, in addition to existing guidance. General concepts of wireless applications are applicable.

(e) Outage vs operation	P	Identified information that may support evaluations of additional relevant use cases, in addition to existing guidance. General concepts of wireless applications are applicable.
(f) Surveillance and maintenance vs operation	P	Identified information that may support evaluations of additional relevant use cases, in addition to existing guidance. General concepts of wireless applications are applicable.
• Additional research to focus on areas identified as desirable applications of wireless through use cases.	P	Information to support this additional effort was identified. Use cases are indeterminate at this time and are subject to external factors (such as cybersecurity issues).
Associated support for above tasks.	X	
Report Out Findings		
• Composite report summarizing the results of the above tasks and outlining potential next steps.	X	
• Suggested revisions to RG 1.180 for exclusion zone calculations	X	
• Specific Letter Reports of above tasks detailing results from efforts.	X	

Legend:

X – Accomplished
S – Performed by Staff
P – Partial Completion

ORNL/SPR-2022/2534 Report

The ORNL/SPR-2022/2534 report delivered an in-depth analysis of potential safety implications tied to the use of wireless technology in NPPs. A key finding of the report was validation of method to calculate the exclusion zone from Regulatory Guide 1.180 for modern wireless devices.

The report initiated a discussion on the potential impact on SR/ITS systems due to the possible expanded use of wireless technologies. It reviewed Regulatory Guide (RG) 1.180 Rev. 2 to determine if revisions were necessary to reflect the current state of practice in evaluating and protecting instrumentation and control (I&C) systems and components from Electromagnetic Interference (EMI) or Radiofrequency Interference (RFI) on safety and non-safety I&C.

The report identified how EMI/RFI from wireless systems could impact these systems and discussed the degradation and failure modes of these components. This information was used for the RG review and for test planning.

To support this effort, ORNL conducted a survey of modern wireless technologies. This knowledge base was fundamental to considering potential EMI/RFI environment changes and subsequent electromagnetic compatibility (EMC) issues for existing plant components resulting from expanded wireless use. The survey was accomplished through a literature review of the technologies and their uses in both nuclear and non-nuclear applications.

The report also discussed laboratory testing used to evaluate the RG 1.180 exclusion zone calculation. The purpose of the testing was to validate the concepts discussed in the RG and to perform a spot-check of test results versus analytical results.

In conclusion, the ORNL/SPR-2022/2534 report provided insights into the potential safety implications of wireless technology use in NPPs and laid the groundwork for future investigations. It discussed the need for ongoing research and analysis and identified the potential need for the NRC to consider such actions as endorsing national or international standards for acceptable EMC, wireless coexistence, interoperability, and other factors.

ORNL/SPR-2022/2534 Findings

The primary finding of note was that continued use of the exclusion zone distance calculation in RG 1.180, Rev 2, provides an acceptable level of protection when used to separate wireless emitters and safety systems. This resolved a safety driver for this research by demonstrating that no changes or revisions to RG 1.180 Rev 2 were needed due to modern wireless devices.

This finding was based on an analysis that utilized previous work performed by ORNL in 2015 under NRC-HQ-60-14-D-0015, "Update to RG 1.180, Revision 2, Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems." This analysis considered new wireless technologies and devices along with supporting test data.

An additional finding was that the exclusion zone calculation in RG 1.180 may result in increased safety margins (i.e., a larger exclusion zone distance than necessary) due to several reasons, such as uncertainty of power values, variations in modulation technologies, and peak versus average power.

S***imulation and Modeling Evaluations***

Simulation and modeling evaluations are valuable tools for understanding the complexity of wireless signal and propagation evaluation. First, these evaluations provide a means to predict and analyze the behavior of wireless systems in a controlled and repeatable environment, which allows for the identification of potential issues and the evaluation of mitigation strategies. Second, these evaluations can assist in more effectively determining, prior to installation, the propagation issues that may occur. This includes examining how different systems can interoperate and interact to avoid issues between the signals or other aspects of RF signal propagation, which could make the effectiveness of the wireless devices less than optimal.

Some ways of doing these evaluations include the use of MATLAB as well as the actual development of programs or the use of routines such as using Python with the requisite associated libraries. Another option is to use a simulation tool such as NS-3, which provides an analytical process to model and evaluate signal propagation and other aspects of wireless communications in the environment. RF propagation and wireless signal analysis is a difficult process, and in a complex environment, a model provides a means to simulate reflections and absorption of different items in the area. Some simplified examples of methods to simulate RF signal propagation are included in the appendix.

Another evaluation approach is application of Artificial Intelligence(AI)/Machine Learning(ML). With the proper tuning, input data, and simulation training, these models may provide insights into how the wireless signal will propagate in complex building environments.

While simulation and modeling evaluations like MATLAB, Python, and NS-3, along with AI and ML techniques, offer valuable insights into wireless signal propagation, they do have their limitations. These tools rely on mathematical models and algorithms that, while sophisticated, may not fully capture the complexity and unpredictability of real-world environments. For instance, factors such as physical obstructions, interference from other devices, and changes in environmental conditions can all impact wireless signal propagation in ways that are difficult to predict accurately with simulations.

In the context of RAR-NRR-2021-014, simulation and model evaluations were not performed. However, they are mentioned in this report to develop the "big picture" of modern wireless technology integration and deployment. These evaluations could also be integrated as part of development of a digital twin for the NPP to simulate the integrated wireless components under different plant conditions. The evaluations could also help understand trade-offs between safety and efficiency, and to develop strategies that balance these competing requirements. These types of evaluations offer insights into how wireless signals might behave, including aiding the identification of solutions to optimize system performance.

Limitations and the Value of In Situ Data Collection

There was insufficient information on the susceptibility of plant systems to high-frequency signals (above 10 GHz) as the upper range of the qualification testing was limited to 10 GHz. Current technologies generally do not utilize such high-frequency signals, but this may become more prevalent in the future. It may be prudent for staff to monitor the development of technology utilizing frequencies above 10 GHz and consider the endorsement of national/international standards to provide additional guidance in this area.

In situ data collection provides valuable site data in the actual environments. These data represent the actual site conditions and is invaluable to verify and validate simulation and modeling tools. In many cases, in-situ measurements may be needed to properly understand the complex RF environment inside of a building. This may be particularly true when multiple RF sources are used in close proximity. Without understanding the RF environment, to include the multiple propagation factors (including reflection and absorption) as well as constructive and destructive interference, it may be difficult to adequately justify what levels of RF energy the SR/ITS systems may experience.

In situ data collection also has its challenges. It can be time-consuming, costly, and subject to its own set of uncertainties. For example, it may not always be feasible to test wireless systems under all possible conditions inside of the reactor containment structure. In some situations, real-world data may be limited in value. This is because real-world data is tied specifically and directly to a specific test pattern environment. A numerical model, backed with information from in situ testing, may provide a useful solution for initial and preliminary design evaluations as well as initial implementation designs.

While simulation and modeling tools have their limitations, they are a part of the toolkit for analyzing and predicting wireless signal propagation. Used in conjunction with in situ testing, these tools can provide an understanding of wireless signal behavior, helping to ensure the safety and reliability of wireless systems.

Regulatory Considerations and Potential Guidance Needs

Application of new wireless technologies into NPPs may present new regulatory considerations. Specifically, while RG 1.180, Rev 2, does not need to be revised based on the findings of the ORNL/SPR-2022/2534 report, this effort identified the potential future need to consider acceptable EMC, wireless coexistence, and interoperability criteria should wireless data ever be used to support safety-related or important-to-safety (SR/ITS) systems and applications.[2] While no operating NRC-licensed reactor currently uses wireless technologies to support SR/ITS functions, a desire to use these technologies may emerge in the future. In such a scenario, guidance on acceptable EMC, wireless coexistence, and interoperability performance criteria that may be acceptable to the NRC staff could facilitate review of these new technologies if they are requested for use in SR/ITS applications.

Organizations such as the Nuclear Energy Institute (NEI) and the DOE Nuclear Energy (NE) are examining the potential increased use of wireless technology. Examples include the DOE Light Water Reactor Sustainability (LWRS)-Modernization Pathway and the DOE Advanced Remote Monitoring (ARM) program efforts, both of which are looking at wireless uses with the potential to save on operations and maintenance (O&M) costs and reduce operator exposure.[3] There is also increasing industry interest, particularly in the domain of advanced reactors, which will potentially lead to the likely need for NRC staff to be prepared to review an application where wireless devices are used for a SR/ITS function.

Future Steps

As discussed in the Regulatory Considerations section, a potential need exists for new NRC staff review guidelines if wireless devices are proposed for use in safety-related or important-to-safety reactor systems. This need pertains to acceptable EMC, wireless coexistence, and interoperability performance criteria which did not need to be considered for wired systems.

One potential solution is for the NRC to consider endorsing performance-based national or international standards for these criteria. The goal would be to develop a consistent and clear process to evaluate wireless technology in a performance-based and technology neutral framework. Ideally, the endorsed standard(s) would consider performance-based security criteria to ensure consideration of cybersecurity concerns unique to wireless technologies. There are several inter-governmental working groups including the Interagency Committee on Standards Policy (ICSP) Advanced Communications Technologies Working Group (ACTWG) that could inform this effort, as well as ongoing initiatives within IEEE and IEC standards organizations.[4]

A successful outcome would be to identify which standards are suitable for NRC to consider endorsing, as well as unique environmental challenges in NRC regulated facilities. Examples

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[2] Cybersecurity aspects of SR/ITS wireless use are outside the scope of this RAR and report.

[3] Activities performed under DOE Assistance Agreement: DE-NE000892, Advanced Remote Monitoring, by Utilities Service Alliance.

[4] Such initiatives include activities under IEEE Communications and Information Security Technical Committee, IEEE Communications Quality & Reliability Technical Committee, and IEC TC 65/SC 65C – Industrial networks.

include wireless data reliability needs (coexistence, interoperability) in areas of high radiation environments, and EMC standards for nearby sensitive digital instrumentation. With the potential demand for increased use of wireless technologies to reduce operation and maintenance costs of the operating fleet as well as integrated deployment of wireless technologies in advanced reactor designs, it may be prudent for staff to develop review guidance for use of these technologies.

Conclusions

This report documents the research results from RAR-NRR-2022-014 and related activities. It explores the background, goals, and the levels of accomplishment of the RAR, including the primary research product, ORNL/SPR-2022/2534. The report outlines identified issues, methods used in their resolutions, or plans for future resolutions.

The report proposes methods and strategies for continuing this research, incorporating new and novel technologies. It discusses specific areas for focus in future work, with a concentration on the potential implications of using wireless technologies in the modernization of the operating reactor fleet or in the integrated deployment of advanced reactor designs.

This research demonstrated that the current agency guidance (e.g., R.G. 1.180, Rev 2) regarding wireless technologies and their interaction with safety systems sufficiently protects safety systems from adverse effects. This guidance is based on the present absence of wireless technologies for SR/ITS functions. However, based on ongoing activities including the DOE-LWRS modernization effort and discussions with advanced reactor vendors, there's potential for proposed use of wireless devices in SR/ITS systems in the future. Therefore, this report recommends subsequent activities that consider endorsing performance-based national or international standards for EMC, wireless coexistence, and interoperability criteria as well as continued staff collaboration on inter-governmental working groups and ongoing initiatives within IEEE and IEC standards organizations.

Appendices

Simulation and Modeling Examples

When it comes to analyzing and predicting the behavior of wireless signals, especially in complex environments like NPPs, simulation and modeling tools are useful. They offer insights into how wireless signals might behave, helping to identify potential challenges and optimize system performance. Some potential uses to evaluate and predict wireless signal propagation using simulation and modeling with certain tools will now be briefly discussed. Specifically, in this section, the use of tools such as MATLAB, Python libraries, and NS-3 are briefly explored for these purposes. The following examples are provided to illustrate the tools' capabilities and not as a recommendation for use or specific operable application.

MATLAB

MATLAB is a platform for numerical computation, visualization, and programming. It is used by engineers to model and simulate wireless communication systems, including the propagation of wireless signals. For instance, the following MATLAB code demonstrates a basic simulation of signal propagation:

```
% Constants
Pt = 30; % Maximum power level of Wi-Fi signal in dBm
Gt = 1; % Transmitter gain
Gr = 1; % Receiver gain
f = 2.4e9; % Frequency of Wi-Fi signal in Hz
c = 3e8; % Speed of light in m/s

% Calculate wavelength
lambda = c / f;

% Distances from the source
d = 0.25:0.25:5;

% Calculate field strength
Pr = Pt + 20*log10(Gt) + 20*log10(Gr) + 20*log10(lambda / (4*pi*d));

% Display results
disp('Field strength at various distances:');
disp(['Distance (m) – Field Strength (dBm)']);
disp([d', Pr']);
```

This code calculates the path loss of a signal as it travels, using a simple path loss model. The path loss exponent can be adjusted to reflect different propagation environments.

Python

Python is a tool for simulating wireless signal propagation with an extensive range of libraries. Libraries like NumPy and SciPy offer numerical computation capabilities, while Matplotlib is used for visualization. Below is a Python version of the MATLAB code above:

```
import numpy as np

# Constants
Pt = 30  # Maximum power level of Wi-Fi signal in dBm
Gt = 1  # Transmitter gain
Gr = 1  # Receiver gain
f = 2.4e9  # Frequency of Wi-Fi signal in Hz
c = 3e8  # Speed of light in m/s

# Calculate wavelength
lambda_ = c / f

# Distances from the source
d = np.arange(0.25, 5.25, 0.25)

# Calculate field strength
Pr = Pt + 20*np.log10(Gt) + 20*np.log10(Gr) + 20*np.log10(lambda_ / (4*np.pi*d))

# Display results
print('Field strength at various distances:')
for I in range(len(d)):
   print"Distance: {:.2f} m–- Field Strength: {:.2f} dB".format(d[i], Pr[i]))
```

NS-3

NS-3 is a discrete-event network simulator that is used for research and development. It provides models for various types of wireless networks, including Wi-Fi. NS-3 allows for more complex and realistic simulations than MATLAB and Python, including the modeling of network protocols and the interaction of multiple devices.

NS-3 does not directly support calculations of field strength. However, it does support calculations of received power, which is closely related. Here is an example of calculating received power at various distances in NS-3:

```
#include“"ns3/core-module.”"
#include“"ns3/mobility-module.”"
#include“"ns3/wifi-module.”"

using namespace ns3;

int main (int argc, char *argv[])
{
  NodeContainer nodes;
  nodes.Create (2);

  YansWifiChannelHelper wifiChannel;
  wifiChannel.SetPropagationDelay “"ns3::ConstantSpeedPropagationDelayMode”");
  wifiChannel.AddPropagationLoss “"ns3::FriisPropagationLossMode”");

  YansWifiPhyHelper wifiPhy = YansWifiPhyHelper::Default ();
  wifiPhy.SetChannel (wifiChannel.Create ());

  WifiHelper wifi;
  wifi.SetStandard (WIFI_PHY_STANDARD_80211a);
  wifi.SetRemoteStationManager “"ns3::ConstantRateWifiManage”",“"DataMod”",
StringValue “"OfdmRate54Mbp”"));

  WifiMacHelper wifiMac;
  wifiMac.SetType “"ns3::AdhocWifiMa”");

  NetDeviceContainer devices = wifi.Install (wifiPhy, wifiMac, nodes);

  MobilityHelper mobility;
  Ptr<ListPositionAllocator> positionAlloc = CreateObject<ListPositionAllocator> ();
  positionAlloc->Add (Vector (0.0, 0.0, 0.0));
  positionAlloc->Add (Vector (5.0, 0.0, 0.0));
  mobility.SetPositionAllocator (positionAlloc);
  mobility.SetMobilityModel “"ns3::ConstantPositionMobilityMode”");
  mobility.Install (nodes);

  Simulator::Stop (Seconds (1.0));

  Ptr<WifiNetDevice> device1 = DynamicCast<WifiNetDevice> (devices.Get (0));
  Ptr<WifiNetDevice> device2 = DynamicCast<WifiNetDevice> (devices.Get (1));
  Ptr<YansWifiPhy> phy1 = DynamicCast<YansWifiPhy> (device1->GetPhy ());
  Ptr<YansWifiPhy> phy2 = DynamicCast<YansWifiPhy> (device2->GetPhy ());

  for (double d = 0.25; d <= 5.0; d += 0.25)
    {
      positionAlloc->SetPosition (nodes.Get (1), Vector (d, 0.0, 0.0));
```

```
    double rxPowerDbm = wifiChannel.GetPropagationLossModel ()->CalcRxPower
(30, phy1, phy2);
    std::cout <<“"Distance:“" << d <<“" m–- Received Power:“" << rxPowerDbm
<<“" dB”" << std::endl;
  }

 Simulator::Run ();
 Simulator::Destroy ();

 return 0;
}
```

This NS-3 script calculates the received power at various distances from the source. Example output of this script is as follows:

```
Distance: 0.25 m–- Received Power: -30.97 dBm
Distance: 0.50 m–- Received Power: -36.98 dBm
Distance: 0.75 m–- Received Power: -40.47 dBm
...
Distance: 5.00 m–- Received Power: -60.97 dBm
```

Closeout for RAR-NRR-2021-014 DATE October 17, 2023

DISTRIBUTION:
JZhao, NRR/DEX/ELTB
NCarte, NRR/DEX/EEOB
LHardin, RES/DE/ICEEB
SWyman, NRR/DEX/EEEB
CCook, RES/DE/ICEEB
MWaters, NSIR/DPR
RStattel, NRR/DEX/EEOB
TMartinezNavedo, NRR/DRO
JMcKirgan, RES/DE
NTaylor, R-IV/DRS/EB2

ADAMS Accession No.: ML21117A273; ML23222A183

OFFICE	RES/DE/ICEEB	RES/DE/ICEEB	NSIR/DPCP/RSB	
NAME	LHardin *LH*	CCook *CC*	MSampson *MS*	
DATE	Sep 27, 2023	Sep 28, 2023	Oct 17, 2023	

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