Implementation of Wireless Technologies in Nuclear Power Plants' Electromagnetic Environment Using Cognitive Radio System

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ABSTRACT

Wireless technologies have increased efficiency in many industrial settings across the world by enabling a mobile workforce and improving communications. Unfortunately, the nuclear power industry has been slow to adopt wireless technology as a result of safety, security, and reliability concerns expressed by regulators and others. A Research and Development (R&D) effort is currently being conducted to address two significant technical concerns for the introduction of wireless technology in nuclear power plants, which are electromagnetic compatibility (EMC) and wireless coexistence.

Most equipment in nuclear power plants has never been tested for vulnerability to wireless transmission. As such, the impact of modern wireless devices on nuclear safety and plant reliability is not understood. Existing guidance from the Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI) rely on the use of exclusion zones to protect plant equipment, which can result in exclusion zones of up to eight feet for some tablet devices rendering them ineffective for the mobile workforce. Another unknown is how different wireless devices will operate in close proximity to one another in the harsh electromagnetic environment of a nuclear power plant. These issues are being addressed through development of a cognitive radio system that has the ability to generate and output multiple wireless signals such as Wi-Fi, Bluetooth, and cellular communications at varying power levels and frequencies. The cognitive radio system is a modular system that can test nuclear plant equipment located in training areas, simulators, and the actual plant environment. In addition to using the system for testing plant equipment to wireless signals and EMC standards, the system can also monitor the radio spectrum for usage in other plant focuses such as cyber security.

The R&D work will provide the objective guidance for the nuclear industry in the two areas mentioned and will develop a cognitive radio system for in-plant EMC and coexistence testing. The system will assist in the seamless use of wireless technology in nuclear power plants while greatly reducing the risks wireless signals may introduce.

Key Words: Wireless, Electromagnetic, Compatibility, Electromagnetic Interference, Coexistence

1 INTRODUCTION

Starting in December 2015, the Nuclear Energy Institute (NEI), the Institute of Nuclear Power Operations (INPO), and the Electric Power Research Institute (EPRI) made a commitment to make nuclear power generation a more competitive source of energy in the United States market. This initiative called "Delivering the Nuclear Promise" drives nuclear power plants to reduce operating costs by 30 percent at the end of 2018. The reduction of operating cost is plant wide and concerns all departments. In Efficiency Bulletin 16-16, condition monitoring of plant equipment is seen as a need to reduce operating cost for plant activities [1]. Also to keep up with other industries, the implementation of wireless devices has increased in the number of uses to decrease plant equipment downtime and to save money in other aspects of nuclear power. In the United States, most of the 100 licensed and operating nuclear power units will likely implement some form of wireless technology in the next 10 years to further assist in reducing operating costs, thus helping meet the Nuclear Promise even after the program is completed in 2018. Utilities are pushing for new technologies such as digital mobile workers, online equipment condition monitoring, and in plant communications to help with all aspects of the plant operation and maintenance. Dwight Clayton of Oak Ridge National Laboratories (ORNL) made a statement in September 2012 that expanding wireless communication systems the nuclear fleet is needed:

"To develop wireless alternatives to costly hardwired cabling for real-time, online monitoring, demonstration of a high-reliability, secure wireless communication system for continuous data transmission is necessary." [2]

The benefits of wireless technology in nuclear power plants are well known and established. The application of wireless sensors for condition monitoring, tablet devices for the mobile work force and electronic work packages, real time radiation dosimetry, and general efficiencies and improvements through the use of cell phones, wireless cameras, and other wireless devices are significant driving forces within the industry [3, 4].

A recent study by the nuclear industry demonstrated savings of nearly 6 million dollars or 50,000 man-hours per year in using wireless technology for voice and data communications in the maintenance department alone [5]. Examples of efficiency gains include: the use of tablet based work orders and calibration procedures, wireless access to plant engineering documentation, voice communication anywhere in the plant, temporary or permanent installation of wireless cameras, and equipment condition monitoring using wireless sensors.

This study was prompted by an electrical fire in a diesel generator at a nuclear power plant in California in 2011 that necessitated a response from the local fire department. The fire department arrived with all their wireless communications equipment including cell phones and handheld radio devices. At the time the utility did not allow the use of wireless devices anywhere within the power block and the firemen were asked to leave their wireless communication equipment with security personnel before entering the plant. This event prompted the utility and other nuclear power plants to investigate the implications of using wireless technologies in and around the plant; especially in the case emergencies such as fire.

Although wireless technology can provide significant benefits, roadblocks still exist in its implementation path in nuclear facilities. EMI/RFI is a main area of concern for utilities [6, 7]. Cell phone and mobile device signals, despite being relatively low power, can potentially have unexpected effects on plant equipment and can even cause plant trips if they are used in close proximity to sensitive instrumentation or equipment. Nevertheless, their use now or in the near future is inevitable in nuclear power plants. Further, wireless technology not only for voice but also for data communications can improve the efficiency of plant operation and maintenance. Over efficiencies gained, nuclear power plant operators need to be informed of the electromagnetic interference risk of wireless technologies and how to adequately prepare the plant for the usage of newer wireless technologies.

2 EXCLUSION ZONES FOR WIRELESS DEVICES

2.1 Current Methodology for Implementing Wireless Devices with Exclusion Zones

For current usage of wireless devices in the nuclear power plant, certain areas of the plant have exclusion zones, other barriers, or signage to prohibit the usage of wireless devices near sensitive equipment. Exclusion zones were created in the early 1980s when plant personnel realized that two-way radios would affect sensitive plant equipment. The most recent guidance on how to establish exclusion zones distances is contained in EPRI TR-102323 Revision 4. The revision 4 guidance defines an equation to determine the minimum exclusion zone [8].

$$V_d = \frac{\sqrt{30\ P_t G_t}}{d} \tag{1}$$

Where V_d = the field strength of the device at a given distance. P_t = output power of the transmitting device in watts. G_t = gain of the transmitting device's antenna. d = distance from the transmitting device.

Per the guidance from the EPRI TR-102323 Revision 4, the maximum electric field emissions from nuclear power plant equipment is 132 dBµV/m or 4 V/m. The equation above is used to determine the distance at which a device's field strength is equal to 4 V/m given the devices P_t and G_t values either as effective radiated power (ERP) or effective isotropic radiated power (EIRP). The field strength of 4 V/m is selected since it is 8 dB below the 10 V/m level used during the MIL-STD RS103 or the International Electrotechnical Commission (IEC) 61000-4-3 radiated immunity test to qualify new plant equipment to electric fields.

For the current process to implement wireless devices in a nuclear power plant and to determine the ERP or EIRP of a device, a few methods can be used, each with advantages and disadvantages which is described below. They are:

1. Device FCC reports
    a. Given over a bandwidth
2. The conducted power given in Laboratory Testing
    a. Conducted power measurement
    b. Radiated power measurement

The power value listed in the FCC Report is the maximum power the device can produce across a specified bandwidth recorded by a spectrum analyzer using a maximum hold function. For devices like two-way radios that has a transmitter output of the total energy over a small bandwidth, this maximum hold process on the spectrum analyzer during emissions tests was an adequate process to test equipment for energy output. However, for common wireless devices today, the energy is often spread over a much larger bandwidth due to digital modulation techniques such as quadrature amplitude modulation, possible frequency hopping, or windowing attributes, such as spread spectrum technologies. With the energy spread over a much wider bandwidth, the amplitude is minimal and relates to a lesser field strength given off by the wireless device when compared to older wireless transmitting devices. Since the analyzer's maximum holding during the emissions measurement is cumulative and not instantaneous, it is not a true representation of a devices transmit power during operation. This can be seen in Figure 1 which is a WirelessHART signal frequency hopping over a given bandwidth and the summation of the signal at the bottom of the figure. These cumulative values could lead to over-conservatism, depending on the device/protocol in question, if the occupied bandwidth is less that measurement bandwidth used for the FCC report such as Bluetooth or other frequency hopping wireless devices.

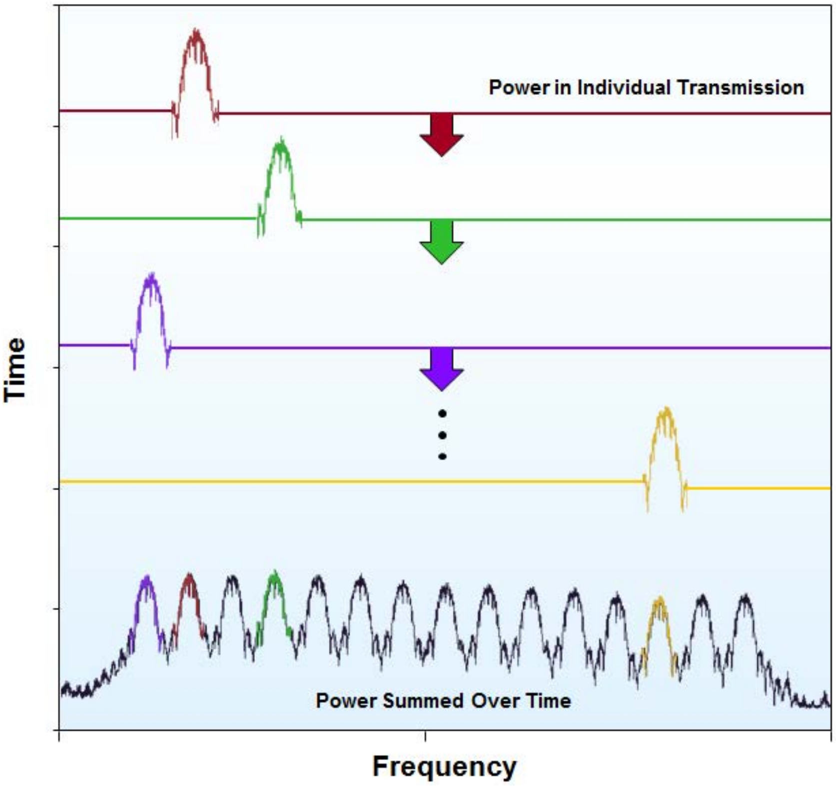
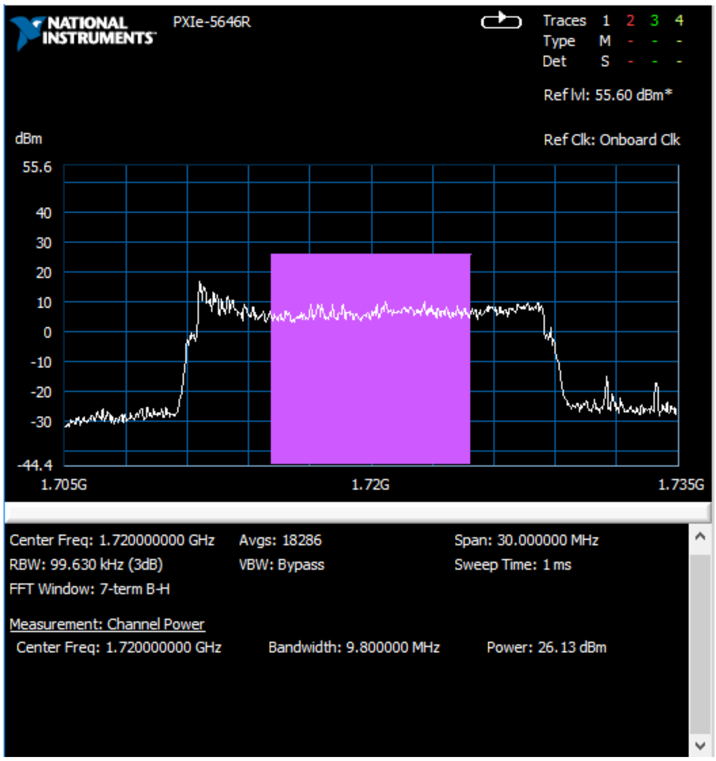


Figure 1. A Spectrum Capture of a Frequency Hopping Signal, WirelessHART, And the Summation of the Signal Over Time

These methods have significant disadvantages for obtaining the exclusion zone distance. The first method is using a FCC report to obtain the power output of a device. However if the total power level listed in the FCC report is used in the calculation, then this could lead to overly conservative exclusion distances. Another method to determine exclusion zones is through laboratory testing each device of interest. The final method would be to test plant equipment to current testing standards, which could be much harsher than actual wireless signals. All methods mentioned can be successful but can also prove to be over conservative and costly to the utility.

2.2 Approach into Understanding Exclusion Zones for Emerging Wireless Technologies

For the usage of emerging wireless technologies such as Long Term Evolution (LTE), Bluetooth, Wi-Fi, or WirelessHART, the wireless signal is spread over a much greater spectrum instead of a narrow bandwidth. Again, as stated in Section 2.1, these different modulations and spread spectrum techniques transmits energy over a much greater spectrum and is not as significant in amplitude as in previously used wireless devices such as two-way radios, which correlate to the field strength emitted from the device. This can be seen in a measurement of a LTE signal for EIRP in Figure 2. A summary of common wireless standards used with the bandwidth and maximum EIRP is shown in Table I.



Ref lvl: 55.60 dBm*

Ref Clk: Onboard Clk

Center Freq: 1.720000000 GHz
Avgs: 18286
Span: 30.000000 MHz
RBW: 99.630 kHz (3dB)
VBW: Bypass
Sweep Time: 1 ms
FFT Window: 7-term B-H

Measurement: Channel Power
Center Freq: 1.720000000 GHz
Bandwidth: 9.800000 MHz
Power: 26.13 dBm

Figure 2. EIRP Calculation of LTE Signal from Vector Signal Analyzer

Table I. The EIRP of Common Wireless Devices

Wireless Protocols	Frequency	Bandwidth	Maximum EIRP (dBm)	Maximum EIRP in Watts
LTE	700 MHz, 1.8 GHZ	20 MHz	24 for 5 MHz	0.251
Wi-Fi	2.4 GHz, 5.8 GHz	20 MHz, 40 MHz, 80 MHz, 160 MHz	36 for 2.4 GHz, 53 for 5.8 GHz	4 for 2.4 GHz, 200 for 5.8 GHz
Bluetooth (Class 1)	2.4 GHz	1 MHz (Frequency Hop)	20 for all channels summed	0.1
WirelessHART	2.4 GHz	2 MHz (Frequency Hop)	10 per channel	.01

With the knowledge of the energy content spread over bandwidth for the emerging wireless protocols, which leads to a lower field strength emitted from the device, new considerations for the exclusion zone calculation need to be made. In the current guidance of EPRI TR-102323 Revision 4, Appendix I gives guidance on how to implement fixed wireless devices operating in the 2.4 GHz band. The guidance states that the transmitter output power of a Wi-Fi base station shall be limited to 27 dBm EIRP (533 mW) to ensure that the field strength is 4 V/m at 1 meter or less. Also, the guidance states that mobile devices shall be limited to 20 dBm EIRP (100 mW) or less unless more robust controls or exclusion zones are in place.

Based on the calculations that are in the EPRI guidance, the exclusion zone distance will be further away (more conservative) because the calculations do not consider the effects of a much wider bandwidth signal and lesser field strength emitted from the wireless base station or mobile device. This could lead to the usage of mobile devices with exclusion distances of multiple feet away from plant instruments that need to be read or manipulated by plant operators in turn leading to impractical usage of mobile devices near the plant instruments.

3 USING COGNITIVE RADIO SYSTEM FOR WIRELESS IMPLEMENTATION

From the research that has been completed to understand the effects of wireless signals on nuclear power plant equipment, an effort is underway to develop in-situ test methods and a test system to subject plant systems to wireless signals. The Cognitive Radio System (CRS) consists of the ability for wireless signal playback from various standards while monitoring both EIRP and electric field. This will provide a safeguard that plant equipment is tested to signals from wireless devices and will give plant operators that these devices can be used near sensitive equipment or have a reduced exclusion zone distance for wireless device usage.

3.1 Comparison of Standardization Testing to Wireless Signal Spectrum

For the new installation of nuclear power plant electronic equipment, electromagnetic compatibility testing is required. This ensures that the new equipment does not emit or nor is susceptible to any electromagnetic interference that is located in the plant. This testing includes emissions and susceptibility measurements of equipment that is going to be installed with guidance on how to qualify new equipment located in Nuclear Regulatory Commission (NRC) Regulatory Guide 1.180 and EPRI TR-102323. For modulation techniques used in the radiated susceptibility tests, the bandwidth of 99 percent of the signal content is less than 22 kHz as seen in Table II. Also included in the table are example LTE signal characteristics for comparison. From the table data, the bandwidth of the signals and the energy content of the signals vary significantly. The energy contained in the susceptibility tests are a narrow bandwidth signal which the EPRI exclusion zone equation uses in calculation. But with wireless devices, the EIRP is spread over a wider bandwidth (megahertz instead of kilohertz). If the EIRP has an occupied bandwidth of greater than a megahertz, the overall amplitude of the signal is decreased if the same energy content is in the signal. Conclusively, the usage of newer wireless technologies will have a different result for plant equipment susceptibilities than what was originally found from the standard testing.

Table II. Radiated Susceptibility Testing Standards in Comparison to Wireless Signals

Testing Standard	Testing Frequencies	Modulations	Bandwidth of 99% of Signal	Field Strength of Test
IEC 61000-4-3	80-1000 MHz	Amplitude	2.18 kHz	10 V/m
MIL-STD-461 RS103	30 MHz – 10 GHz	Pulse	22.03 kHz	10 V/m
LTE	700 MHz, 1.8 GHz	Quadrature Amplitude	20 MHz	Varies*

*Signal's field strength dependent on transmitter output power

3.2 Acquisition of Real-Time Spectrum for Analysis and Playback

To understand the transmissions from wireless devices, measurements were conducted to evaluate the physical layer properties of wireless signals used by cell phones, tablets, and other wireless devices. This research included an evaluation of wireless devices during transmission to understand the duty cycle of devices as well as the coexistence of wireless devices with one another. In the evaluation, the wireless device under test was placed in a communicating mode and the emissions were recorded using a vector signal analyzer. Recording to hard disk enabled further analysis of both the frequency and time domain signatures. With the capabilities of recording up to 200 MHz of bandwidth at one time, plant communications or the actual electromagnetic/radio frequency environment can be recorded and analyzed. During laboratory testing, a WirelessHART device's transmission emissions were recorded to hard disk. From the data, the physical layer of the WirelessHART was analyzed for amplitude and time duration. The WirelessHART device emits a signal of 10 dBm (10 mW of energy) for a duration of 100 micro-seconds. With the signal recorded, the capability of playing back the wireless device signal onto plant equipment or in a controlled environment is available to the end user. Figure 3 and Figure 4 show the time and frequency representation for a WirelessHART transmission.

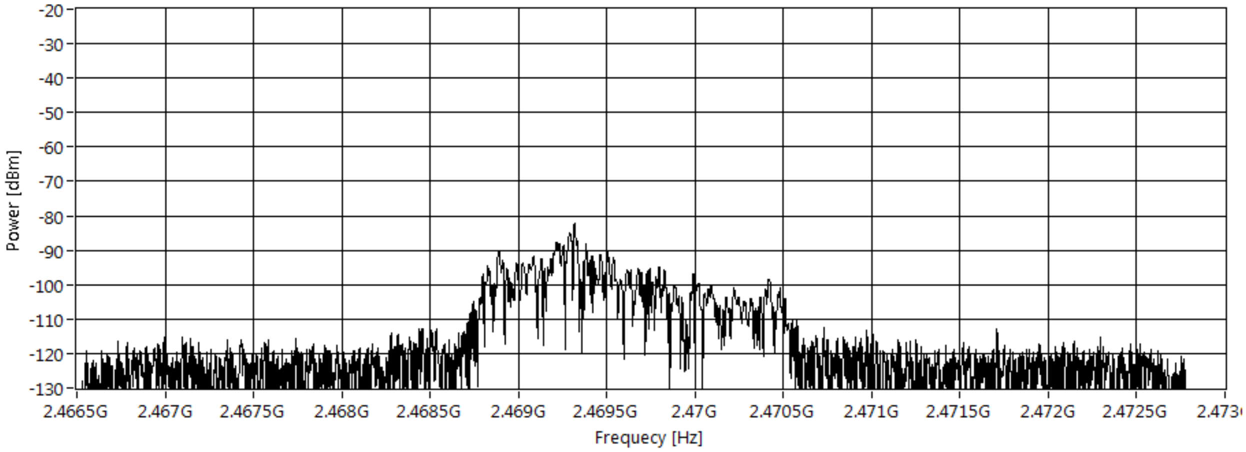


Figure 3. Frequency Content of WirelessHART Transmission as seen on Vector Signal Analyzer

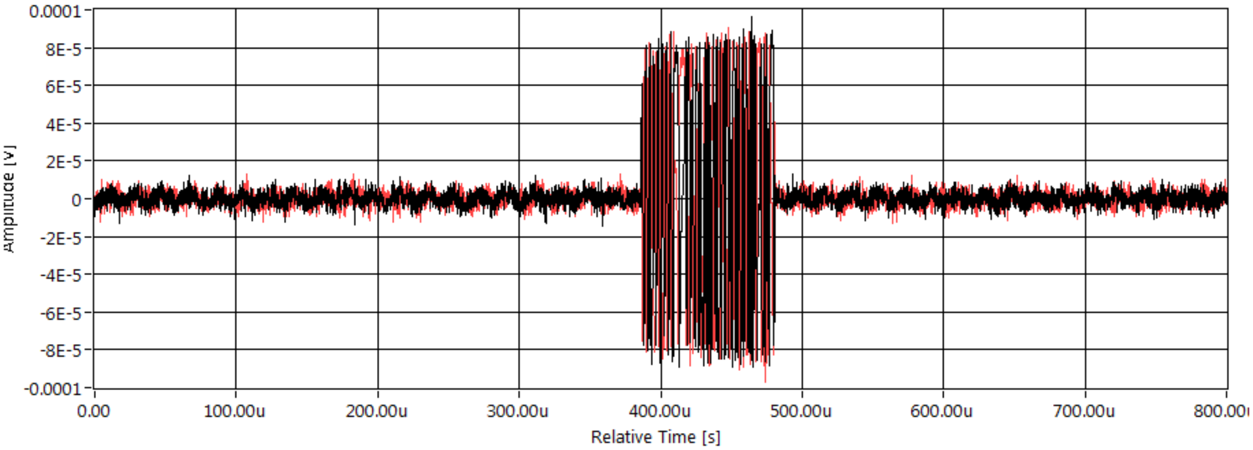


Figure 4. Time Signature of WirelessHART Transmission as seen on Vector Signal Analyzer

4 CONCLUSIONS

Wireless technology will continue to expand and grow into the nuclear power industry and will lead to savings by the industry that will further assist in "Delivering The Nuclear Promise" to make the industry more competitive with other forms of power generation. The use of conservative exclusion zones as current guidance states will hinder the usage of wireless devices in nuclear facilities. By understanding the characteristics of the wireless signal technologies in relationship to frequency, bandwidth, and power output, EMI risk and threats can be reduced; however, there is a need for an improved method for testing plant equipment to these wireless signals. These test methods must be able to be applied in the laboratory and in-situ in the plant environment. These aspects are being addressed through the R&D project currently underway.

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