A ROBUST WIRELESS COMMUNICATION SYSTEM FOR ELECTROMAGNETICALLY HARSH ENVIRONMENTS OF NUCLEAR FACILITIES

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ABSTRACT

Wireless sensors could play a significant role in safety, efficiency, and reliability of instrumentation and control process in current and next generation nuclear power reactors. While conventional narrowband wireless sensors have successfully been used in numerous industrial applications, the RF propagation challenges posed by the heavy metallic and cluttered environment of Nuclear Power Plants (NPPs) has prevented their use in such operations. These challenges include: RF propagation in harsh (reflective, absorptive, cluttered) environments, data security issues, and RF interference to and from other devices in a nuclear reactor. In this introductory paper, first we address how Ultra-wideband (UWB) technology can provide a viable solution for the signal propagation issues in such electromagnetically harsh environments. Second, we present a novel UWB remote powering scheme that allows for battery-free operation of sensors to increase their lifetime. We finalize the paper by presenting the experimental results of using UWB signaling in a representative harsh environment conducted at MIT research reactor. We plan to address the security issues through an innovative UWB communications scheme for sensor data communications in a subsequent paper.

Key Words: Nuclear power reactor, Passive sensors, Remote powering, Ultra-wideband signaling, Wireless sensors.

1 INTRODUCTION

With the recent advancements in wireless technology, it is evident that wireless sensors such as radiation, temperature, pressure, and humidity could play a crucial role in instrumentation and control process of existing or next generation nuclear power reactors. Removing the cables from sensors not only increases the reliability of the monitoring and control system, it also improves the safety and efficiency of the process while minimizing the maintenance required for cable integrity and longevity. To date, several valuable R&D efforts have been conducted for identifying the needs and requirements of wireless technology and characterizing their use in nuclear power plants [1,2]. The past research in this area, through an extensive survey, has identified importance of wireless sensors as well as key issues that need to be resolved for reliable sensor data communications in a nuclear reactor environment. The major concerns regarding wireless transmission in a nuclear reactor have been identified as data security, RF interference, communications through obstructions, and heavily metallic (reflective) environment of a nuclear reactor.

Although wireless sensors have been successfully deployed in a number of industrial applications, they have not yet been widely used in nuclear reactors due to concerns listed above. In an effort to address these concerns, in this paper we introduce an innovative wireless communications system based on ultra-wideband (UWB) technology that can offer the following key benefits to the existing and next generation nuclear reactors:

1)! Provide secure, reliable data transmission with high bandwidth in harsh metallic and obstructive environment of nuclear reactors without interfering with legacy radio signals;
2)! Provide remote powering to some of the existing and/or future sensors to eliminate their need for batteries, or extend the battery life of certain sensors to improve efficiency.

In this paper we start with a brief introduction to UWB signaling [3] and its advantages specific to a nuclear reactor environment. Next, we discuss the concept of UWB remote powering and power harvesting to eliminate the need for using batteries in low power sensors, as well as extending the battery life in sensors that require higher power. Then we present some of the experimental results conducted at MIT research reactor and conclude the paper with a summary of the main observations and path for future research. Fig. 1 represents a pictorial overview of the overall goal of this paper.

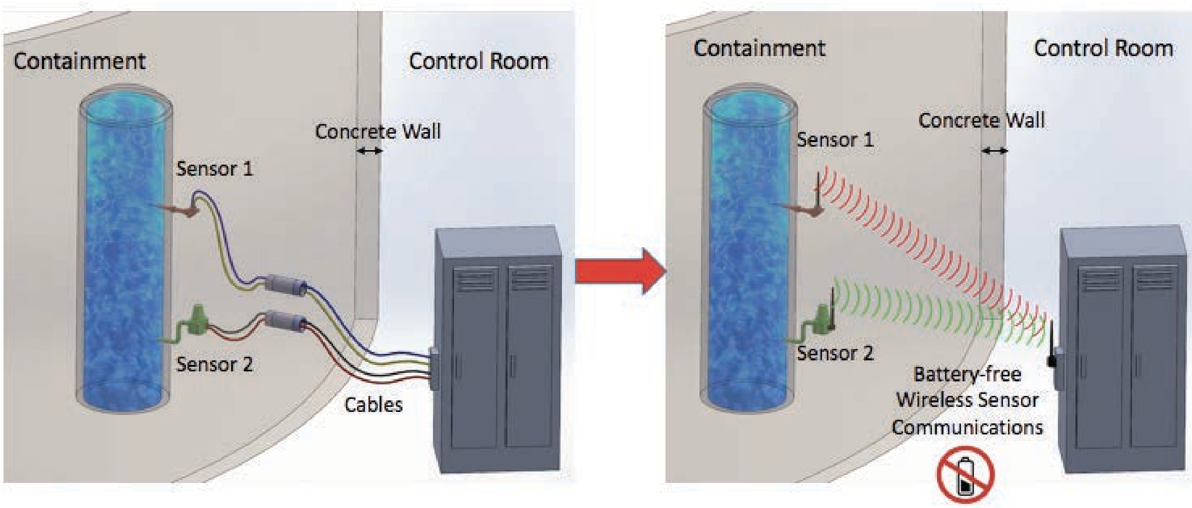

Figure 1: (Left) Current method, wired sensor communications, (b) Secure, battery-free wireless sensor communications that improves I&C reliability and process efficiency in next generation reactors.

2 BRIEF OVERVIEW TO ULTRA-WIDEBAND TECHNOLOGY

Unlike conventional narrowband technology that use continuous waveforms for communications, UWB systems use short duration pulses (sub-nanosecond) as their communication building block. These narrow pulses naturally generate very wide bandwidth in the range of a few GHz in frequency domain. This high bandwidth provides ability to send large amount of data for sensor networks at a very low power level without interfering with other instrumentation devices. Fig. 2 compares narrowband and ultra-wideband signals in both time and frequency domain.

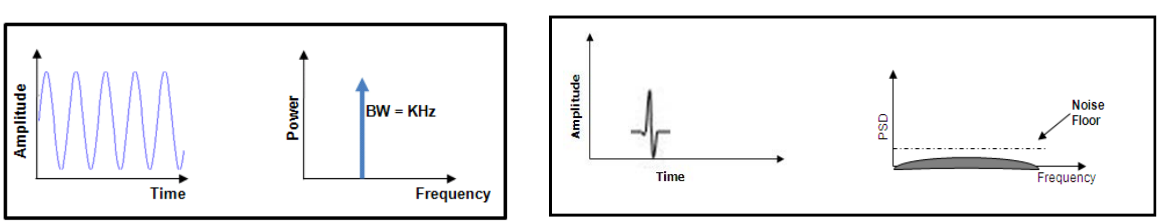

Figure 2: Comparison of a typical narrowband signal with a UWB pulse in both time and frequency domains (left) narrowband, continuous waveform (right) ultra-wideband, pulse based.

Referring to the above figure, the continuous waveforms in narrowband signals generate high spectral power in a very narrow bandwidth (KHz) in frequency domain. This narrowband high spectral power not only can cause interference to other narrowband signals, it can also be easily detected and jammed. Furthermore, this narrow bandwidth limits the data rate for sensor networks. On the contrary, the frequency spectra of the UWB pulses are spread out over many GHz of bandwidth with a power spectral density residing below the noise floor of a narrowband receiver. Therefore, the UWB transmitted pulses are not only very difficult to detect when transmitted with a certain time-space coding, but are effectively invisible to unauthorized receivers. In addition, the extremely wide bandwidth of UWB pulses (GHz) generates large channel capacity and a robust link with respect to large data rates, and is relatively immune to multi-path and diffraction in harsh RF propagation channels such as cluttered and reflective environments. Fig. 3 shows a comparison of narrowband and UWB signals in a metallic multipath channel in the presence of both line-of-sight (LOS) signal and none-line-of-sight (NLOS) signal caused by reflection from metallic objects.

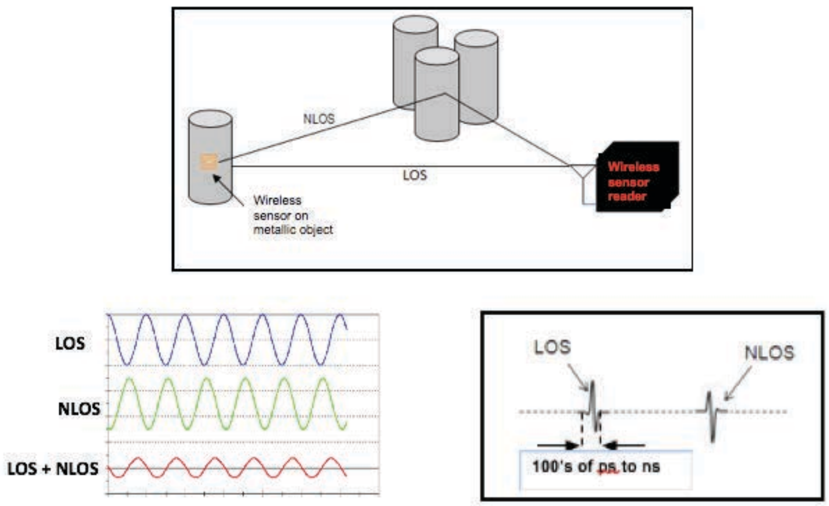

Figure 3: Multipath effect on (left) narrowband signals, and (right) UWB signals.

As shown in the above figure, the continuous wave narrowband LOS signals can experience degradation if destructively added to NLOS reflected signal (for example, dropped calls in an elevator). However, for the UWB pulse the window of opportunity for destructive cancelation is less than a nanosecond which normally doesn’t give enough time for the reflected NLOS pulse to reach the LOS pulse and cause cancellation.

Another advantage of UWB signals for communications in a reactor environment is their ability to provide physical layer encryption by pulse coding techniques. Short duration narrowband pulses can be effectively coded with respect to their shape, polarity, and timing between pulses to look like random noise to an unauthorized receiver. This level of physical layer encryption can be enhanced by MAC layer encryption for added security. Our results for security aspects of UWB communications will be published in a subsequent paper.

As discussed earlier in this paper, utilizing short duration pulses as building blocks of communications in UWB technology allows for reliable transfer of large amounts of data in environments that conventional narrowband signaling faces challenges such as the harsh metallic environment inside nuclear reactors. It’s important to emphasize that to date, all forms of wireless systems using different conventional standards such as Bluetooth, WiFi, Zigbee, etc. share the same challenges as they all use continuous waveform for transmission. Fig. 4 shows experimental data compering frequency spectrum of narrowband and UWB signals in a highly reflective environment (shipboard communications). In this figure, it’s evident that the narrowband signals experience fading and degradation in two different locations on a ship, where the UWB signals carry a steady spectral signature on the exact same two locations.

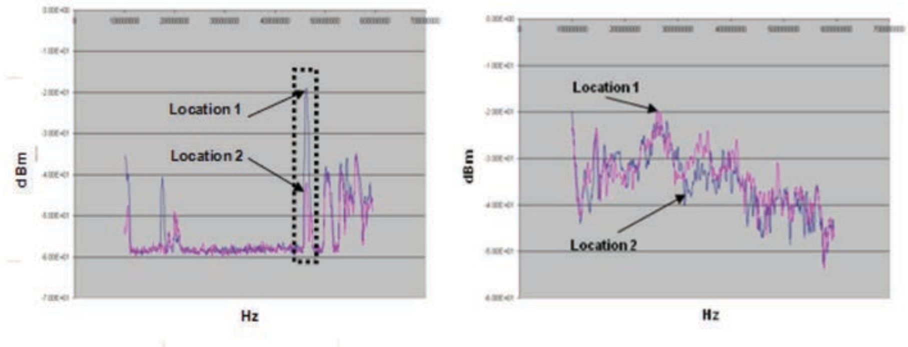

Figure 4: Multipath effect on (left) narrowband signals, and (right) UWB signals. Please note that the vertical axis is not to the same scale for both graphs.

3 REMOTE POWERING BY UWB SIGNALS

Efficient remote powering eliminates the need for sensor batteries and their maintenance requirements, hence providing an indefinite lifetime for sensors. The remote powering range is highly dependent on the voltage level at the storage capacitors after overcoming the diode drop in electronic circuits. With equal average power to a narrowband signal, the pulse based UWB signals are capable of overcoming the diode-drop in electronics circuits and allow for efficient power harvesting for sensors. Furthermore, sensors that require high power, can benefit from UWB remote powering to extend their battery life.

Comparing UWB and narrowband signals with the same average power in Fig. 5, we can see that UWB signals contain significant residual voltage after overcoming the diode drop in a remote electronic circuit. This is due to their high peak power and low duty cycle that provides enough instantaneous power to compensate for the diode drop while still maintaining the low average power.

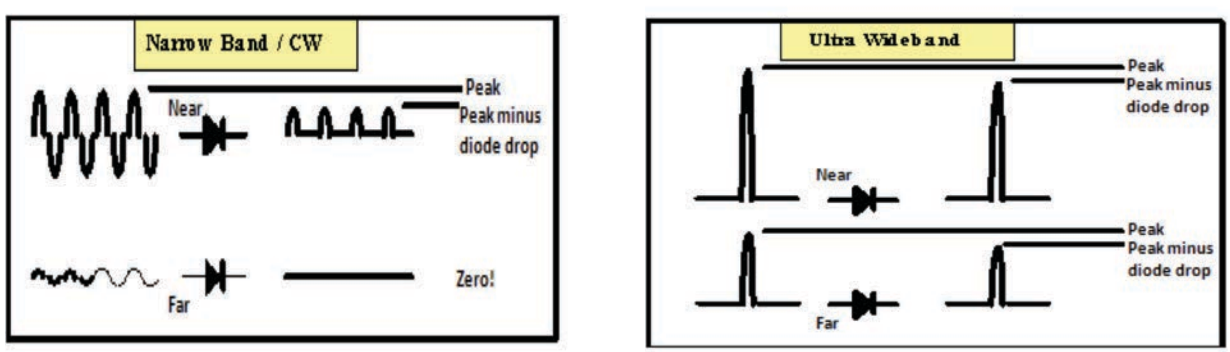

Figure 5: Continuous wave narrowband signals (top) can power up electronic circuits in a short distance. For the same average power, UWB high power, low duty cycle signal (bottom) contains enough energy to power up a device from a far distance.

As shown in the above figure, after overcoming the diode drop (usually 0.7 volts), narrowband signals do not have enough power left to remotely power any electronics circuit from a far distance. However, for the same average power, UWB signals are capable of powering electronic circuits from a farther distance even after compensating for the voltage used in diode drop. It's important to mention that antenna design plays an essential role in the remote powering range; high-gain, directional multi-element antennas, provide remote powering capability at longer distances. Furthermore, ultra-wideband signals can be focused in space and time to form a spot in a distant location using a set of distributed transmitters. In order to form a spot with high signal to noise ratio in a distant location, all elements of the distributed UWB transmitters (array of antennas) have to transmit the same form of UWB pulse. The coherent addition of the pulses can generate a strong signal with high SNR that can be used to remotely power a passive UWB tag from a long distance. Increasing the number of elements in the array of transmitters improves the spot-forming in terms of peak amplitude of the spot, signal-to-noise-ratio (SNR), and range. The parameters that can be used to reduce the spot size and from a localized high energy signal at a distant spot are pulse shape and distance between the antenna elements in the array (could be uniform or non-uniform separation).

Fig. 6 illustrates the concept of using UWB antenna arrays for forming a spot in a specific point in the far field of individual array elements.

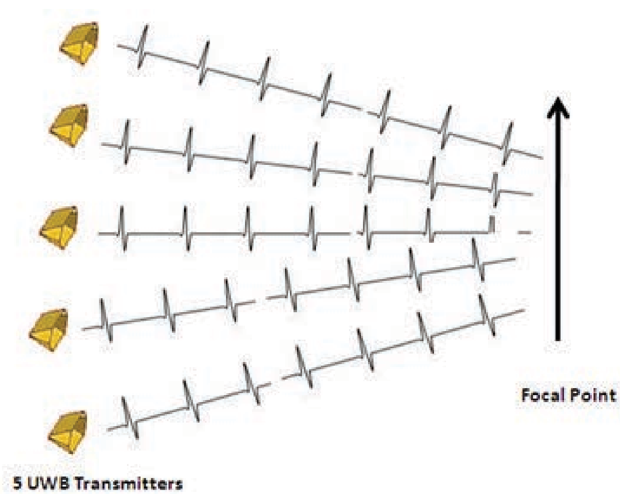

Figure 6: UWB "spot-forming" can localize the energy transferred from multiple antenna arrays to a focal point of interest in both space and time.

Designing an efficient spot in terms of peak amplitude, distance from the array, and sharpness of the spot can significantly improve the UWB remote powering range [4].

4 EXPERIMENTS AT MIT RESEARCH REACTOR

This section reports on our field experiments at MIT research reactor, where a UWB transmitter was placed at various challenging locations inside the equipment room and a receiver placed inside the control room with closed door, receiving temperature data. The environment was specifically challenging for RF signals with respect to multipath phenomenon due to heavy metallic channel in the equipment room, double layered concrete wall of 4 ft thickness, and fully closed metallic door shown in Fig. 7 below.

Figure 7: Example of harsh RF propagation environment of the reactor facility. (Left) Equipment room, (middle) double layered thick walls, (Right) fully closed steel door between the control room -where the receiver was placed- and equipment room where the transmitters were placed.

The goal of this experiment was to characterize UWB signal propagation for reliable communications in a reactor facility. The UWB transmitter and receivers used were battery powered and integrated with a a temperature sensor. Fig. 8 shows the UWB hardware unit which is capable of both transmission and reception.

Figure 8: DSI's UWB sensor communications hardware used at MIT reactor experiments.

In this experiment, one UWB unit acting as a receiver was placed in the control room and another UWB unit acting as transmitter was placed at various locations of the equipment room as shown in Fig. 9.

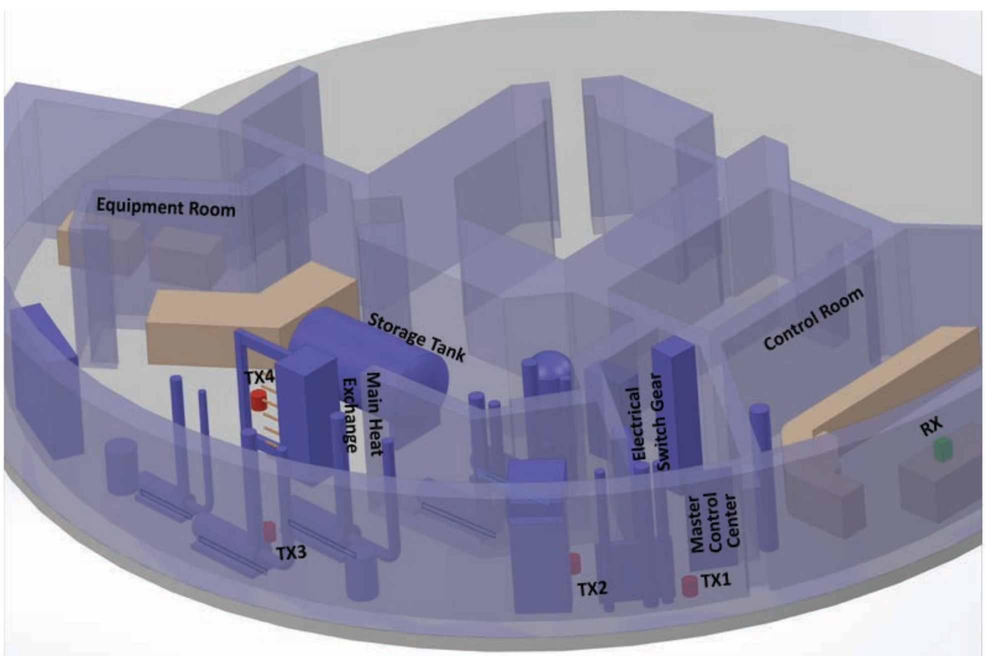

Figure 9: 3-D rendering of the reactor facility showing the location of the receiver (green, RX) and various locations of the transmitter (red, TX).

In this field experiment, the UWB signals propagated through heavy metallic channel of the reactor equipment room including the TX4 location behind the storage tank and main heat exchanger, approximately 50 feet through double thick concrete walls and fully closed steel door (illustrated in Fig. 9, and shown in Fig. 7). Fig. 10 shows a sample of the receiver GUI reporting on increased temperature inside the equipment room.

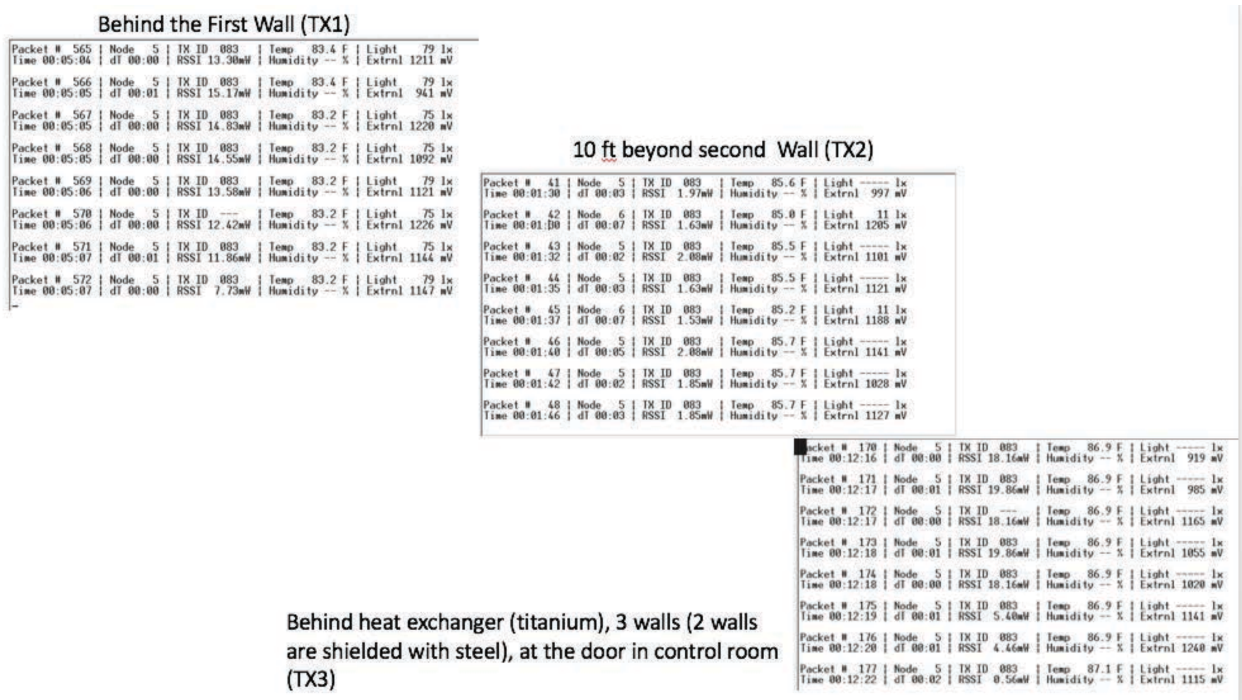

Figure 10: UWB receiver GUI reporting increased temperature as the transmitter (TX) is moved more inside the equipment room (from 83.2° to 85.7° to 87.1°).

5 CONCLUSIONS

Ultra-wideband technology brings significant advantages to wireless communications systems by addressing the key challenges caused by narrowband RF signaling schemes. In this paper, we summarized concepts that can address the shortcomings of traditional wireless systems through the use of UWB signaling for sensor communications at nuclear reactor facilities. The challenges addressed in this paper included: Performance in cluttered and reflective environments, and through the wall transmission. We also reported on a field experiment using UWB signals in MIT research reactor to report on temperature sensors from the equipment room to the control room. Our next step is to use UWB signals for remote powering and test their capabilities in reporting the sensor data passively and address the data security aspects of UWB signaling.

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