ISSUES ASSOCIATED WITH DEPLOYING WIRELESS SYSTEMS IN NUCLEAR FACILITIES*

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ABSTRACT

This paper discusses the technical issues that should be addressed if wireless communications systems are to be deployed in safety-related instrumentation and control applications in nuclear facilities. Distributed data communications networks are nothing new in nuclear facilities and are presently an integral part of safety operations. Although originally intended for wired networks, the safety and analysis framework for these data communications networks can also be applied to wireless communications. Wireless communications do not introduce any new types of communications errors, but the probabilities of the errors do differ between wired and wireless networks.

Issues important for the deployment of wireless systems include coexistence, reliability, signal propagation, and regulatory impact. Coexistence studies are essential to quantify the effects of electromagnetic interference on communications links and can incorporate any combination of three evaluation approaches: analysis, simulation, or experimental measurements. In turn, several performance metrics are needed to quantify the reliability of wireless communications systems. At the physical layer, reliability is theoretically measured by the bit error ratio (BER) (i.e., the average ratio of the bits in error to the total transmitted bits), and an unacceptable BER results in unacceptable communications. Higher layer performance measures depend on the number of packets transmitted, packets received, packets received in error, and packets dropped. Understanding wireless signal propagation in the intended nuclear environment is another issue that has to be addressed. The effects of building materials, metal containment structures, and environmental changes during postulated accidents must be considered in the signal propagation study. The review of these issues resulted in the finding that the deployment strategy for wireless systems is quite different from that for wired systems. As a result, the minimum steps that should be followed in order to achieve a reliable wireless service are outlined.

Key Words: wireless, communications, deployment, nuclear, safety.

1 INTRODUCTION

Wireless communications technology is not currently used in safety-related instrumentation and control (I&C) applications in nuclear facilities, but that may someday change if the technical challenges hindering its introduction can be addressed. This paper discusses the technical issues to be dealt with if wireless systems are to be deployed in safety-related I&C systems. However, before the discussion of technical issues, the case for wireless and the operations of data communications systems, along with

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their associated pitfalls (errors), are introduced. This is followed by the aforementioned discussion of relevant technical issues associated with deploying wireless systems for safety-related I&C applications (i.e., coexistence, reliability, signal propagation, and regulatory impact). The paper is then concluded by outlining a deployment strategy for the inclusion of wireless technology into safety-related systems. Note that the deployment issue of wireless cyber security is not covered in this paper because it is covered in a separate paper by the same authors at this topical meeting.

Commercial power facilities, including nuclear facilities,[1] have started deploying wireless systems for plant monitoring and improving operational information awareness. Present applications of wireless communications in power facilities include voice and data communications to employees and field crews, distribution of supervisory control and data acquisition functions at substations, wireless local area network devices for office use, automated intelligent metering, geographical information systems, work management tools, alarm systems, and emissions monitoring. Other wireless applications include information access, on-line monitoring, remote diagnostics, and mobile communications. It is quickly becoming obvious that power providers are beginning to rely on wireless systems. For safety-related applications, wireless may even one day be a candidate for safety system communications for process control, equipment provided for safe shutdown, postaccident monitoring display instrumentation, preventative interlock features, or any other systems related to safety. One reason for implementing wireless systems is that they may be convenient at plant locations where wired systems are not accessible. Another reason is that they can easily augment wired systems during scheduled plant outages. Implementing wireless systems is by far more cost-effective than running additional wires and cables within a power facility. However, the wireless systems must be reliable, exclusive, and always available.

Data communications networks are presently an integral part of the safety operations in nuclear facilities, and guidance already exists for their application in distributed control network environments. These networks simply accept information in an electronic format and carry it to a final destination. Although information is transmitted in analog form, much of the processing of the information is done through digitization, an irreversible process that introduces errors in the signal. Information is generated at the source, processed at the transmitter, transmitted via transmission media, received and recovered at the receiver, and decoded at the sink. The captured signal at the receiver can be corrupted in many instances and result in a communication failure. Various signal-processing techniques are applied at both ends of the communication link to correctly recover the transmitted message from the corrupted signal in a timely manner. Originally intended for wired networks, the safety and analysis framework for these data communications networks can also be applied to wireless communications.

Wireless communications do not introduce any new types of communication errors. The common error types for wired networks (i.e., repetition, deletion, insertion, incorrect sequence, corruption, delay, too early, jitter, masquerade, and inconsistency) cover all of communication errors for wireless networks as well. The only difference is that the probabilities of the various error types are different in wireless networks. For example, a corruption error is more probable due to higher bit error rates caused by a fading environment, mobility, and interference from other wireless users. In addition, short-term deletions occur more often because of poor connections. It can also be anticipated that a masquerade error is more relevant because the air interface is more vulnerable to intentional or unintentional jamming. Therefore, authentication techniques are more likely to be needed if a wireless communications system is applied. However, signal processing techniques, including diversity developed for wireless communications, may make it less vulnerable overall.

2 COEXISTENCE OF SAFETY-RELATED WIRELESS COMMUNICATIONS

A very important factor in the operation of wireless systems is electromagnetic interference (EMI). Hence, a coexistence study is essential for evaluating the effect of EMI on these systems. Although many

commercial wireless organizations perform a coexistence study when deploying their systems, their approaches are essentially uncoordinated. The Institute of Electrical and Electronics Engineers (IEEE) provides formal guidance for investigating the effects of EMI among wireless devices in IEEE 802.15.2.[2]

There are two specified unlicensed bands for the operation of wireless systems. These are the Industrial, Scientific, and Medical bands, which includes 900 MHz, 2.4 GHz, and 5.8 GHz; and the Unlicensed National Information Infrastructure band, which includes the 5.2 GHz band for broadband access. The Federal Communications Commission (FCC) has issued rules about transmitted power, the use of spread spectrum, and frequency-hopping modulation for wireless devices operating in these frequency bands.[3] Since users in the unlicensed band systems share the same spectrum, there is potential interference among all devices operating in those bands.

2.1 Mitigating Interference: A Physical Layer Solution

For the physical layer (PHY) of wireless systems, there exist many powerful techniques for interference cancellation or suppression. They fall into two complementary signal processing classes: multiuser detection[4] and adaptive single user detection.[5] Most of the present wireless systems are spread-spectrum based with code division multiple access, especially direct sequence spread spectrum (DSSS). However, the performance of DSSS networks suffers from the near-far problem. This problem can be alleviated by using either a multiuser receiver or a single-user adaptive receiver along with centralized or distributed power control. Interference cancellation can also be combined with forward error correction coding for enhancing the throughput of the system.

2.2 Interference Modeling and Performance Evaluation

The effects of EMI are needed to quantify a communication link, and there are three approaches to quantitatively evaluate those effects: analysis, simulation, or experimental measurements.

2.2.1 Mathematical modeling

Quantitative measures are conducted in terms of packet error probability (PEP) or bit error probability. For PEP, analytical results are mainly based on modeling the collision of packets in the network before they reach the designated receiver. PEP is a function of several parameters (e.g., the number of transmitters, the distance between the transmitters and the receiver, the difference in power level between the transmitter and the interferers, and the transmission technology considered). Bit error rate (BER) can be calculated analytically, semianalytically, or by simulations based on assumptions about the transmission technique and associated parameters. The results from mathematical modeling are useful in providing a first-order approximation on the impact of EMI and the resulting performance degradation. However, the assumptions of the mathematical modeling differ from the practical systems. Therefore, mathematical modeling is often used to complement measurements obtained from experimental data.

2.2.2 Experimental modeling

Experimental modeling is by far the most accurate form of modeling for a particular implementation. If the implementation details are completely known, including the various add-ons and parameters, the evaluation can produce very informative results. However, the results obtained are typically not applicable outside the experimental setup of the equipment tested because details about the equipment are often not completely known. Therefore, experimental modeling is useful mostly in the context of specific development and testing, when an empirical model can be developed based on many experimental models.

2.2.3 Simulation modeling

Although analysis is the first choice for accuracy, the analyses of many practical systems are very tedious if not intractable. Experimental modeling is accurate but also specific to a particular implementation. The implementations change with the wireless environment, and the environments often differ distinctly from each other. As a result, experimental models are not practical for general purpose use. Simulation modeling is a practical compromise. The most accurate results can be reached when modeling the behavior of the protocols under consideration if part of the simulation model is obtained through analysis and part is empirically obtained from measurements. Simulation modeling is ideal for evaluating the numerous "what if" scenarios for which experimental models are not practical. Simulations play a critical role in evaluating scalability issues and complex system behavior where the parameters are modified and their effects on overall performance quantified. Details about simulation modeling are described in NUREG/CR-6939.[6]

Two distinct performance analysis techniques can be used to evaluate wireless systems in the presence of EMI: open-loop and closed-loop. The effects of mutual EMI are ignored for the open-loop EMI evaluation technique, while interactions among interfering systems are considered with the closed-loop EMI evaluation technique. Mathematical modeling is more useful to open-loop EMI evaluations, whereas experimental modeling and simulation modeling are better suited for closed-loop EMI evaluations.

2.3 Factors Affecting Coexistence Performance

The performance of a wireless communications system is influenced by many factors. For physical layer design parameters, examples include modulation, error correction coding, multiple-access technique/multiplexing, diversity, transmission power, and various signal-processing techniques to mitigate EMI. Other examples are packet size, offered load, network, and routing. These factors can be divided in two categories: (1) factors affecting only the performance of the system where they are implemented and (2) factors that affect the closed-loop interaction between the interferer and the desired user's system.[7] The factors in the first category are modulation, error correction coding, and receiver signal-processing techniques to improve the performance of the desired user's system. The coexistence factors are in the second category and include processing gain and hopping rate if spread spectrum is used, offered load, packet size, and network topology.

In spread-spectrum systems, the transmission bandwidth of the signal is much larger than the information bandwidth. There are two primary types of spread-spectrum techniques: DSSS and frequency-hopping spread spectrum (FHSS).

2.3.1 Direct sequence spread spectrum

DSSS is considered to be "direct sequence" spread spectrum because each user's data signal is multiplied by a unique high rate signature sequence waveform. DSSS provides natural resistance to multipath fading. If the delay of a multipath component exceeds one chip of duration, a DSSS receiver will treat the multipath as simply another multiple-access interfering component. Desirable properties of this technique include low-power spectral density, multipath resistance, and relatively high capacity.

2.3.2 Frequency hopping spread spectrum

FHSS achieves spectral spreading by transmitting narrowband message signals at successively different carrier frequencies. This process results in inherent frequency diversity, improving the resistance of FHSS systems to both frequency-selective fading and narrowband jamming. The FHSS signal is

obtained by changing the carrier frequency of the narrowband modulated signal according to a pseudonoise sequence. The FHSS system must have a large number of frequencies usable on demand, and the hopping pattern is pseudorandom in nature, as determined by the spreading code. The bandwidth dedicated to an FHSS signal is much larger than the narrowband modulated signal, even though it may not use all of them at the same time. When the hopping rate is slower than the data rate, it is called slow frequency hopping; if the hopping rate is faster than the data rate, it is called fast frequency hopping. In FHSS systems, the processing gain is determined by the total number of different carrier frequencies in the hopping pattern. FHSS with coding can provide a form of frequency diversity against frequency-selective fading.

2.3.3 Effects of spread spectrum and hopping rate on coexistence

Both DSSS and FHSS systems provide some degree of resistance to EMI or jamming. The degree of resistance for both systems is proportional to the processing gain. An FHSS system is particularly resistant to narrowband jamming for the same reasons that it is resistant to the near-far problem. A DSSS system may require adaptive EMI excision filters for adequate narrowband jamming resistance. Because of their noise-like power spectral density, DSSS systems may be resistant to detection and interception in safety-related applications. The following general observations can be made about the two spread-spectrum systems:

- the desired user using the DSSS technique is more prone to having the interfering user use FHSS;
- the desired user using FHSS is less affected by the interfering user using DSSS;
- the desired FHSS user with faster hopping rate is less affected by another user operating in the desired user's frequency band; and
- the desired FHSS user with faster hopping rate will contribute more EMI to other users in the frequency band of the desired user.

2.3.4 Spread-spectrum systems

Since spread-spectrum systems offer a low probability of detection (LPD) or a low probability of interception (LPI), many modern wireless systems are based on these techniques. Comparison of the FHSS and the DSSS systems shows that both of them have advantages and that both suffer from inherent disadvantages. There are many associated signal-processing techniques that can be used to overcome those shortfalls. Traditionally, FHSS systems have been adopted for secure wireless applications because of their simpler design and because techniques are available to overcome the problems that FHSS suffers from. Recently, DSSS systems have been adopted around the world, mainly for commercial wireless systems and some secure wireless systems, because DSSS provides better multipath resistance, the most important factor for implementing any technology in a wireless environment. Additionally, the problems that DSSS systems suffer from, especially near-far and EMI, can be tackled easily with computing power and signal-processing techniques. As a result, many new licensed systems, such as third- or fourth-generation cellular systems, and new unlicensed systems, such as WiFi and Zigbee, are based on DSSS techniques. In addition, communications systems based on an ultra-wideband (UWB) spread-spectrum technique have been standardized by the IEEE 802.15.3 standard.[8] They offer high data rates for short distant applications, and products are available.

2.3.5 Traffic characteristics: offered load and packet size

Interference directly depends on the traffic pattern. Emerging wireless systems are packet based. If the users are not synchronous and the multiple access technique is not time-division multiple-access, packets from users will overlap with each other. If the number of users (load) in the system is higher, there is a higher probability of overlapping the packets during transmission. For a given transmission data rate, the traffic patterns are characterized by the packet size in bits and the offered load in percentage of

the overall system capacity. For a given data rate, the transmission time interval is directly proportional to the packet size. The probability of packet collision depends on the time that a packet is in transmission. Longer packets will have more probability of collision. For higher data rates, the collision decreases. The offered load is inversely proportional to the idle-time interval in the channel. For a given data rate, more packet collisions result if the offered load is greater and the idle time is smaller.

2.3.6 Transmission power

Generally, wireless systems are limited by interference and fading. Increasing the transmission power of a desired user may help the system performance of the desired receiver to some degree, depending on the percentage of the packet error due to the inherent additive white Gaussian noise (AWGN) of the receiver. However, increasing the transmission power of a user will contribute interference to the other users in the system. As a result, wireless systems in the unlicensed band must abide by the maximum allowed transmission power set by the FCC and the standards. Commercial licensed wireless systems are built on the principle of being a "good neighbor." This means that the transmission power is the minimum required power to receive a packet correctly, which in turn results in minimum interference to other users in the system.

3 QUANTIFYING THE RELIABILITY OF WIRELESS COMMUNICATIONS

There are several performance metrics in the evaluation of a communications system. These metrics can be classified in two categories, depending on whether they characterize the performance of the system at the physical layer or at a higher layer.

3.1 Physical Layer Performance Measures

At the physical layer, the reliability of a communications system is measured by its BER. This is a measure of the average ratio of the bits in error to the total transmitted bits. It is useful to measure the BER of a communication medium under the entire range of conditions in which it is intended to operate. Unacceptable BER results in unacceptable communications. Generally, BER values worse (higher) than 10^{-3} are not acceptable for any application. However, some BER requirements are application specific. For example, for video applications the BER value can not be worse (higher) than 10^{-5}. There is a one-to-one relation between the received power divided by the signal-to-noise ratio (SNR) and the BER. In addition, the SNR requirement for a particular BER is also application specific. For an AWGN channel, generally it is considered unacceptable if the SNR requirement for a certain BER value goes above 15 dB. For a fading channel, that value can be as high as 30 dB.

The choice of modulation schemes in the PHY layer is the first step in acquiring the desired BER and is generally followed by forward error-correction coding (FEC). FEC detects and corrects the bits in error after the demodulation. The tradeoff of the FEC is the available bandwidth and decoding complexity versus the BER improvement. Retransmission of the entire packet can be used to improve the packet error rate. Spreading the modulated signal provides LPI and LPD. Spreading also helps against multipath due to fading of the signal. Combinations of modulation, FEC, diversities, retransmission, spreading, and interference cancellation are used to achieve the desired BER. The parameters that need to be considered are (1) required transmitted power, (2) available bandwidth, and (3) receiver complexity.

BER is a theoretical measure of the performance and in a real system; it is not a feasible parameter to measure. Since the BER is a statistically average parameter, the actual error might vary from the anticipated value. However, the BER value is the first order of system performance indicators. A communications system with an unacceptable BER will not work regardless of the techniques employed in the higher layer.

3.2 Higher-Layer Performance Measures

Higher-layer performance measures depend on the packet transmissions, packet formats, number of packets transmitted, number of packets received, number of packets received in error, and number of packets dropped. In other words, the number of packets successfully received within an allowable time indicates the performance of the system quantitatively. Typically most implementations include the following metrics.

Packet Loss—The ratio of packets in error at the receiver over the total number of transmitted packets. If a predetermined number of bits are in error in a packet, the packet is considered a dropped packet.

Delay—A measure of the time it takes a packet to be transmitted and then received at the other end. The total delay primarily consists of transmission delay, queuing delay, and access delay. Transmission delay depends on the transmission bit rate, including retransmissions, and the packet length. Queuing delay is the time delay at the transmitter before transmission. Access delay is the summation of the backoff and scheduling time before a packet is transmitted.

Throughput—A measure of the number of bits successfully received divided by the time it took to transmit them over the medium. Packet throughput is the number of successful packets received at the receiver's application layer divided by the number of layer packets that could be transmitted over the medium.

4 SIGNAL PROPAGATION THROUGH A WIRELESS CHANNEL

Many wireless standards sharing a common spectrum provide services for various indoor environments, such as offices, industrial plants, and residences. . Presently, there are many statistics-based channel models that could be adequate for outdoor environments.[9,10] For indoor wireless services, these statistical-based channel models cannot provide site-specific information because of the complexities and variations of the propagation environments, which are rich in reflections and scatterings. Although the signal propagation characteristics can be accurately obtained by solving Maxwell's equations with the surrounding geometry as boundary conditions, the process is unreasonably cumbersome and impractical, if not intractable. Databases based on site-specific measurements are not practical either.

Although the deployment of commercial cellular systems has motivated extensive study of propagation between a mobile unit and a tall antenna tower, substantially less information is available on propagation between two handheld terminals,[9] which might be the case for nuclear facilities. A generalized site-specific propagation model, based on geometrical ray tracing,[11-13] might be computationally feasible to predict details about a specific site with known parameters such as geometry and building materials. This general site-specific model can be used to develop a suitable model by adjusting the specific parameters. The model needs to be general enough to accumulate signal properties such as polarization, correlation, and coupling loss as well as channel parameters such as geometry, Doppler shift, and dielectric constants. Coherent ray tracing can approximate the scattering of the incoming signal by simple reflections using practical simulation runtimes, whereas solving Maxwell equations or measurement campaigns are tedious to perform.

4.1 General Assumptions for Statistical Fading Models

The standard models conventionally employed for outdoor radio-frequency (RF) propagation are based on assumptions of a very large number of azimuthal plane waves with arbitrary or random RF signal phases, arbitrary azimuthal angles of arrival at the antenna (generally presumed to be

omnidirectional in its horizontal-plane response), and each wave possessing essentially the same average amplitude.[10] Adding further to the validity of these basically statistical models are the very large number of scattering and reflecting surfaces (i.e., buildings, terrain features, and other man-made structures) typically present in the outdoor RF signal environment, particularly in urban and built-up suburban areas. Generally, the classical Rayleigh distribution is utilized to characterize the statistical time-varying nature of the received RF signal envelope of a flat (not frequency-selective) fading signal or the envelope of an individual multipath component when there is no fundamentally dominant signal path whose amplitude markedly exceeds the scattered components. If such a principal path exists, as is true in some outdoor scenarios and in many indoor situations, then a Rician distribution is used to more accurately represent the ensemble of received-signal amplitudes over changes in path and time. Much of the motivation for these and other statistically based propagation models has been the overwhelming complexity of solving for the RF signal field values in complex environments as well as the relative familiarity of the Gaussian, Rayleigh, Rician, and other similar types of distributions underlying these models.

4.2 Overall Path Loss

This section presents simple models for signal propagation through wireless channels.[9,10] The received signal is influenced by a myriad of details from the physical environment of the transmitter, the receiver, and the space between them. Three phenomena—shadowing, Doppler effects, and multipath propagation—introduce severe impairments to wireless signals. Various countermeasures, such as coding, equalization, and diversity, are introduced at the PHY to overcome these impairments to the radio signal. We begin with the amplitude characteristics of the signal received at moving terminals, followed by the temporal characteristics of the signal due to the Doppler effects. Finally, multipath propagation is described briefly.

4.2.1 Amplitude characteristics

The received signal strength indicator from a mobile user linearly decreases with the transmitter-receiver separation distance, both plotted in log scale. For a fixed transmitted power, the path loss is a translation of the measured received powers. Each power measurement is an average energy, generally expressed in dBm. Each power measurement is an average over a time interval on the order of 1 second, corresponding to about 100 wavelengths of the transmitted carrier. Although the signal strengths at various locations equidistant from the transmitter exhibit a wide range of values due to local differences in the environment, a general trend of decreasing signal power with increasing transmitter-to-receiver distance is observed. Slow log-normal fading due to shadowing may explain these variations.

Signal attenuation over distance is observed in free-space wave propagation when the mean received signal power level decays as a function of the distance; this phenomenon, in the three-dimensional nature of the spherical spreading of the radiated energy, is referred to as “path loss.” The most widely used path-loss model for signal-strength prediction and simulation in both indoor and outdoor environments is the log-distance model given by

$$PL(d) = PL(d_0) + 10m\log_{10}(d/d_0) + X_\sigma \ , \qquad (1)$$

where d is the distance (in meters)between the transmitter (TX) and receiver (RX), d_0 is a reference distance that is generally small but outside of the near-field region of the antenna, PL is the path loss in decibels, and m is the path-loss index. The RF shadowing effect by obstacles is represented by X_σ (in dB) and follows an approximately Gaussian distribution with local standard deviations, depending on the specific environment. The path-loss expression [Eq. (1)] reveals how received power generally depends on receiver location for a fixed transmitter.

Typical measurements in industrial environments show the value of *m* ranging from 1.1 to 1.8, which is less than in the ideal free-space case, where *m* is exactly equal to 2.[14] Thus, the received power attenuation due to transmitter-receiver separation alone will often be less than that in a comparable outdoor environment. This is the case in most indoor industrial environments because the dense radio-wave reflections from metal machinery and other surfaces add more RF energy to the total received power. In our simulation, the basic free-space path-loss model is utilized for the sake of simplicity, but it can be easily modified to the actual measured value of *m* in a highly reflective space. The expression of free-space path loss as a function of RF wavelength or frequency is given by

$$PL\ (d) = \left(\frac{\lambda}{2\pi d}\right)^2 = \left(\frac{c}{2\pi d f_c}\right)^2 , \qquad (2)$$

where c is the speed of light, f_c is the RF carrier frequency, λ is the RF carrier wavelength, and d represents the separation (in meters) between the TX and RX.

4.2.2 Multipath fading

In the model described above, there is a bundle of rays with propagation path lengths differing by fractions of a wavelength. Physically, the receiving antenna can have several discrete signal bundles. The differences in delays of arriving multipath reflections can be from tens to thousands of carrier wavelengths. This multipath propagation phenomenon leads to a representation of the impulse response of the radio channel as a tapped delay line filter superimposed on the amplitude model of the Doppler effects.

Multipath results from the fact that the propagation channel typically includes a number of obstructions and reflectors in addition to a more-or-less direct path. Thus, the received signal arrives as a somewhat unpredictable set of reflections accompanying a direct wave, each with its own degree of attenuation and delay. These signal components can constructively or destructively add to give a received signal that varies randomly in amplitude and phase. According to Clarke's standard model for flat fading,[15] in an isotropic (direction-independent) scattering case, the statistical amplitude attenuation of the components can be considered as Rayleigh-distributed, while their respective phase shifts are uniformly distributed over the interval 0 to 2π. In addition, the angles of arrival and the polarizations of the signal components are also usually assumed to be random. If there is a dominant (direct) signal component present, the overall signal attenuation profile will now be considered as a Rician distribution, but the phase will no longer exhibit a uniform distribution. In theory, there are in general an infinite number of propagation paths. Associated with each path are an attenuation factor and a propagation delay. Both of them are time-variant as a result of changes in the structure of the intervening medium. Thus, the mathematical linear time-varying channel impulse response is given in the form of

$$\mathrm{c}(\tau;\, t) = \sum_{k=1}^{\infty} c_k(t) \cdot \delta(t - \tau_k) \ , \qquad (3)$$

where $c_k(t)$ is a complex random process with Rayleigh-distributed amplitude and uniformly distributed phase, and τ_k is the time delay for the *k*th path (k = 1 to ∞). As can be expected, extensive experimental results in Ref. 10 show dense reflections in many urban and industrial plant situations because of metallic wall surfaces, piping, tanks, and other equipment. Therefore, for each principal signal path, it is reasonable to assume a finite number (N) of dominant reflectors with a single line-of-sight path present. Consequently, the theoretically infinite path number in Eq. (3) is reduced to N + 1 paths. In each path, a

dominant component is present, and its attenuation is dependent on the corresponding reflection coefficient and the length of its reflection path. The scattering effect for each path can then be modeled as numerous components with random phase shifts and amplitude fluctuations about the dominant component. The resulting amplitude attenuation for each path then closely follows a Rician-type distribution.

4.2.3 Doppler spectrum

As the wireless terminal moves through an electromagnetic field due to a transmitted signal, it encounters peaks and nulls as the signal varies in a correlated manner. The time scale of this short-time fading effect is proportional to the maximum Doppler frequency, f_d. Despite the much lower speed of relative TX/RX mobile velocities within most urban areas as well as in industrial plants and buildings, the usual form of analysis of the Doppler spectrum still uses the classical Jake's power spectrum density,[16] which was initially developed for the outdoor mobile case. For the indoor industrial case, the fading rate is in general so small that it is reasonable to consider the channel to be stationary for the period of a data symbol. Because Doppler shifts encountered in plant applications are unlikely to exceed 50 Hz, their effects are very minor at normal bit rates of 10 kb/s or higher.

5 REGULATORY IMPACT

As communities move from using fiber-optic backbones to wireless metropolitan-area-sized networks, such as WiMaX, high-bandwidth communication links will become readily available. It is then almost a certain progression that high-bandwidth communication links will be considered for deployment within nuclear facilities. Along with the obvious benefits, providing high-bandwidth data links throughout a facility will also allow the possibility of casual and adverserial access. Thus, an electromagnetic boundary similar to the Internet firewall boundary will need to be established at the physical edge of a nuclear facility that uses wireless communications. For short-distance applications, UWB wireless technology is at a stage of development where it can replace cables for connections between pieces of equipment. The connections might be between two devices that need to transmit high-bandwidth information, such a computer and a printer or a personal digital assistant and a video camera.

In addition to the obvious security and safety concerns introduced by wireless communications, a significant effort will be required to manage the spectrum utilization of all of the technologies mentioned above. Several RFID systems use unlicensed bands that are typically low enough in power and/or duty cycle to not interfere with each other. However, where there is a concentration of sensors, asset tracking, and command-and-control links, there could easily be unforeseen problems. Also, because of the unintentional mixing of signals, two frequencies that are noninterfering can "mix" together and produce a third frequency that does cause interference.

6 CONCLUSIONS

The locations of wireless transmitters must be given adequate thought and planning. The desired coverage area needs to be defined, and a site analysis needs to be developed. If possible, a propagation analysis should be conducted; at a minimum, field tests should be conducted once the RF equipment has been selected.

A consideration that is often overlooked when implementing wireless systems is whether the users will accept it. Most implementations center on cost savings, efficiency, and remote operations and these are very important. However, safety and security are paramount with wireless applications at nuclear facilities and should be addressed early in the process. While the users need to embrace the technology, they also need to remain conscious of the safety implications.

A quality of service (QoS) parameter that is important to wireless networks is the ability to predict and/or guarantee performance. In the case of nuclear facilities, the probability that a message will get through, that it will get through in a certain amount of time, and that the system will know when a message did not get through are paramount. In safety-related systems, performance should be the most important parameter. Because it is not possible to control the transmission medium, wireless systems by their very nature are not deterministic. Measures will have to be applied to increase the *probability*. The system must take into account the probabilities of success at each intervening node between the originator of the message and the final user. Prudent use of redundancy should be considered when deploying wireless systems.

Finally, a chronological order of minimum steps before deployment in order to achieve a reliable service is offered. The deployment strategy for wireless systems is quite different from that for wired systems. At a minimum, it is recommended that the following steps be implemented, in order, before any deployment of a wireless system.

- Determine the QoS to be provided (i.e., the guarantee of a certain level of performance for the particular wireless application). QoS is the fundamental component of related parameters, such as reliability, trustworthiness, and availability.
- Select the wireless technology and protocols.
- Select network topology and information formats.
- Choose between licensed, unlicensed, or combination systems.
- Obtain complete information (terrain data) about the deployment environment's large-scale fading characteristics.
- Use models to study the performance of the system. (e.g., a ray-tracing model for the indoor environment).
- Study the coexistence performance of the system. These coexistence studies are available from standards organizations (e.g., IEEE).
- Analyze the cybersecurity of the system thoroughly according to the needs of the organization. Regulatory guides and related policy recommendations detail the defined goal and the process to obtain cybersecurity. Determine whether the system is adequate to fulfill the cybersecurity requirement.
- Measure the system performance and adjust the design. The performance matrices include QoS, BER, delay, and throughput. A Monte Carlo experiment can be conducted to measure the appropriate metric. Adjusting the position of the wireless devices, the network architecture, or device parameters (e.g., code rate, antenna gain, and filter taps) might improve the performance.
- Perform an integrity check of the system by perturbing the input parameters. Input parameters include antenna alignment, distance between two wireless devices, transmitted power, and available bandwidth.
- Use simulations to address "what if" scenarios. Undesired cases, including some extreme scenarios, can be evaluated using simulations without suffering the consequences of an actual test. Test cases include maximum transmitted power and optimal positioning of the receiver.
- Ensure that the system meets all the redundancy requirements to obtain the required reliability value.
- If replacing an existing wired system, involve the system's experts early enough in the process to maintain similar security for the system. For example, information technology personnel can help to determine any changes in the existing security due to wireless deployments.

- Deploy the system and perform a final evaluation. For example, can the system transmit a minimum data rate of 10 Mbps over 1 km?
- Ensure that at no point will the wireless transmitter power be permitted to exceed the maximum allowable power. This is generally regulated by the standards organizations and ensured by the device manufacturers. Attempts to exceed the limit during operation might cause interference to other users/devices.

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