Industrial Wireless Systems Guidelines: Practical Considerations and Deployment Lifecycle

ABSTRACT

Industrial wireless has a great potential to improve monitoring and control of various processes and equipment in distributed automation systems due to the advances in wireless networks and installation flexibility. However, the harsh industrial environments and interferences from the crowded electromagnetic frequency spectrum make it challenging for industrial wireless to achieve the required performance. Thus, it is important to understand the benefits of industrial wireless at certain industrial settings, the approach for reliable operations, the technologies to be used, and the best practices for successful industrial wireless deployments. With the increase in deployments of existing wireless technologies in various applications in industrial settings, manufacturers need help in making confident decisions in deploying appropriate wireless technologies based on their operating requirements. Hence, the purpose of this article is to present our approach in industrial wireless system deployments by discussing various phases of deployment lifecycle. This approach considers various industrial settings including manufacturing, oil and gas refineries, chemical production, and product assembly. Then we examine the problems and technology spaces for industrial wireless. Furthermore, we discuss various objectives and success criteria for wireless technologies deployments.

THE NEED FOR INDUSTRIAL WIRELESS SYSTEMS

With the advances in wireless devices for the Internet of Things (IoT) and Cyber Physical Systems, the use of industrial wireless has continued to grow at a rapid pace. Industrial wireless has gained a great potential for deployment in industrial automation, including process control, discrete manufacturing, and safety systems. The advantages of applying wireless technologies in industrial systems for monitoring and control of equipment and processes include enabling configuration flexibility, support for mobility, and eliminating costly cabling. Moreover, industrial wireless allows for easier network expansion to improve productivity and efficiency.

Wireless technology has been used in industry for many years in the licensed spectrum bands for interference-free wireless transmissions which ensures flexible networking and reliable over-the-air data communications for plant process monitoring and control. In recent years, license-free spectrum bands, such as the industrial, scientific, and medical (ISM) bands, have proliferated and provided industry more options for building wireless systems, such as wireless networking with mobile workers and wireless sensor networks for process optimization and asset management. However, the explosive growth of such technologies has encountered many challenges, such as interference, congestion, and spectrum planning, especially in large factories with dense deployments and harsh environments. Adoption and use of wireless technologies has often been hampered by a perceived notion, i.e., the lack of reliability, integrity, and security in wireless links. The factory is usually rich in metallic surfaces and obstructions, which result in a harsh radio wave propagation environment [1]. Given these concerns, many questions are often asked such as which wireless technology is best suited for an industrial application and what approach should be taken to ensure reliable operation. Having an appropriate understanding of the capabilities and applications of wireless technologies allows potential users to recognize the benefits of wireless while avoiding the problems of misapplication in challenging industrial environments in which many potential physical obstructions and sources of interference exist.

Industrial wireless practitioners and researchers recognize the need of guidelines, which will help manufacturers, users, and their suppliers to design, assess, select, and deploy wireless systems effectively. Manufacturing organizations often use ad-hoc methodologies to deploy and manage their wireless networks without first understanding their own problem space, selecting appropriate candidate technologies, and developing a plan for spectrum management and growth. Ad-hoc methods are usually suitable for smaller organizations, where engineering resources are limited. Besides "agile" engineering practices, it is important to first understand the problem space, adopt a rigorous candidate selection, and track factory spectrum allocations during deployments. We believe that industrial wireless systems are best deployed and managed when organizations apply an incremental, systematic, and vendor-independent approach to selecting and deploying their wireless networks using engineering best practices and policies.

In this article, we present our approach to selecting and deploying industrial wireless systems in the factory. We begin by discussing the general problem space of wireless in industry. We then discuss various objectives and success criteria for deploying wireless solutions. Next, we highlight the benefits of systems engineering processes and recommend a deployment lifecycle. The deployment lifecycle is a generalized process that includes a business case with clearly stated objectives, a survey of the factory and technical requirements, candidate selection, solution design, and deployment. The approach described in this article reflects best practices developed by the Industrial Wireless Systems Technical Working Group (IWSTWG) managed by the National Institute of Standards and Technology (NIST).

IWSTWG was established in March 2017 at the IEEE Sensors Applications Symposium Workshop on Industrial Wireless sponsored by NIST, and technically supported by the IEEE Industrial Electronics Society and IEEE Instrumentation and Measurement Society [2], [3]. A guidelines document was released in May 2018 and details of our approach was discussed in the guidelines document [4].

THE INDUSTRIAL WIRELESS PROBLEM SPACE

Having a comprehensive understanding of the problems and potential solutions of wireless networks in manufacturing industries significantly eases the challenges of selecting and deploying wireless solutions. Identifying industrial use cases not addressed by existing wireless technologies can lead to targeted growth through technological innovation using new or existing wireless standards. Motivated by the industry needs for independent, best-practice guidelines and solutions to difficult wireless control problems, we begin by providing a taxonomy of industrial problem categories where wireless networking technologies may be deployed followed by our perspective of the state-of-the-art of relevant wireless standards.

Industrial Applications

Applications for industrial wireless are very diverse, and we begin with a short survey of the application areas of industrial networks. The application areas of industrial wireless have been discussed earlier in various articles [5]–[10]. However, in most of these works, the studies are not comprehensive to cover the entire industrial wireless problem space. In [5]–[7], industrial wireless networks (IWN) have been divided into various levels to include field equipment and instrumentation, control and automation systems, and supervisory and management systems. In [8] and [9], focus is placed on the factory instrumentation, where wireless technologies are discussed. In [10], the authors provide a comprehensive analysis of the problem space and a mapping between the industrial problem space and the existing wireless solutions.

To map a specific wireless technology to an application area, we first divide the problem space into a manageable set of classes based on the functions performed inside a factory. Here, the term factory refers to both the factory which is often identified with discrete job-based manufacturing and the plant which is more often identified with flow-based processes. We refer readers to the *Purdue Enterprise Reference Architecture* (ANSI/ISA-95) for more information on the functions of the factory. For the sake of our scope, we limit our perspective to the operational aspect of the factory from the physical ground of the factory up to the enterprise interface. Our classification of the industrial problem and technology spaces is shown in Figure 1. The possible industrial wireless applications within the factory can then be described as follows:

1) *Manufacturing Instrumentation:* This class includes the transmission of measured variables by sensors and manipulated variables to actuators. This functional area often requires deterministic latency and reliability as well as interface compatibility with legacy industrial communications protocols. Latency and reliability requirements will vary depending on consumers of factory information, such as the automation system and optimization applications. Table 1 lists the latency, loss, and scale requirements of typical classes of manufacturing instrumentation applications. Latency is defined as the application layer delay in one direction such as between a sensor and a controller. Reliability is defined as the likelihood that a block of application layer information is lost either from unacceptable delay or noise. Our guidelines adopted the IEC-62264 (ANSI/ISA-95) definitions of flow-based and job-based manufacturing systems [11]. Flow-based systems include those in which raw materials are in continuous motion such as oil refineries, water treatment plants, and chemical reactors. Job-based systems are those that manufacture or assemble products in discrete steps such as an automotive assembly line. Because industrial applications are all unique, and as such have unique latency and reliability requirements, it can be difficult to validate these requirements. Often the requirements presented by industrial device manufacturers can appear daunting and, therefore, should be viewed as a range or upper bounds on performance. Sources for performance requirements of industrial networks may be found in [2], [12]–[14]. The performance requirements provided in [15] are based on experimental results of representative use cases using testbeds. While experimental outcome based on testbeds is useful and necessary, each use case is not statistically representative of an entire class of industrial systems. The data in Table 1 is, therefore, a product of academic sources, collaborations within industry through our technical working group, and the professional experience of the authors.
2) *Personnel Safety:* This class includes all applications with the sole purpose of preventing accidents or injury. All types of accidents are included, such as slips, trips, and falls of workers, air quality monitoring, gas leakage detection and control, and robot-related accidents. Safety applications can be further divided into safety monitoring and safety integration systems (SIS). Safety monitoring systems, such as gas leakage monitoring can tolerate appreciable delay and loss; however, communications within SIS must achieve very low latency and ultra-high reliability and resilience to be trusted. Wireless is rarely used as a primary communication

channel for SIS primarily due to the impact of interference, so this presents an opportunity for research.

3) *Back-haul Connectivity:* Backhaul communications include data transmissions between factory floors and data centers, between various buildings in a plant, and remotely to headquarters in different cities or countries. This class is typically characterized by the large amounts of transferred data. Various wireless technologies for backhaul connectivity are discussed in [16].

4) *Tracking:* In this class of application, wireless is used for tracking, localization, and identification of materials, inventory, personnel, and tools. The characteristics and applications of various tracking, localization, and identification technologies are discussed in [17].

5) *Security and Surveillance:* This class includes transmissions of voice, video, and identification information related to factory floor security. Commercial technologies, such as Wi-Fi, are often used when wires are cost-prohibited; however, their coexistence with other industrial wireless transmissions, such as with factory instrumentation, needs careful spectrum planning before deployment.

6) *Remote Assets:* The use of wireless communications in remote monitoring and control reduces cost significantly. The goal of remote monitoring and control, especially in flow-based industries, is to improve the operation of remote sites while reducing labor, transportation, and installation costs. Security is often one of the major concerns for this class of application due to the geographical remoteness.

7) *Maintenance Support:* This class includes the communication of machine health and status, environment control, such as heating and air conditioning, and software and firmware updates of various components. Depending on the amount of transferred data and the risk level, various wireless technologies can be used. Recently, augmented reality has been used for maintenance supports which require significant bandwidth and high reliability when used, but it provides a valuable resource for on-the-job training and maintenance support [18].

State-of-the-Art of Industrial Wireless Networks

A similar classification can then be applied to the types of IWN. This segmentation of the industrial wireless space can be helpful in determining the appropriateness of specific wireless products to an application. The adoption, development, and application of wireless communication technologies in industrial applications is discussed recently in the literature [2], [19]–[25]. In [2], [19], applications relevant for industrial wireless systems in the Industrial Internet of Things (IIoT) are covered and a survey of a variety of wireless technologies for industrial applications is introduced. In [20], the use of wireless communications for automation applications is briefly discussed where the corresponding special section includes papers dealing with new applications scenarios and new technologies for wireless critical communications. In [21], a survey of industrial wireless systems requirements is presented and possible matches between industrial applications and existing wireless technologies are explored. In [22]–[25], opportunities brought in by introducing IIoT and the challenges for its realization are highlighted. Moreover, technological trends are reviewed and standarizations of connectivity solutions of IIoT are overviewed.

As a result, we have identified patterns of the IWN technology space and they are shown in Figure 1 as follows:

1) *Home and Office*: This includes standards-based communications systems typically found in office environments but may be useful in factories. They include IEEE 802.11 variants and Wi-Fi compliant devices.
2) *Instrumentation*: This includes systems specifically designed for factory instrumentation, building automation, and Internet of Things (IoT). Standards, such as ISA 100.11a, WirelessHART, ZigBee, and Bluetooth Mesh Networking, fall into this category. International standards include the Wireless Networks for Industrial Automation — Factory Automation (WIA-FA) and Process Automation (WIA-PA), or IEC 62948 and IEC 62601, respectively. Many exceptional proprietary options based on familiar low-cost chipsets exist for industrial practices, including strong encryption, frequency hopping, and coexistence management.
3) *Wide-area Sensing*: Some applications require the ability to transmit over long distances with minimal power to conserve battery life for sensing and control over wide geographical distances. These technologies vary in bandwidth and transmit power but share the common element of a low information bit rate, e.g., LoRaWAN and SigFox.
4) *Esoteric*: This includes technologies, such as radiating coaxial cable and tropo-scatter solutions that are designed for applications that have unique requirements and mandate a solution that cannot be met with off-the-shelf alternatives. This category may include systems such as satellite, cellular, optical (visible light), and land-mobile radio networks.

In Table 2, we present a mapping between major industrial applications and current or emerging wireless technologies. This table is an abbreviated version of the one presented in [10].

PRACTICAL GUIDELINES FOR THE WIRELESS LIFECYCLE

Based on the wireless problem space, applications, and availability of IWN discussed, let us discuss how we came up with the guidelines for the entire wireless lifecycle.

Success Criteria

System availability is paramount for any operational systems, such as a factory operation. Prior to embarking on any industrial upgrade or enhancement, objectives and success criteria should be clearly defined. The definition of success criteria is a list of one or more enterprise objectives prior to embarking on a wireless enhancement within a factory. It should not be viewed as a threshold of technical performance. Objectives of industrial wireless deployment are discussed in early stage of the deployment lifecycle and are reviewed throughout the deployment lifecycle. These success criteria relate to the operational performance of the factory rather than the network itself. Economics, risks, and physics of a factory can play important roles in the selection of technologies to be applied. For example, wireless technology is typically preferred for applications with moving objects, areas with limited physical access, situations where wires can cause physical hazards, or the site layouts that change frequently. Wireless can also be used to address operational regulatory compliance for remote installations, e.g., addressing safety regulatory requirements for distant wellheads, where wired solutions could be cost prohibitive. Before beginning a factory enhancement involving wireless technology, we suggest that the enhancement answers at least one of the following criteria shown in Figure 2. These success criteria include the following:

1) *Reliability*: Will the introduction of wireless improve the ability of the factory to conform to the required function or mission under the specified production conditions?
2) *Safety*: Are people or equipment made safer? Will wireless improve the ability of employees to perform their jobs free from recognized hazards including falls, hazardous energy, confined spaces, ergonomics, or hazardous materials?
3) *Efficiency*: Will wireless improve the ability to lower or meet target operating and production costs or reduce maintenance costs?
4) *Quality*: Will wireless be used to improve the ability of the factory to produce products within specified design tolerance or be able to demonstrate design conformity?
5) *Environment*: Will the introduction of wireless technology improve environmental stewardship by better monitoring the industrial process and preventing industrial accidents or minimizing pollution?

6) *Government Regulation*: Will wireless technology enable demonstration of compliance with applicable safety and environmental laws?

Wireless Deployment Lifecycle

Here, we discuss the various stages of the deployment lifecycle and the application-specific details that may be mentioned at each of these stages. Also, we discuss the general steps to be performed at each phase along with expected outputs and highlight the importance of performing these operations. It is important to understand that we do not recommend that organizations modify their engineering procedures to strictly follow our recommendations. The guidance is meant to inform and improve the engineering practices within an organization where improvement is needed. The process is not expected to be serialized but can and should overlap and iterate to include feedback and discussion by stakeholders. The key takeaway from our guidelines is education of factory engineers of wireless principles and best practices as applied to their own enterprise objectives.

A general project lifecycle includes multiple stages to achieve the final goal of having successfully deployed industrial wireless networks satisfying functional requirements defined. Our lifecycle is shown in Figure 3. The first step in the process is Defining Objectives in which the objectives and success criteria are defined and if a wireless system may be considered. Next is the factory survey in which factory operations and surrounding environments are analyzed comprehensively to determine the requirements for candidate solutions. Once the survey has taken place and data from the survey is readily available, a set of candidate solutions should be identified based on a complete set of requirements, and one or more candidate solutions should be selected for deployment based on a merit-based selection process. A solution should then be developed, perhaps simulated, and tested. Performance should be validated against the original requirements and design intent, and a deployment plan should then be devised. The result is a deployed solution that meets the technical requirements and effectively addresses the original business goals.

Each of these lifecycle phases may include a variety of stakeholders. Specifically, defining objectives may include management and engineering staff, candidate comparisons and design may include design and implementation engineers, and deployment may involve both communications and factory floor engineers, operators, and technicians. Moreover, operators deal with networks in later stages during monitoring and maintenance. To be practical, guidelines must be suitable for the educated factory technician or engineer, and they must be relatable to managers to perceive their values to the enterprise. Overall, they must include required details without burdensome mathematics or technical jargon.

Defining Objectives

In this stage, success criteria are considered by stakeholders to justify the need for industrial wireless deployment. The objectives should be clearly enumerated and communicated to all stakeholders. Realistic technological expectations are defined for the wireless deployment and communicated to stakeholders. Thus, it should be clear that wireless technologies cannot serve all applications. Objectives based on success criteria should be measurable, and measurement methods should be selected and approved at this early stage. We recommend that an iterative approach to deployment be adopted within an organization new to wireless, which is shown in Figure 4. This will be helpful in managing expectations and giving the stakeholders time to adapt to the new technology within their operation.

Two important factors should be included in the objectives study. They are the risk assessment and future growth. The mention of wireless deployment is usually coupled by a concern for a lack of security and resilience which can lead to factory down-time and economic loss. Security and resilience may impact a number of the success criteria depending on the way they affect the industrial operation. As an example, if a machine in a production line goes down, both reliability and efficiency are impacted while having a machine that is not operating within design tolerances may impact the quality of the manufactured product. Hence, a risk assessment should be performed to assure a secure and resilient wireless system implementation. The future growth plans should be considered in parallel to wireless deployment where the scalability of current wireless technologies is evaluated to achieve future business goals. A general reference for wireless applicability is given in Table 3.

Factory Survey

Many organizations lack complete awareness of their own factory operations. This is primarily due to obsolete tools and technologies, employee turnover, retirement, and general complexity. More often, operations are captured in paper-based blueprints, which are difficult to analyze without human knowledge that may have been lost. Therefore, it is important to assess the factory operation early in the deployment lifecycle to understand the operation, identify process points of interest, and, if safety or control of any kind is to be implemented, what systems may be affected. The factory survey should identify all machines, processes, design artifacts, programs, and applications to be affected by the deployment.

The physical environment of the deployment site should be reviewed. The detailed site layout determines the physical environment including materials used for various environment components. The measurement and control points are those between which the data will be transferred and hence should be determined accurately. Data collection systems and management locations should be identified. Furthermore, after defining the data points, the process variable specifications are needed to determine deployed network requirements. These specifications should include the amount of data transferred, process variable change rates, delay tolerances, and criticality to site operations.

Results of the survey should also include the operational models and safety requirements, especially when wireless is to be used for safety or control. Operational models define all abstract models, such as equations, simulations, and statistics that help in predicting the industrial operation behaviors. As a result, the wireless network performance can be later validated through simulation using these operational models. The safety requirements are identified to limit the selection of wireless devices to those which satisfy safety requirements including intrinsic safety of the devices themselves.

Candidate Selection

Once objectives are defined and a factory survey has been conducted, candidate solutions can be pursued. It is possible to pursue candidates earlier in the process by consulting industrial wireless vendors for possibilities. Technology vendors and systems integrators are a valuable resource for factory engineers to learn about technology and factory improvement possibilities. Relationships will form between factory representatives and the vendors themselves and often to the benefit of the factory enterprise. Vendors will sometimes provide systems engineering guidance that can be very valuable to factory engineers. Despite these benefits, it is important that vendors do not too heavily influence the requirements analysis phase. Candidate selection is better conducted based on an objective assessment of available solutions to the requirements. Requirements used for evaluation will include technical requirements as well as non-technical requirements. Technical requirements will include items, such as supported radio frequency (RF) bands, data reliability, latency, throughput, system availability, safety, equipment failure rates, cybersecurity, interoperability with other systems, and costs of ownership.

Candidates are identified through vendor consultation, Internet searches, datasheets, trade shows, conferences, and word-of-mouth. The capabilities of candidates are validated against the various requirements to compare the candidates which satisfy these requirements. Validation can be achieved through analysis, simulations, and testing depending on complexity, budget, and technical expertise of the engineering staff. Tools, such as simulation and hardware-in-the-loop (HIL) testbeds, are valuable resources to leverage for assessing highly important or high-risk requirements. Finally, candidates are compared and ranked to select the best candidate to be deployed. We recommend that a scorecard selection method be used to rank candidates and make an informed and unbiased decision. The scorecard selection method is achieved by quantitively grading each candidate for achieving various technical requirements. Then, mathematical and/or logical operations are applied based on the defined objectives to rank, compare, and choose the most suitable candidate. An example of a scorecard can be found in Appendix A-4 in [4].

Solution Design

By this point, a candidate has been selected and a complete solution must be designed and implemented. This phase entails all elements of engineering design to include device placement, antenna selection and positioning, software development for controllers and non-controller computing platforms, databases, interfaces, design validation, and testing. This list is not exhaustive. Because the focus of the design is wireless, frequency planning and topology selections are again considered given data sheets and design decisions. Spectrum management will include updating the enterprise spectrum management plan with new frequency allocations and spectral monitoring techniques. Internal and external regulatory electromagnetic (EM) spectrum approvals must be obtained by this point in the wireless deployment lifecycle.

Quality of Service (QoS) analyses are performed to determine if the wireless design can meet requirements. Validation of the design is usually conducted iteratively through best engineering practices. Channel utilization planning, interference effects, and coverage cells should be planned based on various data points of an industrial site. A QoS analysis can then be conducted to verify through testing or simulation that coverage and ultimately network QoS can be achieved as expected. Commercially available Modification Request Systems (MRS) can be used to track and report results of various testing phases and all the modifications made to correct the problems. Verification of design can be costly for a large-scale deployment. Simulation can be a cost-effective way for experimenting with different topologies, but cannot replace testing with real devices. Simulation requires technical expertise in modeling, simulation tools, and computer programming often not available within small or medium sized enterprises. Simulation expertise can be made available through systems integrators, device manufacturers, universities, and research institutions. For smaller enterprises with more resources, we advocate a mix of simulation and controlled field testing with wireless devices. Network emulation can be employed to enable hardware-in-the-loop simulation such that the impacts of scale, data loss, and delay can be estimated before an operational system is deployed. Black-box test methods also can be a valuable tool for verifying expected performance under controlled conditions; however, for large deployments, we recommended simulating network performance using wireless channel models that include the realistic propagation and interference statistics. Realistic propagation statistics for 2.4 GHz and 5 GHz ISM bands can be found in the industrial wireless propagation report, NIST Technical Note (NIST-TN) 1951 [1], which provides empirical propagation measurement data and statistics. The raw data of measurements at three different sites, a factory, machine shop, and process plant, are available for download. They are currently being used to support research and development of new low-latency reliable wireless protocols [26].

Security, which is important to the success of wireless network implementations, is merely mentioned or even often missing or considered last in a design process. Security should be considered simultaneously with the functional design to include physical security, data security, and spectrum security. We refer readers to several industrial security standards and guidelines that exist, including NIST SP 800-82 and IEC-62443 (ISA-99) [27]. Spectrum monitoring should be included as part of any security risk management plan. We recommend including a security element to the spectrum monitoring system deployed within any factory, during the design phase and prior to deployment. Spectrum monitoring tools can be useful in identifying normal versus anomalous wireless activity, geolocating interference, and projecting growth patterns of factory wireless activity and interference activity as well [28].

One of the important steps while deploying an industrial wireless system is managing the spectral resources within an industrial environment. Frequency harmonization of the RF spectrum becomes essential with the increase of industrial wireless solutions occupying the same RF band. Practical considerations of frequency harmonization include channelization, multiplexing, matching, and data filtering. Details of these considerations can be found in Section 4.4.4 in [4].

Deployment, Monitoring, and Updating

In this phase of the lifecycle, the design of the wireless system is put into production. Deployment is defined as positioning design elements, such as devices, machines, and software into a live operational system. Three stages are included in this phase, which are Deployment (i.e., implementation and provisioning), Monitoring, and Updating. Deployment includes the setup and configuration of various network devices. After deployment, the wireless system is monitored and analyzed including wireless network states, traffic statistics, cybersecurity events, and physical environment changes. Updating is the process of continuously improving the performance of the network through software and firmware updates and tuning of operational parameters for optimization.

Deployment begins with the installation of various wireless equipment where antennas are positioned and oriented to achieve the best transmission quality. Antenna alignment in both polarization and radiation pattern is a key consideration for fixed position wireless devices. Cables are used to position the antennas away from obstructions to improve connection reliability assuring line-of-sight (LOS) coverage. Mobile devices will not have the advantage of a fixed antenna position. For mobile platforms, such as unmanned ground vehicles and mobile robotic platforms, testing of the system to include the physical and control elements under a comprehensive set of wireless channel conditions is essential. Safety systems and wireless interlocks should be exercised as well under a variety of channel conditions to include nominal and worst-case interferences.

Once the wireless system has been deployed and operational, it should be continuously monitored. Monitoring includes capture and analysis of electromagnetic (EM) spectrum, network traffic, and security events. Monitoring can be performed in real-time or off-line in batch mode. Real-time monitoring provides troubleshooting functions to capture the pitfalls of systems that cause factory down-time, loss of data, or injury. We recommend that RF spectrum be monitored and analyzed continuously at various locations. The use of inexpensive software-defined radio platforms makes distributed monitoring of the EM spectrum within the factory possible. Radio activity can be correlated with the industrial site activities to detect any abnormal RF transmissions. The spectrum monitoring system could be integrated with the automation system to provide an automation system that is spectrally aware for reliable sensing and control. This presents an opportunity for academia and industry as interoperation of spectrum monitoring tools and automation systems do not yet exist.

Network upgrades can be performed either in a small or large scale where new nodes are added to the wireless network. Network operation after the upgrades should be verified by using various simulation and testing methods identified during design. Furthermore, during network operations, updates and parameters adjustments should be done regularly to maintain optimized network operations. This presents another area of opportunity. Machine learning techniques can be applied to optimize network parameters on an ongoing basis to improve and maintain latency and reliability within the operation.

FUTURE DIRECTIONS

In the process of developing our guidelines, we have identified areas of research opportunity that include but are not limited to cyber-physical systems modeling, wireless channel models, interoperability between heterogeneous wireless systems, wireless for manufacturing safety, machine learning for network optimization, and test methods. In particular, good cyber-physical models are essential steps toward improving industrial wireless deployments [29]. The current theoretical wireless channel models, including the one specified in IEEE 802.15.4a [30], do not capture the industrial channels close enough. Industrial channels in various scenarios may have significantly variable channel models in confined spaces and factories with large metal machines. RF interferences caused by commercial devices, such as microwave ovens and electro-mechanical effects need also be incorporated into the models. Uncertainty models need to be developed that characterize wireless systems comprehensively from the perspective of instrumentation and propagate network uncertainty into the physical world. Existing models for physical systems are defined for very specific scenarios. A more generic discrete event model which captures a wide range of applications is needed to allow for better system design, and the integration between channel models and physical models must be studied, especially, with different time scales for these systems.

Another important direction related to wireless deployment is testing various network components and parameters. Testing in an industrial setting should include production-related criteria and be performed in an industrial-similar setting. The effects of wireless channels and uncertainty in industrial environments should be characterized mathematically and incorporated into designing industrial wireless networks. Measurement methods must be designed to quantify these uncertainties. Tuning methods based on machine learning that account for the wireless network, the physical system, and the changing factory environments could present interesting challenges to motivated researchers.

A third direction related to both modelling and testing is that of cyber-physical systems simulations. Such simulations are useful in predicting and evaluating the impacts of industrial wireless systems operational performance. Some works in the literature, such as that in [31]–[33], have considered interactions between network and operational systems. Realistic models, experimental results, and data are needed to address the growing needs for reliable wireless communications in industry. More future works are expected for various use cases and simulations of industrial wireless uncertainties impacts on the performance of operational systems.

Finally, the wireless technology space is vast considering the number of unique industrial applications especially those found in discrete manufacturing. Assessing existing wireless technologies and evaluating their abilities to achieve the current and future industrial requirements is an important step to find deficiencies in existing technologies. Hence, testing and comparison of various technologies must be done for various areas of the problem space to identify the applicability of wireless technologies for deployment. It could be of benefit to the academic and industrial communities to devise a design challenge to address this issue. Furthermore, it is important to define realistic industrial wireless network requirements including the required latency, reliability, and scale of the network that need to be validated against the physical requirements of specific classes of industrial applications.

CONCLUSIONS

In this article, we have discussed the problem space and the deployment lifecycle of industrial wireless. Due to the wide range of application areas of industrial wireless and the variance of users through network deployments, both generic and application-specific guidelines are needed to clarify various phases of decision making whether to deploy industrial wireless and thereafter implementing wireless systems. In addition, we have discussed in detail general guidelines for industrial wireless deployments. As a result, we have concluded that there is a need for the standardization and adoption of systems engineering processes to effectively apply wireless technologies within factory systems. Through the adoption of standardized guidelines, reliability of factory operations can thus be maintained while reaping the benefits of deploying wireless technologies in factory environments. We have also shown some opportunities where research is needed to gain some better understandings of industrial wireless usages, practices, and associated problems in industrial settings, through which we can help speed up wide adoptions and deployments of wireless technologies in current industrial scenarios.

References

[1] R. Candell, K. A. Remley, J. T. Quimby, D. Novotny, A. Curtin, P. B. Papazian, M. Kashef, and J. Diener, "Industrial wireless systems radio propagation measurements (NIST-TN 1951)," Gaithersburg, MD, Jan. 2017.

[2] V. K. L. Huang, Z. Pang, C. J. A. Chen, and K. F. Tsang, "New Trends in the Practical Deployment of Industrial Wireless: From Noncritical to Critical Use Cases," *IEEE Ind.*

Electron. Mag., vol. 12, no. 2, pp. 50–58, 2018.

[3] R. Candell, “Industrial wireless systems workshop proceedings (NIST-IR 8174),” Gaithersburg, MD, May 2017.

[4] R. Candell, M. Kashef, K. Lee, Y. Liu, J. Quimby, and K. Remley, “Guide to Industrial Wireless Systems Deployments,” in *NIST Advanced Manufacturing Series 300-4*, 2018.

[5] B. Galloway and G. P. Hancke, “Introduction to Industrial Control Networks,” *IEEE Commun. Surv. Tutorials*, vol. 15, no. 2, pp. 860–880, 2013.

[6] J. R. Moyne and D. M. Tilbury, “The emergence of industrial control networks for manufacturing control, diagnostics, and safety data,” *Proc. IEEE*, vol. 95, no. 1, pp. 29–47, 2007.

[7] “What are industrial communication networks? an overview,” 2017. [Online]. Available: https://www.electricaltechnology.org/2016/12/industrial-communication-networks-systems.html. [Accessed: 09-Feb-2018].

[8] P. Danielis, J. Skodzik, V. Altmann, E. B. Schweissguth, F. Golatowski, D. Timmermann, and J. Schacht, “Survey on real-time communication via Ethernet in industrial automation environments,” in *19th IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2014*, 2014, pp. 1–8.

[9] N. F. Thornhill and W. Ikram, “Wireless communication in process automation: a survey of opportunities, requirements, concerns and challenges,” in *UKACC International Conference on CONTROL 2010*, pp. 471–476.

[10] R. Candell and M. Kashef, “Industrial wireless: Problem space, success considerations,

technologies, and future direction,” in *Proceedings - 2017 Resilience Week, RWS 2017*, 2017, pp. 133–139.

[11] International Electrotechnical Commission, “IEC 62264-1:2013 (ANSI/ISA-95) Enterprise-control system integration – Part 1: Models and terminology.” International Society of Automation, Geneva, 2013.

[12] K. Kusume and M. Fallgren, “Updated scenarios, requirements and KPIs for 5G mobile and wireless system with recommendations for future investigations,” *Mob. Wirel. Commun. enablers twenty-twenty Inf. Soc. Deliv. ICT-317669-METIS/D1.5*, Apr. 2015.

[13] X. Li, D. Li, J. Wan, A. V. Vasilakos, C.-F. Lai, and S. Wang, “A review of industrial wireless networks in the context of Industry 4.0,” *Wirel. Networks*, vol. 23, no. 1, pp. 23–41, Jan. 2017.

[14] European Telecommunications Standards Institute, “ETSI TR 102 889-2 V1.1.1 (2011-08) Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference Document; Short Range Devices (SRD); Part 2: Technical characteristics for SRD equipment for wireless industrial applications using technol.” 2011.

[15] “Requirement Profiles in ZDKI ‘Applications, Requirements and Validation’ of the Accompanying Research – Reliable wireless communication in industry (BZKI) in the BMBF Funding Programme “ICT 2020 – Reliable Wireless Communication in Industry" (ZDKI).” .

[16] “Wireless backhaul spectrum policy recommendations and analysis.” [Online]. Available: http://www.gsma.com/spectrum/wp-content/uploads/2014/12/Wireless-Backhaul-Spectrum-Policy-Recommendations-and-Analysis-Report.-Nov14.pdf. [Accessed: 02-

Sep-2018].

[17] A. A. Khudhair, S. Q. Jabbar, M. Q. Sulttan, and D. Wang, “Wireless indoor localization systems and techniques: Survey and comparative study,” *Indones. J. Electr. Eng. Comput. Sci.*, vol. 3, no. 2, pp. 392–409, 2016.

[18] V. Paelke, “Augmented reality in the smart factory: Supporting workers in an industry 4.0. environment,” in *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*, 2014, pp. 1–4.

[19] Z. Pang, M. Luvisotto, and D. Dzung, “Wireless High-Performance Communications: The Challenges and Opportunities of a New Target,” *IEEE Ind. Electron. Mag.*, vol. 11, no. 3, pp. 20–25, 2017.

[20] L. L. Bello, J. Åkerberg, M. Gidlund, and E. Uhlemann, “Guest Editorial Special Section on New Perspectives on Wireless Communications in Automation: From Industrial Monitoring and Control to Cyber-Physical Systems,” *IEEE Trans. Ind. Informatics*, vol. 13, no. 3, pp. 1393–1397, 2017.

[21] E. Egea-Lopez, A. Martinez-Sala, J. Vales-Alonso, J. Garcia-Haro, and J. Malgosa-Sanahuja, “Wireless communications deployment in industry: A review of issues, options and technologies,” *Computers in Industry*. 2005.

[22] A. W. Colombo, S. Karnouskos, O. Kaynak, Y. Shi, and S. Yin, “Industrial Cyberphysical Systems: A Backbone of the Fourth Industrial Revolution,” *IEEE Ind. Electron. Mag.*, vol. 11, no. 1, pp. 6–16, 2017.

[23] S. Mumtaz, A. Alsohaily, Z. Pang, A. Rayes, K. F. Tsang, and J. Rodriguez, “Massive

Internet of Things for Industrial Applications: Addressing Wireless IIoT Connectivity Challenges and Ecosystem Fragmentation," *IEEE Ind. Electron. Mag.*, vol. 11, no. 1, pp. 28–33, 2017.

[24] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, and M. Gidlund, "Industrial Internet of Things: Challenges, Opportunities, and Directions," *IEEE Trans. Ind. Informatics*, 2018.

[25] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," *IEEE Ind. Electron. Mag.*, vol. 11, no. 1, pp. 17–27, 2017.

[26] R. Candell, "Radio Frequency Measurements for Selected Manufacturing and Industrial Environments," 2016. [Online]. Available: https://www.nist.gov/el/intelligent-systems-division-73500/networked-control-systems-group/project-data-wireless-systems.

[27] K. Stouffer, V. Pillitteri, S. Lightman, M. Abrams, and A. Hahn, "Guide to Industrial Control Systems (ICS) Security (NIST-SP 800-82 Revision 2)," 2011.

[28] M. Aksu and R. Candell, "Requirements for Spectrum Monitoring in Industrial Environments (NIST-IR 8195)," Gaithersburg, MD, 2017.

[29] N. Ericsson, T. Lennvall, J. Akerberg, and M. Bjorkman, "Challenges from research to deployment of industrial distributed control systems," in *2016 IEEE 14th International Conference on Industrial Informatics (INDIN)*, 2016, pp. 68–73.

[30] A. F. Molisch, K. Balakrishnan, C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, "IEEE 802.15.4a channel model - final report," Online]. Available, 2004.

[31] Y. Liu, R. Candell, K. Lee, and N. Moayeri, “A simulation framework for industrial wireless networks and process control systems,” in *2016 IEEE World Conference on Factory Communication Systems (WFCS)*, 2016, pp. 1–11.

[32] J. Geng, H. Li, Y. Liu, Y. Liu, M. Kashef, R. Candell, and S. S. Bhattacharyya, “Model-based cosimulation for industrial wireless networks,” in *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, 2018, pp. 1–10.

[33] H. Neema, J. Gohl, Z. Lattmann, J. Sztipanovits, G. Karsai, S. Neema, T. Bapty, J. Batteh, H. Tummescheit, and C. Sureshkumar, “Model-Based Integration Platform for FMI Co-Simulation and Heterogeneous Simulations of Cyber-Physical Systems,” in *Proceedings of the 10th International Modelica Conference*, 2014, pp. 235–245.

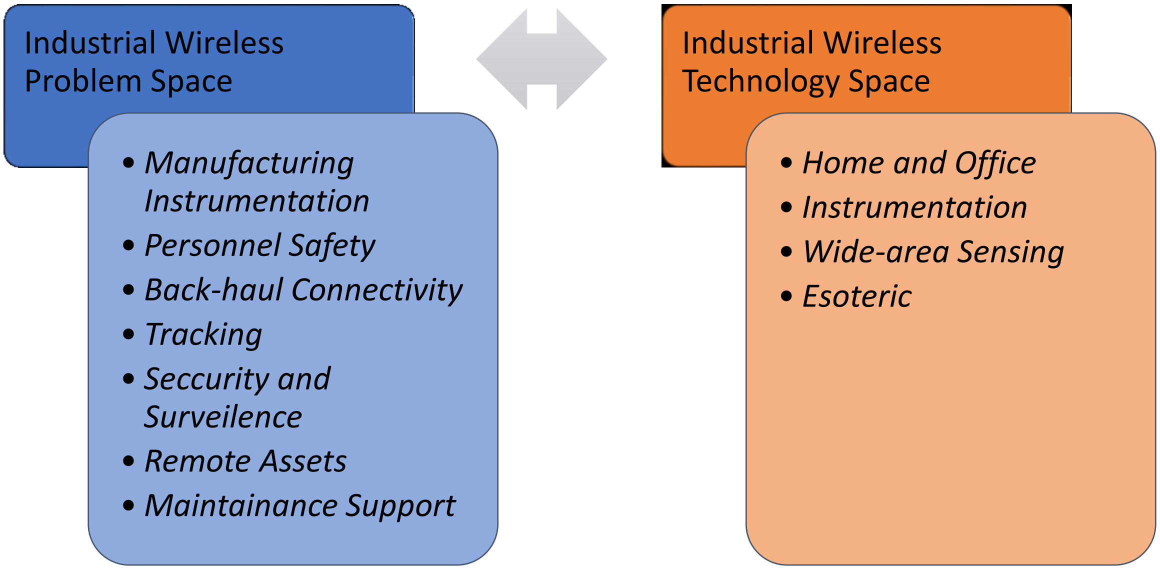

Figure 1: Industrial Wireless Problem and Technology Spaces

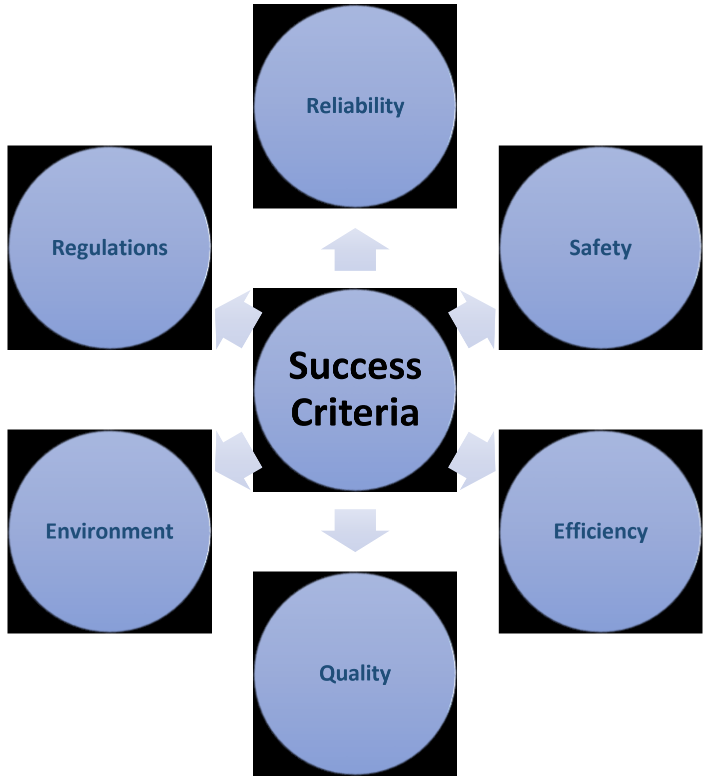

Figure 2: Success Criteria for Industrial Wireless Systems

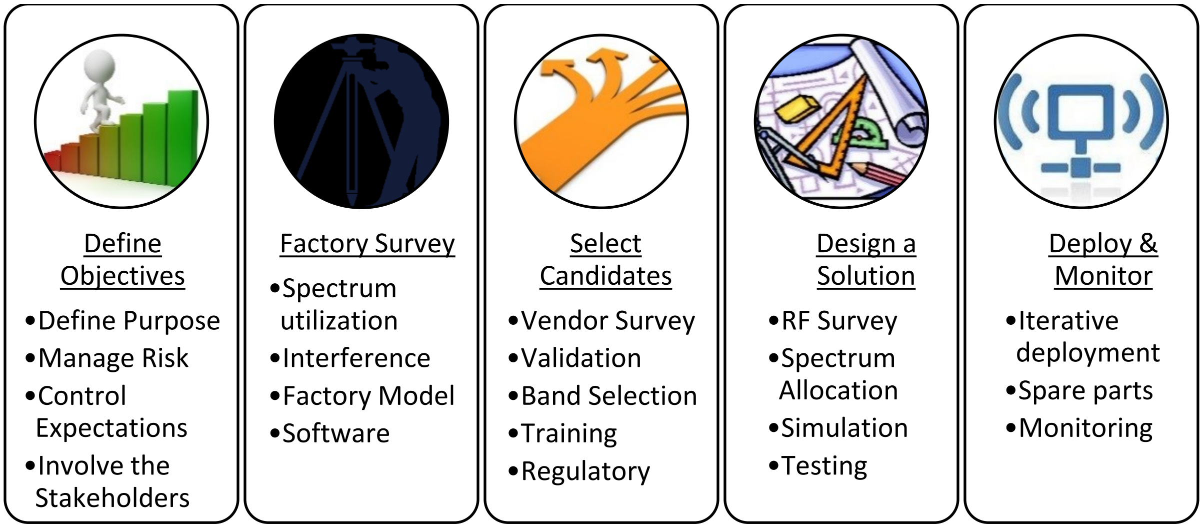

Figure 3. Lifecycle Components of Wireless Systems Deployment

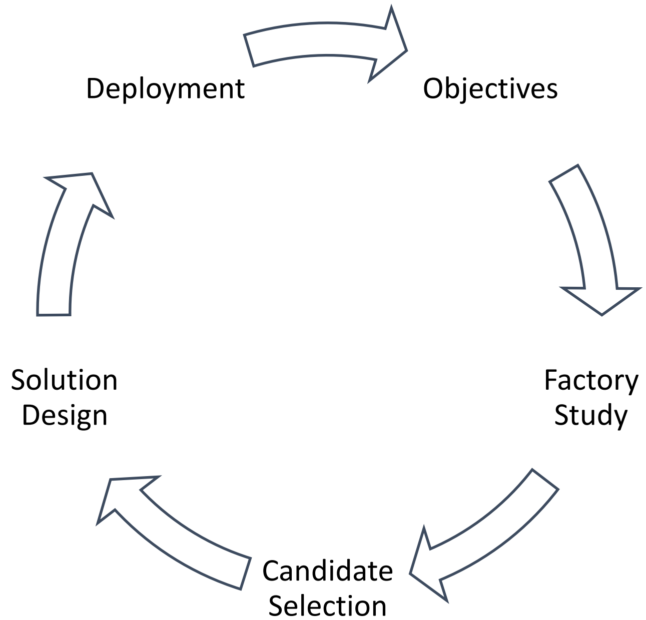

Figure 4. Iterative Wireless Deployment Lifecycle

Table 1. List of Typical Reliability and Latency Requirements for Industrial Systems

Application Class	***Latency,*** l	***Pr. Loss,*** r	***Devices,*** s
Monitoring	$l < 1\mathrm{s}$	$r < 10^{-5}$	$s < 10,000$
Supervisory Control			
Flow-based	$l < 100ms$	$r < 10^{-6}$	$s < 30$
Job-based	$l < 100ms$	$r < 10^{-7}$	$s < 10$
Feedback Control			
Flow-based	$l < 10s$	$r < 10^{-6}$	$s < 1000$
Job-based	$l < 10ms$	$r < 10^{-7}$	$s < 10$
Safety Alarming	$l < 1s$	$r < 10^{-7}$	$s < 10$

Table 2. Applicability of Wireless Technologies

		Flow-based			Job-based			Safety		Back-haul		Tracking			Security			Remote	Maint.		
		Process Monitoring	Supervisory Control	Feedback Control	Factory Monitoring	Assembly: Sensing and Actuation	Quality Inspection	Fall Prevention	Confined Spaces	Nearby or Indoor	Distant	Materials	Tools	Personnel	Voice and Video	Grounds Control	Spectrum Monitoring Data	Monitoring	Machine Health Monitoring	Building Automation	Augmented Reality
Home and Office	IEEE 802.11	●	●	◐	●	◐	◐	◐	○	●	●	ϟ	ϟ	ϟ	●	●	●	◐	◐	●	●
	IEEE 802.15.1	○	○	○	○	◐	●	◐	◐	○	○	◐	●	◐	▼	○	○	○	◐	○	▼
Instrumentation	IEEE 802.15.4 TDMA	●	●	◐	●	◷	◐	◷	◐	▼	▼	ϟ	ϟ	◐	▼	◐	▼	●	○	●	▼
	IEEE 802.15.4 CSMA	◐	◐	○	●	◷	◐	◷	◐	▼	▼	ϟ	ϟ	◐	▼	◐	○	◐	●	●	▼
	IEEE 802.11 TDMA	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	-	-	-	-	-	-	⚹	-	⚹	⚹	⚹	-
Wide-area Sensing	2G/3G	◐	◐	○	○	○	○	◷	◷	◐	◐	○	○	○	○	○	○	◐	◐	▼	▼
	4G	◐	◐	○	○	○	○	◷	◷	◐	◐	○	○	○	●	●	●	◐	○	○	○
	5G	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	●	●	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹
	VLBR WAN	●	●	○	●	◷	◷	◷	○	▼	▼	◐	◐	◐	▼	◷	○	○	◐	◐	○
Esoteric	Geostationary	◐	◐	○	○	○	○	○	○	○	○	○	○	○	◐	○	○	◐	○	○	◐
	Low-earth Orbit	◐	◐	○	○	○	○	○	○	○	◐	○	○	○	◐	◐	◐	◐	◐	○	◐
	Free-space Optics	◐	◐	◐	○	○	○	○	○	●	◐	○	○	○	●	○	○	◐	○	○	◐

Legend: ●: Technology fully supports problem domain, ◐: Supports problem domain with practicality, throughput, latency, reliability, or energy limitations ϟ: Energy requirements of assumed battery-powered devices prevent applicability, ◷: Latency prevents applicability, ▼: Throughput prevents applicability, ⚹: Emerging technology or evolution may support problem domain, ○: Not recommended, -: Not considered by authors.

Table 3. General Appropriateness for Industrial Wireless Applications

Application	*General Recommendation*
Factory and Building Monitoring, IIoT	Yes
Condition Alarming	Yes
Supervisory Control	Yes
Feedback Control Backup to Wired	Yes
Feedback Control Primary	Possible
Safety Monitoring and Alarming	Possible
Personnel Safety	Possible
Safety Integrated Systems	Possible