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Abstract

Industrial wireless is crucial for the vision of increased intelligence in industrial automation and enhanced connectivity in various industrial scenarios. Although general requirements are usually defined for deploying industrial wireless networks in various application classes, the process for individual deployments in specific industrial use cases cannot be directly deduced. It still requires the exact knowledge of the different industrial process data points and their parameters in order to specify the corresponding wireless technology and the deployed network specifics. In this work, we introduce an entity relationship diagram (ERD) for the mapping between individual wireless use cases, their operational environments, the various wireless technology limits, and the deployed wireless technology specifications including the network configuration, the deployed wireless nodes parameters, and the corresponding radio frequency (RF) setup. This ERD represents the initial step to understand the mapping between various industrial use cases and realistic deployed wireless networks, and build a corresponding database that can be helpful in facilitating the procedure for specifying new deployments of industrial wireless networks.

Keywords

Industrial wireless; Entity Relationship Diagram (ERD); deployed wireless network; operational environments; wireless aggressors; industrial wireless technologies.

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1. Introduction

Deployment of wireless communications networks in various diverse industrial use cases is essential to achieve the vision of smart manufacturing, flexible factories, and industry automation. A long list of requirements and features can be considered while designing and deploying an industrial wireless network including latency, reliability, scalability, range, payload size, update rate, operation and implementation cost, security, privacy, energy consumption, and system availability. Multiple reports and surveys have considered these requirements for industrial application classes such as [1] and the references therein. However, these general requirements can be only used on the early design phases to narrow down the set of candidate wireless technologies but cannot further help on the later phases of industrial wireless network deployment process.

A simple mapping from the industrial use case requirements to the achievable wireless technology limits can identify potential candidate technologies for various use case classes. However, in [2], it was shown that the mapping of technologies to the applications is not always unilateral and can be different for a specific application with respect to its unique requirements. Moreover, the achievable wireless technology limits are obtained under specific assumptions about the operational environment, the data statistical characteristics, the deployed network hardware, and other use case parameters. As a result, a better mapping from wireless technologies and the corresponding use case requirements should include various use case characterization factors that can impact the performance of a deployed wireless network.

The specific use case characteristics can have a crucial impact on the design and performance of deployed wireless networks. The use case characteristics include the data generation, the operational space, and the surrounding electromagnetic behavior. The data generation characteristics include the data features for various sensing and actuation points within the industrial operation. The operational space is the physical surroundings of the use case including their shapes, materials, and movements. The electromagnetic interference to a deployed industrial wireless network is emitted from other existing wireless networks and non-communications equipment that create electromagnetic signals. These factors impact the design and optimization of an industrial wireless network that is deployed in a specific use case [3].

A realistic mapping between use case features and a deployed industrial wireless network is necessary to facilitate the wireless adoption in industrial applications. A way to achieve this goal is to understand the connection between industrial use case features, various performance metrics of a deployed wireless network, and its deployment parameters. A step further is to find the practical industrial wireless technology limits that depend on the use case features. A database can be a helpful tool to achieve this goal where the defined relations are instantiated, and hence, the connections are built.

In this work, we start by demonstrating the need for a more individualized mapping between industrial wireless technologies and specific use cases. We then present an entity relationship diagram (ERD) to identify the needed connections between the use case, its various data points, its various characteristics domains, the industrial wireless technology limits, and the deployed wireless network setup. We further identify, through studying the literature, the list of defining features in each entity within the proposed ERD. This work presents the first step in building a database of deployed industrial wireless networks that can facilitate identifying the suitable candidate wireless technologies for individual use cases.

2. Related Work

In [1], the existing wireless user requirements stated by various industry organizations for the factory workcell with supporting rationale were analyzed. The report considered five application classes where their corresponding user requirements are considered. Practical user requirements are derived and rationalized in that report based on the existing use cases within each class. The considered factors are the end-to-end latency, reliability, scale, range, payload size and update rate. Although that work captures the practical user requirements, it captures them for the general application classes without the specific impacts of individual scenarios including the operational space, the diversity of existing data points, and the electromagnetic interference.

In [2], a broad view of the existing wireless internet of things (IoT) connectivity technologies was introduced where various wireless technologies and solutions were discussed. The focus was on the enabling features in wireless IoT for massive connectivity. In particular, the existing wireless IoT communications technologies were classified based on coverage range, reliability and latency. Further, a classification of IoT applications was considered in terms of various service requirements such that a suitable IoT connectivity option was outlined based on the application general characteristics.

In [4], a brief survey of existing IoT wireless technologies and applications was introduced including a set of industry-related application examples. The main focus of the survey is the related considerations for IoT solutions including distributed intelligence, low latency, high data quality, compatibility to existing networks, mobility, security, and privacy. It also discussed the system architecture needed to achieve the required levels of various considerations.

In [5], a general comprehensive survey was introduced on communications solutions for IoT applications which included industrial use cases as a segment of the survey. The main focus of the survey was the general applicability of 5G technology and beyond for wide range of the application domains. It offered a detailed discussion of wireless solution key performance indicators (KPIs) such as latency, reliability, survival time, service availability, energy efficiency, connection density, and data rate. It also discussed the various system components of the wireless technologies and their impact on various KPIs.

In [6], a generic framework was introduced to map the industrial wireless use cases to their various corresponding wireless network design elements. The main focus of this work is to classify the various industrial use case characteristics into three entities, namely, the operational technology (OT) domain, the information technology (IT) domain, and the connecting data services between these two domains. That work introduces an industrial wireless design framework generically by formalizing a unified process to evaluate design elements representing generic service requirements and available resources. However, that work does not introduce the practical usage of the framework for deploying industrial wireless networks.

In [7], a number of potential wireless technologies for industrial applications were discussed and their basic parameter values are briefed including their frequency band, maximum data rate, nominal and factory floor ranges, interference susceptibility, possible topologies, latency, cost, and energy consumption. On the other side of the mapping problem, seven classes of use cases are discussed where ranges of their basic requirements are stated. These requirements are cycle time, packet size, number of devices, simultaneity factor, and estimated data rate. The estimated values for these requirements are obtained from the 3GPP verticals analysis for 5G. That work further suggests potential wireless technologies based on those requirements and wireless technology parameters. However, it does not consider the specific impacts of individual scenarios.

Additionally, the practical deployment for various wireless technologies in some example use case is discussed in [3, 8–14]. Examples of the deployment of specific wireless technologies in specific use case were found in [8, 9]. The impacts of operational space and existing wireless networks in the use cases were considered and practical metrics such as the cost savings were studied. In [3, 10], general practical guidelines for industrial wireless network deployments are considered including frequency band specification, the ingress protection (IP) rating, the access point coverage range, security considerations, antenna type and placement, and environment characteristics considerations. In addition, the practical considerations of various wireless technologies and their applicable use cases are practically discussed in [11–14]. The practical considerations include battery life, security, scalability, interoperability, and time determinism.

3. Industrial Wireless Deployment

3.1. Problem Statement

The main problem in this work is to understand the realistic industrial wireless network deployment parameters and map them to individual use case descriptors, network performance metrics, and the various wireless technology performance limits. An overview of the problem is shown in Fig. 1. The targeted outcome is to facilitate the design and implementation of industrial wireless networks. The studied parameters include the transmit-receive parameters such as the transmission power, the modulation and coding scheme, the frequency band, the redundancy scheme, routing and scheduling protocols, and various

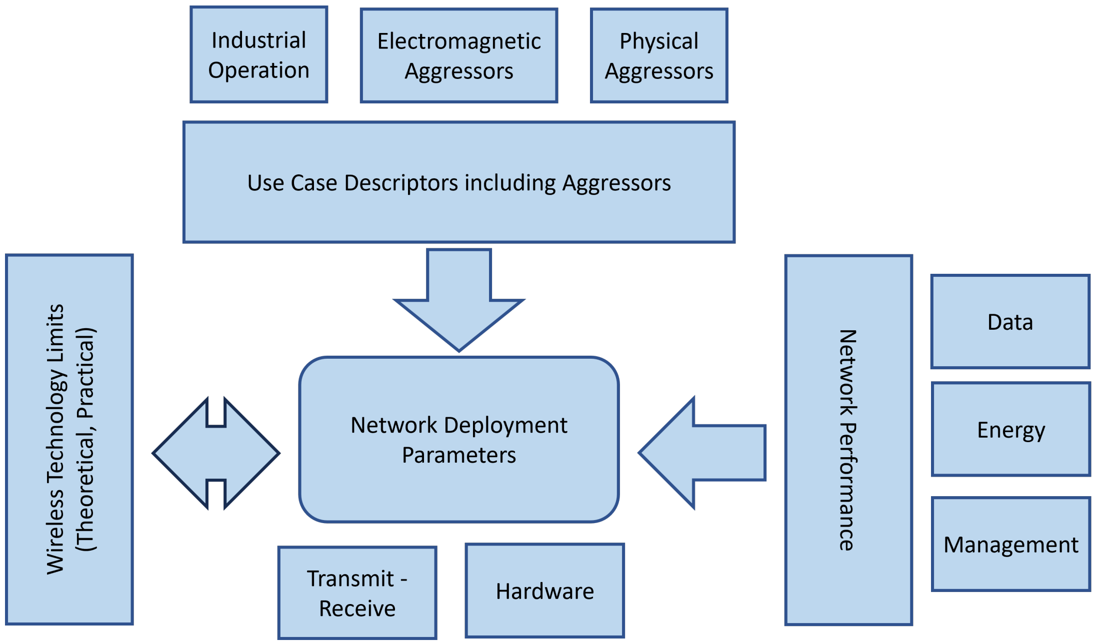

Fig. 1. An overview of the problem to understand the realistic industrial wireless network deployment parameters and map them to individual use case descriptors, network performance metrics, and the various wireless technology performance limits.

procedures at all network layers. Additionally, the hardware selection and setup are crucial for the network deployment including specific manufactured communication equipment, the antenna type and placement, and the interfaces to the industrial processes.

Three main industrial wireless deployment impacting categories are considered. First, the use case descriptors are the individual industrial application characteristics including its operational space. The use case characteristics include characterizing the various data points through the industrial environments. A data point is any entity that sends or receives data during the industrial operation. These data points are characterized by the statistical distribution of the corresponding data. The use case is also characterized by its physical environment including the shapes and material composition of the surrounding equipment, their movements, and the human activity within the environment. Finally, the use case is characterized by the nearby electromagnetic activity including all communications and non-communications emitters through the environment. The communications aggressors include all the coexisting wireless communications networks or any transmitter that emits electromagnetic signals with the purpose of data communications.

The second impacting category is the industrial network performance requirements which are defined by the quantitative requirements of the individual industrial network at the different networking layers. These quantitative values are derived from the industrial operation and its data characteristics. We consider three basic categories of performance metrics, namely, the data, energy, and management performance metrics. The corresponding suggested list of metrics will be stated later. Third, the achievable performance limits of various wireless technologies help in determining an initial set of candidate wireless technologies that satisfy the use case performance requirements. Additionally, the susceptibility of candidate wireless technologies to various types of electromagnetic interference can further narrow the pool of candidates based on the electromagnetic activity around the use case. Note that a double arrow exists by the network deployment parameters and the wireless technology limits in Fig. 1 because a feedback from a deployed industrial wireless network is helpful in determining the practical wireless technology limits in their corresponding use cases.

3.2. Developing an ERD

In order to benefit from the problem definition and utilize these connections between different blocks in Fig. 1, the described connections and blocks should be represented through a standardized and structured approach. Entity relationship models are generally built to organize the available information in a structured way and to define the relationships between various entities within the model. Entity relationship modeling is considered an initial step in database design by defining a generic data representation without taking into consideration the implementation constraints [15].

There are several entity relationship notations for representing data specifications, such as Chen's, Crow's Foot, Barker's, and Unified Modeling Language (UML) through class diagrams. Crow's foot notation is one of the most popular notations for relational database modeling. The most recognizable characteristic of this notation is the graphic symbols that mark the many-sided relationship. These graphic symbols look similar to a crow's foot, which got the notation its name [16].

In this notation, entities are represented with a rectangle and the entity's name is in the upper part of the rectangle. The attributes are listed in the rectangle, below the entity's name. The first of the attributes is the primary key. Entities are connected using relationships. The relationships can be one-sided and many-sided. The one-sided relationships show the minimum number of times that an entity can be connected to another entity which is zero or one. Those relationships are marked with a normal line that has a short vertical line near the entity. Many-sided relationships show the maximum number of times that an entity can be connected to another entity. Those relationships are marked with the the crow's foot symbol near the entity. The relationship can be optional, and it is then marked with a circle.

In Fig. 2, the industrial wireless network deployment ERD is shown when the various attributes are collapsed such that the entities' names are displayed by themselves. The starting point of the ERD is the industrial operation which defines the application-level related feature of the process at which the industrial wireless network is deployed. This industrial operation has to have at least one data point where the data is transferred through the network. However, a data point can be a measurement or control data point. Additionally, the industrial operation is performed with at least one operational space while it could have,

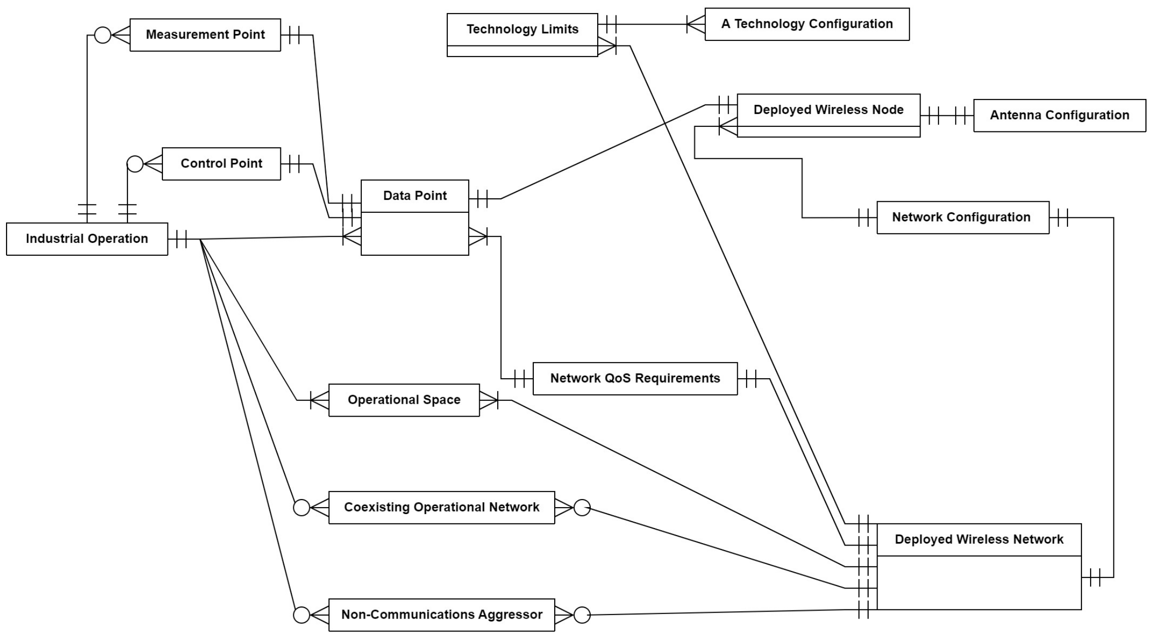

Fig. 2. The industrial wireless network deployment ERD when the various attributes are collapsed such that the entities' names are displayed by themselves.

or have not, electromagnetic interference sources originating from coexisting operational networks or non-communications aggressors.

Combining the characteristics of the various data points of an industrial operation leads to defining the industrial wireless network QoS requirements. The process of specifying and designing an industrial wireless network takes into consideration the network QoS requirements, the existing interference, the physical operational space, and the performance limits and configurations of various wireless technologies. Further, the details of a deployed industrial wireless network is determined including the various operational configurations and deployed wireless nodes' parameters.

3.3. Attributes of Various Entities for Industrial Wireless Deployments

In order to complete the ERD and make it ready to be deployed in building a relational database of deployed industrial wireless networks, a detailed list of attributes associated with all the entities is introduced in Fig. 3. This list includes all the related attributes but cannot be technology or use case specific in order to accommodate all industrial wireless deployments. Additionally, some of the attributes can be not applicable in some deployments and are not to be included.

Industrial Operation
- Brief Description
- Measured Quantities
- Number of nodes

Measurement Point
- Update Rate
- Measured Variable
- Variable Type
- Value Range

Control Point
- Control Cycle
- Manipulated Variable
- Variable Type
- Value Range

Data Point
- Transmission Cycle
- Message Type
- Message Format
- Message Range
- Message Length

Operational Space
- Brief Description
- The size of the space
- Clutter Density
- Clutter Height
- Blockage
- Mobility Speed
- Mobility Path

Coexisting Operational Network
- Wireless Protocol
- Location of Sources
- Frequency Bands / Channels
- Bandwidth
- Expected Transmission Duration
- Activity Duty Distribution
- Estimated Transmit Power
- Distance to the Protected Network

Non-Communications Aggressor
- Type of the Process
- Location of Sources
- Frequency Bands
- Bandwidth
- Expected Transmission Duration
- Activity Duty Distribution
- Estimated Transmit Power
- Distance to the Protected Network
- Modeling Approach

Network QoS Requirements
- Peak Data Rate
- Transmission Reliability
- Transmission Latency
- Transmission Jitter
- Security
- Energy Efficiency
- Clock Synchronization
- Network Formation Requirements
- Recovery Requirements
- Informational Characteristics

Technology Limits
- Peak Data Rate
- Transmission Reliability
- Transmission Latency
- Transmission Jitter
- Security
- Energy Efficiency
- Clock Synchronization
- Configuration Variables

A Technology Configuration
- Configuration Setting
- Peak Data Rate
- Transmission Reliability
- Transmission Latency
- Transmission Jitter
- Security
- Energy Efficiency
- Clock Synchronization

Deployed Wireless Network
- Service Provider
- Device Manufacturers
- Communications Standard
- Operating Frequency Range
- Expected Range

Network Configuration
- Physical Layer Parameters
- Multi-User Access
- Signaling and Coding Rate

Deployed Wireless Node
- Device Manufacturer
- Operating Frequency
- Channels Utilized
- Transmit Power
- Expected Range
- Expected Topology
- Communications Embedding
- Process Interface Type
- Power Supply
- Battery Maintenance Cycle

Antenna Configuration
- Height
- Embedding
- Type
- Placement

Fig. 3. The list of all the attributes associated to the various entities of the proposed ERD for industrial wireless network deployment.

4. Conclusions

In this work, we introduced an entity relationship model for industrial wireless deployments that maps industrial use cases, wireless technology performance limits, and the use case data requirements into the setup and configuration of the deployed industrial wireless network. The use case characteristics included its physical environment and the electromagnetic activity around the industrial use case. This work plays an important role in identifying the main characteristics to practically deploy industrial wireless. It also represents a first step in building a relational database that can facilitate and streamline the process of choosing a suitable wireless technology for an industrial use case. This process, additionally, includes the set up and configuration of the deployed wireless networks such as the hardware selection and setup, and the data transfer configuration parameters.

Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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