INVITED PAPER

Industrial Communication Systems and Their Future Challenges: Next-Generation Ethernet, IIoT, and 5G

This paper presents a comprehensive state of the art of industrial networks, and addresses new perspectives and trends for future directions of research.

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ABSTRACT | Industrial communication systems represent one of the most important innovations of the last decades in the context of factory and process automation systems. They are networks specifically designed to cope with the tight requirements of these challenging application fields such as real time, determinism, and reliability. Moreover, industrial networks are often deployed in environments characterized by strong electromagnetic interference, mechanical stress, critical temperature, and humidity. Over the last three decades, different classes of industrial networks have been developed according to changing requirements and available communication and information technologies. In this paper, we first provide an account of the state of the art, reviewing classical fieldbuses, real-time Ethernet networks, and industrial wireless networks, along with their most relevant features, applications, and performance figures. We introduce the complex standardization framework and analyze the market status and assumptions for future development. In the second part, we address the future perspectives focusing on new technologies, standards, and fields of application. In particular, we consider the time-sensitive networking (TSN) family of standards, Industrial Internet-of-Things (IIoT) systems, high-performance wireless LANs, industrial applications of cellular networks, and Ethernet networks for automotive communication.

KEYWORDS | Determinism; industrial communication systems; Industrial Internet of Things (IIoT); industrial wireless networks; real time; time-sensitive networking (TSN).

I. INTRODUCTION

The term “industrial communication systems” refers to networks typically adopted in factory automation, manufacturing, and process control to implement data exchange between controllers, sensors, actuators, input/output devices, and industrial equipment in general. There are three main types of industrial communication systems, namely, Fieldbuses [1], real-time Ethernet (RTE) [2], and wireless networks [3], which reflect the different phases of their evolution [4].

Industrial networks were first introduced in the early 1980s and, since then, their growth has been impressive in terms of performance and market share. Initially, conceived as mere replacements of point-to-point connections between controllers and sensors/actuators, characterized by limited performance, network size, and spatial extension, these networks rapidly became the backbones of factory automation and process control systems. Over the years, new protocols were designed taking into account novel concepts from the IT world, and performance was improved thanks to the technological progresses. The recent versions of industrial networks are able to ensure

Manuscript received November 11, 2018; revised March 29, 2019 and April 19, 2019; accepted April 22, 2019. Date of publication May 15, 2019; date of current version May 28, 2019. *(Corresponding author: Stefano Vitturi.)*

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Digital Object Identifier 10.1109/JPROC.2019.2913443

a fast and reliable connection of hundreds of nodes, with typical data rates around 100 Mb/s, over wide areas [5].

Today, at the beginning of the fourth industrial revolution, the role played by industrial networks is ever more crucial, since they are expected to satisfy new and more demanding requirements in possibly new operational contexts [6]. An important example in this respect is the widespread adoption of the Industrial Internet of Things (IIoT) that calls for worldwide reliable and fast connection of industrial equipment. Such a goal requires to ensure connectivity down to the most remote field devices by means of suitable communication systems and interfaces [7]. Collected data have to be stored and analyzed, possibly jointly by several distributed devices, for example, by adopting machine learning and data mining approaches. Automated or autonomous actions, too, may require the coordination of individual entities. Also, data sets have to be effectively accessed, ideally from anywhere, via several types of devices, such as Tablet PCs, smartphones, and personal computers [8], [9].

A further example of industrial networks' deployment, with completely different characteristics, is the massive adoption of Ethernet by automotive applications expected in the next years [10]. In this case, fast and precise (and low-cost) communication has to be provided in the spatially restricted in-car domain while possibly ensuring a stable connection to the Internet.

The purpose of this paper is to review industrial networks in factory and process automation and discuss current trends as well as future perspectives in this rapidly evolving scenario, including technological innovations, new fields of application, expected performance, and market trends. Industrial communication systems have been subjects of research and review for many decades. The key contributions of this paper are as follows:

1) a comprehensive overview of networks used in factory automation and process control systems;
2) an analysis of the market status and trends;
3) an assessment of future perspectives that includes next-generation Ethernet, 5G telecommunications, IIoT, software-defined networking (SDN), and networks for automotive applications.

This paper is organized as follows. Section II introduces some related work concerned with industrial communication systems. Section III presents the most important characteristics of industrial networks, such as configurations, typical traffic profiles, and performance requirements. This section also introduces the most meaningful performance indicators. Section IV describes the available industrial networks and explains how, and to which extent, they can meet the aforementioned requirements. This section gives an overview of the long standardization process ending up in the current situation. Section V focuses on future scenarios and investigates the envisaged new fields of applications and their requirements. Finally, Section VI concludes this paper.

II. RELATED WORK

Classical fieldbuses are reviewed in [1] and [11]. These papers provide a critical analysis of this kind of networks, including historical notes discussing the need for industrial communication, industrial traffic characteristics, features, and fields of application. A further contribution concerned with the general aspects of fieldbuses and their applications is [12].

RTE networks are reviewed in [2] and [13]. The author discusses the enhancements of traditional Ethernet networks necessary to achieve real-time performance and focuses on some of the most popular RTE networks, highlighting their most relevant features. Another survey is given in [14]. In this paper, the author takes into consideration the practical aspects concerned with the deployment of RTE networks and discusses some criteria to evaluate their performance. Jasperneite *et al.* [15] introduce a generic RTE system and describe its main building blocks, namely, topology-based addressing, optimized datagram transfer, and synchronous scheduling. RTE networks are also addressed in [16], which focuses on manufacturing control, diagnostics, and safety, and investigates the most suitable networks for such a kind of applications.

Review papers are also available for industrial wireless networks. Willig *et al.* [17] and Pellegrini *et al.* [18] discuss the most important issues concerned with the introduction of wireless systems in an industrial scenario. Willig [3] presents the selected topics of industrial wireless communication systems. One of them is industrial wireless sensor networks (WSNs) in process automation systems. The most important issues concerned with industrial WSNs have been specifically addressed in [19]. Wang and Jiang [20] address industrial wireless sensors and actuators networks and provide a comparison of some popular networks. A further contribution is given by Korber *et al.* [21], where they present a theoretical study of a wireless real-time system for remote sensor/actuator control in automation plants. In [22], a more comprehensive survey on wireless networks for industrial monitoring and control is presented, while Park *et al.* [23] specifically focus on the design of distributed control systems based on wireless networks.

Wireless networks can also be adopted to implement wireless extensions of industrial wired networks. A survey on these hybrid systems when deployed for industrial applications is reported in [24], while Seno *et al.* [25] investigate various protocol architectures for the wireless extension of Ethernet Powerlink [26] based on the IEEE 802.11 Wireless LAN. A prototype implementation of such a hybrid system is then described in [27]. Other examples of hybrid systems are provided in [28]–[30], where the authors address the wireless extension of the widespread Profibus fieldbus.

A major issue in both the theoretical analysis and the development of industrial networks has been the assessment of their real-time performance as this is an essential property to meet the applications' needs. Tovar and Vasques [31] present a theoretical analysis of the Profibus

MAC layer protocol to assess the actual capability of handling real-time traffic. A similar topic is addressed in [32], where the authors describe a schedulability analysis of the real-time traffic for the WorlFIP fieldbus. Cena and Valenzano [33], [34] address controller area network (CAN) and propose some protocol modifications to improve real-time performance, maintaining compatibility with conventional CAN devices. Tian [35] presents the design and implementation concepts of a distributed measurement system based on fieldbus communication.

Prytz [36] presents a performance comparison, based on a theoretical model, of two popular RTE networks, namely, Profinet and EtherCAT. A performance analysis of Ethernet Powerlink based on numerical simulations is proposed in [37]. A schedulability analysis of the Profinet messages under tight temporal constraints is provided in [38], while Schlesinger *et al.* [39] propose, for the same network, a technique based on message packing to improve the scheduling. Lee *et al.* [40] refer to a generic multilayer RTE network architecture and present a worst case communication delay analysis. Mifdaoui *et al.* [41] focus on RTE networks deployed for military applications and provide a performance analysis of master–slave protocol architectures.

The IEEE 802.11 wireless LAN has been often considered in the context of factory automation systems. Notably, the recently published IEC 62948 International Standard [42], referred to as WIA-FA, is based on such a network. A description of WIA-FA along with some significant examples of applications is provided in [43]. The design of a networked control system based on the IEEE 802.11 WLAN is discussed in [44]. The authors consider two different practical implementations: the first one is based on a pure 802.11 MAC, with some modified parameters with respect to the default values, whereas the second one relies on a cooperative protocol implemented on top of IEEE 802.11. Wei *et al.* [45] propose RT-WiFi, a protocol based on a time-division multiple access (TDMA) technique. RT-WiFi, which is logically placed on top of the legacy IEEE 802.11 MAC layer protocol, allows standard WiFi devices to achieve real-time performance and maintains compatibility with the existing commercial products. On the same line, a new isochronous MAC protocol is presented in [46]. A preliminary performance analysis of such protocol showed that, in combination with a traffic scheduler, it is able to satisfy soft real-time constraints. The improvement of the IEEE 802.11 performance is pursued also in [47]. The authors focus on multirate support, a feature explicitly mentioned by the standard, and propose some rate adaptation algorithms specifically conceived for industrial real-time communication.

Moving to industrial WSNs, Petersen and Carlsen [48] provide a comparative performance analysis of two of the most representative standard networks of this type, namely, WirelessHART and ISA 100.11a. WirelessHART is also addressed by Jin *et al.* [49]. They focus on the coexistence among multiple networks and propose two innovative algorithms located at different levels. The first one, which operates at the network management level, has been designed to optimize the channel assignment to the different networks and is able to increase the overall reliability. The second algorithm, adopted at the low communication level, is concerned with the data flow scheduling and allows to improve the timeliness of the whole system. Iqbal *et al.* [50] describe an application of indoor monitoring of machinery and factories. In particular, they propose both a new cooperative scheme and a MAC layer protocol for WSNs that allow to improve the quality of the monitoring application as well as to reduce the energy consumption. Another MAC layer protocol for industrial WSNs is presented in [51]. Such a protocol introduces a priority mechanism to enhance the capabilities of nodes to timely transmit critical messages. A prototype implementation has been carried out on commercial devices based on the IEEE 802.15.4 wireless personal area network (WPAN). The same network has been addressed by Vitturi *et al.* [52], where they describe the design and implementation of an industrial application-layer protocol that relies on the standard IEEE 802.15.4 MAC layer.

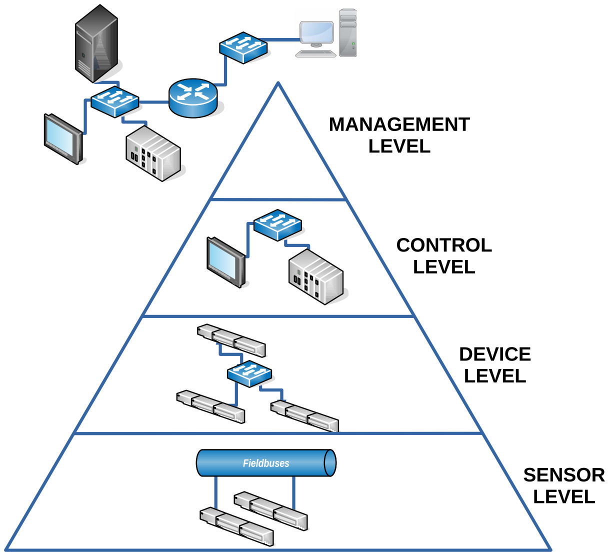

Fig. 1. *Traditional structure of factory automation systems.*

III. CONFIGURATIONS, REQUIREMENTS, AND PERFORMANCE INDICATORS

Industrial networks have typical configurations, types of traffic, and performance requirements that make them distinct and different from the traditional communication systems, usually adopted by general-purpose applications.

A. Configurations and Topologies

Configurations and topologies of industrial networks are functional to the applications they have to serve. In this respect, the main distinction can be made between factory automation and process automation systems.

The traditional structure of factory automation systems is reported in Fig. 1. At the lower levels, industrial

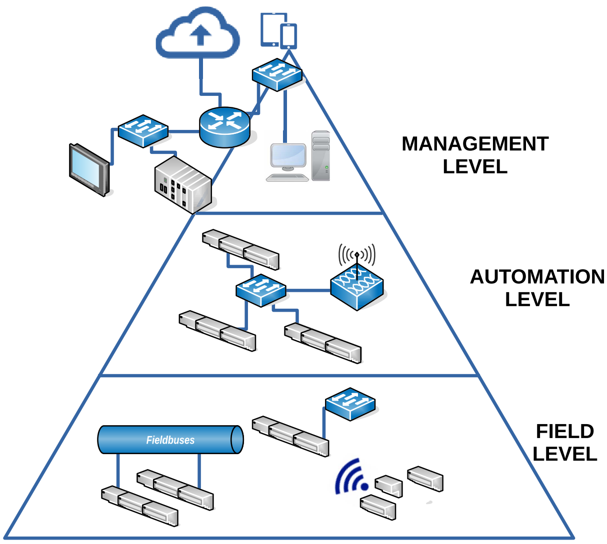

Fig. 2. ***Present structure of factory automation systems.***

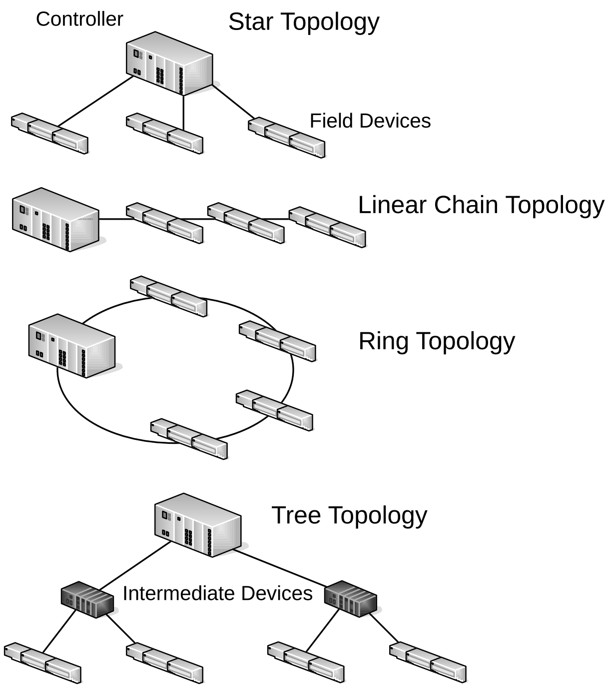

Fig. 3. ***Typical topologies of industrial communication networks.***

networks have to connect a few simple nodes such as sensors and actuators to a controller, usually a programmable logic controller (PLC), a personal computer, or an embedded microcontroller. Typical applications at this level may involve machines (e.g., robots) that perform discrete actions, for example, assembly processes for car production, consumer products, and electronics. At the upper layers, industrial networks connect "intelligent devices" that implement control functions and can be used as intermediate devices toward the management level. Over the years, the structure evolved, as shown in Fig. 2, where industrial networks are ever more deployed with an increased number of nodes and more complex configurations [4], [53], [54].

The adopted topologies, as shown in Fig. 3, may be of various types, such as the popular "star" or "ring" (physical as well as logical), or more specific ones such as "linear" topologies. These latter ones are widespread in the context of networked electrical drives. In these applications, several drives are connected in a daisy chain to a controller which implements the automation tasks [55]–[57]. At the higher levels of factory automation systems, traditional topologies are used, where industrial nodes are connected to either backbone, such as factory Intranets or the Internet.

Process automation systems are typically based on a structure that comprises more levels, as shown in Fig. 4 [58]. These systems are usually adopted by continuous industrial processes such as oil and gas distribution, electric power generation and management, chemical processing, and glass and mineral treating [59]–[61], to mention some. They comprise many nodes, logically positioned at various hierarchical levels and distributed over wide geographical areas. Such features reflect on the networks deployed, which are often based on "tree" "star" and "mesh" topologies. At the lower level, industrial networks are deployed to convey the data flows of process field devices such as instruments and sensors/actuators, to/from concentrator nodes, whereas, at the upper levels, industrial networks are used to connect concentrators and coordinators, up to the management level.

B. Industrial Traffic

The industrial traffic is of two types, namely, cyclic and acyclic. Both types can be originated by various sources, with possibly different timing requirements [62], [63].

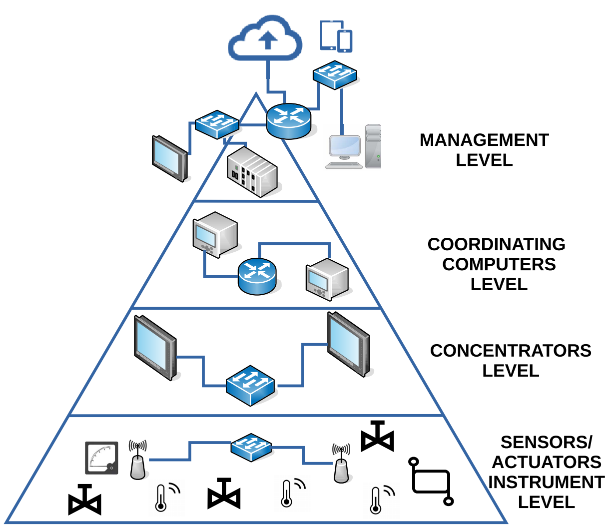

Fig. 4. ***Structure of process automation systems.***

In factory automation systems, at the time in which industrial networks started to be deployed, the cyclic traffic was that generated by the fast data exchange between controllers and field devices. Typical examples are the periodic transfer of sensing values, measurements, and set points. The amounts of data involved in this communication are rather low, usually a few bytes, even if they often have to be exchanged with tight timing. As an example, the velocity control loop of an electrical drive implemented via a networked control system may require the delivery of the set point (which typically comprises 2 bytes) with a period of some hundreds of microseconds [55], [64]. The industrial acyclic traffic is triggered by unpredictable events, such as process alarms. Also, in this case, limited data amounts are transferred, but possibly subjected to severe deadlines.

The aforementioned two types of traffic are typical of the process automation systems as well. However, in such systems, the timing requirements are more relaxed. Indeed, usually, applications have sampling periods of variables that may be in the order of hundreds of ms and alarm notification deadlines in the same order of magnitude [20].

In the late 1990s, multimedia applications have started to be introduced in the industrial scenario. These are, for example, the transfer of images related to defect inspection systems [65], distributed smart cameras systems [66], and intrusion control. Video streaming is another interesting industrial multimedia application [67], [68]. In this context, data may be generated by video compressors at a variable rate and have to be transmitted with low latency over industrial networks.

The type of traffic generated by these applications can be either cyclic or acyclic and may imply the transfer of frames with higher payloads. This reflects on the throughput, which may increase considerably. Moreover, this traffic may be subjected to real-time constraints [69].

A further type of industrial traffic is the nonreal-time traffic generated by the transmission of network maintenance and diagnostic data, which may take place either locally (for example, within a plant or specific equipment), or remotely, for example, toward Internet connections.

C. Requirements and Performance Indicators

Industrial networks have been designed to satisfy the requirements that derive from their heterogeneous fields of applications. The most important ones have been timeliness, reliability, and flexibility [1], [12], [14]. In recent years, openness and security have become of paramount importance [70].

The term timeliness refers to the capability of a network to cope with specific timing constraints. In the context of industrial communication, timeliness is often characterized by determinism and real time [71]. Determinism accounts for the ability to carry out a specific action at a precise instant. Examples are the periodic transmission of a message from a sensor carrying a measurement value or the delivery of a set-point value from a controller. Real-time refers to the ability of a station to correctly deliver a message within a specified deadline. Reliability is another important aspect of industrial scenarios. Industrial networks have also to be flexible to cope with the ever more increasing needs of fast plant reconfiguration and reassembly. Openness and security are more recent requirements. Indeed, modern industrial networks have to ensure the seamless remote access to segments, or even single nodes, located up to the lowest levels of factory and process automation systems. This is, nowadays, feasible via the Internet: industrial automation devices (e.g., programmable controllers or even simpler components such as sensors/actuators) may be equipped with Web server modules. In these new scenarios, security issues have to be addressed. Also, the classical countermeasures against threats adopted by general-purpose networks (e.g., the use of firewalls, cryptography techniques, and intrusion detection systems) might negatively impact the performance of industrial networks. Hence, their possible adoption is not straightforward and has to be investigated [70].

Performance indicators of industrial networks are mostly different from those adopted by general-purpose networks, due to the diverse fields of applications. Typical indexes considered by the later ones, such as data rate, are only of secondary importance for industrial networks.

Some relevant performance indicators have been introduced by the IEC 61784 International Standard [72]. The most meaningful are as follows:

1) delivery time;
2) throughput RT[1];
3) non-RT bandwidth.

The delivery time is defined by IEC 61784, as the "time necessary to convey a service data unit (i.e., the payload of a message containing real-time data) from one source node to a destination node of an industrial network." The measurement is taken at the application-layer interface and hence includes the time necessary to execute the whole protocol stack of the two nodes. The throughput RT is "the number of octets per second transmitted on a specific link of an industrial network exclusively relevant to application-layer (real-time) traffic." Both these indicators allow to assess the actual real-time capabilities of a network. The non-RT bandwidth is the percentage of network bandwidth that can be used, on a specific link, for nonreal-time traffic. This is an indicator which is useful to evaluate the potential degree of openness, since, for example, the traffic to the Internet is typically nonreal time, as discussed in Section III-A.

Other performance indicators have been introduced in [73] and [74]. They are: 1) minimum cycle time (MCT) and 2) jitter.

[1]The IEC 61784 Standard uses the acronym "RTE," with evident reference to RTE networks. In this paper, however, we use "RT," since we will consider such performance indicator also for different networks.

The MCT is an indicator of networks based on a cycle, in which a controller periodically exchanges data with field devices. MCT is defined as the minimum time necessary to execute a cycle. In a network in which a master device periodically polls a set of slaves, the MCT is expressed as

$$\mathrm{MCT} = \sum_{i=1}^{N} T_{P_i} \tag{1}$$

where T_{P_i} is the time necessary to poll the ith slave and N is the number of slaves.

Jitter is an indicator for the precision in performing periodic operations. Let P be the nominal period of a specific operation and P' the period with which such an operation is actually carried out, and then, the jitter (expressed as a percentage) is defined as

$$J = \frac{|P - P'|}{P} \times 100. \tag{2}$$

Delivery time, throughput RT, and non-RT bandwidth together with MCT and Jitter represent a set of indicators suitable to describe the performance of all the industrial networks, as will be discussed later on.

IV. TODAY'S INDUSTRIAL NETWORKS

A. Fieldbuses

Fieldbuses were the first kind of industrial networks. They are communication systems able to connect up to several tens of nodes deployed in the most common topologies, typically at the lowest levels of factory and process automation systems. Representative examples of fieldbus networks are Profibus, WorldFIP, Interbus, ControlNet, Foundation Fieldbus, CANopen, and DeviceNet. Nowadays, fieldbuses are still widespread, even if some of the networks that appeared on the market over the years are no longer supported (e.g., WorldFIP and Interbus) [75].

The performance achievable by these networks clearly depends on several aspects such as number of nodes, configurations, data rate, and so on. In general, delivery time and MCT may be as low as some milliseconds and jitter around some percents [76], [77].

The standardization of fieldbuses underwent a long and partly contentious process [78], which eventually ended with the publication of the IEC 61158 International Standard [79]. IEC 61158 represents a collection of communication profile families (CPFs), each of them including some communication profiles (CPs), which refers to different and well established commercial protocols. Neither DeviceNet nor CANopen is encompassed by IEC 61158 even though they are two widespread fieldbuses. These two networks rely on the popular CAN [80] and are characterized by diverse application-layer protocols. CAN, originally conceived for automotive applications, turned out to be applicable for the industrial scenario as well thanks to its features that allow to achieve a very good performance. DeviceNet and CANopen are defined, respectively, by IEC 62026–3 [81] and EN 50325–4 [82].

B. Real-Time Ethernet Networks

RTE networks started to be deployed in the early 2000s. These networks represent the natural evolution of fieldbuses, since they allow to achieve a better performance to address more challenging applications.

The reference standard for RTE networks is the IEC 61784 part 2 [72], which extends the CPs introduced by IEC 61158 to networks based on Ethernet. Similar to the fieldbus standard, IEC 61784 introduces several CPs which reflect commercial products. Some popular examples are EtherCAT [83], Profinet [84], Ethernet/IP [85], Ethernet Powerlink [26], and Modbus TCP [86].

Most RTE networks have been designed to ensure coexistence between real-time traffic and general-purpose traffic. This is achieved by protocols that allow to implement the separation between these two types of traffic. Such a kind of structure allows to fulfill the severe timing requirements of real-time traffic but cannot ensure complete compatibility with conventional Ethernet devices. A technique often used to achieve traffic separation is TDMA. Protocols based on such a technique are placed on top of the standard Ethernet MAC layer to schedule the access to the physical medium. The network operation is based on a cycle. The cycle is split into two sections, each one reserved to a specific type of traffic. In the real-time section, which usually takes place at the beginning of the cycle, the stations access the network in time slots assigned to them. Conversely, in the nonreal-time section, the access is typically granted on a random basis. Clearly, a design is necessary to avoid that the transmission of nonreal-time frames exceeds the duration of its section and, hence, delays the scheduled beginning of a new cycle.

The TDMA approach is used by Ethernet Powerlink, the isochronous version of Profinet (called Profinet IRT) and EtherCAT. Both Ethernet Powerlink and Profinet IRT use a TDMA protocol with different strategies to implement an effective traffic separation. Ethernet Powerlink is based on a centralized approach with a master device, the Managing Node, which triggers the different phases within the network cycle via broadcast messages delivered to all the other nodes. In Profinet IRT, the devices are kept synchronized through the exchange of specific synchronization frames. All the devices are aware of the time phases within a cycle and can consequently schedule their transmissions. The MAC layer of EtherCAT is based on a master–slave protocol. Slaves are arranged in a physical ring and exchange real-time data with the master by modifying "on-the-fly" the fields of a frame (the EtherCAT telegram) periodically issued by the master. Nonreal-time traffic takes place via specific structures, namely, mailboxes, which can be inserted within an EtherCAT telegram, implementing an effective traffic separation.

A further technique to achieve traffic separation consists in the use of different frame priorities. The RTE protocols assign to the real-time frames, higher priorities than those of the nonreal-time ones. This is typically done in agreement with the IEEE 802.1D Standard [87]. This technique is adopted by Ethernet/IP. Such a network is based on an application-layer protocol called Common Industrial Protocol (CIP), in which real-time functions and services are mapped on the User Datagram Protocol (UDP) at the transport layer, whereas the nonreal-time traffic takes place via the TCP protocol. In this way, the two types of traffic can coexist, provided that the CIP protocol ensures the correct prioritization.

RTE networks and fieldbuses constitute a collection of different technological solutions. From a user perspective, this situation has always been unsatisfactory [78], [88], [89]. After the protracted disputes about the IEC fieldbus standard [90], [91], there had been hope for a truly unified Ethernet-based solution. Unfortunately, market pressure led to a repetition of the unfortunate fieldbus standardization process with the publication and subsequent adoption of a multiface RTE standard, without any serious attempt to establish a unified solution [79], [92]. Furthermore, as discussed earlier, although several RTE networks are standardized by IEC, some of them are no longer compatible with the IEEE 802.3 Ethernet specification.

The performance figures achievable by RTE networks are remarkable. Indeed, the most powerful configurations are able to reach MCTs and delivery times as low as hundreds of microseconds with jitters well below 1%. Throughput of RT traffic is limited to some hundreds of kilobytes per second, leaving sufficient bandwidth for non-RT traffic [36], [73], [93].

Several other examples of RTE networks could be presented. The interested reader can refer to the literature (see [6], [15], [39], [40], [92], and the references therein).

C. Wireless Networks

Wireless networking is the latest technology introduced in the context of industrial communication. Wireless interfaces are appealing since they allow to reduce the cabling and to connect devices that cannot be reached via a wired connection, such as nodes mounted on mobile equipment. The reduction of cabling is also a commercial advantage for practical applications [17], [18]. Unfortunately, the intrinsic uncertainty of the wireless medium results in nonnegligible packet error rates and may introduce random delays in the packet delivery, which have a negative impact on timeliness and reliability [94], [95].

The adoption of wireless networks in the industrial scenario has stimulated various types of research aimed at: 1) evaluating the performance of the available wireless systems in industrial environments and 2) designing new protocols and techniques suitable for this challenging field of application. Examples are provided in [45] and [96]–[98].

Several studies focused on the IEEE 802.11 Wireless LAN family, since the high capacity of these networks makes them ideal for industrial automation applications. They were concerned with specific aspects, such as the definition of new techniques to timely access the physical medium [45], [97], the execution of experimental tests in industrial environments [67], [99], [100], the analysis of the IEEE 802.11n amendment for industrial applications [101], and the adoption of specific rate adaptation techniques [102].

A further wireless network of interest for the industrial scenario is the IEEE 802.15.4 Wireless PAN [103]. The actual real-time capabilities of IEEE 802.15.4 have been addressed by several analyses. Examples are provided in [104] and [105]. Moreover, the IEEE 802.15.4 standard has been adopted by ZigBee [106], a network mostly deployed in building automation but also used in process automation systems [107].

The IEEE 802.15.4 standard has been enhanced by the release of an amendment, namely, IEEE 802.15.4e [108], which introduces five different MAC behavior modes. Among them, time-slotted channel hopping (TSCH), deterministic and synchronous multichannel extension (DSME), and low-latency deterministic network (LLDN) have features that make them suitable for industrial communication and improve the performance of the original standard [109].

In the TSCH behavior mode, nodes are synchronized by the transmission of beacon frames that originate from the PAN coordinator, the node that coordinates network operation, and are propagated by other nodes. Data exchange takes place via structures called slotframes constituted by a sequence of time slots, which may be either reserved or shared. Each time slot is sized to ensure the transmission of a data frame as well as to receive the relevant acknowledgment. The use of reserved slots allows to avoid frame collisions and to achieve deterministic communication. TSCH allows to use several types of configurations, such as tree, star, and mesh. Moreover, the multichannel capability increases its throughput, since a node may transmit (or receive) contemporaneously on different channels, whereas the channel hopping feature ensures a good immunity against in-band interference [110].

In the DSME behavior mode, communication takes place via superframes. The PAN coordinator uses beacons to define a cycle, in which several superframes are transmitted, possibly by other local coordinators, resulting in a multisuperframe structure. Each superframe contains both a contention-free period (CFP) and a contention access period (CAP). The CFP period contains guaranteed time slots (GTSs) that can be profitably used for deterministic communication, whereas the CAP period is reserved for asynchronous traffic. DSE is particularly suitable for multihop and mesh networks. Moreover, it allows multichannel communication by means of two distinct channel diversity strategies.

The LLDN mode is based on a configuration in which nodes are connected to the PAN coordinator. One single superframe (called low-latency superframe) is transmitted periodically by the PAN coordinator. The superframe starts with a beacon and some management time slots. Then, it is followed by two sets of time slots for data exchanging: one for uplink transmission (from nodes to the PAN coordinator) and the other for bidirectional transmission. The typical configuration of LLDN is a star, and the transmission channel is unique and selected by the PAN coordinator. Simultaneous transmissions, however, as suggested by the standard, can be achieved by equipping the PAN coordinator with multiple transceivers [109]. Another strategy to achieve multichannel communication is proposed in [111].

Also, Bluetooth has been investigated in the context of factory automation applications. The physical layer of this network has been adopted by the Wireless Interface for Sensors and Actuators (WISA), an industrial network specifically conceived for the wireless connections between sensors and actuators in factory automation systems [112]. A basic WISA system, called cell, comprises one master [WISA base station (BS)] and up to 120 slave devices. The network operation is based on a cycle in which the BS polls the slaves. Although the transmission rate is limited to 1 Mb/s, the high efficiency of the WISA protocol, as well as the frequency-division multiplexing (FDM) technique employed at the data link layer, allows to achieve a good performance. Indeed, the WISA MCT is 2 ms, whereas the maximum delivery time of an acyclic frame is 15 ms [113]. Moreover, the WISA physical layer adopts a frequency hopping technique that ensures good immunity against in-band interference. WISA BSs have been designed to be connected to wired industrial networks, such as fieldbuses and RTE networks. This allows to implement hybrid wired/wireless configurations in which WISA cells are wireless extensions of wired industrial networks [30].

Wireless networks have also become popular in process automation systems. This is due to the fact that such plants, as discussed in Section III, usually connect nodes distributed over wide areas. The deployment of wired networks in this scenario would have required cumbersome and expensive cabling. Thus, Industrial Wireless Sensor and Actuator Networks (IWSANs) [21], [114] have been introduced, derived from an extension of traditional WSNs [115] to the industrial field of application. The most important IWSANs are WirelessHART [49], [116], ISA 100.11a [117], and WIA-PA [118]. All these networks are International Standards based on the physical layer of IEEE 802.15.4, whereas, at the data link layer, they introduce modifications to improve performance, such as frequency hopping.

From an architectural point of view, the individual IWSAN Standards comprise similar types of devices, deployed at the different levels of process automation systems shown in Fig. 4 [48], [119]. At the lowest level, the field devices implement the interfaces with the plant. Field devices may have routing capabilities or are simply local data collectors. At the upper levels, intermediate/concentrator devices are employed. All the networks have gateway devices that implement the interface between the IWSAN and the plant network(s) located at the management level. The data link layer protocols of IWSANs are based on superframes. These are collections of time slots periodically repeated on the network. Data transmissions take place exclusively during time slots that are either dedicated or shared. Dedicated time slots are used to grant nodes with timely access to the network and hence to transmit messages in a deterministic way. Conversely, shared slots are open to all nodes (or to sets of nodes), which typically use a carrier-sense multiple access (CSMA) technique to gain channel access. With such a technique, determinism cannot be achieved due to possible contentions/collisions among nodes and the random backoff scheme usually adopted to schedule retransmission attempts. Time slots have a fixed duration in WirelessHART networks (10 ms), a configurable duration in ISA 100.11a (either 10 or 12 ms), and a flexible duration in WIA-PA (configured by the network manager node). Due to the need for selecting communication paths among the network nodes for the transmitted frames, IWSANs must have routing functionality. Both WirelessHART and ISA 100.11a use similar routing strategies based on three different policies referred to as graph, superframe, and source routing [120], [121]. Conversely, WIA-PA adopts a static routing handled by the network manager node [122].

IWSANs have been extensively addressed in the literature. The interested reader can refer, for example, to [123]–[128].

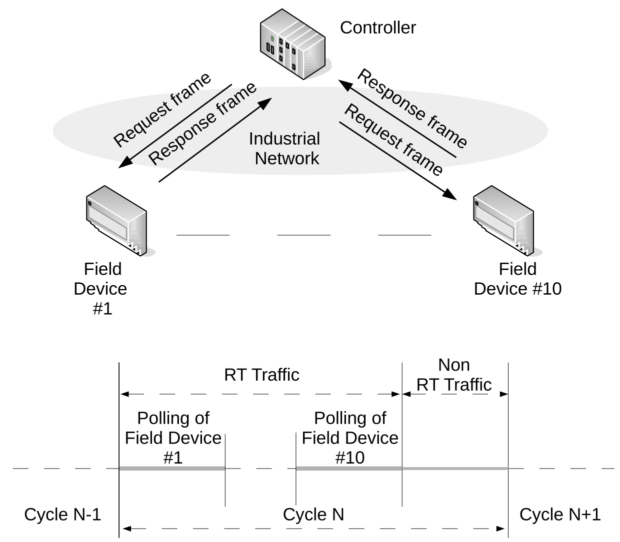

Fig. 5. ***Prototype network setup and operation.***

D. Example of Industrial Network Performance

In order to provide an evaluation of the performance of industrial networks discussed so far, we consider a prototype network that comprises one controller and ten field devices directly connected.

Table 1 Prototype Network Parameters

Parameter	Fieldbus	RTE	Wireless
Transmission speed	1 Mbit/s	100 Mbit/s	54 Mbit/s
Frame Overhead	64 bits	160 bits	270 bits
Total Nr. of I/O bytes	20	20	20
Cycle Time	5 ms	5 ms	5 ms
Stack processing time	100 μs	100 μs	100 μs

The network operation relies on a cycle. Within a cycle, the controller polls the field devices in sequence. Each polling operation starts with a request frame carrying the output data, sent from the controller to a specific field device, and is followed by a response frame carrying the input data, from the addressed field device to the controller. The period of the cyclic operations is set to a fixed value. The proposed one is a good representative of networks deployed at the lowest levels of factory automation systems where limited amounts of data are exchanged between controllers and sensors/actuators. Particularly, it resembles the widespread one-level configuration addressed in [40].

We implement the prototype network using the three different types of industrial networks discussed so far, namely, fieldbuses, RTE, and wireless networks, using the parameters reported in Table 1, which have been selected to reflect those typical of practical applications.

The transmission speed for fieldbuses has been set to 1 Mb/s since it well represents the speeds available for such kind of networks (for example, 1 Mb/s is the maximum rate of CAN as well as one of the available rates of WorldFIP, whereas several Profibus networks work at 1.5 Mb/s). Also, the frame overhead specified for fieldbuses in Table 1 is indicative, since it varies from network to network (for example, the overhead of CAN is 43 bits, whereas the overhead of Profibus is 76 bits). Differently, the overheads specified for RTE and wireless networks exactly reflect those of Ethernet and IEEE 802.11g, respectively. The stack processing time is another indicative value taken from some practical experiments [129]. This value is necessary to calculate the delivery time since such an indicator is measured at the application-layer boundary, and hence, it has to comprise the time necessary to elaborate the whole protocol stack in both the involved devices. Finally, both the number of exchanged I/O bytes (10 input bytes and 10 output bytes) and the cycle time have been selected in agreement with practical applications [38], [130], [131].

Table 2 reports the values of the performance indicators calculated for the prototype network. They have been evaluated under ideal conditions, meaning that data exchange has been supposed to take place successfully without additional delays and packet losses. The MCT has been calculated at the MAC layer boundary, reflecting practical situations in which I/O bytes to be exchanged on the network are available on buffers at the MAC layer. The throughput RT has been calculated as the ratio between the total number of bytes exchanged on a controller-field device link and the MCT. This represents the maximum value achievable by the throughput RT for the specified number of I/O bytes exchanged on the link.

The non-RT bandwidth is expressed as the percentage of bandwidth that can be used for nonreal-time traffic. It has been determined, assuming that the available time interval represented by the difference between the cycle time duration and the MCT can be fully employed for non-RT traffic. In Table 2, the non-RT bandwidth has not been specified for fieldbuses, since such networks do not handle nonreal-time traffic.

E. Market Status and Trends

Several market analyses have been carrying out over the years in the context of industrial networks. They show two well-established products, namely, fieldbuses and RTE, whereas wireless networks represent promising solutions progressively gaining market shares.

According to the analysis reported in [132], the market share of fieldbuses in 2018 was 42%, with an annual growth rate of 6%. The adoption of this kind of networks in the future is expected to be slowly decreasing even if they still represent effective options, particularly in contexts with strong security issues. Indeed, although fieldbuses are not intrinsically secure (they do not implement any specific security features such as authentication and encryption), fieldbus devices are not directly connected to the Internet, which makes them less subject to remote attacks.

RTE networks are expected to be ever more deployed in the next years, driven by the growth of IIoT systems characterized by the need of high performance. RTE new installations have overcome those of fieldbuses in 2018, with a 52% market share. The analysis in [133] reveals an estimated market value of more than \$69 billion in 2023 (it was \$27.23 billion in 2017), with a compound annual growth rate (CAGR) of 16.8%. Moving to industrial wireless communications, the data provided in [132] refers to networks for factory automation. The market share in 2018 is 6%, with an annual growth of 32%. Concerning IWSANs, the analyses reported in [134] and [135] envisage a growth at a CAGR of 12.7%, reaching the global amount of about \$1.2 billion in 2022.

Table 3 summarizes the market data provided in [132]. The column “Growth” reports the increase of the share with respect to the analysis carried out in 2017.

Table 2 Performance Indicators for the Prototype Network

Performance Indicator	Fieldbus	RTE	Wireless
Minimum Cycle Time	4.48 ms	0.11 ms	2.20 ms
Delivery Time	424 μs	205.1 μs	310 μs
Throughput RT	44.6 kB/s	1785.7 kB/s	90.1 kB/s
Non RT Bandwidth	N/A	97.7%	56%

Table 3 Market Status for Industrial Networks According to [132]

Network Type	Share	Growth	Dominant products
Fieldbuses	42%	6%	Profibus (12%), Modbus RTU (6%), CC–Link (6%)
RTE Networks	52%	22%	Ethernet/IP (15%), Profinet (12%), EtherCAT (7%)
Wireless Networks	6%	32%	WLAN (4%) Bluetooth (1%)

V. FUTURE PERSPECTIVES

As discussed in the previous sections, the adoption of industrial networks is expected to increase considerably in the next years. Industry 4.0 and IIoT, or Industrial Internet, will impact on the automation layers in which industrial networks are used. New technology trends will facilitate this development. In the following of this paper, we address some of the most promising research activities and their fields of application.

A. Time-Sensitive Networking

Time-sensitive networking (TSN) is a recent Ethernet standardization initiative and a possible remedy for the scattered RTE scene. Its central goal is to evolve standard Ethernet further and to equip it with native real-time capabilities. Notably, it originated not in the automation domain but in the field of consumer electronics. As early as 2004, an IEEE 802.3 Residential Ethernet Study Group was established with the goal to evaluate the need for Ethernet specifications dedicated to residential, i.e., home entertainment applications. Major contributors were companies such as Broadcom, Nortel, Pioneer, Samsung, NEC, or Gibson Guitar. In 2005, this activity was merged with the IEEE 802.1 Audio Video Bridging Task Group (AVB). The focus of this group was to make Ethernet ready to support audio and video streaming for professional applications. The most important improvement of AVB over standard Ethernet is the ability to guarantee upper delay bounds to all data streams and priorities [136]. Still, there were limitations: the use of a nonpreemptive scheduler did not improve the worst case latency compared with classical IEEE 802.3, and the specified maximum number of seven hops in a line topology effectively made reasonably sized networks impossible.

After adoption of the AVB standard in 2012, it became clear that applications were not only limited to audio or video transmission but also to factory automation and process control [137]. Therefore, the task group was renamed to TSN to better reflect an enlarged scope. The focus of TSN today is to improve real-time capabilities and reliability of standard Ethernet. With a view to industrial automation, it aims at addressing some shortcomings of AVB in order to provide: 1) further reduced latencies and more accurate determinism; 2) independence of physical data transmission rates; 3) native support for higher security and safety; 4) fault tolerance without the need for additional hardware; and 5) interoperability of solutions from different vendors, which is particularly important in an industrial automation context.

The TSN initiative is not one single standard document. Rather, TSN is a kind of toolbox for IEEE 802 networks. About 60 individual IEEE standards are within the scope of TSN, including 13 standards that relate to security. All of them provide enhancements for standard Ethernet mostly on ISO/OSI layer 2. Typical methods are time slot and traffic shaping mechanisms, such as the time-aware traffic shaperİ (IEEE802.1Qbv) to prioritize transmission queues in order to guarantee data rates and latencies. The most crucial element in TSN, from a network structure point of view, is the network switch that has to support the traffic management strategies.

Standardization of TSN is still in progress, but first preliminary implementations in industrial automation, automotive communication, and entertainment solutions already show its feasibility and a higher determinism compared with the state-of-the-art components. The TSN toolbox does not only allow for more flexibility but also requires higher configuration efforts to coordinate all mechanisms for optimal operation of the network. As an example, Steiner *et al.* [138] review the IEEE TSN standards, in particular 802.1Qbv, to illustrate a reference model for traffic planning for time-sensitive communication.

The time-based transmission selection and clock synchronization mechanism defined in the TSN enable the real-time transmission of frames based on a global schedule configured through so-called gate control lists (GCLs). An approach based on a mixture of priority-based scheduling and the time-triggered (TT) concept to enhance the solution space for the GCLs is presented in [139]. The authors analyze the latency bounds for the critical traffic in the TSN network using network calculus, an analysis of the worst case delays that individual critical flows can experience along the hops from sender to receiver(s). Moreover, a validation of the model and analysis by performing experiments on both synthetic and real-world use-cases have been carried out.

Alongside this approach, some studies focus on avoiding that high priority traffic can create problems for other classes: some studies ignored lower priority real-time traffic, such as AVB, resulting in TT configurations that may increase the worst case delays of AVB traffic. Gavrilut *et al.* [140] propose a joint routing and scheduling approach for TT traffic taking into account the AVB traffic such that both TT and the AVB traffic are schedulable. The approach has been evaluated on a number of synthetic and realistic test cases.

Another important research field concerns the feasibility of an extension of the TSN approach to wireless networks. A first roadmap toward this goal is proposed in [141], which identifies five different steps: wireless configuration of wired TSN, hybrid wired-wireless time synchronization, wireless TSN scheduling, wireless redundancy for wired TSN, and wireless TSN switch deployment. While the work in [141] focuses mostly on the challenges in implementing TSN over wireless, regardless of the adopted wireless technology, two main directions are emerging in this latter topic. The first one suggests to use IEEE 802.11 as a candidate technology to extend TSN over wireless, building on the fact that both TSN and IEEE 802.11 are standardized by IEEE. A prototype implementation of the IEEE 802.1AS Precision Time Protocol on IEEE 802.11 has already been carried out [142]. Cavalcanti *et al.* [143] provide a detailed description of the challenges in implementing TSN functionalities over IEEE 802.11 and highlight the opportunities offered by the most recent amendments to this standard, in particular IEEE 802.1ax, toward this goal. The second direction to implement TSN functionalities on wireless systems suggests to build on the ultrareliable and low-latency communication (URLLC) offered by the fifth generation, 5G, of cellular networks. The work in [144] provides a survey of the standards concerned with IEEE TSN and with those of the Internet Engineering Task Force (IETF) Deterministic Networks (detenet) Group. The paper also surveys the studies that specifically target the support of ultralow latency in 5G networks, with the main categories of fronthaul, backhaul, and network management. A preliminary integration of TSN functionalities is considered in the next release of 5G by 3GPP (release 16), targeted by the end of 2019 [145].

Still, it must not be overlooked that Ethernet, IEEE 802.11, and URLLC are only one part of the communication system (the low layers). Equally important is how data are represented and transferred. This is beyond the pure communication protocols and used to be highly vendor-specific. In the recent past, however, Open Platform Communication Unified Architecture (OPC UA) has established itself as a vendor-independent and versatile middleware solution to exchange data within and between automation systems [146].

Furthermore, the OPC Foundation has recently released Part 14 of the OPC UA standard, which introduces a CP based on a publisher–subscriber paradigm [147]. Such a profile appears particularly suitable to tackle the communication requirements of the lower automation layers. Thus, together with TSN as underlying communication infrastructure, OPC UA could become the unified approach to industrial communication that has been sought for the last four decades [148].

B. Next-Generation Industrial Wireless Networks

The available industrial wireless networks for factory automation allow to achieve, at best, soft real-time performance [43], [45], [100]. This prevents their deployment in the most demanding application environments such as motion control and mobile coordinated robotics, to mention some. There are, however, research activities focusing on the design of new industrial wireless systems, able to achieve the performance of the wired counterpart, e.g., RTE networks. These are based on two different approaches.

The first one relies on the definition of a new protocol stack, particularly at both the physical and MAC layers, as described in [149]. In detail, the proposed physical layer is derived from that of IEEE 802.11 in which the header is shortened and some parameters are optimized to achieve low orthogonal frequency-division multiplexing (OFDM) symbol transmission times and to limit the overall number of transmitted OFDM symbols. Clearly, with such a solution, there is no compatibility with legacy IEEE 802.11 systems. Concerning the MAC layer, techniques, such as TDMA and frequency-division multiple access (FDMA), are proposed, since they ensure ordered access to the physical medium. The preliminary tests on a prototype system have been carried out and showed promising results. Indeed, performance figures comparable with those of EtherCAT have been obtained.

The second approach is based on full-duplex (FD) wireless networks. The key feature of such networks is the ability of a node to simultaneously transmit and receive frames [150]. This could be particularly advantageous in industrial wireless systems, since it could improve packet delivery times as well as reliability. A very preliminary analysis on FD industrial wireless systems is provided in [151].

C. Networks and Technologies for IIoT

The IoT is the interconnection of intelligent devices, equipment, management platforms, and so on that, with little to no human intervention, facilitates a smart, connected world. The applications span from wellness and health monitoring to smart utilities and from integrated logistics to autonomous drones, to mention only some. While the IoT is concerned with "things" of any type, the IIoT restricts the "things" to the industrial scenario [152]–[154].

The industrial networks addressed in this paper are good candidates to implement various communication architectures in the IIoT context. Classical fieldbuses, however, cannot be directly included in IIoT systems, since their features (mainly the physical medium they use and the medium access protocols) are not compatible with those of the Internet and their performance is not sufficient for transporting Internet packets. Particularly, these networks do not support IPv6, which is at the basis of IIoT. Nonetheless, interconnection may be achieved via gateway devices [131], [155]. Conversely, RTE networks are definitely suitable for IIoT. Indeed, most of the available RTE networks natively ensure TCP/IP connectivity down to the field devices, because they were designed to combine real-time traffic with nonreal-time IP-based traffic. This feature clearly paves the way to the inclusion of such devices in IIoT systems.

As stressed in [7] and [9], IIoT strongly relies on the availability of wireless connections. The connectivity of the industrial wireless networks has diverse aspects. The IEEE 802.11 WLAN, similar to RTE networks, usually ensures a direct Internet connection via the TCP/IP stack. Industrial WSNs can be considered, actually, "IIoT ready" [156], [157] even if at different levels. A good example in this direction can be seen considering WirelessHART and ISA100.11a networks: both these networks are based on a modified version of the IEEE802.15.4 physical and MAC layers. However, while WirelessHART devices, to reach the Internet, need gateways connected to a HART-over-IP backbone, the protocol stack of ISA100.11a has a network layer based on 6LoWPAN and a transport layer based on UDP [158], which make single field devices directly accessible via the Internet. Such an approach is also adopted in more recent technologies where the IPv6 protocol is being increasingly integrated [159], [160].

The introduction of industrial networks in IIoT systems is rather challenging. Indeed, applications often have diverse and stringent quality-of-service (QoS) requirements in terms of configurations, robustness, reliability, latency, determinism, energy efficiency, battery lifetimes, and security that may be difficult to satisfy [161]–[163]. Research is reported on the suitability and achievable performance figures of industrial networks in this new application scenario [164]–[166].

A novel type of wireless networks currently considered for the IIoT is the low-power wide-area networks (LPWANs) [167]. These networks have been originally conceived for applications such as smart metering [168], remote monitoring, and smart cities [169], possibly over wide geographic areas, thanks to their features such as robust communication, wide coverage ranges, and low power consumption. Such features fit well with applications that may be included in IIoT systems such as indoor industrial monitoring [50] and intrusion detection [170]. Several LPWAN standards are already available, and they are supported by umbrella organizations as well as commercial companies providing technical support and products. The most popular are NB-IoT, SigFox, Ingenu Weightless, and LoRaWAN.

The suitability of LPWANs for IIoT systems, however, has not been adequately addressed yet, and research is still needed. Particularly, depending on the target applications, features, such as reliability, delivery times, determinism, and energy consumption, should be investigated [171], [172]. An important aspect is the behavior of the wireless channel, since it strongly influences the performance of the networks. Unfortunately, most of the analyses carried out so far are concerned with channels for general-purpose communications. Industrial channel features have been only rarely addressed, even if interesting studies on this subject are reported in [95] and [173].

Some analyses regarding the introduction of LPWANs in IIoT systems were started in [174]. Petäjäjärvi *et al.* [175] refer to indoor LoRaWAN applications, whereas, in [176], the adoption of LoRaWAN in the industrial scenario is specifically addressed by means of a realistic simulation model that includes the wireless channel behavior. Nevertheless, the actual Internet capability of LPWANs is still an open issue. For example, the simplest LoRaWAN nodes (called end devices) do not have Internet connectivity. As a consequence, the implementation of the IPv6 stack on such nodes could represent a challenging future activity, as envisaged in [177].

D. 5G Cellular Networks

Cellular networks are also increasingly considered for industrial applications, and especially, the upcoming 5G standard is expected to take a fundamental step in this direction, as discussed in [178], which addresses the deployment of 5G for some time-critical applications such as factory automation systems. The possibility of adding machine-to-machine traffic to human-generated traffic in cellular networks has started to be considered with 4G networks [179], but the 5G is the first cellular standard that explicitly targets industrial use cases. Recently, the 5G Alliance for Connected Industries and Automation (5G-ACIA), including automation industries, telecom operators, and telecom vendors, has published a white paper that addresses use cases and requirements of industrial applications deployed over 5G [180]. The first 5G release, particularly the URLLC, already contains specific features at both the radio interface and the network architecture to enable shorter latency and higher reliability [181], [182], aiming at supporting critical industrial applications whose performance requirements are beyond current 4G deployments.

An interesting application field of 5G is the IIoT, as extensively discussed in [183]. Also, in [184], a communication framework based on 5G is presented to support the deployment of cyber-physical IoT systems with a central controller: multiple sensors and actuators can establish communication links with the central controller in FD mode. Moreover, a comparison with the well-known existing solutions is performed to demonstrate the performance of the proposed one. Finally, Navarro-Ortiz *et al.* [185] propose a strategy to integrate LoRaWAN with 4G/5G mobile networks.

From a technical viewpoint, the potential of 5G networks in industrial automation scenarios is clear: apart from high bandwidth, there will also be strict determinism allowing for synchronized monitoring of processes and coordinated execution of actions. The support of mobile devices far beyond the shop floor boundaries is another advantage. There are, however, also open questions. The most intricate one is of organizational and strategic nature: 5G networks will be operated by telecom providers, and it is by no means clear why the owner of an industrial plant should put the operation of the control network—after all a critical infrastructure—in the hands of a third party. Answers to this question such as suitable operator models are still missing.

E. Software-Defined Networking

SDN [186] is a paradigm based on a clear separation between the control logic of a network and the devices that physically handle the traffic, e.g., switches. SDN introduces the control plane that handles the whole logic of a network and the data plane that handles the actual transmission of user data. The interface between the two planes is achieved by means of an application programming interface (API), called Southbound API, whereas the applications may access the control plane via the Northbound API. The control plane is handled by the SDN controller, which determines the network logic on the basis of the status of the data plane, achieved via the Southbound API, and the requests of the network applications, forwarded via the northbound API. In this way, SDN allows to program the network behavior and, hence, to achieve greater flexibility and lower complexity with respect to the traditional approach.

The introduction of SDN in the industrial communication scenario looks appealing thanks to the benefits it can bring and, hence, may represent an important innovation in this context. In particular, the envisaged high flexibility is one of the key features to ensure fast and dynamic reconfiguration of production lines, as necessary in modern factories. Also, the SDN paradigm may allow to simultaneously handle separate network infrastructures, with different performance requirements, in a centralized and more effective way. Other potential benefits of the centralized approach of SDN are the improvement of both security and reliability.

The study of industrial SDN systems is at the very beginning, and several issues have to be addressed. The most significant are as follows:

1) the design of the control logic suitable for industrial applications;
2) the design of the network devices deployed at the data plane;
3) the definition of the APIs at both the north and south bounds;
4) the performance evaluation of industrial SDN systems.

Henneke *et al.* [187] propose a preliminary analysis that evaluates the impact of the introduction of SDN in the industrial scenario as well as the challenges it poses. Guck *et al.* [188] propose two models based on network calculus to compute the communication delays, which are used by the SDN controller at the control plane, together with other information about the network, to implement the control logic. In [189], a dynamic traffic engine called DTE-SDN is introduced to implement efficient scheduling of delay-sensitive messages. DTE-SDN realizes a sort of feedback algorithm that, based on the information retrieved from the data plane about the status of the network, defines a scheduling scheme that outperforms the most common scheduling algorithms, as demonstrated by the simulation analyses. The impact of SDN on the security of industrial networks is addressed in [190]. The authors investigate the adoption of active switches at the data plane implementing native security functionalities. This allows the dynamic reconfiguration of security policies from the control plane. A prototype of the system has been developed using commercial off-the-shelf components that showed the feasibility and effectiveness of the proposed solution. Finally, Bello *et al.* [191] propose an SDN algorithm to effectively handle node mobility in industrial WSNs.

F. Networks for Automotive Applications

Automotive communication is a special application field somewhat different from that of networks for factory automation and process control. While some performance requirements are similar (e.g., real time and determinism), other characteristics make automotive communication a distinct application domain. This applies, for example, to cabling and topologies that have to fit with the reduced spaces and the presence of strong electromagnetic interferences typical for in-vehicle environments [192]. The continuously increasing complexity of vehicles reflects on their electrical and electronic components such as sensors, actuators, electronic control units (ECU), as well as on the networks that connect them. Also, new generation (possibly autonomous) vehicles have a plethora of new systems (e.g., pedestrian detection, collision avoidance, cruise control, driver assistance, and so on) that need to communicate among each other in a safe and fast way. As a result, the traditional communication solutions, such as those represented by CAN [80] and FlexRay, are becoming unable to satisfy the new requirements and need to be replaced [193].

In this scenario, the deployment of Ethernet networks may become ubiquitous. Ethernet represents the natural solution thanks to the high bandwidth it ensures as well as to the widespread availability of components, technologies, and knowledge. Unfortunately, the legacy version of Ethernet is not able to cope with the aforementioned requirements, which prevented its adoption so far.

TT Ethernet (TTE) may represent an interesting and viable solution, in which it is able to ensure deterministic and hard real-time performance. Indeed, data transmission in TTE is handled on the basis of a global time, and communication activities are controlled by the progression of time, so that each node is able to send messages with predefined periods and phases. TTE services have been already standardized by the Society of Automotive Engineers (SAE) [194].

A further, more recent, opportunity is the aforementioned TSN. This family of standards, actually, fits very well with the new requirements of automotive communications. Synchronization, traffic scheduling, and redundancy, the new features introduced by IEEE 802.1, appear which is able to address the communication needs of future automotive systems [195].

VI. CONCLUSION

In this paper, we provided a review of industrial communication networks which addressed the state of the art and outlined the most interesting future perspectives.

Several activities have been carried out over the years, including research studies, theoretical analyses, experimental sessions, and standardization efforts. These activities have contributed to the widespread adoption of industrial networks.

Most of the future perspectives are oriented to the expansion toward new fields of applications, as well as to the adoption of new, better performing, networks within already consolidated technological contexts, and to the design of new standards and technologies. Outstanding examples in this respect are the introduction of industrial networks in IIoT systems, the design of new generation industrial wireless networks, SDN, and the massive adoption of Ethernet for in-vehicle communication envisaged in the automotive world. The TSN set of standards will likely play a key role in most of these contexts.

Due to the application-driven characteristics of this research, the collaboration between academia, public research institutions, and industrial world is encouraged.

Industrial communication systems, in the next years, will be characterized by a considerable growth in terms of research activities, practical applications, and installations. ■

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