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*Perspective*

# Wireless Technologies for Industry 4.0 Applications

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**Abstract:** Wireless technologies are increasingly used in industrial applications. These technologies reduce cabling, which is costly and troublesome, and introduce several benefits for their application in terms of flexibility to modify the layout of the nodes and scaling of the number of connected devices. They may also introduce new functionalities since they ease the connections to mobile devices or parts. Although they have some drawbacks, they are increasingly accepted in industrial applications, especially for monitoring and supervision tasks. Recently, they are starting to be accepted even for time-critical tasks, for example, in closed-loop control systems involving slow dynamic processes. However, wireless technologies have been evolving very quickly during the last few years, since several relevant technologies are available in the market. For this reason, it may become difficult to select the best alternative. This perspective article intends to guide application designers to choose the most appropriate technology in each case. For this purpose, this article discusses the most relevant wireless technologies in the industry and shows different examples of applications.

**Keywords:** industrial Internet of Things (IIoT); wireless control systems; wireless sensor networks (WSNs); Industry 4.0; cyber–physical systems (CPS)

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## 1. Introduction

The fourth industrial revolution, commonly known as Industry 4.0, introduces new concepts that enforce connectivity, such as cyber–physical systems (CPS), the Internet of Things (IoT), and wireless sensor networks (WSNs) [1]. These concepts are aimed to improve productivity and efficiency in manufacturing processes by connecting sensors, actuators, and controllers, boosting the economy as a result [2,3]. Communication technologies are becoming key enablers in smart manufacturing processes since they ease integration between cyber–physical production systems (CPPS), which are at the core of Industry 4.0. In this scenario, communication technologies are evolving quite rapidly to be able to satisfy the quality-of-service (QoS) needs of modern applications. These technologies are typically used in industrial applications for diverse tasks that involve monitoring, predictive maintenance, supervision, and control operations.

Currently, wired solutions prevail in industrial domains. This is mainly because several standards have reached a high degree of maturity. Some of them are based on industrial Ethernet standards, such as Profinet, Ethernet/IP, or EtherCAT. In fact, it is still common to find even older digital buses in use, such as Profibus, CANbus, or Modbus. These mature technologies are frequently considered safe and reliable, which are key issues in some conservative industrial domains [4]. Wired technologies will clearly remain in use in the future, especially in critical operations, such as closed-loop control over fast dynamic processes. However, wired solutions have several drawbacks: Cabling is expensive and difficult to deploy, it produces not very flexible layouts, and it is complex to use with mobile devices or parts. Unfortunately, these drawbacks introduce some limitations in applications using wired solutions.

In this scenario, wireless technologies enhance the interconnection capabilities at smart factories, thus allowing fully intelligent manufacturing systems [5,6]. Their use may achieve several benefits: (1) introducing higher flexibility to modify the layout of the links, which eases the deployment of the nodes and improves scalability; (2) enhancing the connectivity between decision-taking nodes and mobile devices or parts; and (3) eliminating wires, which reduces the deployment cost. Wireless technologies are becoming key enablers in different domains of the industry and, consequently, becoming increasingly relevant in academia. In fact, during the last few years, their use has remarkably grown in industrial environments. This trend is expected to follow during the next several years. A case in point is the estimated number of connected devices worldwide in 2021, which was around 11.3 billion. This number is expected to reach 29.4 billion devices by 2030 [7].

However, wireless technologies have also some drawbacks that reduce their predictability and augment their error rate. The nature of wave propagation may cause diverse phenomena that reduce the quality of service (QoS) of wireless applications. The most relevant of these are fading, multipath propagation, shadowing, and interferences [8]. These phenomena have an impact on the reliability, integrity, and security of communication links when compared with wired communications. As a result, the bit-error rate increases, which may cause uncertainty in the applications.

The introduction of wireless technologies in industrial facilities must face additional challenges. On the one hand, many industrial applications require deterministic communication links in order to be accepted. Certain QoS parameters, such as the latency, jitter, and error rate, must be bounded. On the other hand, they must operate in environments full of metallic surfaces that may hinder wave propagation. This fact may cause difficulties given the strict requirements in critical applications.

Currently, wireless technologies are frequently accepted in the industry for non-critical applications, i.e., those that involve monitoring, alerting, or data-logging tasks. In these cases, application failures do not have severe safety implications or do not produce large economic losses. However, the use of these technologies in critical applications is still under scrutiny. In fact, this is an interesting research topic that involves the mitigation of the influence of interferences, some of them caused by different technologies, handling the frequency spectrum adequately, and resolving collisions.

To date, no wireless technology has been developed to be valid for all applications. On the contrary, different protocols were created over the years aiming to address specific scenarios. Currently, several WSN standards are available. Some of them are general-purpose standards that are being applied in industrial applications. Others have been specifically designed for industrial applications by adapting standards such as IEEE 802.15.1 [9] and, predominantly, IEEE 802.15.4 [10]. In fact, these standards have become the basis of many wireless technologies used at industrial factories for process automation. Thus, IEEE 802.15.4 is the foundational stone for some standards such as ZigBee, WirelessHART, ISA100.11a, or WIA-PA, whereas IEEE 802.15.1 is the base technology of WISA and WSAN-FA. All these technologies can coexist in the spectrum space but cannot be easily interconnected, so the problem of heterogeneity still persists. Moreover, most of these technologies, e.g., conventional WiFi, operate at the industrial, scientific, and medical (ISM) radio bands, in particular at the 2.4 GHz band, which may become saturated. Thus, interferences among different technologies are difficult to avoid.

This perspective article aims to present an overview of the most relevant technologies currently found in industrial WSN systems. It recaps the major characteristic of each technology, discusses their application domains, and shows some implementation examples. Thus, the authors intend to clarify the potential use of WSN technologies in industrial scenarios and guide application designers to select the most appropriate technology in each case. The layout of this brief perspective article is as follows: Section 2 presents a short overview of different IWSN technologies, including some implementation examples and domains. Finally, Section 3 draws some conclusions.

## 2. State of the Art

Industrial applications can be divided into six different classes depending on their requirements. Table 1 shows the classification proposed by the ISA100 committee [11]. These classes range from critical safety and control applications, which must satisfy very strict requirements in terms of latency, reliability, timing, and jitter, to monitoring applications, in which failures have a limited impact. Table 1 also includes the typical accepted values for latency and packet loss probability [12], as well as some application examples. The most critical class involves safety applications, with strict requirements in terms of determinism, reliability, and data integrity. In these applications, latencies may reach values of up to 10 ms. Closed-loop regulatory control applications also have strong requirements, and the accepted latency values depend on the controlled process dynamics. Classes 2 to 5 have more relaxed requirements, due to their non-critical nature. Currently, wireless technologies are frequently accepted in non-critical operations, which typically involve monitoring, alerting, supervisory control, and data-logging tasks. In those applications, failures do not produce severe consequences or economic losses. Thus, the most problematic applications for wireless technologies involve feedback control and safety operations [4]. Wireless technologies are starting to be accepted in some closed-loop operations, notably in slow dynamics plants, in which the QoS provided by the WSN is able to ensure the required rate. Some application examples may be found in chemical, pulp and paper, or oil and gas industries [13]. These domains are especially suitable for wireless technologies due to the large areas covered, and the difficulties, costs, and safety problems that wiring may introduce.

**Table 1.** Classes of industrial process automation applications.

| Category | Class | Application | Latency | Packet Loss Probability | Description |
|---|---|---|---|---|---|
| Safety | 0 | Emergency action<br>Emergency shutdown<br>Automatic fire control<br>Leak detection | 10 ms deterministic | $<10^{-7}$ | Always critical |
| Control | 1 | Closed-loop regulatory control<br>Direct control of actuators<br>Automated shutdown | 10 ms to 100 ms based on application | $<10^{-7}$ | Often critical |
| | 2 | Closed-loop supervisory control<br>Optimizing control loops | | $<10^{-6}$ | Usually non-critical |
| | 3 | Open-loop control<br>Operator performs manual adjustments | | $<10^{-6}$ | Human in the loop |
| Monitoring | 4 | Alerting<br>Event-based maintenance<br>Vibration monitoring<br>Temperature monitoring | 100 ms average | $<10^{-5}$ | Necessary maintenance;<br>Short-term operational consequences |
| | 5 | Logging and downloading/uploading<br>History collection<br>Sequence-of-events<br>Preventive maintenance records | | $<10^{-5}$ | Preventive maintenance;<br>No immediate consequences |

### *2.1. WiFi*

WiFi, the IEEE 802.11 standard, has come a long way since it was originally defined in 1997. There have been several reviews improving its behavior. IEEE 802.11b was the first version massively adopted, after polishing the details of previous versions. Since then, WiFi has become a very common wireless technology in general-purpose systems. However, some characteristics of the standard, mainly the non-determinism caused by the MAC policies, make it not suitable for some industrial applications. Often, WiFi has been used as a gateway between wired or wireless LANs, and the Internet in industrial automation [14]. Initially, WiFi was deployed over the 2.4 GHz ISM band. More recently, the 5 GHz band has been included. This approach may reduce interference problems between WiFi and other technologies that employ the overpopulated 2.4 GHz band. One of the disadvantages of WiFi, when compared to other wireless technologies, is power consumption. As a result, WiFi devices provide a shorter battery life than other technologies.

The IEEE 802.11ax standard, commercially known as WiFi6, increments the scalability of the nodes connected to one access point. The use of some technologies, e.g., orthogonal frequency-division multiple access (OFDMA), multiple-user multiple-input multiple-output (MU-MIMO), or spatial frequency reuse, may help to deploy a high density of nodes avoiding collisions. WiFi6 claims a latency of 10 ms, which may be adequate for some industrial applications. WiFi6 may reach a data rate of up to 9.6 Gbps. This data rate can only be compared with the latest technologies, such as 5G networks.

WiFi HaLow, or WiFi 802.11ah, follows a different approach. This technology seeks to adapt WiFi to the requirements of IoT systems. The coverage range is increased to around 1 km [15], the power for transmission is reduced, making it more suitable for battery-powered devices, and it is less affected by physical obstacles [16]. This is because it uses sub-GHz frequencies. However, WiFi HaLow presents some drawbacks: the data rate is lower than conventional WiFi, and it is not able to solve the problems of determinism and latency of WiFi.

Since WiFi is widely spread, there have been interesting initiatives to develop WSN systems with real-time requirements. For example, Banz et al. (2020) [17] presented some amendments in the data link layer to allow control applications that require a data sample of up to 1 kHz. The authors tested their approach with a balancing robot as hardware in the loop. In [18], a similar approach was used. In this case, a sampling rate of 1 kHz was required by using advanced control techniques over a real Segway-type balancing robot. In the near future, the introduction of new technologies, such as WiFi6, may become a real alternative for time-critical control applications in industries. There are several monitoring and supervision use cases in the literature. For example, in [19], a scalable IoT architecture was presented based on the edge–fog–cloud paradigm for monitoring the Indoor Environmental Quality (IEQ) combining the use of MQTT over WiFi. The authors of [20] implemented a WiFi HaLow network-based information system for scenario-specific multi-sided applications for the coordination, documentation, and surveillance of rescue forces in mass casualty incidents.

### *2.2. ZigBee*

ZigBee is a technology based on the IEEE 802.15.4 standard, which is used for low-energy communications with a low transmission rate [21]. It was developed in 2004 by the ZigBee Alliance, now inside the Connectivity Standards Alliance (CSA). IEEE 802.15.4 defines the physical and MAC layers, whereas the network and application layers are defined by the Alliance. It supports star, tree, and mesh topologies. The mesh topology tends to be the most used since the availability of redundant paths improves reliability. The star topology, on the other hand, reduces the latency and is the most adequate for achieving tight industrial requirements. ZigBee is conformed by three types of devices:

- One coordinator per network that initializes, maintains, and manages the network;
- Routers, which can find paths for the messages from one node to another;
- End devices, which are normally battery-powered. They collect and transmit data from sensors and may sleep and wake up to extend their battery life.

ZigBee implements self-healing mechanisms in case of lost or changed status of node links. However, it does not implement any system to replace the coordinator in case of failure, with this node thus becoming a single-point failure [22]. In theory, ZigBee supports up to 65,000 nodes per network, but frequently, this number is more limited. The maximum distance between devices can reach 50 m. However, larger distances may be covered by hopping between the nodes.

ZigBee has become a widely used technology in several domains, such as home automation. The major reason behind its popularity is its low cost. In fact, it is an open standard protocol without licensing fees for manufacturers. However, ZigBee is less capable of meeting the industrial requirements of deterministic latency and reliability. That makes ZigBee adequate for less critical tasks, such as monitoring and data acquisition, and, therefore, less suitable for security tasks. An important characteristic of ZigBee is that supports 868 MHz and 915 MHz radio bands, in addition to the 2.4 GHz band; therefore, it can help to avoid using the saturated 2.4 GHz band. This characteristic is important since ZigBee is a low-energy technology, and consequently, it is more influenced by networks such as WiFi.

Common applications of ZigBee networks involve monitoring and data acquisition tasks. For example, in [23], the authors used a ZigBee network to monitor an industrial motor and predict maintenance needs using fuzzy logic. In [24], artificial intelligence was combined with a ZigBee network to reduce costs and energy consumption in a warehouse. There are efforts to implement control tasks using ZigBee networks, but they need to find a solution in case of Qby oS degradation. This question has been tackled in different ways. For example, in [25], a two-level control scheme was presented. The highest level executes sophisticated algorithms, and in case of QoS degradation, the control tasks are shifted to edge devices with lower computing resources. This approach, tested over a robotic arm, avoids the system from becoming uncontrolled. This article proposes the use of the 900 MHz radio band to avoid collisions between the ZigBee and 2.4 GH WiFi technologies. In [26], authors proposed a redundant wireless network based on ZigBee and WiFi to make the ship course-keeping control with a robust PID. Their approach adds compensation control of time delay and packet loss. Other attempts try to achieve higher determinism. For example, in [27], time-division multiple access (TDMA) policies were implemented according to a static schedule. They were applied in a high-precision, micro-positioning application with a piezoelectric actuator (PEA).

An alternative to ZigBee is Z-Wave. This technology is similar to ZigBee. However, Z-Wave is a proprietary technology, provided by Silicon Labs. Although ZigBee is more common in industrial applications, the main advantages of Z-Wave result from its proprietary nature. The compatibility between devices is guaranteed. Z-Wave also provides better security mechanisms [28]. An example of Z-Wave use can be observed in [29], where a Z-Wave network is implemented to achieve real-time control in a smart home.

### *2.3. WirelessHART*

WirelessHART is also based on the IEEE 802.15.4 standard. However, WirelessHART is used for building reliable and secure wireless network systems in industrial applications [10,30]. It was introduced by HART Communication Foundation in 2007. The physical OSI layer is based on the IEEE 802.15.4 standard, but WirelessHART specifies the data, network, transport, and application layers. Transport and application layers are compatible between WirelessHART and the rest of the HART protocols. All devices are time-synchronized and communicate in pre-scheduled, fixed time slots. This is achieved because this technology implements a TDMA network. The use of TDMA reduces collisions and saves power consumption in the devices. WirelessHART operates in the ISM 2.4 GHz band. It implements some mechanisms to coexist in this band, such as Frequency Hopping Spread Spectrum (FHSS) which changes between channels avoiding interferences. WirelessHART allows for the use of star and mesh topologies, but star topology is not recommended. One of the main advantages of WirelessHART is its low energy consumption. Battery-operated devices can reach a battery life of up to 10 years with sampling periods between 4 and 8 s [31]. All devices have routing capabilities. There are six types of devices in WirelessHART:

- Field devices are connected to the sensors and actuators of the processes;

- Router devices are not directly connected to the process. They only have communication functionalities and are especially useful when the networks need to be improved or extended;
- Adapter devices connect wired HART devices to wireless networks;
- Handheld devices are used for installation, diagnosis, and maintenance operations;
- Gateway devices connect the networks to the plant automation host. They translate among different protocols;
- The network manager is responsible for managing the wireless network. This includes the following tasks: scheduling, network path configuration, and reconfigurations. Only one node per network can be active as a network manager, but this technology allows a backup manager to take over in case of failures.

WirelessHART also introduces several layers of protection. All traffic is secured, and the payload is encrypted. All devices need a secret join key and a network ID in order to join the network.

Previous characteristics make WirelessHART able to perform critical control tasks in slow dynamic processes. For example, in [32], a co-designed dynamic PIDPlus controller over the WirelessHART network was presented for the closed-loop control of slow-temperature processes. This work achieved the major requirements for industrial wireless control. In [33], WirelessHART was used to implement temperature control and device diagnostics.

### 2.4. ISA 100.11a

The International Society for Automation (ISA) proposed the ISA 100.11a standard in 2007. This standard introduces a wireless low-bit rate, low-power technology designed for different tasks such as non-critical monitoring, alerting, supervisory control, and open- and closed-loop control applications [11]. The ISA 100.11a standard addresses the performance needs of those applications for latencies on the order of 100 ms. It uses the IEEE 802.15.4 physical layer over the 2.4 GHz band and has a low data link layer. The MAC access is provided by means of TDMA, although it can also be implemented with CSMA-CA. For avoiding collisions in the 2.4 GHz band, it implements diverse mechanisms [34]. (1) Clear channel assessment (CCA): The device that initiates transmission checks whether the channel is busy and cancels the transmission when it is found busy; (2) spectrum management functionality: This mechanism limits the number of used channels to a subset of the available ones; (3) adaptive channel hopping: Devices autonomously avoid channels with a poor history of connectivity. The ISA 100.11a standard allows for the use of star and mesh topologies. There are different types of devices in the ISA 100.11a standard:

- Routing end devices are the I/O devices, connected to the sensors and actuators, with routing capabilities;
- Non-routing end devices are also I/O devices, but they lack routing capabilities;
- Backbone routers are responsible for routing data packets from one subnet over the backbone network to its destination, which can be another subnet or the gateway;
- Handheld devices are used for installation, diagnosis, and maintenance operations;
- System manager, which is the administrator of the network responsible for the configuration of the communication (e.g., resource allocation and scheduling), device management, and run-time control of the network;
- Gateway, which acts as an interface between the field network and the plant network (and control host applications);
- Security manager, which is responsible for managing the security policy of the applications.

The ISA 100.11a standard is designed for non-critical tasks. In fact, it can be introduced in control loops that involve slow dynamic processes. For example, in [35], the authors used the ISA 100.11a standard to control a tank level with a wireless control loop and a PID. The authors evaluated the performance of the standard, which can also provide wireless communications in harsh environments due to its robustness. In [36], a slightly modified version of the ISA 100.11a standard was used for communication tasks in a satellite, considerably reducing the wiring weight, which is a key limiting factor in satellite designs.

### 2.5. WIA

Wireless network for industry automation (WIA) includes three different standards [37]: The first of them is WIA-PA for process automation, the second is called WIA-FA factory automation, and lastly, WIA-NR, which stands for new radio. Every standard combines different technologies. WIA-PA implements the IEEE802.15.4 physical layer over the 2.4 GHz band. The data link, network, and application layers are specifically defined by the WIA standard. WIA-FA adopts the IEEE 802.11 physical layer, whereas the data link and application layers are defined by the WIA standard. WIA-NR uses the physical layer and medium-access control sublayer of 5G and defines the application layer. Every standard adopts different topologies: WIA-PA supports star or hierarchical star–mesh topologies; WIA-FA implements a redundant star topology; and WIA-NR uses a hierarchical star topology that supports device-to-device (D2D) and coordinated multi-point (CoMP) communication. WIA introduces different methods to avoid collisions, such as multi-channel access, adaptive frequency hopping, and time synchronization schemes. In the application layer, WIA facilitates interconnection with other industrial communication technologies. The standard defines different types of devices:

- Field devices are connected to the field I/O devices, such as sensors and actuators;
- Routing devices, access devices, and base stations (PA, FA, and NR, respectively), which are responsible for connecting field devices with gateways;
- Gateways provide a connection between the hosts and WIA networks. A redundant backup gateway can be added to increase the system's robustness;
- Handheld devices enable connection with the routing devices for installation, diagnosis, and maintenance operations.

Several works analyze the application of diverse WIA variants in process and factory automation tasks. An example of its implementation for factory automation is shown in [38], where a 1000-node plant was simulated, proving that WIA-FA is able to meet strict requirements in terms of reliability and timeliness in a large plant. In [39], the authors implemented a WIA-PA network for monitoring different processes. The WIA-NR technology proved to be able to meet high industrial requirements, with low latencies and reliability, as shown in [40].

### 2.6. LPWAN

Low-power, wide-area networks (LPWANs) are wireless networks that are used for long-range communications. They can be used to create networks that cover large areas, enabling IoT networks in large scales such as cities, rural environments, or agricultural fields. Due to the nature of the environments and devices, battery-powered devices are often used. The use of low-power communications increases the autonomy of the batteries, reaching years of battery life, since low-power, low-bit rates reduce consumption. This limitation makes them unsuitable for sending large volumes of data, but they are adequate for transmitting small volumes, such as the magnitudes captured with sensors or commands sent to actuators. Therefore, the main objectives of LPWANs are to achieve (1) long-range, (2) low-power, and (3) low-cost communications. Within the LPWAN communications, several specifications may be found. Below the most relevant ones are introduced, with special emphasis on LoRa, which is shown as an example of these technologies.

LoRa is a type of LPWAN communication technology aimed to provide connectivity of battery-operated devices over a long-range, wide area [41]. In fact, LoRa stands for long range. Its physical layer is based on a proprietary spread spectrum modulation algorithm. LoRa uses different frequency bands depending on the region; for example, in Europe, LoRa is deployed over the 863-873 MHz band. The range that this technology covers varies depending on the terrain obstacles. For example, it typically reaches a 5 km range in urban environments, but in more open environments, LoRa can achieve a range of more than 15 km. LoRa transmissions have very low power consumption, making this technology adequate for battery-powered devices. LoRa only defines the physical layer, whereas the data link and network layers are covered by LoRaWAN (long-range, wide-area network) [42]. LoRaWAN was defined by the LoRa Alliance in 2015. It is a low-transmission rate technology able to achieve data rates between 0.3 kbit/s and 27 kbit/s. Three types of devices are defined:

- Class A devices are most of the time idle. Typically, these devices wake up when an event occurs, such as when a timer expires or a monitoring variable passes a threshold. Then, class A devices initiate the transmission and listen for a response. If nothing is received, devices go back to the idle status for a brief time interval and listen a second time for a response. If during this time, the devices do not receive any message, they go back to sleep until the next event occurs. There is no way to wake up externally an end device. These devices are only suitable for connecting sensors but not actuators. All LoRa devices must support the class A mode of operation.
- Class B devices look for transmission windows in fixed, synchronized, and regularly scheduled time intervals. They can also transmit defined events since they implement class A behavior. These devices are suitable for carrying out periodic operations with both sensors and actuators.
- Class C devices are always listening to messages unless they are sending data. For that reason, they have lower latency than all the LoRa class devices. Class C devices implement two receive windows as class A devices, but they never close the second window until the next transmission is sent. Therefore, they can receive a message at almost any moment. They are suitable for connecting sensors and actuators. As Class C devices must be operative all the time, they do not typically operate with batteries, but they must be connected to power all the time.

LoRa networks consist of different devices, all of them providing unique identifiers. End devices are typically used to connect sensors or actuators. Gateways are used to bridge between LoRa networks and higher bandwidth networks such as WiFi, Ethernet of 3G/4G/5G, or other IP-supported technologies. Multiple gateways can be connected in the same network, reducing the error rate. Finally, network servers manage the entire network, including the application and join servers. The joint servers allow the secure joining of the devices, as well as handling, managing, and interpreting the application data captured from the sensors. LoRa introduces several spreading factors to avoid collisions so that they appear as noise to one another. If packets have the same spreading factor, collisions can occur, but if one of the signals is 6 db stronger than the other, the stronger signal will prevail. The adaptive data rate (ADR) is essential to successfully implement LoRaWAN networks. The closest nodes to the gateway use a lower spread factor to reduce the transmission time.

LoRa is suitable for long-range, low-energy communications, though the transmission speed is low. These characteristics make LoRa difficult to use in closed-loop control applications. Use cases tend to address automation for devices distributed in wide areas. For example, Sánchez Sutil (2020) [43] developed a smart public lighting control, while Usmonov (2017) [44], the authors implemented a LoRa-based wireless control for a drip irrigation system, and in [45], an IoT multi-sensory platform was presented for agriculture monitoring and pump control. Due to the low cost and range capabilities of LoRa, there are attempts to modify it to make LoRa closer to industrial requirements. As an example, Fahmida (2022) [46] developed a real-time scheduling framework (RTPL) for LoRa to enable industrial automation. Their results showed that RTPL achieved, on average, a 75% improvement in real-time performance.

There are other LPWAN specifications. The most important ones, along with LoRa, are Sigfox, NB-IoT, and LTE-M. Sigfox is developed by a French network global operator company of the same name. It uses the 868 MHz band in Europe and the 902 MHz band in the US. The use of ultra-narrowband allows low-energy communication that may cover large areas, with a maximum range of 30–50 km in rural areas. Its main characteristics are the use of differential binary phase-shift keying (DBPSK) and Gaussian frequency-shift keying (GFSK) and a one-hop star topology [47]. Sigfox operates with a closed IoT solution, but the chipset specification is open to manufacturers. NB-IoT is a proprietary technology developed by 3GPP. NB-IoT focuses on indoor coverage. It uses a subset of the LTE standard but limits the bandwidth to a 200 kHz band [48]. Finally, LTE-M, also developed by 3GPP, relies on LTE machine-to-machine communications. The advantages of LTE-M over NB-IoT include its higher data rate, up to 1 Mbps [49], and better mobility, although it requires more bandwidth and is more costly. Both NB-IoT and LTE-M are still under development and are scheduled to be upgraded to be capable of achieving URLCC capabilities with the release-14 version [50]. Therefore, these technologies have the potential to be used in wireless networking if these objectives are fulfilled.

### 2.7. BLE

BLE was defined in 2010 as part of the Bluetooth 4.0 specification. BLE is a short-range, low-energy communication technology. Even though Bluetooth was initially conceived as a star topology, BLE stacks can be modified to support mesh topologies. Thus, the layers above the network layer must be changed to support BLE mesh [51,52]. The BLE physical layer has 40 channels on the ISM 2.4 GHz band. Three of them (channels 37–39) are used as advertising channels (ACs) for device discovery, connection establishment, and broadcasting. The remaining 37 channels (0–36) are data channels (DCs), providing two-way data transfer. BLE implements the adaptive frequency hopping (AFH) technique between DC to minimize the effect of the interferences. The data link layer defines different roles for BLE devices. Specifically, there are three kinds of devices: masters, slaves, and advertisers. First, a device broadcasts its presence. When a connection is established with a central device, the central node acts as master and the peripheral device as slave. Devices can support different roles to create complex topologies. There have been several efforts to standardize BLE mesh, the most important of which are Bluetooth SIG: Bluetooth Smart Mesh and IETF: IPv6 over BLE mesh networks. However, the BLE mesh technology is not considered mature yet.

Some efforts sought to implement real-time capabilities in BLE mesh networks. For example, in [53], multi-hop real-time wireless communications were achieved using the MRT-BLE protocol. Nevertheless, this approach only allows the definition of the topology offline, so there cannot be mobile nodes in the network, which is a clear limitation. Some implementation examples outside real-time domains can be found. For example, in [54], the authors used a BLE network to implement a position algorithm along with WiFi to make more accurate position identification and tracking. Another example can be found in [55], where a BLE mesh was used to make a smart lighting control, extending the coverage area and increasing its flexibility.

### 2.8. 5G

Cellular networks have come a long way since 1G was launched in the early 1980s [56]. These technologies have evolved over the years, augmenting data transmission rates and security and reducing their cost. The introduction of 4G, in the 2010s, was an important achievement since it considerably enhanced the data rate. At the beginning of Industry 4.0, despite its high cost, 4G became an important IoT technology for devices with high mobility. For example, in logistics, the capabilities of 4G facilitate digitization in the industry. More recently, in 2019, the first commercial 5G networks were deployed. This technology promises to revolutionize the wireless communication paradigm, achieving more strict QoS requirements than actual wireless technologies. Notably, 5G uses a millimetric wavelength spectrum [57]. As a result, the range is more limited. For that reason, the deployment of 5G networks is based on a large number of small cellular stations, in contrast to the traditional large cellular towers, which can slow down its deployment outside urban areas.

Currently, 5G is not a cost-effective technology for industrial applications. However, its price is expected to considerably reduce in the near future, thus opening new opportunities. Some experimental 5G technologies may reach 10 Gb/s transfer speeds. It also provides high scalability and massive machine-type communication (mMTC) since it may admit up to 100 nodes/m$^2$. One of the key characteristics of 5G is that it provides ultra-reliable, low-latency communication (uRLLC). In fact, it is expected to have a latency value below 1 ms and a reliability rate of over 99.999%. If these figures are achieved, the requirements of many industrial applications would be satisfied. Indeed, it could become an alternative in devices with high mobility, such as autonomous guided vehicles (AGVs), robots, or logistics.

Private 5G networks are particularly interesting in industrial applications [58]. Private networks may provide dedicated coverage, which is key to having robust indoor networks even in remote areas. Furthermore, there is no contention for network resources as in public networks, adding reliability and robustness to the network. Intrinsic control of the network can be achieved. This allows the implementation of traffic priorities or security policies to ensure data. Private networks can be customized to meet the specific requirements of diverse applications. All these characteristics make private 5G networks reliable and dependable. It is believed that 5G is going to be implemented in many industrial applications since 5G characteristics make it adequate to be used in IoT and IIoT applications. Many domains can benefit from the massive introduction of 5G technologies, such as industrial automation (smart factories), automotive industry and smart cars, warehouse operations, utilities, industrial remote operation, intelligent transportation (logistics), mining operation, railway networks, healthcare, or smart grids and smart cities. Notably, 5G can be key in the achievement of tactile internet [59], becoming the communication technology for haptic systems. Applications in augmented reality, healthcare monitoring and intervention, navigation, and transportation are expected to be developed with this technology in the not-too-far future.

Previously, 5G had to overcome some obstacles: Technological maturity, global standardization, government regulations, and cost are the major concerns for massive 5G adoption. Companies are especially reluctant to change. Significant barriers were identified such as data security and privacy, lack of standards, and challenges of end-to-end implementation [60]. The upgrade or replacement of networks to adopt 5G may involve design problems, training, and, inevitably higher costs [61].

Other technologies are also available for WSN, such us RPMA, eMTC, EC-GSM IoT, Weightless, DASH7, Wi-Sun, and Matter-or-Thread protocol. However, at the moment, they are less common in Industry 4.0 applications.

## 3. Conclusions

Connectivity is a key issue in Industry 4.0 applications since it allows the introduction of new key concepts. Today, wired technologies prevail in industrial scenarios, and they will clearly remain in use in the future, especially in critical applications. However, the use of wireless networks achieves several benefits when compared to wired technologies: They introduce higher flexibility to modify the layout of the links; enhance the connectivity between taking nodes, sensors, and actuators; and eliminate wires, reducing the deployment cost. In fact, they introduce new possibilities into Industry 4.0 applications since they facilitate connection with mobile devices or parts.

Wireless communication technologies had already found a place in factories for non-critical operations, such as data acquisition, monitoring, and supervision. Failures in these tasks do not have severe consequences, which may involve the security of people and assets. However, the use of these technologies in critical applications, for example, in closed-loop control operations, is not mature yet. Some application examples may be found, especially in slow dynamic processes such as those found in the oil, gas, and chemical industries. However, this topic is still under research in academia.

Currently, several protocols are available. Each technology may be valid for different scenarios. The development of the newest technologies, such as WiFi6 and 5G, could allow WSN to compete in performance with traditional wired communications. If they are capable of delivering such promising specs, the introduction of wireless technologies in factories may be disruptive. The flexibility and scalability that offer wireless communications can make the factory evolve into more smart factories, flexible enough to adapt quickly to the needs and circumstances of different products and productive environments. Nevertheless, there are obstacles to overcome. Factories are a really harsh environment for wireless technologies, due to several phenomena such as interferences, shadowing, or fading. Moreover, the cost of the deployment of these technologies is still high. In the short term, it is expected that both wired and wireless technologies coexist in factories. In the long run, it seems clear to the authors that wireless solutions are going to be massively deployed in the industry.

This perspective article covered the most relevant technologies for use in industry. We sought to provide an overview of these technologies and some cases of use to illustrate their application in different domains. Thus, this study helps researchers and application designers to select the most appropriate technology in each case.

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