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Views & Comments

Industrial Wireless Control Networks: From WIA to the Future

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1. Introduction

Industrial automation is undergoing a significant innovation as information, communication, and operation technologies are deeply integrating with each other. Following this trend, industrial wireless control networks (IWCNs) are becoming increasingly attractive to industrial automation since they can help speed up production efficiency, reduce cost, enhance safety, and finally realize intelligent manufacturing [1].

To achieve the above targets, IWCNs must satisfy the various critical communication requirements of industrial automation, such as high reliability, strong timeliness, little jitter, low cost, low power, and high security [2]. However, IWCNs always operate under harsh industrial environments with extremely limited communication resources, such as unlicensed spectrum shared with wireless fidelity (WiFi), Bluetooth, and ZigBee. Thus, academia and industry have spent significant effort in developing IWCNs during the past decades. In particular, WirelessHART, ISA100.11a, and wireless networks for industrial automation-process automation (WIA-PA) were developed for process automation, whereas wireless interface for sensors and actuators (WISA), wireless sensor actuator network for factory automation (WSAN-FA), and wireless networks for industrial automation-factory automation (WIA-FA) were developed for factory automation [3–5]. To date, WirelessHART, ISA100.11a, WIA-PA, and WIA-FA have been the only four international IWCN standards released by the International Electrotechnical Commission.

More recently, International Telecommunications Union and the 3rd Generation Partnership Project (3GPP) have proposed to develop ultra-reliable low latency communication (URLLC) for industrial control [6], as one of the three 5G scenarios. In this way, cloud-based industrial control will be possible since URLLC is based on the long-range 5G wide-area network. This is completely different from existing IWCNs that are based on short-range wireless personal-area or local-area networks. Currently, although URLLC has been standardized, its applications in vertical industries are still being tested and have not been commercially deployed at a large scale. This is mainly due to the fact that the applications of 5G in industry have not undergone a steady evolution process as industrial Ethernet, and different industrial applications have different communication requirements. Typically, most industrial enterprises do not have spectrum license and would like to establish private networks to enhance their security and privacy, whereas commercial 5G networks are managed in the licensed spectrum by mobile operators. Moreover, most industrial control applications are still in the industrial field, and it is unnecessary to transmit all industrial data around the wide-area Internet. Thus, how to achieve URLLC over the unlicensed spectrum to satisfy the critical requirements of field-level industrial control in harsh environment is one of the most challenging problems. To address this challenge, wireless networks for industrial automation-new radio (WIA-NR) was recently developed based on the air-interface of 5G to realize URLLC over the unlicensed spectrum [7].

Currently, WIA-PA, WIA-FA, and WIA-NR have formulated a complete technology family (namely wireless networks for industrial automation (WIA)) to cover different industrial applications, and will further evolve according to industrial requirements. However, the various requirements from vertical industries continuously motivate the evolution of IWCNs, like URLLC towards 6G. Thus, 3GPP establishes a new work item investigating enhanced URLLC [8]. The world's first 6G white paper [9] also confirms the continuous improvement of URLLC whose air-interface latency is enhanced to 0.1 ms. The perspective from *Nature Electronics* [10] proposes five 6G scenarios, wherein secure URLLC is defined. Furthermore, massive URLLC and broadband URLLC are also defined [11]. To summarize, it is believed that URLLC in 6G should achieve less than 0.1 ms latency and higher than 99.9999999% reliability. Such performance will ensure highly accurate industrial control such as micro–nano tele–operation and precision machining. With the continuous enhancement of URLLC, WIA-NR will also evolve towards 6G. As WIA family is developed by the same team with a similar technology roadmap, this paper introduces and compares this technology family and discusses the future of WIA in the 6G era.

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2. Overview of WIA family

2.1. System architecture

WIA defines a group of physical devices including the host computer, gateway device, field device, handheld device, and routing device/access device/base station. With these devices, WIA formulates different topologies as shown in Fig. 1. Specifically, WIA-PA employs a star or hierarchical star–mesh topology, of which star topology is a special case. In contrast, WIA-FA employs a redundant star topology. Furthermore, WIA-NR defines a hierarchical star topology that supports device-to-device (D2D) and coordinate multi-point (CoMP) communication.

Corresponding to different network topologies, WIA employs two system management architectures, namely centralized management, hybrid centralized and distributed management. Specifically, WIA-PA supports both architectures, while WIA-FA and WIA-NR only support the former and the later architectures, respectively.

2.2. Protocol stack

As illustrated in Fig. 2, WIA defines their protocol stacks based on the open system interconnection (OSI) reference model. WIA-PA completely adopts IEEE 802.15.4 as its physical layer (PHY) and medium access control (MAC) sub-layer, and defines its own data link sub-layer, network layer (NET), and application layer (APP), where the MAC sub-layer and the data link sub-layer comprise the date link layer (DLL). WIA-FA only adopts the PHY of IEEE 802.11, and defines DLL and APP. In contrast, WIA-NR employs the PHY, MAC, and radio link control layers of 5G without other protocol layers for wide-area communication, and defines APP. Note that only WIA-PA defines NET because routing devices are wirelessly connected in the mesh topology and addressing/routing must be defined in NET, while access devices or base stations use wired connections whose functions are not defined by WIA-FA or WIA-NR.

In PHY, WIA employs the unlicensed spectrum for worldwide utilization, wherein WIA-PA and WIA-FA work on the 2.4 GHz band, while WIA-NR works on the 5 GHz band. Thus, the listen-before-talk mechanism is employed to satisfy spectrum rules before channel access. This is also one of the most important differences of WIA-NR from the commercial 5G. The fundamental parameters of PHY are summarized in Table 1 [4,5,7].

In DLL, to realize collision-free communication, WIA defines different superframe/slot structures for timeslot communication and designs multi-channel access, adaptive frequency hopping, and time synchronization schemes to enhance reliability and timeliness.

In APP, multiple user application objects (UAOs) implement distributed industrial applications according to the given virtual communication relationship (VCR) which describes the communication resources and paths among UAOs. More importantly, WIA provides protocol adaptation services by tunneling or protocol conversion for heterogeneous industrial communication (e.g., PROFINET and Modbus) in APP. This significantly enhances its interoperability with existing industrial automation systems.

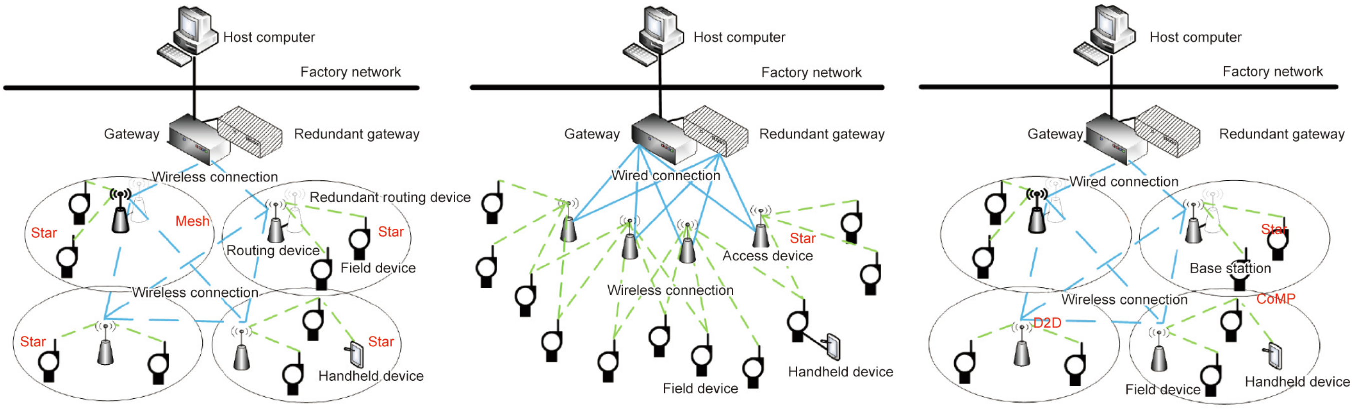
3. Key techniques

3.1. Deterministic timeslot communication

To realize deterministic communication, WIA employs timeslot communication, where a slot is the basic time unit for packet exchange and its length is configurable. As shown in Fig. 3, WIA-PA and WIA-FA further define superframes, while WIA-NR formulates frame and subframe, all based on a collection of slots cyclically repeating at a constant rate. Specifically, WIA-PA defines its superframe based on the IEEE 802.15.4 beacon-enabled superframe which consists of a beacon, an active period and an inactive period. The active period further includes contention access and contention free periods, while the inactive period includes intra-cluster communication, inter-cluster communication, and sleeping periods. The default superframe of WIA-FA is composed of beacon slots, uplink shared timeslots, and downlink timeslots that may be used for management and data transmission. In contrast, with the flexible numerology of 5G, WIA-NR supports multiple kinds of frames by setting the sub-carrier spacing as $2^{\mu} \times 15$ kHz, where $\mu = \{0, 1, 2, 3, 4\}$ is the numerology. As the length of one frame is fixed at 10 ms, one frame can consist of different numbers of slots which may be downlink/uplink slot, downlink/uplink self-contain slot, or flexible slot.

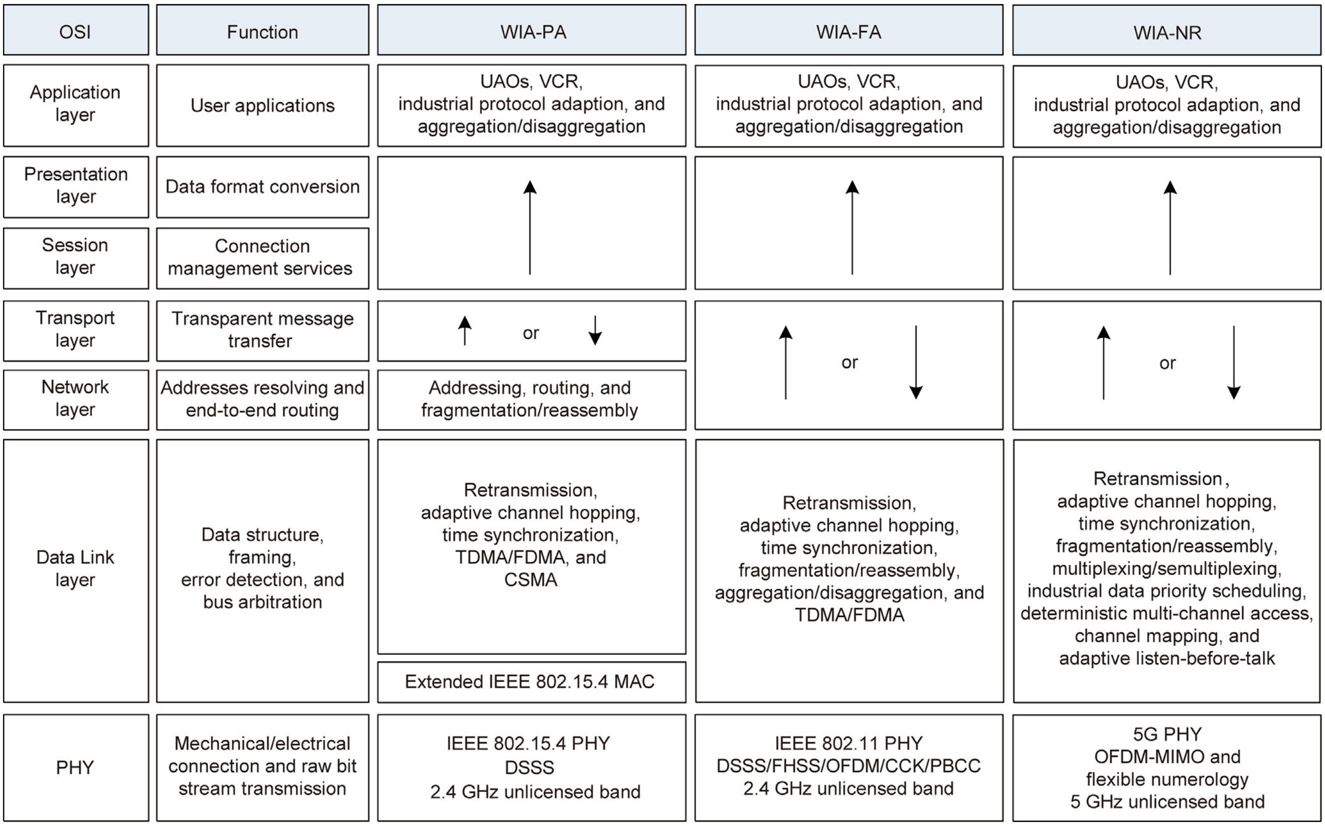
3.2. Multi-channel access with adaptive channel hopping

WIA employs multi-channel access schemes combined with channel hopping to improve the capacity and reliability. Specifically, WIA-PA adopts frequency division multiple access (FDMA) for multi-channel access, combining with time division multiple access (TDMA) for system capacity enhancement. Meanwhile, WIA-PA defines three channel hopping schemes, namely adaptive frequency switching, adaptive frequency hopping, and timeslot



(a) (b) (c)

Fig 1. Network topology of WIA. (a) Hierarchical star–mesh topology of WIA-PA; (b) redundant star topology of WIA-FA; (c) hierarchical star topology of WIA-NR. D2D: device-to-device; CoMP: coordinate multi-point.



OSI	Function	WIA-PA	WIA-FA	WIA-NR
Application layer	User applications	UAOs, VCR, industrial protocol adaption, and aggregation/disaggregation	UAOs, VCR, industrial protocol adaption, and aggregation/disaggregation	UAOs, VCR, industrial protocol adaption, and aggregation/disaggregation
Presentation layer	Data format conversion	↑	↑	↑
Session layer	Connection management services			
Transport layer	Transparent message transfer	↑ or ↓	↑ or ↓	↑ or ↓
Network layer	Addresses resolving and end-to-end routing	Addressing, routing, and fragmentation/reassembly		
Data Link layer	Data structure, framing, error detection, and bus arbitration	Retransmission, adaptive channel hopping, time synchronization, TDMA/FDMA, and CSMA Extended IEEE 802.15.4 MAC	Retransmission, adaptive channel hopping, time synchronization, fragmentation/reassembly, aggregation/disaggregation, and TDMA/FDMA	Retransmission, adaptive channel hopping, time synchronization, fragmentation/reassembly, multiplexing/semultiplexing, industrial data priority scheduling, deterministic multi-channel access, channel mapping, and adaptive listen-before-talk
PHY	Mechanical/electrical connection and raw bit stream transmission	IEEE 802.15.4 PHY DSSS 2.4 GHz unlicensed band	IEEE 802.11 PHY DSSS/FHSS/OFDM/CCK/PBCC 2.4 GHz unlicensed band	5G PHY OFDM-MIMO and flexible numerology 5 GHz unlicensed band

Fig 2. Protocol stack of WIA. ↑ and ↓ indicate that the functions of this layer, when present, can be included in the protocol layer according to the direction of the arrow. OSI: open system interconnection reference model; UAO: user application object; VCR: virtual communication relationship; TDMA: time division multiple access; FDMA: frequency division multiple access; CSMA: carrier sense multiple access; MAC: medium access control; PHY: physical layer; DSSS: direct sequence spread spectrum; FHSS: frequency-hopping spread spectrum; OFDM: orthogonal frequency division multiplexing; CCK: complementary code keying; PBCC: packet binary convolutional code; MIMO: multiple input multiple output.

Table 1
The fundamental parameters of PHY.

Parameter	WIA family		
	WIA-PA	WIA-FA	WIA-NR
Spectrum	2.4 GHz band	2.4 GHz band	5 GHz band
Bandwidth (MHz)	5	20, 40	20, 40, 80, 100, 120, 140, 160
Transmission mode	DSSS	DSSS, FHSS, OFDM, CCK, PBCC	OFDM
Modulation	O-QPSK	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM, 256QAM
Maximum rate	250 kbps	54 Mbps	100 Mbps
Antenna	Single antenna	Single antenna	Multiple antennas

BPSK: binary phase shift keying; QPSK: quadrature phase shift keying; O-QPSK: offset-QPSK; QAM: quadrature amplitude modulation; kbps: kilobit per second; Mbps: megabit per second.

hopping, whose advantages over blind channel hopping are verified in Ref. [12]. WIA-FA employs multiple access devices which are divided into different sets, for parallel access over different channels using FDMA. Similarly, WIA-FA also supports adaptive channel hopping. For WIA-NR, each base station is equipped with multiple antennas for multiple input multiple output (MIMO) transmission and multiple base stations apply CoMP. Furthermore, WIA-NR defines three-level adaptive channel hopping, including slot-based, subframe-based, and frame-based adaptive channel hopping according to the packet loss rate or retransmission.

3.3. Aggregation and disaggregation

To reduce communication traffic and enhance energy efficiency, WIA defines different aggregation and disaggregation schemes that are implemented in different protocol layers as depicted in Fig. 2. WIA-PA defines a two-level aggregation scheme including data aggregation at NET and packet aggregation at APP. WIA-FA defines frame aggregation at DLL, and also supports aggregation and disaggregation at APP for process data. WIA-NR defines a two-level data aggregation scheme at APP for uplink and downlink data transmission.

3.4. Industrial data priority scheduling

To satisfy different industrial applications, WIA performs communication scheduling according to their priorities as shown in Table 2, wherein the priorities are given in descending order. For different priority scheduling, WIA defines three communication modes, namely client/server (C/S), publisher/subscriber (P/S), and report source/sink (R/S). Here, C/S supports unicast communication of dynamic and aperiodic non-real-time data, P/S supports unicast and multicast communication of periodic real-time data, and R/S supports unicast and multicast communication of aperiodic data,

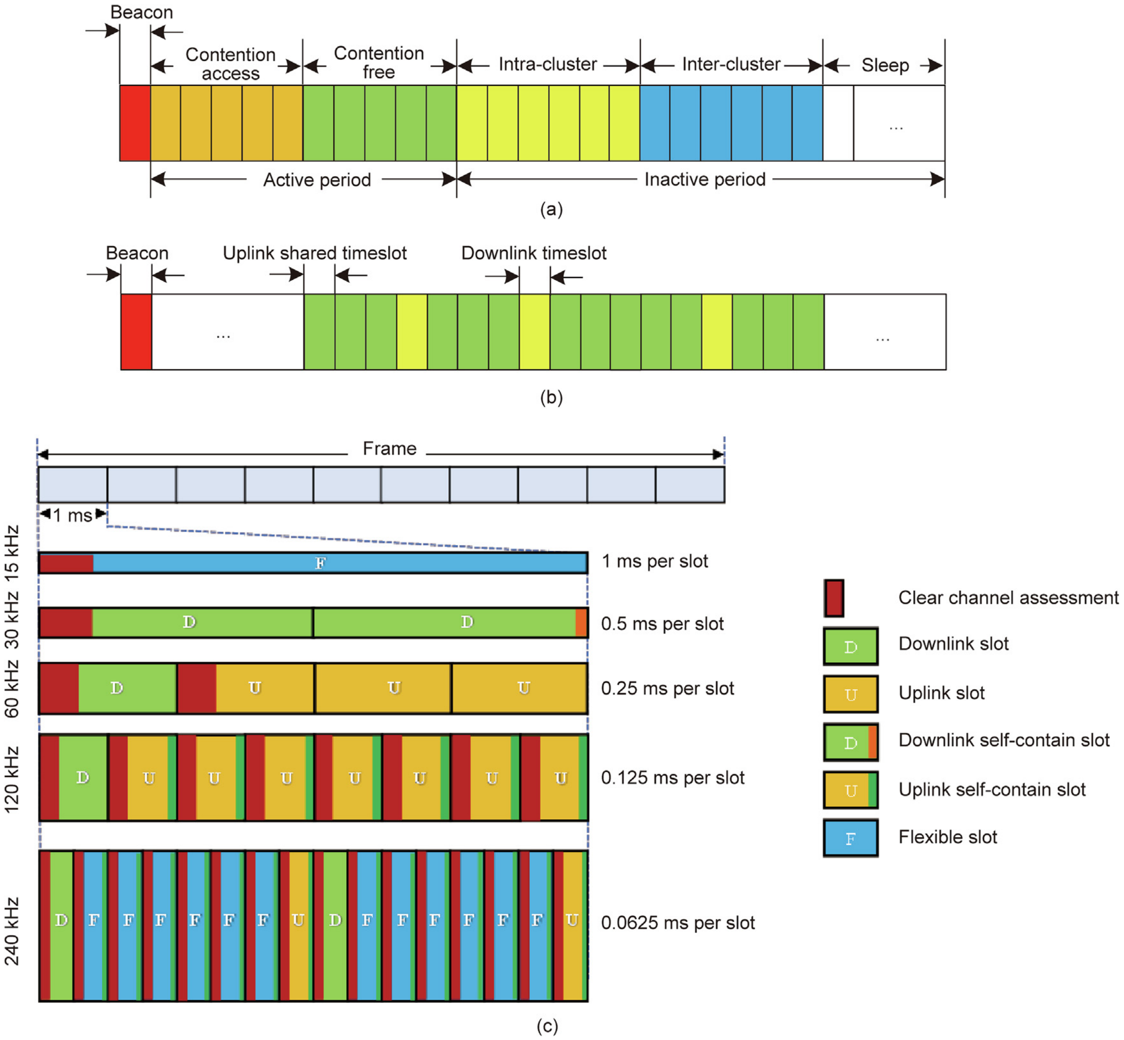


Fig 3. Frame of WIA: (a) superframe of WIA-PA, (b) superframe of WIA-FA, and (c) frame of WIA-NR.

Table 2
Industrial data priority of WIA.

Scheduling mechanism	WIA family		
	WIA-PA	WIA-FA	WIA-NR
Data priority	Command, process data, normal, alarm	Urgent data, periodic process data, aperiodic non-urgent data, periodic management data, and non-real-time data	Aperiodic critical data, periodic critical data, aperiodic non-critical data, and periodic non-critical data
Communication mode	C/S, P/S, and R/S	–	–

C/S: client/server; P/S: publisher/subscriber; R/S: report source/sink.

such as alarms, alerts, or events. To realize these communication modes, we can use C/S VCR, P/S VCR, and R/S VCR.

4. Performance and applications

With technological improvements and standardization, WIA is going deep into different industrial applications. Fig. 4 shows the achievable performance of WIA [4,5,7,12–14].

WIA-PA, as the first developed WIA technology, has been applied for more than a decade. Its products are mature and have occupied a part of the Chinese market. Currently, WIA-PA can support a large-scale network with up to 1000 nodes and a typical rate of 250 kilobits per second (kbps), where the average power at a router with 0.18% duty cycle is as low as 0.63 mW [13]. Meanwhile, WIA-PA achieves more than 99.3% reliability and less than 100 ms end-to-end latency. Using multi-source high-precision clock synchronization technology, WIA-PA can even support real-time closed-loop control by reducing the access latency from 1 s to 10 ms. To date, WIA-PA has been utilized for industrial measurement, monitoring and process control in several industries including petroleum, petrochemical, metallurgy, and power grids.

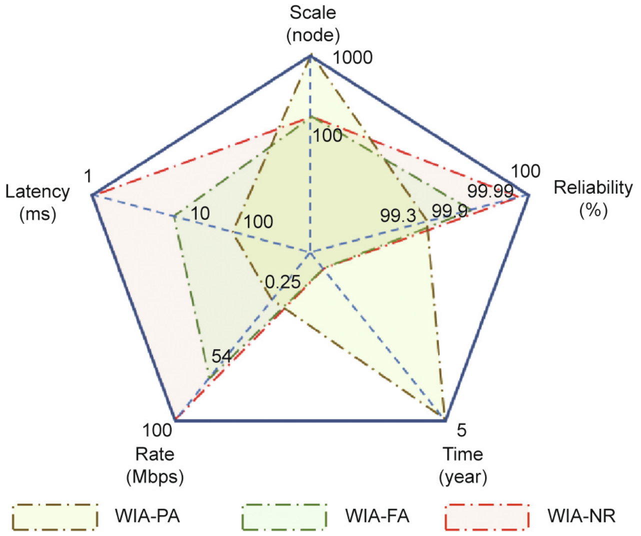


Fig 4. Performance of WIA.

WIA-FA, standardized in 2017, has passed the product testing stage and is extending its practical applications. Currently, WIA-FA achieves higher than 99.99% reliability and less than 10 ms latency, and can support at least 100 nodes with a rate of 54 megabits per second (Mbps). WIA-FA has been used for industrial multimedia communication, and closed-loop control in discrete manufacturing industry, such as robot monitoring and controlling in digital workshops, and automated guided vehicles connecting in logistic sorting systems [5,14].

In contrast, WIA-NR has yet to be practically deployed as the development of WIA-NR has just begun corresponding to 5G. Thus, WIA-NR is still under development and testing. Currently, both system-level simulations and experimental tests indicate that WIA-NR can achieve more than 99.999% reliability and less than 1 ms latency [7]. Such performance meets the basic objective of 5G and can support motion control. However, for more critical industrial control, the timeliness and reliability should be further enhanced. Meanwhile, such performance is also far from the objective of 6G, thereby motivating us to further evolve WIA-NR towards 6G.

5. Evolution of WIA towards 6G

As no single industrial communication technology can address the manifold industrial requirements, neither existing IWCNs (e.g., WirelessHART and WIA-PA) nor industrial Ethernet (e.g., PROFINET and ModBus) will be replaced by 5G or 6G in the short term. That is, multiple industrial communication technologies will coexist and integrate with each other in the long term. Thus, we propose to establish a heterogeneous hierarchical architecture for future IWCNs in the industrial field. As depicted in Fig. 5, WIA-NR provides coarse-grained cover for a factory, while existing industrial communication networks such as WIA-PA and industrial Ethernet keep on providing fine-grained cover in the local area of a factory. WIA-NR connected with the factory backbone network further establishes communication links with the manufacturing execution system (MES) or enterprise resource planning (ERP). In this way, the ultra-reliable and low-latency WIA-NR is responsible for critical industrial control while the low-power and low-cost WIA-PA is responsible for large-scale industrial monitoring and measurement. To realize this paradigm, we are facing the following challenges that should be addressed during the 6G era.

(1) **Heterogeneous interconnection**. To interconnect heterogeneous industrial networks using WIA-NR for unified access, we need to address the protocol adaption problem. The challenges lie in that industrial enterprises have developed hundreds of industrial wired or wireless communication protocols with different stacks, data format, and transmit rate. One promising method is to directly parse different protocols by the gateway. For this case, we can establish a virtual mapping relationship between each industrial protocol and WIA-NR, and perform protocol conversion. However, some industrial protocols may not be open for analysis. For this case, we can utilize tunnel technology to perform transparent transmission. Anyway, how to guarantee the timeliness during protocol parsing and conversion is the most important problem. Furthermore, we can enhance the computing capability of WIA

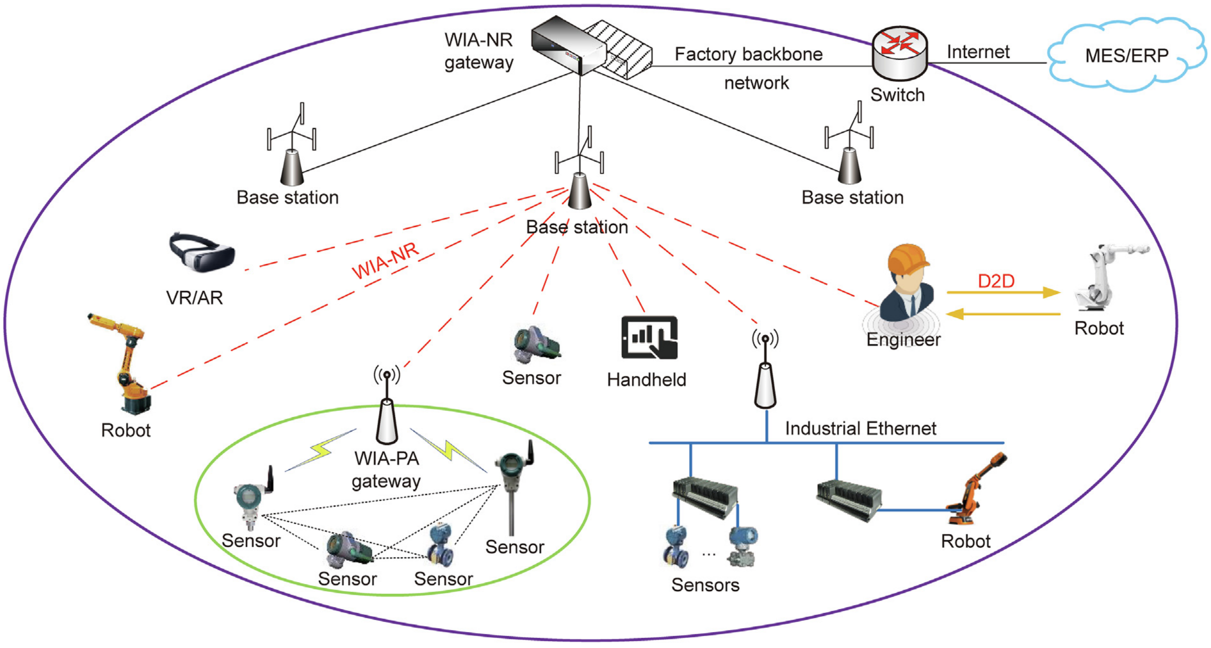


Fig 5. Future IWCNs in the industrial field. MES: manufacturing execution system; ERP: enterprise resource planning; VR: virtual reality; AR: augmented reality.

by deploying distributed edge computing servers for edge computing and caching. In this way, WIA-NR can support complex protocol operations with hard timeliness and therefore satisfy time-critical industrial applications.

(2) **Harmonious coexistence**. As WIA-NR operates over the unlicensed spectrum, anti-interference communication and harmonious coexistence for heterogeneous industrial networks must be deeply investigated for ultra-reliable communications. In general, resource allocation and power control are the basic methods for reducing interference and enhancing reliability. However, how to precisely evaluate the whole channel state and achieve real-time access control is the most important problem. Cognitive radio, which has dynamic spectrum access capability, is always regarded as an option allowing IWCNs to realize ultra-reliable communications [15]. Furthermore, with the fast development of artificial intelligence, intelligent radio [16] can further enhance the cognitive capability over unlicensed spectrum. In the future, WIA-NR empowered with intelligent radio can defeat the random interference in industrial environment and harmoniously coexist with other wireless networks such as WiFi in the unlicensed spectrum.

(3) **Energy efficiency**. Intelligent radio together with other new functions will significantly enhance the energy consumption. Thus, the next problem is to enhance the energy efficiency of WIA-NR. Energy harvesting is a promising way to provide sustainable energy supply since this technology can continuously scavenge energy from ambient energy sources. As such, energy harvesting cognitive radio networks have been investigated for the coexistence of heterogeneous networks [17]. More recently, intelligent symbiotic radio [18] is proposed to simultaneously enhance spectrum and energy efficiencies. It is regarded as a key 6G technology, which should also be a research issue of future IWCNs. With these key technologies, we aim at promoting WIA-NR to support massive URLLC for long-time operation.

(4) **Absolute time synchronization.** The absolute time synchronization with little jitter is required to ensure cooperative control in industrial automation. For example, multiple robots cooperatively execute a task which requires isochronous operations. Obviously, cooperative robots must realize absolute time synchronization. This is different from the time synchronization between user equipment and base station in 5G. As absolute time synchronization has not been investigated prior to 3GPP Release 16, it remains a significant challenge. Thus, we propose to investigate the absolute time synchronization for heterogeneous hierarchical IWCNs in 3GPP [19,20]. In practice, how to enhance the accuracy of time synchronization and reduce jitter must be comprehensively investigated to guarantee the robustness of isochronous operation.

(5) **Multi-priority joint scheduling**. For heterogeneous hierarchical IWCNs, joint scheduling is indispensable since a controller usually interacts with a large number of sensors and actuators belonging to different networks. For such a case, the hybrid centralized and distributed management architecture of WIA-NR should be more effective. As different IWCNs employ different scheduling schemes, the joint scheduling for inter-network is certainly more complex than that for intra-network. To support multiple industrial data priorities, mixed-criticality scheduling [21] is an efficient way to guarantee timeliness and reliability, and should be deeply investigated for future IWCNs. For this case, employing a real-time queue classifier is necessary to facilitate the scheduling of gateway. Meanwhile, cross-layer scheduling and optimization among different protocols can also help facilitate the scheduling problems. Moreover, redefining a unified data priority scheme is also welcome since different industrial networks define different data priority schemes.

In addition to the aforementioned challenges and research issues, realizing heterogeneous hierarchical IWCNs is facing numerous challenges that should be properly addressed in the 6G era. Anyhow, upgrading or even redesigning a new IWCN to proactively embrace vertical industries is always better than reactively waiting current IWCNs being used by industries.

6. Conclusions

This paper studied the current status and future prospects of the WIA technology family, namely WIA-PA, WIA-FA, and WIA-NR. We first presented the background of IWCNs by analyzing the critical communication requirements and development challenges, following by a discussion on the motivation for technological innovations of IWCNs in the 6G era. We then provided an overview on WIA by comparing the different system architectures and protocol stacks. Next, we summarized the key techniques, performance, and applications of WIA. Finally, we proposed a heterogeneous hierarchical architecture for future IWCNs and discussed the challenges and research issues evolving WIA towards 6G.

Acknowledgments

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