The Road to Industry 4.0 and Beyond:
A Communications-, Information-, and Operation Technology Collaboration Perspective

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Abstract—The fourth industrial revolution, i.e., Industry 4.0, is evolving all around the globe. In this article, we introduce the landscape of Industry 4.0 and beyond empowered by the seamless collaboration of communication technology (CT), information technology (IT), and operation technology (OT), i.e., CIOT collaboration. Specifically, CIOT collaboration is regarded as a main improvement of Industry 4.0 compared to the previous industrial revolutions. We commence by reviewing the previous three industrial revolutions and we argue that the key feature of Industry 4.0 is the CIOT collaboration. More particularly, CT domain supports ubiquitous connectivity of the industrial elements and further bridges the physical world and the cyber world, which is a pivotal prerequisite. Then, we present the potential impacts of CIOT collaboration on typical industrial use cases with the objective of creating a more intelligent and human-friendly industry. Furthermore, the technical challenges of paving the way for the CIOT collaboration with an emphasis on the CT domain are discussed. Finally, we shed light on a roadmap for Industry 4.0 and beyond. The salient steps to be taken in the future CIOT collaboration are highlighted, which may be expected to expedite the paradigm shift towards the next industrial revolution.

I. INTRODUCTION

Historically, the **Industrial Revolution** took place based on the development of science and technology, substantially liberating human productivity at the time. By the time of writing, three industrial revolutions have taken place, which were fuelled by steam- and electric power, as well as by information technology. Currently, the fourth industrial revolution, a.k.a., *Industry 4.0*, is afoot across the globe. Industry 4.0 is expected to usher in a new era of intelligent, human-friendly industry, and create an unprecedented global market [1].

Initially proposed in Germany in 2011 as a part of the German economic policy [2], the concept of Industry 4.0 has been generalized over the past few years as the convergence and application of various advanced techniques [3], such as the Internet of Things (IoT), digital twin, big data, artificial intelligence (AI), XR (including *virtual reality, augmented reality, and mixed reality*), etc. More recently, these advanced techniques have been amalgamated and expanded as *the Metaverse* [4], a promising paradigm shift for not only Industry 4.0 but way beyond. It has attracted many countries' attention at both the enterprise and the governmental levels.

The core of Industry 4.0 lies in *interconnection*. Industry 4.0 is also closely related to the industrial IoT (IIoT) [5], [6].

Communication technology (CT) forms an indispensable part of Industry 4.0, since it intrinsically amalgamates the sophisticated operation technology (OT) and information technology (IT) domains in support of the efficient IIoT, as shown in Fig. 1. The performance of CT directly determines the stability, continuity, and flexibility of the global industry.

Nevertheless, establishing a reliable CT domain for industrial applications is a non-trivial task, mainly due to the large-scale connectivity requirements in the face of hostile propagation. Cisco predicted that by 2023, a significant fraction (about 50%, i.e., 14.7 billion) of connected devices and connections will come from machine-to-machine (M2M) interaction [7], which is the common form in industrial scenarios. Things are more urgent for Industry 4.0 and beyond, which requires not only extremely demanding connectivity, but also time sensitivity and security attributes. Fortunately, the rapid development of CTs, including fifth-generation (5G) and even 6G systems, provides effective solutions for Industry 4.0. For instance, recalling the three basic scenarios in 5G, i.e., the enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC), it is expected that the proliferation of 5G techniques will support massive low-latency connectivity, high-rate data transmission, real-time remote control, and high-safety information exchange in industrial applications. Industry 4.0 critically hinges on state-of-the-art CTs.

This article provides an overview of Industry 4.0 and beyond (Industry 4.0+) based on a CT-IT-OT (CIOT) collaboration perspective. In particular, the contributions of this article are threefold:

- After briefly comparing the fourth industrial revolution to the previous ones, we postulate that the CIOT collaboration is the foundation of Industry 4.0 We argue by introducing some critical use cases that the core of Industry 4.0 and beyond lies in the interconnection of a massive number of the existing industrial elements, leading to CIOT collaboration.
- The technical challenges on the road to CIOT collaboration in Industry 4.0 are summarized, and the CIOT-related research directions of the CT domain are introduced, mainly including massive access to the IIoT, information transmission and network management. Some case studies are also conducted to show how the advanced CT domain reshapes the industrial activities.
- We speculate on the ambitious vision of Industry 4.0+ empowered by a suite of inspiring recent advances, such as the industrial Internet of Senses (IIoS), energy-
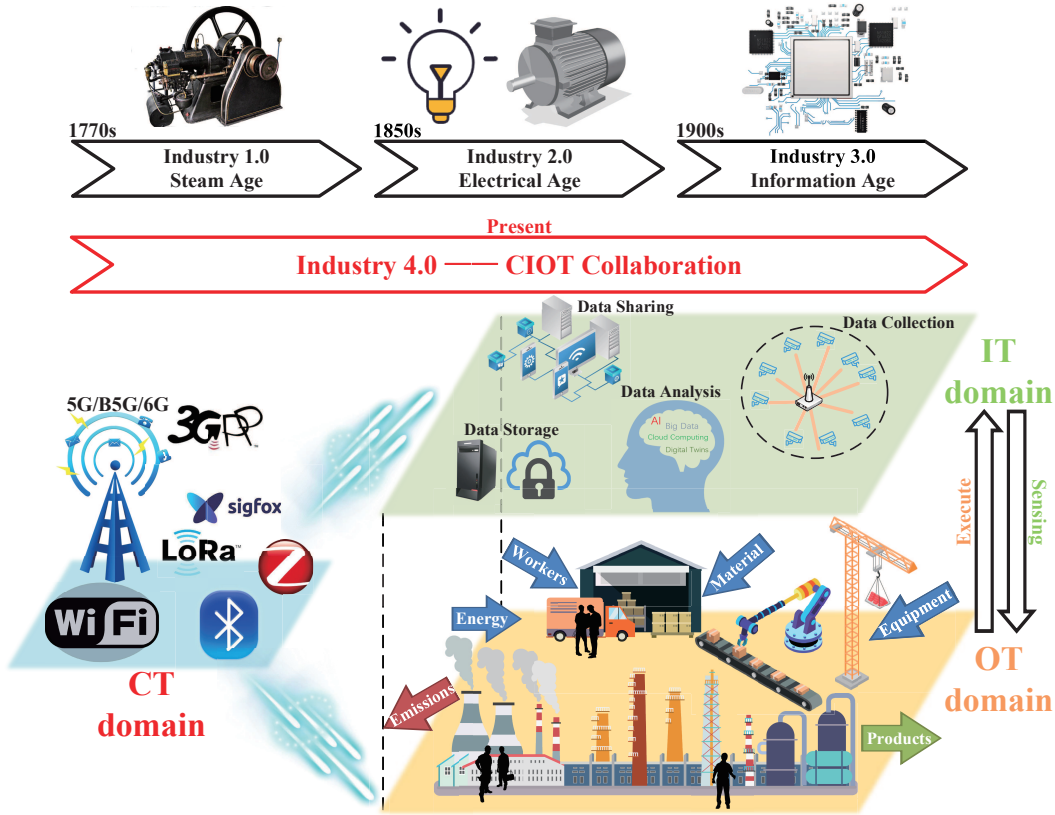
Fig. 1. The procedures and representatives of the previous three industrial revolutions, and the cooperation mechanism in Industry 4.0.

harvesting networks (EHN), data-driven CIOT (DCIOT) collaboration using AI, and the industrial Metaverse, which further pave the way for the associated scientific research. These are also juxtaposed to the corresponding limitations to be tackled for providing guidelines for the community's future research.

II. OVERVIEW OF INDUSTRIAL REVOLUTIONS AND DEVELOPMENT ROADMAP OF INDUSTRY 4.0

In this section, we first highlight the approach of the previous three industrial revolutions, and then provide a blueprint for the evolving Industry 4.0, wherein the CIOT collaboration is a key feature. In particular, we focus on how CIOT-related CT domain will play a dominant role in Industry 4.0.

A. Industry 1.0 to 3.0

The *first* industrial revolution (*Industry 1.0*) was triggered by the first ever commercially successful engine conceived by T. Newcomen in 1712 that replaced 'muscle-power' by uninterrupted 'machine-power'. This was then further improved by J. Watt in 1764. The foundations of the *second* industrial revolution (*Industry 2.0*) were laid by M. Faraday, who formulated the theoretical and practical basis of harnessing electric power [3]. In contrast to the above two revolutions, which were characterized by the different types of energy sources, the *third* industrial revolution (*Industry 3.0*) focused on improving industrial production by jointly using miniaturized electronics and novel IT, paving the way for industrial digitization. In

the same era, modern CT has been pioneered from a practical perspective by G. Marconi in the 1900s and from a theoretical perspective by C. Shannon in the 1940s, providing compelling opportunities for the digital electronic industries. All the previous three industrial revolutions had a huge impact both on today's industrial production, as well as on wealth-creation, and on people's quality of life.

B. Industry 4.0 Based on CIOT Collaboration

The *fourth* industrial revolution, i.e., *Industry 4.0*, hinges on the close collaboration of all three CIOT domains in the process of industrial production, as shown in Fig. 1. The specific missions of the CIOT domains are as follows:

- *The OT domain* encompasses all the industrial elements, which are directly responsible for the operation and maintenance of factories or businesses. It consists of workers, equipment, materials, energy, products, emissions, etc., in all the industrial activities.
- *The IT domain* is the platform that realizes the unified collection, storage, and analysis of the data collected by workers or sensor networks from the OT domain. It is empowered by advanced cloud computing, digital twin, AI, etc.
- *The CT domain* is represented by various wired/wireless and long-/short-distance communication standards and technologies, such as Wi-Fi, Bluetooth, Zigbee, LoRa,
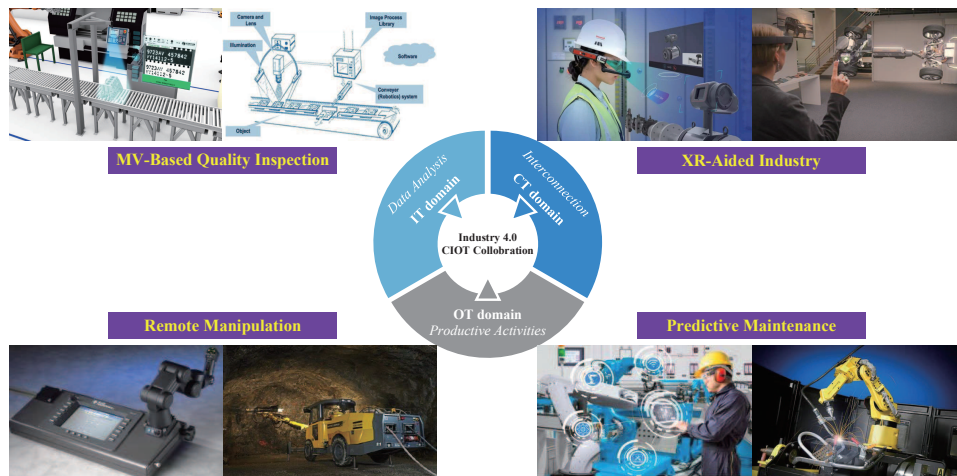
Fig. 2. Potential use cases of Industry 4.0 empowered by the CIOT collaboration.
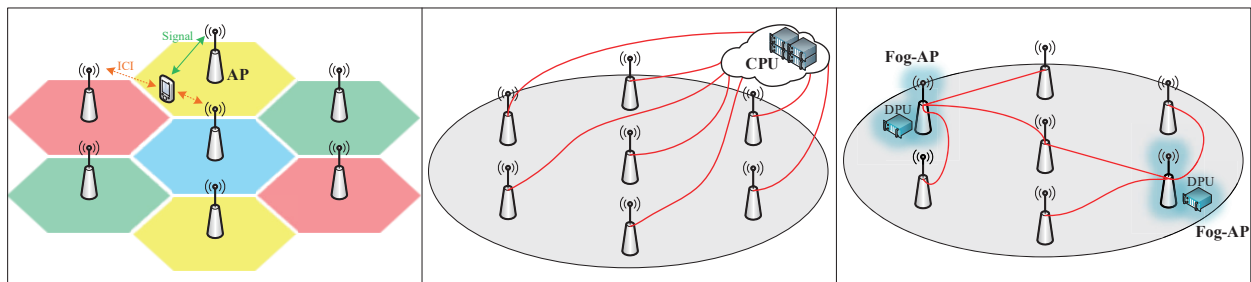

Fig. 3. Three processing paradigms for multi-AP grant-free massive access: (from left to right) non-cooperate architecture, cloud computing architecture, and edge (fog) computing architecture.

Sigfox, NB-IoT, and the cellular networks[1]. They support networking at a given level of service quality assurance for the intelligent control of industries.

Based on the processes of Industry 1.0 to 3.0 discussed in the previous sub-section, we can see that although the OT, IT and CT have already been respectively developed for industrial applications, the CIOT collaboration has not been recognized as a research direction until Industry 4.0 has been launched. As indicated by the terminology, the CIOT collaboration aims for the organic integration of all three CIOT domains, realizing the interaction between the physical world (OT domain) and the digital world (IT domain) via the communication networks (CT domain). As Fig. 1 indicates, in the "sensing" and "execute" process between the IT domain and the OT domain, the CT domain plays a key role, seamlessly amalgamating the physical and the digital worlds. The CT domain becomes so important for the industrial revolution that the "IIoT", where the CTs constitute the foundations, is usually regarded as the indispensable component of Industry 4.0 [5], [6].

C. Impact on Use Cases

Below we discuss the potential use cases in Industry 4.0 empowered by the CIOT collaboration as shown in Fig. 2. We will further demonstrate below that the CT domain is

[1]The length-limitation of the magazine paper precludes the detailed introduction to these standards or techniques. Interested readers are referred to the rich set of related publications.

an integral part of hitherto unexplored promising industrial applications of the near future.

1) Machine Vision (MV)-Based Quality Inspection. The vision information of the products on the production line is collected through high-definition industrial cameras, and then it is transmitted through the uplink by relying on the CT domain. The CT domain ensures high-integrity, low-latency data transmission. Also, the AI-based MV algorithms running on the IT platform will process, analyse, and understand the images received. On this basis, the machines in the IT domain can identify the targets and detect the quality of products on the production line in near-real-time. Compared to the traditional manual quality inspection, the MV-based quality inspection is of higher sensitivity, higher precision, and higher efficiency, which helps reduce the human cost in the manufacturing process.

2) XR-Aided Industry. Based on *virtual reality, augmented reality, and mixed reality* (XR) technologies, the applications of remote assistance, guidance, etc. can be carried out in support of the employees, who learn from each other, work together, and interact with each other. For example, the scenes captured in the production line can be directly passed to the product designer in the form of XR, so that he/she can provide intuitive guidance on improving the production process via reliable communication networks provided by the CT domain. More importantly, XR-based techniques are capable of reminding the workers operating the assembly lines of precautions or raising the alarm in the case of emergencies.

The fully-fledged Industry 4.0 will provide transcoding, 3D reconstruction, object recognition, content management, and other sophisticated XR-based operations.

3) Remote Manipulation. Delicate remote manipulation is of great importance in many industrial scenarios, such as post-disaster reconstruction, replacing manual labor and thus protecting workers from danger. This application requires the ubiquitous connections anytime and anywhere, which is hard to fulfilled by the conventional terrestrial cellular networks. As a remedy, the non-terrestrial network (NTN) will serve as a building block for remote manipulation in the dangerous or unpopulated areas. The utilization of NTN will be further elaborated in Section IV-A. Remote manipulation in Industry 4.0 has tight delay specifications (usually milliseconds level [10]), hence ultra-reliable and low-latency communications are pivotal prerequisites.

4) Predictive Maintenance. Predictive maintenance system can capture some precursors of machine failure by leveraging IoT sensor networks, machine learning algorithms, and big data analysis. This allows machine owners/operators to perform maintenance in advance of its due date, and thus avoids the sudden failure of the production line, which may cause immeasurable loss. According to [9], predictions on the remaining useful life span of the components may be carried out by the digital twin, which constitutes a tangible example of the proposed CIOT collaboration. Naturally, unless the tight communication specifications are satisfied, it is impossible for managers to remotely monitor the status of machines, and hence we cannot benefit from predictive maintenance.

III. RESEARCH DIRECTIONS FOR THE CT DOMAIN

Despite the appealing visions of this emerging industrial revolution, the existing schemes cannot satisfy the tight requirements of the so-called vertical industries in Industry 4.0. Based on the discussions of use cases, we readily see that many technical challenges accrue from the CT domain, which again indicates that the CT domain plays a pivotal role in enabling Industry 4.0. In the rest of this section, we highlight the research directions for the CT domain by reviewing three main aspects of the recently developed CTs, i.e. access paradigm, information transmission, and network management, by discussing their potential applications in Industry 4.0.

A. Massive Access for IIoT

The increasing number of sensors and edge processing elements integrated into the IIoT scenario leads to new challenges for the radio access network (RAN). Massive access technology is the backbone of typical IIoT applications operating under Industry 4.0. In contrast to conventional grant-based access schemes, grant-free massive access schemes allow multiple IIoT nodes to share the same physical time and frequency resources to send their pilot sequences, based on which the subsequent active terminal detection is performed at the access points (APs). As a benefit, reduced latency can be achieved [11]. Furthermore, due to the sporadic tele-traffic generation of IoT applications, only a small portion of IIoT

nodes is simultaneously active. This sparse activity can be effectively exploited by advanced compressive sensing (CS) algorithms, and solves the active node detection problem with the aid of non-orthogonal pilot sequences.

The IIoT nodes of large-scale industrial activities in Industry 4.0 are expected to be distributed across a vast area. The APs should cooperate to offer improved coverage and to reduce the transmit power of energy-constrained nodes. In Fig. 3, three different processing paradigms are considered for multi-AP grant-free massive access [11]. In the non-cooperative architecture of Fig. 3, each IoT node is attached to a single AP, where reduced-dimensional signal processing can be conducted at the cost of potentially severe inter-cell interferences (ICI). By contrast, the cloud computing and edge computing architectures of Fig. 3 allow each AP to serve all the nearby nodes, and these APs are connected either to a single or multiple processing units for joint signal processing, which blurs the traditional concept of "cells" and thus avoids ICI by constructing user-centric clusters relying on fair load-balancing. Compared to cloud computing, where only a single central processing unit (CPU) is responsible for all APs, edge computing offloads the signal processing tasks to multiple distributed processing units (DPUs) deployed at some of the APs (namely, fog-APs), which alleviates the burden imposed both on the backhaul links and on the CPU. Fig. 4 characterizes the performances of these three paradigms. We observe that with the advent of AP-cooperation, ICI-free cloud computing and edge computing become feasible, which improves the active terminal detection probability. Furthermore, by increasing the number of cooperating APs, the performance of edge computing becomes capable of approaching that of cloud computing, despite its reduced latency. Hence, edge computing is a more appealing scheme for Industry 4.0 in support of delay-sensitive applications.

B. Wireless Information Transmission

Due to the explosive growth of connected industrial devices, the resultant "data-tsunami" significantly increases the demand on Industry 4.0. The types of information sources in Industry 4.0 are not limited to conventional symbols or bits, but include the underlying meaning or purpose to be delivered for industrial activities, which leads to the concept
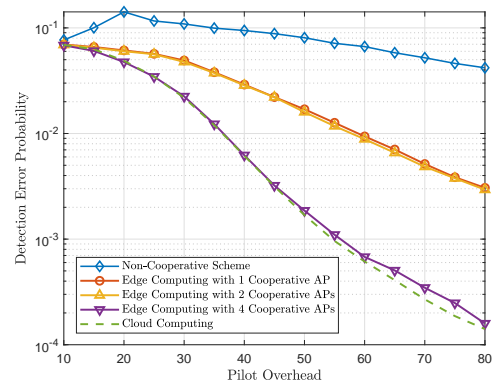

Fig. 4. Performances of different multi-AP grant-free massive access paradigms. A CS-based algorithm in [11] is considered.

of *semantic communications*. In the face of such complex scenarios, more advanced physical layer techniques are required for wireless information transmission (WIT). Increasing the carrier frequency allows us to expand the bandwidth in the millimeter-wave (mmWave) and terahertz (THz) bands at the cost of increasing the path loss. Moreover, the use of high frequency bands facilitates the deployment of massive multiple-input multiple-output (MIMO) systems in a compact space, which can offer: 1) substantially improved beamforming gains to compensate for the increased path loss; and 2) fine-grained spatial multiplexing for simultaneously supporting multi-device communications.

The channels at higher frequencies are also vulnerable to blockage effects, hence the desired line-of-sight link is usually intermittent. This limitation led researches to the conception of a new paradigm for reconfiguring the wireless propagation environment via software-controlled devices for improving the channel conditions with the aid of reconfigurable intelligent surfaces (RISs) [12]. In Industry 4.0 scenarios, inexpensive passive RISs can be deployed for enhancing the channel conditions to boost the system capacity.

Another challenge is that of mitigating the effect of the high Doppler frequencies encountered by high-velocity robotic cars, mining vehicles, freight trains, and unmanned aerial vehicles (UAV) as well as planes. In these high-mobility scenarios, the pilot overhead used for channel estimation and equalization may become excessive, since every time the velocity is doubled, it also must be doubled. In these scenarios, sophisticated non-coherently detected multiple-symbol receivers come to rescue. Novel Doppler-resistant modulation schemes have also been proposed, such as, for example, orthogonal time frequency space (OTFS) modulation. Their applications in Industry 4.0 have to be further investigated.

C. Heterogeneous Networks Management

The networks in Industry 4.0 incorporate diverse components associated with different properties and requirements. Considering the three popular use cases of 5G networks as an example:

- *eMBB* requires abundant bandwidth for transmitting high-definition audio, pictures, videos, and even tactile telepresence information.
- *mMTC*, which can be supported by LTE-M, NB-IoT, Lora, Sigfox, etc. requires high capacity to handle the simultaneous access requests arriving from a massive number of industrial devices.
- *URLLC*, which can be supported both by 5G cellular networks and by dedicated short-range communications (DSRC), requires high reliability and low latency to support the precise control of machines.

This wide variety of specifications renders the networks in Industry 4.0 highly heterogeneous. Therefore it is quite a challenge to achieve efficient network management in these complex networking environments. The innovative concept of *network slicing* is potentially capable of coping with the challenges of heterogeneous networks, where the slices convey the different-specification information streams, as exemplified by critical control signalling, and best-effort Internet browsing. By combining the existing network technologies like virtual private networking, network function virtualization, software-defined networks, and so on, network slicing technology divides a networks into multiple segments, where each segment corresponds to different network requirements, and the segments do not affect each other. In this way, a network-slicing based architecture can simultaneously meet the different networking requirements of different scenarios, dealing with the heterogeneity of the network.

Intelligent AI-based network slicing reduces the cost of network management and improves service diversity [14], which is appealing for Industry 4.0, but the provision of Quality of Service (QoS) and Quality of Experience (QoE) guarantees requires further research.

IV. Future Visions, Opportunities, and Limitations

In this section, we introduce some of the future visions and opportunities of Industry 4.0+, which are shown in the stylized illustrations of Fig. 5. Critical issues and limitations are discussed, which require further research.

A. Industrial Internet of Senses

The paradigm shift from IIoT towards IIoS is promising for Industry 4.0+, which relies on the progress in the fields of both the "Internet" and in the communications of "Senses". As the space for human activities expands across the globe, the support for industry in vast and/or sparsely populated areas (space, oceans, forests, deserts, canyons, to name but a few) attracts much attention. The interconnection, or "Internet", between the industrial elements in such scenarios is not feasible by simply relying on the existing terrestrial communication systems. A key CT-domain enabler of fine-grained connectivity and high-accuracy positioning services is related to the space-air-ground integrated network (SAGIN) concept. By combining the terrestrial systems with the emerging OT-domain techniques, such as low Earth orbiting (LEO) satellites, high-altitude platforms (HAPs), aircraft, UAV swarms, etc., SAGIN will usher in a paradigm shift that will extend the breadth and depth of not only communication services, but also industrial activities.

Furthermore, the term "Senses" in the IoS encompasses a large range of concepts in the IT domains, which helps to support vast applications under Industry 4.0+, such as emission detection, weather prediction, event management, emotion monitoring for workers, etc. In a nutshell, the IIoS assisted by SAGIN, as a typical form of the CIOT collaboration, is capable of monitoring the existing network environment through ubiquitous connection and real-time communications, thus simultaneously improving the QoS and QoE of future industrial networks.

B. Energy Harvesting Network

Wireless power transfer (WPT) is an OT-domain technology that allows a power source to transmit electromagnetic energy to an IoT node over the air, without interconnecting wires [13]. Furthermore, WPT is waterproof or dustproof for contact-free devices, which is suitable for harsh industrial production
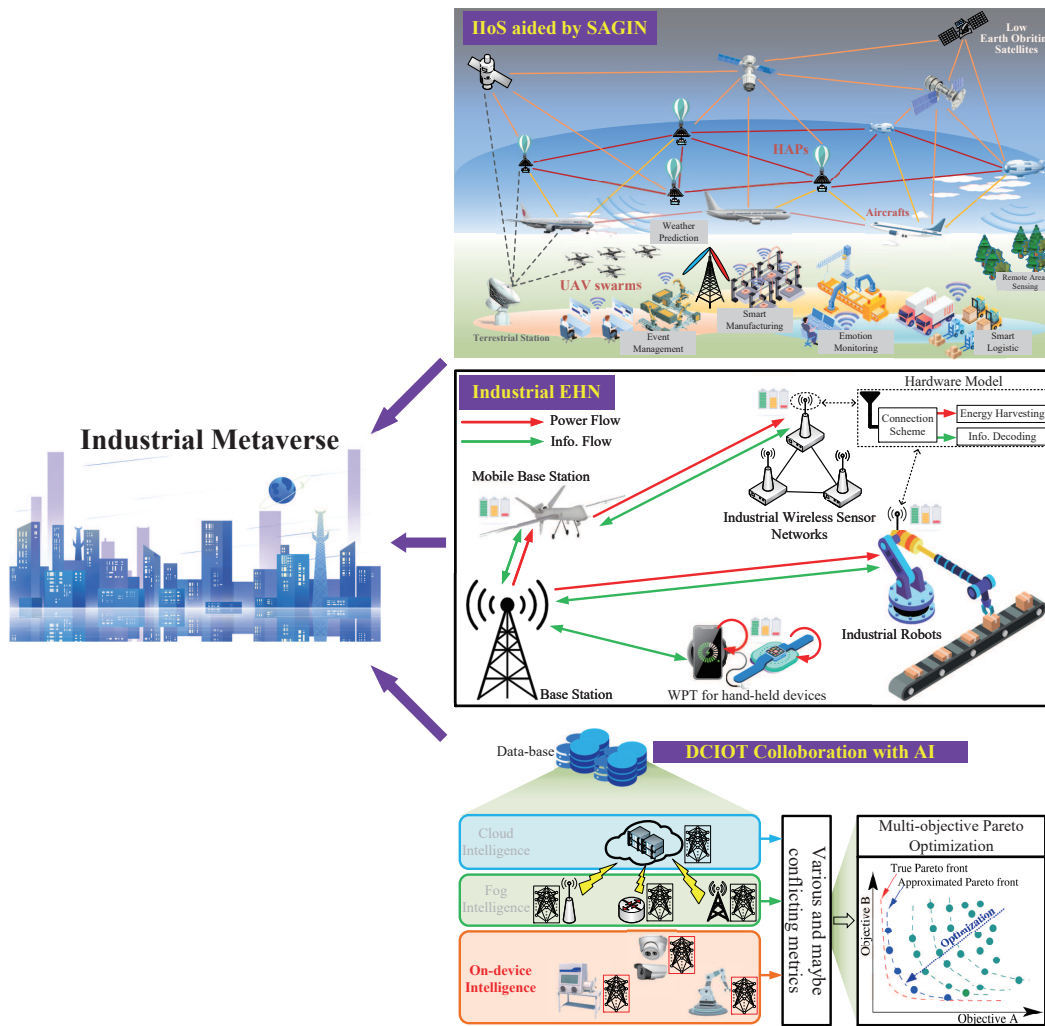
Fig. 5. Ambitious visions of Industry 4.0+.

environments in Industry 4.0+. The current mechanisms of WPT can be categorized into the following types [13]:

- *RF charging,* which has a poor charging efficiency (about 1%-10%) but a remarkable charging distance (of the order of kilometers). It can charge the remote devices operating in harsh environments, such as epidemic outbreak areas.
- *Inductive charging,* which guarantees more than 90% charging efficiency, but only within a very small range (several centimeters). It allows workers in the factories to expediently charge their hand-held devices.
- *Magnetic resonance based charging,* which strikes a charging efficiency vs. distance trade-off. It constitutes the most promising type of WPT for sensor networks, electric vehicles, smart grid, etc. in Industry 4.0+.

More importantly, by combining WPT in the OT domain with WIT in the CT and IT domains, the concept of EHN, a.k.a., simultaneous wireless information and power transfer (SWIPT) [13], is established. With the rapid development of circuit design and implementation, industrial EHN can be readily realized with only minor hardware modification to industrial devices. By carefully designing the on-demand resource allocation scheme between the energy and infor-

mation, EHN has the compelling advantage of concurrently delivering controllable and efficient wireless information and energy in industrial activities, hence SWPIT may be deemed more beneficial than the sum of its constituent parts (WPT and WIT).

C. Data-Driven CIOT Collaboration with AI

Undoubtedly, AI will play, explicitly or implicitly, an important role for Industry 4.0 and Industry 4.0+, as well as for the industrial revolutions of the distant future. Powerful AI techniques have been widely used in diverse research areas in the current era of machine intelligence for promoting the CIOT collaboration. Only by relying on a sufficiently large set of pre-collected data can AI tackle the model-free optimization problems in complex industrial networking setting. Therefore, the CIOT collaboration may be further augmented with the aid of pervasive big data in the form of data-driven CIOT (DCIOT) collaboration, which holds the key for achieving high-level intelligence in Industry 4.0+.

Another critical challenge for AI-aided future industrial networks is their multi-objective optimization relying on multiple metrics. Under the evolving paradigm of *on-device in-*

telligence, AI has been deployed in powerful IoT nodes, as well as in cloud centres (i.e., *cloud intelligence*) or smart APs and gateways (i.e., *fog intelligence*). This architecture is capable of improving both the latency and security, but results in conflicting requirements. One promising solution is based on the notion of multi-objective Pareto-optimization [15] for finding all optimal operating points of a multi-component objective function constituting the optimal Pareto front. Suffice to say that for the solutions on the Pareto front, none of the system parameters can be improved without degrading at least one of the others. In Industry 4.0+, this ubiquitous AI paradigm based on DCIOT collaboration and multi-objective Pareto optimization is capable of supporting self-configuring, self-optimizing, and self-adjusting production environments.

D. Industrial Metaverse

The concept of the Metaverse is evolving rapidly, but its definition varies across different disciplines (see, e.g., [4, Table I]). In the context of industry, we define the industrial Metaverse as an industrial ecological system that intrinsically integrates DCIOT with the real-world industrial activities. By harnessing the emerging techniques of XR, AI, IoT, cloud computing, blockchain, 5G/6G. etc., the industrial Metaverse supports the seamless connection of people and machines in an amalgamated network, acting as the vein of clean and intelligent manufacturing as well as services. In this sense, the industrial Metaverse may be viewed as an evolutionary form of CIOT (or DCIOT) collaboration (see Fig. 5), relying on heterogeneous techniques and disciplines.

E. The Limitations of This Study

In this sub-section, we summarize some limitations of this study concerning the industrial revolution from a CIOT collaboration perspective, which are listed as follows.

- For the manufacturing industries, only the most radical technologies that can be applied to the physical world have practical value. This may be engineered in from the start for Industry 4.0+ to succeed.
- As we argued, the availability of sufficient training data is a prerequisite for intelligent industry. However, much of the data are usually owned by private enterprises or governments, and they cannot be publicly exposed. Hence, in the face of limited data, intelligent industrial networking requires alternative solutions.
- The multidisciplinary nature of industry requires the combination of expertise from different disciplines, including not only engineering, but also economics, sociology, and management, just to name a few. It is necessary to bridge the gap among the different disciplines in support of the evolution to Industry 4.0+.

V. CONCLUSIONS

Based on a CIOT collaboration perspective, this article has explored the landscape of Industry 4.0 and its beyond. Specifically, the concept of CIOT collaboration has been introduced as a paradigm shift for future industry. By seamlessly integrating the OTs found in the physical world with the ITs in the cyber world by relying on advanced CTs, the close CIOT collaboration is set to promote intensified industrial innovation. The critical roles of the CT domain in the challenging use cases of Industry 4.0 have been highlighted. On this basis, we have indicated some of research directions for the CT domain in terms of three salient aspects, namely the massive access paradigm , wireless information transmission, and network management. Furthermore, we have extended our discussions to Industry 4.0+, where some ambitious visions are depicted by highlighting the interplay of the OT, IT, CT, and other disciplines. The industrial revolution based on CIOT collaboration perspective is expected to reshape the industrial activities and transform our society.

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