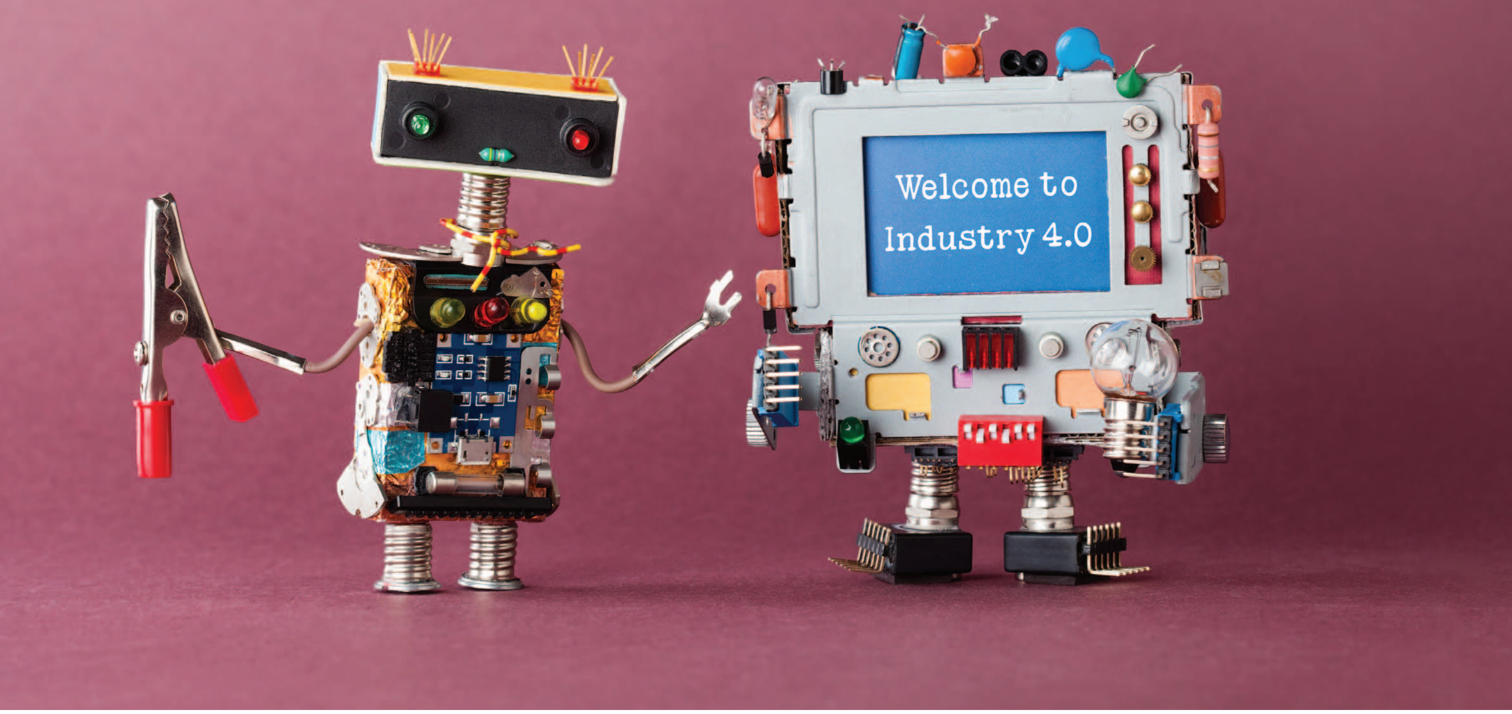
The Future of Industrial Communication

Automation Networks in the Era of the Internet of Things and Industry 4.0



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With the introduction of the Internet of Things (IoT) and cyberphysical system (CPS) concepts in industrial application scenarios, industrial automation is undergoing a tremendous change. This is made possible in part by recent advances in technology that allow interconnection on a wider and more fine-grained scale. The purpose of this article is to review technological trends and the impact they may have on industrial communication. We will review the impact of IoT and CPSs on industrial automation from an industry 4.0 perspective, give a survey of the current state of work on Ethernet time-sensitive networking (TSN), and shed light on the role of fifth-generation (5G) telecom networks in automation. Moreover, we will point out the need for harmonization beyond networking.

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Recent Trends in Automation Technology

The core of distributed automation systems is essentially the reliable exchange of information. Any attempt to steer processes independently of continuous human interaction requires, in a very wide sense, the flow of information between

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To facilitate information exchange, a multitude of industrial communication networks evolved over the years.

some kind of sensors, controllers, and actuators [1]. After the introduction of steam power to relieve workers from hard manual labor and the invention of mass production based on division of labor, the introduction of automation technology was what is today often called the *third industrial revolution* [2]. To facilitate information exchange, a multitude of industrial communication networks evolved over the years, starting from the 1980s. It is noteworthy that these developments, in many cases, picked up and accommodated new technologies emerging in other fields, primarily in the information and communication technology (ICT) world. Ethernet, wireless networks, or web technologies are examples of this cross-fertilization. These new technologies created new opportunities for making information exchange more comprehensive. Consequently, automation systems could grow more complex, too.

The latest trends influencing automation technology are the IoT, CPS, and the emerging tactile Internet. For the latter, [3] mentions industrial automation as a key, steadily growing application field. These concepts are not entirely new and emerged in a context of ICT several years ago. Recently, however, they are penetrating industrial automation and changing the angles from which people look at automation systems [4]–[6]. Moreover, they support recent trends, such as achieving a higher degree of interconnection, cognitive automation, and shifting information collection and processing into cloud-based applications [7]–[9].

Applying the ideas of CPSs and IoT to the industrial automation domain led to the definition of the *Industry 4.0* concept, where 4.0 alludes to a fourth industrial revolution enabled by Internet technologies to create smart products, a smart production, and smart services. Originally developed in Germany, the term has quickly become a buzzword on a global scale [10]. As a kind of response with similar goals, the Industrial Internet initiative (IIC) originated in the United States, although it should be noted that the term was coined much earlier [11].

From a communications perspective, IoT and CPSs rely largely on mobile Internet, i.e., telecommunication networks, which have not played a major role in industrial communication so far. In addition, they require solely Internet-based communication, which has not been possible in industrial automation, either. Both information technology (IT) and telecom networks could not cope with the automation-specific needs for deterministic, reliable, and efficient communication. This seems to be changing now. On the one hand, ongoing work on Ethernet TSN promises hard real-time capabilities. This is seen as a real game changer for real-time automation networking. On the other hand, the telecom industry has discovered industrial automation as a promising application field of their products and seems determined to consider the needs of automation in the development of 5G networks. Both developments, together with unified and semantic information modeling based on web standards, might indeed change the structure of industrial networks, and they might be the prerequisite for actually implementing industrial IoT (IIoT) and CPSs.

A Brief History of Industrial Communication

In the early days of industrial communications, dedicated automation networks called *fieldbus systems* were developed from scratch to overcome the limitations caused by the parallel cabling between sensors, actuators, and controllers and to close the communication gap on the lower levels of the automation pyramid [12]. This also included the physical layers, such as in bus systems like controller area network (CAN), PROFIBUS, or INTERBUS, to name a few. Figure 1 reviews the timeline of this evolution and marks milestones in various technology fields relevant for the evolution of communication in automation. Things changed around the millennium, when Internet technology became popular, and IT became widely used and a part of everyday life. In automation, this stimulated a new wave of Ethernet-based networks that borrowed basic technology from the IT world. The lack of genuine real-time capabilities in standard Ethernet, however, prevented the development of one single Ethernet solution for automation purposes and led, again, to the emergence of dedicated solutions [13], [14]. Approaches interfering with the Ethernet standard, such as PROFINET-isochronous real time (IRT) or EtherCAT, were much scarcer and typically appeared later to meet particularly demanding low-latency requirements, especially in motion control applications. Nevertheless, real-time Ethernet (RTE) is still a vivid research area [15]–[17].

The third evolution phase dealt with wireless networks. The foremost advantage of using wireless connections in industrial automation is that devices and machines can be moved and connected with greater ease and there are no restricting cables. More than ever, basic ICTs were adopted, mainly from the IEEE 802 protocol family. All practically relevant wireless networks in use today build on standards devised for computer networks, such as IEEE 802.11 [18], or wireless personal area networks (WPANs) like IEEE 802.15.1 or IEEE 802.15.4 [19]. The upper layers are, in many cases, consistent with wired networks to retain compatibility, and the main challenge is again to ensure real-time and reliability capabilities [20], [21]. Typically, wireless networks are being used for subsystems in otherwise wired network infrastructures [22], [23]. Industrial automation is a rather conservative domain, and the higher reliability of wired networks often outweighs the flexibility of wireless links. Wireless sensor networks in their pure form, though a vibrant research field [24], [25], are therefore not widely used in automation practice.

Such was the situation until about one or two years ago. Industrial communications was a mixture of fieldbus systems, Ethernet-based approaches, and some wireless solutions [26], [27], all of them struggling with the legacy of four decades of history in a market with life cycles of plants that are in the range of decades. The recent adoption of IoT and CPS concepts in the automation world, however, changes the scenery again. They put the old and still valid quest for integration of information flows in automation into a wider context [28]. The idea that everything in automation is connected and, e.g., that individual products or workpieces are parts of this ecosystem is not new, it was introduced with agent-based distributed manufacturing systems years ago [29]. Nevertheless, recent advances in communication technology allow interconnection on a wider and more fine-grained scale [30]. On the application side of the automation pyramid, the other big trend is to move the business logic into cloud-based applications [7], [8]. This is in line with IT trends and has much to do with new business models of software solution providers on the one hand and the wish to make IT-related costs smaller and more predictable on the customers' side.

The big difference with respect to the previous waves of evolution in industrial communication is that the technological driving force is consumer electronics. So far, the predominant roots of industrial communication were instrumentation and IT. This seems to change. The work on Ethernet TSN originated in the standardization of audio video bridging (AVB) [31]. In addition, the interest of the telecom industry stems from extending their business as mobile Internet providers, which draws from developments in consumer electronics [3]. After all, one of the appealing features of the IoT concept is the promise to use everyday Internet-enabled devices like smartphones or

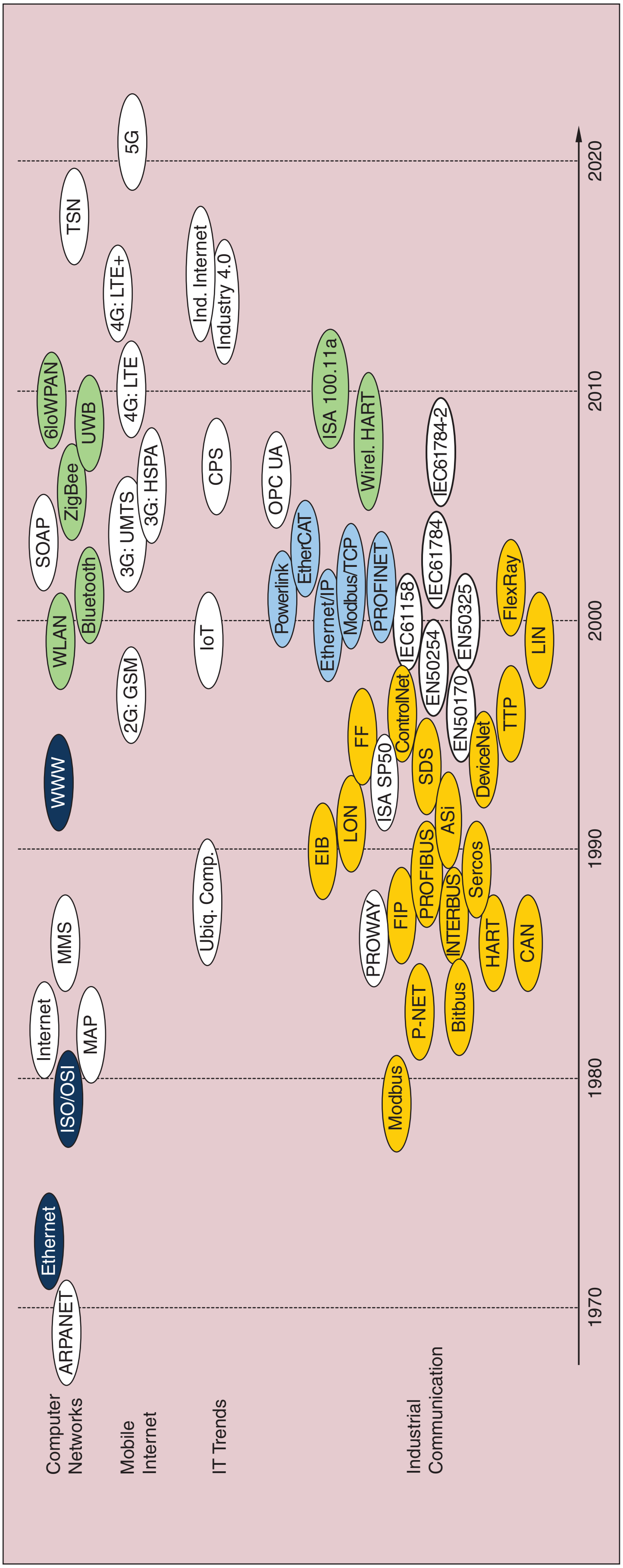

FIGURE 1 – The milestones in the evolution of industrial communication and related technology fields. 2G: second generation; 3G: third generation; 4G: fourth generation; ARPANET: Advanced Research Projects Agency Network; GSM: global system for mobile communication; ISO: International Organization for Standardization; LTE: long-term evolution; WLAN: wireless local area network; WWW: World Wide Web; ASi: actuator/sensor interface; EIB: European installation bus; CAN: controller area network; PROFIBUS: process field bus; FIP: factory instrumentation protocol; HART: highway addressable remote transducer; HSPA: high-speed packet access; LIN: local interconnect network; LON: local operating network; MAP: manufacturing automation protocol; MMS: manufacturing messaging specification; PROWAY: process data highway; SOAP: simple object access protocol; TCP: transport control protocol; TTP: trime triggered protocol; UMTS: universal mobile telecommunications system; UWB: ultrawide band; SDS: smart distributed system; PROFINET: process field net; EtherCAT: Ethernet for control automation technology.

One of the appealing features of the IoT concept is the promise to use everyday Internet-enabled devices as end points for accessing industrial data.

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Figure 2 shows the complexity of communication in industrial automation systems. There are application domains with different requirements, e.g., regarding real time, mobility, safety and security, explosion protection, availability, and so forth. Typically, up to a supervisory control and data acquisition (SCADA) system, industrial communication solutions are heterogeneous but are optimized to fulfill these requirements. They include fieldbuses, industrial Ethernet, and industrial wireless networks. Today, with the adoption of ICTs, local manufacturing clouds are increasingly used. Devices may be connected directly to this cloud. Manufacturing execution systems (MESs) and enterprise resource planning (ERP) solutions are also being integrated into the cloud, as is enterprise ICT. The partners along the value chain may use a private interenterprise cloud with limited access to organize the flow of the product and the information related to the product and its production processes. Finally, other enterprises or customers may access selected information using the Internet or a public cloud.

Overall, there is a tremendous change in specific technologies used for networking in an industrial context. However, what has not changed over time is that application relations exist bundling different categories of communication relations with specific sets of requirements, like hard time boundaries, isochronous communication, low jitter, high availability, and, of course, low cost. From an end user's point of view, the underlying network technologies are of less interest, as long as they meet these requirements. This is especially challenging when new application relations and application flexibility are introduced. A combination of effective runtime solutions with engineering approaches and network management is required.

The Future of Industrial Ethernet

Today, RTE has become a standard in the industrial automation domain. Unfortunately, there is currently no single standard but many different mutually incompatible implementations. The existing RTE solutions are based on Fast Ethernet and can be divided into three classes, which differ in the achieved real-time performance and the necessary extensions of the IEEE 802 standards, as shown in Figure 3 [33]. In class A, the real-time services are realized above the transport layer with cycle times in the range of 100 ms. Modbus-Interface for Distributed Automation (IDA), Ethernet/industrial protocol (IP), and Foundation fieldbus (FF) high-speed Ethernet are implementations that belong to this class. These were the earliest implementations of industrial Ethernet. They build on the entire transport control protocol (TCP)/IP suite and use best-effort bridging. In class B, the real-time services are realized directly on top of the media access control (MAC) layer by using approaches like

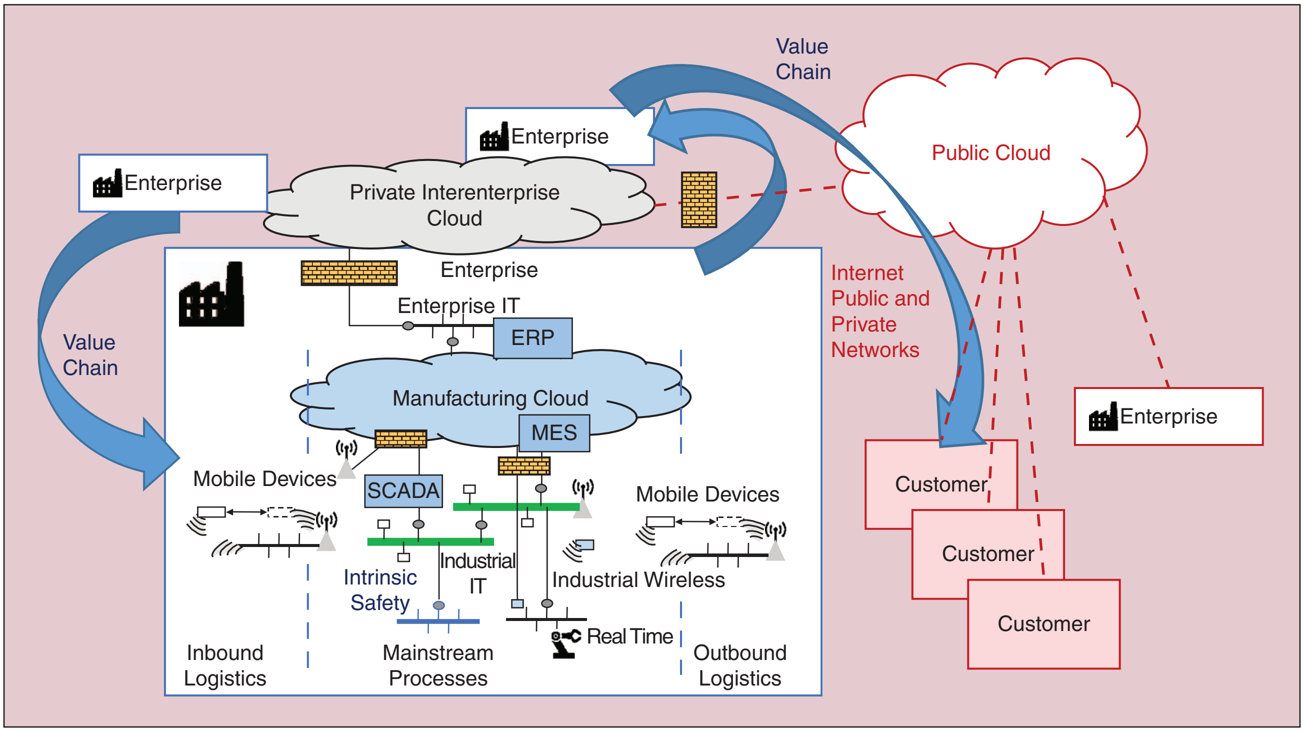

FIGURE 2 – The complexity of communication in industrial automation systems.

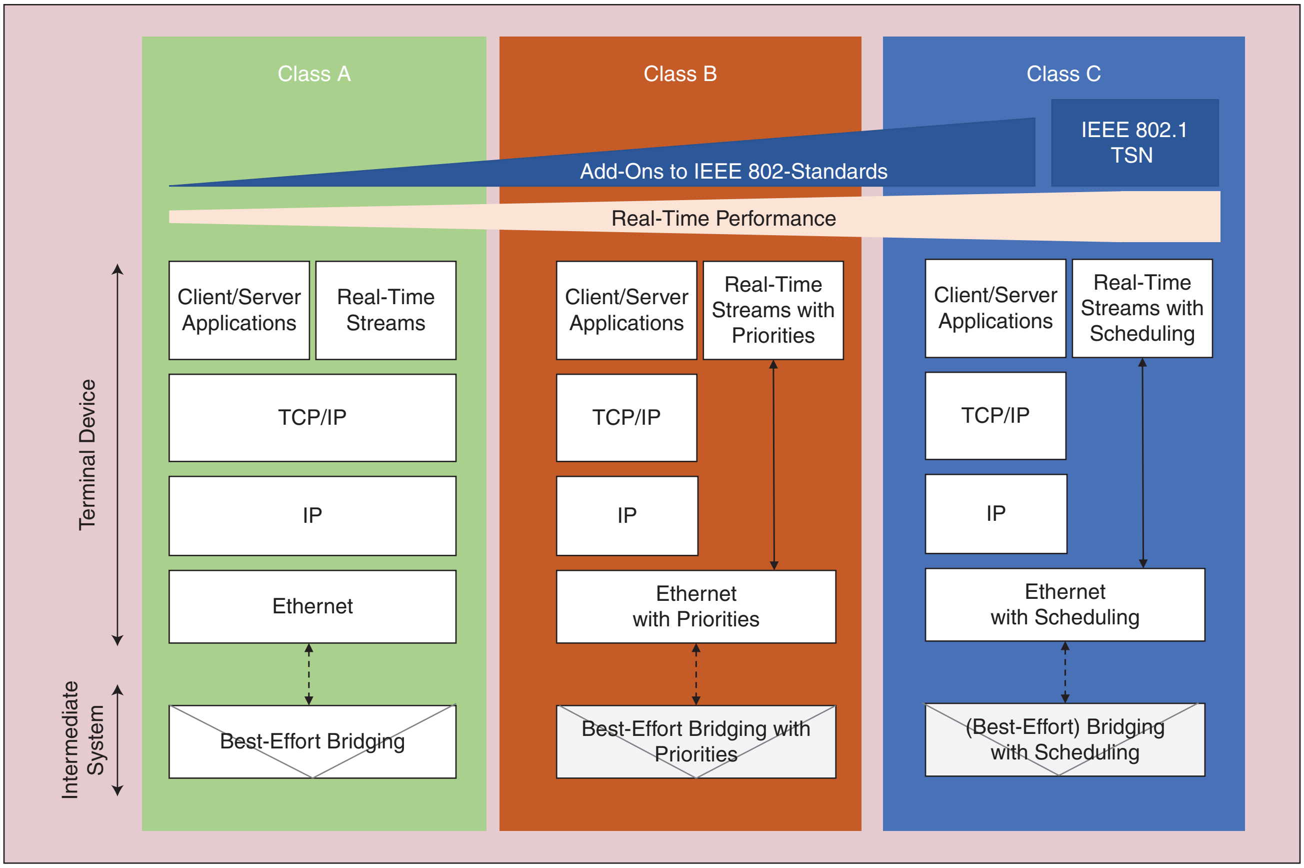

FIGURE 3 — The classification scheme for RTE.

prioritization and virtual local area network (VLAN) tagging to separate real-time data from best-effort traffic. The achievable cycle time using Fast Ethernet is in the range of 10 ms. An example protocol in this class is PROFINET Real Time. These RTE approaches still use standard Ethernet and best-effort bridging with priority support. Class C is the most powerful class, where the real-time communication capabilities are achieved by modifications of the Ethernet MAC layer, like strict communication scheduling and high-precision clock synchronization according to IEEE 1588 in the terminal devices as well as in the bridges [34]. The achievable cycle time lies below 1 ms. Representatives for this group are PROFINET IRT, EtherCAT, time-triggered Ethernet, Sercos III, and Ethernet Powerlink. Here, compatibility with the classical Ethernet standard was finally abandoned to achieve higher performance.

In the meantime, the development of standard Ethernet in the direction of a real-time communication system proceeded in different steps. The IEEE 802.3 Residential Ethernet Study Group was formed in 2004 to explore the need for an Ethernet specification for residential applications, with major contributions from companies like Broadcom, Nortel, Pioneer, Samsung, NEC, and Gibson Brands. This activity was merged into the IEEE 802.1 AVB Task Group in 2005, where key players like Intel, Broadcom, Marvell, and Samsung are involved. The most distinctive feature of AVB is the ability to guarantee upper time bounds to all priorities of all data streams, which is an improvement in comparison with standard Ethernet [31]. Because of the usage of a nonpreemptive scheduler, however, the worst-case latency is not better than best-effort bridging according to IEEE 802.1.

There is a tremendous change in specific technologies used for networking in an industrial context.

Furthermore, the maximum number of seven hops in a line topology is a big limitation for a lot of industrial automation applications. With the completion of the AVB standard in 2012, it became clear that streaming data can also be control data, like that used in automotive and industrial applications [35]. Therefore, the task group changed its name to TSN to better reflect the new, enlarged scope of its standards due to the expanded target applications.

The IEEE TSN Working Group currently aims to improve the reliability and real-time capabilities of standard Ethernet (IEEE 802.3, IEEE 802.1D). In particular, it addresses five essential shortcomings of the AVB standard that are nevertheless crucial requirements for industrial automation:

Although the work on TSN has not yet been completed, the potential for industrial automation applications is appealing.

- reduced latencies and accurate determinism
- independence from physical transmission rates
- fault tolerance without additional hardware
- support for higher security and safety
- interoperability of solutions from different manufacturers.

Table 1 shows the progress of the standardization of the seven current TSN-related standards. In total, 60 IEEE standards are correlated under TSN, including the 13 security-associated standards resulting in several different enhancements for standard Ethernet on layer 2 of the open systems interconnection (OSI) model. Inspired by the already known time slot procedure from PROFINET IRT, the time-aware shaper (IEEE 802.1Qbv) prioritizes different transfer queues in switches. By doing so, a guaranteed data transfer rate and latency can be accomplished even in high-load traffic situations. From a network structure viewpoint, the external or built-in Ethernet switch becomes the most important element, as it must implement all the novel traffic management strategies. With respect to the classification scheme for RTEs shown in Figure 3, TSN belongs to class C. The difference to existing class C RTE solutions, however, is that the necessary real-time support will be included directly in the Ethernet standard. Most of the standards shown in Table 1 are focused on enhancements of the bridging functionality.

While standardization is still in progress, several manufacturers are already able to show preliminary implementations of the new functionalities enabled by TSN. Against the backdrop of industrial automation, [36] demonstrated that these prototypic TSN functions ascertain a much higher determinism than comparable state-of-the-art components. However, the benefits of TSN come with several challenges, like higher configuration efforts, which could be solved, e.g., by autoconfiguration mechanisms [37] or with the help of software-defined networking (SDN) [38].

Although the work on TSN has not yet been completed, the potential for industrial automation applications is appealing. Contrary to previous developments toward RTE requirements and best practices for low latency from the automation domain are taken into account in the standardization of Ethernet itself, rather than putting them on top of the existing standard. This can be expected to make a huge difference in the technology acceptance. That is why user communities for industrial automation networks (e.g., PROFINET), middleware solutions [like OPC Unified Architecture (UA)], automotive communications (BroadR-Reach) or entertainment and infotainment systems already explore the capabilities of TSN.

The Role of 5G Networks in Industrial Automation

Digital transformation is the core of the fourth industrial revolution, and 5G network infrastructures will be key supporting assets. In the next decade, the manufacturing industry is expected to evolve toward a distributed organization of production, with connected goods (products with communication ability), low-energy processes, collaborative robots, and integrated manufacturing and logistics. These concepts are notably embodied under the Industry 4.0 paradigm and led to several application scenarios defined by a working group of the German Plattform Industrie 4.0 [39]. One driving application scenario is to form a network of geographically distributed factories with flexible adaptation of production capabilities and sharing of resources and assets to improve order fulfillment. Among other things, a reliable wide-area communication is needed for this use case. As a result of these transformations, vertical industries will have enhanced technical capacity available to trigger the development of new products and services. A *vertical* in this context represents a system of end-user entities belonging to a certain industry. They reside on top of the networked structure, using end-to-end communication services provided by the 5G network. The network offers a horizontal communication within a vertical structure and across them.

TABLE 1 — THE IEEE STANDARDIZATION PROGRESS OF THE OPEN TSN STANDARDS (SEPTEMBER 2016).

STANDARD	NAME	PROGRESS
IEEE 802.1AS-Rev	Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks	Working group
IEEE 802.1Qbv	Enhancements for Scheduled Traffic	Sponsor ballot
IEEE 802.1Qcc	Stream Reservation Protocol (SRP) Enhancements and Performance Improvements	Task group
IEEE 802.1Qbu	Frame Preemption	Sponsor ballot
IEEE 802.1CB	Frame Replication and Elimination for Reliability	Sponsor ballot
IEEE 802.1Qch	Cyclic Queuing and Forwarding	PAR* approval
IEEE 802.1Qci	Per-Stream Filtering and Policing	PAR approval

*PAR: Project Authorization Request.

In Europe, the next generation of networks is seen as a combined system covering both wired and wireless communication solutions, from private and public communication providers, offering virtualized and physical communication functions. The heterogeneity of such an approach is obvious, as providing a set of suitable application services to the end users will be a core requirement. It is also important to consider end users' requirements. In this context, end users are also regarded as verticals.

For the vertical factories of the future, such requirements have been discussed and put down in a white paper [40]. An analysis of the corresponding requirements shows that latency (below 5 ms), reliability, and density (up to 100 devices/m^2), along with tight constraints on territory and/or population coverage, are the most important performance targets 5G needs to achieve for supporting all possible services of the five investigated sectors. Moreover, with universal availability of instantaneous communications, high level of guaranteed quality of service (QoS), and cost levels appropriate to meet customers' expectations, 5G will pave the way for new business opportunities.

Furthermore, the requirements from the different verticals have been integrated into an overall vision of 5G [41]. A common structure has been developed consisting of different layers with specific levels of abstraction (Figure 4). Intelligent orchestration platforms will emerge from 5G networks and 5G architecture is expected to accommodate a wide range of use cases with advanced requirements, especially in terms of latency, resilience, coverage, and bandwidth. Another major challenge is to provide end-to-end network and cloud infrastructure in the form of slices over the same physical infrastructure to fulfill vertical-specific requirements as well as mobile broadband services in parallel. Such a slice can be seen as a logical network structure with components providing application functions and application relations among them. They contain QoS requirements for the single relations. A slice will be dynamically mapped to a (flexibly changing) network infrastructure. This mapping defines the configuration of the highly manageable infrastructure components. It will be deployed and changed on demand at runtime, always promising a resource-efficient network configuration.

In the next decade, the manufacturing industry is expected to evolve toward a distributed organization of production.

It should be noted that 5G is more than mobile Internet and, therefore, more than the simple extension of today's telecom networks. 5G needs to integrate different enabling technologies (e.g., mobile, wired, satellite, and optical), spectrum regulatory frameworks (e.g., licensed and unlicensed), and enabling capabilities (e.g., IoT, CPSs). To cope with the increasing diversity of wireless IoT systems in manufacturing, there is the need for novel capabilities to ensure the same level of reliability as offered in wired topologies. Given the nondeterministic behavior of the wireless medium, new challenges arise to manage the spectrum, in particular in environments where the number of wireless applications and devices are increasing. Compared to other industries, the wireless industrial Internet has one of the most stringent requirements in terms of latencies and reliability, in particular for use in time-critical closed-loop communication scenarios. Open questions still exist to manage

- coexistence of different wireless protocols and systems
- coexistence of different wired protocols
- interoperability between communication systems
- seamless engineering, adaptive during operation (based on previously collected real-life data).

For enabling the coexistence of wireless technologies, new protocols are needed to manage the cooperation of technologies working in the same frequency band or to spread the usage over multiple frequency bands in a coordinated and adaptive way. The main objective is to increase the capacity of current wireless technologies through self-organizing 5G technology and prepare for future scenarios where up to 100 sensors can be operated per cubic meter without compromising the availability of robots or connected machines.

Adoption of Internet technology will enable easier integration of workflows through standardized interfaces. Each of the workflows may have different requirements with respect to bandwidth, latency, and availability, and, as a result, the cost for networking should be linked to the needs. In addition, end-to-end communication may require the integration of public cellular networking technologies (such as 5G) with private networks (such as picocells or meshed networking topologies). The concepts of network virtualization, SDN, and distributed cloud resource management can be leveraged to give the factory operator a unified view on the network. There is the opportunity for the 5G community to extend the management capabilities beyond the networking aspects and include networked services for security, data analytics, and cloud/edge computing.

Harmonization Above the Networks

The previous sections showed that communication infrastructures in automation systems are complex and are getting even more complex and even more heterogeneous. Coming back to the starting point of this article, i.e., the transfer of information between different entities in an industrial automation system, it is evident that communication networks alone will not be sufficient. The actual transport of information is only one aspect. Equally important are the description and modeling of information as well as definitions how to access it. These aspects are not fully covered in communication

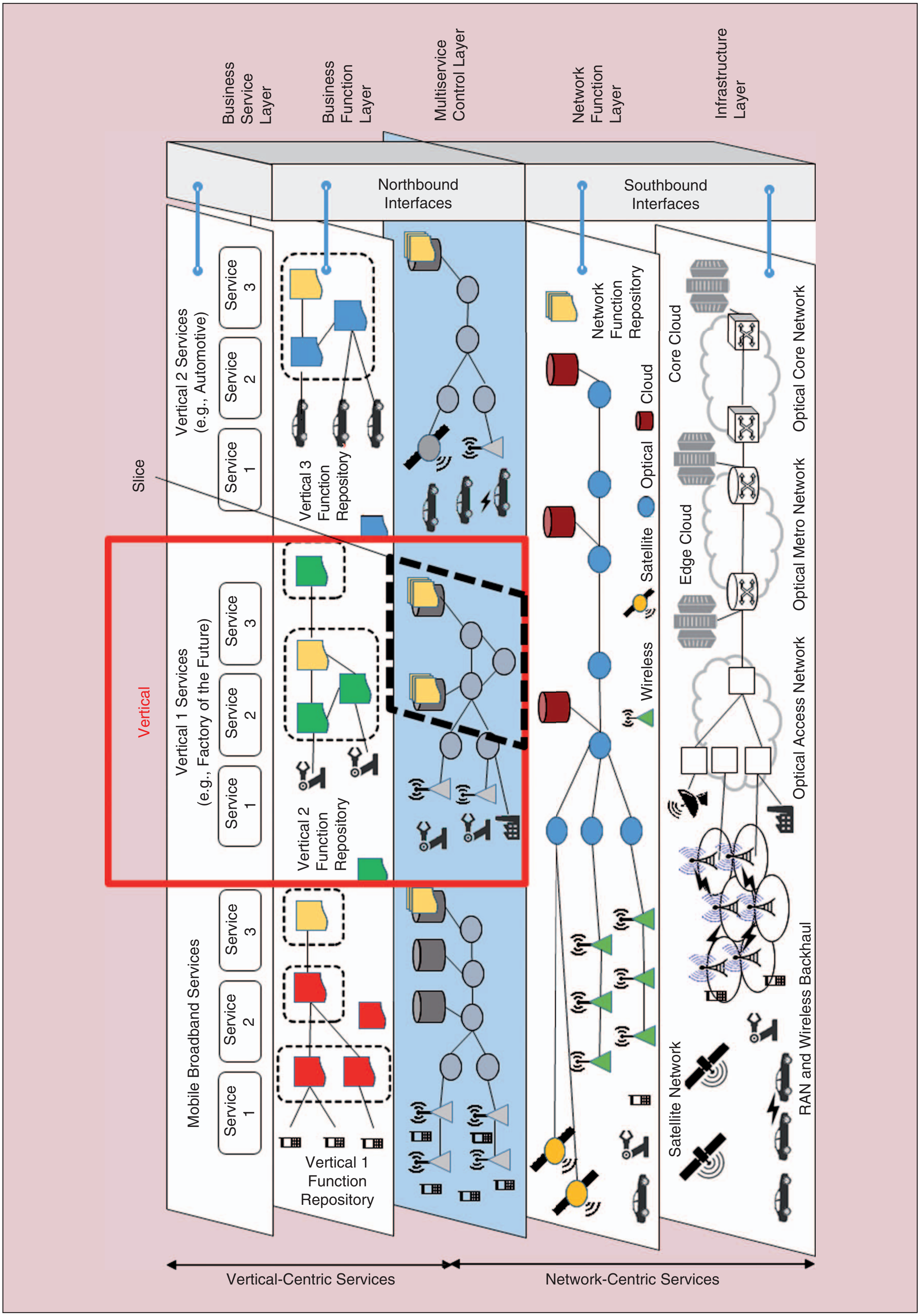

FIGURE 4 – The integrated 5G architecture for mobile broadband and vertical services [41]. RAN: radio access network.

standards, let alone treated in a harmonized way. They must be tackled above the actual networks.

Years ago, a generic communication model was established consisting of the three layers of networks, middleware, and application [42]. This general approach is still valid and even more than before (Figure 5). The uppermost layer is built by the application functions that need to be interconnected, the middle layer covers the (partly application-agnostic) communication services and the middleware management services, and the lowest layer contains the transport-oriented protocols guaranteeing the required QoS.

Application functions and information models are the building blocks for actual business functions. In the terminology of service-oriented architectures, the higher-level business services are orchestrations of application functions. The application functions are more and more exposed via services. Pushed by the Industry 4.0 idea, these services and the related information models are under definition for different application domains and contexts.

Because the application functions should be applicable to different resources, they cannot rely on specific communication functions directly. Generic communication services are required. They will be provided by the middle layer. This layer benefits from Internet technologies such as web services or recent IoT-specific protocols. In addition, IT technologies adopted for automation purposes, such as OPC UA, will be used here [43], [44]. Which protocols will be used depends on the level of functional hierarchy according to IEC 62264-1, the resource capabilities, the QoS requested from the application, and so forth.

The transport-oriented technologies like fieldbuses, industrial Ethernet, and industrial wireless approaches provide a communication system guaranteeing the application demands regarding reliability, availability, real-time behavior, and so forth on one hand, and the flexibility and (self-)adaptability of future industrial automation and production systems on the other hand. Depending on these demands, varying along the functional hierarchy, the existence of one single system fulfilling all the requirements is doubtful. In addition, the resource capabilities of the connected components need to be considered [45], [46].

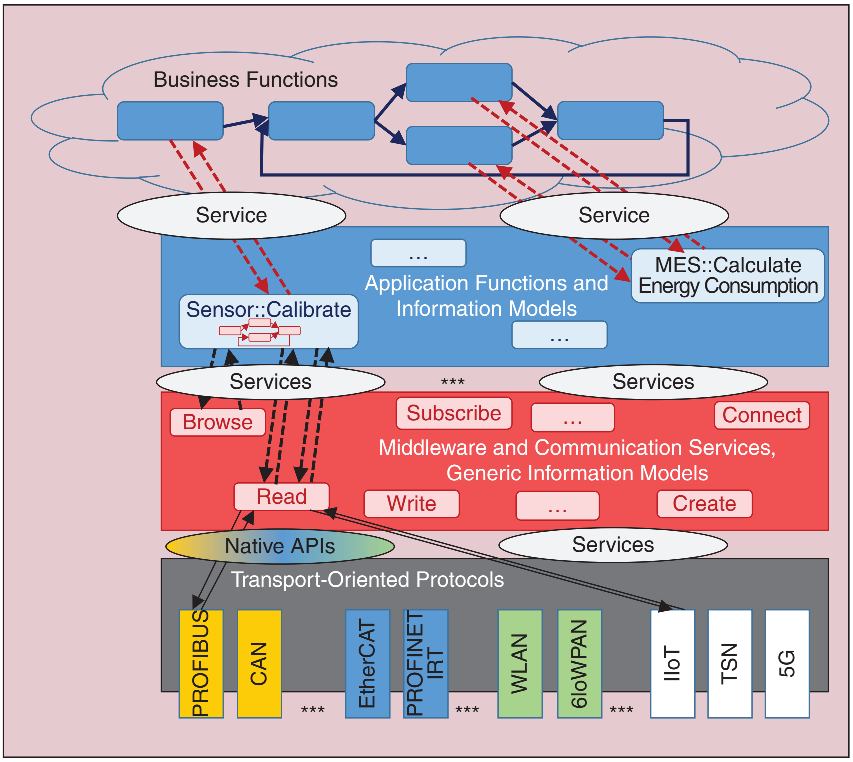

FIGURE 5 – The three levels of industrial communication: application, communication services and middleware, and transport protocols. API: application programming interface.

Intelligent orchestration platforms will emerge from 5G networks.

As described in the "The Role of 5G Networks in Industrial Automation" section, new technologies like 5G communication will penetrate this level as well. Will Ethernet and 5G mobile communication replace all existing industrial communication systems? Likely they will not. There will still be wired or wireless legacy systems, which will be in operation for years and maybe decades to come. To interconnect all of these, proxies and gateways will be needed [47], even though one of the aims of especially the development of Ethernet-based automation networks was to eliminate the need for gateways. Moreover, such gateways could be more than just protocol and data conversion units, they will have to act as smart entities controlling and representing the underlying automation (sub)system. Last but not least, they can also secure access to parts of the system [32].

The heterogeneity will rather increase. This calls for harmonized service layers and for network function virtualization (NFV) at these lower layers. But also for these legacy systems, services and data models on the higher levels should be consistent with the new networks, so that there is some form of uniform data exchange at the higher networking layers, irrespective of the underlying communication systems. IT in automation finally seems to be mature enough to meet this challenge.

Conclusions

Industrial communication systems underwent a long evolution with many

Network harmonization on a logical level is one of the challenges to face.

influences from technologies from outside the actual automation domain. The fundamental requirements always remained unchanged: to exchange information about industrial processes in a timely, reliable, and possibly uniform way. The absence of an optimum technology to meet these goals inspired engineers and stimulated a multitude of diverse and incompatible solutions, and the calls for unified approaches were heard but not heeded. Even when the technology basis shifted toward ICT standards, the variety of solutions remained and even got worse. Is there a hope that things will finally change back to the desirable? Perhaps there is.

For the first time, the requirements of industrial automation applications are taken into account in the development of a new ICT standard. Ethernet TSN has the potential to satisfy even demanding requirements without the need of dedicated add-ons tailored to the demands of automation. On top of such a novel network that can equally accommodate both real-time and best-effort traffic, existing high-level automation protocols could be placed for backward compatibility or a middleware such as OPC UA that serves the needs of automation as far as functionality and data models are concerned but builds on established and widespread Internet technology for the communication services.

The massive interest of telecom industries in industrial applications is without precedence and a direct consequence of the adoption of IoT and CPS scenarios. Contrary to the development of Ethernet TSN, the possible application of 5G networks in automation is not an expression of a steady evolution but indeed rather disruptive. Nevertheless, it is unlikely that 5G will be able to satisfy all stringent automation demands for real time and completely replace dedicated industrial automation networks. Rather, it might work as a kind of backbone or to attach less critical data points. On top of mobile networks, however, the same higher-level protocols could be placed, as in the case of Ethernet.

What does this development mean for research and education? This, of course, depends largely on the viewpoint. From an application point of view, industrial communication needs to fulfill the requirements, nothing else. The specific technology is mostly out of scope of end users. They will rely on service providers guaranteeing QoS for the intended application, regardless if this is provided by networks they own themselves or by public or private networks. Network harmonization on a logical level, by defining generic communication services and adequate information models, is one of the challenges to face.

From a communication provider view, however, there might be still the need to further optimize or even develop specific industrial technologies, especially when harsh application requirements need to be met. The adoption of IoT technologies and concepts in automation will grow substantially. These technologies need to be evaluated and need to be further tailored to industrial automation needs. For 5G, similar tasks can be seen. The integration of end users representing the verticals is promising. One of the main challenges of future industrial communication will be the management of complexity and heterogeneity. NFV and the use of SDN could be enabling technologies to provide a flexible network topology and its monitoring and management to meet the requirements of the end users along the life cycle of an enterprise.

Biographies

Martin Wollschlaeger (martin.wollschlaeger@tu-dresden.de) studied electrical engineering at Otto-von-Guericke University of Magdeburg, Germany, where he received a Ph.D. degree in 1991 and a Habilitation degree in 2001 for research in automation and control system. He is a full professor at Technische Universität (TU) Dresden, Germany, for industrial communications and director of the Institute of Applied Computer Science, Faculty of Computer Science at TU Dresden. His research topics are industrial communication systems and automation networks, information modeling, middleware concepts, management of heterogeneous networks, life-cycle management, and semantic descriptions. He is actively involved in standardization activities at the German Commission for Electrical, Electronic & Information Technologies of DIN and VDE and with the International Electrotechnical Commission Technical Committee 65.

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Institute for Industrial Information Technologies as well as the Fraunhofer Anwendungszentrum Industrial Automation in Lemgo, Germany. He is one of the main initiators of the Centrum Industrial IT, which is Germany's first science-to-business center in the field of industrial automation. He initiated the SmartFactoryOWL, which is a research and demonstration factory for ICT-based automation technologies operated by Fraunhofer and the OWL University. His current research interests include distributed real-time systems, especially in the domain of intelligent automation.

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