Real-Time Networks and Protocols for Factory Automation and Process Control Systems

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I. INTRODUCTION

Information is the key element in modern factory automation and process control systems, and one of the most difficult tasks is to provide, distribute, and properly process it. Information transfer and processing in this scenario depend to a large extent on appropriate communication systems, usually referred to as "industrial networks." Significance, content, and properties of information may, of course, vary within a given application context. For instance, a distributed control system typically handles sensor and actuator information with stringent real-time requirements, whereas production planning needs to cope with huge amounts of data, such as those concerned with customer orders or bills of material, with more relaxed timing. The industrial networks deployed at the various hierarchical levels of automation systems thus have to meet different requirements, to ensure that timely and reliable data flows are maintained among the different components they connect, such as field devices, controllers, human–machine interface (HMI) systems, cloud computers, manufacturing execution systems (MES), and so on [1], [2]. According to the specific needs of the numerous application fields such as manufacturing, electrical power distribution, motion control, environmental monitoring, and chemical processes, to mention but a few [3], [4], industrial networks may have diverse architectures, traffic types, and performance.

This Special Issue provides a state-of-the-art view and investigates new perspectives in the context of industrial communication systems.

Developing appropriate technological building blocks for industrial communication has been a core issue of academic and industrial research in the past decades. The first type of industrial networks, called fieldbuses, started to appear in the early 1980s and reached their heyday around 1990. These were followed by real-time Ethernet networks around the early 2000s and, some years later, by industrial wireless networks. Given the long lifespan of industrial plants, all these communication systems are still available and in use, also in mixed configurations [5].

A multitude of research studies, both theoretical and applied, have been carried out over the years, deeply involving multidisciplinary scientific and industrial communities. Activities have focused on many aspects, such as the design of new protocols, the definition of information models, or more recently the adaptation of IT concepts for automation applications.

Digital Object Identifier 10.1109/JPROC.2019.2915391

Also, tremendous efforts have been made in defining comprehensive International Standards, in a context that was often influenced by strong commercial interests [6], [7]. Ultimately, the aforementioned activities had the goal to make information available and manageable in increasingly complex and more demanding automation systems.

Looking back, we recognize that the evolution of industrial networks has been impressive, not only from a technical viewpoint. Market success in the early years was slow and required an unprecedented collaboration of competing automation vendors in joint technology marketing and further developments. Today, it is estimated that some hundreds of millions of nodes are deployed around the world in applications of whatever type. The market values are in the order of tens of billion USD, with high compound annual growth rates (CAGR) [8]–[10].

The industrial automation scenario, however, is continuously evolving. Industry 4.0 and Industrial Internet of Things (IIoT) are revolutionizing the manufacturing scenarios, enabling new production strategies, characterized by better efficiency, flexibility, rapid answers to the market requests, and energy efficiency [11], [12]. This poses new challenges to industrial networks, which are requested to provide better performance in terms of timeliness, reliability, security, and connectivity [13]. On the other hand, new communication technologies, being developed for the information technology (IT) world, also offer promising chances for the further evolution of automation systems.

This special issue addresses topics of prominent importance in the context of industrial communication systems. It provides a comprehensive state of the art and investigates new perspectives, such as time-sensitive networking (TSN), 5G systems for industrial automation, and networks for IIoT applications. This special issue comprises 13 invited papers, authored by selected teams of researchers and practitioners from academia and industry, who are well recognized worldwide experts in their fields.

II. OVERVIEW OF THIS SPECIAL ISSUE

All the papers of this special issue have been conceived to be accessible to nonspecialists while remaining, at the same time, significant contributions for the research communities of the areas they cover. They deal with both theoretical and practical aspects, which may draw the attention of academic researchers, as well as that of application experts and practitioners, stimulating their collaboration.

A. Four Papers Address the State of the Art of Industrial Networks and Key Aspects Such as Coexistence With Information Technologies, Fault Tolerance, and Synchronization

"Industrial communication systems and their future challenges: Next generation Ethernet, IIoT, and 5G" by Vitturi *et al.* presents a comprehensive overview of the diverse scenery of contemporary industrial networks. After introducing the state of the art and an essential market analysis, this paper addresses new perspectives and trends for future development, focusing on novel technologies and standards such as the TSN, IIoT, and industrial applications of 5G cellular networks.

"Coexistence standardization of operation technology and information technology" by Felser *et al.* is concerned with standardization aspects. This paper takes into consideration the available standards for networks deployed in factory automation and process control systems, called operation technology (OT) networks, and investigates the coexistence with those of the IT. The proposed analysis shows that, although the requirements of the distinct network systems are considerably different, coexistence is achievable, and also that some standards of the two technologies can be successfully merged.

"Fault tolerance in highly reliable Ethernet-based industrial systems" by Alvárez *et al.* addresses an essential shortcoming of conventional Ethernet: the lack of appropriate services to fulfill the demanding requirement of reliability in distributed real-time control systems. Notably, it is not sufficient to employ fault tolerance mechanisms only in the actual Ethernet network infrastructures. Rather, also the nodes must be designed for reliability. The paper presents a survey of fault tolerance mechanisms to make Ethernet-based industrial networks reliable.

"Performance and reliability aspects of clock synchronization techniques for industrial automation" by Kerö *et al.* deals with synchronization aspects of distributed nodes connected to industrial networks, specifically, real-time Ethernet networks. The paper focuses on standards like precision time protocol (PTP, defined by the IEEE 1588) and the IEEE 802.1AS, used in the context of TSN. Also, the paper discusses the causes of possible synchronization deterioration and presents some successful techniques to address such kind of problems.

B. Three Papers Are Concerned With Real-Time Wireless Networks for Factory Automation

"Real-time and reliable industrial control over wireless LANs: Algorithms, protocols, and future directions" by Tramarin *et al.* is concerned with the deployment of the IEEE 802.11 Wireless LAN for time-critical distributed applications, such as networked control systems. After providing an essential analysis of the IEEE 802.11 family of protocols, the paper focuses on the most effective techniques to improve the real-time capabilities of IEEE 802.11. In particular, it investigates rate adaptation algorithms and time-division multiple access (TDMA) techniques to access the transmission medium. The paper proposes also some practical implementation details of the proposed solutions, and, moreover, it provides an analysis of the open issues along with a discussion on future perspectives.

"WIA-FA and its applications to digital factory: A wireless network solution for factory automation" by Liang *et al.* presents the Wireless networks for Industrial Automation–Factory Automation (WIA–FA), a standard network recently approved by the International Electrotechnical Commission, based on the IEEE 802.11 physical layer for real-time industrial communication. The paper starts introducing the main features of WIA–FA such as architecture, topology, and protocol stack. Then, it focuses on performance and provides some meaningful practical examples of applications in which WIA–FA is deployed, such as control of robotic systems and automatic guided vehicles.

"High-performance wireless networks for industrial control applications: New targets and feasibility" by Luvisotto *et al.* addresses the design and implementation of a new generation of industrial wireless networks, capable of providing performance in the same order of magnitude of the (wired) real-time Ethernet networks. The paper first provides the details of the physical layer design and then reports the outcomes of an extensive experimental campaign carried out on a demonstrator system, based on software-defined radios, which showed the feasibility of the proposed high-performance wireless networks.

C. Three Papers Focus on the IEEE Time-Sensitive Networking, a Collection of Standards Conceived to Introduce Real-Time Capabilities in Ethernet That Can Be Extended to WLANs and 5G

"A perspective on IEEE time-sensitive networking for industrial communication and automation systems" by Lo Bello and Steiner presents a comprehensive overview of TSN in industrial communication and automation systems. The specific TSN standards and projects are discussed in detail, as well as their applicability to various industrial fields of application, with critical views and directions for future research.

"An introduction to OPC UA TSN for industrial communication systems" by Bruckner *et al.* introduces the status, open challenges, and research directions of the Open Platform Communication Unified Architecture TSN (OPC UA TSN). The authors anticipate that OPC UA TSN will reveal itself as a game changer in the field of industrial automation, being a candidate for establishing a holistic communication infrastructure, from the sensor to the cloud.

"Extending accurate time distribution and timeliness capabilities over the air to enable future wireless industrial automation systems" by Cavalcanti *et al.* addresses the extension of the TSN to wireless systems for industrial communication. New generation wireless networks are specifically considered, such as IEEE 802.11ax and 5G cellular systems. Also, the paper presents a reference architecture for industrial automation conceived to integrate TSN capabilities over wired and wireless communication systems.

D. Three Papers Address Industrial Internet-of-Things Protocols and Applications

"6TiSCH: Industrial performance for IPv6 Internet-of-Things networks" by Vilajosana *et al.* looks into the convergence of operational and information technologies in industrial applications. Traditional wireless industrial networks based on time-slotted channel hopping are reliable and energy efficient, but were originally designed to meet the requirements of automation systems from a decade ago, and are not suitable for IP compliance or standardized network management and operation. This paper introduces ongoing standardization work by the Internet Engineering Task Force to ultimately bridge the performance of industrial solutions with IP-compliant networks.

"Wireless network design for emerging IIoT applications: Reference framework and use cases" by Liu *et al.* is also concerned with wireless networks that have played a subordinate role in traditional automation systems but are gaining importance in the context of the IIoT. The design of wireless systems requires close cooperation between OT engineers, IT system architects, and network planners. Based on four application examples, the paper discusses a novel reference framework for wireless system design in IIoT use cases. The idea is to provide a generic design process to assist OT engineers to better recognize wireless communication challenges in their plants and to help industrial IT specialists to come up with efficient wireless solutions to meet demanding needs in factory environments.

"Toward cloud-assisted industrial IoT platform for large-scale continuous condition monitoring" by Wang *et al.* describes how modern IoT technologies may be used to enhance process control systems to fill a gap left by traditional process monitoring systems: the inclusion of device and process characteristics for accurate condition monitoring. State-of-the-art industrial communication systems lack performance to deal with a large amount of related data. The approach discussed in the paper integrates existing communication infrastructures into an IIoT and private cloud architecture to perform streaming data analytics designed for fault detection and prediction. ■

Acknowledgment

The guest editors would like to thank the invited authors for preparing their valuable contributions and all the reviewers for their qualified continuous support in all the steps of the review procedure. They would also like to thank the Editorial Board of the PROCEEDINGS OF THE IEEE for giving them the opportunity to organize this special issue. Finally, they would like to thank J. Sun, Senior Publications Editor, and V. Daimle, Managing Editor, for their professional, precious, and kind assistance during the whole preparation of this special issue.

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ABOUT THE GUEST EDITORS

Stefano Vitturi (Senior Member, IEEE) received the Laurea degree in electronics engineering from the University of Padua, Padua, Italy, in 1984.

From 1985 to 2001, he was involved in the control and data acquisition system of RFX, a nuclear fusion experiment built in Padua within the framework of the European fusion research program, where he was the Head of the Automation and Informatics Group. Since 1994, he has been an Adjunct Professor with the University of Padua. In 2003, he founded the Institute of Electronics and Computer and Telecommunications, National Research Council of Italy (CNR-IEIIT) Padua Territorial Site, Padua, of which he is currently the Head. Since 2002, he has been a Senior Researcher with the CNR-IEIIT. He has been responsible for several research contracts stipulated with Italian companies. Also, he has been involved in several national and international projects, serving as a Local Coordinator in some cases, workpackage, and Task Leader in some other ones. The European Project IMPROVE, in which he was responsible for the National Research Council of Italy Unit, has been awarded the 2012 ENIAC JU Innovation Awards of the European Community. He has coauthored more than 130 publications, including 53 journal papers, ten book chapters, and more than 70 papers in peer-reviewed proceedings of international conferences. His current research interests include industrial automation systems and industrial communication networks, especially the design and implementation of real-time protocols.

Dr. Vitturi has been involved in the organization of several international conferences, serving as the Program Chair for the IEEE World Conference on Factory Communication System (WFCS 2015) and as the Track Chair in various editions of the IEEE Conference on Emerging Technologies and Factory Automation (ETFA), and as a Program Committee Member for several conferences such as IEEE INDIN, IEEE ICIT, IEEE ETFA, IEEE ISIE, and IFAC FeT. He is the Co-Chair of the SubCommittee on Industrial Communication Systems of the IEEE IES Technical Committee on Factory Automation (TCFA). He was a recipient of the Best Paper Award at the IEEE World Conference on Factory Communication System, WFCS 2016. He is an Associate Editor of the IEEE Transactions on Industrial Informatics and has been a Guest Editor of three special sections for the same journal. He served as a reviewer for several prestigious journals, including the IEEE Transactions on Industrial Informatics, the IEEE Transactions on Industrial Electronics, the IEEE Transactions on Automation Science and Engineering, IEEE Communication Letters, *IEEE Industrial Electronics Magazine*, IEEE Systems Journal, *Elsevier Computer Communications*, *Computer Networks*, and *Computer Standards and Interfaces*. He has been involved in the standardization activities of industrial communication networks since their beginning, as a member of the national committee TC65, and an Expert of the International Committee IEC SC 65C, WG 13 (Cyber Security). He has been responsible for the Italian Profibus Competence Center from 1997 to 2001 and has been an Honorary Member of the Italian Profibus Organization since 1998.

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General Chair of ISPCS 2007, WFCS 2008, 2010, 2012, 2015, 2016, 2019, ETFA 2020, and INDIN 2021. He was a recipient of three national innovation awards for research works in his team. His coauthored papers received best paper awards at the IEEE Conference on Emerging Technologies and Factory Automation in 2008, the IEEE Sensors Conference in 2010, *IEEE Industrial Electronics Magazine* in 2011, and the IEEE Workshop on Factory Communication Systems in 2014. He is a regular reviewer for several international journals, has been a Guest Editor for a number of Special Sections in various IEEE journals, is a past Editor-in-Chief of the *IEEE Industrial Electronics Magazine*, and an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS and IEEE SENSORS JOURNAL. He has been involved in the standardization of industrial communication systems for more than 20 years within the scope of IEC SC65 and its national and European mirror committees. In 2014, he was elected as an IEEE Fellow for his contributions to synchronization and security in automation networks.

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Dr. Pang is the Co-Chair of TC in the Technical Committee on Industrial Informatics. He is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS, and IEEE REVIEWS IN BIOMEDICAL ENGINEERING; a Guest Editor of IEEE ACCESS; and an Editorial Board Member of *Journal of Management Analytics* (Taylor & Francis), *Journal of Industrial Information Integration* (Elsevier), and the *International Journal of Modeling, Simulation, and Scientific Computing* (WorldScientific).