Guest Editorial
Special Section on Communications in Automation–Innovation Drivers and New Trends

THE evolution of automation systems has always been the result of continuous improvements to state-of-the-art systems, occasionally punctuated with significant paradigm and architectural changes that acted as innovation drivers. This happened with the industrial revolutions, which had in their origin the appearance of disruptive technologies, such as the steam engine and machine tools (first industrial revolution); electrification, mass production, and assembly lines (second industrial revolution); use of microprocessors and software (third industrial revolution).

The introduction of computers and software in the automation world, associated with the third industrial revolution, came along with the adoption of the computer integrated manufacturing concept, which defines a hierarchical and layered structure for the information flow on factory and process automation systems [1]. In this context, fieldbuses were designed to support frequent exchanges of small amounts of data under time, precedence, and dependability constraints. With the evolution of the technology, the complexity and functionality of the automation systems increased to a point in which the massive amount of information exchanged exceeded, in many cases, the capacity of traditional fieldbuses. For this reason, Ethernet was introduced on the lower layers of the automation world. Despite standardization and their wide adoption in industrial environments, industrial Ethernet solutions do not represent the ultimate achievement for Ethernet-based communication in automation. In fact, there is still room for future advancements, typically associated with performance improvements like for the support of real-time event-triggered control flows in EtherCAT [2] or the more efficient bandwidth utilization for star and tree configurations in the popular Profinet IRT RTE network [3].

Full-duplex Ethernet switches improved industrial communications compared with previous solutions [4]. However, the quality of service support they provided was not enough to cope with the latency bounds required by industrial applications, and several paradigms and protocols, both from the academia and industry, were proposed to address these limitations. For instance, the flexible time-triggered communications on switched Ethernet [5] and the hard real-time Ethernet switching [6] family of protocols were designed to support heterogeneous traffic types as well as dynamic reconfiguration and adaptation. Later on they were extended to support multihop communications [7], admission control [8], dependability and fault-tolerance [9], and standards-based stream reservations [10].

A further push in the evolution of real-time Ethernet came from automotive communications, starting in 2008, when BMW introduced the unshielded twisted pair 100 Mb/s Ethernet for diagnostics, thus drastically reducing the ECU software update (flashing) times. In modern cars, with their real-time and bandwidth greedy functionalities and services (e.g., multimedia/infotainment, advanced driver assistance systems, etc.), essential motivations are the need to reduce wiring, weight, costs, and the number of gateways, while ensuring interoperability, flexibility, and scalability for cross-domain communication [11].

In this context, the efficient integration in one network of multiple traffic flows with different arrival patterns and real-time requirements has been addressed by recent IEEE standards, such as the Audio Video Bridging (AVB) and the ones produced by the Time-Sensitive Networking (TSN) Working Group. These standards provide a rich toolbox for IEEE 802 networks, enabling them to achieve properties such as guaranteed packet transport with bounded latency, low packet delay variation, and low packet loss. Recent works address the schedulability analysis of AVB-based networks [12], also with support for scheduled traffic [13]. The TSN standards, among other things, dramatically push Ethernet as the main innovation driver for automotive communications, opening new application scenarios such as connected cars and autonomous driving (with higher levels of autonomy than those that are available in cars nowadays). Moreover, they are evolving into a promising solution for next-generation industrial communications [14].

Another main innovation in these early days of the fourth Industrial Revolution is the digitization of the manufacturing sector [15] and [16]. The main drivers of this revolution are the dramatic increase in data storage capacity, computational power, and connectivity (specially low-power wireless networks); the emergence of analytics and business-intelligence capabilities; the emergence of new forms of human-machine interaction (e.g. augmented-reality systems) and improvements in the interface with the physical world (e.g., advanced robotics, 3-D printing). In this scenario, the term Industrial Internet of Things (IIoT) designates a growing trend in the industry towards the adoption of Internet of Things technologies in order to increase the flexibility, dynamism, and efficiency of industrial processes. In an IIoT-like scenario, industrial processes integrate sensors and

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actuators, linked through local data networks to SCADA (supervision, control, and data acquisition) servers, as well as to cloud-based systems.

There are still several technological challenges that must be overcome before IIoT becoming a mainstream technology. One of these challenges regards the automation communication protocols, which are typically time-triggered and statically configured, thus limiting the traffic classes that they can service in an efficient way. In addition, many of them do not allow a direct interface between the production networks and the management networks, namely, the cloud, forcing the use of bridges, which hinder and limit access to data and increases the complexity of the network configuration. Finally, security at different levels of communication is one of the main concerns in IIoT [17].

IIoT has a potential strong synergy with software defined networking (SDN). SDN is a network management paradigm characterized by decoupling the control plane (i.e., the decisions about where the packets are to be sent) from the data plane (i.e., the hardware that carries packets forwarding). SDN can act as the open technology that manages the network platforms interconnecting the IIoT sensors, thus avoiding the constraints caused by the lack of interoperability between the current platforms [18]. However, the approaches that are suitable for meeting the QoS requirements on bandwidth and latency of large data centers [19] are not adequate for the automation requirements. Extensions to control and data plane protocols and technologies have been proposed to support multimedia traffic, such as the Real-Time Media North Bound Interface RTM-NBI [20], as well as to reduce the latency, improve the real-time behavior, determinism, and scalability of SDN networks.

The IIoT trend contributes to push the already increasing adoption of wireless technologies in automation even further. For instance, Bluetooth Low Energy (BLE) is a very attractive option for IIoT applications, thanks to its low cost, low energy consumption and widespread adoption in handheld devices, such as smartphones and tablets. For this reason, recent works addressed BLE in smart homes [21] and in industrial communications, introducing new features, such as real-time traffic support over master-slave mesh networks [22] or efficient broadcast configurations [23].

Wireless networks for automation systems have to meet the timing constraints of the supported applications, therefore the latency from the source node to the destination node has to be predictable [24]. Topology management can help [25] to achieve bounded delays while reducing energy consumption. Whenever needed, low power modes of wireless protocols can be optimally exploited through a careful tuning of the duty cycle [26]. Amendments to standards like IEEE 802.15.4e or IEEE 802.11n are designed to match the diverse requirements of different industrial application domains. Wireless networks are also becoming increasingly important in smart grids and electrical substations automation, where new standards, such as the IEEE 802.11ac, shall cope with strict requirements on latency, throughput and coexistence [27]. However, as for their wired counterparts, the publication of wireless standards is not the end of the story, but instead, it is the starting point for investigations aimed to push forward either the technology performance bounds or their application domain boundaries. Many recent approaches in the literature dealt with different research aspects, proposing scheduling techniques, either based on TDMA or CSMA, redundancy techniques to improve reliability [28], load balancing [29] for improving flexibility, cooperative relays and network coding [30]–[32], multichannel communications [33], and MAC-based [34] or fuzzy-based techniques to provide safety and quality of service [35].

The papers in this Special Section address many of the research issues previously mentioned.

The paper “A Dynamic Rate Selection Algorithm for IEEE 802.11 Industrial Wireless LAN” by F. Tramarin, S. Vitturi, and M. Luvisotto proposes a novel rate selection technique for industrial wireless networks called RSIN, which aims at satisfying the traffic real-time constraints while minimizing the transmission error probability. RSIN aims to find the number of attempts and the relevant sequence of rates to be used for the transmission of a packet, with the goal of minimizing the error probability while meeting the packet deadline. The solution requires the ability to measure the signal to noise ratio value on a per-packet basis, which is feasible on several wireless network interface cards. Performance was assessed through both simulations and experiments on a Linux-based implementation on COTS devices. The results show that RSIN is a suitable technique for real-time industrial communication, which outperforms other rate selection solutions.

The paper “Experimental Evaluation of Seamless Redundancy Applied to Industrial Wi-Fi Networks” by G. Cena, S. Scanzio, and A. Valenzano investigates the advantages of using seamless redundancy to improve Wi-Fi behavior. The improvements that can be achieved through the use of redundant channels mainly depend on the assumption that physical channels are independent. To validate this assumption, the paper presents experiments of redundant wireless transmission using IEEE 802.11g over two separate channels in different environments. The results obtained both in a lab environment with uncontrolled noise and in an industrial environment show that, when Wi-Fi networks are properly configured, the correlation between channels is low and the difference between the theoretical estimates and measurements of the transmission latency and loss ratio is never greater than 10%. This proves that seamless redundancy can improve the predictability of wireless communication without the need for introducing big changes in the communication hardware.

The paper “Enhancing Communication Determinism in Wi-Fi Networks for Soft Real-Time Industrial Applications” by L. Seno, G. Cena, S. Scanzio, A. Valenzano, and C. Zunino presents a solution based on combining scheduling, retransmission and channel redundancy techniques to support soft real-time traffic in industrial wireless networks. Automated repeat request techniques are applied to increase the probability of successful delivery of messages. For message transmission and retransmission a centralized scheduling based on the Earliest Deadline First algorithm is adopted, while for channel redundancy seamless redundancy is exploited (based on the results of the previously described paper). Finally, to increase the probability of successful transmission, the unused bandwidth is utilized for retransmissions during runtime. Experimental results obtained with IEEE 802.11 COTS devices show that the proposed framework achieves significant improvements even under high packet error probabilities.

The paper "TDMA Versus CSMA/CA for Wireless Multihop Communications: A Stochastic Worst-Case Delay Analysis" by Q. Wang, K. Jaffres-Runser, Y. Xu, J. Scharbarg, Z. An, and C. Fraboul proposes two analytical models for wireless multihop communications and uses them to compare the timing behavior of TDMA and CSMA/CA access methods. Two topologies are considered, i.e., a linear one, with one flow and multiple relay nodes, and another with two flows and two relay nodes. The proposed analytical models allow to capture the delay distributions and extract the probabilistic worst-case end-to-end delays for both the considered access methods. An accurate simulator is used to validate the correctness of the presented analytical models. The results obtained show that the TDMA worst-case bound performance significantly depends on the selection of the TDMA slot duration and payload and that with a suitable configuration TDMA can significantly outperform CSMA/CA.

The paper "Efficient Ambiguity Resolution in Wireless Localization Systems" by B. Elwischger and T. Sauter proposes a novel method to overcome the problem of multiple solutions in multilateration. The paper focuses on Time Difference of Arrival (TDOA) localization and compares various algorithms, such as direct computation and iterative approaches. As exact direct methods are prone to ambiguous solutions and iterative methods may not converge or be trapped in local minima, a variant of direct computation is proposed, where the overdetermined system of equations is split into subsets that can be solved exactly. Ambiguous pairs of solutions can then be resolved immediately, and the remaining solution candidates are combined using a weighted sample mean approach. This divide and conquer structure has high computational efficiency and lends itself to parallel implementation, which is beneficial in distributed sensor networks. Both simulation and experimental results show that the approach is viable and also applicable to other localization schemes than TDOA.

The paper "Characterising Multi-hop Aerial Networks of low-cost commercial-off-the-shelf (COTS) Multi-rotors" by L. R. Pinto, A. Moreira, L. Almeida, and A. Rowe, focuses on IEEE 802.11-based communication of COTS unmanned aerial vehicles (UAVs) to provide online video monitoring systems. Building on the results of extensive measurements, performed with two UAVs to assess the impact of distance, packet size, and orientation on the packet delivery ratio, a model for the UAV-to-UAV link quality is derived, to evaluate the packet delivery ratio as a function of the link length. A TDMA-based multihop topology using other UAVs as relays is proposed to increase the network range. The performance of the proposed model was evaluated in real experiments and the optimal number of relays that provide maximum throughput was obtained.

The paper "Clock Synchronization over IEEE 802.11–A Survey of Methodologies and Protocols," by A. Mahmood, R. Exel, H. Trsek, and T. Sauter reviews clock synchronization (CS) in industrial wireless LANs. For many distributed real-time applications, synchronization of local time bases is a prerequisite, irrespective of the communication technology being used. CS is not usually a service provided by the communication system itself, therefore, many dedicated protocols have emerged over the years to implement synchronization on top of standardized networks. Wireless networks are particularly demanding in this respect, as the communication is less reliable and stable compared to wired communication systems. The paper looks into the different parameters affecting the performance of distributed clock synchronization in WLANs and compare existing techniques. Current trends are also identified, i.e., fault-tolerant, robust and secure clock synchronization.

The paper "Theoretical and Experimental Evaluation of Ethernet Powerlink Poll Response Chaining Mechanism" by M. Knezic, B. Dokic, and Z. Ivanovic presents a theoretical model to evaluate the real-time performance of Ethernet Powerlink (EPL) working both in the standard mode and in the PollResponse Chaining (PRC) mode. The PRC mechanism improves the network performance when nodes exchange small amount of data, especially in linear topologies. To characterize the timing parameters of EPL devices, an extensive measurements campaign on real network prototypes is performed. Then, the paper identifies some limitation of the current PRC, which is time-triggered, and suggests a modification based on the event-triggering paradigm to improve flexibility. To prove the feasibility of the proposed solution, this one is implemented and then validated considering different network configurations. Simulations run using the OMNeT++ framework are presented to assess the performance gain achievable using the presented solution.

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Lucia Lo Bello (M'02–SM'09) received the M.S. degree in electronic engineering and the Ph.D. degree in computer engineering from the University of Catania, Catania, Italy, in 1994 and 1998, respectively.

She is an Associate Professor at the University of Catania. She was also a Guest Professor at the University of Malardalen, Västerås, Sweden, in 2014.

Prof. Lo Bello received the IES 2008 Early Career Award. Currently she is the Chair of the IES Technical Committee on Factory Automation for the 2016–2017 term and a member at large of the IES AdCom. She has authored or coauthored more than 140 technical papers in the area of real-time embedded systems, automotive networks, industrial automation networks, and wireless sensor networks.

Moris Behnam received the B.Eng. and M.Sc. degrees in computer and control engineering from the University of Technology, Baghdad, Iraq, in 1995, and the MS.c., Licentiate, and Ph.D. degrees in computer science and engineering from Malarladen University, Västerås, Sweden, in 1998, 2005, 2008, and 2010, respectively.

He is currently a Senior Lecturer in the Network and Embedded Systems NES division, Malarladen University, where he is the Head of the NES division. His research interests include real-time scheduling, synchronization protocols, multicore/multiprocessor systems, distributed embedded real-time systems, cloud computing, and virtualization techniques.

Paulo Pedreiras (M‘03–SM’16) received the Licenciatura degree in electronics and telecommunications engineering from the University of Aveiro, Aveiro, Portugal, in 1997 and the Ph.D. degree in electrical engineering from the same university in 2003.

He is currently an Assistant Professor at the University of Aveiro, and a Senior Researcher at the Instituto de Telecomunicacoes, where he coordinates the Embedded Systems Group – Aveiro. His main research interests include distributed embedded systems, real-time networks, real-time operating systems, intelligent transportation systems, and mobile robotics.

Thilo Sauter (M’93–SM’09–F’14) received the Dipl.-Ing. and Ph.D. degrees in electrical engineering from TU Wien, Vienna, Austria, in 1992 and 1999, respectively.

Until 2003, he led the Factory Communication Group at the Institute of Computer Technology. From 2004 to 2013, he was the Founding Director of the Institute for Integrated Sensor Systems at the Austrian Academy of Sciences. Since 2013, he has been with the Center for Integrated Sensor Systems at the Danube University Krems, Krems an der Donau, Austria, and an Associate Professor at TU Wien since 2014. His current research interests include smart sensors and automation networks with focus on real-time, security, interconnection, and integration issues.