Guest Editorial Special Section on Communication in Automation

Gianluca Cena, Françoise Simonot-Lion

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AS A MATTER of fact, the availability of low-cost devices provided with non-negligible processing power and increased reliability is changing deeply everyone's life. For example, more and more control and monitoring functions can be currently realized by means of computer-based systems. Moreover, in the past decade intensive studies have been carried out about high-performance communication systems, which concern real-time data exchanges, quality-of-service, validation techniques for distributed applications, and so on. As a consequence, the deployment of applications is nowadays moving from centralized solutions to distributed architectures, where processing (and working, as well) is spread across many intelligent devices. Despite this trend, it has been observed mainly in traditional application domains, e.g., banking, finance, trading, etc., where the main challenges are preserving the integrity of information and ensuring the security of transactions, it is also affecting in a significant way automation environments: automated factory and process control systems, embedded and distributed control in transportation systems (railway, avionic and automotive), home/building automation, ambient assistant living, medical monitoring, and so on.

This Special Section basically targets industrial and control applications, where the main issues are providing the level of flexibility demanded by modern production plants and an appropriate level of performance, so as to meet productivity objectives, while ensuring at the same time safety properties and reduced production costs. These seemingly conflicting goals have led industrial automation systems to become everyday more and more complex, which also means that a growing amount of information has to be exchanged under specific timing and reliability constraints through suitable communication systems. Therefore, the need has arisen to investigate advanced communication technologies suitable for automation environments. Obviously, properties such as bounded end-to-end response times, low jitters on cyclic data exchanges, freshness of data, temporal and spatial data consistency and so on [1] have still to be ensured. The verification of these properties can be achieved either in a deterministic way for strict real-time functions or, when the environment is partially known and subject to hazards, according to a probabilistic approach.

Let us recall quickly the main steps that characterized the transition from old-fashioned automated manufacturing systems to the current state-of-the-art industrial plants. The interested reader can find a brief survey on the subject in [2] and [3]. The biggest advance likely took place at the end of the 1970s, when digital serial communication techniques were introduced at the shop floor to replace point-to-point analogue links between controllers and field devices. In particular, fieldbuses have been the most popular way for connecting equipment in automated control systems for two decades. Thanks to their peculiar *medium access control* (MAC) techniques, conceived to guarantee deterministically bounded transmission latencies, this kind of networks became the *de facto* standard whenever real-time process data had to be exchanged. At the same time, they succeeded to provide the required degree of flexibility, by enabling remote configuration, management, and diagnostic operations. The main problem with fieldbuses was that they were confined to the factory automation world only. As a consequence, performance did not increase in a noticeable way over the years, while costs remained quite high. What is worse, the high number of different solutions, each of which backed by a specific manufacturer, implied an unsatisfactorily low degree of interoperability among them, and with the office automation world as well.

The next big step concerning communication for automation took place with the advent of the new millennium. Basically, it consisted in the understanding that no tangible improvement would have been possible for factory automation environments, unless some synergy were made with the office automation and consumer worlds. From a practical point-of-view, this meant applying technologies derived from ICT—with the required changes—to industrial and production plants. This led initially to the birth of the so called "industrial Ethernet" solutions. In practice, a new class has been introduced of field networks that rely for the lowest layers of their protocol stack on conventional Ethernet. The immediate advantages of such a choice were a simpler, unified cabling, interoperability at the physical and frame level, and a clear leap on transmission speeds (100 Mb/s and beyond).

As Ethernet is intrinsically unable to ensure deterministic behavior, not even when full-duplex solutions based on switched local area networks (LANs) are taken into account, suitable modifications had to be brought in order to grant the required level of determinism. This implied that several solutions appeared, which basically differ in the approach they followed to support real-time data exchanges. The performance these solutions feature, in terms of the amount of process data that can be exchanged in the unit of time, are very high, usually one or two orders of magnitude higher than conventional fieldbuses. In some cases, cycle times can be as low as 100 microseconds (or less), with jitters under 1 μs, which makes them perfectly suitable for motion control. Moreover, despite they usually cannot be connected directly to the Ethernet factory backbone, a satisfactory degree of connectivity is often ensured.

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More recently, wireless communication technologies have been increasingly considered as a means to increase flexibility and lowering cabling costs in industrial environments. In the case of equipment with moving parts, they could also improve long-term reliability. Basically, such a kind of networks can be used for two different purposes, i.e., either to support real-time process data exchanges between controllers and decentralized peripherals at the shop floor or to collect environmental data from a multitude of sensors spread over a large plant area. In the former case, the use of wireless LANs (WLANs), such as those based on IEEE 802.11 technology is often envisaged [4], because of the high bit-rate that achieves short transmission latencies. Obviously, the conventional carrier sense multiple access/collision avoidance (CSMA/CA) mechanism these networks rely on is not natively able to show real-time behavior. Besides recent standard solutions, which add quality-of-service (QoS) mechanisms to WLANs (i.e., traffic prioritization and parameterization in 802.11e), in the past few years, a number of works have appeared in literature aimed at introducing new approaches to enhance determinism in wireless networks. In the latter case, instead, wireless sensor networks (WSNs), such as those based on IEEE 802.15.4 low-rate wireless personal area networks (LR-WPANs), are often taken into account as a means to gather large amounts of data from the plant easily and inexpensively. Thanks to energy harvesting techniques, self-powered autonomous wireless nodes can be conceived, which have (in theory, at least) unlimited lifetime. Concerning WSNs, one of the most interesting aspects research activities now mainly focus on is about the ways latencies can be reduced to an acceptable level for industrial control applications.

It is worth noting that communication in automation is not confined to industrial contexts only. Besides automated factory and process control environments, two very important fields which most benefit from advanced digital communications technologies are automotive applications and building automation systems. Concerning the automotive domain, a main challenge is to ensure safety at the lowest cost [5]. In the near future, the international draft standard ISO WD 26262 [6] (that derives from the generic standard IEC 61508 [7]) will impose to verify that, for each embedded function characterized by a given *automotive safety integrity level* (ASIL), the distributed system supporting that function has the required properties according to the specified ASIL. In this context, the communication architecture [8] has to be carefully specified and timing properties have to be evaluated through models and confirmed by an intensive testing process. It should be noted, that for critical in-vehicle systems like, e.g., the chassis domain, the time triggered approach [9] brings well-suited solutions—despite their lack of flexibility. Next-generation X-by-wire systems will require extremely high levels of determinism and, mostly, fault-tolerance, at a cost that should remain acceptable for mass production. The TTP/C [10] and FlexRay [11] networks, or the basic software of AUTOSAR [12] devoted to communication, are good candidates for the implementation of such systems. Unlike industrial automation systems, interoperability with the office automation world is not a requisite in this case.

A final mention has to be done to the upper layers of distributed industrial automation systems. Again, concepts borrowed from the ICT world have been applied here in the past decade, such as for instance XML, UML, mobile agents and so on, in order to allow system integrators to design, deploy and maintain complex automation systems easily, inexpensively, and effectively. By adopting description languages and processing platforms that are common to the information systems already deployed in office automation environments, control and supervisory applications can be rapidly developed. Thanks to the seamless cooperation between applications and devices, the concepts of "global integration" and "complete connectivity," whose basic ideas first appeared more than two decades ago in the context of the *computer integrated manufacturing* (CIM) model, can now be effectively exploited.

This Special Section on "Communication in Automation" presents seven papers that deal with relevant aspects pertaining to the topics highlighted above. Quite obviously, they cannot provide a comprehensive overview on the whole subject (nor they are intended to). Nevertheless, they are able to give some useful insight about the most recent advances in this field. The papers included in this Special Section cover a quite wide spectrum of topics, ranging from wired industrial communication systems aimed at providing strict real-time behavior, to hybrid systems obtained by adding wireless extensions to the wired backbone, to completely wireless industrial solutions able to ensure high determinism. Novel approaches have been described as well, aimed at improving either routing in WSNs or CSMA schemes so as to make them more suitable for the use in industrial automation systems. Finally, a testing approach for safety-critical automotive networks has been introduced and formally validated, and an agent platform defined and implemented that requires less resources, while granting higher performances and a methodology proposed and verified for assessing the performance of WSNs under cross-channel interference.

Building on the fieldbus technology, that was introduced in automated factory environments more than two decades ago, Real-Time Ethernet (RTE) systems have been recently proposed as the second-generation industrial communication systems. Several different approaches have appeared for RTEs during the past years, most of which conceived for specific application domains. From the users' point-of-view, the transition from a proved fieldbus to an RTE solution only makes sense provided that several system properties are improved significantly in comparison to the state-of-the-art.

The paper "*A Proposal for a Generic Real-Time Ethernet System*," by Jasperneite *et al.*, proposes a new architecture for an advanced RTE system that is based on three building blocks, i.e., topology-based addressing, optimized datagram transfer, and synchronous scheduling on top of the Ethernet protocol. Such techniques permit reduced deployment efforts, which rely on the knowledge about the physical network topology, and achieve increased levels of both performance and determinism thanks to a highly-efficient data gathering technique and the traffic light principle, respectively.

Besides conventional (wired) RTE solutions, the industrial communication scenario is currently experiencing the introduction of wireless networks at all levels of factory automation systems. The benefits that derive from such technologies are manifold, even if wireless systems cannot be thought of as a complete replacement of wired networks. Rather, they will be adopted more and more in the near future to build up hybrid wired/wireless configurations. In particular, it is envisaged that wireless networks may be employed to implement extensions of wired systems—including the existing installations.

The paper "*Analysis of Ethernet Powerlink Wireless Extensions Based on the IEEE 802.11 WLAN*," by Vitturi *et al.*, considers the wireless extensions of Ethernet Powerlink—a very popular Real-Time Ethernet solution—by means of IEEE 802.11 WLANs. In particular, it focuses on a widespread network configuration and addresses two kinds of extensions that are based on bridges and gateways, respectively. In this paper, an analysis of hybrid networks is also provided aimed at evaluating the most relevant performance indexes. As reliability represents a critical issue for wireless networks, the analysis takes into account interference, as well as fading, in the wireless segment. The results, obtained from theoretical analysis and validated through numerical simulations, provide useful insights on the overall performance of hybrid networks.

The next step concerning the use of wireless technologies in factory environments is, obviously, the adoption of completely wireless solutions. The deployment of such technologies in industrial networks is very promising, mainly due to their inherent flexibility. However, current wireless solutions lack the ability to provide deterministic, low-delay data exchange services, as required by many industrial applications. Moreover, the non-negligible level of interference generated by industrial equipment limits severely the network extension. Multihop solutions, when combining frame forwarding with higher node density, have the potential to provide the required coverage, while keeping the radio communication range short. However, in such solutions, the medium access time in each traversed node, as well as the forwarding delay (i.e., the time required for packets to be processed, switched, and queued at each node), additively contribute to the end-to-end delay.

The paper "*Time Driven Access and Forwarding for Industrial Wireless Multihop Networks*," by Marchetto *et al.*, describes time-driven access and forwarding (TAF), a solution conceived for guaranteeing deterministic delays at both the access and forwarding levels in wireless multihop networks. The properties of TAF have been analyzed, and its performance in industrial scenarios assessed.

Besides conventional high-performance WLANs, wireless sensor networks are also being considered for the use in industrial environments, mainly to deal with the need to acquire large amounts of environmental data to carry out, e.g., preventive maintenance. Ensuring timely delivery of information in WSNs can be achieved in several ways and, in particular, by means of proper routing mechanisms.

The paper "*Enhancing Real-Time Delivery in Wireless Sensor Networks with Two-Hop Information*," by Chen *et al.*, proposes a two-hop routing protocol for real-time wireless sensor networks based on neighborhood information. The same approach of mapping the packet deadline to a velocity is adopted, as in SPEED. However, the routing decision is now made based on a novel two-hop velocity integrated with energy balancing mechanisms. Initiative drop control is embedded, to enhance energy utilization efficiency, while reducing packet deadline miss ratio. Simulation results show that the new protocol leads to lower packet deadline miss ratio and higher energy efficiency than existing popular schemes, and indicate a promising direction for supporting real-time QoS in WSNs.

Due to flexibility, simplicity, and robustness of random access schemes, CSMA-based protocols constitute the heart of modern media access control mechanisms for wireless networks, as well as for some building automation network (e.g., LonTalk). Despite being unable to ensure strict real-time behavior, such an approach may still be profitably employed in several industrial environments, when constraints on transmission latencies are not too tight.

The paper "*Average Utilization of CSMA with Geometric Distribution in Varying Load Conditions*," by Miśkowicz, addresses the performance of fixed-size contention window CSMA protocols with geometric distribution for the slot selection probability (G-CSMA). This scheme, also known as Sift, was initially proposed for large-scale event-driven wireless sensor networks. The goal of this paper is to evaluate meaningful performance indices (throughput, protocol capacity, collision rate and mean access delay) for G-CSMA in the context of both data-centric dense sensor networks and node-centric industrial automation systems. An analytic approach based on stochastic analysis with simulative validation has been applied. To demonstrate how the protocol is able to cope with bursty traffic, the average throughput defined over a specified range of workloads was taken into account. Then, G-CSMA has been compared to conventional CSMA schemes with uniform distribution. Results show that G-CSMA is an overload-tolerant event-driven MAC protocol, since the average throughput may be kept high for a wide range of workloads.

Besides the industrial networks described above, very important examples of communication solutions defined explicitly for supporting control systems are found in the automotive domain. Because of the severe safety requirements of vehicle control systems, new-generation solutions such as TTP/C and FlexRay were mainly conceived to feature an unprecedented degree of determinism and reliability, much higher than in automated factory applications. This also means, that in such networks the ability to carry out proper testing is of utmost importance, even during the normal operation. Deterministic replay is a common technique used for testing distributed systems in order to reproduce a scenario and drive the system under test to a given state.

The paper "*Safely Stimulating the Clock Synchronization Algorithm in Time-Triggered Systems—A Combined Formal and Experimental Approach*," by Armengaud *et al.*, describes an approach where an *a priori* defined bus traffic is replayed to influence the clock synchronization mechanism. Beyond testing this distributed mechanism itself, the aim is to draw conclusions on the nodes' bus receiver operation. Since these replay activities are part of a transparent online test procedure, it is important to ensure that they do not represent a threat for proper system operation. A generic formal proof is presented for TTP/C, while for the case of FlexRay it has been formally proven that the system precision can be bounded according to the replay operation applied. The approach has been confirmed and illustrated through experimental results.

While all the previous papers focus on the lower layers of the communication stack, and deal with the mechanisms to be put into effect for achieving real-time behavior, there is no doubt that the upper layers in industrial distributed applications are important as well in order to provide a high degree of flexibility, yet maintaining the required level of performance. Recently, distributed agents are being adopted in automated control systems, where they are used for monitoring, data collection, fault diagnosis, and control purposes. However, the existing agent platforms do not always fulfill the requirements of automation applications concerning real-time properties and resource usage. Often, they offer much more functionality that strictly required, and this introduces significant overhead on both design efforts and runtime resources.

The paper "*Software Agents in Industry: A Customized Framework in Theory and Praxis*," by Theiss *et al.*, describes the architecture of a resource-efficient platform that relies on the well-known concept of agent and discusses several performance issues. The platform has been implemented both in Java and in some variants of C++. Results of several performance tests are presented and compared to the established agent platform JADE. Finally, a practical use case is shown, where the platform is used to drive a hardware-in-the-loop emulation and testing environment.

When dealing with wireless communication technologies, such as, for example, IEEE 802.15.4, characteristics pertaining to the physical layer may affect suitability for the use in production environments in a noticeable way. Therefore, they have to be taken into account properly. As wireless industrial networks may comprise a large number of devices and transmission delays increase with the number of nodes, a possible solution to keep latencies low is using multiple radio channels to implement several small-sized communication cells. Although in IEEE 802.15.4 radio channels do not overlap, recent literature showed that interference may actually occur.

The paper "*Coexistence Issues of Multiple Co-Located IEEE 802.15.4/ZigBee Networks Running on Adjacent Radio Channels in Industrial Environments*," by Lo Bello *et al.*, provides a better understanding of cross-channel interference in co-located IEEE 802.15.4 industrial networks and proposes a general methodology for assessing their performance under different conditions. This methodology allows a network designer to carry out accurate on-site assessments, and can be used in real industrial plants to perform measurements directly in the environment-under-test. A case study based on COTS IEEE 802.15.4 devices is presented, in order to show how the methodology can be applied to a real scenario. The results obtained by varying the number of interferers and some parameters at the MAC level are then discussed.

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GIANLUCA CENA, *Guest Editor*
Italian National Research Council, IEIIT-CNR
10129 Torino, Italy
(gianluca.cena@polito.it)

FRANÇOISE SIMONOT-LION, *Guest Editor*
University of Nancy, LORIA
54506 Vandœuvre-lès-Nancy, France
(simonot@loria.fr)

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Gianluca Cena (SM'09) received the Laurea degree in electronic engineering and the Ph.D. degree in information and system engineering from the Politecnico di Torino, Torino, Italy, in 1991 and 1996, respectively.

In 1995, he became an Assistant Professor at the Department of Computer Engineering, Politecnico di Torino and, in 2001, he joined the Italian National Research Council (CNR) as a Senior Researcher. Since 2005, he has been Director of Research with the Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni (IEIIT-CNR), where he is engaged in research activities concerning communications in manufacturing and automotive environments. He served as Program Co-Chairman for the 2006 and 2008 editions of the IEEE Workshop on Factory Communication Systems. He coauthored more than 80 technical papers in the area of computer communications. His current research interests include industrial communication systems, wired and wireless protocols, and real-time networks.

Dr. Cena is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS.

Françoise Simonot-Lion is a Professor of Computer Science at Nancy Université, Nancy, France. Since 1997, she has been the scientific leader of the Real Time and InterOperability (TRIO) research team, an INRIA project at LORIA Laboratory, Nancy. Its main research topics are on the one hand, modeling and verification techniques for the design of optimized real-time distributed applications under safety constraints, and on the other hand, specification of embedded services ensuring a real-time quality-of-service (scheduling of tasks and messages, real-time middleware, and frame packing). She served as Program Co-Chairman for the 2008 edition of the IEEE Workshop on Factory Communication Systems. She coauthored more than 70 technical paper in the area of real-time systems modeling and analysis. She is Co-Chair of the subcommittee "Automotive Electronic and Embedded Systems" of the IEEE Industrial Electronic Society (IES)—TCFA.