Guest Editorial Special Section on New Perspectives on Wireless Communications in Automation: From Industrial Monitoring and Control to Cyber-Physical Systems

WIRELESS communication is becoming increasingly important for industrial automation and many solutions have started to appear on the market. However, most of the available solutions target monitoring applications with slow refresh rates and with the downlink designed for best-effort traffic, thus neglecting actuators [1]. Critical communication applications are defined as applications that require high reliability, i.e., that data packets are delivered with very high probability within a certain deadline, to avoid serious consequences (bodily injury, human losses, severe environmental impact, or great financial loss). It is challenging to simultaneously provide low latencies (end-to-end delay) and high reliability, especially over wireless links, which are inherently unpredictable. Suitable solutions exist that work well in specific contexts. For instance, in the context of industrial wireless sensor and actuator networks (IWSAN), a priority-enhanced MAC protocol [2] enabling high-priority traffic to hijack the transmission bandwidth of the low-priority traffic proved to be able to efficiently handle different traffic classes with diverse latency requirements, thus significantly improving the delivery latency compared to the current industrial standards. In the same context of IWSANs, the use of network coding in a packet forwarding scheme proved to be effective for improving reliable downlink transmissions [3]. However, in general, availability and predictability remain two of the most important properties to be enforced in industrial automation systems, which makes the use of wireless communication a tough challenge. Moving toward control over wireless links, there is a huge gap between state-of-the-art solutions and what is actually needed in order to meet the industrial requirements, in terms of bounded latencies, high reliability, energy efficiency, security, dependability, and adaptivity. All this together might seem like an unrealistic target, as in the case of the first industrial fieldbuses in the early 1990s. Nevertheless, wired fieldbuses are now a central component when deploying modern automation systems. It is clear that wired fieldbuses do not provide unlimited range or unlimited capacity and they are not immune to bit errors in the physical layer. However, a careful and joint design of all communication layers with the common goal of achieving availability and predictability for time-sensitive applications is the key of their success. Of course, comparing with wired fieldbuses, the wireless medium introduces new challenges, but the problems somewhat resemble those that were faced before the mainstream use of packet switched networks, when the serial fieldbuses shared the medium with a practical bit-error probability in the order of 10^{-4}. Those fieldbuses have evolved from the early 1990s into different flavors based on packet switched Ethernet and are the backbones of today's automation networks [4]. From this, it is apparent that the success of wireless communications in industrial automation relies on solutions that span over all layers and is not by any means limited to the performance of the physical and medium access layers alone.

While bringing new opportunities that significantly contribute to advance the automation sector, wireless technologies also pose novel challenges. For instance, to support Industrial Internet of Things applications [5], more attention has to be paid to energy efficiency of wireless communications. In the literature, techniques are already proposed that adopt topology management to achieve bounded delays while reducing energy consumption [6] or that achieve energy efficiency exploiting the low-power modes of wireless protocols through a proper tuning of the duty cycle [7]. However, today novel low-power low-cost technologies, such as Bluetooth Low Energy, are becoming increasingly interesting for Industrial Internet of Things applications and, for this reason, new features, such as efficient broadcast configurations [8] or real-time traffic support over master-slave mesh networks [9] are being investigated.

In addition to that, wireless communication is also steadily penetrating other application areas in automation, such as cyber-physical systems, in which communication, computing, and control are tightly coupled and network-related effects, such as jitter, packet loss, and resource contention, can affect the stability and dynamics of the physical subsystems. Wireless networks are also gaining importance in smart grids, where new standards, such as the IEEE 802.11ac, are to support peculiar and compelling requirements, such as high transfer rate, reduced latency, and enhanced coexistence [10]. For this reason, there is a need to disseminate, streamline, and investigate research findings coming from several different application domains. The

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challenge is exploiting the similarities between the different domains while coping with the peculiar requirements of each specific automation application.

This Special Section on "New perspectives on wireless communications in automation: From industrial monitoring and control to cyber-physical systems" of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS tackles the main research issues in the development, adoption, and application of wireless communications for a broad range of automation applications. The selected nine high-quality contributions cover a broad spectrum of topics for wireless networks in automation, including novel technologies and applications scenarios. In fact, along with papers proposing comprehensive solutions for time-critical applications, time synchronization, localization, and routing, the Special Section also includes papers dealing with new applications scenarios, such as smart grids, and new technologies, such as millimeter wave communications, which introduce novel challenges for wireless critical communications.

The paper "Delay-minimized routing in mobile cognitive networks for time-critical applications," by Tang *et al.*, deals with the challenge of spectrum scarcity of wireless networks and presents a novel routing scheme for cognitive radio networks that support time-critical applications in mobile scenarios. Cognitive radio networks are a promising technique to take advantage of temporarily unused frequency channels, but also to avoid interference, as cognitive radios monitor the channel to sense activities of other users. This is even more apparent when the network contains mobile nodes. To this end, the paper identifies that routing and channel assignment should be done jointly, as the channel quality is location and time dependent. In addition, a novel routing metric is defined, which includes a delay estimation model that captures the cochannel interference. The resulting scheme is a cross-layer approach that jointly determines which routes and channels to use based on delay prediction. The performance of the proposed heuristic routing algorithm is demonstrated via ns2 simulations and shows clear improvements in terms of packet loss rate, throughput, and average end-to-end delay.

The paper "Performance evaluations and measurements of the REALFLOW routing protocol in wireless industrial networks," by Yu *et al.*, addresses reliable real-time communication over multiple wireless links in industrial environments. Very few papers address reliable and deadline-constrained communication in wireless networks, even though that is predominant in process and factory automation applications. REALFLOW is a flooding-based approach that achieves reliable communication between sensor nodes and is also able to meet the hard deadlines of several automation applications. The advantages of a flooding-based approach are the use of multipath diversity and wireless broadcast transmissions, in which the adjacent nodes of a transmitting node may overhear the packets, thus making packet forwarding more flexible. Another advantage of REALFLOW and its broadcasting approach is that link-level acknowledgment can be avoided, thus reducing the latency. The REALFLOW protocol was implemented in hardware and then evaluated in a real industrial environment, collecting results during several hours.

The paper "DISTY: Dynamic stochastic time synchronization for wireless sensor networks," by Masood *et al.*, focuses on time synchronization in wireless sensor networks. Time synchronization, an essential building block in wireless sensor networks, is quite challenging due to the use of low-precision oscillators and to the limited computational power of cheap devices. In general, time synchronization algorithms can be classified as centralized or decentralized. Centralized approaches are typically easy to implement, but the drawbacks are packet losses and timestamp instability. In DISTY, the authors' approach is to forecast the clock offset using the Box-Jenkins method known from time series analysis. Such prediction works very well for commercially available wireless sensor platforms to synchronize all devices to a central master device. The synchronization solution is analyzed on real hardware in both indoor and outdoor experiments running over several days. The obtained results show that the synchronization error with the given hardware is only a few clock ticks for a considerable forecast horizon.

The paper "Optimizing time of arrival localization solutions for challenging industrial environments", by Van Haute *et al.*, deals with localization. Accurate positioning can enable many features, including positioning of people and various devices in industrial environments. Although there is a significant number of research papers in the area of RF-based localization, little work exists about industrial environments and confined areas. Some proposals based on fingerprinting and triangulation techniques are available, but they are not sufficiently robust against outliers and changes in the environment. It is therefore important to use more accurate channel models, especially for time-of-flight range-based approaches. The industrial indoor environment is extremely difficult to model, so having access to realistic environments to test and validate new concepts is of high importance. In the paper, a large-scale wireless testbed is used to test and evaluate various localization solutions. In particular, a time-of-arrival approach is considered and the experiments reveal that the impact on accuracy is highly dependent on factors such as antenna height, multiantenna orientation, and distance.

The paper "Distributed unbiased FIR filtering with average consensus on measurements for WSNs," by Vazquez-Olguin *et al.*, addresses the case of providing robust estimators of a quantity measured by distributed industrial wirelss sensor networks. Very often, wireless sensor networks are used to provide environmental sensing or monitoring in industrial settings. A specific quantity is measured by a large number of sensors typically distributed in environments where disturbances of different types occur. Many of these noise patterns are not well specified, but high quality estimation with low complexity is still desired, such that the quantity can be monitored and interacted with during runtime. Finite-impulse response filtering in industrial wireless sensor networks can provide robust consensus-based estimation while operating under harsh conditions. The proposed distributed unbiased finite-impulse response filter, called micro-UFIR filter, is based on average consensus on measurements and, unlike the micro-Kalman filter, is robust against modeling errors in uncertain noise environments. The robustness of the micro-UFIR filter is shown analytically and is also supported by simulations of a vehicle traveling circularly on a ground space covered by the wireless sensor network.

The paper "Ultra high performance wireless control for critical applications: Challenges and directions," by Luvisotto *et al.*, focuses on potential future wireless control applications within industrial automation targeting Gb/s data rate and 10 μs level cycle time. The work discusses and evaluates existing wireless solutions and points out the improvements that are needed in the physical and medium access control layers to achieve a wireless high-performance system. Link-level performance, and in particular, the scheduling unit, is identified as the bottleneck in the realization of high-performance wireless solutions. Further, the paper assesses the performance of the most advanced current wireless standards, identified as IEEE 802.11ac/ad, IEEE 802.15.3c, and LTE-A and concludes that none of them is able to fully meet the required performance. The paper also points out new and promising trends, such as mmWave communications and 5G networks. Finally, the paper concludes by proposing a clean-slate system design with a joint PHY and MAC layer so that packet detection, synchronization, and channel equalization can be performed in a very fast way and using short preambles.

As mentioned previously, this Special Section also covers some new trends. The paper "Exploiting mm-wave communications to boost the performance of industrial wireless networks," by Saponara *et al.*, explores the potential of using milimeter waves, i.e., frequencies above 60 GHz, as the physical layer in industrial wireless networks. By exploiting the worldwide-free band of several GHz available around 60 GHz, mmW links allow to achieve a performance boosting of up to two orders of magnitude compared to conventional wireless links. One of the reasons for this is that the 60 GHz band provides interference separation from operating frequencies of electrical machines, switching converters, and other industrial wireless networks (e.g., 802.11 or 802.15). However, this comes at the expense of a higher pathloss associated with this high frequency. By applying, e.g., time slotted channel hopping and frequency-diversity, reliable communication was achieved at a distance of tens of meters for a single hop, even in harsh environments. The paper proposes propagation, signal and noise models for the 60 GHz band that consider the harsh conditions encountered in industrial settings.

Smart grids today are cyber-physical systems that require advanced communication technologies to support efficient, reliable, and timely message exchanges between energy providers and consumers. The paper "Efficient 5G small cell planning with eMBMS for optimal demand response in smart grids," by Saxena *et al.* proposes an efficient planning strategy of small cells, based on the emerging 5G evolved multimedia broadcast and multicast services, between aggregators and consumers to efficiently implement so-called demand-response (DR) features. Smart grids can reduce peak demand by providing information and incentives to consumers and encouraging them to participate in DR programs. In the paper, it is pointed out that optimal multicast scheduling and radio resource management problem is NP-complete, and thus both dynamic programming and greedy heuristics solutions for achieving near optimal scheduling of DR programs are proposed. Extensive OPNET simulation results show that the proposed solutions can achieve a 30% reduction of the energy production cost with a significant shift in peak energy load, low latency, and packet drop.

Finally, the paper "Dynamic secrets and secret keys based scheme for securing last mile smart grid wireless communication," by Saxena and Grijalva, deals with security of the smart grid network, a crucial issue, as security has a big impact on the availability, reliability, and efficiency of the power system. The paper proposes a novel dynamic secret scheme for secure communications between the supervisory node and the control nodes that generates a series of dynamic secrets over the communication network, which are used to generate secret keys for data encryption. Frequent generation of dynamic secrets and secret keys of the encryption scheme provides adequate security against several types of attacks over the wireless network. This is due to the fact that there are inevitable and unpredictable errors in the wireless communication, which prevent the adversary from tracing and obtaining the secrets for a sufficient duration of time. The results of the performance evaluation and experimental analysis presented in the paper show that the proposed procedures for generating dynamic secrets, secret keys, and ciphertexts are lightweight, thus providing for manageable overheads and fast execution.

Summarizing, the selected nine papers address several important areas, challenges and novel approaches toward increasing the use and applicability of wireless communications in the automation sector, as well as future challenges toward new and more demanding application scenarios.

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