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Guest Editorial
From Industrial Wireless Sensor Networks to Industrial Internet of Things

INDUSTRIAL networks connect sensors and actuators in various industrial facilities, such as oil and gas production facilities, paper plants, car manufactories, and underground mines. Industrial Internet of Things (IIoT) is a paradigm that involves a network of physical objects containing embedded technologies to collect, communicate, sense, and interact with their internal states or the external environment through wireless or wired connections brilliant machines, advanced analytics, and people at work and deliver valuable new insights like never before. These insights can then help drive smarter, faster business decisions for industrial companies. The global IIoT market was valued at USD 312.79 billion in 2017 and is expected to reach USD 700.38 billion by 2023, witnessing a compound annual growth rate of 14.36% during the forecast period, 2018–2023.[1]

A key component in supporting future IIoT framework is that the underlying communication infrastructure is required to provide definite and trustworthy performance, strong reliability, and bounded latencies, while supporting self-healing and flexible network deployment [1]. In the last decade, wireless solutions started to penetrate automation industries mainly targeting monitoring and slow control applications. Today, most of the deployed wireless systems in factory automation are based on WiFi (IEEE 802.11) or Bluetooth (IEEE 802.15.1) and in process automation are wireless sensor networks based on industrial wireless standards such as WirelessHART[2] and ISA100.[3] However, the interest for time- and mission-critical applications [2] has increased in the last few years. Real-time scheduling, routing, and scheduling-control co-design issues in large-scale deployment of such applications raise a number of challenges that are yet to be addressed. Existing wireless systems in the automation domain are mainly using the unlicensed 2.4 GHz ISM frequency band since it can be used all over the world. As many other devices also operate in this band, such systems are prone to disturbances and external interferences, and are often affected by nonnegligible packet loss rates, random delays, and jitter. All these sum up and make it very difficult to achieve deterministic communication, which is paramount in industrial applications. There exist some interesting approaches to improve link reliability by using tools from machine learning to detect and mitigate interference [3].

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The aforementioned wireless systems face limitations in terms of scalability and coverage when very large areas need to be covered. While cellular technologies such as 3/4/5G technologies promise to connect massive devices over long distances, they require infrastructure support and licensed band and costly solutions. Moreover, even if the marketing sheets of 5G are promising, there are many technical challenges ahead [6] before there is standard that fulfills the industrial automation requirements. Moreover, sound business models are also challenging for 5G. IIoT applications typically require relatively small throughput per node and the capacity is not a main concern. Instead, the need of connecting a very large number of devices to the Internet at low cost, with limited hardware capabilities and limited energy resources (e.g., small batteries) make latency, energy efficiency, cost, reliability/availability, and security/privacy more desired features.

Since the Internet is designed for best effort services, there is a fundamental challenge to design and support applications in the industrial automation domain that demands real-time performance at different levels. In the past, most industrial wireless systems applied the time-division multiple access mechanism associated with fixed time slot size for channel access. However, along with the emergence of new industrial applications that are requiring higher data rates, online configurable wireless medium access control (MAC) layer designs are becoming more attractive. Along with this trend, adaptive time synchronization plays an important role, especially when the network size grows. In addition, state-of-the-art network resource management in industrial wireless systems rely on centralized and periodic approaches to gather the network health status, and then recompute and distribute the updated network schedule information. When such systems evolve into the IIoT scale, hybrid or even fully distributed approaches should be developed to scale up and deal with various external interferences and internal system perturbation, while still meeting the desired real-time performance [4].

Security and privacy in IIoT becomes a critical concern when devices will be connected to Internet and various edge/cloud solutions. In the past, security was addressed physically isolating systems; nowadays it is mainly ensured by means of cryptography. In the past, close and obscure designs help the isolation of vulnerable components; nowadays well-accepted and largely tested open standard approaches and protocols must be adopted. However, cryptography does not come for free, but has a relative high price in term of computational burden. Even if hardware accelerators are typically available, it is not feasible to protect all the communication layers. When possible, encryption should be provided between communication endpoints at the higher layers of the stack and authentication should be assessed at lower ones; legacy protocols not offering integrity and confidentiality should be forwarded by encrypted tunnels. Mutual authentication between endpoints is usually provided by means of certificates, which requires an out-of-band mechanism for provisioning. Additionally, enciphering data poses problems in searching across large dataset. For all these reasons, security and confidentiality is a continuously evolving topic and an abundant literature is available. For instance, searchable encryption was introduced to allow users to search on encrypted data and certificate-less algorithms have been designed [5]. To conserve energy and reduce price, IIoT devices are often weak in terms of CPU and memory, making the use of complicated trust and security mechanisms impossible or extremely hard to implement. It is reasonable to expect that an IIoT will comprise a large set of nodes communicating on different levels and with different security demands.

This Special Section on "From industrial wireless sensor networks to industrial Internet of Things" 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 eleven high-quality contributions cover a broad spectrum of topics for wireless networks in automation, including novel technologies and applications scenarios. Along with papers proposing comprehensive solutions for time-critical applications, time synchronization, error detection in industrial wireless sensor networks (IWSNs), and radio channel modeling, the Special Section also includes papers dealing with new technologies, such as unmanned aerial vehicles (UAVs), which introduce novel challenges for wireless critical communications.

The paper "Temperature-resilient time synchronization for the Internet of Things" by Elsts *et al.* propose a method for adaptive temperature-resilient time synchronization to counteract temperature-dependent clock frequency changes in TSCH networks. Time synchronization is an essential building block in wireless sensor networks and is quite challenging due to the use of low-precision oscillators and to the limited computational power of cheap devices. Obtained simulation results show that with one synchronization messages per 10 min, the system shows a 0.26-ms maximal synchronization error for indoor scenario and a 0.88-ms error in a temperature chamber where it undergoes a 60 °C change in the temperature. Finally, the proposed method has low computational and sensing requirements, which make it easy to implement in low-power IoT nodes equipped with common-off-the-shelf temperature sensors.

The paper "Topology control strategy for movable sensor networks in ultradeep shafts" by Zhou *et al.* deals with the challenge of designing chain-type sensor networks (CWSNs) in ultradeep shafts used for exploring underground mineral resources. CWSNs are generally static and used in situations involving situations due to the natural formation of the landscape or manmade infrastructure over long distances. Due to safety reasons, it is important to monitor the ultradeep shafts in real time and using static CWSNs will not work in a satisfactory way and there is a need for mobile CWSNs to visual monitor the ultradeep shafts. The paper proposes a topology control algorithm, and by arranging a wire rope as carrier of the linear network in the shaft, mobile nodes with a self-contained energy supply are arranged on the wire rope. The paper also proposes collaborative repair strategies at network level in cases of movement and communication failures.

The paper "Cloud-orchestrated physical topology discovery of large-scale IoT systems using UAVs" by Yu *et al.* highlights the problem of covering large-scale IoT systems distributed over a large areas using UAV. The key to a successful large-scale IoT system is that the cloud needs to know the physical topology to improve the operational effectiveness of large-scale IoT applications. The proposed discovery scheme consists of two phases, logical discovery topology and network-wide-3-D localization. To assess the effectiveness and accuracy of the aforementioned phases, extensive simulations were done.

Smart interconnection in manufacturing has recently gained interest in both academia and industry. The paper "IIHub: An industrial Internet-of-things hub toward smart manufacturing based on cyber-physical system" by Tao *et al.* proposes and designs an IIoT hub to solve the challenges of smart and configurable interconnection for heterogeneous equipments. The proposed solution is divided into three modules, i.e., customized access (CA) module, access hub, and local service pool. One major feature of the proposed industrial Internet-of-Things hub (IIHub) is a set of flexible CA-modules that are compatible with different communication interfaces and protocols. These CA-modules can be configured or programmed to connect heterogeneous physical manufacturing resources with different intelligence levels. To validate the proposed framework, the authors developed a prototype for smart metering production to illustrate the functions of the proposed IIHub.

The paper "Performance analysis of CSMA/CA and PCA for time critical industrial IoT applications" by Malyala and Pachamuthu developed an analytical model to analyze the performance of IEEE 802.15.4-2015 MAC layer for both beacon-enabled and nonbeacon-enabled personal area networks. Recently, IEEE 80215.4-2105 introduced a new prioritized contention access (PCA) mechanism to transfer time-critical packets with low channel access latency. This paper propose a mathematical model that analyze the new PCA mechanism and, then, compare the performance with classical CSMA/CA for different traffic classes. Moreover, to validate the accuracy and performance of the proposed model, the authors implemented their solution in real sensor devices.

The paper "MAC protocols for wake-up radio: Principles, modeling and performance analysis" by Ghose *et al.* proposes three wake-up radio (WuR) protocols and the performance evaluation particularly focus on collision avoidance under various traffic conditions. WuR is an emerging technology for smart sensor networks and the Internet of Things with the ambitious goal of minimizing the power needed to communicate, thus enabling a new generation of applications. WuRs should exhibit low latency coupled with high sensitivity, addressing capabilities with ultralow power budget. Hence, since there is no mechanism adopted in WuR for collision avoidance, heavy packet losses will occur, especially if multiple nodes detect an abnormality, such as a fire, and report it at the same time. To handle such cases, the authors propose a new set of transmission protocols. The proposed CCA-WuR protocol is suited for applications where short delay and high energy-efficient communication is required. Meanwhile, CCA-WuR and adaptive WuR protocols are preferable when packet delivery reliability is of more importance.

Industrial environments are often characterized by complex factors such as fading and interference, which affect the quality of communication. The paper "On threshold-free error detection for industrial wireless sensor networks" by Gao *et al.* provides an approach to detect errors in IWSNs. To detect erroneous data will become even more important in the future with the expected growth in collecting data for monitoring and control purposes. A failure in data readings might have severe impact on control performance and in this paper, the authors propose a two-stage error detection approach without requiring a threshold to judge if a reading is normal or erroneous. Simulations on real datasets show that the proposed solution detects errors accurately with low false alarm rates.

Telemonitoring of diaphragmatic electromyogram (EMGdi) signal using IoT is considered to be a promising solution for personalized medicine. The paper "Compressed acquisition and denoising recovery of EMGdi signal in WSNs and IoT" by Wu *et al.* proposes a solution to overcome the nonenergy efficient solutions for data acquisitions that exist today. In order to have a system that works for low-power WBAN system, the authors use compressed sensing methods since that enables lower energy data compression. Moreover, compressed sensing also reduces the cost of the system since the measurements are sparse binary metrics. However, EMGdi signals are not sparse and cannot be reconstructed with current existing compressed sensing methods so the authors propose the use of an approximated l_0 (AL0) norm based method by projecting the gradient descent solution to the reconstruction feasible set.

The paper "Confident information coverage hole healing in hybrid industrial wireless sensor networks" by Deng *et al.* deals with an important problem in wireless sensor networks. In most cases, sensor nodes are deployed in remote and sometimes in inaccessible areas that makes maintaining coverage and connectivity a major problem. Coverage holes occur as a result of node failure or initial deployment and can severely degrade the network performance. The authors' solution to the problem is to consider both static and mobile nodes, whereas the static nodes are responsible for hole detection and mobile sensors are used for hole healing. To solve the problem, the authors consider a two energy-efficient heuristic solutions based on a centralized algorithm and one decentralized algorithm. Obtained simulation results show that the proposed solution can efficiently heal coverage holes.

The paper "Improving RSSI-based path-loss models accuracy for critical infrastructures: A smart grid substation case-study" by Sandoval *et al.* presents a path-loss model for smart grid substation. In order to design a proper radio system, it is of utmost importance to do a proper radio channel characterization to understand how the radio waves propagate and how the radio system should handle external interference. The authors present two models based on received signal strength indicator (RSSI) and, then, benchmark the model with a ground-truth vector network analyzer (VNA) model in a grid substation scenario. To capture the RSSI traces, the authors are using three different WSN platforms that are based on IEEE 802.15.4 standard. The proposed model will be valuable for performing network simulations, where applications are targeting wireless communication in substation automation.

The paper "Achieving hybrid wired/wireless industrial networks with WDetServ: Reliability-based scheduling for delay guarantees" by Zoppi *et al.* proposes a quality of service aware framework for hybrid wired–wireless networks. This paper first describes an enhanced version of the *DetServ* model devoted to wireless TSCH solutions. Subsequently, an innovative scheduler is designed able to satisfy both time deadlines and target reliability, even in the presence of dynamic interference.

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

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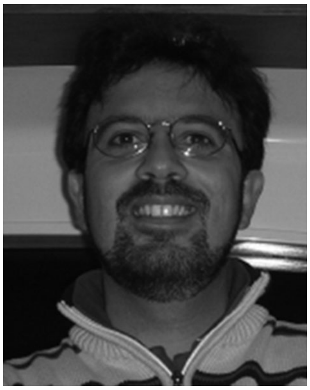

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