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EDITORIAL

IEEE ACCESS SPECIAL SECTION: ADVANCES ON HIGH PERFORMANCE WIRELESS NETWORKS FOR AUTOMATION AND IIoT

Technologies for making devices communicate seamlessly over the air are expected to be adopted more and more in future digital ecosystems, including cyber-physical systems. In the latter case, machine-to-machine (M2M) interactions are often characterized by tight timing constraints. When communication takes place on shared and noisy media, timeliness is customarily specified as the probability that a message is delivered within specific deadlines, which depend on the dynamics of the controlled system. A fair amount of effort was spent in the past two decades to improve wireless communication technologies, and there is now the expectation that in the future, they could be (almost) as dependable as wires.

One of the primary enablers of this (r)evolution is probably constituted by the Industrial Internet of Things (IIoT) which, besides next-generation industrial plants (as envisaged by Industry 4.0 and 5.0), can be profitably applied to smart environments, smart utilities, smart transportation, and smart agriculture, to cite a few. According to IIoT, applications are hidden details about the underlying physical network, and correct operation is ensured as long as constraints on reliability and timeliness of end-to-end data transfers are overall met by the different technologies on which the constituting subnetworks rely. Additional requirements have to be considered sometimes as well, which impact on feasibility (technical, economical, and ecological aspects). For example, power consumption in self-powered devices may affect maintenance costs and battery waste, whereas transmission range is a critical aspect in brownfield scenarios, where a suitable communication infrastructure cannot always be easily deployed.

Because of the inherent complexity of wirelessly interconnected distributed systems, the relevant key performance indicators (KPIs) to be used for design and optimization are application-driven, and the work of designers customarily involves finding a compromise between a plurality of aspects including, e.g., dependability, latency and jitter, power consumption, covered area, and node density.

It is worth stressing that, when dealing with communication for automation and IIoT, the term "high performance" does not refer simply to raw throughput but rather to the ability of the network to satisfy in the best way and at the same time all the increasingly demanding requirements and constraints, both functional (mobility through wireless communication, ability to operate self-powered for very long times, support for safety and security, clock synchronization, localization, etc.) and about performance (as expressed by the above KPIs), dictated by modern distributed control applications for specific classes of (cyber-)physical systems. A relevant example concerns time: deterministically bounded transmission latency and precise synchronization are essential for control applications; if the density of nodes is high, coordinated access to the channel is needed to achieve these goals. Similarly, when nodes are not fixed, low energy consumption and seamless mobility are additionally required. In this kind of network, achieving high performance implies that these aspects must also be dealt with and the related behavior optimized.

While a single winning wireless technology cannot be clearly identified for universal adoption with the IIoT, several competing solutions are currently available off-the-shelf. In the context of unlicensed bands, which are particularly appealing to users because they do not imply any fees, some of the most important ones are IEEE 802.11 (Wi-Fi), for which activities related to the definition of the eighth generation about ultra-high reliability (UHR) have just started, wireless sensor and actuator networks (WSN/WSAN) based on IEEE 802.15.4, including DSME and TSCH (Zigbee, WIA-PA, WirelessHART, ISA100.11a, 6TiSCH, etc.), Bluetooth Low Energy (BLE, adopted, e.g., in IO-Link Wireless), and long range wide area networks (LoRaWAN). Concerning solutions operating in licensed bands, recent additions to 5G/6G like Ultra Reliable Low Latency Communications (URLLC) and Massive Machine-Type Communications (mMTC), for time-sensitive applications and ultra-dense systems, respectively, are deemed particularly relevant in view of their use in the context of automation and sensing.

Current research on deterministic, high-speed, highly dependable, and low-power networks opens a promising door for the evolution of wireless communications in automated systems, which will be heterogeneous in nature but, at the same time, capable of meeting very demanding constraints, including the ability to reliably close control loops over the air.

This Special Section aims to provide a forum for the academic and industrial communities to present the latest advances on this subject, with a specific focus on automation. The scientific community enthusiastically responded to the Call for Papers with 105 submissions. Following a rigorous review process, 22 articles were eventually chosen for inclusion in this Special Section.

The first three contributions concern the state-of-the-art.

In [A1], Sharma et al. concentrate on consequences for 6G in automation, and present an overview about ongoing digital transformation, adaptive industrial use cases, and wearable robotics, which focus on a cyber-physical continuum. To support this evolving continuum, a fully converged end-to-end deterministic communication infrastructure is outlined, with scalable operation and service provisioning ensuring effective implementation. Main challenges are addressed, as there is predictability of stochastic communications, and end-to-end integration of cyber-physical systems.

In [A2], Mostaani et al. provide a comprehensive survey of the new task-oriented communication design, considering principles of communications, control theory, and computer science. The article discusses various applications for the new design approach, from industrial IoT to autonomous vehicles, and highlights some of the open research questions in this domain.

In [A3], Enenche et al. used network coding (NC) to meet the stringent constraints related to reliability in the context of IIoT. In addition to giving more freedom in traditional automatic repeat request (ARQ) schemas based on acknowledgment (ACK) frames, NC can effectively improve reliability in the case of unconfirmed communications, such as user datagram protocol (UDP). This survey focuses on network coding-based approaches to maintain better communication quality in the context of URLLC in the case of lossy networks and for both confirmed and unconfirmed transmissions.

The next seven articles focus on aspects related to time, reliability, and energy.

In [A4], Chandramouli et al. address time synchronization and distribution services as a fundamental capability for enabling new immersive use cases in next-generation 5G-Advanced and 6G networks. The article discusses in detail the time synchronization and timing resiliency enablers under development in the latest cellular standards and highlights gaps and future research challenges. Communication systems have been traditionally designed to be application agnostic, but more and more emerging applications pose specific requirements for communication systems and can benefit from a new paradigm that focuses on the efficient completion of the task at hand.

In [A5], Joo et al. discussed the contexts of vehicle-to-everything (V2X), unmanned vehicles (UVs), and time-constrained wireless networking in general. The concepts of reinforcement learning, time-sensitive networking (TSN), and software-defined networking were mixed together to obtain the goal of improving the real-time quality of a wireless link without deteriorating the quality of background traffic. This system was implemented on a real testbed, and results showed consistent improvements in terms of jitter for time-constrained traffic and throughput for background traffic.

In [A6], Janjić et al. present an over-the-air synchronization using a dual-channel receiver, focusing on digital beamforming (BF) and radio source localization. The receivers connect to a fusion center through digital links, assuming dominant line-of-sight conditions, constant time offsets, and variable frequency offsets. The presented localization is utilized with wideband and narrowband pilots from a beacon.

In [A7], Alawad et al. propose a new probabilistic model based on variational autoencoders (VAE) to reconstruct transmitted symbols without sending the data bits over the wireless link. Modulation and demodulation are performed by a deep neural network (DNN) based on the VAE architecture. Spectrum efficiency enhancements are presented based on simulation models considering different scenarios and fading channel models.

In [A8], Urke et al. exploited the determinism of slotted networks such as time slotted channel hopping (TSCH) and the possibility of relying on scheduled traffic to meet the strict requirements about latency and reliability of the IIoT. A flow-based scheduler named Layered was proposed, in which resources are allocated to traffic flows by reserving dedicated resources at each hop of the path. Theoretical analysis and simulation show how Layered improves spatial reuse and performance at the expense of energy consumption.

The integration of machine learning (ML) techniques in the Routing Protocol for Low-Power and Lossy Networks (RPL) was analyzed by Santos et al. [A9] in the context of wireless smart grid networks (WSGNs). The proposed ML-RPL protocol aims at optimizing routing decisions by providing the probability of successfully reaching a destination. Nodes use this probability to select the best route. ML-RPL tested in a real scenario showed reliability and end-to-end latency improvements.

Underwater acoustic cluster networks (UACNs) are a peculiar sort of wireless network that suits dynamic underwater environments. In [A10], Ghazy et al. propose L3EACH-V2, a framework based on the low-energy adaptive clustering hierarchy (LEACH) protocol that increases efficiency by using shorter local identifiers (ID) and exploiting spatial ID reuse. This approach is proven able to reduce energy consumption and to increase throughput over its competing solutions like Distributed Id assignment and topology discoV-Ery (DIVE).

The next three articles are about localization.

Localization plays a major role in many IIoT scenarios as it triggers problems specifically in indoor environments. In [A11], Pătru et al. presented a method where a high-performance wireless flexible time division multiple access (TDMA) scheduling scheme is introduced to utilize time difference of arrival (TDOA) localization that fully exploits the channel diversity in the environment. The presented localization FlexTDOA enables accurate localization, with a specific focus on non-line-of-sight scenarios usual in indoor factory environments.

Additionally, positioning in Wi-Fi indoor networks through location fingerprinting is discussed in [A12] by Hu and Hu. The proposed algorithm, named static continuous statistical characteristics-soft range limited-self-adaptive WKNN (SCSC-SRL-SAWKNN), which is based on the well-known Kalman filter, addresses some limitations of weighted K-nearest neighbors (WKNN) commonly used in these contexts. The experimental results show that it outperforms the analyzed traditional algorithms in terms of both location trajectory and localization accuracy.

Unmanned aerial vehicles (UAVs) can be employed for disaster rescue, enabling user equipment (UE) of trapped people to be located accurately. Partial GNSS-denied (global navigation satellite system) scenarios and the simultaneous movement of UAVs and UEs may result in poor performance. In [A13], Zheng et al. proposed a fusion scheme that relies on multiple UAVs and user-side inertial measurements that provides highly accurate and stable positioning services for mobile UEs on the ground.

Security in wireless networks was analyzed in two contributions.

In [A14], Gul et al. look at the impact of wireless channel dynamics on the performance of learning models applied to radio frequency (RF) fingerprinting, which is an important tool to secure wireless communications used in critical infrastructures. The results show significant enhancements in RF identification accuracy with the proposed fine-grained augmentation approach.

In [A15], Tyler et al. deal with the topic of security within IoT systems, which often evolve and grow over time without a certain data security strategy. This article investigates specific emitter identification (SEI) as an effective and cost-efficient approach to improving IoT security, characterized by its passive functionality. In this work, the authors carried out six experiments focusing on improving multi-day SEI performance through experimentation with multiple waveforms, deeper convolutional neural networks (CNNs), increasing the number of waveforms, considering channel model impacts, as well as two-channel mitigation techniques.

Finally, the last seven articles regard improvements related to the networking quality and to the Quality of Service (QoS) in general.

TSN is nowadays a very relevant topic for enabling deterministic communication over Ethernet networks deployed in industrial scenarios. Extending TSN functionality to 5G as well, in such a way to support mobility, poses a number of challenges. In [A16], Luque-Schempp et al. propose an automata learning approach to enable zero-touch configuration for the QoS of 5G flows. A functional testbed has been implemented to practically show the advantages the AutomAdapt solution achieves.

Tag collision is a major research challenge that should be solved when applying radio frequency identification (RFID) in IoT applications. In [A17], Umelo et al. proposed a novel method of grouping and counting RFID tags such that the reader is equipped with information on the estimate of tags within its read range. Through extensive Monte Carlo simulation, this research work demonstrated that the new method can have better performance compared with traditional approaches in terms of identification time, system efficiency, and success rate.

Emerging technologies, e.g., mobile edge computing (MEC) and digital twin (DT), can be combined to provide enhanced quality of service for mobile users in the 6G era. In [A18], Chen et al. proposed a new DT-empowered MEC architecture to support mobile users (MUs) offloading dependency-aware tasks, in which the computation offloading and resource allocation are jointly optimized, so that the system's energy consumption can be minimized. The proposed research was evaluated with extensive simulation.

As highlighted in [A19], Saeed and Ullah's multiple controllers are a prerequisite to improve scalability in software-defined networking (SDN). One of the most significant challenges, consisting of the best placement of controllers, has been addressed in this work through the proposed constrained multi-objective heuristic placement approach (CMOPHA), which is based on the NSGA-II algorithm. A simulation based on real traces shows how CMOPHA can improve network key performance indicators such as hop count, latency, computation time, and availability of the network.

Long-range wireless access, high flexibility, and energy efficiency are important factors that should be considered and solved in many Internet of Things (IoT) applications. Low-power wide area network (LPWAN) technologies are recognized as one of the main drivers for IoT expansion. In [A20], Nikitin and Davidchack studied a new practical approach for energy-efficient power control. The new approach can be used for scaling LPWANs with realistic desired and/or actual areal distributions of the uplink nodes under diverse propagation conditions.

Digital twins based on finite state machines (FSMs) are the topic discussed by Strelec et al. [A21], and the proposed FSM model can be used to simulate an industrial production process. It can be integrated with the production line, or it can be exploited for developing IoT devices. In addition, it permits the verification of an implementation without a physical prototype or to test hybrid implementations where only part of the hardware is effectively realized. The effectiveness of the proposed model has been demonstrated through concrete examples.

Finally, in [A22], Beohar et al. proposed a novel performance evaluation framework, considering energy harvesting in battery-based, point-to-point connections for applications with QoS requirements. For the framework, the authors proposed a probabilistic energy-outage approach, including a virtual battery queuing model to leverage the large deviation principle theory. The proposed approach was validated analytically using several relevant scenarios.

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APPENDIX: RELATED ARTICLES

[A1] G. P. Sharma, D. Patel, J. Sachs, M. De Andrade, J. Farkas, J. Harmatos, B. Varga, H.-P. Bernhard, R. Muzaffar, M. Ahmed, F. Dürr, D. Bruckner, E. M. De Oca, D. Houatra, H. Zhang, and J. Gross, "Toward deterministic communications in 6G networks: State of the art, open challenges and the way forward," *IEEE Access*, vol. 11, pp. 106898–106923, 2023.

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[A13] Y. Zheng, Y. Xie, and J. Li, "Multi-UAV collaboration and IMU fusion localization method in partial GNSS-denied scenarios," *IEEE Access*, vol. 11, pp. 105499–105512, 2023.

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