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Editorial

Special Issue: Quality of Service in Wireless Sensor/Actuator Networks and Systems

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1. Introduction

Wireless communications have long been a part of our daily lives: from remote controls to baby monitors, from cellular to local area networks, connecting us to the Internet and integrating our various gadgets and peripherals. However, industrialists have been very conservative in allowing wireless to enter their factory automation and process control systems. This has been mainly because "wireless" technologies had only been used in very specific and limited industrial scenarios (e.g., to facilitate point-to-point connections) and often granted insufficient reliability, security, or lifetime guarantees.

As wireless technology matured (e.g., IEEE 802.11-based and IEEE 802.15.4-based), wireless sensors, actuators, and controllers started penetrating the factory floor, complementing or even replacing their wired counterparts. While these "hybrid" wired/wireless systems are already a commodity, we are at the dawn of a new era, where computers, sensors, and actuators are becoming increasingly embedded and ubiquitous, scaling up systems at unprecedented levels. The number of (embedded, networked) devices will grow dramatically, while the size of individual devices/nodes will necessarily shrink. The so-called "Internet-of-Things" and "Industry 4.0" are very broad umbrellas that fit into this paradigm.

Wireless sensor/actuators networks (WSANs) are thus being increasingly used in a panoply of applications, such as industrial automation, process control, ambient assisted living, structural health monitoring, and homeland security. Most of these applications require specific quality-of-service (QoS) guarantees from their underlying communication infrastructures (regardless of their wireless, wired, or hybrid nature).

While QoS has been traditionally associated with bit/data rate, network throughput, message delay, and bit/packet error rate, these properties alone do not reflect the overall "quality of service" that needs to be provided for such applications (and for their users). Other (non-functional) properties such as scalability, security, mobility, or energy sustainability must also be considered in the design of such complex cyber-physical systems. Importantly, these properties often conflict.

This special issue targeted contributions in wireless sensor/actuator networks and systems (WSANSs) addressing QoS properties (hopefully in combination) such as reliability and robustness, timeliness and real-time, scalability, mobility, security and privacy, and energy efficiency and sustainability. We sought for works that were sufficiently mature, tested, and evaluated through analytical, simulation, or experimental models. Extensions to previously published works were eligible, provided that this fact was clearly stated in the submission and that the new contribution was significant.

We were envisaging works covering one or more of the following WSAN topics, with QoS as an overarching aspect:

- System architectures: e.g., improving hardware (e.g., radio technology), software (including operating systems), and communication network architectures to achieve better QoS; scalability; WSAN integration in, and interoperability with, legacy wired systems; cross-layer design.

- Reliability and robustness: improving communication errors detection/correction, hardware robustness, and systems reliability in general.
- Timeliness and real-time: improving the timing behavior and reducing/bounding (end-to-end) communication delays; innovative time synchronization techniques.
- Security and privacy: new mechanisms to grant adequate levels of security/privacy without jeopardizing energy and time.
- Mobility: mechanisms to support mobile devices in a seamless and transparent way, while still respecting overall QoS requirements.
- Energy sustainability, efficiency, and harvesting: improving devices/system lifetime, e.g., through optimized communications scheduling/duty-cycling and energy/delay trade-offs.
- Radio interference identification and mitigation: improving the detection, classification, and mitigation of communication errors deriving from radio propagation and interference.
- Communication and network protocols: QoS add-ons; performance/worst-case analysis (analytical, simulation, and experimental).
- QoS in the Internet-of-Things, Cyber-Physical Systems, and Industry 4.0 contexts.
- Experimental facilities and test-beds, pilot demonstrations/deployments; innovative simulation and emulation models, platforms, and methodologies.
- Real-world applications, such as in smart health, environmental/structural monitoring, factory automation, process control, smart buildings, body sensor networks, vehicular networks, or security/surveillance.
- Communication standards and technologies for WSAN and LPWAN, e.g., IEEE 802.11, WiFi, IEEE 802.15.4, ZigBee, 6loWPAN, WirelessHART, ISA SP100, LoRa, SigFox, and Narrowband-IoT and their integration/interoperability with wired networks and with the Internet/Cloud.
- Novel communication technologies to overcome an increasingly overcrowded radio spectrum (e.g., visible light, mm-wave, thermal, vibration, acoustic) communication.

2. Summary of Contributions

This special issue gathers together an extremely rich set of contributions, addressing several WSAN domains and sharing QoS as a common denominator. Eight papers have made it through a rigorous and iterative peer-reviewing process (three reviews per paper, at least two review rounds), involving 38 authors from all over the world (North and South America, Europe, Asia, and Australia) from academia, industry, and the military. Each paper features at least one reference author which is highly reputed in this scientific domain, totaling over one hundred thousand citations altogether.

Papers cover a wide range of topics, namely the optimization of retransmission scheduling in IEEE 802.15.4e WSANs [1], an experimental evaluation of LoRa reliability [2], the estimation of WSAN lifetime based on innovative battery models [3], a novel radio interference classification method for WSANs [4], a dynamic QoS-aware MAC that can be boosted for long-range communications [5], an RSSI-based model-learning for target localization/tracking [6], using sensor network calculus for designing WSANs with predictable e2e delays [7], and decision-centric WSAN resource management [8]. A brief summary of each paper is provided here.

The first paper to be published in this special issue, [1], investigates how the reliability of Industrial WSANs based on the IEEE 802.15.4e LLDN (low-latency deterministic network) protocol can be increased. The authors explore the inherent characteristics of the protocol to reschedule predetermined retransmission slots in a clever way, improving the reliability of uplink (sensor nodes -> coordinator) traffic and maximizing the probability of correct packet delivery. Importantly, two basic retransmission scheduling mechanisms are proposed that are backward compatible with the standard protocol, while two other approaches relying on cooperative relayers lead to more substantial gains but require minor changes to the standard. The authors build on two channel models: one static (fixed randomly chosen

PER) and another one time-varying (hopping between two randomly chosen PERs) and evaluate the performance (essentially the superframe packet success rate) using a custom-made simulator.

The authors of [2] report the main results of an extensive experimental evaluation of the reliability of LoRa, one of the most prominent long-range low-power WSAN to date, along with SigFox and Narrowband-IoT. The authors focus on the impact of physical layer settings and ambient temperature on effective data rate and energy efficiency. The authors build on indoor, outdoor, and underground experiments, concluding, e.g., that, when sensor nodes are at the boundaries of their communication range, it is better to use higher bit rates together with a retransmission scheme, rather than selecting a slower setting that maximizes PDR. It is also systematically shown that there is a direct correlation between ambient temperature, PDR, and received radio signal strength, for different LoRa radios. Over a range of 60 °C, the received signal strength consistently decreases 1 dBm/10 °C, which has a great impact for nodes at the edge of the communication range: a perfectly good link at 15 °C becomes unusable at 60 °C.

WSANs are typically dependent (at least partially) on battery-powered devices. Therefore, estimating their current energy capacity and their lifetime may be of paramount importance, namely for energy-aware protocols and resource management. However, operating temperature and discharge current variations have a great impact on most electrochemical batteries' capacity, rendering the estimation of their voltage/charge behavior over time a tricky task. The authors of [3] propose an analytical model to estimate the state-of-charge and voltage of batteries based on their temperature, avoiding more expensive and energy-consuming hardware-based solutions that may compromise WSANs scalability. The authors implement, evaluate, and validate their analytical model through experiments over six different low-power low-memory COTS WSAN nodes (from the Atmel ATmega and SAM families).

Most WSAN technologies operate in the license-free ISM band, so communications are prone to external and cross-technology interference, namely from other wireless networks (e.g., WiFi and Bluetooth) and a myriad of daily use devices sharing the same spectrum (e.g., microwave ovens, baby monitors, cordless phones, audio/video transmitters, and remote controls). While some WSAN applications may cope with lost packets and extra communication delays, when we look into industrial WSAN application contexts, things may radically change, as reliability and timeliness are usually at stake. In this context, the authors of [4] describe a novel method for classifying interference sources in IEEE 802.15.4-based IWSANs, which may then be complemented with interference mitigation techniques. This scheme builds on a machine learning technique (support vector machines) for classifying interference from IEEE 802.11 networks and microwave ovens, as well as the presence of interference-free channels. Extensive tests in three industrial scenarios show that a high classification accuracy (over 80%) can be obtained in a very short channel sensing time (below 300 ms). The computational effort and memory footprint are very small, enabling this classifier to be implemented in low-cost COTS WSAN hardware.

Unmanned aerial vehicles (UAVs) are becoming a commodity. While up to a decade ago they were used for very specific applications such as search & rescue and homeland security), nowadays it is increasingly common to use such devices for environmental monitoring, forest surveillance, 3D-mapping, and companies/sites promotion. Some scenarios may involve several UAVs intercommunicating and interoperating among each other (in swarms) and with fixed and mobile infrastructures, devices, and people on the ground. In such multi-agent cyber-physical ecosystems, localization/tracking and wireless communications are paramount and extremely challenging, considering that QoS must be guaranteed in highly dynamic, uncontrolled, open-space, and large-scale settings. The authors of [5,6] engineer solutions toward this end.

The authors of [5] elaborate on a cooperative MAC protocol specifically designed for networks of UAVs, supporting traffic differentiation between best-effort (on-demand) and guaranteed bandwidth (periodic). The authors complement this data-link layer protocol with two mechanisms that improve the reliability and range of communications, namely an adaptive antenna array that enables omnidirectional and directional transmissions and a cooperative relayer mechanism. The proposed mechanism is evaluated through a probabilistic model (Markov chain) and simulations (ns2 and MatLab), proving its efficiency against four reference protocols.

RSSI-based object/target localization and tracking mechanisms usually feature a training phase for mitigating the particularities of each environment and optimizing their accuracy. The authors of [6] propose two run-time (on-line) model-learning mechanisms that overcome the cons of pre-run-time (off-line) alternatives, namely in terms of (wasted) time, flexibility, and adaptability to changes in highly dynamic scenarios. Both mechanisms have been implemented and experimentally evaluated in a 2D test-bed with a set of anchor nodes and mobile robots, showing significant improvements over traditional RSSI-range models.

A priori determination of WSAN performance is quite challenging, particularly when we aim at achieving the best energy-bandwidth tradeoff (worst-case dimensioning) in large-scale networks, considering the particularities of the communication stack (e.g., MAC and routing protocols non-determinism) and the dynamics of the environment (topology, obstacles, mobility, and EMI). It is fundamental to check if/how WSAN application requirements can be met, for instance concerning timeliness (e.g., maximum end-to-end delay of 3 s), reliability (a packet error rate below 1%), and scalability (a network must support up to 1000 nodes and cover an area with a 2 km radius), so that network parameters such as bit rate, nodes'/clusters' duty-cycle, TDMA slots reservation, and routers' buffer size can bed tune/optimized. The authors of [7] wrap up relevant work on *sensor network calculus*, a mathematical methodology that has been tailored (actually by the first author, over a decade ago) for worst-case analysis and dimensioning in sensor networks. The paper describes tools and applications of sensor network calculus and points out new research directions, such as encompassing stochastic models, downstream control traffic, and mobility support.

Last (but definitely not least), the authors of [8] address decision-centric resource management in QoS-aware WSAN systems, enabling the optimization of communication protocols, data storage, and scheduling policies for critical data collection, specifically for meeting decision needs. Toward this end, resource management heuristics/algorithms are proposed that meet at least the three following conditions: (i) collected data must have enough quality to support a user's decision; (ii) it should be recent (fresh) enough; (iii) the user's decision (based on the collected data) must meet the decision deadline. What sensors need to be activated to take the best decision at the lowest possible (resources) cost? How often do nodes need to sense the physical world and to communicate data? In which order (scheduling) should they be sampled? The proposed methodology and architecture (dubbed *Athena*) answers these questions, and has been evaluated (via simulation) considering a post-disaster route-finding scenario, proving to outperform traditional alternatives.

3. Conclusions

This special issue features eight extremely interesting and top-quality papers, browsing different scientific and technological issues related to WSANs, but all of them gravitate around a major concern: the Quality-of-Service (QoS) of communication networks and, in a broader perspective, of overall WSAN-based systems (hardware, software, and communication components).

It is widely accepted that the *non-functional* (QoS) properties of computing systems (namely WSAN systems) are at least as important as their *functional* counterparts. Guaranteeing that all QoS requirements are met is a challenging task, particularly considering their "conflicting" nature. For instance, guaranteeing that the end-to-end communication delay of a certain message stream is always smaller than a certain deadline may conflict with node/system lifetime requirements, since increasing the bit rate and/or the duty-cycle (of routing nodes) will demand more energy; increasing security may lead to extra energy consumption and processing/communication delays, due to the intrinsic algorithms and longer (encrypted) messages. All eight papers encompass these concerns, in one way or another.

We are moving into the realm of a new era, where ubiquitous computing is factually entering our daily lives, through different vests (e.g., "smart" phones, appliances, homes, cars, cities), but all share the need for underlying WSAN infrastructures. The scalability of these systems/applications, the close interaction with the physical world, and the dynamics of the agents involved and of the environment, will continue to challenge the exceptional researchers that have contributed to this special issue. I thank them here for their hard work and dedication and for their perseverance in revising and fine-tuning the papers toward their camera-ready versions.

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