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Editorial

Advanced Wireless Sensor Networks: Applications, Challenges and Research Trends

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1. Introduction to the Applications, Challenges, and Research Trends in Wireless Sensor Networks

A typical wireless sensor network (WSN) contains wirelessly interconnected devices, called sensor nodes, which have sensing, processing, and communication abilities and are disseminated within an area of interest. A WSN also includes at least one sink node, called the base station, which has enhanced energy, computational, and communication resources. Within a WSN, while sensor nodes monitor ambient conditions, process the relative data, and transmit them to other sensor nodes and the base station, the latter controls the operation of the specific WSN and its communication with other WSNs and/or the final user [1].

Taking advantage of the combined capabilities of its constituting elements, WSNs can monitor the conditions existing in areas of interest of almost any kind and size. This is the reason why, although WSNs were initially invented to be used exclusively in military sector, currently they are not only considered to be the basis of the Internet of Things (IoT), but also support a continuously growing range of applications that are associated with almost any sector of human activity, ranging from the environment and flora and fauna, to industry, urban activities, and healthcare [2].

On the other hand, the operation of WSNs is obstructed because of various reasons. First of all, WSNs have certain restrictions. Specifically, the energy sufficiency of typical sensors nodes is extremely limited. This is because their energy is typically supplied by batteries which, in most cases, are impractical to either recharge or replace, since the positions of the sensor nodes are usually difficult or even impossible to reach. Therefore, the attainment of energy conservation is a vital issue for WSNs. That is why, while energy saving is necessitated, energy sustainability is pursued through many different methodologies and means [3–6].

Additionally, sensor nodes have limited resources in terms of the storage and processing of data. Thus, data management in WSNs is by itself a very challenging issue of scientific research [7–10].

Moreover, wireless communications have inborn limitations regarding transmission power, transmission speed, the capacity of communication channels, and their vulnerability to interferences and intrusion that impede WSNs. Consequently, numerous challenges regarding WSNs arise [11–13].

Furthermore, in most cases, the incorporation of a large number of sensor nodes in WSNs makes it particularly challenging to achieve specific goals associated with tasks such as connectivity preservation with coverage maximization [14–16], congestion avoidance [17–19], quality of service attainment [20,21], security provision [22,23], data aggregation [24,25], fault tolerance [26,27], and node localization [28,29]. In many cases, the performance optimization of WSNs concerns more than one of the aforementioned metrics, thus necessitating the usage of multi-objective optimization algorithms [30,31].

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Citation: Kandris, D.; Anastasiadis, E. Advanced Wireless Sensor Networks: Applications, Challenges and Research Trends. *Electronics* **2024**, *13*, 2268. https://doi.org/10.3390/electronics13122268

Received: 3 June 2024
Accepted: 6 June 2024
Published: 9 June 2024

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At the same time, emerging developments in several sectors of science and technology, such as the Internet of Things [32,33], machine learning [34,35], deep learning [36,37], big data [38–40], 5G [41–43], edge computing [44], energy harvesting [3,45,46], and wireless power transfer [3,46,47] seem to be promising to support and enhance the operation of WSNs, thus triggering corresponding research trends.

2. Overview of this Special Issue

The Special Issue, entitled "Advanced Wireless Sensor Networks: Applications, Challenges and Research Trends", attracted the interest of many researchers associated with the topics mentioned in the previous section, and finally, after a double-blind review process, ten high-quality papers were selected for publication. In this section, a brief overview of these ten contributions is provided in order to encourage the reader to explore them in more detail.

The research article by Singh et al., the first contribution of this Special Issue, investigates the integration of WSNs with machine learning and deep learning techniques to enhance soil moisture estimations for agricultural and environmental management purposes. Specifically, this study evaluates five machine learning/deep learning methods and demonstrates the effectiveness of the long short-term memory (LSTM) model in accurately estimating soil moisture levels across different regions. By leveraging WSN-driven data alongside satellite observations and climate models, the proposed methodology offers a practical approach for high-resolution soil moisture estimation, with implications for precision agriculture and environmental monitoring. The paper concludes by identifying future research directions to further improve soil moisture estimation models and their applicability in real-world scenarios.

The second contribution, by Pinto Neves et al., introduces a novel firmware update method for microcontrollers, aiming to minimize downtime and optimize data transmission during updates. Unlike traditional methods that replace the entire program, this approach enables updating specific code segments without interrupting ongoing operations. Implemented and validated on a PIC18F27K42 microcontroller, the method showcases reduced downtime, less than 10 ms, and good recoverability in failure scenarios. However, it has limitations, such as updating only up to eight rows at a time and requiring full control over functionalities, excluding compatibility with operating systems or hardware abstraction layers. Despite these limitations, the method demonstrates easy replication across various microcontrollers, indicating broad applicability. Future research directions include exploring radio transmission options and automating memory partitioning for improved efficiency, suggesting a promising avenue for advancing firmware update practices in microcontroller-based systems.

The third contribution of this Special Issue is a paper by Wang et al. that addresses the challenge of channel collisions in dense long-range wide-area networks (LoRaWANs) by proposing a novel time-allocation adaptive data rate (TA-ADR) algorithm. By introducing the concept of time intervals for node transmissions, the TA-ADR algorithm aims to allocate independent time slots to each node, mitigating data collision issues in densely populated scenarios and optimizing network performance. Practically, the specific algorithm dynamically adjusts the spreading factor (SF) and transmission power (TP) for LoRa nodes, intelligently scheduling transmission times to reduce the risk of data collisions and enhance transmission efficiency. Simulations conducted in a dense LoRaWAN environment demonstrate significant improvements over existing algorithms, achieving an approximate 30.35% enhancement in data transmission rate, 24.57% reduction in energy consumption, and 31.25% increase in average network throughput compared to the ADR+ algorithm.

The paper by Tu et al., referred to as the fourth contribution of this Special Issue, addresses the challenge of complexity in multi-user detection (MUD) schemes for uplink massive multiple-input multiple-output (M-MIMO) systems by proposing a novel mixed over-relaxation (MOR) algorithm, combining the advantages of successive over-relaxation (SOR) and accelerated over-relaxation (AOR) methods. The MOR algorithm aims to reduce

the bit error rate (BER), computational complexity, and adapt to both 4G and beyond fifth-generation (B5G) environments. By dividing MOR into initial and collaboration stages, the algorithm achieves rapid convergence and refinement performance through alternating iterations. Simulations demonstrate significant improvements in BER performance compared to traditional SOR and AOR methods, achieving approximately 99.999% and 99.998% improvement, respectively, while keeping the complexity at O(N^2). The collaborative architecture of MOR effectively balances BER performance and computational complexity, making it suitable for M-MIMO orthogonal frequency division multiplexing (OFDM) and universal filtered multi-carrier (UFMC) systems in both 4G and B5G environments, presenting a promising solution for future wireless communication systems.

The fifth contribution of the Special Issue is a paper by Xu et al. that introduces a Q-learning and efficient low-quantity charge (QL-ELQC) method tailored for the smoke alarm unit within a power system, aiming to enhance the lifetime of wireless sensor network nodes. Actually, traditional medium-access control protocols often overlook the alarm state, prompting the need for an optimized approach. The QL-ELQC method, considering the relationship between sensor data conditions and RF module activation, indeed optimizes the standby and active periods of nodes based on quantity charge models. By effectively managing the duty cycle, the proposed method mitigates the continuous state–action space limitations of Q-learning. Simulation results demonstrate significant improvements in latency and energy efficiency compared to existing schemes, with experimental validation aligning with theoretical expectations. The extension of the lifetime of nodes provided by the proposed method is particularly beneficial in scenarios where battery replacement or recharging is impractical, thus offering a promising solution for enhancing WSN longevity in alarm systems under harsh environmental conditions.

The paper by Kovtun et al. is the sixth contribution of this Special Issue. It investigates the process of information transfer between sensor network end IoT devices and hubs at the transport protocol level, focusing on leveraging the 5G platform. Viewing this process as a semi-Markov model with nested Markov chains, the study derives a stationary distribution of the sliding window size, crucial for determining information flow intensity. A recursive method with linear computational complexity is formalized to calculate this distribution. Using this, a distribution function characterizing communication channel bandwidth is formulated. The study showcases the potential of TCP protocol in handling massive IoT traffic but highlights security concerns. Future research aims to optimize TCP parameters for precise Quality of Service (QoS) policies in 5G clusters supporting sensor networks, contributing to advancements in ultra-reliable low-latency communications (URLLCs), massive machine-type communications (mMTCs), and enhanced mobile broadband (eMBB) technologies.

The seventh contribution of this Special Issue is a research article by El Boudani et al. It introduces a novel approach for enhancing indoor positioning accuracy in 5G IoT networks, crucial for identity and context-aware applications such as simultaneous localization and mapping (SLAM). Utilizing a K-nearest neighbors and deep neural network (K-DNN) algorithm, the study proposes a method that incorporates a fusion of Bluetooth low-energy (BLE) and wireless local area network (WLAN) signals, along with a unique data augmentation concept for received signal strength (RSS)-based fingerprinting, resulting in a 3D fused hybrid radiomap. This hybrid approach aims to improve 3D localization accuracy by addressing challenges such as outlier detection and reducing labor costs during data collection. The implementation demonstrates promising results, achieving a 91% classification accuracy in 1D and submeter accuracy in 2D positioning. The study underscores the potential of cooperative machine learning localization and suggests future directions for expanding the model's capabilities, including integrating data from different azimuth angles and incorporating floor-level detection for multi-story buildings.

The eighth contribution is an article by Kou et al. that addresses authentication and key negotiation challenges in unmanned aerial vehicle mobile ad hoc networks (UAVMANETs) for secure communication among multiple UAVs. By introducing a Latin square approach,

the authentication process is simplified, enhancing the efficiency of signature aggregation within the Boneh–Lynn–Shacham (BLS) signature scheme and aggregating keys negotiated via the elliptic curve Diffie–Hellman (ECDH) protocol into new keys. This innovative protocol ensures secure communication over insecure channels, crucial for UAVMANETs operating in open wireless environments. Through security analysis and simulations, the proposed scheme demonstrates improved efficiency in authentication and key negotiation while meeting stringent security requirements. However, future research is suggested to address scenarios involving dynamic changes in group membership, aiming to design a more flexible protocol tailored to the dynamic nature of UAV networks.

Christakis et al., in their research article, which is the ninth contribution of this Special Issue, investigate the use of low-cost electrochemical sensors in WSNs for air quality monitoring in urban environments, addressing the challenge of sensor aging that affects measurement accuracy. Through a long-term experimental study, the researchers compared sensor data with official air monitoring instruments, revealing that aging due to factors such as gas exposure and temperature fluctuations degrades sensor performance. To mitigate this, they developed novel corrective formulae using specific coefficients, which adjust for aging and temperature variations respectively. Their methodology demonstrated high reliability and accuracy for nitrogen dioxide (NO_2) and ozone (O_3) sensors without the need for frequent recalibration, making it feasible to deploy cost-effective and dense air quality monitoring networks in smart cities.

Finally, the tenth contribution of this Special Issue is a paper by Pu et al. that addresses the challenge of ensuring data freshness in industrial wireless sensor networks (IWSNs). Specifically, this research article proposes a scheduling algorithm that maintains the age of information (AoI) of each data packet within a bounded interval. Recognizing that optimizing the average AoI alone is insufficient for industrial applications, the authors developed a low-complexity AoI-bounded scheduling algorithm that guarantees timely data delivery, critical for the stability of industrial control systems. The algorithm adjusts the transmission intervals and superframe lengths based on the nodes' sampling periods, ensuring schedulability and reducing peak AoI by allocating additional time slots to nodes with higher requirements. Numerical examples demonstrate the effectiveness of this approach in maintaining bounded AoI, thus enhancing the reliability and real-time performance of IWSNs in industrial settings.

3. Conclusions

The Guest Editors of this Special Issue believe that WSNs will continue being at the epicenter of scientific interest, and hope that this collection of articles will be helpful to scientists who focus their research efforts on this challenging domain.

Author Contributions: Conceptualization, D.K. and E.A.; writing—original draft preparation, D.K. and E.A.; writing—review and editing, D.K. and E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This article received no external funding.

Acknowledgments: The Guest Editors of this Special Issue sincerely thank all the scientists who submitted their research articles, the reviewers who assisted in evaluating these manuscripts, and both the Editorial Board Members and the Editors of *Electronics* for their overall support.

Conflicts of Interest: The authors declare no conflicts of interest.

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