

Guest Editorial

Special Section on

Industrial Wireless Sensor Networks

GIVEN the competitive industrial manufacturing market, there is an increasing demand to improve process efficiencies, comply with environmental regulations, and meet corporate financial objectives. Thus, both existing industrial systems and new emerging industrial applications require intelligent and low-cost industrial automation solutions to improve efficiency, productivity, as well as safety. The collaborative intelligence and low-cost nature of industrial wireless sensor networks (IWSNs) offer several advantages over traditional wired industrial monitoring and control systems, such as flexibility, self-configuration, rapid deployment, and an inherent intelligent processing capability. To this end, IWSN-based automation systems are increasingly taking advantage of the opportunities presented by innovative developments in information and communication technologies (ICT). IWSNs play a vital role in creating a highly reliable and self-healing industrial system that rapidly responds to real-time events appropriately and, consequently, can play a crucial role in creating more reliable, efficient, and productive industrial systems, thus contributing towards industries' competitiveness in the marketplace. The specific constraints of the industrial automation domain on the other hand lead to new requirements towards the dependability, especially reliability, safety and security, of the ICT applied.

A recent report from TechNavio, with inputs from industry experts, forecasts the IWSN market in the Americas, Europe, Middle East and Africa, and the Asia-Pacific, to grow at a compound annual growth rate (CAGR) of 14.4% over the period 2012–2016 [1]. The report designates the cost benefit of wireless sensors compared to traditional wired sensors to be one of the key factors contributing to this market. Additional conduits are not required for installations in industrial structures and in case of a connectivity problem it can be easily isolated and rectified. Wireless sensors offer advantages over wired sensors in the industrial segment due to innovative trends in the development of wireless technologies. However, the lack of standardization of different wireless sensing technologies has been identified as a challenge to the growth of this market. Interoperability between different wireless sensors across all applications is a prerequisite. A high adoption of wireless technologies such as Bluetooth, ZigBee, and Wi-Fi has already been witnessed. Other solutions such as WirelessHART, SP100, or Wibree have also contributed to the widespread use of IWSNs across various applications. The adoption of wireless technology for different applications is expected to be high during the forecast period.

There is general consensus that the concept of Wireless Sensor Networks (WSNs) originated from the Distributed

Sensor Networks (DSN) program at the United States Defense Advanced Research Projects Agency (DARPA), which started in 1980 and soon progressed into academia and scientific research institutions worldwide [2]. However, only with recent advances in the essential technologies, such as semiconductor, networking and material science, has the real potential of WSNs been realized with a new generation of sensing nodes emerging. Recent advances in these technologies, as well as the relevant protocols, software and intelligence, are driving the ubiquitous deployment of large-scale WSNs. Today's WSNs differ significantly from those designed and implemented from about 5 to 10 years ago. They have lower deployment and maintenance costs, have better resources such as computational capabilities and memory, last longer and are more rugged and compact. They are deployed in increasing numbers in many application scenarios. However, when we consider the industrial application of WSNs, in which case we refer to industrial wireless sensor networks, i.e., IWSNs, there remain significant research and development challenges looking for acceptable solutions before wider acceptance in the marketplace.

The unique challenges and constraints of the industrial environment were first presented in the seminal paper by Gungor and Hancke in 2009 [3]. It provided a contemporary view of the state-of-the-art of IWSNs and introduced technical challenges and design principles in terms of hardware and software development, system architectures and protocols. It discussed specific underlying technologies, such as wireless transmission and energy-harvesting, as well as IWSN standards. Unresolved research issues were introduced.

A second paper to have had a significant impact on the research community was on the opportunities and challenges of IWSNs in smart grids [4]. IWSNs are widely recognized as a vital component of the next-generation electric power system offering capabilities that can enhance various aspects, such as generation, delivery, and utilization. This paper points out the challenges posed by the harsh and multifaceted electrical power system surroundings with regards to the reliability of transmission within IWSNs. It presents results of experiments that have been done on IEEE 802.15.4-compliant wireless sensor nodes in a real scenario of power delivery and distribution systems by measuring channel characteristics, background noise and attenuation in the 2.4-GHz frequency band. These results provide valuable insights for design decisions and tradeoffs for smart-grid applications. It also points out the research areas yet to be addressed.

The first authoritative book on the state-of-the-art of IWSNs appeared in April 2013 [5]. Researchers from around the world contributed on diverse, but pertinent topics, such as software and hardware platforms and protocols and standards, important

for dealing with the unique challenges facing IWSN systems. It comprehensively reviews emerging and already deployed IWSN technologies and applications, as well as technical challenges and design goals. In addition, typical topics covered are wireless technologies, energy harvesting, and network and resource management. It discusses issues in industrial applications, such as latency, fault tolerance, synchronization, real-time constraints, network security, and cross-layer design. Specific wireless communication standards for industrial applications are presented.

The goal of this Special Section on Industrial Wireless Sensor Networks was to build on the logical development and state-of-the-art as depicted above and focus on the development, adoption, and application of WSNs for the industrial environment with its unique requirements. This is the second Special Section on this topic. The first one was published in 2009 and covered the state-of-the-art and technical challenges facing the acceptance of this concept at the time [6].

It is clear that there remain many issues to be addressed adequately despite considerable research, as confirmed by a paper from industry [7]. In this paper, the authors present the key requirements for typical process automation applications and outline the major issues, i.e., safety, security and availability, which need to be addressed before IWSNs will be fully adopted in process automation applications. New application areas and the resulting developments at the interface of information and communication technologies and these application environments were solicited for this Special Section. Many manuscript submissions were received and the rest of this editorial includes discussion of the papers accepted at the time of going to press.

Routing algorithms remain an active topic for research, especially aimed at conserving energy consumption within the resource constrained environment of a typical sensor node, thus extending the lifetime of a sensor node. In [8], an energy-balanced routing method based on forward-aware factor (FAF-EBRM) is proposed for effectively transmitting sensing data to the receiver, taking into account the limited energy and communication ability of sensor nodes. The protocol selects the next-hop node according to link weight and forward energy density. A reconstruction mechanism for local topology is included. FAF-EBRM is experimentally compared to other protocols such as LEACH and EEUC and the results show superior behavior in terms of energy consumption, lifetime, and quality-of-service.

In [9], the authors describe the real-time implementation of a Harmony Search Algorithm (HSA)-based clustering protocol for energy efficient WSNs. Again this has the goal of extending the life of the sensor node by using less energy, which is achieved by a proposed framework that enables the development of optimized cluster-based protocols.

A music-based metaheuristic optimization method, known as the Harmony Search Algorithm (HSA), is used to design and implement a protocol in real-time, which minimizes the intracluster distances between the cluster members and their cluster heads (CHs) and optimizes the energy distribution of the WSN. An experiment was performed in a real case scenario for detecting fire by monitoring ambient temperature. The results indicate that the proposed HSA protocol performs better,

i.e., the WSN's lifetime has been extended, than well-known cluster-based protocols developed for WSNs, such as Low-Energy Adaptive Clustering Hierarchy-Centralized (LEACH-C) and one using Fuzzy C-Means (FCM).

Providing reliable and efficient communication for IWSNs within a dynamic and harsh industrial environment is a major challenge and one that attracts significant research. In [10], a reliable reactive routing enhancement (R3E) for IWSNs is presented to increase the resilience to link dynamics of unreliable wireless links by utilizing the local path diversity. This is achieved through the introduction of a biased back off scheme during the route discovery phase to find a robust guide path. This provides forwarding opportunities, which enable the progression of data packets towards the destination by cooperation of the nodes without utilizing the location information. Extensive simulations indicate that, while high-energy efficiency and low delivery latency is preserved, the packet delivery ratio is superior to other protocols.

The IEEE 802.15 Task Group 4e was commissioned to amend the MAC of the existing standard 802.15.4-2006, with the intention to enhance and add functionality to the 802.15.4-2006 MAC to, amongst others, better support industrial applications. The IEEE 802.15.4e MAC Enhancement Standard document was approved for publication by the IEEE Standards Association Board in February 2012, and publication took place about one month later. Adaptive synchronization for IEEE802.15.4e Networks is the topic presented in [11]. This was implemented as part of IEEE802.15.4e in the OpenWSN protocol stack, and was validated through comprehensive experimentation. This fulfill the need of industrial low-power wireless mesh networks moving towards time synchronized medium access control (MAC) protocols which are able to yield over 99.9% end-to-end reliability, and radio duty cycles well below 1%. Motes use time slots to communicate, which require neighbor motes to maintain their clocks' alignment within 1 ms. However, relative clock drift takes place between nodes due to temperature and supply voltage changes and fabrication differences, thus requiring periodical resynchronization through pairwise communication. The synchronization period is typically determined *a priori*, based on the worst case drift. This paper, however, introduces a novel technique which measures and models the relative clock drift between neighbor motes, thereby reducing the effective drift rate. Neighbor motes re-synchronize only when needed instead of resynchronizing at a preset rate as is the existing procedure. The net result is a reduction of the minimum achievable duty cycle of an idle network by a factor of 10, which extends the network lifetime due to the lower node power consumption.

In [12], the authors address the task of mixed sound verification in WSN-based home environments. Successful analysis and verification will enable the automation system to perform certain functions based on recognition of specific sound control signals embedded within the composite or mixed sound signal. However, poor recognition results leading to inappropriate responses could occur if the target source is contaminated. This paper proposes a framework for dealing with this problem, consisting of sound separation and verification techniques based on a WSN. A convoluted blind source separation system with

source number estimation using time-frequency clustering is introduced in the sound separation phase. A proposed phase compensation technique is used to estimate an accurate mixing matrix, which is used for reconstructing the separated sound sources. In the verification phase, Mel Frequency Cepstral Coefficients (MFCC) and Fisher scores derived from the wavelet packet decomposition are used as features for support vector machines. The proposed system for mixed sound verification has shown to be robust and feasible for the envisaged application in a WSN-based home environment.

While paper [12] focuses on feature selection or extraction from audio signals, the following paper [13] considers the extraction of features from acceleration sensor signals in order to identify human activities or behavior, an aspect that has received a lot of attention in industrial informatics due to the rapid development of intelligent sensing and growing industrial safety demands. This requires two components, i.e., innovative sensing electronics and suitable intelligence algorithms. In recent years, many effective methods have been proposed to automatically recognize human behavior. These can be grouped into two categories: computer vision-based and accelerometer-based systems. Vision-based human behavior analysis systems do not perform well in the industrial environment, because they are sensitive to lighting conditions. Hence, accelerometer-based physical activity recognition has become the preferred technique. It uses signals from the accelerometer attached to the human body to analyze and classify physical activities such as walking, running and standing. This paper describes the use of WSNs in a novel way for human behavior recognition, where the data is prepared appropriately for transmission to a server for processing and then returned via the WSN. The proposed scheme uses Hamming compressed sensing (HCS), which is suitable for transmission by a WSN, then transmits the compressed activities signals to the network server for decoding using HCS. The network server performs the main recognition computing process, consisting of a new dimension reduction algorithm termed Rank Preserving Discriminant Analysis (RPDA), which trains a RPDA projection matrix by using a small number of labeled samples stored in the network server, and classifying the RPDA projected samples by using the nearest neighbor classifier. Experiments conducted on the SCUT Naturalistic 3D Acceleration-based Activity (SCUT NAA) dataset illustrates the effectiveness of RPDA for human behavior recognition.

In [14], the authors address a vital issue of IWSAN communication, i.e., transmission bandwidth priority of critical traffic over non critical traffic. Exceeding the required delay bound for unpredictable and emergency traffic could lead to system instability, economic and material losses, system failure and, ultimately, a threat to human safety. However, guaranteeing the timely delivery of the IWSAN critical traffic and its prioritization over regular traffic (e.g., noncritical monitoring traffic) is a significant challenge. The paper proposes PriorityMAC, a Priority enhanced Medium Access Control (MAC) protocol, designed for critical traffic in IWSANs, and the first priority-enhanced MAC protocol compatible with IWSAN industrial standards. The authors present the design, implementation, performance analysis and evaluation of PriorityMAC, which in-

cludes a series of novel mechanisms (e.g., High Priority Indication Space) to give high priority traffic first rights to the transmission bandwidth of the low priority traffic. PriorityMAC is implemented in TinyOS and evaluated on a testbed of TelosB motes. The experimental results indicate that PriorityMAC efficiently handles different traffic categories with different latency requirements, thereby achieving a significant improvement of the delivery latency compared to the current industrial standards. The paper contributes to the field in a number of significant ways. The PriorityMAC protocol differentiates in terms of service for traffic priority categories. It utilizes the industrial standards, WirelessHART and ISA100.11a, as a baseline and employs a novel MAC scheme to enhance the access for the critical and aperiodic traffic. PriorityMAC achieves a significant reduction of latency: an experimental comparison with the priority access methods in the current industrial standards reveals an average reduction in latency of 94% for highest priority traffic and 93% for secondary priority traffic. The reduction is achieved at the expense of only 0.17% increase in third priority traffic access delay and 0.19% deferring ratio from the lowest-priority packets. PriorityMAC was implemented using TinyOS and evaluated on a testbed of TelosB motes.

In [15], a multi-interface ZigBee building area network (MIZBAN) for a high traffic advanced metering infrastructure (AMI) for high rise buildings is proposed. Meter management functions such as demand response for smart grid applications are supported. The high traffic communication in these buildings are catered for by developing a multi-interface management framework to coordinate the operation between multiple interfaces based on a newly defined tree based mesh ZigBee (T-Mesh) topology, which supports both mesh and tree routing in a single network. To evaluate MIZBAN, the proposed system was physically deployed in a five floor building. Based on the measured data, simulations were performed to extend the analysis to a twenty-three floor building. These revealed that MIZBAN yields an improvement in round trip time of the backbone and the floor network by 75% and 67% respectively. This paper provides the design engineer with six recommendations for a generic MIZBAN design, which will fulfill the requirement for demand response by the U.S. government, i.e., a latency of less than 0.25 s.

As a conclusion, some general design goals for IWSNs are listed. More details can be found in [3]:

- Small and low-cost sensor nodes.
- Scalable architectures and efficient protocols
- Localized processing and data fusion
- Resource-efficient design
- Self-configuration and self-organization
- Adaptive network operation
- Time synchronization
- Fault tolerance and reliability
- Application-specific design
- Security

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