

Industrial Wireless Sensor Networks: Challenges, Design Principles, and Technical Approaches

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Abstract: In today's competitive industry marketplace, the companies face growing demands to improve process efficiencies, comply with environmental regulations, and meet corporate financial objectives. Given the increasing age of many industrial systems and the dynamic industrial manufacturing market, intelligent and low-cost industrial automation systems are required to improve the productivity and efficiency of such systems. The collaborative nature of industrial wireless sensor networks (IWSNs) brings several advantages over traditional wired industrial monitoring and control systems, including self-organization, rapid deployment, flexibility, and inherent intelligent-processing capability. In this regard, IWSN plays a vital role in creating a highly reliable and self-healing industrial system that rapidly responds to real-time events with appropriate actions. In this paper, first, technical challenges and design principles are introduced in terms of hardware development, system architectures and protocols, and software development. Specifically, radio technologies, energy-harvesting techniques, and cross-layer design for IWSNs have been discussed. In addition, IWSN standards are presented for the system owners, who plan to utilize new IWSN technologies for industrial automation applications. In this paper, our aim is to provide a contemporary look at the current state of the art in IWSNs and discuss the still-open research issues in this field and, hence, to make the decision-making process more effective and direct.

Index Terms—Cross-layer design, industrial wireless sensor networks (IWSNs), ISA100, ultra wide band (UWB), wireless HART, ZigBee, 6LoWPAN.

I. INTRODUCTION

In today's competitive industry marketplace, the companies face growing demands to improve process efficiencies, comply with environmental regulations, and meet corporate financial objectives. Given the increasing age of many industrial systems and the dynamic industrial manufacturing market, intelligent and low-cost industrial automation systems are required to improve the productivity and efficiency of such system. Traditionally, industrial automation systems are realized through wired communications. However, the wired automation systems require expensive communication cables to be installed and regularly maintained, and thus, they are not widely implemented in industrial plants because of their high cost. Therefore, there is an urgent need for cost-effective wireless automation systems that enable significant savings and reduce air-pollutant emissions by optimizing the management of industrial systems. With the recent advances in wireless sensor networks (WSNs), the realization of low-cost embedded industrial automation systems have become feasible. In these systems, wireless tiny sensor nodes are installed on industrial equipment and monitor the parameters critical to each equipment's efficiency based on a combination of measurements such as vibration, temperature, pressure, and power quality. These data are then wirelessly transmitted to a

sink node that analyzes the data from each sensor. Any potential problems are notified to the plant personnel as an advanced warning system. This enables plant personnel to repair or replace equipment, before their efficiency drops or they fail entirely. In this way, catastrophic equipment failures and the associated repair and replacement costs can be prevented, while complying with strict environmental regulations.

The collaborative nature of IWSNs brings several advantages over traditional wired industrial monitoring and control systems, including self-organization, rapid deployment, flexibility, and inherent intelligent-processing capability. In this regard, WSN plays a vital role in creating a highly reliable and self-healing industrial system that rapidly responds to real-time events with appropriate actions. However, to realize the envisioned industrial applications and, hence, take the advantages of the potential gains of WSN, effective communication protocols, which can address the unique challenges posed by such systems, are required.

Due to unique characteristics and technical challenges, developing a WSN for industrial applications requires a combination of expertise from several different disciplines. First of all, industrial expertise and knowledge are required for application-domain-specific knowledge. Second, sensor-technology expertise is essential to fully understand issues associated with sensor calibration, transducers, and

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERCE)
Vol 4, Issue 5, May 2017**

clock-drift. Third, RF design and propagation environment expertise is necessary to address communication challenges and RF interference problems in industrial environments. Finally, networking expertise is needed for understanding the hierarchical network architectures and integrating different networks, which are required for industrial WSNs (IWSNs) to provide flexible and scalable architectures for heterogeneous applications.

Recently, many researchers have been engaged in developing schemes that address the unique challenges of IWSNs. In this paper, first, technical challenges and design principles are introduced in terms of hardware and software developments and system architecture and protocol design. Specifically, radio technologies, energy-harvesting techniques, and cross-layer design for IWSNs are discussed. In addition, IWSN standards are presented for the system owners, who plan to utilize new IWSN technologies for industrial automation applications. In this paper, our aim is to provide a contemporary look at the current state of the art in IWSNs and discuss the still-open research issues in this field and, hence, to make the decision-making process more effective and direct.

II. CHALLENGES

The major technical challenges for realization of IWSNs can be outlined as follows.

- 1) **Resource constraints:** The design and implementation of IWSNs are constrained by three types of resources: a) energy; b) memory; and c) processing. Constrained by the limited physical size, sensor nodes have limited battery energy supply. At the same time, their memories are limited and have restricted computational capabilities.
- 2) **Dynamic topologies and harsh environmental conditions:** In industrial environments, the topology and connectivity of the network may vary due to link and sensor-node failures. Furthermore, sensors may also be subject to RF interference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other conditions that challenge performance. These harsh environmental conditions and dynamic network topologies may cause a portion of industrial sensor nodes to malfunction.
- 3) **Quality-of-service (QoS) requirements:** The wide variety of applications envisaged on IWSNs will have different QoS requirements and specifications. The QoS provided by IWSNs refers to the accuracy between the data reported to the sink node (the control center) and what is actually occurring in the industrial environment. In addition, since sensor data are typically time-sensitive, e.g., alarm notifications for the industrial facilities, it is important to receive the data at the sink in a timely manner. Data with long latency due to processing or communication may be outdated and lead to wrong decisions in the monitoring system.
- 4) **Data redundancy:** Because of the high density in the network topology, sensor observations are highly correlated in the space domain. In addition, the nature of the physical phenomenon constitutes the temporal correlation between each consecutive observation of the sensor node.
- 5) **Packet errors and variable-link capacity:** Compared to wired networks, in IWSNs, the attainable capacity of each wireless link depends on the interference level perceived at the receiver, and high bit error rates ($BER = 10^{-2} - 10^{-6}$) are observed in communication. In addition, wireless links exhibit widely varying characteristics over time and space due to obstructions and noisy environment. Thus, capacity and delay attainable at each link are location-dependent and vary continuously, making QoS provisioning a challenging task.
- 6) **Security:** Security should be an essential feature in the design of IWSNs to make the communication safe from external denial-of-service (DoS) attacks and intrusion. IWSNs have special characteristics that enable new ways of security attacks. Passive attacks are carried out by eavesdropping on transmissions including traffic analysis or disclosure of message contents. Active attacks consist of modification, fabrication, and interruption, which in IWSN cases may include node capturing, routing attacks, or flooding.
- 7) **Large-scale deployment and ad hoc architecture:** Most IWSNs contain a large number of sensor nodes (hundreds to thousands or even more), which might be spread randomly over the deployment field. Moreover, the lack of predetermined network infrastructure necessitates the IWSNs to establish connections and maintain network connectivity autonomously.
- 8) **Integration with Internet and other networks:** It is of fundamental importance for the commercial development of IWSNs to provide services that allow the querying of the network to retrieve useful information from anywhere and at any time. For this reason, the IWSNs should be remotely accessible from the Internet and, hence, need to be integrated with the Internet Protocol

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERECE)
Vol 4, Issue 5, May 2017**

(IP) architecture. The current sensor-network platforms use gateways for integration between IWSNs and the Internet. Note that although today's sensor networks use gateways for integration between IWSNs and the Internet, the sensor nodes may have IP connectivity in the future.

III. DESIGN GOALS

The existing and potential applications of IWSNs span a very wide range, including building automation, industrial-process automation, electric-utility automation, automatic meter reading, and inventory management. To deal with the technical challenges and meet the diverse IWSN application requirements, the following design goals need to be followed.

- 1) **Low-cost and small sensor nodes:** Compact and low-cost sensor devices are essential to accomplish large-scale deployments of IWSNs. Note that the system owner should consider the cost of ownership (packaging requirements, modifications, maintainability, etc.), implementation costs, replacement and logistics costs, and training and servicing costs as well as the per unit costs all together.
- 2) **Scalable architectures and efficient protocols:** The IWSNs support heterogeneous industrial applications with different requirements. It is necessary to develop flexible and scalable architectures that can accommodate the requirements of all these applications in the same infrastructure. Modular and hierarchical systems can enhance the system flexibility, robustness, and reliability. In addition, interoperability with existing legacy solutions, such as fieldbus- and Ethernet-based systems, is required.
- 3) **Data fusion and localized processing:** Instead of sending the raw data to the sink node directly, sensor nodes can locally filter the sensed data based on the application requirements and transmit only the processed data, i.e., in-network processing. Thus, only necessary information is transported to the end-user and communication overhead can be significantly reduced.
- 4) **Resource-efficient design:** In IWSNs, energy efficiency is important to maximize the network lifetime while providing the QoS required by the application. Energy saving can be accomplished in every component of the network by integrating network functionalities with energy-efficient protocols, e.g., energy-aware routing on network layer, energy-saving mode on MAC layer, etc.
- 5) **Self-configuration and self-organization:** In IWSNs, the dynamic topologies caused by node failure/mobility/ temporary power-down and large-scale node deployments necessitate self-organizing architectures and protocols. Note that, with the use of self-configurable IWSNs, new sensor nodes can be added to replace failed sensor nodes in the deployment field, and existing nodes can also be removed from the system without affecting the general objective of the application.
- 6) **Adaptive network operation:** The adaptability of IWSNs is extremely crucial, since it enables end-users to cope with dynamic/varying wireless-channel conditions in industrial environments and new connectivity requirements driven by new industrial processes. To balance the tradeoffs among resources, accuracy, latency, and time-synchronization requirements, adaptive signal-processing algorithms and communication protocols are required.
- 7) **Time synchronization:** In IWSNs, large numbers of sensor nodes need to collaborate to perform the sensing task, and the collected data are usually delay-sensitive. Thus, time synchronization is one of the key design goals for communication protocol design to meet the deadlines of the application. However, due to resource and size limitations and lack of a fixed infrastructure, as well as the dynamic topologies in IWSNs, existing time-synchronization strategies designed for other traditional wired and wireless networks may not be appropriate for IWSNs. Adaptive and scalable time-synchronization protocols are required for IWSNs.
- 8) **Fault tolerance and reliability:** In IWSNs, based on the application requirements, the sensed data should be reliably transferred to the sink node. Similarly, the programming/re-tasking data for sensor operation, command, and queries should be reliably delivered to the target sensor nodes to assure the proper functioning of the IWSN. However, for many IWSN applications, the sensed data are exchanged over time-varying and error-prone wireless medium. Thus, data verification and correction on each communication layer and self-recovery procedures

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERECE)
Vol 4, Issue 5, May 2017**

are extremely critical to provide accurate results to the end-user.

- 9) **Application-specific design:** In IWSNs, there exists no one-size-fits-all solution; instead, the alternative designs and techniques should be developed based on the application-specific QoS requirements and constraints.
- 10) **Secure design:** When designing the security mechanisms for IWSNs, both low-level (key establishment and trust control, secrecy and authentication, privacy, robustness to communication DoS, secure routing, resilience to node capture) and high-level (secure group management, intrusion detection, secure data aggregation) security primitives should be addressed. In addition, because of resource limitations in IWSNs, the overhead associated with security protocols should be balanced against other QoS performance requirements.

It is very challenging to meet all aforementioned design goals simultaneously. Fortunately, most IWSN designs have different requirements and priorities on design objectives. Therefore, the network designers and application developers should balance the tradeoffs among the different parameters when designing protocols and architectures for IWSNs. Table I summarizes the technical challenges and corresponding design goals for IWSNs.

IV. DESIGN PRINCIPLES AND TECHNICAL APPROACHES

In this section, the design principles and technical approaches in IWSNs are broadly classified into three categories: 1) hardware development; 2) software development; and 3) system architecture and protocol design.

A. Hardware Development

- 1) **Low-Power and Low-Cost Sensor-Node Development:** An IWSN node integrates sensing, data collection and processing, and wireless communications along with an attached power supply on a single chip. The hardware architecture of a typical industrial sensor node is composed of four basic components.
- 2) **Sensor:** Sensors are hardware devices that produce measurable response to a change in a physical condition. e.g., temperature, pressure, voltage, current, etc. The analog signals produced by the sensors based on the

observed phenomenon are converted to digital signals by the analog-to-digital converters and sent to processor for further processing. Several sources of power consumption in sensors are as follows: 1) signal sampling and conversion of physical signals to electrical ones; 2) signal conditioning; and 3) analog-to-digital conversion.

- 3) **Processor:** The processing unit, which is generally associated with a small storage unit, performs tasks, processes data, and controls the functionality of other components in the sensor node.
- 4) **Transceiver:** A transceiver unit connects the node to the network. Generally, radios used in the transceivers of industrial sensor nodes operate in four different modes: transmit; receive; idle; and sleep. Radios operating in idle mode results in power consumption, almost equal to power consumed in receive mode.
- 5) **Power source:** One of the most important components of an industrial sensor node is the power source. In sensor networks, power consumption is generally divided into three domains: sensing, data processing, and communication. Compared to sensing and data processing, much more energy is required for data communication in a typical sensor node. Hence, local data processing is crucial in minimizing power consumption in IWSNs.
- 6) **Radio Technologies:** In industrial environments, the coverage area of IWSNs, as well as the reliability of the data, may suffer from noise, co channel interferences, multipath propagation, and other interference. For example, the signal strength may be severely affected by the reflections from the walls (multipath propagation), interferences from other devices using ISM bands, and by the noise generated from the equipment or heavy machinery. In these conditions, it is important that data reliability and integrity are maintained for mission-critical information.
- 7) **Energy-Harvesting Techniques:** In IWSNs, the use of batteries as power source for the sensor nodes can be troublesome due to their limited lifetime, making periodic replacements unavoidable. In this respect, energy-harvesting (also referred to as energy scavenging) techniques, which extract energy from the environment where the sensor itself lies, offer another important way to prolong the lifetime of sensor devices. Systems able to perpetually power sensors based on simple commercial off-the-shelf photovoltaic cells coupled with rechargeable batteries and super capacitors have already been demonstrated. In the state of the art in

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERECE)
Vol 4, Issue 5, May 2017**

more unconventional techniques for energy harvesting is surveyed. Technologies to generate energy from background radio signals, thermoelectric conversion, vibrational excitation, and the human body are investigated. As far as collecting energy from background radio signals is concerned, unfortunately, an electric field of 1 V/m yields only 0.26 IW/cm², as opposed to 100 IW/cm² produced by a crystalline silicon solar cell exposed to bright sunlight. Electric fields of intensity of a few volts per meter are only encountered close to strong transmitters. Another practice, which consists in broadcasting RF energy deliberately to power-electronic devices, is severely limited by legal limits set by health and safety concerns. Recently, it has also been demonstrated that wireless power transfer using magnetic coupling between two copper coils is possible. While thermoelectric conversion may not be suitable for wireless devices, harvesting energy from vibrations in the surrounding environment may provide another useful source of energy. Vibrational magnetic power generators based on moving magnets or coils may yield powers that range from tens of microwatts when based on micro electromechanical-system technologies to over a milliwatt for larger devices. Other vibrational micro generators are based on charged capacitors with moving plates and, depending on their excitation and power conditioning, yield power on the order of 10 μ W. Other energy-scavenging approaches employ piezoelectric materials. It is reported that these materials can generate power between 100 and 330 μ W/cm³.

B. Software Development

- 1) **API:** In IWSNs, the application software should be accessible through a simple application programming interface (API) customized for both standards-based and customer-specific requirements. This also enables rapid developments and network deployments. With the proper API, the underlying network complexity can be transparent to the end-users who are experts in their specific application domain but not necessarily experts in networking and wireless communications. Moreover, the deployed sensor network should be able to integrate seamlessly with the legacy fieldbus systems existing in the most of industrial facilities.
- 2) **Operating System and Middleware Design:** In IWSNs, the design of operating system is very critical to

balance the tradeoff between energy and QoS requirements. In this regard, TinyOS is one of the earliest operating systems dedicated for tiny sensor nodes. It incorporates a component-based architecture, which minimize the code size and provides a flexible platform for implementing new communication protocols. It fits in 178 B of memory and supports communication, multitasking, and code modularity. Furthermore, in IWSNs, the design of a proper middleware is required for an efficient network and system management. In this regard, the middleware abstracts the system as a collection of massively distributed objects and enables industrial sensor applications to originate queries and tasks, gather responses and results, and monitors the changes within the network. For example, the sensor information networking architecture provides a middleware implementation of the general abstraction and describes sensor query and tasking language to implement such middleware architecture.

- 3) **System Installation and Commissioning:** During installation of IWSNs, the system owners must be able to indicate to the system what a sensor is monitoring and where it is. After deployment in the field, network management and commissioning tools are essential. For example, a graphical user display could display network connectivity and help the system owner to set the operational parameters of the sensor nodes. Network-management tools can also provide whole network-performance analysis and other management features, such as detecting failed nodes (e.g., for replacement), assigning sensing tasks, monitoring network health, upgrading firmware, and providing QoS provisioning.

C. System Architecture and Protocol Design

- 1) **Network Architecture:** In IWSNs, designing a scalable network architecture is of primary importance. One of the design approaches is to deploy homogeneous sensors and program each sensor to perform all possible application tasks. Such an approach yields a flat single-tier network of homogeneous sensor nodes. An alternative multitier approach is to utilize heterogeneous elements. In this approach, resource-constrained low-power elements are in charge of performing simpler tasks, such as detecting scalar physical measurements, while resource-rich high-power devices (such as gateways) perform more complex tasks. In multitier

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERECE)
Vol 4, Issue 5, May 2017**

approaches, the system partitioning/clustering is applied to reduce power dissipation in the sensor nodes by spreading some of the complex energy-consuming computation among resource-rich nodes that are not energy constrained. Generally, IWSNs support several heterogeneous and independent applications with different requirements. Therefore, it is necessary to develop flexible and hierarchical architectures that can accommodate the requirements of all these applications in the same infrastructure.

- 2) **Data Aggregation and Fusion:** In IWSNs, local processing of raw data before directly forwarding reduces the amount of communication and improve the communication efficiency (information per-bit transmitted). Data aggregation and fusion are typical localized mechanisms for the purpose of in-network data processing in IWSNs. These mechanisms minimize traffic load (in terms of number and/or length of packets) through eliminating redundancy. Specifically, when an intermediate node receives data from multiple-source nodes, instead of for-warding all of them directly, it checks the contents of incoming data and then combines them by eliminating redundant information under some accuracy constraints. In this way, dense spatial sampling of events and optimized processing and communication through data fusion can be achieved.
- 3) **Cross-Layer Design:** In multi hop IWSNs, there is an interdependence among functions handled at all layers of the communication-protocol stack . The physical, MAC, and routing layers, together, influence the contention for available network resources. The physical layer has a direct impact on multiple access of nodes in wireless channels by affecting the interference levels at the receivers. The MAC layer determines the bandwidth allocated to each transmitter, which naturally affects the performance of the physical layer in terms of successfully detecting the desired signals. On the other hand, as a result of transmission schedules, high packet delays and low bandwidth can occur, forcing the routing layer to change its route decisions. Different routing decisions change the set of nodes to be scheduled, and thereby impact the performance of the MAC layer. Furthermore, congestion control and power control are also inherently coupled, as the capacity available on each link depends on the transmission power. Therefore, technical challenges caused by harsh industrial conditions and application-specific QoS requirements in

IWSNs call for new research on cross-layer optimization and design methodologies to leverage potential improvements of exchanging information between different layers of the communication stack. However, it is still important to keep some form of logical separation of these functionalities to preserve modularity, and ease of design and testing.

V. STANDARDIZATION ACTIVITIES

In this section, major standardization efforts related to IWSNs are briefly described.

A. ZigBee

ZigBee is a mesh-networking standard based on IEEE 802.15.4 radio technology targeted at industrial control and monitoring, building and home automation, embedded sensing, and energy system automation. ZigBee is promoted by a large consortium of industry players. The good characteristics of the ZigBee are extremely low energy consumption and support for several different topologies, which makes it a good candidate for several sensor network applications . However, in, it is reported that ZigBee cannot meet all the requirements for at least some industrial applications. For example, it cannot serve the high number of nodes within the specified cycle time.

B. Wireless HART

Wireless HART is an extension of the HART protocol and is specifically designed for process monitoring and control. Wireless HART was added to the overall HART protocol suite as part of the HART 7 Specification, which was approved by the HART Communication Foundation in June 2007. The technology employs IEEE 802.15.4-based radio, frequency hopping, redundant data paths, and retry mechanisms. Wireless HART networks utilize mesh networking, in which each device is able to transmit its own data as well as relay information from other devices in the network .

C. UWB

Ultrawideband (UWB) is a short-range wireless-communication technology based on transmission of very short impulses emitted in periodic sequences. The initial applications of UWB include multimedia and personal area networking. Recently, UWB-based industrial applications have gained attention, . On the other hand, UWB is not a viable approach for communication over longer distances or measuring data from unsafe zone because of high peak energy of pulses. The advantages of UWB are good localization capabilities], possibility to share previously allocated radio-

**International Journal of Engineering Research in Electronics and Communication
Engineering (IJERECE)
Vol 4, Issue 5, May 2017**

frequency bands by hiding signals under noise floor, ability to transmit high data rates with low power, good security characteristics due to the unique mode of operation, and ability to cope with multipath environments. The existing challenges lie in, e.g., hardware development, dealing with MAC and multipath interference, and understanding propagation characteristics.

D. IETF 6LoWPAN

6LoWPAN aims for standard IP communication over low-power wireless IEEE 802.15.4 networks utilizing IP version 6 (IPv6). The advantages of 6LoWPAN from the industrial point of view are ability to communicate directly with other IP devices locally or via IP network (e.g., Internet, Ethernet), exist-ing architecture and security, established application level data model and services (e.g., HTTP, HTML, XML), established network-management tools, transport protocols, and existing support for an IP option in most industrial wireless standards.

E. ISA100

The ISA100 working group is focused on a reliable wireless communication system for monitoring and control applications. This group is currently working on a standard, which will lead to an interconnectivity of wireless solutions for the industry automation. The group also takes the special demands of the process industry into account.

F. Bluetooth and Bluetooth Low Energy

Bluetooth has been considered as one possible alternative for WSN implementation. However, due to its high complexity and inadequate power characteristics for sensors, the interest toward Bluetooth-based WSN applications has decreased. Bluetooth-Low-Energy specification is a part of the Bluetooth specification as an ultralow-power technology addressing devices with very low battery capacity. This extension to Bluetooth allows for data rates of up to 1 Mb/s over distances of 5–10 m in the 2.45-GHz band. Although Bluetooth Low Energy is similar to Bluetooth and can employ the same chips and antennas, it has some important differences. Bluetooth Low Energy has a variable-length packet structure, compared to Bluetooth's fixed length. It also employs a different modulation scheme.

VI. CONCLUSION

The IWSNs have the potential to improve productivity of industrial systems by providing greater awareness, control, and integration of business processes. Despite of the great

progress on development of IWSNs, quite a few issues still need to be explored in the future. For example, an efficient deployment of IWSNs in the real world is highly dependent on the ability to devise analytical models to evaluate and predict IWSNs performance characteristics, such as communication latency and reliability and energy efficiency. However, because of the diverse industrial-application requirements and large scale of the network, several technical problems still remain to be solved in analytical IWSN models. Other open issues include optimal sensor-node deployment, localization, security, and interoperability between different IWSN manufacturers. Finally, to cope with RF interference and dynamic/varying wireless-channel conditions in industrial environments, porting a cognitive radio paradigm to a low-power industrial sensor node and developing controlling mechanisms for channel hand-off is another challenging area yet to be explored.

VII. REFERENCES

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