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A Systematic Review on Industrial Wireless Sensor Networks

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Abstract The recent technology boom in wireless sensor network opens new opportunities for boosting efficiency and productivity of industrial manufacture by providing low cost, great automation and distributed control systems. Since designing an industrial wireless sensor network (IWSN) is significantly depended on the industrial environments, application requirements, and the characteristics of the available wireless technologies, a systematic approach for investigating IWSN designs is considered in this paper. Various design challenges, issues and possible solutions regarding IWSNs design are addressed.

Key words: Industrial wireless sensor networks (IWSNs), IEEE 802.15.4, ZigBee

1. Introduction

Nowadays, the competitive industrial marketplace and the stringent environmental regulations make the industrial companies have to face growing demands of improving process efficiencies to meet both the corporate financial and the environmental objectives. Thus, an intelligent, reliable and low-cost industrial automation system to improve the productivity and efficiency is urgently demanded by the industrial arena. Thanks to the recent advances in Micro-Electro-Mechanical system (MEMS) technology, wireless communications, and digital electronics, some low-cost, low-power and multifunctional wireless sensor networks (WSNs) based automation systems have emerged in the industrial sector to avoid the challenges of using wired systems. By comparing with a wired system, wireless automation systems have many inherent advantages, such as relatively low system and infrastructure costs, convenience of installation, easy upgrading and relocating with great physical mobility. As a ubiquitous technology, general issues regarding a WSN design have inspired tremendous research interests [1, 2] in the past decades. But existing surveys on WSNs just focused on some generic issues of WSNs rather than considering the issues occurred in some specific application domains. According to [3], developing a good WSN system needs multidisciplinary knowledge about application domains, hardware and software constraints, the network architecture, and communication protocols. Thus, a general WSN survey is hard to satisfy the scattered design criteria and requirements from variously application areas. Furthermore, industrial WSNs (IWSN) are normally deployed in harsh environments, where a strong electromagnetic power source can deteriorate the transmission quality and bring errors, or even result in failure of the WSN system that may lead to loss of production or even lives. Hence the design criteria and requirements of IWSNs are often much stricter than in other domains. To this end, a more specific technical review dedicating to industrial applications is strongly desired. Recently, some technical surveys regarding IWSNs have emerged. [4] presented a specific survey on implementing wireless technologies in industrial sectors. Some industrial environmental factors, in particular Radio Frequency (RF) interference, which exert a strong influence on the WSN system design, has been addressed. [5] compared several existing industrial wireless technologies and the comparison result can be used to guide a selection of proper WSN technology for a specific industrial application. Additionally, several more comprehensive reviews on most recent developments and challenging issues of IWSNs have been published[6-8]. But none of these works have given a fully integrated view of all the factors driving the design of IWSNs, especially from a systematic perspective. As designing an IWSN is very complicated, if the survey is not from the systematic perspective, some critical design factors might not be covered and unexperienced system designers might struggle to obtain useful information from it. According to these, a systematic approach for investigating IWSNs is presented in this paper. To simplify the complicated system design procedure and to clarify numerous design factors, the systematic approach in accordance with generic system design procedure is proposed to review various design factors, available technologies and research issues. This work also can be used as design guidance for an IWSN design.

The remainder of this paper is organized as follows: In Section 2, a generic design procedure for guiding an IWSN design is presented. Then the factors and features of industrial environments, applications, and available WSN technologies are summarised in Section 3. Section 4 proposes the design challenges, design guidelines and some possible solutions regarding IWSN design. Section 5 concludes this paper.

2. Design Guidance for IWSNs

Despite the fact that the use of wireless technologies within industry has been actively explored over the past ten years, application development for IWSNs remains a challenge. This is because in principle an IWSN would be designed in a holistic way of selecting multidiscipline areas of factors and knowledge from operating environment, transmission media, sensor network topology, hardware constraints, power consumption, production cost, fault tolerance, scalability and security. These factors have been addressed separately by many surveys but none of them have fully integrated a view of all factors to drive the design of IWSN, especially from the systematic perspective. Since most of the existing IWSNs have been designed based on the trail-and-error procedure, the systems' performances are highly dependent on the experience of the developers. As IWSNs usually face dynamically harsh environments, the developed systems with the aforementioned design procedure may cause some problems when they are implemented in these environments. In the context of these reasons, a generic design flow for developing IWSNs is proposed in Figure 1. The basic design principle for designing an IWSN is to find a proper WSN solution and system architecture that simultaneously meets the design criteria and requirements from both the application and environment domains. According to Figure 1, the first design step is to determine all the design criteria, factors and features from the target environment and the specific application. In order to simplify the complicated design procedure and clarify numerous factors, all obtained factors and parameters are classified into different classes with different design priority levels. After outlining the characteristics of the available WSN technologies, a suitable wireless technology and system architecture could be designed by meeting the combination requirements from both the environment and application domains. Since the IWSN's performance is highly influenced by variously dynamic system and environment parameters, in order to avoid blindness design, the third step is to predict and examine the performance of the system in a theoretical way. A sensor network simulator is usually used since it is considered as the best way to bridge the gap between physical and theoretical worlds. By adjusting various system parameters such as data rate, power source types and communication strategies, the performance of the system can be roughly estimated, and then the outputs feedback to the system designers, who will trade off these parameters and select a proper and efficient way to build up the system. Last but not the least, after real system being developed, it will be implemented in the real environment to verify the performance. The developers examine the system and amend their design by checking gathered evaluation result before the system is being delivered to the end users.

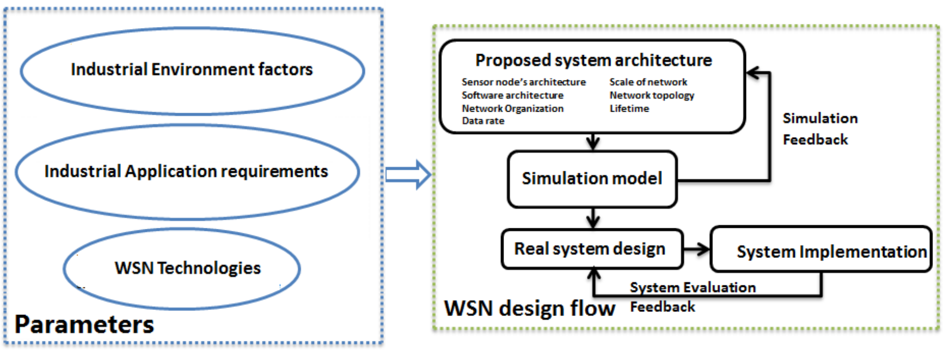

Figure 1 A generic design flow for developing a WSN for industrial applications

3. Determining System Parameters

3.1 Industrial Environment Characteristics

As mentioned in lots of works, the first technical challenge in building an IWSN is that the system will be built to perform mission-critical tasks withstanding the extremely high and low operating temperatures, high humidity levels, strong vibrations, airborne contaminants, potentially exposed to corrosive chemicals or explosive situations, and stationary metal equipment affecting transmission pathways along with excessive electromagnetic noise (RF interference), the characteristics of the target industrial environment are the foremost type of design factors that should be determined. Moreover, since deploying WSNs in industrial environments is often subject to RF interference, caused by noise, co-channel interferences, multipath propagation and other interferences, an investigation of addressing RF interference issues in IWSNs is critical. This could be found in [4] where various RF interference sources from industrial sectors are addressed. On the other hand, the industrial environments also offer some benefits for designing WSNs. For instance, for some specific applications, sensor nodes are usually installed in a fixed place where the line power supply is often available. In this case, the compactness and mobility are not critical design requirements.

3.2. Application Requirements

With recent technical advances, numerous WSN applications have emerged in industries. In fact, each type of application has different design requirements such as cost, lifetime, data rate, size and scalability, coverage range, bandwidth, mobility, dynamics, heterogeneity, real time communication, safety, security, duty cycle, energy consumption, integration, and reliability etc. The extremely dynamic design requirements make the IWSN design very complicated and lots of trade-offs between these parameters should be considered. Hence, how to distinguish these parameters with different priority levels for a specific application is important. From an industrial perspective, ISA SP100 workgroup classify IWSNs into six classes, which include: monitoring without immediate operational consequences, monitoring with short-term operational consequences, open-loop control, closed-loop supervisory control, closed-loop regulatory control and Emergency action, with different message priorities. Please refer to [9] for detailed description of this classification,

3.3 WSN Technologies

Nowadays, several WSN technologies and standards were or are being developed for industrial applications. Each of them has its own strengths and shortages when employed in different applications. Some existing popular WSN technologies and their own features are outlined in this section. Generally, developing a WSN can be divided into development of sensor node and wireless network parts.

Figure 2 shows a structural view of a wireless sensor node composed of four basic components, which are sensing, processing, communication and power subsystems. For the sensing subsystem, it consists of different types of sensors, which are employed to covert physical phenomenon to electrical signals. The processing subsystem, which builds up by a microprocessor associated with numbers of Analogy to Digital Converters (ADCs) and a small memory, is used to process signal and to schedule the tasks. Additionally, some application dependent additional components such as a location finding system and a mobilizer might be included in this subsystem according to different application requirements. The third component is the communication subsystem, which includes a modulator/demodulator associated with an antenna to receive and transmit the signal to other sensor nodes in the same network. The last component is a power subsystem, where energy required for the entire wireless sensor node is obtained from this part. Since energy efficiency is critical for any wireless sensor node, a power manager is normally employed to handle on board power sources such as batteries or exotic energy harvesting units.

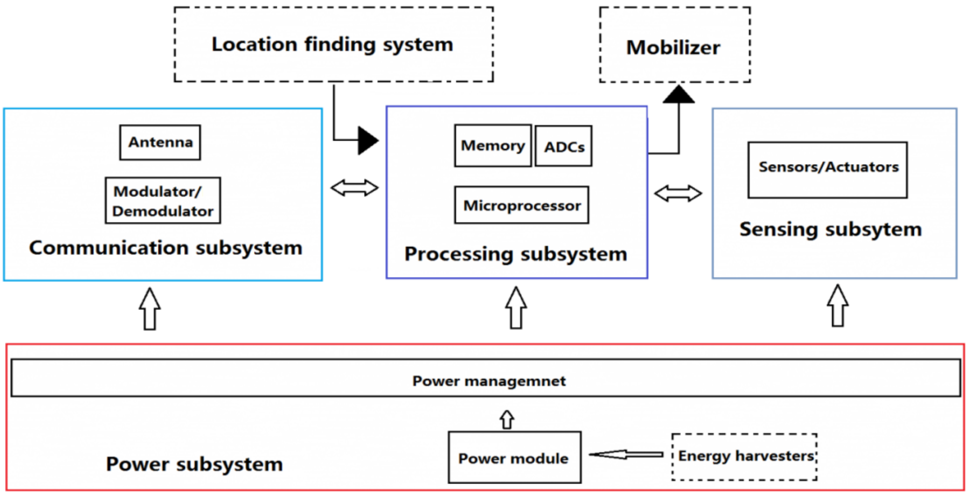

Figure 2 The block diagram of wireless sensor node

For wireless senor network part, a typical sensor network communication architecture is depicted in Figure 3, which consists of an application layer, a transport layer, a network layer, a data link layer, a physical layer, a power management plane, a mobility management plane, and a task management plane, to handle the communication protocol.

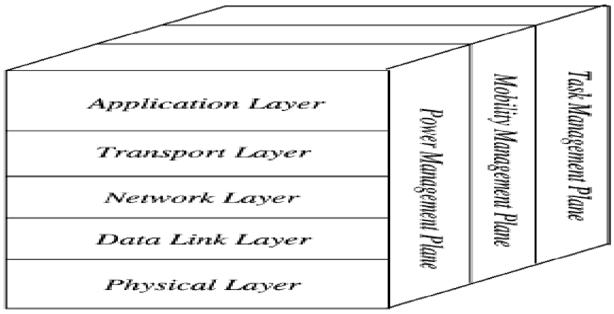

Figure 3. The sensor networks protocol stack [1]

On the application layer, different types of application software, depending on the sensing tasks, can be built on it. For the transport layer, it is usually implemented only if end-users access the WSN through the internet [9]. The network layer, including adaptive topology management and topological routing, is designed for routing the data from the transport layers of the source nodes to the corresponding layers of the sink node. Star, mesh and hybrid-star network topologies can be selected in this layer depending on the applications. The data-link layer is responsible for multiplexing of data streams, data frame detection, medium access control (MAC) and error control to ensure reliable point-to-point and point-to-multipoint connections in a communication network. As the MAC controls the radio, it has a remarkable impact on the overall energy consumption and node lifetime [10]. Since the environment is noisy and sensor nodes can be mobile, the MAC protocol must be power aware and able to minimize collision with neighbors' broadcast [10]. The tasks of the physical layer include frequency selection, carrier frequency generation, signal detection, modulation and data encryption. Additionally, the power, mobility, and task management planes monitor the power, movement, and task distribution among the sensor nodes to help the sensor nodes coordinate the sensing task and lower the overall power consumption [10]. For more detailed description of the WSN protocol stack refer to [10, 11].

During the past decade, standardized wireless communication standards like IEEE 802.11 (Wi-fi), IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4, addressing and purposing in specific requirements, respectively, have dominated the IWSNs. As outlined in [12], IEEE 802.15.4, which is designed for low rate wireless personal area network, was demonstrated to be the most suitable for industrial machine condition monitoring [12]. In this paper, we only focus on the wireless solutions based on IEEE 802.15.4. Table 1 provides a briefly technical comparison between ZigBeePro, WirelessHART, and ISA 100.11a protocols, which are all built on IEEE 802.15.4 standard. However, due to lack of the comparison results between these protocols in the context of the industrial applications, it is still hard for inexperienced system designers to select an appropriate wireless standard for their application. This area should be replenished in the future.

Table 1. Comparison of Industrial Communication protocols, sources (ZigBee, 2010), (WirelessHART,2008) and (ISA100.11a,2009) [12]

	ZigBee Pro	WirelessHART	ISA 100.11a
Transceiver	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4
Topology	Mesh, Tree	Mesh	Hopping
Encryption	AES128	AES128	AES128
Superframe slot size	N/A	10ms	10-12ms
Channel access	CSMA	TDMA	TDMA and contention access
Frame Integrity Check	32 bit	32 bit	32 bit or 64 bit
Expansion/New	Extension of ZigBee	Extension of HART protocol	New protocol
Determinism	No	Yes	Yes
Channel blacklisting	Preferred channel	Blacklist	Blacklist
Battery life	Best	Good	Good
Reliability in harsh environment	Low	Good	Good

4. Designing and Deploying an IWSN

4.1 Guidelines for designing IWSNs

After determining all these factors, parameters and features from three domains, the system can be designed. Several important factors that influence the performance of the IWSN along with trade-off decisions are discussed in this section. In order to follow the proposed system design procedure, the following descriptions are divided into the sensor node (hardware) and the network (software) aspects.

From the hardware design point of view, some stringent constraints for designing wireless sensor nodes should be considered and overcome. Firstly, as IWSNs are often deployed in harsh industrial environments, the sensor nodes should be adaptive to the environmental conditions, especially to extreme environmental conditions, as is mentioned in Section 3.1. Secondly, because a sensor node is just a fraction of a WSN, to make large scale industrial deployment economically feasible, single node must be very low cost. Thirdly, in order to make the system unobtrusively to industrial production, a compact size is desirable for sensor nodes. But this parameter is restricted by a given customer application. Furthermore, since the industrial sensor nodes are often distributed in remote sensing area, the lifetime of a sensor node should be long enough or otherwise the system is unfeasible. As the lifetime of a sensor node highly depends on the lifespan of the power sources, research efforts focusing on extending the lifetime of sensor node often refer to energy. Due to the size limitation along with expected long lifespan, power always becomes a bottleneck for using WSN technology. Although a wired power source might be applicable in some industrial applications, it is not preferred or feasible for most application cases, where the nodes can only be powered by batteries. Some research efforts such as energy efficient design, dynamic power management and energy aware protocols are stepped into this area in a bid to reduce the power consumption. A more detailed survey focused on this part can be found in [13]. On the other hand, energy harvesting technologies [14], which are the promising technology to enhance the capability of energy resources, have drawn the attention of the research community in the last few years. As the environmental sources are unstable and only a small portion of energy could be harvested, how to efficiently integrate an energy harvester with a sensor node is still challenging. Last, as shown in Figure 2, the microprocessor is the heart of any sensor nodes. Hence, selection of an appropriate microprocessor is vital for whole system design. Normally, an ideal microprocessor is characterized with powerful computation capability, ultra-low power consumption, large memory, compact size and small cost. But unfortunately, all these features cannot coexist in the current microprocessors. An introduction and comparison of available microprocessors were listed in [15]. A compromise should be made between the system performance and price according to the customer application.

Despite a good sensor node is an important parameter for a WSN, it is sufficient to represent a good WSN. Comparing with designing a sensor node, to design a good WSN is more complicated and more challenging, as numerous factors from environment and application should be considered, especially some of these factors have a conflicting impact on each other in most cases. Hence, trade-off decisions are unavoidable in the network design to make these factors working harmonically. Firstly, by considering the environmental factors, the WSN should be adaptive to industrial environments. The topology and connectivity of the network is determined by the size and shape of the geographical area. For instance, the star topology is sufficient for a small scale network where sensor nodes can directly communicate with the base station. And a hybrid-star or mesh topology is desirable when the system wants to cover a larger geographical area. In this manner, the number and the location of sensor nodes, the availability of router nodes and physical separation among nodes should be determined. Second, because IWSNs often face harsh environments where some sensor nodes may fail or be blocked due to lack of power or physical damage or environment interference, the network should have a high reliability or fault tolerance capability. The fault tolerance capability is the ability to sustain sensor network functionalities with any interruption due to sensor node failures. It varies from different customer application requirements. To balance the trade-offs among resources, accuracy, latency, and time synchronization requirements, adaptive signal-processing algorithms and communication protocols are required [4]. Thirdly, the system should be cost effective. If deploying an IWSN is more expensive than installing a wired sensor system in an industrial sector, it is not cost effective and consequently it would not worth to be installed. The cost of a single node can be used to justify the overall cost of the network. Fourthly, the same as sensor node design, energy efficiency design is always critical for forming a sensor network. According to recent literature, a typical method for designing an extremely low power IWSN is to reduce the duty cycle of each node. But this method would decrease the network responsiveness, reliability and scalability. Hence, some more efforts to solve these problems could be found in [16] by using energy efficient MAC protocol designs. Moreover, throughput and Quality of Service (QoS) requirements are important for designing IWSN. These parameters vary between various application requirements. Generally, the throughput of IWSNs refers to data rate. The higher data rate means the more accurate the system can achieve. Oppositely, the higher data rate often increases network traffic which means more collision will occur directly. When collision happens, the data packets, which are affected by collision, need to be discarded and resent, and the more energy will be consumed by the system in this case. Data fusion technology, by which the sensor nodes can locally filter the sensed data based on the application requirements and transmit only the processed data to the gateway instead of sending the raw data, is considered as a promise solution for solving this problem. But this technology is limited by the hardware constraints of the sensor nodes, which normally have small memory and limited processing capability. In addition, different applications have different latency requirements even if all the industrial applications need a real time communication capability. As mentioned previously, the industrial applications can be classified into six groups with different message critical levels. The system developers can make decision of the message latency level based on this classification. For instance, in the emergency action system design, because sensor data are typically time-sensitive, it is important to receive the data at the sink in a timely manner; otherwise data with a long latency may lead to a wrong decision. Hence, a very stringent time manner is required in this case. Normally, time synchronization is used to make sensor nodes collaborate to perform the sensing task. However, due to resource and size constraints 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 [4] and adaptive and scalable time-synchronization protocols are required for IWSNs [4]. Moreover, a good network should be scalable. This is because industrial applications always want the system to provide services that allow the querying of the network to retrieve useful information from anywhere and at any time [4]. For this reason, it is necessary to develop flexible and scalable architectures that can accommodate the requirements of heterogeneous industrial application in the same infrastructure [4]. In addition, interoperability with existing legacy solutions, such as fieldbus and Ethernet-based system is required [4]. However, scalability refers to increasing the size of the network that affects message latency, lifetime of battery powered sensor nodes, and overall network reliability. Hence, the system developer should trade off these parameters with the application and environment requirements. Like any other industrial systems, security is always a critical design factor for any IWSNs. According to [18], the attacks occurs in IWSNs can be divided into passive attacks, which are carried out by eavesdropping on transmissions, and active attacks, which consist of modification, fabrication, and interruption. For detailed description of WSN security issues and WSN security designs refer to [17]. Last, hardware constraints should also be considered in network protocol design. This is because the performance of the network is highly depended on the energy, memory and processing capability of the sensor nodes and these parameters always limited the network protocol designs. More details of routing protocol design were presented in [18].

4.2 Simulation and Implementation

As mentioned previously, numerical design parameters are considered in guaranteeing a good IWSN design. In order to ensure a good IWSN design by maximizing the different network performance parameters such as network lifetime, network throughput and latency, reliability, scalability etc., a good simulation tool is needed to estimate network performance before the system being deployed. Recently, some simulation tools are available from both academic [19] and commercial areas [20]. But unfortunately, none of these simulation tools are designed for IWSNs, especially for using in a harsh environment. Moreover, IWSNs are heterogeneous networks, which include two or three types of sensor nodes, but current network simulator can only set one type of sensor node to form a network. Hence, the simulation results are normally cannot be used to examine the real situation. According to this, to design a good network simulator for IWSN is extremely important in the future.

Deploying IWSNs in the real industrial environment is challenging because the system performance is highly influenced by different node deployment strategies. [20] proposed three practical rules for implementing a mesh IWSNs in the real environment. According to their rules, a mesh network should have a minimum 25% of device within the effective range of the gateway node, whose RF antenna should be mounted at least 2 meters from the ground level without any obstacles, and every end device should have a minimum three neighbors in its effective range to ensure a mesh connection. The similar work was held by [21], where they claimed when applying WSNs in industrial environments, some real-world challenges, including wireless-link quality dynamics, noise and interference, cannot be neglected. Some environment factors, which impact on communication range and reliability of the system, have been addressed. [22] reviewed 40 wireless sensor network deployments and concluded that simplicity and extensibility are preferred over scalability when designing a WSN which contains less than one hundred nodes. They also showed that simple tie synchronization with millisecond accuracy is sufficient for most deployments. But the harsh industrial environment is not considered in these works and should be investigated in future.

5. Conclusion

IWSNs offer vast opportunities for stretching the productivity and efficiency of industrial manufacturing. Despite of the great progress on development of IWSNs, some research issues still need to be explored. Unlike other surveys, this survey addressed various design issues for regarding an IWSN design by following the proposed system design procedure. The design guidelines, research issues and possible solutions are mentioned for guiding an IWSN design. In order to evaluate this paper, the future work will focus on designing and implementing an IWSN in a real industrial environment by following the proposed design guidelines.

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