Review of Industrial Standards for Wireless Sensor Networks

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Abstract Wireless sensor networks (WSNs) are the today's most interesting and exciting research area. It is supporting a large number of application domains and now planning for supporting wide industrial applications. As the requirements for industrial application domain are different from other WSN applications, hence, various standards are defined by some industrial alliances like HART, Zigbee to meet the requirements of industrial domain. This paper discusses various WSN standards specific for industrial domain along with their applications and limitations. It also lists and discusses various unsolved challenges in IEEE 802.15.4e industrial standard. Finally, a comparative analysis of these standards is provided and the research gaps are discussed.

Keywords Wireless sensor networks · Standards · TSCH · TSMP · Industrial automation

1 Introduction to Wireless Sensor Network (WSN)

WSN consists of sensor devices that are densely deployed in hostile environments to gather sensory information from temperature, pressure, humidity, wind direction and speed, illumination, sound and vibration intensity to pollutant levels, chemical concentration, and many more. Each sensor node has memory, communication device, controller, power supply and sensor/actuator that provide the capability to sense, process, and communicate data.

Initially, the sensor nodes have limited computing power and operate on batteries and are used only for military applications [1, 2]. But with the advancements in technology, wireless communication and batteries WSN eliminate the

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need of human presence in dangerous and hostile environment, in addition to providing facility to monitor and collect data from these environments. Also they reduce the cost incurred due to placement and maintenance of wires. Therefore, the application domain of WSN is spreading from military applications to factory automation, disaster management (like wildfire), biodiversity mapping (observing wildlife patterns), intelligent buildings, home automation, industrial automation, facility management, machine surveillance, medicine, healthcare, traffic control and surveillance, environment monitoring [3, 4], underwater monitoring, and many more.

WSN used in industrial applications known as IWSN (Industrial WSN) [5] and is different from traditional WSN in terms of requirements. A general WSN has the requirement of small node size, low-cost low-power consumption, self-configuration, scalable, robust, adaptable, reliable secure, efficient channel utilization, and QoS support. In addition to these requirements, IWSN has the following requirements of interoperability, resistance to noise, coexistence, link reliability, deterministic latency, support for multiple source and sinks, service differentiation, predictive behavior, application-specific protocols and facility for data aggregation [6–8]. According to International Society of Automation, there are six classes of industrial systems, viz. safety systems (like fire alarm systems hence delay intolerant), closed loop regulatory and supervising systems (these are based on feedbacks with a difference whether feedbacks or measurements are periodically required or not), open loop control systems (WSN is used only for data collection and is human operated), next is alerting system (like temperature monitoring), and finally information gathering systems.

This paper focuses on various wireless standards that are specific for industrial applications of WSN like WirelessHART [9], ISA 100.11a [10], Zigbee Pro [11], 6LoWPAN [12], IEEE 802.15.4e [13].

Section 2 discusses briefly various industrial standards for WSN with detailed comparative analysis in Sect. 3 followed by conclusion in Sect. 4.

2 Industrial Standards for WSN

The basic requirements for an IWSN are low power, high administration, reliability, maintenance, easy deployment, and low cost. Considering these goals various standards like WirelessHART [9], ISA 100.11a [10], Zigbee Pro [11] have been established by various working groups like HART Communication Foundation (HCF) [14], Zigbee Alliance [15], and International Society of Automation [16]. All these standards are based on IEEE 802.15.4 [17]. This paper also discusses a MAC layer amendment to IEEE 802.15.4 for industrial applications known as IEEE 802.15.4e [13].

2.1 WirelessHART

WirelessHART is the industrial standard developed by HART Communication Foundation (HCF) based on HART communication protocol and IEEE 802.15.4-2006 for process automation. The protocol stack of WirelessHART as shown in Fig. 1a implements physical layer of IEEE 802.15.4-2006 with operational frequency of 2.4 GHz and modulation technique by combining frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS) for efficient data transmission. At link layer, it extends the functionality of IEEE 802.15.4 MAC by adding the time slots of 10 ms and using Time Synchronized Mesh Protocol (TSMP) [18] that uses TDMA (Time Division Multiple Access) for channel access and reduces the number of collisions. For efficient channel usage, channel blacklisting (blacklisting the channels which exhibit large interference) and channel hopping are used. Network layer is responsible for routing and security. The network manager is responsible for creating, maintaining, and scheduling the network. WirelessHART employs redundant routing at the network layer. The basic features of WirelessHART, include self-healing and self-organization, robust, simple to implement, interoperable with other HART devices, energy efficient, scalability, can be achieved either by using multiple WirelessHART gateway or multiple access point, always on security, used for both star and mesh topologies, time synchronization.

Besides the various benefits of WirelessHART, it suffers from some drawbacks or limitations. Firstly, it is used for specific application domain of process automation and is not operable with other IEEE 802.15.4-based standards. Secondly, only dedicated links are present, and there is no provision related to shared links. Finally, the scheduling algorithm used is centralized scheduling algorithm.

	(a)	(b)	(c)	(d)
Application layer	HART protocol	Services for appli cation layer & no process control applications	Zigbee device objects	Application layer
Session layer	Not defined	Not defined	Not defined	Not defined
Presentation layer	Not defined	Not defined	Not defined	Not defined
Transport layer	End to end reliability	UDP	Not defined	UDP | ICMP
Network layer	Self healing network	6LoWPAN & IPv6	Security mgt. | Network mgt. | Routing mgt.	IPv6 Adaption layer
Data link layer	TSMP for time synchroni-zation IEEE 802.15.4-MAC	Mac extension for channel hopping, time syn & graph routing IEEE 802.15.4-MAC	IEEE 802.15.4-MAC	IEEE 802.15.4-MAC
Physical layer	IEEE 802.15.4 PHY	IEEE 802.15.4 PHY	IEEE 802.15.4 PHY	IEEE 802.15.4 PHY

Fig. 1 Protocol stack of **a** WirelessHart. **b** Zigbee. **c** ISA 100.11a. **d** 6LoWPAN

2.2 ISA 100.11a

ISA 100.11a developed by ISA 100 working group provides robust and secure communication for process automation application domain [10]. ISA defines a protocol stack for ISA 100.11a which is built on top of IEEE 802.15.4 standard having same PHY (physical layer) features as WirelessHART, i.e., operates on 2.4 GHz frequency with DSSS and FHSS modulations. The data link layer extends the capability of IEEE 802.15.4 MAC features by supporting frequency hopping, graph routing and time slotted, time domain multiple access (a combination of TDMA and CSMA) that reduces interference and noise. Various channel hopping techniques are used by ISA 100.11a like slow, fast, and fixed hopping. The network and transport layers support the features of 6LoWPAN, IPV6, and UDP, respectively. The protocol stack of ISA 100.11a is depicted in Fig. 1b. It provides the following features that make it suitable for IWSN, i.e., determinism, reliability, security, support for multiple protocols and applications, flexibility, work in both star and mesh topologies, coexistence with other wireless technology, larger address space, configurable time slots.

Limitations. Following are some limitations of ISA 100.11a. It is not interoperable with other IEEE 802.15.4-based devices. There is high implementation cost and slow hopping results in increased power consumption as receiver remains on for a longer time.

2.3 Zigbee

Zigbee is the standard created by Zigbee Alliance suitable for control and monitoring applications. It is also built on top of IEEE 802.15.4 standard with 2.4 GHz operating frequency and can form star, mesh, and cluster tree topologies. It defines its own network layer for different networking capabilities, and application layer provides a framework for application development and communication. Two implementation options for a Zigbee standard are provided. One is for smaller networks (Zigbee) and other for larger networks (Zigbee Pro). The protocol stack is shown in Fig. 1c. The salient features of Zigbee can be summarized as supports star, cluster tree and mesh network topologies, robust, large number of nodes can be added, long range, easy deployment, supports low to medium data rates, low power and low cost, self-organizing and self-healing.

Limitations of Zigbee can be counted as they are interoperable with only Zigbee devices. There is no frequency diversity. They are prone to security threats. Static channel usages increase interference and hence delay. They support no path diversity, i.e., if a path is broken new path must be set up. It follows a random process for address assignments. Further, due to ad hoc on-demand distance vector (AODV) routing protocol there is lack of scalability. Finally, it also lacks energy-saving mechanism.

2.4 6LoWPAN

6LoWPAN, an acronym for IPv6 over low-power wireless personal area network, is developed by international engineering task force (IETF) and based on IEEE 802.15.4 PHY and MAC layer to integrate TCP/IP with WSN. It is developed for embedded applications that require deployment of large number of sensor nodes to cover a large geographic area with low cost, power, and computations. The integration of IPv6 provides Internet connectivity at low data rates with low duty cycle. The basic features of 6LoWPAN are smaller packet size, header compression, and fragmentation, scalable due to adopting adaption layer, supports mobility, and easy network management due to IPv6, reliable, and reduce latency. Its protocol stack is depicted in Fig. 1d. **Some limitations of 6LoWPAN are** they are more prone to link failures. Interference is present, and providing end-to-end security is still an open issue.

2.5 IEEE 802.15.4e

IEEE 802.15.4e [13] is the MAC layer amendment in the IEEE 802.15.-2011 [17] standard and released in 2012 to provide better opportunities for industrial applications and to become compatible with Chinese WPAN. Main ideas are taken from WirelessHART and ISA 100.11a. Major amendments in 802.154e can be categorized in two broad classes.

MAC Behavior Modes. These are specified for support of specific industrial application domains. These are briefed below.

TSCH, i.e., Time Slotted Channel Hopping is defined for application domains such as process automation. It takes some of its features from TSMP [18] like time slots (supports both dedicated and shared links) that are helpful in distributed transmission, time synchronization, multiple access. The main concepts of TSCH are the use of *slot frames* for data transmission and receiving, channel hopping to mitigate the effect of multipath fading and interference, a modified CSMA/CA algorithm for collision avoidance with in a slot.

But there are many drawbacks of TSCH like the maximum duration for a time slot is not specified by the standard also there is lack of proper Advertisement protocol. The author in [19] specifies a random advertisement protocol for Internet of Things (IoT) which is a generalization protocol specified in [20]. How the additional communication resources (slot frames and links) are allocated to devices. This issue is left for upper layers so in this concern some work is done in [21] and [22] where the authors specified a centralized (TASA-TSCH) and a decentralized algorithm to deal with this problem. But the issues with centralized and decentralized algorithms remain the same that is of static topology and mobility. *Deterministic and Synchronous Multi-channel Extension (DSME*) is designed specifically for industrial and commercial applications with stringent timeliness and reliability requirements. It supports the features of multi-superframe (combination of superframes), multi-channel, and group acknowledgment for scalability, robustness, and flexibility. It also provides the features of distributed beacon scheduling and distributed slot selection for scalability and incorporates channel adaptation and channel hopping as channel diversity methods. The standard only explains the method of executing a schedule but it does not specify how that beacon schedule is formed and how to perform slot selection. The authors in [23, 24] represent a solution for this problem. *LLDN, i.e., Low Latency Deterministic Network* is used for applications requiring very low latency requirement (e.g., factory automation, robot control). It works in star topology only and uses beacon and assigned time slots to provide determinism. It is designed for small networks and small frames. *Radio Frequency Identification Blink (BLINK)* is used for identification, tracking, and location applications. *Asynchronous multi-channel adaptation (AMCA)* is restricted to application domains where large deployments are required *(e.*g., process automation/control, infrastructure monitoring). It works in non-beacon enabled mode. The issues with this approach are firstly, it works for single hop topology and secondly, the standard does not specify any method to determine the line quality indication (LQI) or receive signal strength (RSS).

General functional improvements. They are defined for supporting the MAC behavior modes to enhance their functionality. These are described below.

Low-energy (LE) protocol is introduced for allowing using minimal amount of energy very low duty cycle devices can send ad hoc data. There are two types of LE: coordinated sampled listening (CSL) which specifies how receiving devices periodically monitors the channel and receiver initiated transmission (RIT)—here, transmitting devices only transmit to a receiving device upon receiving a data request frame. *Information elements (IE*) are added to provide extensible MAC data transfers. These are useful in adding information to existing frame format without adding new frames. *Enhanced beacons (EB) and enhanced beacon requests (EBR*) are used to allow coordinator devices to send beacons with specifically requested data. EB is used with TSCH and DSME with relevant IEs. *The MAC multipurpose frame* provides the scalability and extensibility to allow standard to address new application needs with minimal MAC changes. *MAC performance metrics* provide upper layers with critical information on the quality of the communication links, and *FastA* reduces the time required to associate. It is optional and not defined in 802.15.4 devices.

3 Comparison of Different Industrial Standards for WSN

Table 1 compares the above-explained industrial standards [25–27] on the basis of various factors and provides an overview of their strength and limitations.

Table 1 Comparison of different industrial standards

Feature	IEEE 802.15.4e	WirelessHART	ISA 100.11a	Zigbee	6LoWPAN
Application domain	Process automation, factory automation, home automation, smart metering	Process automation	Process automation	Home automation	Internet of things and industrial monitoring
Topology	Star and mesh	Mesh, star (not recommended)	Mesh and star	Star, mesh, and cluster tree	Mesh
Physical layer	IEEE 802.15.4-2011	IEEE 802.15.4-2006	IEEE 802.15.4-2006	IEEE 802.15.4-2003	IEEE 802.15.4-2003
Operating frequency	Variable	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz
Modulation	DSSS and FHSS	DSSS and FHSS	DSSS and FHSS	DSSS and FHSS	DSSS and FHSS
IEEE 802.15.4 MAC layer mode	Both beacon enabled and non-beacon enabled	Non-beacon enabled based on TDMA	Non-beacon enabled based on TDMA and CSMA	Non-beacon enabled	Non-beacon enabled
Time synchronization	Yes	Yes	Yes	No	No
Addressing (in bits)	16 or 64	16 or 64	16, 64 or 128	16 or 64	128
Interoperability with other 802.15.4 devices	Yes	No, only with other HART devices	No, only coexistence with WirelessHART, 6loWPAN	No, only with other Zigbee devices	No
Routing protocol	N/A, applicability for higher layer	Redundant routing (source and graph routing)	Redundant routing (source and graph routing)	AODV	RPL

(continued)

Table 1 (continued)

Feature	IEEE 802.15.4e	WirelessHART	ISA 100.11a	Zigbee	6LoWPAN
Robustness	Present	Present	Present	Present	Present
Scalability	Unknown	Present either using multiple gateway or multiple access point	Present	Present	Present
Self-organization	Yes	Yes	Yes	Yes	Yes
Self-healing	Unknown	Yes using health reports	Yes	Yes	Yes
Security	N/A	Yes	Yes	Yes	Yes
Cost	Low	High	High	Low	Low
Data rate	Variable	250 kbps	Low data rates	250 kbps	20–250 kbps
Channel hopping	Yes	Yes [18]	Yes [18]	No	No
Channel blacklisting	Yes [28, 29]	Yes [18]	Yes [18]	No	No
Power consumption	Low	Low	Low	Low	Medium
Network management	Unknown	High	High	Medium	High

3.1 Research Gaps

The various research gaps that exist in these standards can be formulated as, firstly, because IEEE 802.15.4e is drafted in 2012 and provides details about physical and MAC layers only, so it provides procedure for executing a method like beacon scheduling but does not provide any algorithm to create and maintain them. Hence, there are many open issues remain unsolved till date regarding this standard. Secondly, the complete procedure for TSCH PAN Formation is specified but how the issues related to slot and link scheduling and assignment will be solved is left for upper layers. Thirdly, the advertisement protocol, i.e., how a PAN coordinator will determine the rate of advertisement and choose a suitable PAN identifier from a list of PANid is not specified. Finally, rest all the standards are interoperable with similar type of devices but they are compatible with other IEEE 802.15.4 based 219 devices.

4 Conclusion

This paper reviewed various industrial standards like WirelessHART, ISA 100.11a, Zigbee, 6LoWPAN, and IEEE 802.15.4e and compared them on various factors. Zigbee is suitable for applications that need low-power consumptions, short range, low complexity, and low data rates like chronic disease monitoring, home automation, Zigbee smart energy profile offers utility to handle demand response and provide control for load support but is not as suitable for industrial domain as other standards due to lack of determinism property, and it cannot provide QoS support for deterministic latency, and it cannot scale with large systems. Furthermore, it employs only DSSS that results in performance degradation in case of continuous noise. Similarly 6LoWPAN is the technology that offers low cost, easy deployment, and adaptability features but has comparatively high power consumption. It has its main application in Internet of Things (IoT) as it can connect to other IP-based technologies without additional routers or proxies. Therefore, HART Communication Foundation proposes WirelessHART as complete industrial solution by adding wireless interface, end-to-end reliability, secure communication and form a self-healing and self-organizing network properties to wired HART along with channel hopping and channel blacklisting features. It found its great applications in process automation and control. But again it lacks the deterministic latency feature required for commercial applications and cannot support multiple protocols. In contrast to this, ISA 100.11a is the standard that supports deterministic timing requirement needed for control applications such as reliable monitoring and alerting, predictive maintenance, condition monitoring, factory automation, asset maintenance, location services, and logistics. Hence, it is the much suitable standard but it is not backward compatible with other standards.

Although they all have same underlying principles based on IEEE 802.15.4, they are not interoperable with each other and are specific for a particular type of application domain either process automation or home automation or smart metering. Hence to overcome the issues related to these standards, IEEE task group 4 has amended IEEE 802.15.4 with the specific features of WirelessHART and ISA 100.11a and added some new features to it so that a generic standard can be formulated for industrial domain as presented it as IEEE 802.15.4e.

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