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# Comparison of IWSN MAC Protocols for IEC 61850 Applications

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**Abstract**: Electric power utilities need status and conditions monitoring of assets in addition to measured and metered data, in order to increase the reliability of power delivery. One of the main standards in the scope of communication networks and systems in electrical power grid is IEC 61850. In smart grid applications, IEC61850 is accepted and deployed for in substation automation as well as other applications such as Condition Monitoring Diagnosis (CMD). Wireless Sensor Networks (WSNs) facilitate the realization of CMD of any device, anytime, anywhere by any service. This provides the use of Internet of Things (IoT) technology for CMD. Some WSN communication profiles are based on IEEE802.15.4 and have specific industrial applications, where time and reliability are critical parameters. In this paper, the specifications of Wireless HART, ISA100.11, and WIA-PA as the most popular industrial WSN protocols are reviewed, in order to define the suitability in supporting IEC61850 message types for smart grid Machine to Machine (M2M) communications. It is concluded that ISA100.11 is much more appropriate to adopt for IEC61850 Manufacturing Message Specification (MMS) messages.

**Keywords**: CMD, IEC 61850, ISA100.11, IWSN, TSCH MAC protocol, WIA-PA, Wireless HART.

## I. INTRODUCTION

Today, sensors and wireless communication technologies play a major role in many industries. Pervasive use of Wireless Sensor Networks (WSNs) provides different devices the ability to be monitored and controlled anytime, anywhere and by any service. Therefore, WSNs by allowing “ubiquitous sensing” over the whole processes are one of the most important technologies in Internet of Things (IoT) and Machine to Machine (M2M) area for industrial applications. Research on WSN technologies started back in the 1980s and it was only since 2001 that WSNs generated an increased interest for industrial and research purposes [1]. Low latency and reliable communication are the most important requirements on a WSN for industrial automation and process monitoring.

The IEEE 802.15.4 standard specifies the PHY layer and MAC sub-layer properties for LR-WPAN [2] and the upper layers are left to be developed according to the market needs. Many popular protocols including Zig Bee [3], Wireless HART [4], ISA 100.11 [5], 6LoWPAN [6], WiMi [7] and SimpliciTI [8] do work based on this IEEE standard. Many industrial applications are time-critical and have high reliability and hard real-time requirements. Thus, in 2012 IEEE 802.15.4e [9] was developed for Industrial Wireless Sensor Networks (IWSNs) by IEEE 802.15.4 working group. There are many MAC protocols for industrial applications defined by IEEE 802.15.4e such as Time Slotted Channel Hopping (TSCH), Low Latency Deterministic Networks (LLDN), Deterministic and Synchronous Multi-channel Extension (DSME), Radio Frequency Identification blink (RFID), and Asynchronous Multi-Channel Adaptation (AMCA). Three well-known IWSN protocols of Wireless HART, ISA100.11a, and WIA-PA (Wireless networks for Industrial Automation – Process Automation), utilize TSCH with different parameters as MAC sub-layer protocol. The International Electro technical Commission (IEC) as the international standard and conformity assessment body for all fields of electro-technology, has been standardized Wireless HART, ISA100.11a, and WIA-PA as IWSN protocols (TABLE I), while Zig Bee, the most well-known protocol in WSNs, has not been accepted as an standard protocol by the IEC, yet.

TABLE I: IWSN PROTOCOLS AND IEC STANDARDS

| IWSN protocol | IEC standard |
|---|---|
| Wireless HART | IEC 62591-1: Industrial communication networks - Wireless communication network and communication profiles – Wireless HART™ [10]. |
| WIA-PA | IEC 62061: Wireless networks for Industrial Automation - Process Automation (WIA-PA) built on IEEE STD 802.15.4 [11]. |
| ISA100.11a | IEC 62734: Industrial networks - Wireless communication network and communication profiles - ISA 100.11a [12]. |

In the near future, smart grid and IoT concepts will become a reality and this requires interaction between autonomous devices for automation purposes. Furthermore, the objectives of smart grid demand more individual pieces of information across a more diverse range of equipment and functions. Monitoring, metering, measuring, protection, control, and configuring of assets

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are critical functions in smart grid and therefore, for data integration and information exchange between such devices, a standard protocol is required. One of the main standards in the scope of automation in electrical power grid is the IEC 61850. Recently, the communication networks and systems based on IEC 61850 are moving out from "in substations" to the broader area of "power utility automation" [13]. The IEC 61850 is a message protocol that can provide a simple, reliable and inexpensive automation system for secondary systems of substations. The IEC 61850-90-3 is currently in preparation for describing the detailed use cases for IEC 61850 based condition monitoring diagnosis (CMD) of power electric equipments.

Hence, the performance criteria are usually considered in according to IEC standards for electric power industries. Therefore, for WSN applications in electric power industry, the IEC based standards according to TABLE I are the preferred choice. However, it is essential to investigate these protocols for any application (e.g. the IEC 61850 based applications in the smart grid) because of differences between IWSNs protocol specifications. In this paper, the specifications of IWSNs MAC protocols for messages based on IEC 61850 in smart grid have been compared. Our purpose is to illustrate which MAC protocol of IWSNs is appropriate for messages based on the IEC 61850. In section II the architecture and requirements of IEC 61850 communications for automation purposes are explained. In section III some other smart grid applications based on IEC 61850 are reviewed. In section IV and V the main characteristics of IEEE 802.15.4 standard and IEEE 802.15.4e MAC protocols are overviewed. Section VI compares the IWSN protocols based on IEEE 802.15.4e for IEC 61850 applications, and finally section VII concludes the paper.

## II. IEC 61850 ARCHITECTURE AND REQUIREMENTS

The automation system according to IEC 61850 is divided into three levels (station, bay, and process), two buses (station and process), and eleven logical interfaces as shown in Fig. 1. Intelligent Electronic Devices (IEDs) are the element of Distributed Control System (DCS) and it is introduced by some Logical Nodes (LNs). They communicate with each other and control centre in order to perform an automation network. The station bus facilitates the communication between the station level and bay level IEDs. For this communication application, interfaces are applied between them i.e. IF1, IF3, IF6, IF8 and IF9. Similarly, process bus is used for data exchange purpose between bay level and process level devices. Interface IF4 and IF5 support this communication. Moreover, IF2 and IF11 refer to data exchange between substations e.g. for line protection, interlocking functions or other inter-substation automatics.

The transfer time requirements for functions may be different depending on the message types and voltage level and the role of substation, i.e. on distribution and transmission level. The messages are mapped into six types with different communication stacks as shown in Fig. 2 (extracted from [14]).

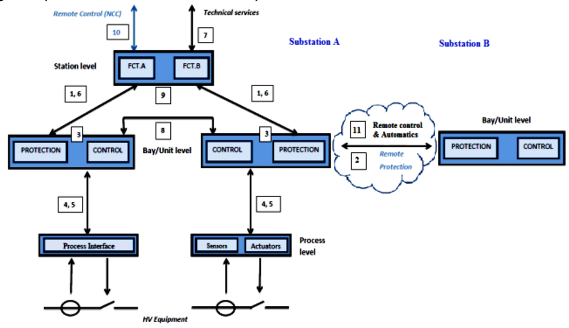


Fig.1. Levels and logical interfaces in substation automation systems [14].

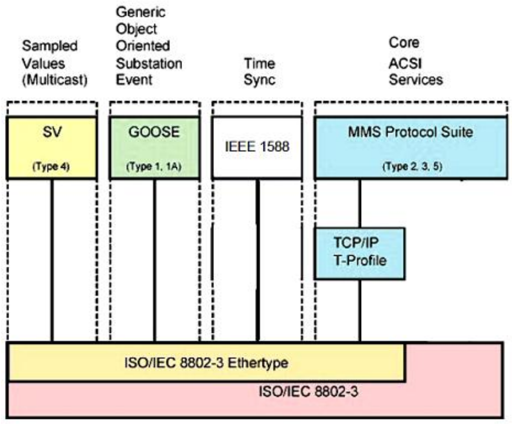


Fig. 2. IEC 61850 Message Communication Stack.

The Generic Object Oriented Substation Event (GOOSE) messages (type1, 1A) and raw data samples (type 4) are time critical. Therefore, the Sample Values (SV) and GOOSE messages are transmitted directly through MAC and PHY layers. The medium speed message (type 2), the low speed message (type 3), and the file transfer functions (type 5) are mapped to Manufacturing Message Specification (MMS) protocol suits which has a TCP/IP stack. The Command messages and file transfer with access control (type 6) is based on type 3 but with additional password and/or verification procedures. The time synchronization is according to IEEE 1588 mechanism (The IEEE 1588 uses data for synchronization). The performance class of different message types, protocols, and functions of interface numbers used in Fig. 1 has been summarized in TABLE II (extracted from [14]). The IEC 61850 messages are categorized in P1-P12 for performance classes and TT0-TT6 for transfer time classes.

Raw data messages are sample values of voltage and current for measuring and metering purposes. Their specifications and requirements are as TABLE III (extracted from [14, 15]). The sampling rate determines the time interval between adjacent samples, which is more than 480 in this case. Besides, the transfer time of SVs must be less than 10ms. Therefore, the communication network must support the transmission of samples with

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determined sample rates in guaranteed delay. This concept defines the minimum length of payload in each frame.

TABLE III
RAW DATA SPECIFICATIONS FOR MEASURING AND METERING.

| Raw data for: | Data type | Description | Resolution (bit) | Rate (sample/s) |
|---|---|---|---|---|
| Protection and Control | Voltage | T.T=10ms, TT5, P8 | 13 | 480 |
| | Current | | 13 | |
| | Voltage | T.T=3ms, TT6, P7 | 16 | 960 |
| | Current | | 16 | |
| | Voltage | T.T=3ms, TT6, P7 | 16 | 1920 |
| | Current | | 18 | |
| Metering | Voltage | Up to 5th harmonic T.T=3ms | 12 | 1500 |
| | Current | | 14 | |
| | Voltage | Up to 13th harmonic T.T=3ms | 14 | 4000 |
| | Current | | 16 | |
| | Voltage | Up to 40th harmonic T.T=3ms | 16 | 12000 |

TABLE II. PERFORMANCE REQUIREMENT OF MESSAGE TYPES AND PROTOCOLS.

| Message type | | Message protocol | Performance class | Transfer time class | Transfer time (ms) | Typical for IF |
|---|---|---|---|---|---|---|
| Type 1 – Fast messages | A "Trip" | GOOSE | P1 | TT6 | ≤ 3 | 3,5,8 |
| | | | P2 | TT5 | ≤ 10 | 2,3,11 |
| | B "Others" | MMS | P3 | TT4 | ≤20 | 2,3,8,11 |
| Type 2 – Medium speed messages (Automatics) | | MMS | P4 | TT3 | ≤100 | 2,3,8,9,11 |
| Type 3 – Low speed messages (Operator) | | MMS | P5 | TT2 | ≤500 | 1,3,4,5,6,7, 8, 9, 10 |
| | | | P6 | TT1 | ≤1000 | 1,3,4,5,6,7, 8, 9, 10 |
| Type 4 – Raw data messages (Samples) | | SV | P7 | TT6 | ≤3 | 4,8 |
| | | | P8 | TT5 | ≤10 | 4,8 |
| Type 5 – File transfer functions | | MMS | P9 | TT0 | ≤10 000 | 1, 4, 5,6,7,10 |
| Type 6 – Command messages and file transfer with access control | | MMS | P10 | TT2 | ≤500 | 1,3, 4, 5,6, 7, 8, 9,10 |
| | | | P11 | TT1 | ≤1000 | 1, 3, 4, 5,6, 7, 8, 9,10 |
| | | | P12 | TT0 | ≤10 000 | 1, 4, 5,6,7,10 |

## III. USING IEC 61850 FOR SMART GRID APPLICATIONS

In this section, using IEC 61850 for some smart grid applications is overviewed. Three levels of automation system mentioned in previous section can be considered for other applications in smart grid, too. For example: in Electric Vehicle (EV) information exchange based on IEC 61850, we can consider the EV as a process level (physical level) and IEDs as a bay level, that are responsible for information exchange between EV devices in physical level and system/station level that controls, sets and manages the EV devices.

Besides, condition monitoring which helps to keep a constant watch over various assets with information received from installed monitoring tools, is one of the major issues to improve the reliability of power system by preventing failure. It makes available data for asset management by using intelligent sensors. In fact, each sensor can be considered as a LN (Logical Node) in process level, which provides information with given communication, attributes and control of the asset for station level or IED in bay level. The IEC 61850 based messages for most of applications could be mapped into MMS protocol suit, which has a TCP/IP stack and the time synchronization of messages for time stamp is in according to IEEE 1588. Besides, the transfer time of these messages could be more than 20ms, as stated in TABLE I. It must be pointed that the resolution and frequency of sending this information depends on the application; it can be information of a LN from transformer winding temperature sensor, which needs to be once a minute, or can be a LN that provides the ambient temperature, which needs to be just once an hour. Besides, since the sensors are located in a dispersed manner, if the wireless network could meet the requirements, it will be the best approach for communication.

## IV. OVERVIEW OF THE IEEE 802.15.4 PROTOCOLS

IEEE 802.15.4 standard is appealing for many different applications and is the dominant protocol of WSNs. It specifies the physical layer and the MAC sub-layer for low-rate Wireless Personal Area Networks (WPANs). The IEEE 802.15.4 can operate in three license free industrial scientific medical (ISM) frequency bands. The 2.4 GHz band is the most widely used in view of the fact that it is available globally and this brings many economies of scale. TABLE IV shows the brief specification of PHY layer of IEEE 802.15.4 in 2.4GHz band (extracted from [2]).

TABLE IV: SPECIFICATION OF PHY LAYER OF IEEE STD. 802.15.4-2011 IN 2.4GHZ.

| Modulation scheme | PHY rate (kb/s) | Bit/Sym | Symbol rate (ksym/s) | Symbol duration(us) |
|---|---|---|---|---|
| **OQPSK** | 250 | 4 | 62.5 | 16 |
| **DQPSK** | 250 | 1.5 | 166.667 | 6 |
| **DQCSK** | 1000 | 6 | 166.667 | 6 |

This standard defines two channel access methods: the beacon-enabled, which uses a slotted CSMA/CA for Contention Access Period (CAP) and the optional Guaranteed Time Slot (GTS) allocation mechanism as Collision Free Period (CFP), and an un-slotted CSMA/CA without beacons [2]. For deterministic performances, utilizing the slotted MAC where the communication is allocated based on the super frame that comprises a number of slots in either CAP or CFP is recommended. This is essential to reduce the possibility of collision and to meet the deterministic timing critical requirement of industrial applications. The super frame structure of beacon-enabled IEEE 802.15.4 is shown in Fig. 3.

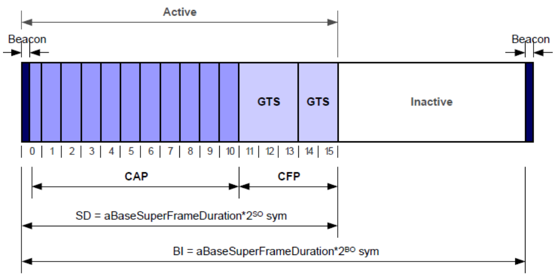


Fig.3. IEEE std. 802.15.4-2011 Super frame Structure [2].

## V. IEEE 802.15.4E MAC PROTOCOLS

IEEE std. 802.15.4-2011 provides up to seven GTSs in a single channel and thus, it is not able to support large networks. Also, the minimum duration of super frame is

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about 15ms. Many industrial applications require data within 10ms. Therefore, a modified structure must be used. IEEE std. 802.15.4e-2012 extends IEEE std. 802.15.4-2011 by having four access methods, including non-competitive expansion GTS method based on beacon supporting the process automation-oriented WIA-PA, non-beacon non-competitive TDMA method supporting the process automation-oriented Wireless HART and ISA100.11a, competitive access based on beacon method supporting factory automation applications, and non-beacon competitive access method supporting ZigBee and IEEE 802.15.5 [1]. IEEE std. 802.15.4e-2012 grouped MAC protocols as follows:

- TSCH mode, for application domains such as process automation,
- LLDN mode, for application domains such as factory automation,
- DSME mode, for general industrial and commercial application domains,
- RFID mode, for application domains such as item and people identification, location, and tracking,
- AMCA mode, for large infrastructure application domains.

The TSCH mode uses time synchronized communication and channel hopping to provide network robustness through spectral and temporal redundancy. TSCH is also topology independent; it can be used to form any topology from a star to a full mesh one. The LLDN mode uses super frame structure with fixed length and dedicated timeslots (TDMA scheme) for each LLDN device to support deterministic system. The super frame is synchronized with a beacon transmitted periodically from the LLDN PAN coordinator. The number of slots in a super frame determines the number of LLDN devices that can access each channel. This solution can be extended by operating the LLDN PAN coordinator with multiple transceivers on different channels to support a high number of LLDN devices. Besides, it can be used only in star topology.

The DSME mode enhances IEEE Std. 802.15.4-2011 in two important directions: extension of GTS time slots' number by grouping multiple super frames to form a multi-super frame and the number of used frequency channels. Similar to GTS, DSME runs on Beacon-enabled PANs. All the devices in PAN synchronize to multi-super frames via beacon frames. A multi-super frame is a cycle of super frames, where each super frame includes the beacon frame, the CAP, and CFP [16]. The RFID or blink mode provides a method for a device to communicate its ID without prior association and without an acknowledgement. The frame can be used by “transmit only” devices to coexist within a network, utilizing an Aloha protocol [9]. The AMCA mode is targeted to application domains where large deployments are required, such as smart utility networks, infrastructure monitoring networks, and process control networks. In such networks using a single, common channel for communication may not allow to connect all the devices in the same PAN. In addition, the variance of channel quality is typically large, and link asymmetry may occur between two neighboring devices. The AMCA mode can be used in a non beacon-enabled PAN [16].

Wireless HART, ISA100.11a, and WIA-PA, the most popular IWSNs are based on TSCH mode with little modifications. ISA100.12, and Wireless HART convergence subcommittee is intend to find a technical path to converge the Wireless HART specification (IEC 62591) with that of ISA 100.11a (IEC 62734), abandoned its work in 2013 without finding a single convergence solution [17]. In section V these IWSN specifications are compared in order to define the best one for IEC 61850 applications.

## VI. COMPARISON OF IWSNS MAC PROTOCOLS FOR APPLICATIONS BASED ON IEC 61850

Wireless HART, ISA100.11a and WIA-PA work based on TSCH MAC protocol. They use 2.4GHz ISM band with different modulation schemes and MAC mechanisms. As shown in Fig. 4, these IWSN protocols allow the devices to share a slot or dedicatedly occupy a slot. In the Wireless HART, the principle super frame will be composited by GTS, which is CFP-like, the common way used in industrial applications for collecting sensor/actuator's data to guarantee the critical time requirement. At the same time, an additional super frame can use shared slots and dedicated slots. The length of the super frame can be adapted to the needs of the application, and the slot length is fixed to 10ms. ISA100.11a supports configurable timeslot lengths. There is an extension scheme for frequency hopping and slotted hopping. It has slotted hoping and slow hopping mechanisms [18]. The carrier sensing scheme can be disabled to reduce possible delay transmission. WIA-PA is a cross-layer design and supports the frequency hopping slots, the TDMA and CSMA hybrid channel access mechanism [18]. 6LoWPAN, Internet Protocol version 6 (IPv6) over the low power PAN is a protocol for general applications. Also 6tisch, architecture for IPv6 over the TSCH mode of IEEE 802.15.4e is developed by IETF, for using

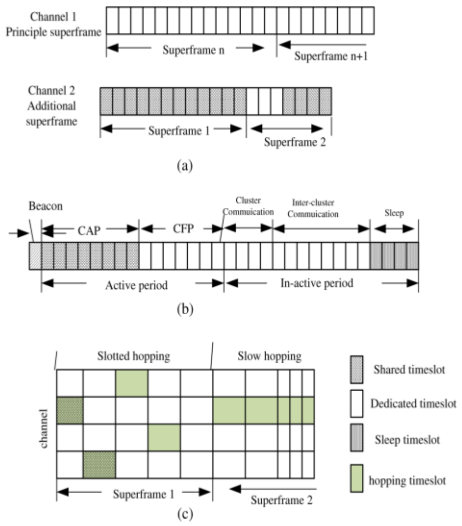


Fig.4. Super frame structure of the mainstream IWSN standards: (a) Wireless HART; (b) WIA-PA; and (c) ISA100.11 [10–12].

IEEE802.15.4e TSCH in an IoT context [19]. At this time, only ISA100.11 fully supports the IPv6 at its layer. Furthermore, time synchronization method of ISA100.11 is based on IEEE 1588. Although [20, 21] proposed a gateway for Wireless HART and Zig bee to IEC 61850, but this solution increases the delay in the order of 250ms, because of required protocol conversions. However, the ISA100.11 does not require any gateway to support IEC 61850. Therefore, this protocol is much more suitable for M2M communication based on IEC 61850 applications.

## VII. CONCLUSION

The main specifications of communication networks for IEC 61850 devices are:

- The SV and GOOSE messages are time-critical; they require transfer times less than 10ms.
- The MMS transfer time can be more than 20ms.
- The MMS uses TCP/IP for transport and network layers.
- The time synchronization is in accordance with IEEE 1588.

The IWSNs that standardized with IEC are Wireless HART, ISA100.11a and WIA-PA, which the PHY layer and MAC sub-layer are defined as IEEE 802.15.4. They use TSCH mode to provide deterministic latency, and much more reliable communication. As a result, among the IWSN protocols, ISA100.11 has specifications that make it much more proper for applications based on IEC 61850. Because it supports configurable timeslot length for MAC sub-layer, different channel hopping mechanism, IP protocol stack for network layer, and time synchronization methods according to IEEE 1588.

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## BIOGRAPHY

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