# Comparative Study of Wireless Sensor Network Standards for application in Electrical Substations

Fabrice Labeau
McGill University
Montreal, Canada
fabrice.labeau@mcgill.ca

Akash Agarwal
Indian Institute of Technology, Patna
India

Basile Agba
Hydro-Québec (IREQ)
Varennes, Canada

***Abstract*—Power utilities around the world are modernizing their grid by adding layers of communication capabilities to allow for more advanced control, monitoring and preventive maintenance. Wireless Sensor Networks (WSNs), due to their ease of deployment, low cost and flexibility, are considered as a solution to provide diagnostics information about the health of the connected devices and equipment in the electrical grid. However, in specific environments such as high voltage substations, the equipment in the grid produces a strong and specific radio noise, which is impulsive in nature. The robustness of off-the-shelf equipment to this type of noise is not guaranteed; it is therefore important to analyze the characteristics of devices, algorithms and protocols to understand whether they are suited to such harsh environments. In this paper, we review several WSN standards: 6LoWPAN, Zigbee, WirelessHART, ISA100.11a and OCARI. Physical layer specifications (IEEE 802.15.4) are similar for all standards, with considerable architectural differences present in the higher layers. The purpose of this paper is to determine the appropriate WSN standard that could support reliable communication in the impulsive noise environment, in electrical substations. Our review concludes that the WirelessHART sensor network is one of the most suitable to be implemented in a harsh impulsive noise environment.**

***Keywords—Wireless Sensor Networks; 6LoWPAN; Zigbee; WirelessHART; ISA100.11a; OCARI; impulsive noise environment; reliable communication.***

## I. INTRODUCTION

Today, electrical substations require real-time information for adaptive energy allocation to the end users, for efficient delivery of power to the customers and to increase profitability. To address such needs, advanced wireless devices with low power and mobile sensors are emerging. Such sensor devices monitor the equipment in the substation and provide adaptive, self-healing electric automation system for tele-maintenance, tele-protection and tele-control [1]. Several Wireless Sensor Network (WSN) standards currently exist, such as 6LowPAN, Zigbee, ISA100.11a, WirelessHART and, more recently, Optimization of communication for Ad-hoc reliable industrial networks (OCARI) [2]. However, their implementation in the electrical substation is an open area for research. In the rest of the paper all the above mentioned standards will be collectively termed as 'WSN standards'

The impact of WSN in electrical substation depends on the reliable communication in the harsh and complex impulsive noise environment (INE) of the electric substation [3]. In order to deploy WSN in smart grids, the knowledge of parameters such as wireless channel model or link quality information in such an environment is essential.

This paper provides the description and study of the above mentioned WSN standards along with their stack structures and network architectures. Also, an overview of the measurement and characteristics of impulsive noise such as impulse rate, amplitude, duration and rising time etc. in the electric power systems environment (400/275/132-kV) is provided.

The rest of the paper is organized as follows: In Section II, an overview of the estimation and characteristics of impulsive noise environment is provided. In Section III, we study the protocol stack structure of WSN standards. In Section IV, we compare the WSN standards, to figure out the most suitable for application in the INE. Finally, we conclude in Section V.

## II. IMPULSIVE NOISE ENVIRONMENT IN ELECTRICAL SUBSTATION

It is known that the noise environment in electrical substations is adverse and typically is impulsive [4]. Such impulsive nature of noise degrades the communication carried out on operating frequency band of the wireless network, deployed in such an environment [3]. The major sources of impulsive noise in an electricity substation are (1) Partial Discharge (PD), which typically is caused due to imperfect insulation, and (2) Sferic Radiation (SR), which results from operation of circuit breakers and isolators etc. Both of these processes produce radio waves that can be measured using UHF antennas. Apart from the electrical substations, atmospheric noise and other man-made noises also are the sources of impulsive noise.

The estimation of impulsive noise can help in assessment of difficulties in the deployment of a wireless network. Much effort has already been laid towards measurement of impulsive noise in a variety of physical environments. For instance, the statistical characterization of the wireless channel such as shadowing deviation and path loss, has been studied under various environments within the substation, such as 500 kV substations, an industrial power control room, and an underground network transformer vault [5].

Various other experiments for the estimation of impulsive noise in different frequency bands have also been conducted. According to the measurement set up in [6], four types of antennas are used for monitoring the partial discharge. Two quasi-TEM half horns, designed to capture signals in frequency bands 0.716 – 1.98 GHz and 1.92 – 5 GHz, a high band (HB) horn, that covers the range 2 – 6 GHz and a low band (LB) horn to cover the range 0.7 – 2 GHz. The fourth antenna is a di-cone antenna to collect data below 700 MHz. It is observed that some external interferences are encountered during the on-site partial discharge measurements such as discrete spectral interferences, periodic pulse shaped

This work was supported by Hydro-Québec, the Natural Sciences and Engineering Research Council of Canada and McGill University in the framework of the NSERC/Hydro-Québec Industrial Research Chair in Interactive Information Infrastructure for the Power Grid.

**978-1-4673-9354-6/15/$31.00 ©2015 IEEE**

interferences from power electronics or other periodic switching etc., and Sferic radiation [4].

Similarly, in [7], the directional wideband antenna is used, which covers the ISM band from 800 MHz to 2.5 GHz, to evaluate the mean pulse duration, maximum amplitude and mean number of discharges, in different voltage areas. According to the measurement results in [7], there is a correlation between the amplitude and the pulse duration distributions.

In [8], the discrete wavelet packet transform technique is used to remove the partial discharge from other interferences in [6]. With this separation we observe the various characteristics of the impulsive noise, such as impulse rate, amplitude, duration of impulse and rise time of impulse. Different distributions are observed from all the above mentioned four antennas used. Of which the di-cone and HB horn antennas show Gaussian normal distribution for impulsive noise amplitude [6]. But LB horn antenna shows a sharp glitch in the PDF close to 0 mV, which suggests the presence of two impulsive noise processes, having a strong periodic or quasi-periodic component [6]. Also, the PDF of the rise times and impulse durations from all the antennas show peaks at nearly 100 ns and 50 ns respectively, which demonstrates that the rise times and durations of impulsive noise are extremely short.

Hence, accurate estimation of the impulsive noise channel model specifically for electrical substation could enable a system designer to appropriately design the physical and MAC layer specifications of a wireless network, to achieve more reliable throughput.

## III. WSN Standards Specification Overview

### *A. 6LoWPAN*

6LoWPAN is an IPV6 based low powered Wireless Personal Area Network (WAN) [9]. The nodes in 6LoWPAN are connected in a star or mesh topology and usually support the data rate of 20- 250 kbps to a distance of nearly ten meters. This standard is developed so that wireless sensor devices can connect to existing IP networks, such as IPV4 networks, without the need of translation gateways or proxies [9]. $2^{128}$The 6LoWPAN stack structure is illustrated in Fig.1.a. In the protocol stack, the link layer is divided into IEEE 802.15.4 MAC sub-layer and 6LoWPAN adaptation layer. [9].

The 6LoWPAN standard physical layer is based on IEEE 802.15.4-2006 (PHY) with 868/914 MHz or 2.4 GHz radio [10]. The 6LoWPAN MAC sub-layer is fully compliant with IEEE 802.15.4-2006 MAC [10]. The IEEE 802.15.4 MAC superframe structure is bounded by beacons sent by coordinators (first slot of superframe) and is divided into 16 time slots. Optionally the superframe can be divided into active region and inactive region. During the inactive region the coordinator may enter the low power mode or sleep mode. The active period is subdivided into the contention access period (CAP) and the contention free period (CFP) or the guaranteed time slots (GTS). When a device wishes to transmit in the CAP period then it has to compete with other devices using a slotted CSMA-CA mechanism. The 6LoWPAN adaptation layer accomplishes the task of fragmentation, header compression and reassembly of the IPV6 packets to fit in IEEE 802.15.4 specified frame. This standard also supports the low power listening mode (LPL) to achieve low power mode operation in the network and to access the channel in completely distributed and unsynchronized way, through appropriate selection of sleep interval for the devices [10][11][12].

In terms of IP layer routing, 6LoWPAN support protocols such as Routing Protocols of Low power and Lossy networks (RPL) [13], that mitigates problems such as non-deterministic link statistics and lack of visibility into physical topology.

6LoWPAN supports only link layer security through 128-bit Advanced Encryption Scheme (AES) encryption, which can provide shielding from foreign attackers and outside networks.

Co-existence with other devices such as Wi-Fi, is not efficient, because of the use of same channel by all the devices. Some advantage can be taken of using the 2.4 GHz radio, but even then only three (15, 20 and 25) out of sixteen channels will avoid interference [14].

Due to its internet compatibility and the use of IP based network management tools such as Simple Network Management Protocol (SNMP), 6LoWPAN is easily integrated in other environments. 6LoWPAN also offers interoperability with other wireless 802.15.4 devices and with any other IP network link.

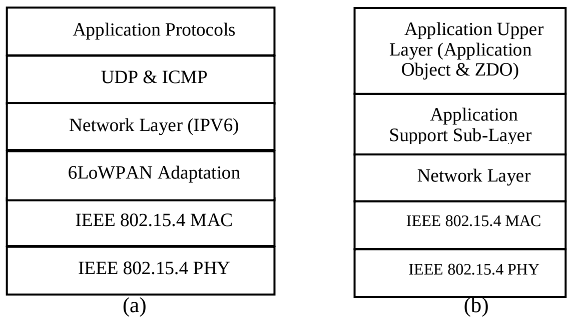



Fig.1 (a) 6LoWPAN protocol stack (adapted from Z. Shelby and C. Bormann, [9]), (b) Zigbee Stack Structure (adapted from Zigbee Document 053474r17, [15])

### *B. Zigbee*

Currently, in smart grids the most widely used WSN protocol is Zigbee. It basically deals with the upper network and application layers. The nodes in Zigbee are connected in a star, mesh and tree topology [15]. Zigbee is designed for local networks in home environments, and it cannot directly communicate to servers on internet [15]. As the size of the link layer address is 16 bits, therefore a total of $2^{16}$ devices can be supported in a network. Zigbee network architecture supports three types of devices namely the Zigbee coordinator (ZC), Zigbee Router (ZR) and Zigbee end device [15].

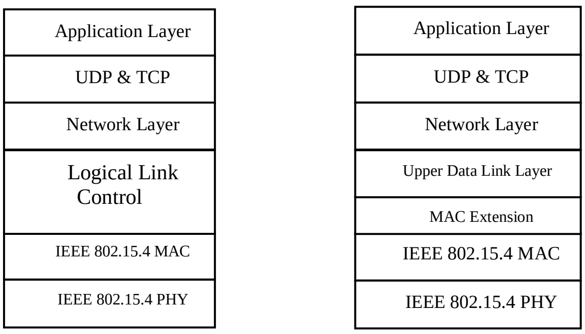
The Zigbee standard physical layer is based on IEEE 802.15.4-2003 (PHY) with 868/914 MHz or 2.4 GHz radio. The data link layer is the IEEE 802.15.4-2003 MAC sub-layer as defined in [16]. IEEE 802.15.4-2003 MAC superframe structure is the same as that of IEEE 802.15.4-2006. Mostly, this standard works in non-beaconed mode [15]. The stack structure defined for Zigbee standard is shown in Fig.1.b.

The network layer provides services to the application support sub layer, and supports Ad-hoc on-demand distance vector routing protocol (AODV) and Tree routing protocol [18]. The transport layer protocol is not defined in Zigbee. This standard supports Network and Application layer security through 128-bit AES encryption, where 128-bit link key is used for end-to-end security between two devices and 128-bit network key is shared by all devices in the network. According to [15], though frequency agility is supported to mitigate interferences from other non-Zigbee devices, for a large interval of time (in hours) devices in the network use the same channel. Hence, the performance of Zigbee devices degrades in presence of other RF devices, such as Wi-Fi.

Zigbee offers interoperability with other Zigbee devices with the same profile, but it needs an application layer translator/gateway to communicate with internet.

### *C. WirelessHART*

WirelessHART technology provides a robust wireless protocol for the full range of process measurement, control, and asset management applications [17]. It is based on HART communication protocol [18], in which the two-way communication can be carried over legacy 4-20 mA wire. WirelessHART network supports star topology, mesh topology and a combination of both. In Fig.2.a, the stack structure of WirelessHART is depicted. As the size of the link layer address is 16 bits, thus up to $2^{16}$ devices within a network are supported. But the high packet latency and power consumption in the network could limit the device scalability [18].




(a) (b)

Fig.2.(a) WirelessHART Stack Structure (adapted from S. Petersen and S. Carlsen, [18]), (b) ISA100.11a stack model (adapted from S. Petersen and S. Carlsen, [18])

The WirelessHART network architecture consists of field devices for field sensing and actuating functions, routers (all devices have routing capability), Gateway to translate protocols between the application layer of the device following this standard and other devices, Access Points to connect the wireless mesh network to the gateway, and Handheld device and Adapter device to provide physical and logical connection to the external devices to the wireless network [17].

This standard is based on IEEE 802.15.4–2006 (PHY) 2.4 GHz radio [10]. The data link layer is divided into Logical Link Control (LLC), and MAC sub-layer fully which is based on IEEE 802.15.4-2006 MAC specification [10]. This standard uses TDMA mechanism to allocate fixed time slots of 10ms each, which is allocated for device-to-device communication without waiting for other devices. The channel sharing is carried out through the CSMA-CA mechanism, specifically through carrier sense only (CSO) mode. A unique channel per time slot (frequency hopping) is assigned to the communicating devices for interference free communication, thereby making devices immune against the interference from other RF devices, operating in the same band.

In this standard, the mandatory protection in data link and network layer is provided through Symmetric AES 128-bit keys. Three types of keys namely: join keys, network keys and session keys are used. Session keys are allotted for device to device communication, and network and join keys are used by all devices.

WirelessHART offers interoperability with devices using the same 'HART' communication protocol, but it does not support compatibility with internet, however many companies manufacture WirelessHART based devices such as ABB, Pepperl + Fachs, Emerson, MACTeK etc. [18].

### *D. ISA100.11a*

ISA100.11a is an industrial project, a part of ISA100, which belongs to a family of standards for wireless systems for industrial automation, process control and related applications. ISA100.11a supports star topology, mesh topology and the combination of the two. The standard is based on IPV6. ISA100.11a network supports star topology, mesh topology and the combination of the two. This standard resembles WirelessHART in many aspects. The architectural and analytical differences between both are studied in [18] and [20]. This standard is compliant with the 6LoWPAN standard, as its network and transport layers are based on it. Fig.2.b shows the stack structure of ISA100.11a standard.

This standard is based on IEEE 802.15.4–2006 (PHY) 2.4 GHz radio [10]. In ISA100.11a the data link layer is divided into IEEE 802.15.4-2006 MAC sub-layer, Upper Data Link Sub-layer (DLL) and Data link shim layer between MAC and Upper DLL. The functions of upper DLL sub-layer is TDMA, channel hopping and mesh routing. The MAC sub-layer is responsible for transmission and reception of individual frames, using the CSMA-CA mechanism. The CSMA-CA back-off and retry mechanism is different in ISA100.11a. It involves the use of spatial diversity, time diversity and frequency diversity as the retry mechanism. For this standard the use of CSMA technique, as supported by IEEE 802.15.4 PHY is optional. Depending on the system configuration, the physical layer shall disable CSMA as requested by data link layer.

This standard also uses TDMA and channel hopping with ARQ mechanism for interference suppression from, and coexistence with other RF devices. As compared to WirelessHART, ISA100.11a defines three types of channel hopping mechanisms namely, slotted hopping, slow hopping and hybrid operation. In slotted hopping, equal length time slots are used. Each time slot uses a different radio channel in a hopping pattern. Timeslot scale is between 10 to 12 ms per hop. This kind of hopping pattern requires quite tight time synchronization between time slots. Slow hopping on the other hand, allows a set of adjacent timeslots to be combined on a single radio channel. In this case, timeslot scale is typically 100 to 400ms per hop. Time synchronization is relaxed in this type of hopping. The hybrid operation is the combination of the two for a particular arrangement.

In ISA100.11a, and according to [20], the manufacturers are not interested in being interoperable. As this standard is compliant with 6LoWPAN to handle IPV6 traffic, it is also compatible with internet. Some companies manufacture devices based on this protocol such as Honeywell and Yokogawa [20]. This standard supports symmetric AES 128-bit encryption.

### *E. OCARI*

This is another wireless sensor network protocol which is aimed at providing reliable communication in harsh environments such as Power Grids, Warships etc. The goal of this protocol is to provide maximum life time to the network devices, and hence the network. This standard is still under development, and it is been promoted as an open source standard for industrial wireless technology [2]. In OCARI, the concentration is towards the improvement of Zigbee standard. Fig.3.depicts the protocol stack structure of OCARI. This standard supports tree topology. The OCARI network consists of an OCARI end device, OCARI cell coordinator, and a workshop coordinator.

The OCARI standard is based on IEEE 802.15.4–2006 (PHY) 2.4 GHz radio [10]. The data link layer of OCARI standard is based on a synchronized tree based MaCARI protocol [21] instead of IEEE 802.15.4 MAC. This link layer protocol ensures regular sleep schedules to the network devices and bounded end–to-end delay [21]. Unscheduled activities periods are similar to the inactivity period of IEEE 802.15.4 superframe structure. During this period, the coordinators can communicate among themselves using the CSMA-CA mechanism. The messages which do not require bounded end-to-end delay can be sent during this time period.

The main aim of this protocol is to increase the network lifetime by utilizing low power of the network devices. For this purpose, the network layer uses energy efficient routing algorithms along with the node activity scheduling algorithms.

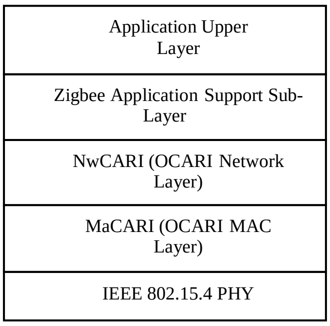



Fig.3. OCARI stack structure (adapted from K. Al Agha, M. Bertin et al, [2])

The properties like co-existence with other RF devices, interoperability and market availability and support are not as easy to assess given the novelty of this proposed protocol.

## IV. COMPARISON

In industrial applications the factors such as the network lifetime, coexistence with other RF devices, interoperability, market availability, network security and reliability, are of prime importance to decide the deployment of a WSN in a specific environment.

WirelessHART supports fixed time slots with channel hopping for inter-device communication, which prevents from interference with other RF devices and reduces power consumption. In ISA100.11a, the configuration of time slots is flexible and hence, interference and utilization of power increases. Zigbee on the other hand, supports almost no frequency hopping, which enhances the message collisions, and hence the power consumption. Also ZC and Zigbee routers need to be continuously awake to listen to the channel, which increases utilization of power. In 6LoWPAN, devices operate on the same frequency band, due to which interference with other existing RF devices increases, and hence the power consumption. In OCARI, the MaCARI protocol provides low power mode operation to maximize the network lifetime.

In WirelessHART and ISA100.11a, coexistence with other existing RF devices in the network is somewhat better than other WSN standards, as discussed.

The network security is supported and mandatory in WirelessHART than in ISA100.11a. The benefit of data-link and network/transport layer security is to have in-network and external network protection. Zigbee on the other hand supports layer security on demand. 6LowPAN just supports data-link security.

The market support of WirelessHART is comparatively better as compared to other WSN standards. Zigbee on the other hand is a widely used standard in smart grid applications, but its non-compatibility with internet makes it more complicated to integrate with other systems.

As both ISA100.11a and 6LoWPAN support IPV6 based traffic, therefore the networks formed by them are quite scalable. WirelessHART and Zigbee on the other hand, being non-compatible with internet are not so scalable.

Except ISA100.11a, all the other standards support the property of interoperability.

If we study the application of Zigbee and 6LoWPAN in smart grids then, we observe that the application of 6LoWPAN in smart grids is more robust than that of Zigbee [22]. The reason is that the IP compatibility and architecture of 6LoWPAN makes it more immune to the network breakdowns, whereas the total network breakdown will occur if the Zigbee controller (ZC) managing Zigbee network collapses. Similarly in ISA100.11a, only one router carries all the routing operations. If that fails, network breakdown could occur. Contrary to that, in WirelessHART all the devices possess routing capability, thus in case of failure of any one, another could route data.

Now, comparing the protocol stack structures and characteristics of WSN standards, it could be seen that for WirelessHART, the properties such as 2.4 GHz band operation, lower power consumption, time slotted channel hopping, channel black listing, fixed time slot communication among devices, network layer graph and source routing, interoperability, and security at both data link and network layers, propose it to be a good option among all WSN standards, to be tested in the impulsive noise environment, in the electrical substation.

But, in [14] and [23] it has been shown that the performance of WirelessHART degrades when deployed in coexistence with IEEE 802.11 network. It has been shown in [14] that, with the increase in the traffic on IEEE 802.11 network, the packet loss increases significantly in WirelessHART network. Also, it is shown in [23] that, if the duty cycle of the nodes in WLAN network increase, then it will deteriorate the performance of WirelessHART network (packet loss) significantly. In 2.4GHz band, the IEEE 802.15.4 PHY channels that do not interfere with the IEEE 802.11 b/g PHY channels are 15, 20 and 25. In order to deploy WirelessHART in coexistence with 802.11 b/g, the radio planning for the site is essential. Also, considering the security conditions, in WirelessHART standard, the security on the network and the data link layer is mandatory and requires extra processing time and energy [18]. Thus, there could be an issue of extended battery life of the nodes and hence the network life time.

# V. CONCLUSION

In this paper, the specifications of standards such as 6LoWPAN, Zigbee, WirelessHART, ISA100.11a and OCARI has been reviewed. The stack comparison of these standards along with their major properties such as coexistence, interoperability, network lifetime, market availability and support etc. has been done. Also, an overview of the impulsive noise in the electricity transmission substation has been provided. The channel hopping capability is carried through the MAC layer and higher layers so that the users of 802.15.4 radios have the ability to select the best available channel for operation. Through this selection, routing protocols can select the appropriate routes, and also the interference by other devices present in the nearby environment can be mitigated. Through our review it could be concluded that WirelessHART network with the above mentioned properties could be the most suitable for implementation and testing for packet error rates in the impulsive noise environment present in electrical substations.

As the ISA100.11a protocol suite resembles that of WirelessHART, with non-compulsory layer security requirements, it would be interesting in future work to study and analyze the performance of ISA100.11a in the impulsive noise environment, as this property of ISA100.11a could provide additional power reduction and reduced processing time and memory consumption. Also, performance tests of ISA100.11 in coexistence with other RF devices in the industrial plant such as WLAN could be an interesting area to study.

As 6LoWPAN network is based on IPV6 addressing, therefore even if the edge router or intermediate router fails, the information can still be extracted from 6LoWPAN end nodes, as each node has an IPV6 address. The application of this idea has been proposed for smart grids in [22], but has not been tested for packet error rates in the impulsive noise environment. Hence, the performance analysis of 6LoWPAN protocol suite with appropriate node duty cycles would also be an interesting study to analyze.

# REFERENCES


[1] V. C. Gungor and F. C. Lambert, “A survey on communication networks for electric system automation,” *Comput. Netw.*, vol. 50, no. 7, pp. 877–897, May 2006.

[2] K. Al-Agha, M.-H. Bertin, T. Dang, A. Guitton, P. Minet, T. Val, and J.-B. Viollet, “Which Wireless Technology for Industrial Wireless Sensor Networks? The Development of OCARI Technology,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4266–4278, 2009.

[3] G. Madi, F. Sacuto, B. Vrigneau, B. L. Agba, Y. Pousset, R. Vauzelle, and F. Gagnon, “Impacts of impulsive noise from partial discharges on wireless systems performance: application to MIMO precoders,” *EURASIP J. Wirel. Commun. Netw.*, vol. 2011, no. 1, p. 186, Nov. 2011.

[4] S. A. Bhatti, I. A. Glover, R. Atkinson, Q. Shan, Y. Yang, J. M. R. de S Neto, and J. S. da Rocha Neto, “Vulnerability of Bluetooth to impulsive noise in Electricity transmission substations,” in *IET International Conference on Wireless Sensor Network, 2010. IET-WSN*, 2010, pp. 53–58.

[5] V. C. Gungor, B. Lu, and G. P. Hancke, “Opportunities and Challenges of Wireless Sensor Networks in Smart Grid,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3557–3564, 2010.

[6] Q. Shan, I. A. Glover, R. C. Atkinson, S. A. Bhatti, I. E. Portugues, P. J. Moore, R. Rutherford, M. de Fátima Queiroz Vieira , A. M. N. Lima, and B. A. de Souza, “Estimation of Impulsive Noise in an Electricity Substation,” *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 3, pp. 653–663, 2011.

[7] F. Sacuto, F. Labeau, J. Beland, M. Kassouf, S. Morin, S. Poirier, and B. L. Agba, “Impulsive Noise Measurement in Power Substations for Channel Modeling in ISM Band,” presented at the 2012 CIGRE Canada Conference, Montreal, 2012.

[8] L. Satish and B. Nazneen, “Wavelet-based denoising of partial discharge signals buried in excessive noise and interference,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 10, no. 2, pp. 354–367, 2003.

[9] Z. Shelby and C. Bormann, *6LoWPAN: The Wireless Embedded Internet*. Wiley, 2009.

[10] “Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (WPANs),” IEEE 802.15.4, 2006.

[11] B. Krishnamachari, *Networking Wireless Sensors*. Cambridge University Press, 2005.

[12] E. Toscano and L. Lo Bello, “Comparative assessments of IEEE 802.15.4/ZigBee and 6LoWPAN for low-power industrial WSNs in realistic scenarios,” in *2012 9th IEEE International Workshop on Factory Communication Systems (WFCS)*, 2012, pp. 115–124.

[13] J. W. H. <jhui@archrock.com>, “The Routing Protocol for Low-Power and Lossy Networks (RPL) Option for Carrying RPL Information in Data-Plane Datagrams.” [Online]. Available: http://tools.ietf.org/html/draft-ietf-6man-rpl-option-06. [Accessed: 01-Dec-2013].

[14] L. Angrisani, M. Bertocco, D. Fortin, and A. Sona, “Experimental Study of Coexistence Issues Between IEEE 802.11b and IEEE 802.15.4 Wireless Networks,” *IEEE Trans. Instrum. Meas.*, vol. 57, no. 8, pp. 1514–1523, 2008.

[15] “ZigBee Document 053474r17.” Zigbee Alliance, Jan-2008.

[16] “Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (WPANs).” IEEE 802.15.4, 2003.

[17] “Industrial communication networks – Wireless communication network and communication profiles – WirelessHART.” International Electrotechnical Commission, Apr-2010.

[18] S. Petersen and S. Carlsen, “WirelessHART Versus ISA100.11a: The Format War Hits the Factory Floor,” *IEEE Ind. Electron. Mag.*, vol. 5, no. 4, pp. 23–34, 2011.

[19] “ISA100.11a.” International Society of Automation, May-2011.

[20] M. Nixon, “A Comparison of WirelessHART and ISA100.11a.” Emerson Process Management.

[21] G. Chalhoub, A. Guitton, and M. Misson, “MAC specifications for a WPAN allowing both energy saving and guaranteed delay,” in *Wireless Sensor and Actor Networks II*, A. Miri, Ed. Springer US, 2008, pp. 221–232.

[22] C.-W. Lu, S.-C. Li, and Q. Wu, “Interconnecting ZigBee and 6LoWPAN wireless sensor networks for smart grid applications,” in *2011 Fifth International Conference on Sensing Technology (ICST)*, 2011, pp. 267–272.

[23] S. Petersen and S. Carlsen, “Performance evaluation of WirelessHART for factory automation,” in *IEEE Conference on Emerging Technologies Factory Automation, 2009. ETFA 2009*, 2009, pp. 1–9.