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# Zigbee Performance During Severe Interruptions in Electric Power Systems

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*Abstract*— **The goal of this paper is to investigate the reliability of ZigBee based wireless sensor networks in transforming existing power systems into future smart grids. The performance of the communication network for specific propagation environment and frequency band is investigated. The interrupting RF signals generated from harsh normal and abnormal operating conditions in power system environment are investigated. High noise level in 13 to 16kV HV systems, impulsive transients of 10 to 34kV according to IEEE Std. 792 turn-to-turn tests as well as partial discharge activities in 4 to 24kV free space are tested using real laboratory data. The interruption limits of ZigBee coordinator and device units during these conditions are defined.**

***Keywords— Wireless Sensors, ZigBee, Impulsive Transients, Partial Discharge.***

## I. Introduction

The emergence of low-cost, low-power, multi-functional miniature sensor devices, has made it possible to monitor, measure and react to changes in different physical phenomenon in electric power systems. Wireless sensors are equipped with a radio transceiver and a set of transducers through which they acquire information about the surrounding system. When deployed in large quantities in a sensor field, these sensors can automatically organize themselves to form an ad hoc multi-hop network to communicate with each other and with one or more coordinators. A diverse set of applications for sensor networks encompassing different fields have already emerged including energy, machine malfunction, medicine, agriculture, environment, military, inventory monitoring, intrusion detection, motion tracking, toys and many others. The delivery of the IEEE 802.15.4 standard for the physical and medium access control (MAC) layers and the development of ZigBee standard for the network and application layers have paved the road for widely accepting the sensor devices in different applications [1].

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The smart grid concept specifies the addition of intelligence and two-way digital communication to the power grid to significantly improve system reliability and security. Grid-integration of renewable systems and energy storage, rapid outage detection, real-time pricing feedback to end-users, and better routing of power and demand management as well as energy efficiency, power system reliability and the environmental impact of conventional fuel plants are all drivers for more intelligent or smart grids [2]. Intelligent power networks are expected to incorporate millions of sensors all connected through an advanced, two-way communications and data acquisition system to provide real-time monitoring, diagnosis and control.

IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth), IEEE 802.15.3 (UWB), and IEEE 802.15.4 (ZigBee) are candidate for integrating sensors with wireless technologies in order to provide reliable data and transferring existing power systems into smart grids. The low data rate, low cost, low power consumption, support of mesh topology that enables self-forming and self-healing, and secure wireless communication protocol offered by ZigBee provide more attractive features among others that satisfy our objective towards a smart grid [3, 4].

These unique characteristics of ZigBee-based WSNs make them the ideal applicant for system monitoring in utility and industrial environments. It is expected by the United States Department of Energy (DOE) that the widespread deployment of WSN in industry could improve overall production efficiency by 11% to 18% and in addition reduce industrial emissions by more than 25% [5,6].

Recently, ZigBee network has been proposed in different research areas in power systems. The IEEE 802.15.4 was used to construct a wireless, nonintrusive, intelligent, and low-cost energy management system [5]. The motor terminal voltages and currents information are sent through a WSN for energy evaluation and condition monitoring. In [7] WSNs are used to monitor partial discharge data from an ageing HVDC reactor. A Power Monitoring Module (PMM) is proposed in [8] which integrates ZigBee and disgital signal processing techniques for wireless communication, and real-time power parameters computation. The proposed system is stand-alone and wirelessly communicate with outside systems hence can be used in monitoring different points in the power system.

Due to the nature of harsh operating conditions and high noise levels expected in the electric substations, many researchers have tackled IEEE 802.15.4-compliant sensor network in such environment and for future smart grid applications. In [9] a

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comprehensive experimental field tests and statistical characterization of the wireless channel have been performed on IEEE 802.15.4. The impact of electromagnetic noise on the communications performance of a ZigBee sensor network is presented in [4]. The impact of 400kV substation PD activities and switching/fault transients on the performance of ZigBee equipment is presented in [10]. In [11] the interference between Zigbee channels with wireless local area networks (WLAN) based on 802.11 specifications is discussed. WLAN or WiFi in residential, commercial and business buildings shares the same license-free 2.4GHz Industrial, Scientific and Medical (ISM) frequency band with ZigBee. An energy detection approach and active scan for smart channel selection are utilized to avoid channels interference.

However, harsh and complex electric power system environments pose great challenges in the reliability of WSN communications in smart grid applications [9]. Under normal operation conditions, internal and external noises always exist and switching of either capacitor banks or reactors generate a large magnetic field in the vicinity of the switched device. Under abnormal operation conditions, the high noise level, switching phenomena and impulsive transient events during faults generate RF with a wide frequency band that may interfere with ZigBee devices. The magnitude and the frequency content of these events vary within the power system according to applied voltage level, the type of equipment and the quality of maintenance as well as type of operation and frequency of switching. Although there exist radio propagation measurements in office buildings and factories, link quality characterization of ZigBee networks in HV power system environments are yet to be efficiently studied and addressed [9].

The goal of this paper is to investigate the reliability of the ZigBee based WSN in designing and deploying a reliable smart grid. Interruption in ZigBee networks due to high noise level, impulsive transients during turn-to-turn faults as well as partial discharge activities in free space are investigated using real data at UoW high voltage lab, AUS and UAEU power system labs. The performance of the wireless communication network for specific propagation environment is investigated.

The paper is organized as follows. A brief introduction to ZigBee overview is presented in section II. The experimental setup and data collection are presented in Section III. Section IV presents the results of ZigBee under normal and abnormal power system operation environment. The Conclusion and references are presented in section VI and VII simultaneously.

## II. ZIGBEE OVERVIEW

The ZigBee Alliance [12] has developed a specification for reliable, cost-effective, low-power, low data rate wireless networking protocol that is built on top of the IEEE802.15.4 standard [13]. An overview of the ZigBee protocol stack is shown in Fig. 1 [1]. ZigBee technology is expected to be embedded in a wide range of products and applications across consumer, commercial, industrial and government markets worldwide [1]. The IEEE 802.15.4 standard defines the physical and MAC layers for low cost, low rate personal area networks, while ZigBee defines the network layer specifications for star, tree and peer-to-peer network topologies and provides a framework for application programming in the application layer.

The IEEE 802.15.4 standard [13] defines the characteristics of the physical and MAC layers for Low-Rate Wireless Personal Area Networks (LR-WPAN). LR-WPAN is easy to install, provide reliable data transfer, operate in a short-range, extremely low cost, and has a reasonable battery life, while maintaining a simple and flexible protocol stack.

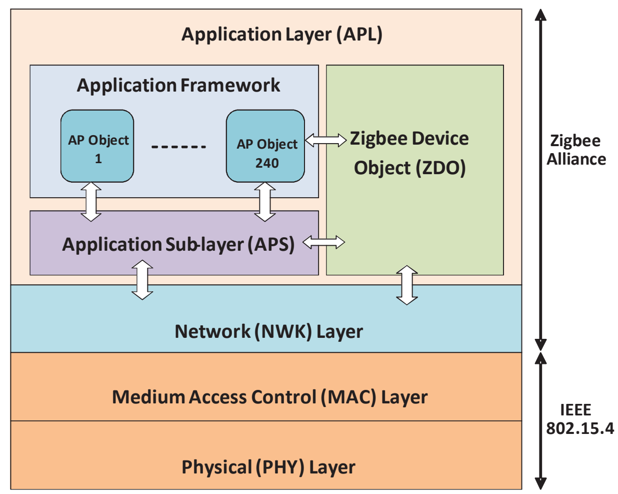



Fig. 1: ZigBee stack architecture.

The physical layer supports three frequency bands; a 2450 MHz band (with 16 channels), a 915 MHz band (with 10 channels) and a 868 MHz band (1 channel). The access mode for all these frequency bands is Direct Sequence Spread Spectrum (DSSS). The 2450 MHz band employs Offset Quadrature Phase Shift Keying (O-QPSK) for modulation while the 868/915 MHz bands use Binary Phase Shift Keying (BPSK). Table I summarizes the main features of the three bands. The physical layer also supports functionalities for channel selection, link quality estimation, energy detection measurement and clear channel assessment.

TABLE I
RADIO FRONT-END AND PHYSICAL LAYER SPECIFICATION

| | *2450 MHz* | *915 MHz* | *868 MHz* |
|---|---|---|---|
| Data rate | 250 kbps | 40 kbps | 20 kbps |
| No. of channels | 16 | 10 | 1 |
| Modulation | O-QPSK | BPSK | BPSK |
| Chip pseudo-noise seq. | 32 | 15 | 15 |
| Bit per symbol | 4 | 1 | 1 |
| Symbol period | 16 µs | 24 µs | 49 µs |

## III. EXPERIMENTAL SETUP AND DATA COLLECTION

The following interruptions result from power system harsh conditions are considered in this study:

1. High noise level
2. Partial discharge (PD) activities in free space
3. Impulsive transients during windings turn-to-turn faults.

The model 2920 RF Vector Signal Generator with a frequency range of 10MHz to 6GHZ and -125dBm to+13dBm output power is used as source of noise. The effect of the noise power and source location on the communications quality of ZigBee coordinator and device units is investigated. A spectrum analyzer with frequency range of 189 kHz to 8 GHz was used to measure the absolute power of noise signals captured close to the coordinator and device units.

The PD in air testing system comprises, test transformer, regulator, calibration capacitor, control unit, and coupling capacitor. The PD was measured using a digital wide-band partial discharge detector that meets all IEC and IEEE/ANSI standards for partial discharge testing. The experimental setup of ZigBee testing during PD activities is shown in Fig.2.

*(a)* *(b)*

Fig. 2: PD activities during 4 to 24 kV Applied voltage, a- experimental setup and b- ZigBee device and PD source.

The impulse testing voltage was generated using a 600 kV, 30 kJ impulse generator that can produce a steep front fast impulse with < 200 ns rise time [14, 15]. The impulse waveform was measured using a 500pF capacitor divider with a ratio of 600:1.4 and a 200 MHz bandwidth digital oscilloscope. The impulsive generator is used to implement different tests such as lightning impulse withstand test, lightning impulse flashover test and special non-standard impulse flashover and withstand test. The impulse test set up is shown in Fig. 3. The stator winding of 4 kV induction machine was subjected to turn-to-turn and turn-to-ground steep front impulse voltages with rise time of 100 ns. The ZigBee device unit is localized close to the current transformer and its' communication quality is investigated.

The XBee Series 2 OEM RF Modules [16] operate within the ZigBee protocol and support the needs of low-cost, low-power wireless sensor networks was used in this paper. The modules require minimal power and provide reliable delivery of data between remote devices. The modules operate within the ISM 2.4 GHz frequency band. To form a ZigBee network, a coordinator must be started on a channel and PAN (Personal Area Network) ID. Once the coordinator starts, routers and end device can join the network. Each router and coordinator can support up to 8 end device units. Table II presents the specification of the ZigBee units used in this study.

*(a)* *(b)*

Fig. 3: Impulse test of 4 kV coil of an induction machine, a- experimental setup and b- ZigBee device unit and measuring CT.

TABLE II
TECHNICAL SPECIFICATION OF THE XBEE UNIT.

| Specification | XBee Series 2 |
|---|---|
| Indoor/Urban Range | Up to 133 ft. (40 m) |
| Outdoor line-of-sight | Up to 400 ft. (120 m) |
| Transmit Power | 2 mW (+3 dBm) |
| Receiver Sensitivity | -96 dBm |
| RF Data Rate | 250,000 bps |
| Number of Channels | 16 Direct Sequence Channels |
| Supported Network Topologies | Point-to-point, Point-to-multipoint, Peer-to-peer & Mesh |

## IV. APPLICATION AND RESULTS

In this application, a pair of XBEE nodes is used as coordinator unit (transmitter) and device unit (receiver). The distance between the units and the strength of the applied interruptions are varied. The coordinator sends receives a group of data packets through a device unit in a loop. The data size and timeout rate and the quality of communication were investigated by monitoring the number of goad and bad data and Received Signal Strength indicator (RSSI).

The fast Fourier transform (FFT) and the energy of the expansion coefficients of the Wavelet transform are used to analyze current data captured and monitoring their energy distribution at different frequency bands [17]. The FFT is computed using the following relation:

$$X_k = \sum_{n=0}^{N-1} x[n] e^{-j2\pi k \frac{n}{N}} \qquad k = 0, \dots, N-1 \qquad [1]$$

Where $x[n]$ is a discrete signal of $N$ sampling points. In Wavelet transform, the signal is presented as a series of expansion coefficients and a combination of the scaling function $\phi(t)$ and wavelets function $\psi(t)$ as:

$$f(t) = \sum_k c_o(k)\phi(t-k) + \sum_k \sum_{j=0}^{J-1} d_j(k) 2^{j/2} \psi(2^j t - k) \qquad [2]$$

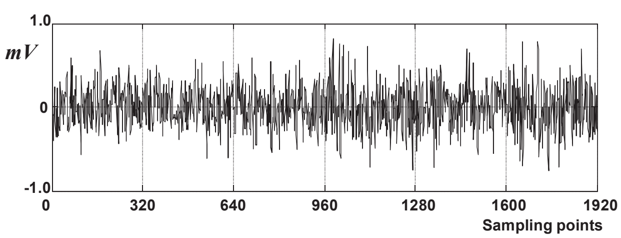
The norm of wavelet detail coefficients at different resolution levels ($\|d_j(k)\|_2$) is used for monitoring the distribution of signal energy at different resolution levels (frequency bands).

*Case 1: Noise at high voltage*

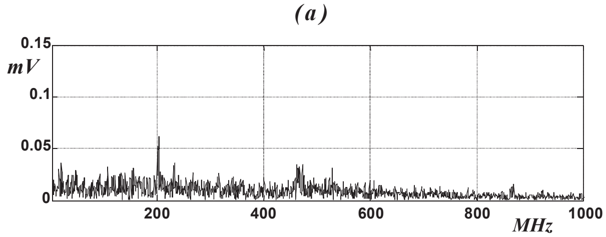
Internal and external power system interferences have a direct effect on the sensitivity and reliability of wireless sensor acquired data. In high voltage electric power systems, power line carrier (PLC) and radio communication systems generate a discrete spectral interference (DSI). Power electronic devices generate periodic pulse shaped interferences. Stochastic pulse shaped interferences are generated from switching operations, lightning, arcing between adjacent metallic contacts, arcing from slip ring and shaft grounding brushes in rotating machines, PD and corona [18].

Fig. 4 shows the noise captured in a current signal, in the grounding conductor while the applied voltage on an insulating material varied from 13kV to 16 kV [19]. The time domain noise signal is shown in Fig. 4a and the frequency content of the noise is shown in Fig. 4b. The noise energy is distributed over a wide frequency band and its power decreases as frequency increases. This noise in the current signal reflects a similar frequency band in the RF signal that may interrupt the quality of communication in ZigBee network.

In order to quantify the noise level that causes interruption to ZigBee network, the RF signal generator is used as a source of noise and adjusted for a carrier signal at 2.465 GHz and a noise signal of 2.5 MHz band. The output power of the RF noise source is adjusted to -11 db at which some of the packets were interrupted. The ZigBee coordinator and device units are located 6 meters away from the noise source. The distance between the two units is changed and RSSI as well as the number of good/bad packets are monitored. The spectrum analyzer is used to measure the power of the noise signals close to the ZigBee units. Table III shows the data collected during this experiment.




*(a)*




*(b)*

Fig. 4: noise signal captured at different voltage levels, a- time domain and b-frequency content.

According to specifications mentioned in Table II, ZigBee transmitted power is +3dBm and the sensitivity of the receiver is -96 dBm. However, as the noise power measured close to ZigBee units research -70dBm, the quality of communication is interrupted. More interruption is achieved as the distance between the two units is increased (RSSI = - 45dBm).

TABLE III
NOISE EFFECT ON THE ZIGBEE UNITS

| Distance between Units (m) | 3.25 | 6.0 |
|---|---|---|
| RSSI | -40dBm | - 45dBm |
| Total No. of Packets | 53 | 91 |
| No. of Good Packets | 50 | 50 |
| No. of Bad Packets | 3 | 40 |
| Power at Device Unit | - 70dBm | - 70dBm |
| Power at Coordinator Unit | -70dBm | -73dBm |

*Case 2: Partial Discharge Test*

Both PD and corona discharges are usually available in the vicinity of high voltage equipment. RF antenna, high frequency current transformer (HFCT), acoustic sensors and capacitive couplers are the most important PD on-line monitoring sensors. The generated electromagnetic waves due to PD discharges have a wide frequency range from tens of MHz to few GHz. Such wide frequency range might interfere with the ZigBee operating frequency bands (see Table I).

The setup shown in Fig. 2 was used to investigate ZigBee behavior during PD activities in free space. The PD was generated using a sharp electrode connected to a 300 kV PD free transformer. The voltage level was increased gradually from 4.0kV to 24.0kV and the level of the PD was continuously monitored (18 to 1000 pc) as indicated in Table IV. The ZigBee device unit is located close to the PD source (See Fig. 2b) and the coordinator unit is located 3 meters away. Three different operation scenarios are considered where a 32 byte data is transmitted from coordinator to device unit and back to coordinator unit. Data received timeout is set at 100 ms and 60 packets were communicated, 1000 ms timeout and 123 packets were communicated and finally the data size is doubled to 64 bytes and 50 packets were communicated with 1400 ms data receive timeout. In all the previous scenarios data transmitted and returned to coordinator without any error as indicated in Table IV.

TABLE IV
PD ACTIVITIES AT DIFFERENT VOLTAGE LEVELS

| Applied Voltage (kV) | **4** | **8** | **10** | **13** | **15** | **18** | **20** | **24** |
|---|---|---|---|---|---|---|---|---|
| Detected PD (pC) | 18 | 18 | 33 | 40 | 95 | 115 | 500 | 1000 |
| Data packets Good/Bad | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** | 50**G** 0**B** |

*Case 3: Impulse Test*

The IEEE std 792, evaluation of the impulse voltage capability of insulation systems for ac electric machinery employing form-wound stator coils and IEEE 522, testing turn insulation of form-wound stator coils for alternating-current electric machines are implemented in ZigBee investigation.

Turn-to-Turn test generates large currents. The applied impulse in this test has a 0.1 to 0.2 microsecond wave front at a voltage level of 3 per unit. The decay or "tail" of the impulse should be at least 10 times the rise time or "front." Unit voltage is defined as or 0.82 E where E is the rated line-to-line rms voltage in a three-phase machine. The voltage is applied multi-times. If no failures occur then the applied voltage is increased by 10% and the impulse test is repeated. Continue to increase the voltage in increments of 10% of the starting level until failure occurs. For uniformity, the break down test should be made at room temperature.

To investigate the effect of the impulsive event on a ZigBee performance, a high voltage impulse waveform is applied to the stator winding of 4 kV induction machine (see Fig. 3) and the following different scenarios are considered:

In the first scenario, the ZigBee device unit is located at 2.0 meters away from the CT (source of magnetic field) and the coordinator is located 3 meters away. The ISSR was -65 and the data received timeout is set to 1000 ms. A 40 data packets were communicated (loop) between the coordinator and device units and the applied impulses are varied between 10 and 30 kV. As indicated in Table V, for 10 to 25kV applied pulses, 40 data packets were communicated without a single interruption. At 30kV applied pulse only one data packet was lost.

TABLE V
ZIGBEE DEVICE UNIT 2 METERS AWAY FROM SOURCE

| Applied Impulse (kV) | **10** | **15** | **20** | **25** | **30** |
|---|---|---|---|---|---|
| Data packets | 40**G** | 40**G** | 40**G** | 40**G** | 39**G** |
| Good/Bad | 0**B** | 0**B** | 0**B** | 0**B** | 1**B** |

In the second scenario, the ZigBee end unit is located at 10 cm away from the CT (source of magnetic field). The ISSR was -55 and the data received time out is 1000 ms. A series of data packets are communicated between the coordinator and end unit and the applied pulses are varied between 10 and 35 kV. In some of these cases up to 3 data packets are lost. The data lost is not directly related to applied voltage magnitude (See Table VI).

TABLE VI
ZIGBEE DEVICE UNIT 10 CM AWAY FROM SOURCE

| Applied Impulse (kV) | **10** | **15** | **20** | **25** | **30** | **35** | **35** |
|---|---|---|---|---|---|---|---|
| Data packets | 40**G** | 41**G** | 40**G** | 40**G** | 40**G** | 40**G** | 40**G** |
| Good/Bad | 3**B** | 3**B** | 0**B** | 1**B** | 0**B** | 0**B** | 0**B** |

In the third scenario the coil insulation was deteriorated under the applied testing pulse. A series of data packets (25 to 104) are communicated between the coordinator and end unit while the applied pulses are varied between 10 and 30 kV. At 30kV applied voltage, the PER is increased and finally ZigBee lost communication. (See Table VII).

TABLE VII

ZIGBEE DEVICE UNIT 10 CM AWAY FROM SOURCE

| Applied Impulse (kV) | **10** | **15** | **20** | **25** | **30** | **30** |
|---|---|---|---|---|---|---|
| Data packets | 50**G** | 98**G** | 35**G** | 25**G** | 79**G** | **ZigBee Lost** |
| Good/Bad | 4**B** | 6**B** | 3**B** | 0**B** | 21**B** | |

During this interruption, the ISSR moves very fast from -55 to -104 and the coordinator unit lost the integration with the wireless system.

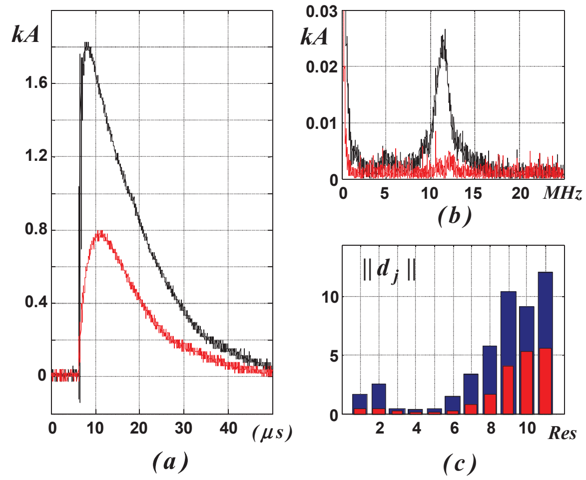



Fig. 5: captured current signals during impulse test a- current signals at 12 kV (red) and 30kV applied voltages, b- FFT of the current signals, and b- Norm of WT of the current signals.

Fig.5 shows the results of applied the impulse test until a failure occurs in the stator winding coil and ZigBee coordinator interrupted. Fig. 5a shows the minimum and maximum currents generated from increasing the applied voltage from 12kV up to 30kV, where ZigBee coordinator lost. The frequency content of the current signal is shown in Fig. 5b where most of the signal energy localized between 10 and 15 MHz.

While FFT is a very efficient computational tool for spectrum analysis of a discrete-time periodic signal, the FFT has a limited capability while analyzes non-periodic disturbances and extract time-frequency information. This is due to utilizing the global functions $e^{jwt}$ to transform the signal from the time-domain into the frequency-domain. The wavelet multi-resolution is furthermore implemented for signal processing. The wavelet norm of multi-resolution coefficients shows that most of the signal's energy is localized at low resolution levels as shown in Fig. 5c. However as the applied pulse voltage increases, the generated current signal energy increases at the 2nd resolution level (6.25-12.5 MHz).

## VII. CONCLUSION

The reliability of ZigBee based wireless sensor networks under sever interruption conditions in distribution power system are investigated. High noise level in 13 to 16kV systems, impulsive transients of 10 to 34kV according to IEEE Std. 792 turn-to-turn tests as well as partial discharge activities in 4.0kV to 24kV free space are tested using real laboratory data. The ZigBee coordinator and device units during PD activities show reliable performance in data communications. However high noise level and impulsive faults impose limitations on Zigbee reliability according to the distance between units and/or interruption severity.

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