Laboratory Assessment of WLAN Performance Degradation in the Presence of Impulsive Noise

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***Abstract*—a laboratory test to assess the impact of impulsive noise on the performance of WLAN equipment is described. The test is put in the context of a larger programme of work to assess the performance ands reliability of wireless equipment subject to partial discharge noise in high voltage electricity supply substations. The character of partial discharge and WLAN technology are briefly reviewed. The laboratory test methodology is reported and some preliminary results are presented. A related forthcoming field-trial for tests of WLAN equipment in a 275/400 kV air-insulated substation is briefly described.**

Keywords - Partial discharge; WLAN; IEEE 802.11 a/b/g; electricity supply substation; WPAN.

I. INTRODUCTION*

The infrastructure investment in a national power transmission system is colossal. It is therefore necessary to operate such systems as efficiently as possible, consistent with maintaining acceptable security of supply. Efficient and reliable operation demands continuous monitoring of the system state resulting in instrumentation and control equipment being widely scattered throughout substation compounds. Information and control signals for both normal and abnormal operation are traditionally connected, using cables or optical fibres, to a SCADA (Supervision, Control and Data Acquisition) system [1] and/or its successor UCA (Utilities Communication Architecture) system [2]. Ethernet local area network (LAN) implementations of such UCA/SCADA systems, which simplify the addition/reconfiguration of instrumentation and the coordination of protection systems, have been proposed and are already being evaluated [3].

Significant flexibility and cost advantages over a wired LAN infrastructure would be gained, however, if signals could be routed around electricity substation compounds wirelessly. Furthermore, wireless communication technologies hold out the prospect of ‘hot-line’, sensors that can be deployed on energized high-voltage (HV) equipment without the inconvenience and costs associated with bridging the system’s primary insulation [4, 5]. WLAN and WPAN technologies represent obvious opportunities to realize these advantages.

The casual deployment of wireless technologies for critical functions is not, however, without risk. Whilst the naturally occurring noise environment is relatively benign at WLAN and WPAN frequencies [6] the man-made noise environment within a substation compound is complex and hostile due, for example, to PD from imperfect insulation and sferic radiation from switching and fault transients. (The term sferic usually relates to radiation from a lightening event but is used here as a shorthand for similar radiation arising from any large current transient.) The latter is of particular concern since it is on just such occasions that control and protection equipment is required to operate reliably. It is possibly for this reason that UCA demonstration systems have until now employed a ‘wired’ (often fibre) transmission medium e.g. [7].

An investigation into the vulnerability of WLAN and WPAN technologies to impulsive noise in electricity transmission substations has been proposed [8]. One of the project objectives requires an assessment of WLAN technology in impulsive noise environments and its suitability for deployment in HV substations. As part of this assessment a laboratory test of WLAN equipment have been carried out and a field-trial is about to be undertaken.

The laboratory test replaces the antennas and radio path between WLAN transceivers with high-quality coaxial cable and appropriate microwave attenuators.

The field-trial comprises a deployment of WLAN equipment in a 275/400 kV electricity supply substation.

II. PD IN SUBSTATIONS**

An electrical discharge is partial if it fails to fully bridge the space between a pair of electrodes. It can occur around an electrode in a gas (corona), within gas bubbles in a liquid or within the space created by voids in a solid. HV plant (e.g. transformers, switchgear, cables) is especially prone to PD if its insulation is damaged and/or as its insulation ages. If remedial action is not taken the insulation can be seriously compromised leading, ultimately, to catastrophic failure. PD current pulses in strong insulators (e.g. SF_6) can have rise-times as short as 50 ps

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and may contain significant energy at frequencies up to 3 GHz [9]. Such impulsive signals can give rise to electromagnetic resonances within the conducting enclosures in which they occur.

PD propagation within a Gas Insulated Substation (GIS) is by a combination of transverse electric (TE), transverse magnetic (TM) and transverse electromagnetic (TEM) modes [10]. Laboratory tests have suggested that two principal mechanisms are responsible for PD signal damping. These are reflections due to characteristic impedance discontinuities (such as is caused by spacers) and energy conversion from TEM to TE or TM modes [11]. Although the character of PD appears to have some dependence on the size and geometry of plant components (e.g. insulating spacers, L-shaped buses, T-branch buses) damping typically appears to become significant somewhere between 100 MHz and 300 MHz and increases with increasing frequency above this [12]. PD energy in the frequency range 0.5 - 1.2 GHz, however, is readily radiated from apertures formed, for example, by insulating spacers or bushings [13].

Energy from PD processes can be radiated whenever spectral components arising from current pulse edges extend into the radio frequency (RF) region [14]. Signals radiated from open-air substations are typically stronger than those from underground substations due, in the latter case, to an enclosing metallic tank located in a steel-reinforced concrete building [15].

III. WLAN

The initial IEEE WLAN standard (802.11) was published in 1997. Since then, several variations of this standard have been launched including IEEE 802.11a/b/c/d/e/f/g/h/i [16]. A brief overview the most important of these standards (802.11a/b/g) and studies assessing the performance of equipment conforming to them is given below.

IEEE 802.11a operates in the 5 GHz band and uses orthogonal frequency division multiplexing (OFDM). It can support data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. The different transmission rates are obtained by varying the modulation order and/or the channel code rates. The system uses 52 subcarriers that are modulated using BPSK, QPSK, 16- or 64-quadrature amplitude modulation (QAM). The error correction coding uses a convolution encoder with a coding rate of 1/2, 2/3 or 3/4.

IEEE 802.11b operates in the 2.4 GHz band and variously uses direct sequence spread spectrum (DSSS) or frequency hopping spread spectrum (FHSS). It supports transmission rates of 1, 2, 5.5 and 11 Mbps. The different transmission rates are obtained with varying the modulation type. 1 Mbps is realized using differential binary phase shift keying (DBPSK) whilst 2 Mbps uses differential quadrature phase shift keying (DQPSK). Higher data rates of 5.5 Mbps and 11 Mbps use complementary code keying (CCK).

IEEE 802.11g is a hybrid of 802.11a and 802.11b. It operates in 2.4 GHz band but uses OFDM. It supports data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. The different transmission rates are obtained by varying the modulation order and/or the channel code rates, in the same way as 802.11a.

Since some of the WLAN standards share the 2.4 GHz ISM frequency band with wireless personal area network (WPAN) technologies such as Bluetooth and ZigBee, significant work has been carried out to assess their coexisting performance [17-20]. WLANs were originally intended only for indoor use. There has been a tendency, however, to widen their area of application into other environments An experimental assessment, for example, of the performance of vehicle-born WLANs in suburban, urban and motorway environments has been reported [21]. (A particularly unusual study evaluates WLAN performance on the Martian surface [22]). The studies assess performance using throughput, packet error rate (PER) and bit error rate (BER). Most of the assessments rely on simulations; [21] being a notable exception.

An investigation closely related to the work reported here concludes that WLAN technology could be used in an integrated electricity substation control system [23]. An assumption, based on a review of literature, is that substation RFI/EMI in the 802.11 frequency band (2.4 and 5 GHz) is small and so its impact can be tolerated. The authors are not aware, however, of any experimental work to support this. The laboratory test and practical field-trial described in sections 4 and 5 are intended to address this neglected area.

IV. LABORATORY TEST

The laboratory test was carried out in the Geoffrey Smith Intelligent Dynamic Communications Laboratory at the University of Strathclyde. Two tests have been carried out; the first without any external interference and the second with controlled impulsive noise. The test without external interference represents a control. The methodologies are described below.

A. Test without any External Interference

The system without external interference consists of two terminals, one a data source and the other a data sink, as shown in Figure 1. The source and sink terminals each comprise a WLAN kit interfaced to a laptop computer. The WLAN kits are CSR's UniFi-1 (IEEE802.11b/g) modules based on UniSira kits. The RF frequency band is 2.4 GHz and a total of 14 channels are used. The maximum air-interface data throughput is 11Mbps for 802.11b and 54 Mbps for 802.11g. The typical RF output power is 0 dBm for 802.11b and -1dBm for 802.11g. The typical sensitivity of the WLAN modules is -84 dBm for 11 Mbps and is -71 dBm for 54 Mbps [24]. Communication between the WLAN module and the computer (2.33 GHz, 1 GB RAM, 120 GB HDD) is via a Serial Peripheral Interface (SPI) to parallel port. The communications channel between data source and sink was replaced with microwave coaxial cable and adjustable microwave attenuators. The cables and attenuators are specified for operation between DC and 18 GHz, and DC and 20 GHz, respectively. The WLAN kits are enclosed in metallic boxes to provide shielding from external radio frequency/electromagnetic interference (RFI/EMI). The practical test system is shown in Figure 2.

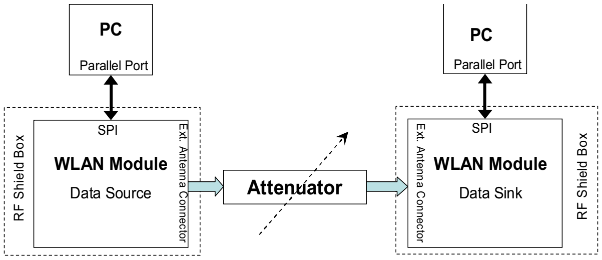

Figure 1. Schematic illustration of of test system without external interference.

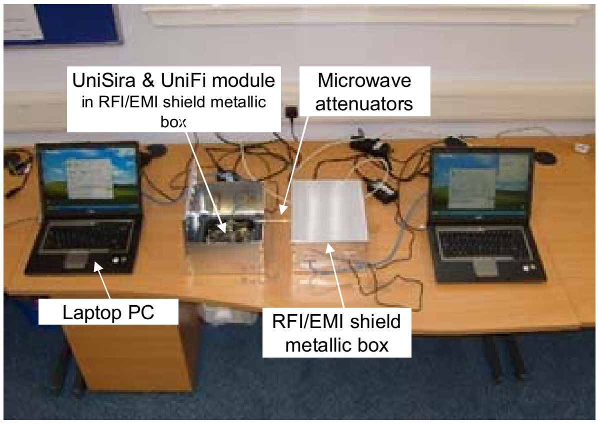

Figure 2. Test system without external interference.

B. Test with Controlled Impulsive Noise

The test system incorporating external impulsive noise consists of two data terminals, an impulsive noise source and a power combiner, Figure 3. The data terminals are identical to those of the data source and data sink described in Section 4.1. The wireless communications channel between source and sink, without using antenna, is replaced with microwave cables and adjustable microwave attenuators. The impulsive noise source comprises a pulse generator and microwave attenuators allowing adjustment of the impulse energy. The power combiner adds the impulsive noise to the source signal. The combined signal is transmitted to the data sink. The specifications of the cables and attenuators are the same as those described in Section 4.1. The WLAN kits are also enclosed in metallic boxes to provide shielding from RFI/EMI. The test system is shown in Figure 4.

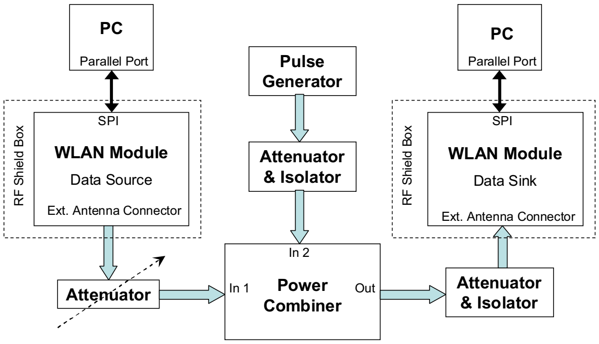

Figure 3. Schematic liiustration of test system incorporating external impulsive noise

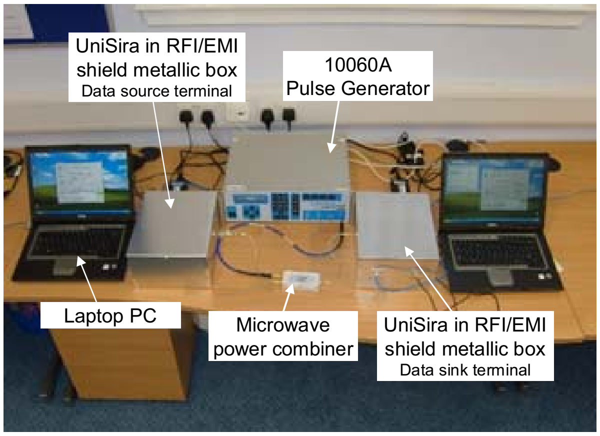

Figure 4. Test system incorporating controlled impulsive noise.

V. PRELIMINARY RESULTS

The laboratory tests were carried out with the UniFi-1 module transmitter and receiver settings listed in Table I. The transmit power level and data rates are the modules' specified maxima. The setting of the interval between fames is great than the expected maximum jitter (< 30µs). The payload length was set to the maximum allowed by the UniFi-1 module specification. Frame filtering refers to the disregarding of any frames whose MAC address does not match the MAC address specified (e.g. frames from other interfering WLAN transmissions). The attenuation of the path between transmitter and receiver for the laboratory tests was adjusted to yield a practical RSSI of -50 dBm for 11 Mbps and -56 dBm for 54 bps. The RSSI is subject to small changes (of the order of 2 dB) over the period of a test (approximately 10 hours).

TABLE I. UNIFI-1 MODULE SETTINGS

Parameter	**Unifi-1 module**	
	Transmitter	***Receiver***
Frequency Band	2.4 GHz	2.4GHz
Channel Index	1	1
Power Level	0 dBm	0dBm
Data Rate (Mbps)	11, 54	N/A
Interval between Frames	50 µs	N/A
Network	Ad Hoc	Ad Hoc
Frame	Independent BSS	N/A
Payload Length	2304 bytes (Random)	N/A
Frame Filtering	N/A	Yes

Results for the laboratory test without external RFI/EMI are summarized in Table II. (RSSI, SNR and latency are average values.)

TABLE II. TEST RESULTS WITHOUT EXTERNAL INTERFERENCE

Parameters	Test in data rate	
	11 Mbps	*54Mbps*
RSSI (dBm)	-50	-56
SNR (dB)	8	24
Total Frames Transmitted	36,952,327	177,344,255
FER	4.43×10^{-5}	2.52×10^{-3}
Latency (µs)	1950.4	417.1

The controlled impulsive signal comprises 10 ns, 0.316 V, pulses with variable repetition frequency. The results for the test are presented as frame error ratio (FER) and latency versus pulse rate in Figures 7 and 8 respectively for a transmission rate of 11 Mbps and in Figures 9 and 10 respectively for 54Mbps.

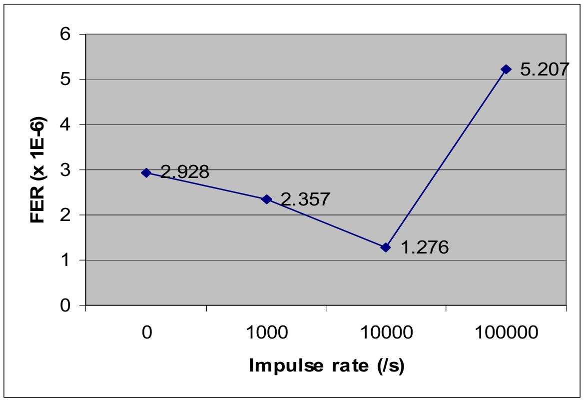

Figure 5. FER versus impulse rate (for 11Mbps).

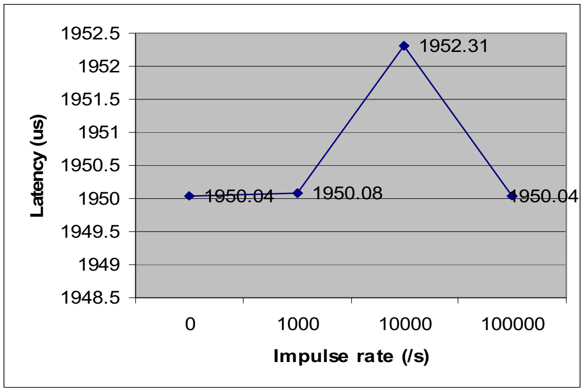

Figure 6. Latency versus impulse rate (for 11Mbps).

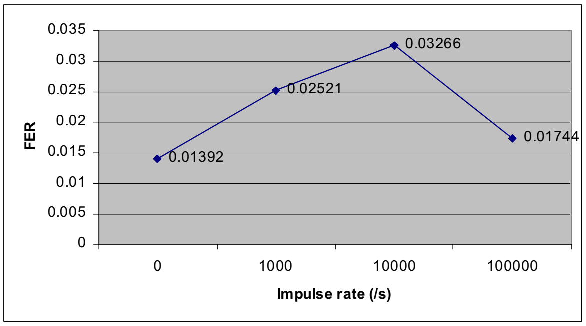

Figure 7. FER versus impulse rate (for 54 Mbps).

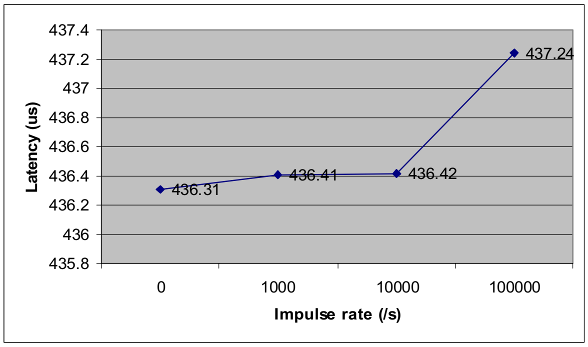

Figure 8. Latency versus impulse rate (for 54Mbps).

VI. FIELD TRIAL

A field-trial is planned to be carried out in a 400 kV Air Insulated Substation (AIS) at Strathaven in Scotland, Figure 9. The trial will assess the performance of a WLAN subject to the realistic impulsive noise arising as a consequence of PD in this type of environment. A schematic diagram of the field trial equipment is shown in Figure 10. The terminal hardware, interface and settings will be identical to those used in the laboratory tests reported here except that the WLAN kits will not enclosed in metallic boxes.

Figure 9. 400kV AIS power substation.

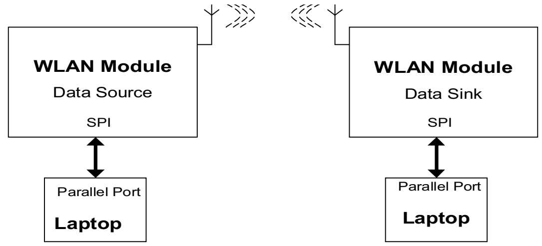

Figure 10. Schematics of field trial system.

VII. CONCLUSION

The advantages and risks of deploying WLAN and WPAN technology in the electromagnetically challenging environment of electricity supply substations have been discussed. The character of PD and its potential to produce high frequency radiation within a substation environment has been summarised and the important electrical parameters of WLAN technology have been reviewed. The laboratory tests which excludes all external RFI/EMI and which includes controlled impulsive noise for assessing WLAN 802.11 b/g performance have been reported. A field trial to determine the practical performance of WLAN technology operating in the severe electromagnetic environment of a 400 kV AIS will be deployed in short future.

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REFERENCES

[1] "Definition, Specification , and Analysis of Systems Used for Supervisory Control, Data Acquisition, and Automatic Control," in *IEEE Standard C37.1*, 1994.

[2] "Communications Networks and Systems in Substations-Part1: Introduction and overview," in *IEC Standard 61850-1*, 2003.

[3] R. Ehlers, "Using UCA to integrate and deliver diagnostic data from substation," in *12th substation equipment diagnostics conference* New Orleans, USA, 2004.

[4] H. Sedding, S. Bomben, S. Rizzeto, and R. Densley, "Assessment of station cable condition using wireless telemetry and diagnostic tests.

[5] P. Duggan, P. DilLilo, P. DiScala, R. Schwabe, J. Braun, N. Fujimoto, and S. Rizzetto, "Field experience with live wireless telemetry sensors on power equipment operating to 345kV," in *12th substation equipment diagnostics conference* New Orleans, USA, 2004.

[6] "Radio noise," in *ITU-R Recommendation*, 2003, pp. 372-378.

[7] B. Smith, C. McClure, and R. Ehlers, "Integrating UCA at the TVA/Tiptonville switching station for SCADA and relay protection applications," in *12th substation equipment diagnostics conference* New Orleans, USA, 2004.

[8] I. A. Glover, Q. Shan, P. J. Mooore, I. E. Portugues, and R. J. Watson "An investigation into the vulnerability of WLAN and WPAN technologies to impulsive noise in electricity transmission substations," in *Ninth International Symposium on Communication Theory and Applications ISCTA'07*, Ambleside, Lake District, UK, 2007.

[9] M. D. Judd, O. Farish, J. S. Pearson, and B. F. Hampton, "Dielectric windows for UHF partial discharge detection," *Dielectrics and Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on],* vol. 8, pp. 953-958, 2001.

[10] C. Chang, C. S. Chang, J. Jin, T. Hoshino, M. Hanai, and N. Kobayashi, "Source classification of partial discharge for gas insulated substation using waveshape pattern recognition," *Dielectrics and Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on],* vol. 12, pp. 374-386, 2005.

[11] H. Imagawa, K. Emoto, H. Murase, H. Koyama, R. Tsuge, S. Maruyama, and T. Sakakibara, "PD signal propagation characteristics in GIS and its location system by frequency components comparison," *Power Delivery, IEEE Transactions on,* vol. 16, pp. 564-570, 2001.

[12] T. Sakakibara, H. Murase, E. Haginomori, S. Wakabayashi, K. Emoto, and A. Ogawa, "Study of propagation phenomena of partial discharge pulses in gas insulated substation," *Power Delivery, IEEE Transactions on,* vol. 13, pp. 768-776, 1998.

[13] T. Hoshino, K. Kato, N. Hayakawa, and H. Okuno, "Frequency characteristics of electromagnetic wave radiated from GIS apertures," *Power Delivery, IEEE Transactions on,* vol. 16, pp. 552-557, 2001.

[14] P. J. Moore, I. E. Portugues, and I. A. Glover, "Radiometric location of partial discharge sources on energized high-Voltage plant," *Power Delivery, IEEE Transactions on,* vol. 20, pp. 2264-2272, 2005.

[15] M. Hikita, H. Yamashita, T. Hoshino, T. Kato, N. Hayakawa, T. Ueda, and H. Okubo, "Electromagnetic noise spectrum caused by partial discharge in air at high voltage substations," *Power Delivery, IEEE Transactions on,* vol. 13, pp. 434-439, 1998.

[16] A. Athanasopoulos, E. Topalis, C. Antonopoulos, and S. A. K. S. Koubias, "Evaluation Analysis of the Performance of IEEE 802.11b and IEEE 802.11g Standards," in *Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies, 2006. ICN/ICONS/MCL 2006. International Conference on*, 2006, pp. 141-141.

[17] K. Shuaib, M. Boulmalf, F. Sallabi, and A. A. L. A. Lakas, "Co-existence of Zigbee and WLAN, A Performance Study," in *Wireless Telecommunications Symposium, 2006. WTS '06*, 2006, pp. 1-6.

[18] A. K. Arumugam, A. Doufexi, A. R. Nix, and P. N. A. F. P. N. Fletcher, "An investigation of the coexistence of 802.11g WLAN and high data rate Bluetooth enabled consumer electronic devices in indoor home and office environments," *Consumer Electronics, IEEE Transactions on,* vol. 49, pp. 587-596, 2003.

[19] J. Jung-Hyuck and H. Jayant, "Performance evaluation of multiple IEEE 802.11b WLAN stations in the presence of Bluetooth radio interference," in *Communications, 2003. ICC '03. IEEE International Conference on*, 2003, pp. 1163-1168 vol.2.

[20] F. Wang, A. Nallanathan, and G. H. Krishna, "Performance of physical (PHY) and medium access control (MAC) layers of IEEE 802.11b in the presence of Bluetooth piconets," in *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual*, 2003, pp. 1489-1492 vol.2.

[21] J. P. Singh, N. Bambos, B. Srinivasan, and D. A. C. D. Clawin, "Wireless LAN performance under varied stress conditions in vehicular traffic scenarios," in *Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall. 2002 IEEE 56th*, 2002, pp. 743-747 vol.2.

[22] D. K. Borah, A. Daga, G. R. Lovelace, and P. A. D. L. P. De Leon, "Performance evaluation of the IEEE 802.11a and b WLAN physical layer on the Martian surface," in *Aerospace Conference, 2005 IEEE*, 2005, pp. 1429-1437.

[23] Y. W. Chen, Y. X. Xia, F. Zhou, X. A. T. X. Tian, L. A. L. L. Liu, Y. A. Z. Y. Zhang, and P. C. A. W. P. C. Wu, "WLAN based integrated substation control system (WISCS)," in *Advances in Power System Control, Operation and Management, 2003. ASDCOM 2003. Sixth International Conference on (Conf. Publ. No. 497)*, 2003, pp. 215-223.

[24] CSR, “Data sheet for UF1050B-IC-E”, Issue 1, 25 Jan 2008.

[25] Shan Q., Glover I. A., Moore P. J., Portugues I. E. and Watson R. J., (2007). Performance of ZigBee in electricity supply substations, IEEE WICOM 2007, 21-25 Sept 2007, Vol 1, pp 3871--387.