Industrial Wireless Sensor Networks (ISWN): Requirements and Solutions

Abdullah Al-Yami, Wajih Abu-Al-Saud, Kamal Harb, and Baqer Al-Ramadan
abdullah.yami.22@aramco.com, kharb@uohb.edu.sa, {Wajih, Bramadan}@kfupm.edu.sa
KFUPM, Dhahran, Saudi Arabia

***Abstract*—Industrial Wireless Sensor Networks (IWSN) are preferred over bulky wired networks in industrial monitoring and automation. These sensors are used to access locations, which are technically unreachable. The use of IWSN not only reduced the cost of automation systems but also played a significant role in alarm management by real time data transfer. ZigBee and WirelessHART are already deployed protocols for IWSN. ISA100.11a developed by International Society of Automation was specially designed for IWSN. The main features of this standard are low power consumption, real time fast data transfer, scalability, security, reliability, co-existence with other network architectures and robustness in harsh industrial environments. To achieve these features, these protocols use layer structure, which provides security, fast and reliable data transfer. IEEE 802.15.4 is used at its physical layer with variable data slots. This paper presents the results of the simulation of ISA100 done on Pymote framework which is extended by one of the authors. A test bed is implemented in the lab using the Yokogawa field devices. This paper discusses the simulated and practical results obtained from operation of ISA100.11a.**

Keywords—ISA100.11a; Yokogwa field wireless deivces; Industrial wirelsless sensor networks; IWSN; OMNET++;

I. INTRODUCTION

Wireless Sensor Networks (WSN) [1][2] are small sensors that are deployed in remote locations to sense particular conditions and send information pertaining to these conditions to a Central Control Room (CCR). WSN are ad hoc in nature and their number is often large. They work with limited resources and are usually non replaceable. WSN have endless applications; it can be used in defense to monitor borders. They are also used by environmentalists to monitor environmental changes such as temperature and humidity in certain regions. For industries, WSNs can sense temperature, pressure, etc. of certain devices. WSN have certain limitations such as low range, small battery size, and non-reusable structure which require a very resource efficient algorithm. Industrial Wireless Sensor Network (IWSN) evolved from WSN and are specially designed keeping in mind the demands and nature of industry [1]-[4].

IWSNs use replaceable batteries and generally have wider range than WSNs. IWSNs have an edge over traditional wired structures since they can be installed easily anywhere in industry without heavy support structures. IWSNs can also work efficiently where wired networks are technically not installable such as on moving or rotating objects.

Another important industrial requirement is the stability of the system. The system should be stable and easy to handle and maintain [5]. Also, deployed networks should be reliable and secure with high data rate support. Many protocols are developed that support the above functionalities. Zigbee is a wireless open global standard which satisfies the unique needs of low power, low cost and wireless mobile-to-mobile (M2M) networking. It is also used in IWSNs [6]. Zigbee is standardized by Zigbee alliance which consists of more than 300 companies. It can support star, mesh and tree topologies [7][8].

Another developed protocol is Highway Addressable Remote Transducer Protocol commonly known as WirelessHART and approved by International Electrotechnical Commission (IEC). WirelessHART is simple, secure, reliable, and uses TDMA with mesh topology. HART, like OSI model, uses many layers that add to security, integrity and reliability of the system [9]. The power consumption of HART is low compared to Zigbee with high security standard.

ISA100, designed by International Society of Automation, supports high data rates up to 250 Kbps. Security and Integrity is provided by layered architecture. 6LoWPAN, used in network layer, provides efficient routing and also enables IWSN to co-exist with other IWSN protocols. At the level of Physical Layer, IEEE 802.1.5.4 is used, which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) [4][10][11]. ISA works on 2.4 GHz free band with 16 channels. Transmitter complexity is significantly decreased by using Orthogonal Quadrature Phase Shift Keying (O-QPSK), which avoids the zero state and thus has a constant envelope transmission [12][13].

ISA100 uses the following layers to optimize performance:

1. A graphical user interface at its application layer.
2. For fast and reliable data transfer, UDP is used at the transport layer.
3. At the network layer, IPV6 over Low power Wireless Personal Area Network (6LoWPAN) which can work with other networks.
4. At the data link layer, variable slot scheme is used.
5. IEEE 802.15.4 is used at the physical layer, which is spectrally efficient and minimizes collisions between the adjacent nodes.

IWSN protocols usually use two type of devices to send data to CCR.

1) Field devices whose prime function is to sense the data and transmit it.

2) Gateway devices are responsible for receiving data and providing reliable transmission to CCR. Field devices can also reroute the packet to gateway devices. Far end devices usually transfer data over more than one hop.

TABLE I. ZIGBEE TEST OUTPUT FOR HUMIDITY AND TEMPERATURE.

Device	09:00 AM	10:00 AM	11:00 AM	12:00 PM	01:00 PM	02:00 PM	03:00 PM
2091	6302.2	6610.5	6785.4	7583.3	8714.4	9341.3	8184.7
2094	6328.1	6590.7	6767.0	6910.9	6974.3	7000.3	8126.4
2103	6346.5	6628.2	6835.1	7902.9	8350.3	9231.3	8135.6
2105	6324.3	6514.1	6738.8	6898.2	7324.0	7480.0	7411.3
2107	6335.0	6635.3	6824.5	7612.7	8846.6	9494.0	7964.1

This paper provides a lab test evaluation of both indoor and outdoor Zigbee, WirelessHART and ISA100-based systems. The kit presented in Figure 1 is used for Zigbee testing. Zigbee tests are performed on Memsic WSN kits. The topologies and results are compared. The remaining part of the paper simulates the ISA100 on Pymote, which is a Python based framework for WSN simulation and was extended to support our simulation.

This paper is described in four sections. Section II describes the lab test by using Zigbee and WilessHart protocol. Section III presents ISA100 simulation. The purpose of the ISA100 is to find the appropriate range and terrain of the IWSN. It also describes different methods related to wireless communications. Discussion and results are also presented. Finally, we conclude this study in Section IV.

II. LAB TEST

A. *Zigbee Test*

Zigbee is currently the oldest and most widely used WSN protocol. Many vendors provide Zigbee-based products [7]. Memsic Inc. is one such manufacturer, whose devices can be used for conducting outdoor tests. These devices are able to sense voltage, humidity, temperature and pressure in a particular location. Their WSN kit provides an end-to-end enabling platform for the creation of wireless sensor networks. A windows application called MoteView is provided as an interface between a user and the deployed sensor network. MoteView also provides the tools to simplify deployment and monitoring. It also makes it easy to connect to a database, to analyze, and to graph sensor readings. It also provides node health statistics in terms of transmission quality, number of drop packets, retries, etc.

The topology for our experiment is shown in Figure 1. Devices numbered 2091, 2094, 2103, 2105, 2107 as presented in TABLE I. act as sensor devices which sense the above mentioned parameters and send them to gateway device GW.

Upon receiving the data, the GW displays the transmitted values in a GUI and alarms are raised if some parameter makes an abrupt change. For illustration, one of the collected parameters containing humidity and temperature (Humtemp) is shown in TABLE I.

At the start of the test, packets started flowing from sensor devices to the gateway device at regular intervals. TABLE I. shows the Humtemp data received from sensor devices averaged over an hour.

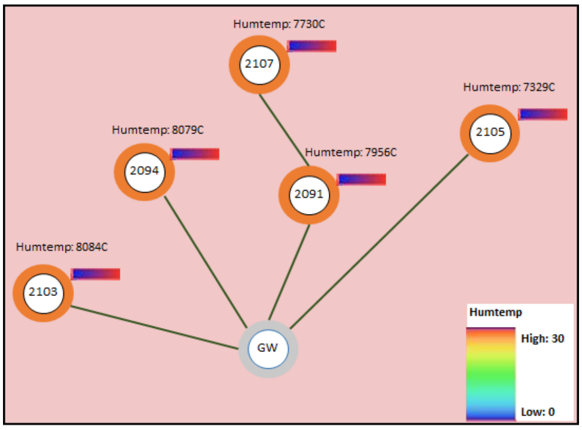

Figure 1. Topology for humidity/temperature measurements.

B. *WirelessHART Test*

Another industrial protocol is WirelessHART, which can coexist with other networks. This test is performed on Emerson devices, which use HART as shown in 0. Like other devices, the kit composes of sensor and gateway devices, where the used topology is shown in Figure 2, which serve to collect and transfer data.

The HART uses mesh protocol and when the setup is turned on, each device is connected to every other device in its range. The link configuration and stability according to the device tags is shown in Figure 2, which explains the link of gateway with the sensor nodes. It also shows the number of neighbor sensors against every device as well. The reliability of the link and Received Signal Strength Intensity (RSSI) is also depicted.

C. *ISA100 Test*

The purpose of this experiment is to find the appropriate range and terrain of the IWSN. Instruments used for testing are the Yokogawa wireless kit shown in Figure 3, which consist of field and gateway devices. If the path stability or reliability decreases as a result of any environmental change, the device will try to switch to an alternative path.

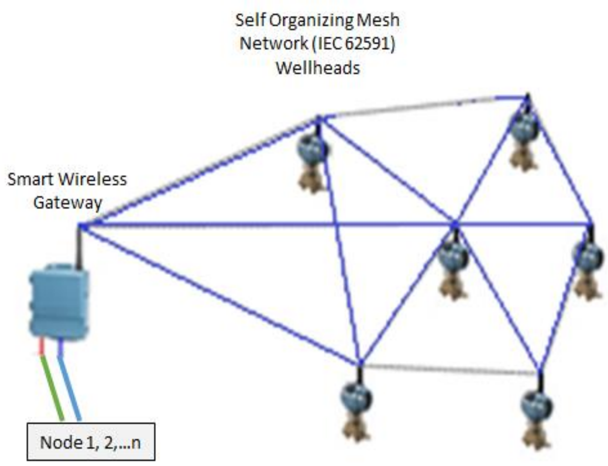

Figure 2. Wireless HART test topology.

TABLE II. GUI APPLICATION OF HART TEST.

HART Tag	Node state	Active neighbors	Neighbors	Service Denied	Reliability	Missed Updates	Path Stability	RSSI	Joins	Join Time
385PT0026A	●	SFNY 385PT0701B 385PT0211B 385PT0501B	4	●	100.0%	0	100.0%	-49 dB	1	11/24/11 23:21:44
385PT0211B	●	SFNY 385PTT0806 385PT0026A 385PT0501B	4	●	100.0%	0	100.0%	-44 dB	1	11/24/11 23:21:26
385PT0501B	●	SFNY 385PT0211B 385PT0026A	3	●	100.0%	0	100.0%	-57 dB	1	11/24/11 23:20:35
385PT0701B	●	SFNY 385PT0026A	2	●	100.0%	0	100.0%	-49 dB	1	11/24/11 23:21:50
385PT0806	●	SFNY 385PT0211B 385PT0807	3	●	100.0%	0	100.0%	-44 dB	1	11/24/11 23:21:02
385TT0807	●	SFNY 385PTT0806	2	●	100.0%	0	100.0%	-60 dB	1	11/24/11 23:21:08

Figure 3. Yokogawa field device kit.

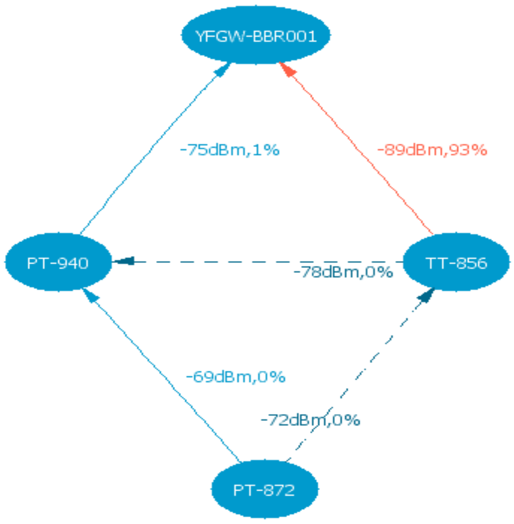

Figure 4. ISA100 test for irregular surface.

The test was performed in two terrains, namely Plane ground and Rough ground (in which there are buildings and structures separating the field device from the gateway device). Two different environments are chosen so as to find the attenuation and signal degradation in the two surface cases.

These experiments were conducted at King Fahad University of Petroleum and Minerals (KFUPM) in an outdoor environment. Figure 3 shows the real test on rough ground. Topologies used for this experiment for the irregular and regular surfaces are shown in Figure 4 and

Figure 5, respectively. A temperature sensor and two pressure sensors are used to sense the data and transfer it to the gateway device. TABLE III. shows the device type and tags used.

ISA100 takes into account the direct communication node and neighboring node for data transfer and in case if one node goes down it can automatically switch to another route based on the Packet Error Rate (PER) and RSSI. In the two topologies, we have seen that the sensor devices are connected to the gateway device directly or indirectly.

There are two kinds of connections shown in the topologies. Solid lines are actual communication routing between the device and gateway. In Figure 4, the device TT-856 was experiencing a higher PER while communicating to gateway device. Dotted lines are alternate routes, which are used in case of fault or errors. For each link, the RSSI and PER as a percentage are indicated.

 ISBN: 978-1-61208-453-4

TABLE III. ISA100 DEVICE TAGS AND TYPES.

Device TAG	Functionality	Type
PT-872	IO Device +Router	Pressure Sensor
PT-940	IO Device +Router	Pressure Sensor
TT-856	IO Device +Router	Temperature Sensor
YFGW-BBR001	Gateway Device	Gateway Device

TABLE IV. NETWORK STATISTICS COLLECTED FROM ISA TEST.

Device TAG	Average Distance		Average RSSI (dBm)		Average PER (%) and Hop count	
	Flat Terrain	Rough Terrain	Flat Terrain	Rough Terrain	Flat Terrain	Rough Terrain
PT-872	600 m	1000 m	-73	-69	0 / 1	0 / 2
PT-940	600 m	1000 m	-76	-75	0 / 1	1 /1
TT-856	600 m	1000 m	-81	**-89**	0 / 1	**93 / 1**
				-75		**0.63 / 2**

As the direct link was noisy, so the data was transmitted by alternate route. A detailed statistics after collecting data from the two terrains is clearly shown in TABLE IV. . Here, we can see the low RSSI and high PER being highlighted.

D. Discussion

In the lab test, protocols stack that are available in the market are tested. Zigbee is the earliest with simple protocol set. HART and ISA100 are developed later with high data rate, efficiency and reliability. Zigbee application does not show the network related stats but depicts a clear picture of the parameters. HART on the other hand has support to the other networks and it can also show the clear picture of network elements in GUI. ISA100 significantly shows good results in different terrains. These lab tests help in understanding the difference in protocols and application level support provided by the vendors in industry.

III. ISA100 SIMULATION

Simulation has always been very popular among network-related research. Several simulators have been developed to implement and study algorithms for wireless networks. Some are general purpose while others are design for specific purpose and vary in features and the level of complexity. They support certain hardware and communication layers assumptions, and provide set of tools for deployment scenarios, modeling, analysis, and visualization. Classical simulation tools include NS-2/3, OPNET, OMNeT++, J-Sim, and TOSSIM [14][15][16].

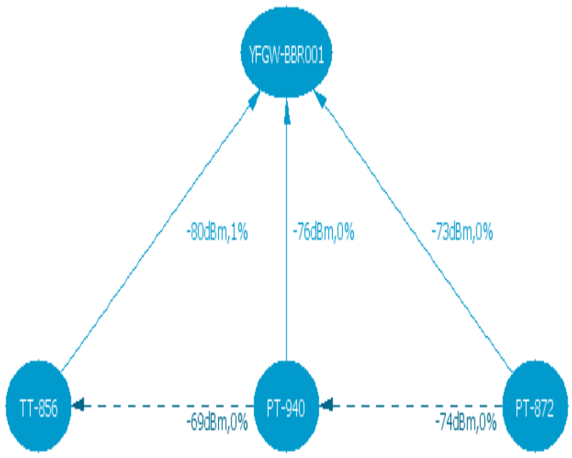

Figure 5. ISA 100 test for plane surface.

After some research, we concluded that Python-based tools completely fulfill our requirements. We decided to use Pymote, which is a high level Python library specifically designed for wireless networks to perform event based simulation of distributed algorithms [17][18]. The user can implement their ideas in Python; which has become popular in academia and industry. The library is developed without much abstraction and therefore can be used or extended using Python's highly expressive native syntax. The library particularly focuses on fast and accurate implementation of ideas at algorithm level using formally defined distributed computing environment.

A. The Simulation

The base station is placed in middle of n randomly deployed EHWSN nodes over a 600 m by 600 m area. We consider registration and data packet sizes of 100 bytes while the acknowledgment packet size of 15 bytes. Some other parameters are shown in TABLE V. 5.

A simple topology generated for simulation using the Pymote is shown in Figure 6. The center node (#1) acts as the base station for the other nodes (numbered 2 to 11). First, we evaluate the performance by changing the number of nodes (from 5 to 50). In this simulation, we kept the fixed data rate of one message every 5 seconds. Secondly, we vary the data rate from one message every 5 seconds to a message every second and keep the number of nodes fixed at 10.

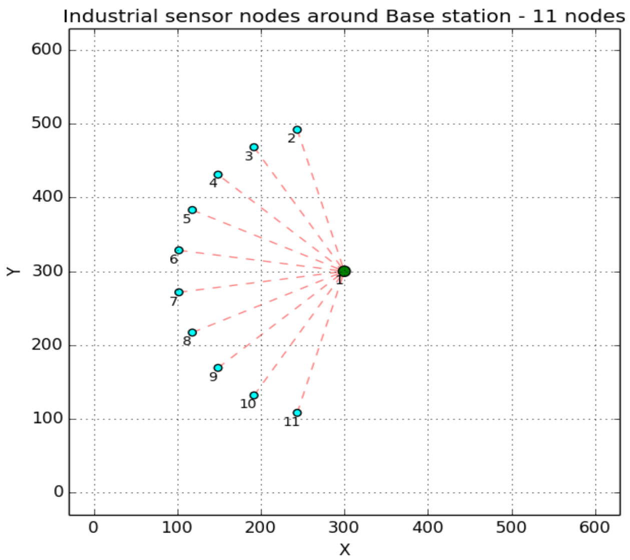

Figure 6. Topology with 10 nodes.

TABLE V. Simulation parameters.

Parameter	Name	Value
Min. Received signal power threshold	P_RX_THRESHOLD	-70 dbm
Frequency	FREQ	2.4 Ghz
n	No. of nodes	5 - 50
S_d	Data packet size	100 bytes
S_a	Ack packet size	15 bytes

Energy consumption for all nodes combined, and base station (in mJoules). The results for simulation run for 5 to 45 nodes (with increment of 5) is shown in Figure 7. Count of received packet and lost packets at the base station are also shown in the same figure.

For the following simulation, the number of nodes are kept fixed at 10 and monitor the link quality index (LQI) and RSSI of received signal at the base station when nodes were sending data at variable rate. The SNR levels are shown in Figure 8. The simulation results are comparable with the experimental results in terms of PER and RSSI.

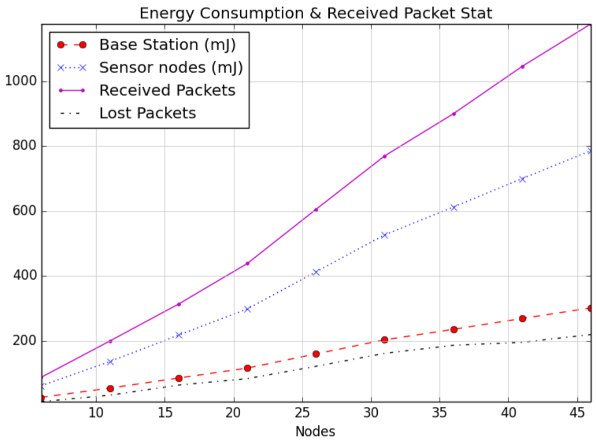

Figure 7. Energy consumption and stats at base station.

IV. CONCLUSION

In this paper, we have studied and conducted the lab test of Zigbee, Wireless HART and ISA100. The results are compared and analyzed in order to evaluate the best protocol for IWSNs. ISA100 was also simulated using the Pymote framework Based on the studies it can be concluded that ISA100 is better than HART and far better than Zigbee protocol. ISA100 uses CSMA-CA with OQPSK, which make it efficient at its physical layer. For routing, IPV6 helps ISA100 to coexist with any other legacy network. IPV6 also helps to carry traffic over a network without any routing gateway support. The Yokogawa field wireless kit offers a far better range that is greater than 800 meters, which is suitable for bigger industries and cuts the cost of additional gateway devices used to connect all the edges in a factory. The results of the simulation of ISA100 done on Pymote framework are comparable with the experimental results.

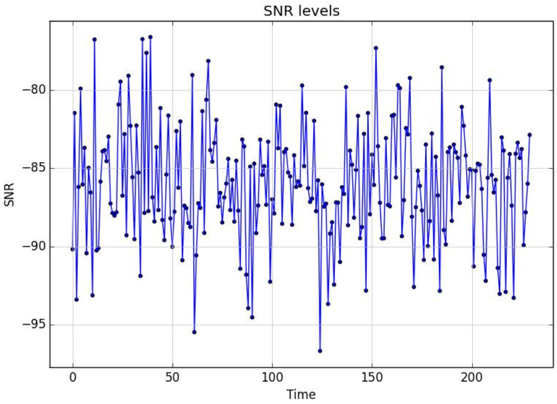

Figure 8. SNR of received signal at base station.

ACKNOWLEDGMENT

The authors wish to thank the management of Saudi Aramco for supporting this research and for facilitating the logistics needed for installing IWSN system and collecting data. In addition, the experiment was made possible by the support of Yokogawa and Emerson who supplied the gateway and field devices.

REFERENCES

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," IEEE Communications Magazine, Aug. 2002, vol. 40, no. 8, pp. 102–114.

[2] A. Al-Yami, K. Harb, and S. H. Abdul-Jauwad, "Industrial Wireless Sensor Networks in the Perspective of Diversity and Spectral Efficiency," Proc. of the IEEE 11th Malaysia International Conference on Communication (MICC 2013), Malaysia, Kuala Lumpur, Nov. 2013, pp. 390–395.

[3] M.-S. Pan and Y.-C. Tseng, "Communication Protocols and Applications for Zigbee-Based Wireless Sensor Networks," Taiwan-French Conference on Information Technology, March 2006, pp. 1–8.

[4] A. Al-Yami and W. Abu-Al-Saud, "Practical vs. Simulated Results of ISA100 Physical Layer," Proc. of the IEEE Sixth International Conference on Intelligent Systems, Modelling and Simulation, Malaysia, Feb. 2015, pp. 226–230.

[5] A. Willig, K. Matheus, and A. Wolisz, "Wireless Technology in Industrial Networks," Proceedings IEEE, June 2005, Vol. 93, no. 6, pp. 1130–1151.

[6] J. Song, S. Han, A. K. Mok, D. Chen, M. Lucas, and M. Nixon, "WirelessHART: Applying Wireless Technology in Real-Time Industrial Process Control," Real-Time and Embedded Technology and Applications Symposium (RTAS) IEEE, April 2008, pp. 377–386.

[7] Zigbee alliance, "ZigBee: The Open, Global Wireless Standard for Connecting Everyday Devices," Website: http://zigbee.org, last accessed date Oct. 2015.

[8] J. P. Thomese, "Fieldbus Technology in Industrial Automation," proceedings of the IEEE, June 2005, Vol. 93, no. 6, pp. 1073–1101.

[9] P. Ferrari, A. Flammini, S. Rinaldi, and E. Sisinni, "Performance assessment of a WirelessHART network in a real-world testbed," IEEE International in Instrumentation and Measurement Technology Conference (MTC), May 2012, pp. 953–957.

[10] N. Q. Dinh, K. Sung-Wook, and K. Dong-Sung, "Performance evaluation of priority CSMA-CA mechanism on ISA100.11a wireless network," Computer Standards & Interfaces, Elsevier, Jan. 2012, vol. 34, no. 1, pp. 117–123.

[11] P. Park, P. D. Marco, P. Soldati, C. Fischione, and K. H. Johansson, "A Generalized Markov Chain Model for Effective Analysis of Slotted IEEE 802.15.4," Mobile Adhoc and Sensor Systems, IEEE 6th International Conference, Macau, Oct. 2009, pp. 130–139.

[12] M. Nixon, “A Comparison of WirelessHART and ISA100.11a,” Whitepaper, Emerson Process Management, July 2012, pp. 1–36.

[13] ISA100 Wireless Compliance Institute, “Isa100 wireless systems for automation,” Website: https://www.isa.org/isa100/, last accessed date Sept. 2015.

[14] A. Sobeih, W. Chen, J. Hou, and L. Kung, “J-sim: A simulation environment for wireless sensor networks,” in Proceedings of the 38th annual Symposium on Simulation. IEEE Computer Society Washington, DC, USA, 2005, pp. 175–187.

[15] Q. Ali, A. Abdulmaojod, and H. Ahmed, “Simulation & Performance Study of Wireless Sensor Network (WSN) Using MATLAB,” 1st International Conference on Energy, Power and Control (EPC-IQ), Nov. 2010, pp. 307–314.

[16] I. A. Qutaiba (2012), Simulation Framework of Wireless Sensor Network (WSN) Using MATLAB/SIMULINK Software, MATLAB - A Fundamental Tool for Scientific Computing and Engineering Applications - Volume 2, Prof. Vasilios Katsikis (Ed.), ISBN: 978-953-51-0751-4, InTech, DOI: 10.5772/46467. Available from: http://www.intechopen.com/books/matlab-a-fundamental-tool-for-scientific-computing-and-engineering-applications-volume-3, last accessed date Oct. 2015.

[17] Y. Tselishchev, A. Boulis, and L. Libman, “Experiences and Lessons from Implementing a Wireless Sensor Network MAC Protocol in the Castalia Simulator,” Wireless Communications and Networking Conference (WCNC), 2010 IEEE, April 2010, vol. 1, no. 6, doi: 10.1109/WCNC.2010.5506096, pp. 18–21.

[18] D. Arbula and K. Lenac, “Pymote: High Level Python Library for Event-Based Simulation and Evaluation of Distributed Algorithms,” International Journal of Distributed Sensor Networks, Dec. 2012, vol. 2013, pp. 1-12.