International Journal of Latest Trends in Engineering and Technology
Vol.(10)Issue(1), pp.359-365
DOI: http://dx.doi.org/10.21172/1.101.65
e-ISSN:2278-621X

IEEE 802.15.4: A BASE FOR SEVERAL WIRELESS IOT NETWORK PROTOCOLS

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Abstract- IEEE 802.15.4 is an underlying standard for IoT protocols. The IoT network resides a huge number of low-power, low-cost devices that are able to connect to each other and can be managed through some kind of mass device management system. An essential aspect of the network is the way the devices communicate with each other. Standard IEEE 802.15.4 is for Low-Rate Wireless Personal Area Networks (LR-WPANs). It explains the PHY and MAC layers of LR-WPANs. Attempts have been done by the separate alliances of the companies to specify the upper layers of the network stack such as Z-Wave, ZigBee, Thread, Wireless HART, ISA 100.11a and 6LoWPAN whose Physical and Medium access control layer are predefined by the standard IEEE 802.15.4. Thus, an exhaustive research on the IEEE 802.15.4 was carried out and this paper contains the brief study of LR-WPANs, their PHY and MAC layers and their importance in IoT protocols. It also contains a review of some lacking features in this standard based protocols.
Keywords – IEEE 802.15.4, MAC, PHY, ZigBee, Z-wave, Thread, Wireless HART, 6LoWPAN, ISA 100.11a, LR-WPAN, IoT

1. INTRODUCTION

From the last few years, there is a rapid growth in wireless technologies that are connected to the internet. The IoT is a wireless technology that helps to connect everyone, anytime. Therefore, IoT communication protocols were developed for providing network communication. IEEE 802.15.4 is a well-defined standard that defines the working of "Low-Rate Wireless Personal Area Networks (LR-WPANs)" [24]. It is a low power, low cost, low data rate and easily enabled standard that's why it is used in IoT technologies. It enumerates the physical and medium access control layer for LR-WPANs. It is the base for the IoT protocols. IoT protocols such as ZigBee, Wireless HART, Z-Wave, ISA 100.11a and Thread specification further adds to the standard by evolving the upper layers. It can also be used with the 6LoWPAN technology. This 6LoWPAN technology is used to deliver the IPv6 over wireless personal area networks (WPANs) to define the upper layers. Therefore, this standard performs an important part in the wireless IoT networking protocols.

The rest of the paper is structured as follows. In section II, discuss the related work presented by the authors. In Section III, we give a brief study on IEEE 802.15.4 along with its architecture. Then, in section IV, discuss the various IoT protocols stack where IEEE 802.15.4 layers act as base layers for communication purpose. In section V, we discuss the research gaps in this standard based protocols and in section VI, we concluded the work.

2. RELATED WORK

There are several survey paper that handles different aspects of standardization in IoT. There are papers which discuss a specific layer of standardizations such as communication protocols. Examples of such surveys include a survey of IoT protocols where IEEE 802.15.4 is used as the base layer for providing a whole protocol stack. In [1], [4], [7] survey papers, the author discussed the standard IEEE 802.15.4, its feature and its architecture. In [2], [5], [6], [8], [9] the authors describe the ZigBee protocol along with its stack functioning. In [10], [11], [12] the authors discuss about the 6LoWPAN communication protocol. In [13], [14], [15], [16] the authors give full description on thread protocol. In [17], [18], [20] the authors describe the ISA 100.11a protocol. Moreover, they gave a comparative study on ISA100.11a and Wireless HART. In [19], [21] the authors describe Wireless HART protocol stack along with HART brief description. In [22], [23] there is an overview of a Z-Wave protocol.

3. IEEE 802.15.4 - A BRIEF STUDY

The aim of the standard is to specify a base format. The protocols which are able to adopt this standard specification can be added to this standard by the approach of forming the upper layers. ZigBee is the first well-known protocol that is closely conjoined with the IEEE 802.15.4 protocol. In fact, to specify a full protocol stack, the ZigBee Alliance works in collaboration with the "IEEE Task Group 4" [25]. The ZigBee protocol specifies its layers i.e. network and application layers

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leading above the standard's MAC and Physical layers. Standard IEEE 802.15.4 is devised for "low data rate, low cost and low power wireless personal area networks" [26]. The raw bit rate for 2.4GHz based DSSS PHY is 250kbps. Since this standard is used by IoT devices so not much data rate is required. The data rate is small, so the packet size is also small, maximum 128-byte packet format including 16 bit CRC. It uses 2.4GHz ISM band which is the same band as used by WIFI, Bluetooth etc. Channel access is via CSMA-CA using random backoff techniques i.e. after sensing the channel idle, the node firstly backoff for a random time and then transmits and if the channel is sensed non-idle, then back off a number of backoff periods in "ms". The MAC frame formats used by the IEEE 802.15.4 are Data, Acknowledgement, MAC Command and Beacon frame.

It consists of one PHY layer and one MAC layer. IEEE 802.15.4 presents a flexible MAC protocol. According to the characteristics of different applications, this highly flexible protocol serves good efficiency for data transmission.

It consists of two types of functional devices that are "full function device" (FFD) and "reduced function device" (RFD). FFD plays a role as PAN coordinator, RFD receiver/transmitter. Whereas, RFD act only as a device receiver/transmitter. These devices also function in these two topologies which are "star and peer to peer", as per the application requirement. The table 1 below shows the general characteristic of the IEEE 802.15.4 standard.

Table 1. IEEE 802.15.4 FEATURES

Characteristics	IEEE 802.15.4
Frequency band	868MHz/915MHz (Europe/America) and 2.4 GHz (worldwide)
Range	10-20 m
Data rate	868MHz:20kbps, 915MHz:40kbps, 2.4 GHz:250kbps
Latency	below 15 ms
Number of channels	868MHz:1, 915MHz:10, 2.4 GHz:16
Channel Bandwidth	868MHz:600KHz, 915MHz:2MHz, 2.4 GHz:5MHz
Channel access	CSMA-CA
Network devices	FFD and RFD
Topologies	Star, peer to peer topology
Architecture	consists of physical layer as well as MAC layer
forms of communication	Broadcast and Unicast
Addressing	64 bit extended, 16-bit short address

4. ARCHITECTURE

In order to simplify the standard, the architecture of IEEE 802.15.4 is specified in a number of blocks called as layers. Each layer responsibility is to provide services to the higher layers. Figure 1 shows the IEEE 802.15.4 protocol stack.

The next higher layers shown in Figure1, consist of two layers. One of them is a network layer and the other is an application layer. The functioning of the network layer is to provide network security, network configuration, message routing, authenticity and confidentiality of a transmission. An application layer works are to send messages between certain devices, reassembles packets, manage group addresses and also transports data. These layers are not specified, outside the scope of this standard.

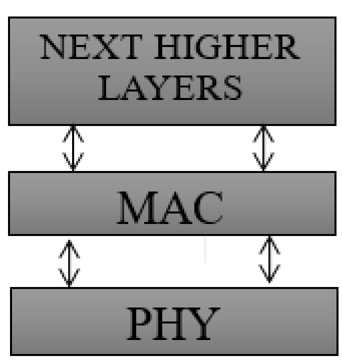

Fig. 1. IEEE 802.15.4 protocol stack

4.1 Physical layer
The standard describes an RF-based Phase-Shift-Key transceiver in a physical layer which is competent of transmitting the data up to 250 kilobits per second (kbps) in the air. Transceiver utilizes a subset of 27 available channels in particular band called ISM band (depending on the geographic region) as shown in table 2 [27]. With the use of Direct-Sequence Spread Spectrum, fading issues are controlled. The characteristics provided by PHY are activation and deactivation of the radio transceiver, transmitting as well as receiving packets across the physical medium, link quality indication (LQI), energy detection (ED), channel selection, clear channel assessment (CCA) [2].

Table 2. Frequency Ranges of IEEE 802.15.4

RF Band	Frequency Range	Data Rate	Channel number(s)	Geographical Area
868MHz	868.3MHz	20kbps	1 channel	Europe
915MHz	902-928MHz	40kbps	10 channels	America, Australia
2400MHz	2405-2480MHz	250kbps	16 channels	Worldwide

4.2 MAC layer
The layer on the top of physical layer in IEEE 802.15.4 stack is the MAC layer. It adds an interface between higher layers and the PHY layer. The MAC which provides an interface between PHY and upper layers manages the beacon i.e. it creates beacons when the device is a coordinator. It also synchronizes to other's beacons when the device is a coordinator. It also supports other features such as PAN association and disassociation, handles and maintains the GTS mechanism and manages the channel access. It enables the transmission of MAC frames with the use of a physical channel.

5. IEEE 802.15.4 BASED WIRELESS IoT PROTOCOL STACKS
This section introduces the IoT protocols such as ZigBee, Z-Wave, Thread, Wireless HART, ISA 100.11a and 6LoWPAN which corresponds to the IEEE 802.15.4 standard respectively. Standard specifies only "the physical (PHY) and medium access control (MAC) layers" in its network stack. For every above mentioned wireless IoT network protocol, companies' form a separate unit of members which collaborated to evolve the required specifications that include the network, transport, security and application layers so that the commercial importance of the protocols could be realized [28]. Therefore, the various wireless IoT protocol stacks are as follow:

5.1. ZigBee over IEEE 802.15.4
Open system interconnection (OSI) model is the basic model followed by every protocol for the formation of its architecture. Similarly, ZigBee follows OSI model to develop on IEEE 802.15.4 to form a whole network stack. IEEE 802.15.4 specifies the "physical and media access control layer" which are known as the base layers for ZigBee. The rest layers are network and application layer which are specified by the ZigBee Alliance. "Fig. 2," shows the protocol stack of ZigBee.

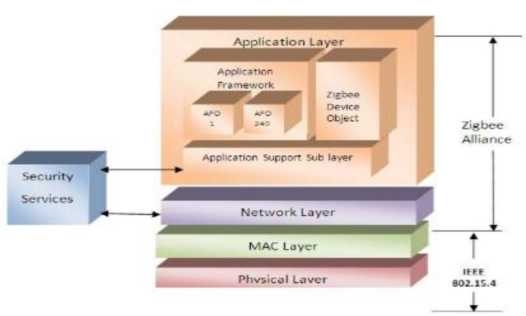

Fig. 2. ZigBee protocol stack [6]

The functioning of "physical and MAC layer" of IEEE 802.15.4 discussed in above section. The network layer provides a link between MAC Layer and application layer. Its functioning is to provide network routing, network formation, network configuration, network security, authenticity and confidentiality of a transmission and manipulation. This layer provides security as well as permits low power devices to improve their battery life extensions. Application Layer is the topmost layer of the protocol stack. It manages the application objects. This layer categorized into the Application Support, Application objects, and the ZigBee Device Objects sub-layers. The "Application support (APS) sub-layer" provides services which are necessary for application and ZigBee devices to link with the network layer through a basic set of services. "The application objects (APO)" work is to manage and control the layers in the stack [6]. The "ZigBee device object" is an effort to addresses the service discovery, binding and security operations.

5.2. 6LoWPAN over IEEE 802.15.4

6LoWPAN stack layers consist of 6 layers as shown in "Fig. 3". These layers are PHY layer, MAC layer, network layer (combination of adaptive layer and IPv6, RPL), transport layer and application layer. Fundamentally, 6LoWPAN stack implies the way to describe in what manner the IEEE 802.15.4 devices i.e. FFD/RFD communicate with each other over a wireless access medium. 6LoWAPN stack is based on IEEE standard 802.15.4 that efficiently describe "the physical and media access control (MAC) layers" as discussed in above section.

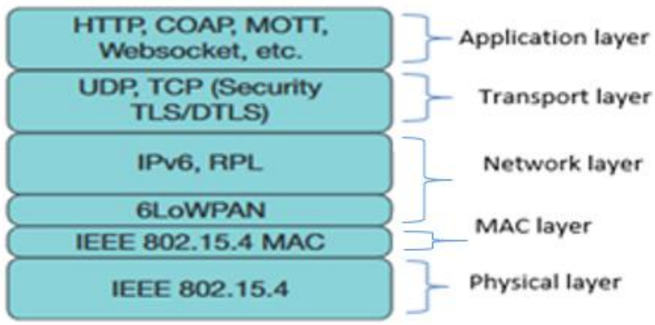

Fig.3. 6LoWPAN protocol stack

The adaptation layer in 6LoWPAN resides in the network layer also helps to provide an adaptation from IPv6 to IEEE 802.15.4. The network layer in 6LoWPAN adds the internetworking capability to nodes [11]. Forethought of this network layer is routing and addressing the data. Similarly, the transport layer is liable for transferring data from one to one process. The data is transfer to the "correct application process on the host computers by this layer" [10]. "User Datagram Protocol (UDP) and Transmission Control Protocol (TCP)" are the two types of transport protocols present in this layer. TCP is a connection-based protocol having a large overhead. Therefore it is not preferable for ultra-low power-demanding devices. For those devices, UDP can be a better option because it is a lower overhead and connectionless protocol. At last, the application layer responsibility is formatting the data. It also confirms that the data is carried in application-optimal schemes.

5.3. Thread over IEEE 802.15.4

Thread defines all the layers as OSI model defines but all of the layers in the thread protocol stack are pre-existing protocols. Thread specifies the way how the layers are combined together. IEEE 802.15.4 protocol is used at "the physical and MAC layer" of thread protocol stack, just like with ZigBee. A perfect combination of 6LoWPAN "IPv6 over Low power Wireless Personal Area Networks", IPv6 and UDP (User Datagram Protocol) are used at the network and transport layers of thread stack. IEEE 802.15.4 is a communication standard for low power wireless personal area networks is used as RF (Radio Frequency) connectivity protocol in Thread [14].

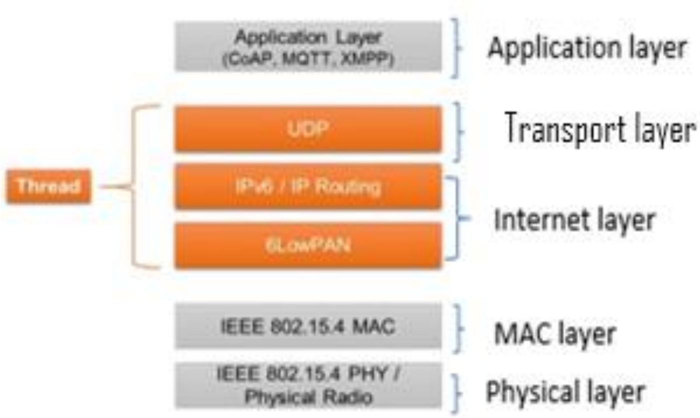

Fig.4. Thread protocol stack

Thread uses 6LoWPAN and IPv6 connectivity on the top of IEEE 802.15.4 layers. IPV6 functionality provides the devices to communicate with one another and also provide access to internet services. 6LoWPAN acknowledges the IPv6 packets to be transmitted and received over IEEE 802.15.4 based wireless networks [14]. In the thread protocol stack, 6LoWPAN lies on top of IEEE 802.15.4. It interprets two mechanism that are "encapsulation mechanism and header compression mechanism" for allowing IPv6 packets to transmit or receive. Header compression mechanism will compress the header in the packet before transmission whereas the encapsulation mechanism will secure the packet. The Thread stack handles messaging between devices using UDP (User Datagram Protocol). UDP lies above the 6LoWPAN in the protocol stack. UDP is preferred over TCP in IoT scenarios. At last, the application layer responsibility is formatting the data.

5.4. ISA 100.11a over IEEE 802.15.4

The ISA-100.11a protocol stack is as shown in "Fig. 5" and it developed with widely accepted and proven standards; for example, the mesh network is integrated to IPv6. This will allow the ISA-100.11a to provide highly scalable solutions. With the help of "IEEE 802.15.4 PHY and MAC layers" these IPv6 based mesh networks are formed. Not only mesh networks, it also provides support to other topologies such as Star topology. ISA100.11a protocol adds the upper layer as shown in "Fig. 5". These layers are ISA100.11a-upper data link layer, transport layer (combination of IPv6 and UDP) and application layer. Functioning of Upper data link layer is to provide a support for channel hopping, TDMA, and mesh routing. Transport layer functioning is to transmit IPv6 packets whereas the capability of application layer is to perform tunnelling and also allows users to maintain the compatibility with existing protocols that are presently in use in their plants.

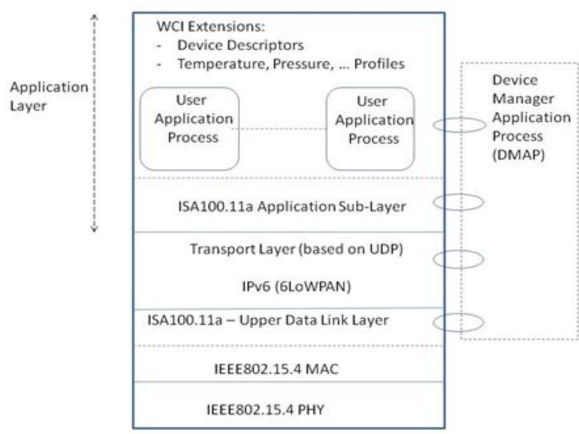

Fig.5. ISA 100.11a protocol stack [17]

5.5. Wireless HART over IEEE 802.15.4

The Wireless HART protocol stack is as shown in "Fig. 6". The working of the physical layer is same as the 2.4GHz DSSS IEEE 802.15.4 as discussed in above section. This layer specifies the signaling method, signal strength and device sensitivity properties of radio just like the IEEE 802.15.4. In MAC layer, Wireless HART specification includes the use of "time division multiple access (TDMA)" technology for collision-free communications and also use 10ms time slot in TDMA. The network layer provides routing and security facilities inside the network. In Wireless HART, within the wireless network, the movement of frames is between devices in the MAC layer, on the other hand, the movement of frames is between end-to-end devices in the network layer [20]. Other functions like timetables and route tables also possess in the network layer. Role of route tables in Wireless HART is to provide route communications along with graphs whereas the role of timetables is to assign bandwidth to particular services.

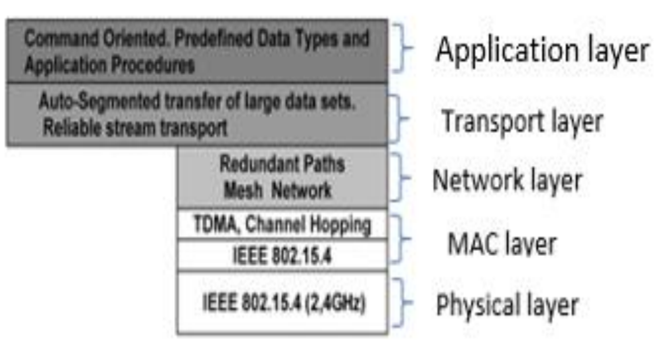

Fig.6. Wireless HART protocol stack

The Wireless HART transport layer functioning is to supports a reliable transport service which are provided to the application layer. When these services are selected by the application layer interface, the packets transmitted over the network are recognized by the end device so that started device can retransmit the lost packets [20]. In wireless HART, the uppermost layer is the application layer and its functioning is to extract the command from the transmitted message, then execute the command and at last generates the response. Its functioning is as same as HART functioning.

5.6. Z-Wave over IEEE 802.15.4

Just like an OSI model, Z-Wave protocol stack consists of 5 layers that are “PHY, MAC, transport, network and application layers” as shown in “Fig. 7”. The primary functions of these protocol layers are described in a manner. The “PHY layer and MAC layer” are based on the standard IEEE 802.15.4 as represented in “Fig. 7”. The working of the physical layer is just as IEEE 802.15.4. Its work is to take care of modulation and RF channel assignment. The MAC layer work is to control the medium between nodes. There is a CSMA mechanism which is used in MAC layer for controlling the channels. On the basis of collision avoidance algorithm and back off algorithm provided in CSMA mechanism can help the MAC to control the medium between nodes. Also, it takes care of Home ID and Node ID. The transport layer provides the function such as transmission and reception of frames, retransmission of frames if needed and provide cyclic redundancy checks. The network layer functioning is to provide frame routing, scanning topology and maintaining routing table [22]. The application layer provides the control of data in the frames. In Z-Wave protocol specifications, the security layer is not defined and hence its implementation specific.

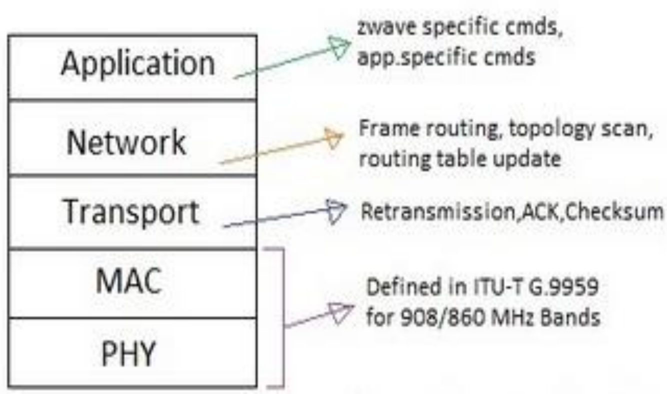

Fig.7. Z-Wave protocol stack [22]

6. RESEARCH GAP

The various research gaps that exist in these IoT protocols can be formulated as, firstly the IEEE 802.15.4 is simple, low-rate, low-power, low-cost and easily enabled wireless protocol. It describes the PHY and MAC layers only. The other layers are not specified by the standard. There are various IoT protocols whose networking stack involves the *IEEE* 802.15.4 layers as the base layers. Noticeable wireless IoT protocol stacks applying IEEE 802.15.4 involve ZigBee, Wireless HART, ISA100.11a, Thread, Z-Wave, and 6LoWPAN. The essential problem related with these protocols stacks is that these stacks don’t support internet protocol version 4 (IPv4). The reason behind this in-congeniality is that these all IoT protocols are low power and low data rate protocols which are not able to carry heavyweight IPv4 data. Secondly, the problem related with these IEEE 802.15.4 based protocols is that they don’t natively support multicast mode of communication.

7.CONCLUSION

This paper concluded that IEEE 802.15.4 has proven to be a suitable technology to be used in the Internet of Things. Its features such as less data transmitted, less complex modulation, less frame overhead and better power management mechanisms make it better suited for low-power networks. Therefore, several wireless IoT protocols such as ZigBee, ISA 100.11a, 6LoWPAN, Wireless HART, Z-Wave, and Thread uses IEEE 802.15.4 in their protocol stack for communication aspect. This paper also concluded that there is a gap exist in these IEEE 802.15.4 based wireless IoT protocols stack.

8. REFERENCES

[1] K. Devadiga, “IEEE 802.15.4 and the Internet of things,” Aalto University School of Science, pp. 1-4.
[2] S. C. Ergen, “ZigBee/IEEE 802.15.4 Summary,” pp. 1-37, September 10, 2004.
[3] T. Salman, “Internet of Things Protocols and Standards,” Recent Advances in Networking (Data Center Virtualization, SDN, Big Data, Internet of Things), 2015, pp. 1-28.
[4] 802.15.4-2003, IEEE standard, Wireless medium access control and physical layer specifications for low-rate wireless personal area networks, 2003.
[5] L. Pengfei, L. Jiakun, N. Luhua, and W. Bo, “Research and Application of ZigBee Protocol Stack,” International Conference on Measuring Technology and Mechatronics Automation, IEEE computer society, 2010, pp. 1031-1034.
[6] C. M. Ramya ; M. Shanmugaraj ; R. Prabakaran, “Study on ZigBee technology,” 3rd International Conference on Electronics Computer Technology (ICECT), IEEE, 2011 ,pp. 297-301.

[7] P. baronti, P. pillai, V.chook, S. chessa, A. gotta, and Y. fun hu, "Wireless sensor networks: a survey on the state of the art and the 802.15.4 and ZigBee standards," Computer Communications, Vol. 30, Issue 7, 26 May 2007, pp. 1655-1695.
[8] ZigBee Allianee.ZigBee Specification Document 053474r13.
[9] ZigBee Allianee.ZigBee Specification Document 053474r17.
[10] J. Olsson, "6LoWPAN demystified," Texas Instruments, pp. 1-13, October 2014.
[11] N. H. A. Ismail, R. Hassan, and K. W. M. Ghazali, "a study on protocol stack in 6LoWPAN model," Journal of Theoretical and Applied Information Technology, Vol. 41, No.2, pp. 220-229, 31st July 2012.
[12] C. S. Kushalnagar, N.G. Montenegro, "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals," 2007, pp. 1-13.
[13] D. Williams, "A Battle of IoT Protocols: ZigBee vs Thread," all about circuits, January 23, 2017.
[14] A. Chakrabarti, "Thread – An Open Standard Protocol for Home Automation," Nov 17, 2015.
[15] K. Strayer, "Can the "Gorilla" Deliver? Assessing the Security of Google's New "Thread" Internet of Things (IoT) Protocol," Advanced Network Intrusion Detection GIAC (GCIA), September 2017.
[16] "Thread Stack Fundamentals white paper," thread group, pp. 1-19, July 13, 2015.
[17] M. Taneja, "ISA100.11a Analysis," oneM2M partners, pp. 1-8, 22 November 2013.
[18] M. S. Costa and J. L. M. Amaral, "Analysis of wireless industrial automation standards: ISA-100.11a and WirelessHART," ISA, InTech Magazine, December 2012.
[19] G. Lohmann, "Technical white paper Wireless technology Wireless Hart," Pepperl+Fuchs, pp. 1-16, February 2011.
[20] M. Nixon, "A Comparison of WirelessHART™ and ISA100.11a," Final, pp. 1-39, September 23, 2012.
[21] D. Gustafsson, "WirelessHART- Implementation and Evaluation on Wireless Sensors," Stockholm, Sweden, pp. 1-51, April 2009.
[22] "z-wave protocol stack: z-wave protocol layer basics," RF wireless world.
[23] JFR, "Z-Wave Protocol Overview," Zensys, pp. 1-20, 24 April 2006.
[24] M. G. Gutierrez, "a VANETs routing protocol adaptation to WSN," embedded systems and wireless technology theory and practical applications, 2012.
[25] L. Xiaoyun, C.J. Bleakley, and W. Bobe, "enhanced beacon-enabled mode for improved IEEE 802.15.4 low data rate performance," wireless networks, Vol. 18, Issue 1, springer, pp 59–74, January 2012.
[26] S. Brienza, M. Roveri, D. Deguglielmo, and G. Anastasi, "just-in-time adaptive algorithm for optimal parameter setting in 802.15.4 WSNs," ACM transaction on autonomous and adaptive systems, 2016.
[27] J. T. Adams, "Wireless Sensors and Controls Make the Organic Building," Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, 2006.
[28] J. S. Lee, C. C. Chuang, and C. C. Shen, "Applications of Short-Range Wireless Technologies to Industrial Automation: A ZigBee Approach," Fifth Advanced International Conference on Telecommunications, IEEE, 2009.