2019 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress

The Implementation of Wireless Industrial Internet of Things (IIoT) Based upon IEEE 802.15.4-2015 TSCH Access Mode

Ho-Ting Wu, Kai-Wei Ke, Song-Ferng Wang, Po-Hung Chen, Guan-De Lee, Chen-Yu Tseng, Chen-Yu Ho
Dept. of Computer Science and Information Engineering, National Taipei University of Technology, Taiwan, R.O.C.

In this paper, we develop and implement key network technologies to build wireless IIoT architecture and communication protocol stacks based upon IEEE 802.15.4-2015 TSCH Access Mode. We design a delay-sensitive scheduling mechanism and a dynamic bandwidth allocation algorithm, which are not specified in the IEEE 802.15.4-2015 TSCH standard. Furthermore, fast network formation and maintenance mechanisms are also developed to enhance system performance. The network topology constructed and configured by embedded RPL routing strategy can be observed from the web UI. The packet transmission delay and packet delivery rate (PDR) performance are exhibited to validate the effectiveness of the implementation to achieve the QoS requirements of low delay, high reliability and low power consumption imposed by IIoT environment.

Keywords—Industrial Internet of Things (IIoT); IEEE 802.15.4-2015; Time Slotted Channel Hopping (TSCH); Scheduling algorithm; Packet delivery rate.

1. Introduction

With the advances of embedded system, communication technology and sensing devices, the wireless sensor network (WSN) has been extended to serve as the basic network architecture for the state-of-the-art wireless internet of things (IoT) system [1]. An IoT system often consists of a significant amount of low powered sensing nodes, which communicate with each other through low speed and unstable wireless communication links. In addition, an IoT system utilizes the simplified IPv6 packet format to accommodate the addressing requirements and to achieve energy efficiency. In order to apply the current WSN technology to wireless industrial internet of things (IIoT) architecture, it is noted that the wireless IIoT often experiences interference intensive and unreliable wireless communication channels caused by the heterogeneous wireless networking environments. Thus, its stringent QoS requirement of low powered, real-time, and highly reliable transmission cannot be realized easily by the off-the-shelf consumer-typed wireless IoT technologies. Therefore, distinguished communication protocol stacks and associated systems and mechanisms need to be designed to meet the desired network performance of wireless IIOT architecture.

The traditional IEEE 802.15.4 based technology such as Zigbee system has been employed widely and found commercial success in WSN application. However, such technology uses carrier sense multiple access (CSMA) MAC protocol to compete for access opportunities, which requires all sensor nodes to be active (system ON) all the time, leading to significant waste of energy consumption for battery operated senor nodes. Besides, such system typically uses the single communication channel to transmit and receive data, which may suffer heavy interference caused by other wireless sources using the same 2.4 GHz ISM frequency band. Therefore, significant packet loss rate may occur in such scenario. With these drawbacks, the traditional IEEE 802.15.4 technology cannot satisfy the requirements of high reliability and low-powered operation in IIoT applications. This had triggered the development of IEEE 802.15.4-2015 Time Slotted Channel Hopping (TSCH) access mode [2] in recent years. The time slotted mode operation enables the TDMA-like slotframe structure to achieve low delay performance along with the low powered benefits. The multiple communication channel hopping operation is effective in mitigating channel interference. Furthermore, to facilitate the wireless IIoT application, the IETF 6TiSCH working group [3] has proposed IPv6 based IIoT communication protocol stacks for low-powered and lossy networks (LLN) scenario. These protocol stacks include IEEE 802.15.4 TSCH access mode as its data link layer protocol, as shown in Fig. 1.

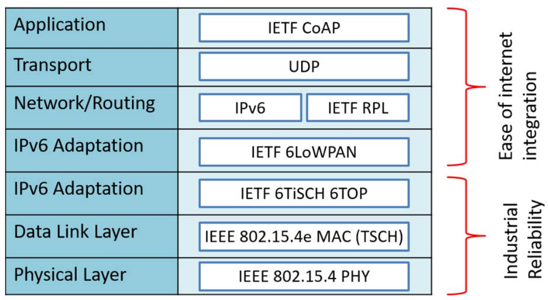

Fig. 1 IETF wireless IIOT Communication Protocol Stack

In this paper, we develop and implement key network technologies to build such wireless IIoT architecture and communication protocol stacks [4]. The system architecture is shown in Fig. 2. A remote internet user may use the Web UI to view the sensed data and the updated status of the sensor nodes. The network manager functions as the control center to establish and maintain the network topology. Based upon the network topology and traffic load, the network manager executes a scheduling algorithm to construct the scheduling table, from which it assigns each sensor node the specific slots and channels to transmit or receive packets accordingly. The scheduling table is sent downward toward sensor nodes via CoAP (Constrained Application Protocol) requested messages. Sensor nodes complete the assigned tasks and sends the sensed data using CoAP response message. To ensure the proper delivery of scheduling table, a scheduling inspection algorithm is also implemented in the network manager to verify the

This research is supported by Ministry of Science and Technology of Taiwan, R.O.C. with project number: MOST 107-2221-E-027-033-

978-1-7281-3024-8/19/$31.00 ©2019 IEEE
DOI 10.1109/DASC/PiCom/CBDCom/CyberSciTech.2019.00075

correctness of the delivery for preventing the scheduling error from packet loss.

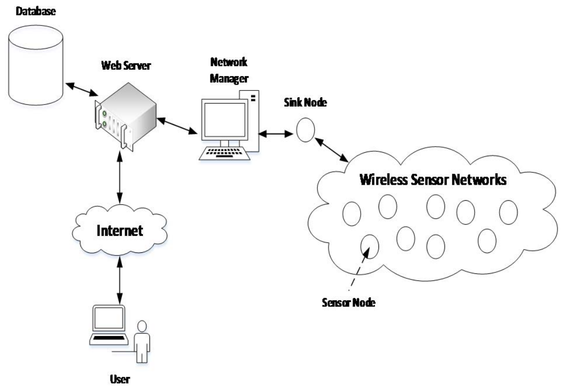

Fig.2 The system architecture of wireless IIoT system

The web UI shown in Fig. 3 depicts the network routing topology (left graph) constructed from RPL (IPv6 Routing Protocol for Low power and Lossy network) mechanism and the sensor node control panel (right graph) of this system.

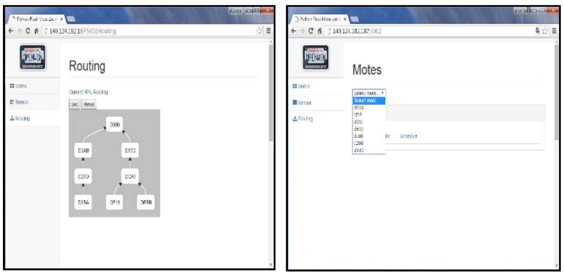

Fig. 3 The Web UI exhibiting the routing and control panel

In the IEEE 802.15.4-2015 standard, no specific scheduling mechanism is defined for the TSCH access mode [5]. Therefore, as previously mentioned, we have designed a centralized scheduling algorithm to realize the scheduling table and conduct its performance analysis. The schedule table instructs sensor nodes when to transmit or receive data/control packets on specific time slots (TS) and wireless channels. A delay-sensitive multi-channel TDMA scheduling mechanism using channel hopping technique is designed, targeting to complete the transmission of cycle-based generated packets in the shortest time. All sensor nodes can thus transmit and receive packets according to the scheduling table without data collision. Therefore, packet transmission delay is predictable and bounded. In addition, our scheduling algorithm allocates different transmission resources to sensors nodes with various packet generation patterns and QoS requirements such that differentiated services can be provided. It is shown that our scheduling mechanisms are capable of fulfilling the low delayed transmission requirements of IIoT.

In the case of constantly varying network topology, we further propose a distributed scheduling mechanism incorporated with the dynamic bandwidth allocation algorithm. Based upon the observed local status, each node is able to identify the updated available idle slots. Thus, the distributed scheduling mechanism allows each individual sensor node to build up the basic dedicated Tx/Rx link with its parent and children nodes in the scheduling initialization stage. As the network topology evolves, the dynamic bandwidth allocation algorithm is activated to enable each sensor nodal link pair to adjust their allocated bandwidth adaptively according to the measured traffic loading.

As the traffic load of IoT system increases to a congested status, we propose the enhanced congestion control mechanism for the CoAP protocol to boost system performance. The CoAP protocol is operated on top of UDP and has implemented basic congestion control function by itself. However, the CoAP congestion control mechanism is not able to adapt well to the ever changing network environments. In this work, we propose effective mechanisms to provide dynamic adjustment of RTO (Retransmission Time Out) and obtain more accurate RTT (Round Trip Time) values to be adaptive to the instantaneously varying network conditions. Through system simulation, we evaluate the throughput and energy efficiency achieved by the proposed mechanism, and also compare these performance indexes with those obtained from other existing congestion control algorithms. The experimental results reveal that our proposed congestion mechanism is more effective in achieving a higher network throughput and the lower retransmission rate. This validates the merit of the proposed mechanism in relieving the network congestion as network load increases.

It is noted that a new joining sensor node is operated at the full energy mode until it receives at least one valid Enhanced Beacon (EB) signal in the IEEE 802.15.4 network. The node will then change to power saving mode. In this work, we propose both fast network formation mechanism and network maintenance process, which are not specified in IEEE 802.15.4-2015 standard. The network formation time is reduced by decreasing the slotframe size during network formation period. As network topology stabilizes and transits into the network maintenance mode, the Distance-2 algorithm is employed to reduce the occurrence of EB collision. Furthermore, channel quality and nodal density estimation mechanisms are incorporated to regulate how often the EB signal is sent. Performance results reveal that network formation efficiency and network maintenance reliability are improved simultaneously.

2. Experiment environment and set up

The mentioned communication protocols and scheduling mechanisms are implemented and carried out at the network manager agent within a personal computer as well as at the sensor nodes with TI CC2538 SoCs [7] shown in Fig. 4.

Fig. 4 A TI CC2538 Sock sensor board

Extensive experiments are conducted in the wireless and broadband network laboratory of computer science and information engineering department at our school. Fig. 5 exhibits a snapshot of one experiment environment and layout, where the network consists of 8 sensor nodes and one root node (border router). Periodical packets with higher priority are generated more frequently and are sent before those packets with lower priority to realize the differentiated services. Therefore, these high-priority packets experience lower packet delays. Average end-to-end packet latency (in number of time slots with the duration of one time slot = 10 ms) shown in Fig. 5 indicates that low packet delay of smaller than 2 seconds is achieved. At the same time, high PSR (Packet Success Rate) of greater than 98% is obtained, validating the effectiveness of our design and implementation.

mote	packet_tcflow	event_threshold	max	min	packet_count	average_latency	PSR
fd00::212:4b00:615:a5ca	2	5	82211	32	82170	6.5603	0.9999
fd00::212:4b00:615:a5ca	0	20	20561	16	20447	22.2848	0.9952
fd00::212:4b00:615:a595	2	5	82316	140	82132	13.7823	0.9995
fd00::212:4b00:615:a595	1	10	41216	129	41062	27.0084	0.9994
fd00::212:4b00:615:a5d4	1	10	41307	220	40840	73.3270	0.9940
fd00::212:4b00:615:a67d	2	20	20747	205	20541	10.5191	0.9999
fd00::212:4b00:615:a67d	1	20	20747	205	20543	28.3545	1.0000
fd00::212:4b00:615:a5dd	0	20	20755	213	20531	64.5812	0.9994
fd00::212:4b00:615:a5ab	0	20	20555	15	20207	272.8839	0.9837
fd00::212:4b00:615:a5ab	2	20	20555	13	20278	131.3561	0.9871
fd00::212:4b00:615:a703	1	10	41314	234	40689	88.3069	0.9905
fd00::212:4b00:615:a703	0	20	20765	226	20316	192.7757	0.9891
fd00::212:4b00:615:a715	0	20	20587	48	20463	68.2142	0.9963

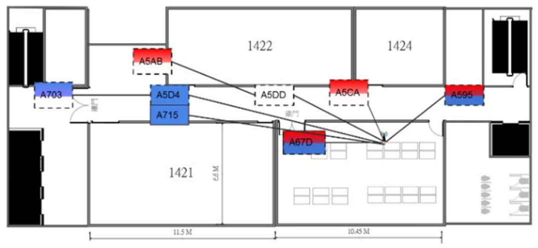

Fig 5. Experiment environment and performance results

3. Conclusions

In this paper, we have described the system architecture and protocol stacks of the IEEE 802.15.4 based wireless IIoT system. We have designed and implemented scheduling mechanisms and the dynamic bandwidth allocation algorithm, which are not specified in the IEEE 802.15.4 standard. The fast network formulation and maintenance processes and the enhanced congestion control algorithm are proposed to enhance system performance. Extensive experiments are carried out to verify that the implementation of such system is able to satisfy the stringent QoS requirements of wireless IIoT environments.

References

[1] A. Kumar S., K. Ovsthus and L. Kristensen, “An Industrial Perspective on Wireless Sensor Networks – A Survey of Requirements, Protocols, and Challenges,” IEEE Communications Surveys & Tutorials, Vol. 16, No. 3, pp. 1391-1411, 2014.

[2] “IEEE Standard for Local-Rate Networks,” IEEE Std 802.15.4-2015, (Revision of IEEE Std 802.15.4-2011), pp. 1-709., April, 2016.

[3] P. Thubert, “An architecture for IPv6 over the TSCH mode of IEEE 802.15.4,” IETF Std. draft-ietf-6tisch-architecture-08 [work-in-progress], May 2015.

[4] H.-T. Wu, K.-W. Ke, Bo-Yu Huang, Liang-Lin Yan and Chun-Ting Lin, " IEEE802.15.4e Based Scheduling Mechanisms and Systems for Industrial Internet of Things," Proc. of the 20th International Conference on Sensor Networks (ICSN 2018), 2018.

[5] WATTEYNE, Thomas; PALATTELLA, M.; GRIECO, L, “Using IEEE 802.15. 4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement,” Internet Engineering Task Force, RFC 7554, May 2015.

[6] https://www.ti.com.