SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 18, No. 1, February 2021, 63-73
UDC: 004.78:620.9 DOI: https://doi.org/10.2298/SJEE2101063P

An Energy Efficient Hybrid MAC Protocol for Smart Home Networks

Atul Kumar Pandey[1], Nisha Gupta[2]

Abstract: In this paper cluster-based hybrid MAC (CB-HMAC) protocol, based on IEEE 802.15.4 MAC is proposed for smart home networks. The CB-HMAC is specially designed for short packet transmission in a dense home network environment. Simulation results show that the proposed CB-HMAC is more energy-efficient than other medium access control (MAC) protocols without sacrificing much delay and throughput.

Keywords: Energy management, Medium access control (MAC), Smart Home networks, Wireless personal area network.

1 Introduction

Applications of the wireless sensor network (WSN) has increased tremendously in the past few years. One of the most exciting applications of WSN is in the next generation smart homes, which would consist of a network of home devices such as thermostats, door locks, alarm sensors, light bulbs, and fans, etc. communicating in the wireless environment. In all these applications the power requirement is very low. The existing 802.11 wireless local area network (WLAN) protocol is inappropriate for home networks due to its redundant data rate and high-power consumption. The Bluetooth protocol is also inappropriate for the home networking environment due to the limitation of the number of nodes that can be connected simultaneously and also due to the high level of power consumption. The implementation of wireless sensor network IEEE 802.15.4 [1] and Zigbee [2] are generally suitable for low data rate control and sensor applications in wireless networks and are most suited for home networking applications that require little or no intervention over a large period. The low data rate provided by IEEE 802.15.4, allows communication among devices scattered in the dense environment with consideration to very low battery power consumption. The IEEE 802.15.4 [1 – 7] devices are appropriate for home

[1]Department of Electronics and Communication Engineering, Birla Institute of Technology, Mesra, Patna Campus, Patna 800014, India; E-mail: atulkrpandey@gmail.com
[2]Department of Electronics and Communication Engineering, Birla Institute of Technology, Mesra,, Ranchi 835215, India; E-mail: ngupta@bitmesra.ac.in

environments requiring low cost and low data rate over short distances using low-rate wireless personal area network (WPAN) [5].

An IEEE 802.15.4 standard and its home networking applications are discussed in [1]. A survey of suitable emerging solutions for wireless home automation networks (WHANs) such as ZigBee, Z-Wave, and Wavenis, etc is presented in [2]. In [8], the networks of a smart home are studied within a small area of 20m×20m. The binary tree routing protocol (BTRP) is utilized here to reduce energy consumption and delay. In [9], a node-grouping super frame division MAC protocol for smart home applications is presented. This protocol is based on the IEEE802.15.4 MAC protocol and utilizes the concept of prioritization for handling emergencies. It outperforms the IEEE802.15.4 MAC in terms of energy efficiency, delay, packet delivery ratio, and throughput. In [10], a voice-controlled wireless smart home system is investigated for old and disabled persons. It utilizes LabView software and ZigBee wireless modules to implement the voice recognition system and wireless system respectively. This system is designed to control the home appliance by using voice commands. The holistic approach [11], is proposed to improve ZigBee performance for home automation networks. To achieve enhanced network performance in terms of packet delivery ratio, delay, and energy efficiency, it utilizes an alternative protocol stack configuration. In [12], a home energy management (HEM) scheme is presented for future smart grids. This scheme is based on home appliances coordination. The proposed HEM scheme adopts ZigBee protocol for message passing among diverse objects in a wireless sensor home area network (WSHAN). In [13], a survey on hybrid MAC protocols is investigated for improving the delivery of safety and non-safety messages. A lightweight WSN MAC protocol is proposed for the smart home applications in [14]. This protocol is designed to solve the unreliability problems due to contention-based channel access in IEEE 802.15.4, which results in a low packet delivery ratio. In [15], an AM-DisCNT (angular multi-hop distance-based clustering network transmission) protocol and improved AM-DisCNT protocols are presented. To achieve uniform energy consumption in the network it adopts a circular region for sensor nodes deployment. It utilizes the maximum residual energy of sensor nodes for CH selection. In [16], the issue of reducing energy consumption due to packet retransmission by reducing the packet loss in the first attempt is elaborated. A cluster-based medium access control (CB-MAC) protocol for vehicular ad hoc networks (VANETs) is presented in [17]. The cluster head (CH) selection and cluster formation are described to perform efficient communication within the cluster as well as outside the cluster. Latency analysis of wireless networks for proximity services (ProSe), in smart home and building automation (BA) is described in [18]. To develop the probability distribution of the MAC layer service time and characterize the behavior of the backoff mechanism in CSMA/CA, a Markov chain model is utilized.

Despite the number of MAC protocols designed for smart home networks, there is still some improvement space for the design of a MAC protocol suitable for home networks. In this paper, the design of an energy- efficient cluster-based hybrid MAC protocol is proposed to meet the constraints and considerations of the WSNs in the home networking environment.

2 Implementation of CB-HMAC Protocol

Most of the MAC protocols in a WSN employ TDMA or CSMA/CA technique. The proposed CB-HMAC protocol is a hybrid MAC protocol that takes into account, the advantages of the two techniques to increase energy efficiency. The concept of CB-HMAC is originally derived from IEEE 802.15.4 [1].

The implementation of CB-HMAC protocol follows several steps as stated below:

Step 1:

The cluster setup period is used to form clusters in the network. All the nodes in the network are randomly deployed in a circular region to fill in the coverage area and to ensure the even consumption of energy in the entire wireless sensor network similar to AM-DisCNT [15]. The complete network is divided into two concentric circles as shown in Fig. 1. The base station (BS) is placed in the centre of the two concentric circles. Inner circle nodes are supposed to send their status directly to the BS due to minimum distance. Nodes in the outer circle perform communication through the cluster formation.

Step 2:

Next, in the cluster setup period BS allocates N number of CSMA/CA slots to N clusters in intra-cluster communication period, which means that the designated nodes of slot 2-to-N are scheduled to wait for a certain time until they start transmitting. Over each CSMA/CA slot, packets from cluster members are gathered at their corresponding cluster heads. After transmission, the members of each cluster go to sleep until the arrival of the next frame. The number of nodes that participate in inter-cluster communication using MOD-CRMAC [19] protocol consists of un-clustered nodes or common nodes with CHs that are supposed to talk to the base station directly.

Step 3:

In the notification period, the base station broadcasts the number of common nodes with cluster heads M_c and the number of the reservation slots n.

Step 4:

During the contention reservation period, if the number of the members M_c in the MOD-CRMAC group is less than or equal to the number of reservation slots n, then each node that has packets in the queue randomly chooses a reservation slot to send the reservation packet otherwise reservation is assigned a probability p. The reservation packet includes the following information: number of packets in the queue of the node; an urgent degree of the node, which depends on how long the node has waited since its last transmission. Some reservation packets may collide because they are accidentally sent in the same reservation slots. Others will arrive at the BS successfully. The BS arranges more urgent nodes in anterior slots of the data transmission period. The number of slots, assigned to each node depends on their queue length.

Step 5:

Finally, in the announcement period, the base station broadcasts the arrangement on slot allocation. All the nodes receive the broadcast and go to sleep.

Step 6:

In the data transmission period, nodes wake up and send packets in corresponding slots. At the end of this period, the un-clustered nodes switch to sleep mode and all the cluster heads wake up and listen to their cluster members in the CSMA period of the next frame.

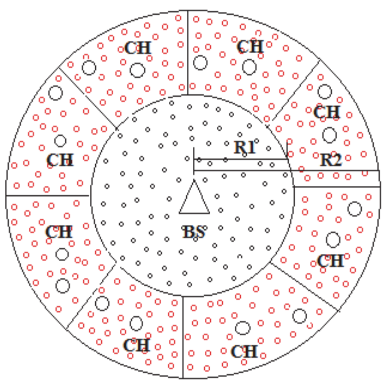

Fig. 1 – *Network architecture.*

Fig. 2 presents the CB-HMAC algorithm in the form of a timeline diagram with all phases. In CB-HMAC protocol, the time scale is segmented into a cluster setup and several superframe segments. Further, each superframe is segmented into intra-cluster communication period (*i.e.,* communication within clusters), and inter-cluster communication period (*i.e.*, communication outside clusters). The intra-cluster communication period is again divided into N number of CSMA/CA slots. The inter-cluster communication period is composed of contention reservation period (CRP), announcement period (AP) and data transmission period (DTP). Further, DTP is divided into several data transmission slots.

The intra-cluster communication protocol needs to be scalable and adaptive. Therefore, a multi-slot CSMA/CA mechanism is selected for intra-cluster communications to reduce the energy consumption of the network. It reduces the idle listening time by splitting the intra-cluster communication period into multiple small CSMA/CA time slots. In each slot, only a few numbers of nodes can access the channel. Before the arrival of each slot, the designated nodes keep sleeping instead of listening. Since sleep power is minor to listen power, the scheme can decrease the total energy waste. However, as a consequence of the trade-off, the delay of an individual node is increased. On the other hand, dynamic TDMA based MAC protocol (*i.e.,* MOD-CRMAC) is selected for inter-cluster communication.

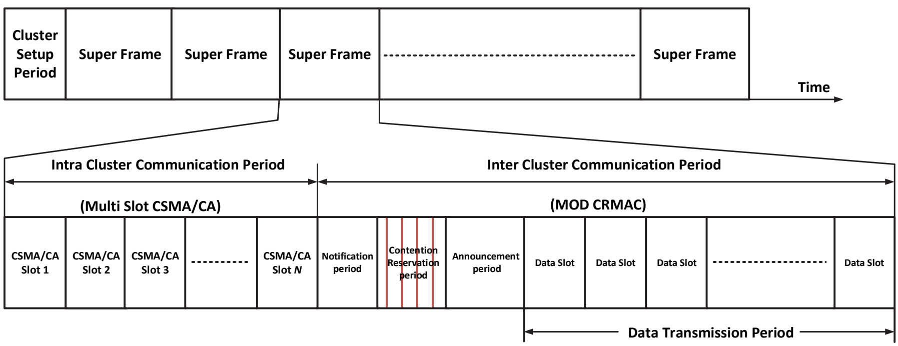

Fig. 2 – *Timeline diagram of the proposed CB-HMAC protocol.*

The intra-cluster communication protocol needs to be scalable and adaptive. Therefore, a multi-slot CSMA/CA mechanism is selected for intra-cluster communications to reduce the energy consumption of the network. It reduces the idle listening time by splitting the intra-cluster communication period into multiple small CSMA/CA time slots. In each slot, only a few numbers of nodes can access the channel. Before the arrival of each slot, the designated nodes keep sleeping instead of listening. Since sleep power is minor to listen power, the scheme can decrease the total energy waste. However, as a consequence of the trade-off, the delay of an individual node is increased. On the other hand, dynamic TDMA based MAC protocol (*i.e.,* MOD-CRMAC) is selected for inter-cluster communication.

3 Result and Analysis

Simulations are performed in MATLAB (R2012b) on a PC machine. This section discusses the assumptions, models, and parameters used for the simulations along with the simulation results.

3.1 Assumptions

To perform the simulations, the following assumptions are made:

– To simplify the simulation procedure, the traffic is first generated at the beginning of the simulation for all the nodes in the networks for the entire simulation time. The packets thus generated are then stored in the nodes transmit buffer.
– There is no constraint on the buffer size of the nodes, *i.e.,* they have unlimited transmit and receive buffer sizes.
– In multi-slot CSMA/CA, the binary exponential back-off [20] mechanism is used to reduce the collisions.
– A perfect wireless channel is assumed for transmission and reception, *i.e.,* there is no bandwidth constraint.
– The radio transceiver of the node is TR1000 from RF Monolithics [21] datasheet.

3.2 Traffic model

The traffic model used in the present simulation considers the shifted Poisson distribution [22] model to describe the generation of traffic based on packets arrival rate. The probability density function of Poisson traffic for the inter-arrival time T can be expressed as:

$$f_T(t) = b\,\mathrm{e}^{-b(t-a)},\ t \geq a, \tag{1}$$

where, $a > 0$, which represents the minimum time between adjacent packets and b determines how fast the exponential function decays with time. The values of a and b with parameters λ, σ, and α can be calculated as follows:

$$a = \alpha/\sigma, \tag{2}$$

$$b = (1/\alpha) \times [\sigma\,\lambda/(\sigma - \lambda)], \tag{3}$$

where, λ, σ and α are designated as average data rate, maximum burst rate, and average packet length in bits. The values of λ and σ can be calculated as a function of packet inter-arrival time T as follows:

$$\lambda = 1/T, \tag{4}$$

$$\sigma = 1/(T - \theta), \tag{5}$$

where θ is a constant value between 1 and $T-1$. In this simulation, θ is assumed to be 1.

3.3 Simulation parameters

The parameter values used in the simulations are presented in **Table 1**. For the sake of simplicity in the simulation process, time is divided into frames of 1s duration, and the simulation time is taken 200s. For the multi-slot CSMA/CA with *N* slots, the listen period is 400/*N* ms. The packet size of the data is fixed with 38 bytes which take only 20 ms to send it through the radio channel. For the MOD-CRMAC, the listen period is 600 ms. It is assumed that the *K* number of nodes are randomly deployed in the circular network of radius R_2 of 100 m to provide a full coverage area.

Table 1

Model parameter used in simulation.

Parameter	Value	Unit
Average packet inter-arrival Time T	5	Seconds
Number of CSMA/CA Slots	N	-
Number of Nodes K	100-500	-
Frame duration T_f	1	Second
CSMA/CS Slot duration T_l	0.4/N	Second
No. of initial reservation slots	8	-
Node transmitting power	24.75	mW
Node listening power	13.5	mW
Node sleeping power	5	µW
Node transmitting data rate	19.2	Kbps
Average packet length α	38	Bytes
Simulation time	200	Seconds

3.4 Simulation results

Sensor nodes having transmission distances higher than $R-R_1$ are clustered in CB-HMAC. Fig. 3 shows that CB-HMAC consumes less energy compared to MOD-CRMAC without clustering. From Fig. 3 it is clear that partial clustering outperforms in contrast to non-clustering and complete-clustering in terms of energy efficiency. From energy consumption point of view, it is evident that the proposed CB-HMAC with *R*=25 m consumes the least power than *R*=75 m. In fact, by increasing the value of *R,* the number of nodes inside the clusters decreases, *i.e.*, nodes assigned in each slot of the intra-cluster communication period decrease. This in turn decreases delay and energy consumption. At the same time number of common nodes increases. All common nodes with cluster heads using MOD-CRMAC to send the data packets to the BS in the next part of the current frame, will further reduce energy consumption and increase the delay. Therefore, overall energy consumption is minimized at the cost of higher delay and lower throughput.

Fig. 4 presents the energy performance of the proposed MAC protocol for the energy consumption per bit.

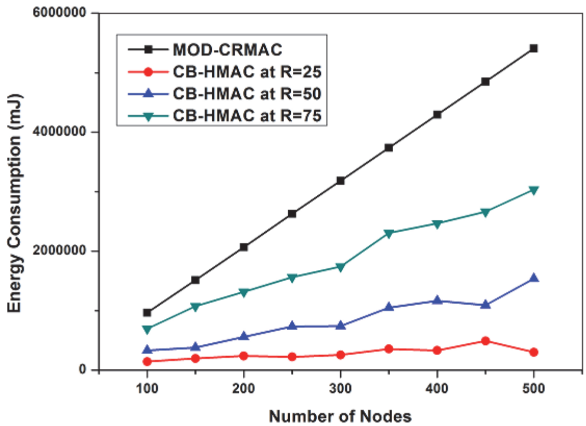

Fig. 3 – *Energy performance of CB-HMAC and MOD-CRMAC.*

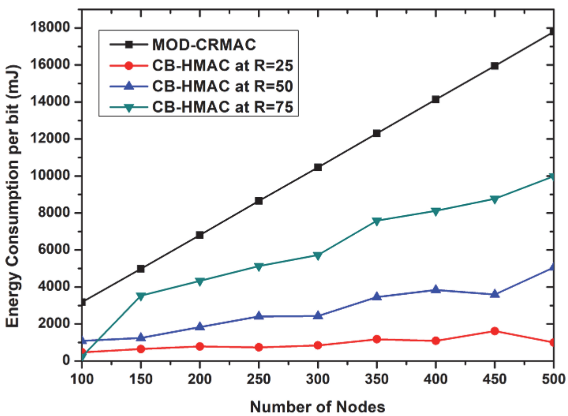

Fig. 4 – *Energy consumption per bit of CB-HMAC and MOD-CRMAC.*

Next in Fig. 5, one can see that the delay performance of the proposed CB-HMAC is sacrificed in comparison to the MOD-CRMAC to achieve less power consumption. The additional delay in the proposed CB-HMAC is because of the clustering, which enables energy saving and makes the protocol more scalable. The additional delay per frame in CB-HMAC is due to delay produced by multiple CSMA/CA slots, and reservation period in MOD-CRMAC. The delay produced by CB-HMAC increases for higher values of R such as $R = 50$ m and $R = 75$ m due to a reduced number of nodes in CSMA/CA slots and also increases the number of nodes in the MOD-CRMAC period.

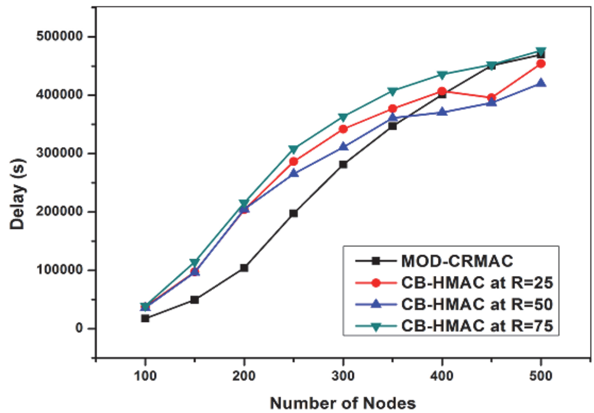

Fig. 5 – *Delay performance of CB-HMAC and MOD-CRMAC.*

Furthermore, in Fig. 6, it is noticed that the throughput performance of proposed CB-HMAC is sacrificed for achieving less power consumption. The proposed CB-HMAC protocol has lower throughput than MOD-CRMAC. The throughput of CB-HMAC is reduced by increasing the value of R due to the clustering.

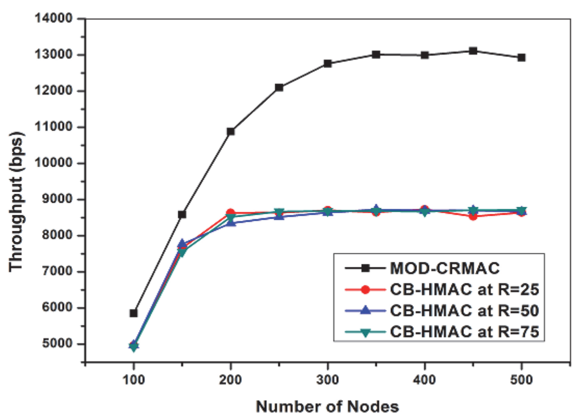

Fig. 6 – *Throughput performance of CB-HMAC and MOD-CRMAC.*

Since the overall system energy consumption can be reduced by choosing a minimum value of *R*, the profits on individual node lifetime are sufficient to overcome the loss in the lifetime of cluster heads. To avoid exhausting cluster heads too fast, one way is to let cluster members be the head in turn.

4 Conclusion

The proposed CB-HMAC protocol borrows an idea from existing low power WSN MAC protocols in the frame structure, scheduling, and algorithms, etc. Based on the Poisson traffic model, their performances have been measured in three aspects: packet delay, energy consumption, and system throughput. Clustering is the key energy-saving scheme in the proposed MAC protocol. In the proposed scheme, the transmission power of the nodes gets lowered down after they are put into clusters. To make the most of the advantage of CSMA/CA and CRMAC, the former is selected for intra-cluster communication with multiple CSMA/CA slots to further decrease idle listening and CRMAC with a small modification in contention reservation period known as MOD-CRMAC for inter-cluster communication. Simulation results show that compared to MOD-CRMAC with no clusters, the proposed CB-HMAC saves more energy at the cost of time efficiency. The design fulfils the goals to save the system energy consumption and extends the battery lifetime of sensor nodes.

5 References

[1] E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, V. Bahl: Home NetWorking with IEEE 802.15. 4: A Developing Standard for Low-Rate Wireless Personal Area Networks, IEEE Communications Magazine, Vol. 40, No. 8, August 2002, pp. 70 – 77.

[2] C. Gomez, J. Paradells: Wireless Home Automation Networks: A Survey of Architectures and Technologies, IEEE Communications Magazine, Vol. 48, No. 6, June 2010, pp. 92 – 101.

[3] S. Tennina, O. Gaddour, A. Koubâa, F. Royo, M. Alves, M. Abid: Z-Monitor: A Protocol Analyzer for IEEE 802.15. 4-based Low-Power Wireless Networks, Computer Networks, Vol. 95, February 2016, pp. 77 – 96.

[4] C. T. Kone, A. Hafid, M. Boushaba: Performance Management of IEEE 802.15.4 Wireless Sensor Network for Precision Agriculture, IEEE Sensors Journal, Vol. 15, No. 10, October 2015, pp. 5734 – 5747.

[5] Y. Jang, Y. Kim, S. Park, S. Choi: Link Adaptation Strategies for IEEE 802.15.4 WPANs: Protocol Design and Performance Evaluation, Journal of Communications and Networks, Vol. 21, No. 4, August 2019, pp. 376 – 384.

[6] D. Striccoli, G. Boggia, L. A. Grieco: A Markov Model for Characterizing IEEE 802.15. 4 MAC Layer in Noisy Environments, IEEE Transactions on Industrial Electronics, Vol. 62, No. 8, August 2015, pp. 5133 – 5142.

[7] P. Luong, T. M. Nguyen, L. B. Le: Throughput Analysis for Coexisting IEEE 802.15.4 and 802.11 Networks under Unsaturated Traffic, EURASIP Journal on Wireless Communications and Networking, Vol. 2016, May 2016, pp. 1 – 14.

[8] G. Huang, X. Li, J. He: Binary Tree Routing for Parallel Data Gathering in Sensor Networks of Smart Home, Proceedings of the International Conference on Sensing, Computing and Automation (ICSCA2006), Chongqing, China, May 2006, pp. 792 – 707.

[9] G. Ma, C. Shen, B. Chen: A Node-Grouping Superframe-Division MAC Protocol for Smart Home Based on IEEE802. 15.4 Protocol, Proceedings of the International Conference on Wireless Communications and Applications, Sanya, China, August 2011, pp. 125 – 136.

[10] T. Obaid, H. Rashed, A. A. El Nour, M. Rehan, M. M. Saleh, M. Tarique: ZigBee Based Voice Controlled Wireless Smart Home System, International Journal of Wireless & Mobile Networks, Vol. 6, No. 1, February 2014, pp. 47 – 59.

[11] A. Betzler, C. Gomez, I. Demirkol, J. Paradells: A Holistic Approach to ZigBee Performance Enhancement for Home Automation Networks, Sensors, Vol. 14, No. 8, August 2014, pp. 14932 – 14970.

[12] A. Mahmood, I. Khan, S. Razzaq, Z. Najam, N. A. Khan, M. A. Rehman, N. Javaid: Home Appliances Coordination Scheme for Energy Management (HACS4EM) Using Wireless Sensor Networks in Smart Grids, Procedia Computer Science, Vol. 32, 2014, pp. 469 – 476.

[13] V. Jayaraj, C. Hemanth, R. G. Sangeetha: A Survey on Hybrid MAC Protocols for Vehicular Ad-Hoc Networks, Vehicular Communications, Vol. 6, October 2016, pp. 29 – 36.

[14] C.- H. Chen, M.- Y. Lin, W.- H. Lin: Designing and Implementing a Lightweight WSN MAC Protocol for Smart Home Networking Applications, Journal of Circuits, Systems and Computers, Vol. 26, No. 3, March 2017, pp. 1 – 20.

[15] M. Akbar, N. Javaid, M. Imran, A. Rao, M. S. Younis, I. A. Niaz: A Multi-Hop Angular Routing Protocol for Wireless Sensor Networks, International Journal of Distributed Sensor Networks, Vol. 12, No. 9, September 2016, pp. 5 – 13.

[16] S. D. Trapasiya, H. B. Soni: Energy Efficient Policy Selection in Wireless Sensor Network Using Cross Layer Approach, IET Wireless Sensor Systems, Vol. 7, No. 6, December 2017, pp. 191 – 197.

[17] A. F. M. Shahen Shah, H. Ilhan, U. Tureli: CB-MAC: A Novel Cluster-Based MAC Protocol for VANETs, IET Intelligent Transport Systems, Vol. 13, No. 4, April 2019, pp. 587 – 595.

[18] D. Lan, Z. Pang, C. Fischione, Y. Liu, A. Taherkordi, F. Eliassen: Latency Analysis of Wireless Networks for Proximity Services in Smart Home and Building Automation: The Case of Thread, IEEE Access, Vol. 7, January 2019, pp. 4857 – 4867.

[19] G. Ma, D. Qiu: An Efficient MAC Protocol Based on Hybrid Superframe for Wireless Sensor Networks, Proceedings of the 4th International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China, October 2008, pp. 1 – 4.

[20] Y.- H. Zhu, X.- Z. Tian, J. Zheng: Performance Analysis of the Binary Exponential Backoff Algorithm for IEEE 802.11 Based Mobile Ad Hoc Networks, Proceedings of the IEEE International Conference on Communications (ICC), Kyoto, Japan, June 2011, pp. 1 – 6.

[21] Electronic Components Datasheet Search – Hybrid Transceiver,
Available at: https://pdf1.alldatasheet.com/datasheet-pdf/view/106155/RFM/TR1000.html

[22] M. K. Jha, A. K. Pandey, D. Pal, A. Mohan: An Energy-Efficient Multi-Layer MAC (ML-MAC) Protocol for Wireless Sensor Networks, AEU-International Journal of Electronics and Communications, Vol. 65, No. 3, March 2011, pp. 209 – 216.