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A novel scheme to improve lifetime and real-time support for IEEE 802.15.4 based wireless personal area networks

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ABSTRACT

IEEE 802.15.4 defines the working of physical and media access layers of a Low-Rate Wireless Personal Area Network (LR-WPAN). A LR-WPAN is a low cost, low power, and low data-rate network that offers reasonable lifetime and reliable data transfer within a limited range. However, it faces several challenges whilst dealing with applications that are having strict timeliness, energy, and bandwidth requirements. This paper proposes an efficient superframe structure for the MAC layer of IEEE 802.15.4 networks that intends to deal with these challenges by varying the functionalities of Guaranteed Time Slot (GTS) bits. Simulations of different GTS allocation techniques show that our enhanced scheme outperforms the original standard as well as previous techniques in terms of energy consumption, average delay, maximum GTS allocation and reliability.

1. Introduction

The vast array of applications for wireless personal area network WPAN has made them the central attention of the worldwide research community. Application for WPAN's are environmental monitoring, military, healthcare and civil engineering [1]. WPAN consists of freestanding, independent, and compact battery-powered wireless nodes with constrained processing, energy, and communication capability. Because the existing stacks of communications, namely IEEE 802.11 and 802.16, were not intended to operate under these limits, a new physical and Medium Access Control-MAC stack dubbed IEEE 802.15.4 emerged as a result. For the applications of Low-Rate Wireless Personal Area Network (LR-WPAN) where improved dependability with fewer power consumption is required, the IEEE 802.15.4 standard was created. [2, 3].

The superframe of 802.15.4 MAC layer has both inactive and active period, controlled by two parameters – the Superframe Order (SO) and Beacon Order (BO). Within the active period, devices may transmit data during the Contention Access Period (CAP) or Contention Free Period (CFP). If BO > SO, then the inactive period increases. Guaranteed Time Slots (GTSs) allocated during the CFP are used for assigning dedicated time-slots to devices. Devices can utilize these time slots to send data that is created at regular intervals without having to share the channel with other users. The number of Guaranteed Time Slots (GTSs) is limited to seven in one superframe.

In this paper, we review literature which aims to further improve the power consumption [4], [5, 6] bytes received, delay [7], and other performance parameters of standard 802.15.4 and propose an enhanced 802.15.4. We have categorized the different approaches for improving IEEE 802.15.4 protocol according to the mechanism they use for improvement. For example, GTS allocation-based schemes [8], provide better GTS utilization, reduce the delay, and decrease energy consumption. Our proposed standard of 802.15.4 was tested in the OMNeT++ simulator with total data packets sent, average energy consumption, total bytes received, and delay duration as the evaluation metrics. The results of the simulations showed that the newly proposed schemes improve the network energy consumption while also increasing the number of devices that can share the GTS. The proposed schemes require very small implementation changes and are backward compatible with the original standard.

The rest of this paper is outlined as follows. Section 2 discussed the related work for allocation of GTS while Section 3 demonstrates an overview of the IEEE802.15.4. Section 4 presents our proposed GTS allocation scheme. Section 5 gives detail about OMNeT++ simulator to evaluate our proposed scheme against the original protocol. Section 6 is about results and simulation. Finally, Section 6 concludes our work and gives some future work directions.

2. Related Work

The proposed algorithm for the energy management, due to the widespread of LR-WPAN in different domains, several techniques have been proposed to better utilize the GTS bandwidth and increase the number of associated devices beyond 7. In [9], the author suggests an alternative GTS allocation mechanism in which each GTS is divided in half to form two new GTSs. These two procedures merely divide the existing GTSs into new GTSs without taking the data frames length into account. Li et al. [10] introduced a synchronous low power listening technique in order to minimize power consumption. For real-time communication applications where tighter latency limitations are necessary, Chen et al. [11] presented the Explicit GTS Sharing and Allocation Scheme (EGSA).

A multi-hop communication strategy that uses the IEEE 802.15.4 standard's GTS mechanism and adheres to superframe structure is proposed in [12], with claims of reduced delay and improved packet delivery ratio. In [13], an Unbalanced GTS Allocation System (UGAS) is put out. A Real-Time and an Adaptive GTS Allocation Method compatible with IEEE 802.15.4 standard and designed for such applications was proposed by Feng Xia et al. [14]. According to authors, the standard GTS use is increased by the proposed approach. The authors of [2] claim that their body area network control and scheduling method achieves 100% compliance with time limitations.

The PAN controller then uses these details to adjust the GTS size and further accept or reject the request. In a nutshell, those schemes and similar ones, which adjust the GTS duration according to the traffic characteristic, better enhance the WPAN performance. However, the constant duration used of all GTSs again prevents them from attaining the maximum possible performance.

In this paper, we tackle this problem by using GTS durations that vary from one timeslot to another, based on the characteristics of the requesting device. Our approach does not only allocate the maximum possible number of devices, but it also takes the performance to the maximum and make energy consumption into minimum.

3. IEEE 802.15.4 Overview

As a MAC and Physical layer standard, IEEE 802.15.4 was developed with LR-WPAN. Reduced Functional Devices (RFDs) and Fully Functional Devices (FFDs) are the two categories of wireless nodes in a LR-WPAN. While RFD can only function as a simple wireless node, FFD can work as a Coordinator, a PAN Coordinator, or a simple node. A FFD can share its data with another FFD or an RFD, but an RFD can't share its data with another RFD; this is why RFDs are always located at the network's end. LR-WPAN may function in either a star topology or a peer-to-peer topology. In a star topology, the coordinator is accessible to the nodes connected to it, but in a peer-to-peer topology, the coordinators share information with one another. The IEEE802.15.4 standard could be configured in one of two modes of operations, namely beacon-enabled and non-beacon-enabled modes. In the non-beacon enabled mode, the standard does not guarantee a specific QoS. Nonetheless, the PAN controller and end devices simply exchange messages through unslotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol. In contrast, the beacon-enabled mode ensures this guaranteed performance.

Fig. 1 shows the structure of IEEE 802.15.4 superframe. At the boundary of the superframe, beacons are sent from the PAN controller to all associated devices. These beacons first ensure that devices within the network are all synchronized with the coordinator. Furthermore, they provide information about the network configuration, such as the superframe structure, devices address, and the PAN identifier. As shown in the Figure, the superframe is divided into active and inactive periods. The active period is further partitioned into CAP and CFP. According to the original standard, the active period is divided into 16 timeslots of equal duration. The first timeslot is dedicated to the beacon. The CAP timeslots are shared between devices using the CSMA/CA protocol. The CFP could have a maximum of 7 guaranteed timeslots that are allocated to devices that require a certain level of QoS. The communication between these devices and the PAN controller is done using the ALOHA protocol. Limiting the CFP to 7 GTSs ensures that the CAP has a minimum of 9 timeslots. This constraint cannot be violated in the standard and we refer to it by aMinCAPLength constraint. Finally, the CFP length limitation unfortunately prevents the original standard from providing guaranteed performance to more than 7 devices.

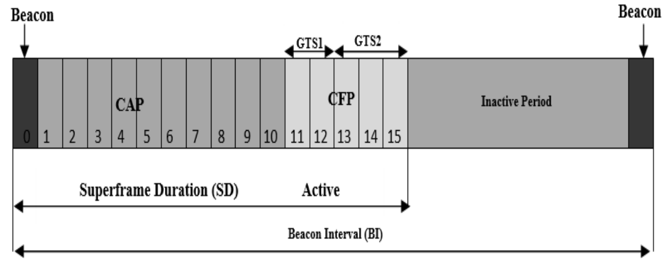

Fig. 1. Standard IEEE 802.15.4 superframe structure

The duration between two successive beacons, Beacon Interval (BI), and the duration of the active period, Superframe Duration (SD) could be controlled by two parameters. These are the Beacon Order (BO) and the Superframe Order (SO), respectively. The two parameters should be equal to 15 for the non-beacon-enabled mode. Nevertheless, they could take any value between 0 and 14 for the beacon-enabled one. Increasing the value of the two parameters would increase their corresponding durations. This in turn increases the duration of the 16 available timeslots. Most devices and sensors within LR-WPAN has short traffic packets. In the original standard, the PAN controller could only allocate the whole timeslot to an associated device. Therefore, increasing the values of BO and SO increases the probability of the bandwidth being wasted. Therefore, most of previous studies employ values between 2 and 8 for the two parameters. With no exception, we follow these studies and use the same values for both BO and SO. Finally, the beacon interval, the superframe duration, the timeslots, and the minimum CAP duration are mathematically represented by the following Equations.

$$BI = \frac{\text{aBaseSuperframeDuration} \times 2^{BO}}{R_S} \tag{1}$$

$$SD = \frac{\text{aBaseSuperframeDuration} \times 2^{SO}}{R_S} \tag{2}$$

$$T_{slot} = \frac{\text{SD}}{16} \tag{3}$$

$$\text{aMinCAPLength} = 9 \times \text{Tslot} = \text{SD} - 7 \times \text{Tslot} \tag{4}$$

Where aBaseSuperframeDuration and RS are the minimum accepted superframe duration and the symbol data rate, respectively. According to the original standard, they are equal to 960 symbols and 62,500 symbol/s. Finally, SO and BO are the superframe and beacon order, respectively. The two parameters are decided by the PAN controller and transmitted to associated devices in the synchronization beacon.

4. GTS Allocation

In this section, we present our GTS allocation scheme in details. As mentioned in overview section, we target the beacon enabled mode of the IEEE 802.15.4. Accordingly, each device requests an allocation of single or multiple GTSs from the PAN coordinator by sending a specific GTS allocation command. The command includes the traffic characteristics of the transmitted packets. Based on these characteristics, the PAN controller decides whether to accept or reject the GTS allocation request. The decision is built on the available capacity in the current superframe. Considering previously allocated devices, the PAN controller ensures that the requested time could be accommodated in the CFP without violating the aMinCAPLength constraint, as represented by Eq. (4). Let Tf represents the total amount of time needed to transmit one packet from the sender and receive an acknowledgement from the receiver. Tf includes the time for data transmission, acknowledgement (ACK), and interframe spacing (IFS).

It could therefore be calculated as

Tf = Tdata + macAckWaitDuration + TLIIFS

Where Tdata is used for time to transmit a packet data. TLIFS indicates the duration of interframe spacing (IFS). It depends on the length of transmitted packets. If that length is less than a certain threshold, aMaxSIFSFrameSize = 144 bits, TLIFS is consequently the time corresponding to 48 bits. Otherwise, TLIFS is that of 160 bits. Finally, macAckWaitDuration is the maximum waiting time for the arrival of the acknowledgement frame. According of the IEEE802.15.4 standard, the macAckWaitDuration is represented by

macAckWaitDuration = phySHRDuration + aTurnaroundTime + aUnitBackoffPeriod +ceiling (6 × phySymbolsPerOctet)

After calculating Tf, the beginning of the CFP period, i.e., GTS start time, could be calculated by

GTSStartTime = finalCAP - Tf

Where finalCAP indicates the end of the CAP period before new request. It is initialized at the beginning, i.e., before allocating any device, to the end of the active period. Finally, the PAN controller could only allocate the requested GTS slots to the requesting device if GTSStartTime is greater than or equal to the minimum CAP constraint, as represented by Eq. 4. A communication sequence for the GTS allocation is shown in Fig. 2.

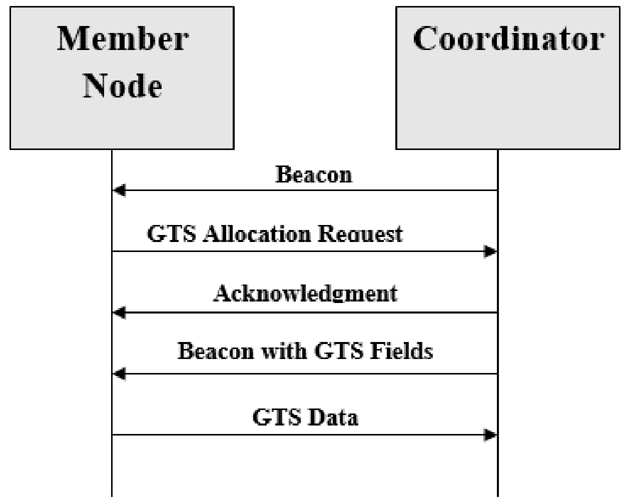

Fig. 2. GTS allocation procedure

Algorithm 1 shows the steps of our scheme in details. During the initialization phase, our scheme starts by calculating BI, SD, and aMinCAPLength according to Eq. 1, 2 and 4, respectively. Moreover, the total allocated GTS duration, totalGTSDuration, is initialized to zero and the end of the CAP period, finalCAP, is assigned equal to the end of the active period. Once a GTS allocation request is received by the PAN controller, it first checks the requesting device. If the device is unknown, not associated, or previously allocated GTS slots, the request is dropped. Otherwise, the PAN controller calculates the total required time, Tf, for the device to complete its requested communication, according to Eq. 5. If this required time exceeds the currently available capacity of the CFP, the request is rejected. In other words, if the calculated GTS start time, GTSStartTime according to Eq. 6, would exist inside the CAP period, the requested communication could not be accommodated and its corresponding request is therefore dropped.

Algorithm 1

GTS allocation scheme

Inputs: SO, BO

1. Initialization

- Calculate BI, according to eq. (1)
- Calculate SD, according to eq. (2)
- The minimum CAP duration aMinCAPLength calculation according to eq. (4)
- finalCAP = SD ± totalGTSDuration
- totalGTSDuration = 0

2. If (GTS request command received) // The request includes the size of transmitted data, Tdata

3. If (requesting device is associated && not allocated GTS slots)

4. Tf = Tdata + TLIFS + macAckWaitDuration

5. GTSStartTime = finalCAP - Tf

6. If (aMinCAPLength> GTSStartTime)

7. Guaranteed Time Slots request rejected

8. Else

9. finalCAP = GTSStartTime

10. totalGTSDuration = Tf + totalGTSDuration

11. Add the device address, Tf and GTSStartTime to the GTS descriptor

12. End if

13. End if

14. End if

In contrary, if the GTS start time is found greater than the minimum length of the CAP, aMinCAPLength, the request is accepted. Accordingly, the total GTS duration and the end of the CAP are updated. The device is then added to the GTS descriptor. In other words, a new entry with the device address, the beginning of its allocated GTS slot, and the length of this slot is inserted into the descriptor. It is again worth emphasizing that our scheme allocates a variable-length GTS slot to each device, based on its actual requested needs. This in turn eliminates the slot size-induced bandwidth problem completely.

Finally, Fig. 3 shows a comparison between our scheme and the original IEEE 802.15.4 standard.

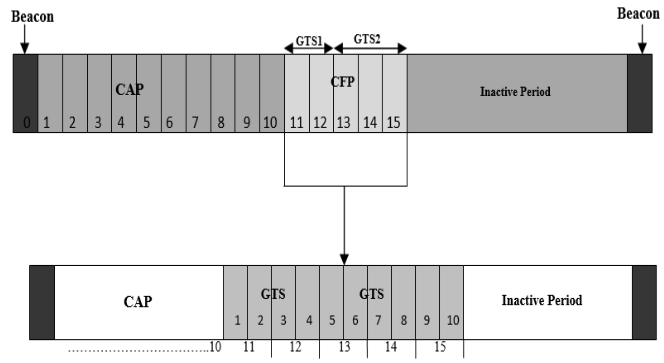

Fig. 3. Enhanced IEEE 802.15.4 superframe format

5. Performance Evolution by Omnet++

The performance of our enhanced GTS allocation scheme evaluated in this section. When comparing our suggested schemes to the IEEE 802.15.4 (standard), we employed the OMNeT++ simulator. Because of its modular design and use of the NED language to facilitate simulation settings, the open-source OMNeT++ is ideally suited for modeling wireless networks [15]. With an eye toward IEEE Std. 802.15.4-2006, the GTS transfer and energy models are incorporated into IEEE 802.15.4 model. In this paradigm, the application layer is responsible for traffic generator implementation, while the network, battery, and physical layers each have their own dedicated modules. The two data communication modes available in this device are called Direct Transmissions and GTS Transmissions. Altering the model's omnetpp.ini configuration file is how environmental parameters are configured.

At the application module, we employed both Exponential and On-OFF traffic generators to create random packets. According to the energy model presented in [15], the radio can be in one of four states: receiving, transmitting, idle, or sleep. The amount of energy used is determined by multiplying the amount of time spent in each state via radio with the state's average energy usage. Since the energy used by the CPU is so negligible in comparison to that of the radio, the authors of [15] do not factor it into their model. Scalar representations of the metric values are stored using NED language.

Table 1

The GTS Slot Splitting Scheme calibration used in experiments showing following states' radio energy consumption.

Parameter	Value
Idle State (Battery usage)	0.38 mA
Battery Initial Capacity	24 mAh
Sleep State (Battery usage)	0.03 mA
Transmit State (Battery usage)	15.34 mA
Receiving State (Battery usage)	18.49 mA

6. Simulation and Results

Our experimental findings that evaluate the efficacy of our enhanced schemes in relation to the standard IEEE 802.15.4 specification. All tests are conducted with the OMNeT++ simulator [15] and the IEEE 802.15.4 model. Experiments employ a star network with a centralized PAN coordinator. Each node in the PAN follows the beacon frame's guidelines for superframe construction when corresponding with the coordinator. We use the values specified in the original standard for the physical and MAC layers. Throughout our simulation experiments, a star topology with one PAN coordinator and 70 end devices is employed. The distance between the PAN coordinator and those devices is set equal to 10m. In our energy consumption simulation, we consider the StateBasedEpEnergyConsumer as the energy consumer module.

6.1 Comparison Between The Numbers of Allocated Devices in IEEE 802.15.4

Fig. 4. shows the number of devices that are successfully allocated using our scheme and original standard of SO, our scheme manages to accommodate a number of devices that is orders of magnitude higher. As SO increases, the CFP increases. However, the original standard could not get benefits from that and it saturates at its maximum possible 7 devices. In contrary, our enhanced scheme significantly manages to allocate more devices. For SO=8, it approaches very close to 70, which is the total number of devices used in the simulation. These results clearly identifies that our scheme makes the best use of the available CFP time. They also clarify the suitability of our scheme to larger networks with a maximum number of devices (70).

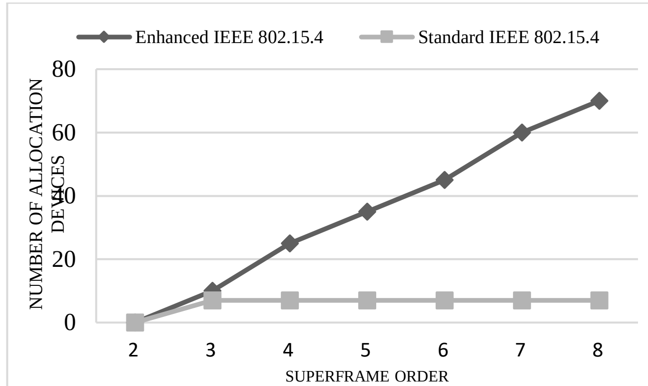

Fig. 4. Comparison between the numbers of allocated devices resulted from the original and enhanced standard

6.2 Total Bytes Received by IEEE 802.15.4

An increase in the number of bytes received by the PAN coordinator is of great advantage to WPAN used for remote sensing of extensive environmental data. The average number of bytes received by the PAN coordinator was significantly increased after we implemented our scheme. Our method improves the total number of bytes acknowledged by the coordinator (PAN) by 62% for SO=2 values. Our enhanced standard scheme increased the number of received bytes by 36% for a SO=8 value. Our suggested system transfers the bandwidth savings from the CFP to the CAP period.

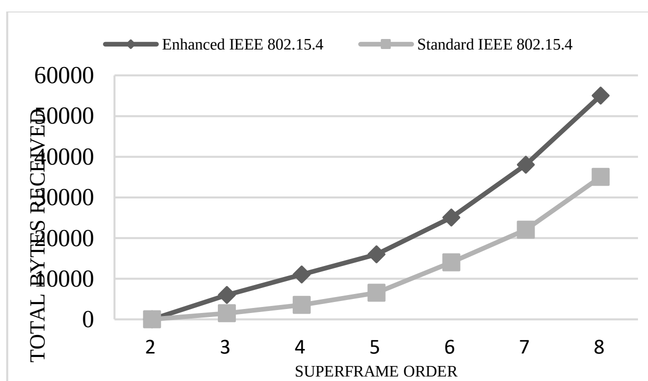

Fig. 5. Comparison between total bytes received resulted from the original and enhanced standard

6.3 Average Packet Delivered by IEEE 802.15.4

As was said before, the dependability of packet delivery is more important than any other criterion for particular

WPAN applications. Applications deployed in emergency scenarios, such as medical sensor equipment etc. You can see how reliable our system is in comparison to the standard in Fig. 6. For all values of SO and BO, our system outperforms the original standard. Our enhanced standard showed best performance from SO = 2 to SO = 8, when compared to the standard.

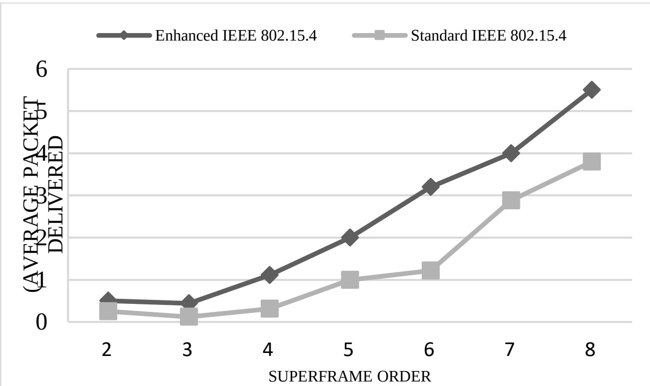

Fig. 6. Comparison between average packet delivered resulted from original and enhanced standard

6.4 Average Energy Consumption

Fig. 7 showed average energy consumption of our enhanced standard as well as that of the original standard. Our enhanced standard showed less energy consumption as compared to original standard. Since devices enter sleep mode following packet transmission in GTS, the extra unused time of a GTS slot is equivalent to nothing more than wasted bandwidth and cannot be used to save energy. The Experimental overview discusses the requirements of energy of devices in its various operating modes. Most of the power is used during packet transfers and acknowledgement receipt, while most of the power is wasted during the transceiver's idle state. We present a protocol for wireless personal area networks (WPANs) that prioritizes minimizing idle energy consumption without sacrificing packet delivery or the number of packets received. In general, the increase in energy consumption is not linearly related to packet transmission increase because our technique decreases the idle and sleep periods. The average amount of energy used was less in our scheme for very high SO levels (SO=8).

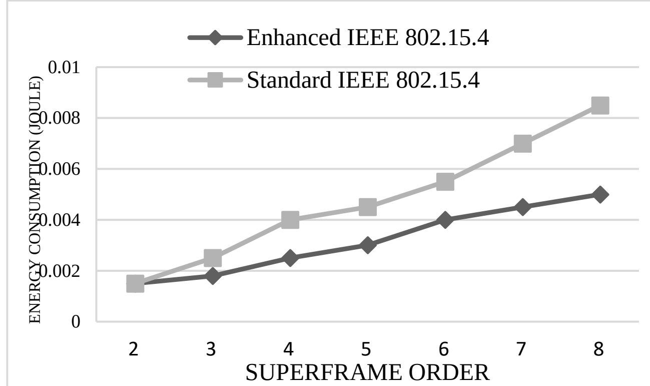

Fig. 7. Comparison between average energy consumption resulted from the original and enhanced standard

6.5 Delay in IEEE 802.15.4

It is important to note that the BO affects which superframe order results in the smallest delay bound. The delay bound grows with the superframe order for small burst sizes. Enhanced IEEE 802.15.4 vs. standard IEEE 802.15.4 delay comparison is shown in Fig. 8. The superframe order SO = 2 is optimal for delivering the smallest delay bound since the effect of delay is more significant than the effect of guaranteed bandwidth. You should also take into account that the delay limitations guaranteed by SO = 8 are smaller than those for SO = 3 and SO = 4 in this scenario. When each node requesting the GTS has to send the same amount of data during each beacon period, as seen in Fig. 8. Nonetheless, the information that is affixed to each node is distinct from that of the other nodes. The results showed that for various amounts of SO, the standard introduces a significant amount of delay.

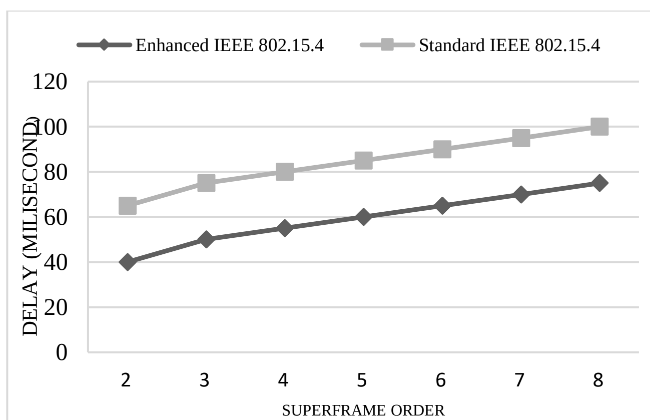

Fig. 8. Comparison between delay in IEEE 802.15.4 resulted from the original and our enhanced standard

The detailed result summary of simulation is shown below in Table 2.

Table 2

Results Summary

SO	Numbers of allocated devices		Total Bytes Received		Average Packet Delivered		Average Energy Consumption (J)		Total Delay	
	Standard IEEE 802.15.4	Enhanced Standard IEEE 802.15.4	Standard IEEE 802.15.4	Enhanced Standard IEEE 802.15.4	Standard IEEE 802.15.4	Enhanced Standard IEEE 802.15.4	Standard IEEE 802.15.4	Enhanced Standard IEEE 802.15.4	Standard IEEE 802.15.4	Enhanced Standard IEEE 802.15.4
2	0	0	1000	1217	0.250	0.510	0.0015	0.0015	67	41
3	7	10	1528	6162	0.121	0.441	0.0025	0.0018	77	52
4	7	25	3584	11522	0.312	1.110	0.004	0.0025	82	56
5	7	35	6571	16172	1.021	2.001	0.0045	0.003	86	61
6	7	45	14624	25621	1.221	3.201	0.0055	0.004	91	66
7	7	60	22431	38621	2.881	4.021	0.007	0.0045	97	71
8	7	70	35162	55231	3.814	5.502	0.0085	0.005	101	77

7. Conclusion

Before WPAN to be effectively used for large-scale applications, the IEEE 802.15.4 standard still needs significant revisions. Recent efforts have targeted decreasing power usage while increasing GTS utilization and ensuring system dependability. As part of this research, we have provided updates to the IEEE 802.15.4 protocol that enhance its capacity for GTS allocation. First, we seek to make GTS allocation more equitable in use cases when a long expiry period for GTS deallocation prohibits GTS slots from being made available to other devices in the network. Our innovative technique can be useful for remote sensing applications that are used to regularly prioritize sensing of crucial data. Using the simulation model that has been built for OMNeT++, we performed a simulated performance analysis. Based on the previous studies, we evaluated our enhanced protocol for a variety of BO and SO values to see how they affect the protocol's performance. Total data packets sent, average energy consumption, total bytes received, and delay duration were used for analysis. Using simulations, we were able to demonstrate that our proposed work increases GTS use, increases packet dependability, and makes GTS allocation realistic. The suggested works may be implemented with little changes to the existing IEEE 802.15.4 protocol and are compatible with earlier versions of the standard.

In the future, we plan to extend our work by using a more efficient techniques. Currently, the First Come First Serve (FCFS) technique is used. This technique lacks the sufficient scheduling flexibility and we believe that more elaborate schemes could significantly enhance the performance of the IEEE802.15.4.

7. References

[1] S.H. Ahmed, G. Kim, D. Kim, "Cyber-physical system: architecture, applications and research challenges", IFIP Wireless Days, Valencia, Spain, Nov. 2013.

[2] A. Moravejosharieh, J. Lloret, "A survey of IEEE 802.15. 4 effective system parameters for wireless body sensor networks", International Journal of Communication Systems, 29, 1269-1292, 2016.

[3] Networks, I.S.f.L.-R.W. IEEE Std 802.15. 4-2015 (Revision of IEEE Std 802.15. 4-2011). 2016.

[4] M.H.S. Gilani, L. Sarrafi, M. Abbaspour, "An adaptive CSMA/TDMA hybrid MAC for energy and throughput improvement of wireless sensor networks", Ad Hoc Networks, 11, 1297-1304, 2013.

[5] Z.A. Khan, M.B. Rasheed, N. Javaid, B. Robertson, "Effect of packet inter-arrival time on the energy consumption of beacon enabled MAC protocol for body area networks", Procedia Computer Science, 32, 579-586, 2014.

[6] C.H. Oliveira, Y. Ghamri-Doudane, S. Lohier,

"A duty cycle self-adaptation algorithm for the 802.15. 4 wireless sensor networks", Proceedings of the Global Information Infrastructure Symposium-GIIS, pp. 1-7, 2013.

[7] H. Rasouli, H.; Kavian, Y.S.; Rashvand, H.F. "ADCA: Adaptive duty cycle algorithm for energy efficient IEEE 802.15. 4 beacon-enabled wireless sensor networks", IEEE sensors journal, 14, 3893-3902, 2014.

[8] M.U.H. Al Rasyid, B.H. Lee, A. Sudarsono, "PEGAS: Partitioned GTS allocation scheme for IEEE 802.15.4 networks", Proceedings of the 2013 International Conference on Computer, Control, Informatics and Its Applications, pp. 29-32, 2013.

[9] S.E. Haque, "Efficient GTS allocation schemes for IEEE 802.15.4", 2012.

[10] X. Li, C.J. Bleakley, W. Bober, "Enhanced beacon-enabled mode for improved IEEE 802.15.4 low data rate performance", Wireless Networks, 18, 59-74, 2012.

[11] J. Chen, L.L. Ferreira, E. Tovar, "An explicit GTS allocation algorithm for IEEE 802.15.4", Proceedings of the ETFA2011, pp. 1-8, 2011.

[12] W. Choi, S. Lee, "A novel GTS mechanism for reliable multihop transmission in the IEEE 802.15.4 Network", International Journal of Distributed Sensor Networks, 8, 796426, 2012.

[13] N.T. Le, S. Choi, Y.M. Jang, "A new QoS resource allocation scheme using GTS for WPANs", Wireless Personal Communications, 67, 25-45, 2012.

[14] F. Xia, R. Hao, J. Li, N. Xiong, L.T. Yang, Y. Zhang, "Adaptive GTS allocation in IEEE 802.15.4 for real-time wireless sensor networks", Journal of Systems Architecture, 59, 1231-1242, 2013.

[15] F. Chen, F. Dressler, "A simulation model of IEEE 802.15. 4 in OMNeT++", Proc. of the 6th GI/ITG KuVS Fachgesprach Drahtlose Sensornetze, 35-38, 2007.

