

An Adaptive Superframe Duration Allocation Algorithm for Resource-Efficient Beacon Scheduling

Young-Ae Jeon*, Sang-Sung Choi*, Dae-Young Kim**, and Kwang-il Hwang***

Abstract

Beacon scheduling is considered to be one of the most significant challenges for energy-efficient Low-Rate Wireless Personal Area Network (LR-WPAN) multi-hop networks. The emerging new standard, IEEE802.15.4e, contains a distributed beacon scheduling functionality that utilizes a specific bitmap and multi-superframe structure. However, this new standard does not provide a critical recipe for superframe duration (SD) allocation in beacon scheduling. Therefore, in this paper, we first introduce three different SD allocation approaches, LSB first, MSB first, and random. Via experiments we show that IEEE802.15.4e DSME beacon scheduling performs differently for different SD allocation schemes. Based on our experimental results we propose an adaptive SD allocation (ASDA) algorithm. It utilizes a single indicator, a distributed neighboring slot incremter (DNSI). The experimental results demonstrate that the ASDA has a superior performance over other methods from the viewpoint of resource efficiency.

Keywords

Beacon Scheduling, Energy Efficient, IEEE802.15.4, IEEE802.15.4e, LR-WPAN, Superframe Duration Allocation

1. Introduction

Most wireless sensor networks have been developed based on the IEEE802.15.4 [1] standard, which supports various topologies, such as star, peer-to-peer, and a clustered tree, and different modes of operation, such as the beacon-enabled mode and the non-beacon mode. In particular, since a superframe structure in a beacon-enabled mode enables an energy efficient network to be constructed, most wireless sensor applications have made an attempt to use IEEE802.15.4 as their PHY and MAC layer. However, in multi-hop networks, beacon packets from different nodes have a high collision probability, and a beacon collision problem is therefore considered to be one of the most significant challenges in designing a multi-hop network that is based on IEEE802.15.4.

Over the past few years, several studies [2-13] have been conducted on improving the energy efficiency and reliability in multi-hop networks that are based on IEEE802.15.4. Most of them have mainly focused on solving beacon collision problems. More specifically, the authors of [2-9] proposed the use of beacon scheduling algorithms and protocols for multi-hop tree networks that are based on

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ZigBee [14]. While these studies addressed the beacon-collision problem in a multi-hop network, most of them have only focused on the tree architecture in which some failures can make a partial or entire network lose connectivity to its root. Instead, a mesh architecture, which is able to provide high reliability and a fast error recoverability by maintaining multiple paths, is more suitable for various applications with different network topologies. Other bodies of research [10-12] have dealt with beacon scheduling methodologies for mesh-based multi-hop networks. However, these proposals, which are based on IEEE802.15.4, do not overcome the inherent limitations of PHY and MAC. In parallel, TG4e [15] has rolled out the IEEE802.15.4e draft for an enhancement of the MAC layer of IEEE802.15.4-2006. In particular, the emerging new standard, IEEE802.15.4e, or more specifically, the deterministic and synchronous multichannel extension (DSME) capability, contains a mesh-enabled, beacon-scheduling functionality that utilizes a specific bitmap and a multi-superframe structure. However, the standard does not yet provide a critical recipe for a superframe duration (SD) allocation method or for concrete implementation details on the proposed beacon scheduling. Therefore, critical system performance, in terms of resource use, such as processing, memory, and energy, might depend significantly on which SD index allocation algorithm is applied. In this paper, we provide concrete implementation guidelines for IEEE802.15.4e beacon scheduling, and then carry out various experiments on different SD allocation algorithms, which include the least significant bit (LSB) first, most significant bit (MSB) first, and random. Based on the results of our experiments, we also propose an adaptive SD allocation algorithm that utilizes a distributed neighboring slot incremter (DNSI), instead of using a SD bitmap, to manage neighboring scheduled beacon slots.

The remainder of this paper is organized as follows: in Section 2, various beacon scheduling algorithms and protocols for multi-hop communications based on IEEE802.15.4 are investigated. Section 3 provides an overview of the new standard, IEEE802.15.4e DSME, particularly for beacon scheduling functionality. In Section 4, we carry out various experiments on different SD allocation methods, and thoroughly analyze the experimental results from the viewpoint of resource efficiency. Based on the results of our experiments, Section 5 describes the development of an adaptive SD allocation algorithm for resource-efficient beacon scheduling. Next, a performance comparison is evaluated in Section 6. Finally, Section 7 provides some concluding remarks regarding this proposal.

2. Related Work

Over the last few years, a lot of research has focused on beacon scheduling to efficiently manage beacon collisions in multi-hop communication that is based on IEEE802.15.4. Some researchers [2-9] have focused on preventing beacon collisions among coordinators or routers in a tree network. Two different proposals by TG4b [2] have dealt with beacon collision and interference problems among different coordinators. The first approach is to use a contention-free time slot in its active period by utilizing a specific indicator called a `beacon_tx_offset` between the parent beacon and child beacon. Moreover, this approach was reflected in the ZigBee specifications [14]. The second approach uses a dedicated beacon-only period in which only scheduled beacon frames are allowed to transmit. However, this research did not address the issue of time offset selection by neighboring coordinators. A time-division beacon scheduling method for clusters has been proposed by Koubaa et al. [3]. Based on the assumption that PAN coordinators are aware of their neighbors' location and connection

information, each PAN coordinator schedules all coordinators and routers. A method proposed by Cho and An [4] first constructs clusters using different transmission power, and then makes the PAN coordinator allocate a beacon slot and a group ID to the group headers. However, this approach might give the PAN coordinator increased overhead due to a centralized beacon slot allocation. A slotted beacon scheduling method proposed by Ahn et al. [5] uses a slot allocation method coupled with the Cskip address allocation scheme used for ZigBee. In addition, a method to use separate slots for an uplink and a downlink in a superframe was proposed by Yeh et al. [6]. To efficiently reuse slots in a tree network, a stochastic beacon scheduling method has been introduced in [7]. For a specific sensor application, such as target monitoring, an adaptive beacon interval method, with respect to varying the detection level of the target, has been proposed by Chen et al. [8]. In addition, Kim and Yoon [9] proposed a tree-routing protocol based on a hybrid scheme combining distributed and stochastic addressing methods. Although these studies address a beacon-collision problem in a multi-hop network, most of them have focused only on a tree architecture in which failures of some point can make a partial or entire network lose connectivity to its root.

A mesh architecture, which is able to provide high reliability and a fast error recoverability by maintaining multiple paths, is more suitable for various applications with different network topologies. Burda and Wietfeld [10] made an attempt to construct autonomous and distributed mesh networks in the beacon-enabled mode, in which the PAN coordinator selects and allocates a random beacon slot for slot request nodes. However, this algorithm requires a long integrity checking time and still has a high collision probability of the request packets. The WPAN mesh network proposed by TG5 [11] characterizes block address assignments and a connection matrix. Even though this standard is to construct a mesh network based on WPAN, asynchronous energy saving in non-beacon mode might increase unnecessary delays and the wasting of energy. Moreover, the initial setup phase is still based on a tree topology. In addition, MeshMAC [12] proposed a distributed beacon scheduling for a mesh network, but it did not address a neighboring beacon slot collection method, which is the key point of distributed beacon scheduling. The IEEE802.15.4e standard [15], more specifically, DSME capability, provides the specifications regarding the concept level of bitmap-based distributed beacon scheduling. However, the standard does not yet provide a critical recipe for an SD allocation method or concrete implementation details regarding the proposed beacon scheduling.

Our former work [13] dealt with a distributed, fast beacon scheduling method for mesh networks. However, while we previously presented only a conceptual model for bitmap-free beacon scheduling, this paper provides a more concrete, explicit SD allocation algorithm and beacon scheduling methodology by introducing three possible SD allocation algorithms and analyzing the IEEE802.15.4e DSME beacon scheduling through various experiments.

3. Overview of IEEE802.15.4E Beacon Scheduling

IEEE802.15.4e DSME is one of the different operation modes of eMAC (TSCH, LLDN, RFID Blink, DSME, and AMCA), and characterizes mesh-based beacon collision free networks. In particular, the distributed beacon scheduling functionality is one of the outstanding new features in the DSME standard. DSME beacon scheduling is based on the multi-superframe structure in a beacon interval of a PAN coordinator node. This feature allows neighboring nodes to allocate different beacon slots in a

distributed way. To allocate its own beacon slot, each node manages the SD indexes of its neighboring nodes. More specifically, the SD index information of all neighboring nodes is represented as a bitmap structure and issued through an enhanced beacon frame. A coordinator who wants to join the PAN can collect its neighboring SD index information from received beacon frames, allocate a vacant SD index slot for itself, and broadcast an allocation notification command frame containing its allocated SD index value to its neighbors. All nodes receiving the frame check whether the allocated SD index value exists or not in their man-aging neighbor SD index bitmap. If it does, the nodes reply with a collision notification command frame to the sender. Otherwise, the new SD index value is marked as 'Active.' As a result, each node can realize the SD index allocation information through their two-hop neighbors. This distributed beacon scheduling can construct a beacon-enabled mesh network. However, the standard does not provide the following critical ingredients for a slot allocation or implementation details about beacon scheduling functionality. It is important to note that these matters, which are not specified in the DSME standard, might generate a significant performance variation in the resource usage for items, such as processing, memory, and energy, depending on the implementation methodologies that are applied.

4. Experimental Study on Three Possible SD Allocation Approaches

In this section, we first provide concrete implementation guidelines for IEEE802.15.4e DSME beacon scheduling, and then introduce three possible SD allocation algorithms. Based on the design and implementation guidelines, we carried out various experiments on different SD allocation methods, and thoroughly analyzed the experimental results based on their resource efficiency.

4.1 Implementation Considerations

The DSME standard only considers a single SD bitmap and macSDBitmap in macPIB for beacon scheduling, but two independent bitmap spaces (a beacon bitmap and a neighbor [NBR] bitmap) are needed for real implementation. A beacon bitmap is needed, so that it can seek its own SD index location. The bitmap field included in an extended beacon is copied to the beacon bitmap. A node can select a slot out of the vacant SD slots in the bitmap for its candidate SD index, and the corresponding bit in the bitmap is then set. The node then broadcasts an allocation notification message with its new candidate SD index. The neighbor nodes that received the allocation notification message check whether the received SD index value already exists in the neighbor bitmap. If so, the neighbor node notifies the originator that the SD index is already occupied by sending a collision notification message. The originator that received the collision notification message reselects its candidate SD index and then broadcasts an allocation notification with this new SD index. This SD allocation procedure is repeated until collision notification messages are no longer received. While a beacon bitmap is used to seek its own candidate SD index from the received beacon, the neighbor bitmap is used to notify neighbors of the latest neighbor SD index information and is contained in its cyclic extended beacon. Even though the usage of two independent bitmaps is not specified in the DSME standard, utilizing these two independent bitmaps is indispensable for DSME beacon scheduling operations. SD allocation starts by receiving an extended beacon containing the SD bitmap field. As mentioned previously, every node

should select a vacant slot (superframe) to be used for its SD index, based on the SD bitmap. However, the standard does not provide the criteria for selecting an SD index from the received beacon bitmap.

Therefore, we are introducing three different selection algorithms: LSB first, MSB first, and random.

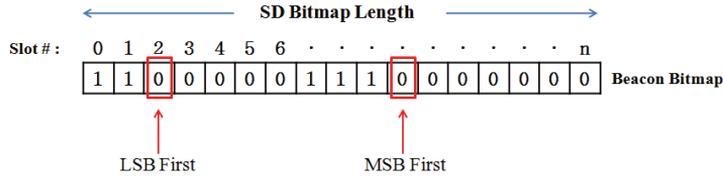
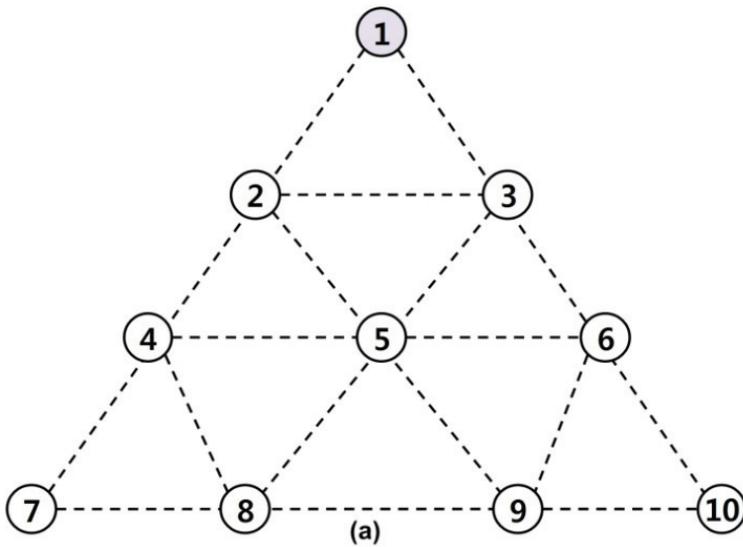


Fig. 1. Superframe duration (SD) allocation criteria.



	Node1	Node2	Node3	Node4	Node5
LSBfirst	NBR bitmap	0000 0111	0001 1111	0011 0111	0101 1011
	SD index	0000 0001	0000 0010	0000 0100	0000 1000
MSBfirst	NBR bitmap	0000 0111	0001 1111	0011 0111	0111 1010
	SD index	0000 0001	0000 0010	0000 0100	0000 1000
RANDOM	NBR bitmap	0000 1000 0000 0101	0000 1001 0000 1101	0001 1001 0000 0101	0000 1001 0000 1101
	SD index	0000 0000 0000 0001	0000 1000 0000 0000	0000 0000 0000 0100	0000 0000 0000 1000
LSBfirst	NBR bitmap	1011 0101	0100 1001	1101 1001	1111 0001
	SD index	0010 0000	0000 0001	0100 0000	1000 0000
MSBfirst	NBR bitmap	1 1011 0100	0110 1000	1111 1000	1 1111 0000
	SD index	0 0010 0000	0010 0000	0100 0000	0 1000 0000
RANDOM	NBR bitmap	0001 1001 0000 1100	0000 0000 0000 1101	1000 0001 0000 1101	1001 0001 0000 1001
	SD index	0001 0000 0000 0000	0000 0000 0000 0100	0000 0000 0000 0000	0000 0000 0000 1000

(b)

Fig. 2. Beacon scheduling results of MSB first, LSB first, and random.

Fig. 1 describes the criteria for LSB first and MSB first from the received SD bitmap. The LSB first scheme seeks the least slot value out of all of the vacant slots (0). Conversely, the MSB first scheme selects a vacant slot immediately following the allocated slot with the largest value. Lastly, the random scheme selects a vacant slot randomly within the SD bitmap length. Fig. 2(b) lists the results of the DSME beacon scheduling on individual SD allocation mechanisms (LSB first, MSB first, and random),

on the same network topology, which is shown in Fig. 2(a). The results demonstrate that the SD index allocation of each node differs according to the underlying SD allocation method. Therefore, we presume that the DSME beacon scheduling might show a different performance according to the SD allocation scheme that is applied.

4.2 Experimental Analysis

In this subsection, an experimental study of DSME beacon scheduling on different SD allocation schemes is described. To perform more extensive evaluations, we developed a WPAN beacon scheduling simulator framework in which each algorithm is implemented independently using C and C++. The developed simulator constructs entities of each node based on various input parameters, as shown in Table 1, and an even-driven scheduler processes various events that occur during the run time. The simulator also supports various topologies, and in particular, we used the following three different types of topologies for our experiments: tree, mesh, and cluster. On each topology, we observed the association completion time, the required bitmap size, and the amount of traffic by varying the network size from 3×3 to 10×10 in the tree and mesh topologies, and from 10 to 100 cluster members in the cluster topology, as shown in Fig. 3.

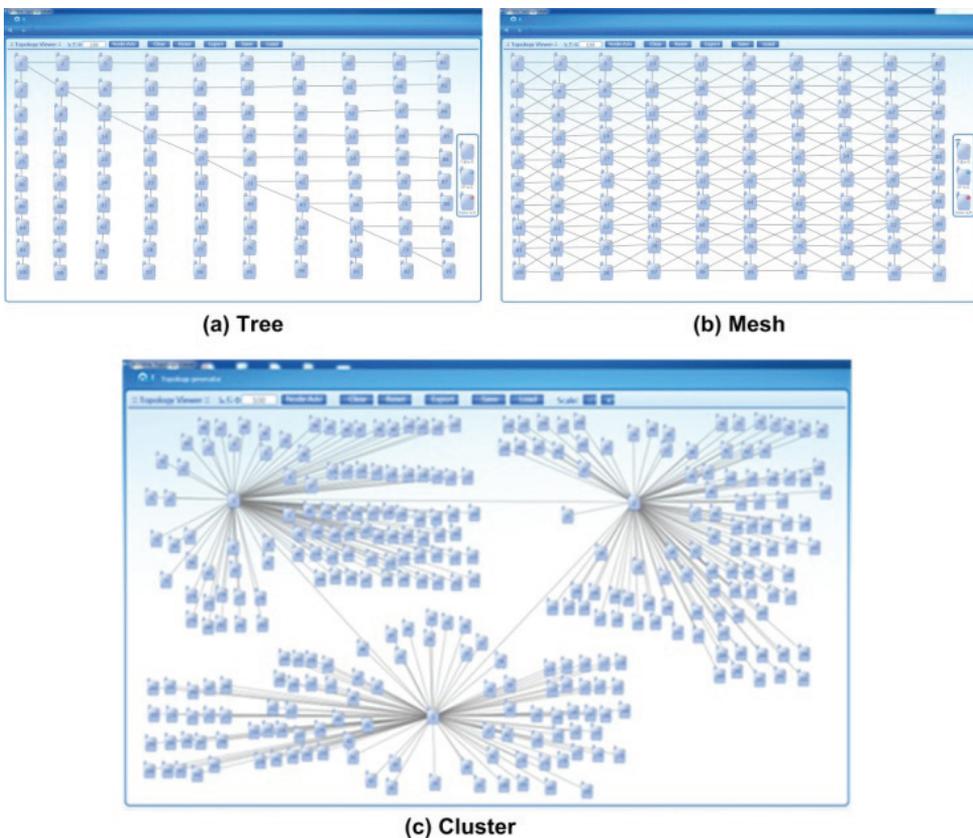


Fig. 3. Experimental topologies: tree, mesh, and cluster.

Table 1. Experimental parameters

Parameter	value
aBaseSlotDuration	60 Symbols
aNumSuperframeSlots	16
aBaseSuperframeDuration	960 Symbols
MaxNumOfNodesInSlot	256
MaxBitmapLength	512 bits
SO (Superframe Order)	1
MO (Multiframe Order)	0
BO (Beacon Order)	Variable
MaxNumOfNBRNode	32
MaxNumOfNodes	1000
Symbol Time	16 μs

T	Tree												Mesh												T	Cluster											
	128				256				512				128				256				512					128				256				512			
	N	A	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L		M	R	L	M	R	L	M	R				
3 X 3	61	61	1044		61	61	3533		61	61	5975		61	61	46		61	61	2212		61	61	5115	30	46	46	6528		46	46	7864		46	46	7511		
4 X 4	2012	108	3287		3978	108	6697		7910	108	11766		123	138	1260		123	138	6344		123	138	5775	40	61	46	7880		61	46	7219		61	46	8340		
5 X 5	3963	138	4086		7895	138	7496		15759	138	14577		2028	215	2181		3994	215	3471		7926	215	14131	50	77	46	7880		77	46	5100		77	46	7880		
6 X 6	5914	169	4378		11812	169	11981		23608	169	15160		2120	292	4255		4086	292	9308		8018	292	14116	60	92	46	9984		92	46	6620		92	46	9062		
7 X 7	5944	200	6267		11843	200	15206		23639	200	26204		4009	384	4531		7941	384	8786		15805	384	19154	70	108	46	8617		108	46	7235		108	46	7880		
8 X 8	7895	230	7511		15759	230	19814		31488	230	28093		5929	476	5192		11827	476	8095		23624	476	21427	80	123	46	11812		123	46	16343		123	46	13056		
9 X 9	9846	261	12948		19676	261	19983		39337	261	35082		4070	568	4454		8003	568	9093		15867	568	19476	90	138	46	22072		138	46	15744		138	46	15744		
10 X 10	9876	292	9247		19707	292	19845		39368	292	43546		5960	676	5484		11858	676	7081		23101	676	21458	100	154	46	30459		154	46	12380		154	46	23578		

T:Topology, N: Network Size, B: Beacon Interval, A: Algorithm, L: LSB First, M: MSB First, R: Random, Unit: msec

(a) Association Complete Time

T	Tree												Mesh												T	Cluster											
	128				256				512				128				256				512					128				256				512			
	N	A	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L		M	R	L	M	R	L	M	R				
3 X 3	5	7	124		5	7	230		5	7	452		9	9	128		9	9	227		9	9	333	30	33	33	127		33	33	256		33	33	510		
4 X 4	5	9	121		5	9	247		5	9	501		10	14	109		10	14	233		10	14	456	40	43	43	127		43	43	256		43	43	505		
5 X 5	5	11	119		5	11	232		5	11	511		11	19	126		11	19	241		11	19	507	50	53	53	128		53	53	255		53	53	509		
6 X 6	5	13	122		5	13	250		5	13	505		11	24	124		11	24	256		11	24	485	60	63	63	128		63	63	255		63	63	511		
7 X 7	5	15	117		5	15	251		5	15	490		11	31	126		11	31	241		11	31	511	70	73	73	127		73	73	256		73	73	510		
8 X 8	5	17	128		5	17	255		5	17	510		11	38	124		11	38	244		11	38	495	80	83	83	128		83	83	256		83	83	511		
9 X 9	5	19	128		5	19	255		5	19	509		13	45	128		13	45	249		13	45	509	90	93	93	128		93	93	255		93	93	509		
10 X 10	5	21	128		5	21	255		5	21	503		11	52	128		11	52	256		11	52	509	100	103	103	128		103	103	256		103	103	511		

T:Topology, N: Network Size, B: Beacon Interval, A: Algorithm, L: LSB First, M: MSB First, R: Random, Unit: Bits

(b) Required Bitmap Size

T	Tree												Mesh												T	Cluster											
	128				256				512				128				256				512					128				256				512			
	N	A	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L		M	R	L	M	R	L	M	R				
3 X 3	21	21	12		21	21	13		21	21	12		22	22	12		22	22	12		22	22	12	30	273	273	368		273	273	240		273	273	151		
4 X 4	42	39	40		42	39	28		42	39	31		42	42	21		42	42	29		42	42	23	40	363	363	622		363	363	309		363	363	238		
5 X 5	73	60	61		73	60	56		73	60	50		77	69	38		77	69	47		77	69	50	50	453	453	755		453	453	355		453	453	230		
6 X 6	114	86	84		114	86	92		114	86	79		119	98	84		119	98	84		119	98	74	60	543	543	1146		543	543	458		543	543	405		
7 X 7	163	116	139		163	116	138		163	116	132		177	135	113		177	135	110		177	135	93	70	633	633	1118		633	633	570		633	633	322		
8 X 8	235	150	200		235	150	242		235	150	197		260	174	147		260	174	134		260	174	110	80	723	723	1665		723	723	1254		723	723	594		
9 X 9	321	188	383		321	188	302		321	188	251		294	222	177		294	222	182		294	222	187	90	813	813	3292		813	813	1409		813	813	759		
10 X 10	415	230	338		415	230	312		415	230	459		381	267	242		381	267	186		381	267	231	100	903	903	4862		903	903	1284		903	903	1179		

T:Topology, N: Network Size, B: Beacon Interval, A: Algorithm, L: LSB First, M: MSB First, R: Random, Unit: Packets

(c) The number of Traffic

Fig. 4. Summary of the experimental results.

4.2.1 Association completion time

Fig. 4(a) shows the experimental results of the association completion time under various conditions. The association completion time is defined as the time until the superframe allocation of all nodes is completed. Therefore, we measured the time spent until the end of the superframe allocation of the last node was completed, starting from the first beacon reception of the PAN coordinator. The results demonstrate that the MSB first scheme outperforms the LSB first and random schemes under all circumstances. In particular, LSB first shows a large variation in the association completion time with respect to a varying network size. In the LSB first scheme, if a node selects a vacant slot preceding the current ongoing superframe number, the node should wait until its SD index turns in the next beacon interval, and it can then continue to carry out the beacon scheduling with its children. These situations frequently occur in the random scheme, as well as in LSB first. In particular, the larger the network size and the smaller the connected links, the more the delay is increased. On the other hand, since MSB first always seeks a vacant slot immediately following the allocated slot with the largest value, the new SD index does not precede the current ongoing superframe number. Therefore, any unnecessary delay until the next beacon interval is removed. The results also show that the MSB first scheme allows all nodes to be associated within 700 ms in each topology with 100 nodes at a maximum BO size of 512. On the other hand, it shows that LSB first spends more than 10 beacon intervals for the association completion.

4.2.2 Required bitmap size

The bitmap that reflects the neighboring SD index information is included in its extended beacon and is transmitted periodically together with the latest neighbor information. The bitmap length is specified in the SD bitmap length field of the extended beacon. The SD bitmap length is generally defined as 2 (BO-SO) bits, and the BO value should be no more than 10, including the mandatory header fields, since the maximum frame size of IEEE802.15.4 is limited to 128 bytes. That is, the maximum available length is 512 bits (64 bytes). Furthermore, if the length is too small, the number of available superframes for the new nodes is insufficient, and the PAN coordinator should start with a length that is great enough to accommodate the nodes which will be associated. For example, if it is expected that at least 100 nodes will be associated with the network, the PAN coordinator should secure a bitmap space of at least 128 bits, the BO value of which is 8. Under these conditions, Fig. 3(b) shows the required bitmap size for all of the nodes that will be associated with the network. The required bitmap size represents the maximum occupied bitmap size during the association procedure. It is notable that LSB first shows a considerable reduction of bitmap size over LSB first and the random scheme, even if the network size is increased. This is because LSB first selects the front-most vacant slot, and thus, the superframe reuse ratio is increased. Accordingly, the required bitmap size can be reduced. Since the random scheme selects a vacant slot randomly within the maximum SD index length, the slot reuse ratio is very low, and thus, an increased bitmap size is required. Since a bitmap represents the allocation information of all neighbors within two hops, the bitmap size might vary according to the number of connected links. More specifically, the required bitmap size is increased proportionally to the number of connected links. Therefore, the required bitmap size, $L(i)$, of an arbitrary node is determined as follows:

$$\forall i \text{ and } j \in M \text{ and } i, j > 0, L(i) = N(A_i) + \max_{j \in A_i} \{N(A_j)\} \quad (1)$$

where, M is a set of nodes in the network, and $N(A_i)$ represents the total number of neighboring nodes of node i .

In particular, in a cluster topology, the required bitmap size is the sum of the number of cluster headers and the total number of cluster members of a cluster, which has the largest number of cluster members among the clusters. In this case, the bitmap size of both the MSB first and LSB first reach the maximum value. The results show that in the case of a cluster topology, in which there are three clusters and each cluster has 100 members, the required bitmap size is 103. The results prove (1). Therefore, as the number of connected links is increased, the required bitmap size in all of the allocation schemes is also increased.

4.2.3 The traffic amount

Fig. 4(c) shows the amount of traffic, which includes all beacon, allocation notification, and collision notification messages generated during beacon scheduling. The results show that LSB first generates the most amount of traffic. This increased traffic amount is caused by additional allocation messages due to collisions that occur during beacon allocation and because of beacon messages that are generated during a long association time. It is important to note that, in a mesh topology, the random scheme generates less traffic than the other two schemes. Since the random method randomly selects a vacant slot when a beacon bitmap is received, the collision ratio in the network is decreased. However, the performance is degraded in the case of a tree topology, which has few link connections, or a cluster topology, which has numerous link connections.

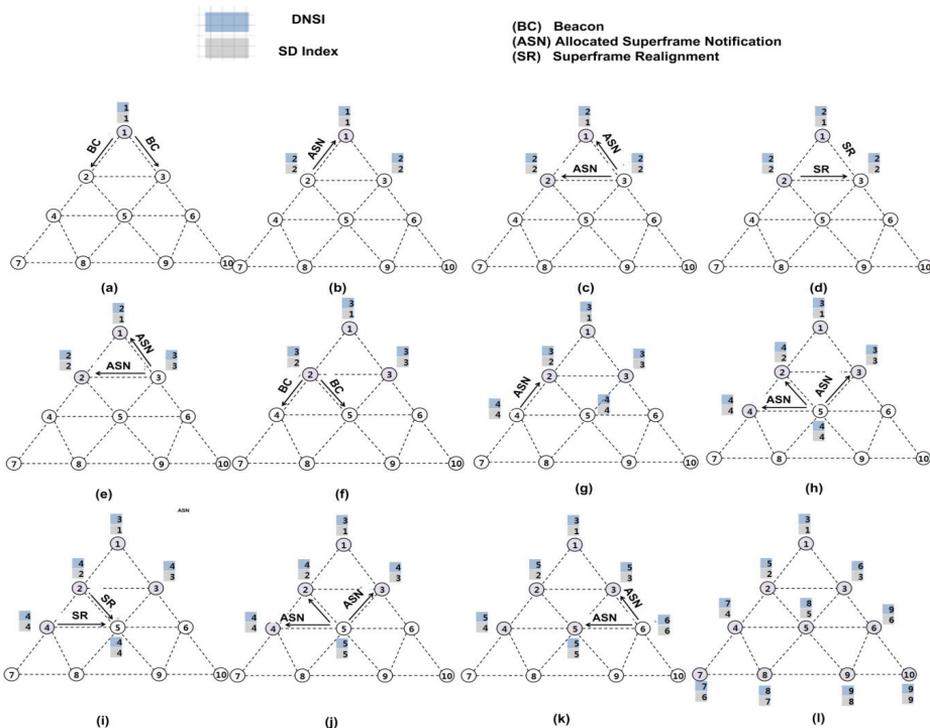


Fig. 5. Beacon scheduling operation based on ASDA.

4.3 Summary

We verified that IEEE802.15.4e DSME beacon scheduling performs differently based on the SD allocation schemes applied. LSB first shows a superior performance for the required bitmap size. In fact, LSB first makes it possible to allocate all nodes with only 11 bits, even in a 10×10 mesh network. However, the experimental results revealed that LSB first generates too much traffic, and in particular, has a long association time. Therefore, this might lead to a large amount of energy being wasted during network construction time. The MSB shows the fastest association, but the required bitmap size is significantly increased along with the network size. The increased bitmap size expands the beacon frame size, thus lengthening the channel occupancy time. Eventually, it might bring an increase in the collision probability and error rates. Furthermore, the increased bitmap size brings about wasted memory resources, and it may eventually become impossible for some nodes to be allocated if the bitmap size exceeds 64 bytes. These limitations are not suitable for a large-scale network covering a wide area. The random scheme shows a slightly better performance in terms of the traffic amount, but it also demonstrates the worst performance in the association completion time and required bitmap size. Therefore, this scheme is not desirable as an SD allocation mechanism for DSME beacon scheduling. As a result, all SD allocation schemes have both strengths and weaknesses. Therefore, it is necessary to develop a new SD allocation mechanism that can accommodate all of these strengths.

5. Adaptive Superframe Duration Allocation

In this section, we describe an adaptive SD allocation (ASDA) algorithm for resource-efficient beacon scheduling that is based on the experimental results performed in the previous section. Since all of the methods (LSB first, MSB first, and random) perform bitmap-based SD allocation, they cannot overcome the limitations of the bitmap itself. Therefore, instead of using a bitmap, we attempted using a different approach for SD allocation utilizing a DNSI to manage neighboring scheduled beacon slots. In addition, the allocation notification message and collision notification message used in IEEE802.15.4e DSME are replaced with an allocated superframe notification message and superframe realignment message, respectively. First, each node initializes the DNSI value by '0,' and the PAN coordinator sends its periodic extended beacon containing its current DNSI value. If node i receives an extended beacon from node j , it compares its current DNSI value with the DNSI value in the received beacon. If $DNSI(i) \leq DNSI(j)$, node i applies $DNSI(i) = DNSI(j) + 1$, and then broadcasts an allocated superframe notification message containing the updated DNSI value and starts an allocation timer. The neighboring nodes that receive the allocated superframe notification message compare the DNSI value with its own DNSI. If node k receives an allocated superframe notification from node i , and $DNSI(k) \geq DNSI(i)$, node k sends a superframe realignment message with its current DNSI value to the originator. However, if $DNSI(k) < DNSI(i)$, node k applies $DNSI(k) = DNSI(i)$. Upon receipt of a superframe realignment message, node i restarts the allocation timer and compares its current DNSI value with the DNSI value received from node k . If $DNSI(i) \leq DNSI(k)$, node i applies $DNSI(i) = DNSI(k) + 1$, and then rebroadcasts the allocated superframe notification message containing the updated DNSI value. This process lasts until the allocation timer expires. As soon as the timer expires, the SD index value of node i is determined to be the current DNSI value. Through this iterative DNSI

increment process, each node can allocate a unique SD index within two neighbors. This is because the DNSI value of the node, which has already completed allocation, represents the maximum DNSI value of their neighboring nodes, and the SD index value of a new node becomes a value greater than the maximum DNSI value out of all active neighboring nodes. Fig. 5(a)–(k) illustrate the process of beacon scheduling used in the proposed SD allocation algorithm; the final result of which is shown in (1). In this way, the proposed SD allocation scheme is simple, but it enables fully distributed beacon scheduling among the neighbor nodes. Furthermore, compared to the other SD index allocation algorithms based on a bitmap, the ASDA, which utilizes only a single variable, DNSI, can reduce the wasting of memory resources, as it requires only 1 or 2 bytes of memory space.

6. Performance Evaluations

In this section, a performance evaluation of the proposed ASDA is described, as compared to the LSB first, MSB first, and random methods. The ASDA experiments were conducted under the same experimental environment described in Section 3.

Fig. 6 shows variations in the association completion time of each algorithm with respect to a varying BO size of 64 to 512 bits. Note that the ASDA outperforms the LSB first and random schemes and shows a similar association completion time as the MSB first scheme, which has a superior performance. In addition, the results also demonstrate that the proposed scheme is rarely affected by a variation in the BO size, and the association of all of the nodes is complete within 670 ms for every BO size. Since the ASDA does not utilize a bitmap, and all of the nodes always select a vacant slot after the current ongoing superframe value for their SD index, an unnecessary delay until the next beacon interval might be removed.

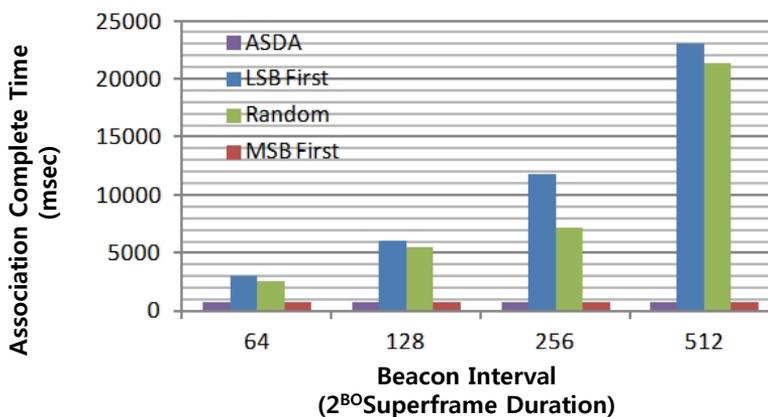


Fig. 6. Comparative results of the association completion time.

Fig. 7 shows the comparative results of the ASDA, LSB first, and MSB first methods with respect to the required bitmap size. Since the random method leads to too much bitmap waste, as discussed in Section 3, it is excluded in this experiment. The results show that the ASDA outperforms even MSB first, which has a superior performance in terms of the required bitmap size. In fact, the ASDA allows

100 nodes to be allocated in just 4 bits at a BO size of 64 bits, and 7 bits at BO sizes of 128, 256, and 512 bits. On the other hand, the bitmap of LSB first is increased by 52 bits. This reduction in the required bitmap size is enabled by SD allocation utilizing a single variable of a fixed length (DNSI), rather than using a bitmap. For algorithms that use a bitmap, as the number of connected links is increased, the number of bitmaps is also increased as in (1), and the maximum bitmap size cannot exceed 512 bits (64 bytes). On the other hand, the ASDA can accommodate a maximum of 65,535 neighbors with only a single variable (DNSI) of 16 bits in length. Fig. 8 shows the comparative results with respect to the amount of traffic. The random method has the smallest amount of traffic, but is not desirable when considering other performance aspects, as discussed in the previous section. The results demonstrate that the ASDA generates a reasonable amount of traffic. As a result, the experimental results demonstrate that the ASDA, which overcomes the limitations of algorithms that depend on a bitmap, has a superior performance over the other methods in various aspects. In other words, the ASDA enables resource-efficient beacon scheduling.

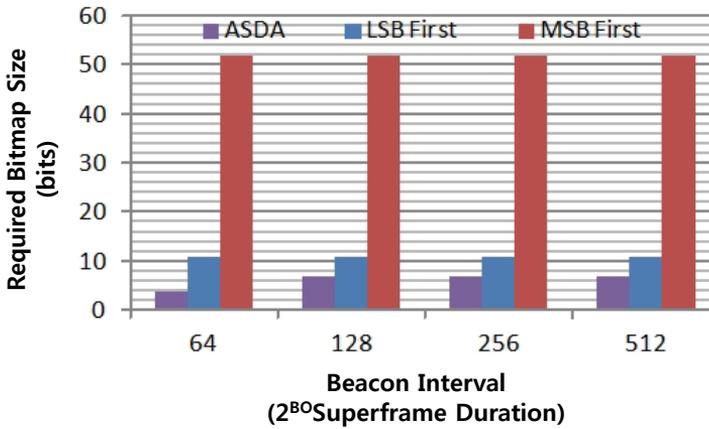


Fig. 7. Comparative results based on the required bitmap size.

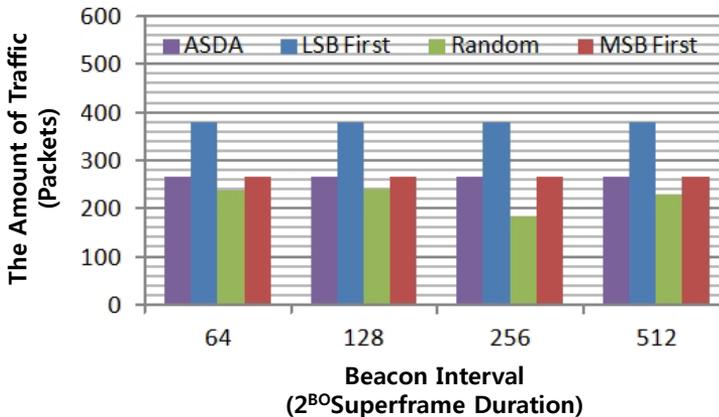


Fig. 8. Comparative results based on the traffic amount.

7. Conclusion

In this paper, we emphasized the design and implementation of the SD allocation algorithm for resource-efficient beacon scheduling. In particular, it was demonstrated experimentally that the ASDA enables an energy-efficient association by reducing an unnecessary active waiting period for completing the association procedure of all of the nodes in the network; it minimizes memory utilization, which is necessary for beacon scheduling, by utilizing only a fixed-length single variable for representing neighboring SD indexes; and it saves more energy by generating a small amount of traffic during the beacon scheduling procedure. Therefore, it is expected that the several features of ASDA will provide a major contribution to the design of resource-efficient beacon scheduling for various applications that require an adaptive Low-Rate Wireless Personal Area Network (LR-WPAN).

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