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Bandwidth-Oriented Allocation of GTS Slots for IEEE802.15.4

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***Abstract*:** IEEE802.15.4 gains more popularity as a standard communication protocol for Wireless Personal Area Networks (WPAN). IEEE802.15.4 tries to ensure the requested performance for associated devices by allocating fixed-length Guaranteed Time Slots (GTSs) to these devices. However, the original standard suffers from a scalability problem, as it supports a maximum of seven devices. Furthermore, as all timeslots have fixed length, more time is often allocated to devices than their actual need. This is known as a bandwidth underutilization or a slot size-induced bandwidth waste problem. In this paper, we propose an efficient scheme to assign GTS slots to IEEE802.15.4. Our scheme uses variable-length timeslots that are allocated to devices based on their actual bandwidth. Simulations of different GTS allocation techniques are conducted using OMNeT++ simulator. These simulations show that our scheme outperforms the standard as well as previous techniques, which employ fixed-length timeslots. Obtained experimental results prove that our allocation scheme could support a number of devices that is orders of magnitude higher than previous allocation techniques. It also overcomes the bandwidth underutilization problem by taking the bandwidth waste into minimum.

***Keywords*:** IEEE802.15.4, low rate wireless personal area networks (LR-WPAN), slot size-induced bandwidth waste, throughput, wireless sensor networks (WSN).

1. Introduction

In recent years, the use of Low Rate Wireless Personal Area Networks (LR-WPANs) and Wireless Sensor Networks (WSNs) significantly expands in different application domains. Few examples of these domains are environment monitoring, health care, surveillance, and tracking. LR-WPAN is characterized by low data rate, low latency, low power consumption, and short-range radio communication. IEEE802.15.4 is the most widely used communication protocol for LR-WPAN [1].

It is a simple protocol that covers only two layers; the physical and the Medium Access Control (MAC) layers. Despite this simplicity, IEEE802.15.4 proves itself as a reliable communication standard [2].

IEEE802.15.4 could be configured in one of two operation modes; beacon and non-beacon modes. In this paper, we are mainly concerned with the beacon mode, as it is the one that assures a guaranteed performance to its associated devices. This guaranteed performance is secured by reserving specific period, or periods, in the superframe for any device that requests a certain Quality of Service (QoS). In the original standard, each period is called a Guaranteed Time Slot (GTS). The greatest allowable number of GTSs is 7. In turn, this limits the number of associated devices, which have guaranteed performance, into 7. As LR-WPAN is widely deployed in many applications with increasing number of connected devices and sensors, this limited number of GTSs constitutes the first drawback of the original protocol. As such, for large Personal Area Network (PAN), many devices might not be allocated the bandwidth they request. Therefore, researchers tried to modify the original standard to be able to accommodate more devices. In this paper, we also tackle this problem by presenting a new GTS allocation technique that maximizes the number of associated devices for IEEE802.15.4.

The second challenge that affects the performance of IEEE802.15.4 is the improper use of the available bandwidth. The original protocol uses constant duration for all GTSs. These GTSs are allocated to requesting devices, irrespective of their actual need. In many instances, the device uses only a portion of this duration and leaves the rest non-utilizable. In the literature, this problem is known as the bandwidth underutilization or the slot size-induced bandwidth waste problem. Researchers tried to overcome this problem by shortening the GTS duration. However, as the requested bandwidth is not known apriori, this technique could not completely cancel the waste problem. In this paper, we propose a bandwidth-oriented GTS allocation scheme that completely removes any bandwidth waste. Unlike previous allocation techniques, ours use GTSs with variable durations. The size of each GTS is dynamically decided according to the requested bandwidth by the associated device. This proper GTS allocation would take the bandwidth underutilization problem into minimum, Furthermore, it would realize the maximum possible number of associated devices.

The rest of this paper is outlined as follows. Section 2 demonstrates an overview of the IEEE802.15.4 LR-WPAN protocol, Section 3 discusses previous related work for GTS allocation. Section 4 presents our bandwidth-oriented GTS allocation scheme. Section 5 gives out results and evaluates our proposed scheme against the original protocol as well as other protocols from the literature. Finally, Section 6 concludes our work and gives some directions for future work.

2. Overview of the IEEE802.15.4 MAC Protocol

The IEEE802.15.4 standard could be configured in one of two operational modes, 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.

Figure 1 shows the structure of the beacon-enabled IEEE802.15.4 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 addresses, and the PAN identifier. As shown in the figure, the superframe is divided into active and optional inactive periods. The active period is further partitioned into a Contention Access Period (CAP) and a Contention Free Period (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 throughout this paper by aMinCAPLength constraint. Finally, the CFP length limitation unfortunately prevents the original standard from providing guaranteed performance to more than 7 devices.

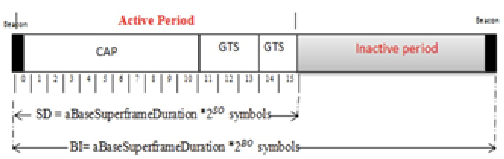

Figure 1. IEEE802.15.4 superframe structure in the beacon-enabled mode

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

Table 1. The value of SD, Tslot, and aMinCAPLength for different value of SO

SO	**SD** (sec)	$\mathbf{T_{solt}}$ (sec)	**aMinCAPLength** (sec)
0	0.01536	0.00096	0.00864
1	0.03072	0.00192	0.01728
2	0.06144	0.00384	0.03456
3	0.12288	0.00768	0.06912
4	0.24576	0.01536	0.13824
5	0.49152	0.03072	0.27648
6	0.98304	0.06144	0.55296
7	1.96608	0.12288	1.10592
8	3.93216	0.24576	2.21184
9	7.86432	0.49152	4.42368
10	15.72864	0.98304	8.84736
11	31.45728	1.96608	17.69472
12	62.91456	3.93216	35.38944
13	125.82912	7.86432	70.77888
14	251.65824	15.72864	141.55776

BO and SO increases the probability of the bandwidth being wasted. Therefore, most of previous studies employ values between 2 and 6 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. Table 1 also gives the values of the superframe duration, the timeslot, and the minimum CAP duration for different values of SO.

$$BI = \frac{aBaseSuperframeDuration \times 2^{BO}}{R_s} \quad (1)$$

$$SD = \frac{aBaseSuperframeDuration \times 2^{SO}}{R_s} \quad (2)$$

$$T_{slot} = \frac{SD}{16} \quad (3)$$

$$aMinCAPLenght = \times T_{slot} = SD - 7 \times T_{slot} \quad (4)$$

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, BO and SO are the beacon and superframe order, respectively. The two parameters are decided by the PAN controller and transmitted to associated devices in the synchronization beacon.

3. Literature Review

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. Bhosale and Ladhe presented a survey on many of these techniques [3]. Most of the previous studies tried to reduce the slot size-induced bandwidth waste problem by reducing the slot duration. For example, in [4], Cheng et al. proposed splitting the CFP into 16 smaller timeslots instead of the large 7 ones in the original standard. This fine partitioning better utilizes the bandwidth of the network and allows more devices to be allocated. The same slot splitting idea was extended in [5] by dynamically deciding the number of timeslots during the runtime. The author further presented a technique to share these timeslots between associated devices. The proposed slot sharing technique is only suitable to devices that have predictive periodic traffic. As such, the traffic of different devices, which share the same GTS, would never collide. In [6], each timeslot is extensively divided into tiny ones according to the value of the superframe order. For example, if SO=14, each timeslot is further divided into 14 ones, which results in a total of $7 \times 14 = 98$ tiny GTS slots. In summary, those aforementioned techniques and similar ones, which employ GTSs with small equal duration, managed to reduce the slot size-induced bandwidth waste problem. However, they do not prevent the problem completely. Moreover, although they often allow more than 7 devices to be associated, they could not reach the maximum possible number of devices.

Similar to the aforementioned methodologies, Ko and Chou aimed to solve the bandwidth waste problem by adjusting the slot duration [7]. They rather achieved this adjustment by dynamically changing the beacon interval and superframe duration. Decreasing any of them would directly shorten the CFP and consequently the slot size. Although the proposed technique enhances the IEEE802.15.4 performance, it suffers from the same drawbacks as the previous ones. In other words, it neither takes the bandwidth waste into minimum nor allocates the maximum possible number of devices.

The latency of time-sensitive applications was reduced in [8] by removing the inactive period. Authors also evaluated different techniques that employ fixed-duration timeslots. Their results proved that the performance of these techniques is close to each other, in terms of the throughput and the number of allocated devices. The concept of adjusting the timeslots according to the actual data frame is also addressed in the literature. For example, two GTS allocation schemes, i-GAME [9] and SUDAS [10], were presented to determine the duration of GTS slots according to the length of the data frame and the packet arrival rate. In these two schemes, requesting devices should provide details about their traffic characteristics, such as average arrival rate and maximum burst size. 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 traffic 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 the bandwidth waste problem into the minimum.

4. Bandwidth-Oriented GTS Allocation Scheme

In this section, we present our GTS allocation scheme in details. As mentioned in Section 2, we target the beacon-enabled mode of the IEEE802.15.4. 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

$$T_f = T_{data} + macAckWaitDuration + T_{LIFS} \tag{5}$$

Where Tdata is the time to transmit a data packet. 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 [2], the macAckWaitDuration is represented by

$$\begin{aligned} macAckWaitDuration &= aUnitBackoffPeriod \\ &+ aTurnaroundTime + phySHRDuration \\ &+ ceiling\,(6 \times phySymbolsPerOctet) \end{aligned} \tag{6}$$

Where, in this paper, we assume using the O-QPSK PHY modulation scheme. Therefore, aUnitBackoffPeriod, aTurnaroundTime, phySHRDuration, and phySymbolsPerOctet have constant values equal to 20, 12, 10, and 2, respectively. Finally, the number 6 in the equation is the sum of octets of the PHY header plus that of the PHY Service Data Unit (PSDU) in the acknowledgment.

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

$$GTSStartTime = finalCAP - T_f \tag{7}$$

Where finalCAP indicates the end of the CAP period before receiving the 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).

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), Eq. (2), and Eq. (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, T_f, 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. 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 table. 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 table. 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, Figure 2 shows a comparison between the GTS allocation of our scheme and that of the original IEEE802.15.4 standard.

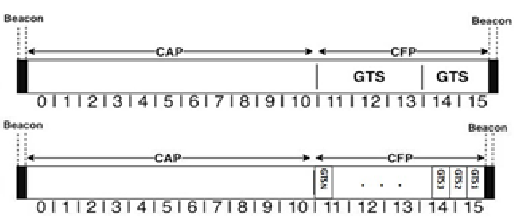

Figure 2. Comparison between the GTS allocation of our proposed scheme, at the bottom, and that of the original standard, at the top.

5. Performance Evaluation

In this section, we evaluate the performance of our proposed GTS allocation scheme. Therefore, simulation models have been implemented by INET library and OMNeT++ simulator. INET library is an open-source model for wired and wireless networks [11]. The performance of our proposed scheme is compared to that of the IEEE802.15.4 standard. As mentioned in Section 3, allocation techniques, which employ fixed-length timeslots, are shown to have a close performance to each other. Therefore, we suffice by including the slot splitting technique, which is presented in [5], in our evaluation. This later technique is already compared to the original standard in [5]. Consequently, scaled values of the slot splitting technique, with respect to the original IEEE802.15.4 standard, are included in our results. 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

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Algorithm 1: GTS allocation scheme

Input: BO, SO
Initialization

- Calculate the beacon interval (BI), according to Eq. (1)
- Calculate the superframe duration (SD), according to Eq. (2)
- Calculate the minimum CAP duration, aMinCAPLength, according to Eq. (4)
- $totalGTSDuration = 0$
- $finalCAP = \text{SD} - totalGTSDuration$

if *(GTS request command received)* **then**
  // The request includes the size of transmitted data, T_{data}
  if *(requesting device is associated && not allocated GTS slots)* **then**
    $T_f = Tdata + macAckWaitDuration + T_{LIFS}$
    $GTSStartTime = finalCAP - T_f$
    if $(GTSStartTime < aMinCAPLength)$ **then**
      GTS request rejected
    else
      $finalCAP = GTSStartTime$
      $totalGTSDuration = totalGTSDuration + T_f$
      Add the device address, $GTSStartTime$, and T_f to the GTS descriptor

Table 2. Used simulation parameters

Parameter	Value
queueLength	10 packet
Bitrate	250 Kbps
ccaDetectionTime	0.000128 sec
useMACAcks	True
BO=S0	2,3,4,5,6
BEmin	3
BEMAX	5
PWRtx	100mw
PWRrx	10mw
PWRidle	3mw
PWRbusy	5mw

order to achieve a low network latency, the inactive period is removed by setting BO=SO. In our energy consumption simulation, we consider the StateBasedEpEnergyConsumer as the energy consumer module. Finally, Table 2 summarizes the rest of the used simulation parameters and their values.

Figure 3 shows the number of devices that are successfully allocated using our scheme as well as those of the original standard and the slot splitting technique. For different values of SO, our scheme manages to accommodate a number of devices that is orders of magnitude higher than that of these two considered techniques. 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. Similarly, the slot splitting technique saturates at 16 devices. In contrary, our scheme significantly outperforms them and manages to allocate more devices. For SO=6, 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 clarifies the suitability of our scheme to bigger networks with a large number of devices.

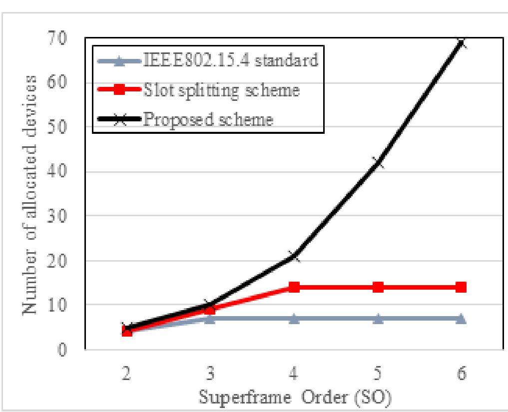

Figure 3. Comparison between the numbers of allocated devices resulted from our proposed scheme, the original standard, and the slot splitting technique.

Figure 4 shows the average throughput resulted from our scheme as well as the two other considered techniques. Throughout the simulated range of SO, our proposed scheme manages to achieve a throughput that is higher than that of the two techniques. For example, for SO=6, the resultant throughput from our scheme is about 28.4% and 5.9% higher than that of the original standard and the slot splitting technique, respectively. This enhancement returns to the optimal utilization of the available bandwidth by our scheme. Using variable-length timeslots apparently prevents any portion of the CFP from being left unused. These results show how efficient our scheme is in maximizing the throughput and minimizing the slot size-induced bandwidth waste problem.

In order to evaluate the impact of the extra processing in our scheme onto the energy consumption, Figure 5 presents the residual energy capacity of our scheme as well as that of the original standard and the slot splitting technique. As expected, the figure shows that our scheme consumes more energy than the other two techniques, specially for larger values of SO. Nevertheless, the figure proves that the consumed energy by our scheme is close to the two other techniques. For example, for SO=6, our scheme consumes only 0.0016 mJ and 0.0012 mJ more than the original IEEE802.15.4 standard and the slot splitting technique, respectively. Considering the benefits of our scheme with respect to the throughput and the number of allocated devices, this insignificant extra energy consumption should not prevent our scheme from being widely used with LR-WPAN.

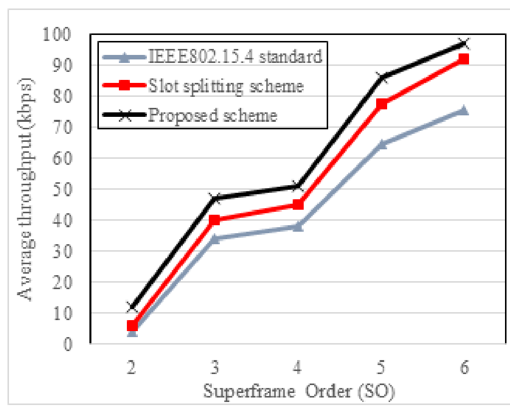

Figure 4. Comparison between the throughputs resulted from our proposed scheme, the original standard, and the slot splitting technique.

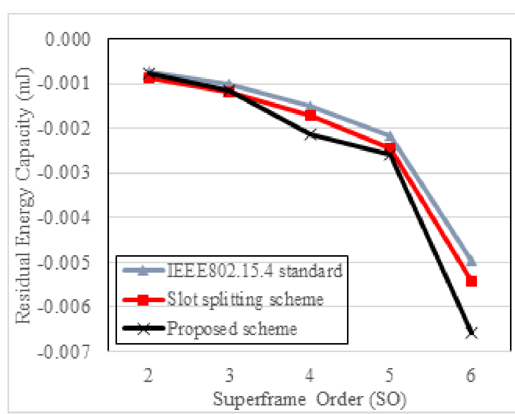

Figure 5. Comparison between the residual energy capacity of our proposed scheme and that of the original standard.

6. Conclusions and Future Work

In the paper, we presented an enhanced bandwidth-oriented GTS allocation scheme for IEEE802.15.4. Our scheme allocates GTS slots in a way that eliminates the slot size-induced bandwidth waste problem. This is realized by using a variable slot size, which is calculated based on the actual traffic of the requesting device. Experimental results show that our scheme not only enhances the throughput, with respect to the original standard and the constant-duration techniques, but it also allocates a significant large number of associated devices. All these performance enhancements are achieved with minimal impact on the energy consumption.

In the future, we plan to extend our work by employing a more efficient scheduling technique. 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.

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