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An Efficient GTS Allocation Scheme for IEEE 802.15.4 MAC Layer

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Abstract. Based on IEEE 802.15.4, the contention-free period (CFP) adopts a guarantee time slot (GTS) mechanism to ensure each device can access the radio channel. However, it is hard to get the authority to access the radio channel due to more competitor access the radio channel simultaneously. To cope with this issue, we proposed a guarantee time slot mechanism to enhance the performance and utilization by using CFP. Our proposed method ensures each device has the authority to access the radio channel without any additional step. By comparing with the method of IEEE 802.15.4, the experimental results show that data average transmission delay and energy consumption can be reduced dramatically. In addition, the bandwidth and performance of network is improved since the pre-allocation mechanism can reduce the number of control packets. Several experiments have been conducted to demonstrate the performance of our work

Keywords: ZigBee, GTS, Cluster Tree, Beacon, MAC Layer.

1. Introduction

In recent decade, Wireles Sensor Networks (WSNs) have been improved and applied popularly in many fields because of low cost, low power consumption, small size and short transmission distance [1-4]. Hence, the ZigBee standard has been proposed to satisfy these requirements to achieve the goal of longer lifetime with higher reliability [5]. In general, the ZigBee tree routing is a popular mechanism and has been applied in many applications. Because the routing table is not necessary when transmitting data, the tree routing mechanism is suitable for small, cost oriented and resource limited network applications. However, the number of intermediate nodes is increased dramatically while applying to a large range network. It requires more energy consumption and delay time such that the performance and life cycle of total system are decrease. To cope with this issue, [6] provides a shortcut tree routing method. This paper provides a shot cut path for transmission to save more energy and reduce delay time.

The risk of losing channel access authority is possibly happened in the star or tree topology network. This is because that IEEE 802.15.4 adopts the policy of CSMA/CA to access the radio channel. [7] presents a back off assignment mechanism to avoid collision while accessing radio channel. The IEEE 802.15.4 proposes a guarantee time slot (GTS) mechanism to ensure the requirement of bandwidth and delay can be satisfied. However, the channel access successful possibility is highly related with the number of access nodes while using CSMA/CA mechanism. Moreover, the CAP is used to obtain the authority of using the radio channel in GTS mechanism. This increases the difficulty of accessing radio channel. In our method, we propose a pre-allocation time slot mechanism to ensure the radio channel to be accessed without considering the contention activities. By means of cancelling the contention access period (CAP) in CSMA/CA, this paper proposes a new concept of guarantee time slot (GTS) to ensure the total superframe to be occupied by contention free period (CFP) to increase the bandwidth of GTS. This method has the advantage of: (1) to reduce the energy consumption caused by the CSMA/CA mechanism, (2) to decrease the number of control packets and (3) to improve the delay effect.

2. Related Works

Regarding the GTS mechanism, NGA [8] and i-GAME [9] provide bandwidth allocation method to decrease the waste of bandwidth. NGA divides the CFP into 16 time slots with equal size to allocate the time slot to decrease the waste of CFP. Its drawback is to compete with other devices to acquire the access authority by means of CAP. Hence, the bandwidth of CFP becomes small and the probability of allocation is smaller due to more competitors. In contrast, the i-GAME provides a mechanism to allow more devices in one GTS. It induces more delay if there are more devices in one time slot. Most of the previous mentioned papers are focused on using the CFP area to allocate the GTS. Following the CSMA/CA protocol, each device must get the authority of allocating one time slot during the period of CAP to access the channel. However, the access probability is decrease if more devices want to access the channel such that more energy consumption is required during this compete period. Thus, a new GTS allocation scheme had been proposed to reduce the transmission power consumption and delay time [10]. [11] presented a slotted beacon scheduling to reduce the power consumption while considering the hierarchical tree topology and beacon-enabled network. The energy efficiency for each different method had been compared and analyzed in [12]. It proposed several new schemes to reduce power consumption for personal area network (PAN).

This paper proposes a new mechanism to combine the CAP and CFP together to allocate the time slot again for each device. We adopt the ZigBee tree routing structure to demonstrate the efficiency of our work. This paper applies a pre-allocation schema to solve the energy consumption induced from CSMA/CA mechanism such that it can be used to decrease the GTS requests, to remove the control packet, and to reduce the delay and energy consumption. Here, we have illustrated the cluster tree based network as an example to demonstrate the performance of our proposed method for simplicity. In addition, our method can be easily further applied to different network topology. However, the node number calculation algorithm is required to develop again for each different network.

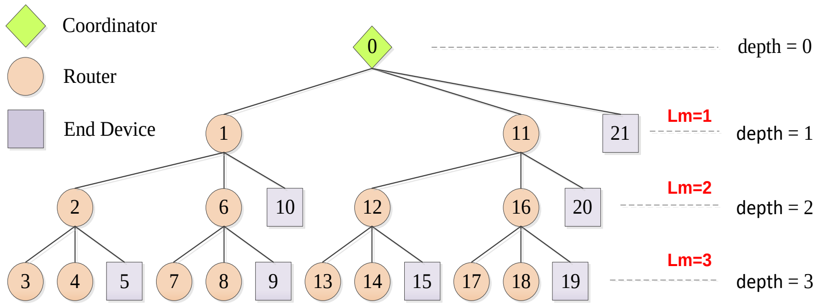

Fig. 1 Zigbee tree topology

3. New GTS Allocation Scheme

Based on the network address allocation method of IEEE 802.15.4 specification, we assign each device in the Zigbee network with a dedicate network address. After that, the topologic relation between each device can be constructed. The router or coordinate device (i.e. parent device) can assign time slot to each child device as a GTS for communication. In Zigbee, the device network address assigned mechanism is fulfilled in a distributed manner. To obtain network address, there are three topological parameters to be defined: the number of child devices (Cm), the network maximum depth value (Lm) and the maximum number of router under parent node (Rm). In Equation 3.1, the PAN coordinator (i.e. parent) can compute the Cskip(d) as an offset to derive network starting address for each child device if three parameters have been provided for any given parent device with depth value d.

$$\text{Cskip(d)}=\begin{cases} 1+Cm\cdot(Lm-d-1) & Rm=1 \\ \frac{1+Cm-Rm-Cm\cdot Rm^{Lm-d-1}}{1-Rm} & Rm\neq 1 \end{cases} \qquad (3.1)$$

Our method doesn't require the CAP for doing the CSMA/CA activities while considering to accessing the communication channel. Thus, the CAP can be used for transmitting data between parent node and child node to avoid collision and save energy. Once the ZigBee network has been set up, each parent device (coordinator or router) decide the GTS size for each child device according to the parameter Cm. In this paper, the maximum Cm should not be over 15 because each superframe includes 16 time slots and one is already dedicated to beacon. In other words, each allocated GTS size is identical to one time slot size in superframe as the Cm is equal to 15.

According to the specification of IEEE 802.15.4, beacon interval (BI), superframe duration (SD), beacon order (BO) and superframe order (SO) can be used to described the relation between beacon frame and superframe. The superframe duration and beacon interval can be computed as Equations 3.2 and 3.3, where aBaseSuperframeDuartion is a time unit. The length of each time slot can be obtained by using Equation 3.4. Superframe Duration can be denoted as $F_S(SO)$,which can be divided into 16 portions. The new superframe contention free period can be found as Equation 3.5 in which one time slot is already used by beacon signal. Thus, the allocated GTS size for each device can be computed as Equation 3.6 for the case with Cm child device.

$$\begin{aligned} F_S(SO) &= \text{Superframe Duration(SD)} \\ &= \text{aBaseSuperframeDuartion} * 2^{SO} \end{aligned} \tag{3.2}$$

$$\begin{aligned} F_B(BO) &= \text{Beacon Interval(BI)} \\ &= \text{aBaseSuperframeDuartion} * 2^{BO} \end{aligned} \tag{3.3}$$

$$\text{Length of Time Slot}: \; L_{TS}(SO) = \frac{F_S(SO)}{16} \tag{3.4}$$

$$newCFP(SO) = F_S(SO) - L_{TS}(SO) \tag{3.5}$$

$$\text{Length of GTS}: \; L_{GTS}(Cm, SO) = \left\lfloor newCFP(SO) \times \frac{1}{Cm} \right\rfloor \tag{3.6}$$

We propose a method to compute the GTS for each device. The device can be divided as coordinator, router and end device, where only the coordinator and router can issue the beacon signal and the GTS to their corresponding child device. We illustrate the tree topologic structure as our basis to demonstrate our proposed method.

Algorithm 1 GTS communication scheme in the coordinator

```
MAC layer use GTS allocation scheme
define the Superframe Duration(SD) = $F_S(SO)$
define the Beacon Interval(BI) = $F_B(BO)$
define the length of time slot $L_{TS}(SO) = \frac{F_S(SO)}{16}$
newCFP (SO) = $F_S(SO) - L_{TS}(SO)$
Each length of GTS : $L_{GTS}(Cm,SO) = \left\lfloor newCFP(SO) \times \frac{1}{Cm} \right\rfloor$
for $i_{th}$=1 to $i_{th} \le Cm$
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```
8.      Starting time of $GTS(i_{th}) = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (i_{th} - 1)$
9.  end for
10. Send a beacon signal for synchronization
```

To ensure the integration operations smoothly, we have presented three algorithms in corresponding to coordinator, router and end device, respectively. First, for the coordinator algorithm as shown in algorithm 1, the row 2 to 4 gives the definition of parameter used in this algorithm. The row 5 finds the size of new CFP. The size of allocated GTS for each device is obtained by the row 6, where Cm represents the number of child devices under the coordinator. The starting time of GTS for each device can be obtained in the row 7 and 8. The Equation 3.7 indicates that the starting time of GTS for each device is related to the assigned network address of child device (i.e. *i*). The assigned sequence of GTS for each child device follows the network address of joining parent net. The parent device can communicate with the child device during this GTS period after the synchronization is initialized by the beacon signal.

$$GTS(i_{th}) = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (i_{th} - 1), \text{where } i = i \text{ th Cm} \tag{3.7}$$

Algorithm 2 GTS communication scheme in the router

```
1.  MAC layer use GTS communication scheme
2.  define the Superframe Duration(SD) = $F_S(SO)$
3.  define the Beacon Interval(BI) = $F_B(BO)$
4.  define the length of time slot $L_{TS}(SO) = \frac{F_S(SO)}{16}$
5.  newCFP (SO) = $F_S(SO) - L_{TS}(SO)$
6.  Each length of GTS : $L_{GTS}(Cm,SO) = \left\lfloor newCFP(SO) \times \frac{1}{Cm} \right\rfloor$
7.  if receive a Beacon signal with synchronization
8.  then k is computed by: $k = \frac{A_k - A_{parent} - 1 + Cskip_{parent}(d)}{Cskip_{parent}(d)}$
9.  Starting time of $GTS_{parent} = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (k - 1)$
10. end if
11. After $SD_{parent}$ of period then Allocate GTS for children
12. for $i_{th}$=1 to $i_{th} \le Cm$
13. Starting time of $GTS(i_{th}) = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (i_{th} - 1)$
14. end for
15. Send a beacon signal for synchronization
```

Second, for algorithm 2, the row 2 to 5 is the same as algorithm 1. The row 6 is to compute the GTS size L_{GTS} of each router device. The row 7 to 10 is to find the starting time of GTS of router device, which is assigned by the parent device.

$$k = \frac{A_k - A_{parent} - 1 + Cskip_{parent}(d)}{Cskip_{parent}(d)}, \qquad \text{where k = k th Router} \qquad (3.8)$$

$$GTS_{parent} = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (k-1) \qquad (3.9)$$

In Equation 3.8, A_k is the network address of router, A_{parent} is the network address of parent and $Cskip_{parent}$(d) is the offset address for each different router. The k denotes the k_{th} router of parent device. Thus, we can compute the starting time of accessing channel for each different router in terms of k as Equation 3.9 shows. The router communicates with its parent during time slot GTS_{parent}. The row 11 indicates that the processing sequence is from parent to child. After the Superframe Duration of parent, the router assigns GTS to its child device by following the sequence of network address. The rows 12, 13 and 14 compute the starting time of GTS for each child device. We can assign each different starting time for each child device based on a different i_{th}, where the i_{th} denotes the number of child device for a router. The router communicates with its child device during time slot $GTS(i_{th})$.

```
Algorithm 3 GTS communication scheme in the end device

1.  MAC layer use GTS communication scheme with parent
2.  define the Superframe Duration(SD) = $F_S(SO)$
3.  define the Beacon Interval(BI) = $F_B(BO)$
4.  define the length of time slot $L_{TS}(SO) = \frac{F_S(SO)}{16}$
5.  $CFP_{parent}$ = newCFP(SO) = $F_S(SO) - L_{TS}(SO)$
6.  Each length of $GTS_{parent} = \left\lfloor newCFP(SO) \times \frac{1}{Cm} \right\rfloor$
7.  if receive a beacon signal with synchronization
8.  then
        $n = A_n - A_{parent} - Cskip_{parent}(d) \times Rm$
9.  Starting time of $GTS(i_{th}) = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (n + Rm - 1)$
10. end if
```

Similarly, for the algorithm 3, the row 2 to 6 gives definitions regarding superframe duration, beacon interval and length of time slot to find the size of CFP_{parent} and GTS_{parent}. The row 7 indicates that the beacon signal is received for synchronization. The row 8 identifies the end device is the n_{th} device in parent net based on Equation 3.10.

$$n = A_n - A_{parent} - Cskip_{parent}(\mathrm{d}) \times Rm$$
$$\mathrm{n} = \mathrm{n}_{th} \text{ end device} \qquad (3.10)$$

In Equation 3.10, A_n is the network address of end device assigned by its parent device, A_{parent} is the network address of parent device, $Cskip_{parent}$(d) is the offset and Rm is the number of router in child devices. The $n+Rm$ can be used to represent the i_{th} Cm child device in parent net. We can compute the staring time of GTS for each child device based on Equation 3.11. The end device communicates with its parent in time slot $GTS(i_{th})$.

$$GTS(i_{th}) = \frac{F_S(SO)}{16} + L_{GTS}(Cm, SO) \cdot (n + Rm - 1)$$
$$\text{,where } n+Rm = i_{th}\,Cm \qquad (3.11)$$

To evaluate these algorithms, we illustrate an example to demonstrate our proposed method. Let's illustrate an example using a ZigBee tree based topologic as shown in Fig. 1. In this example, the coordinator locates start at the network address 0 with depth equal to 0, where we assume Cm=3, Lm=3 and Rm=2. Then, the Cskip can be computed as Cskip(0)=10, Cskip(1)=4 and Cskip(2)=1. The network address for the device with depth =1 can be assigned as 1, 11 and 21 by the coordinator. The status inside superframe is shown in Fig. 2 after executing the synchronization of parent and child devices. The contention free period includes GTS for each different device because of no channel contention access required in our method. The communication with coordinator is necessary to obtain the GTS allocation command. In this case, the coordinator (0) generates the beacon signal to synchronize with devices 1, 11 and 21 in the first time slot and then the coordinator (0) communicates with device 1, 11 and 21 within the period GTS1, GTS2 and GTS3, respectively. After that, the device 1 starts to synchronize with devices 2, 6 and 10 during this inactive period of coordinator (0). Similarly, the status inside superframe for the case between router and its child devices can be shown in Fig. 3, where the communication with router is required. The device 6 starts to synchronize with devices 7, 8 and 9 within this inactive period of device 1. The communication between the parent and child devices can be conducted in the pre-allocate GTS. We can ensure that the fairness of accessing bandwidth based on the pre-allocate GTS mechanism. The total quantity of packet and delay time can thus be reduced and improved because the child device doesn't require to asking its corresponding parent device to send or cancel the control packet for GTS. In addition, the energy consumption can be reduced since the CSMA/CA mechanism is not required in our research. The superframe for the routers 1, 11, 2, 6, 12 and 16 with depth varied from 1 to 3 can be shown together as Fig. 4.

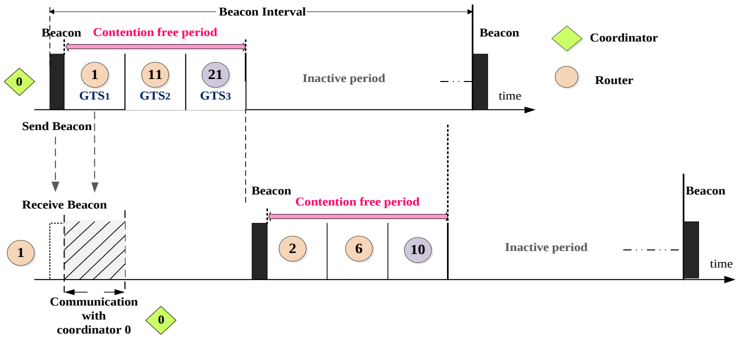


Fig. 2 The relation between coordinator and child device

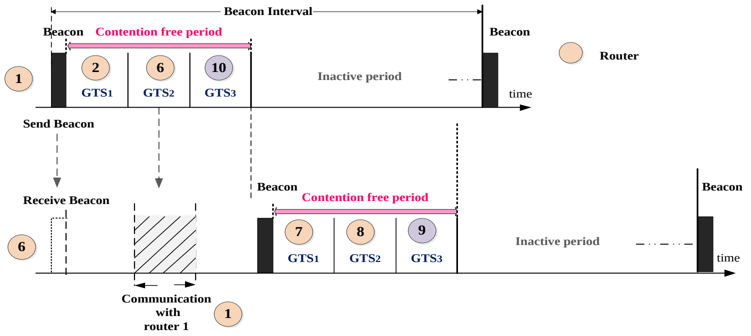


Fig. 3 The relation between router and child device

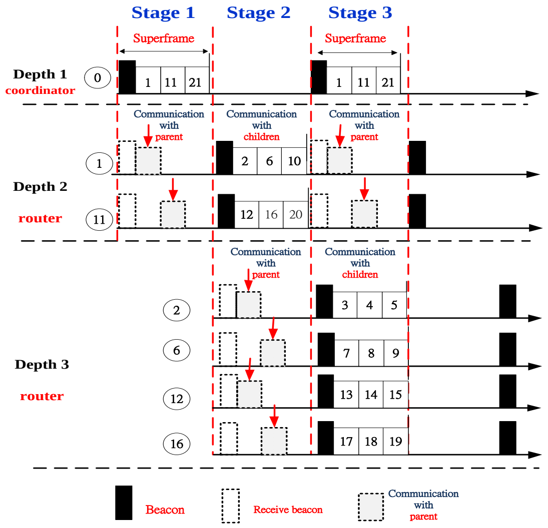


Fig. 4 The relation between depth 1 to 3 for tree-topology

4. Experimental Results

To evaluate our proposed method, our simulation environment is based on NS2 version 2.34 as a basis to demonstrate the performance and correctness of our work. In this experiment, we illustrate a tree type sensor network as an example shown in Fig. 1, where its corresponding parameters can be set as Cm=3, Rm=2 and Lm=3. For simplicity, we assume that the traditional GTS allocation mechanism (OSA GTS) with CSMA/CA can be 100% success without any loss. In other words, the compared method with us is an optimal case. In here, we assume SO from 2 to 4 and BO various from 3 to 5 to observe the variation after increasing the beacon interval.

To examine the delay effects in our method, we treat the coordinate as a sink node to accept the signal from other nodes. First, we assume depth=3 to simulate the packet is transmitted from the node with depth=3 to the sink node. Similarly, the rest nodes follow the same way by transmitting data repeatedly along with the directions as Fig. 5. The simulation results can be shown in Fig. 6 to 11 with assigning SO=2~4 and BO=3~5, where the input data arrival rate can vary from 0.1 to 1. The Fig. 6, 8 and 10 show the transmit delay with respect to BO=3, BO=4 and BO=5, respectively. Similarly, the Fig. 7, 9 and 11 show the energy consumption for the BO=3, BO=4 and BO=5. First, for the average delay results, the OSA GTS average delay is larger than the NSA GTS over 100 % because the NSA GTS doesn’t need ‘acquire’ and ‘cancel’ activities because of pre-allocate GTS scheme. Hence, the communication can be executed immediately between parent and child devices after receiving the parent device’s beacon signal. However, the OSA GTS needs to wait for beacon signal in the next superframe and then receive the related GTS information to allocate the radio channel. After that, the communication between parent and child devices can be started. Therefore, the delay overhead of OSA GTS is more than the NSA GTS. For the OSA GTS, the delay is increased as if the arrival rate is becoming greater (i.e. 0.1 to 1) since the arrival packets during the CAP period will be totally handled in the next GTS. In contrast, the NSA GTS keeps the uniform delay regardless of the change of arrival rate. The energy consumption of OSA GTS is larger than NSA GTS scheme because OSA GTS requires one more superframe to transmit data packet if the radio channel is allocated successfully. To implement such a system, we need to modify the sensor node by adding our proposed algorithm.

To further compare the delay effects, we propose the formula:

$$\text{ADRI}=\frac{OSA\ GTS\ Average\ Delay-NSA\ GTS\ Average\ Delay}{OSA\ GTS\ Average\ Delay}\times 100\%$$

as Average Delay Reduction Index (ADRI) to indicate the average delay. The ADRI with SO=2, 3, 4 and BO=3, 4, 5 can be shown in Fig. 12, 13 and 14, respectively. Based on the ADRI with SO=2~4 and BO=3~5, the average improvement rate is over 51%, especially for the case with SO=4, BO=5 and arrival rate=0.1, where its improve rate is 80%. It is obviously to indicate that low transmission delay can be obtained by the NSA GTS method.

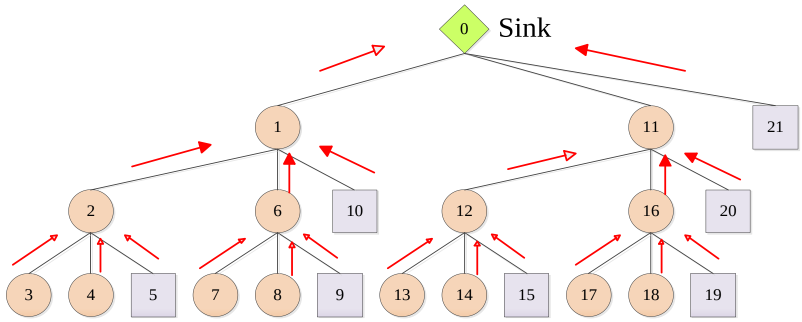
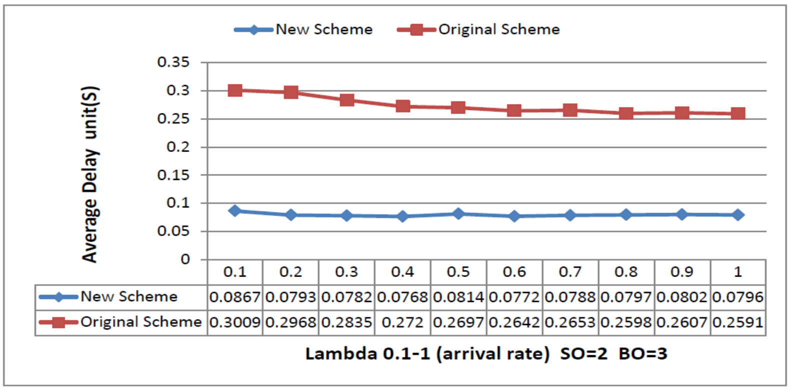
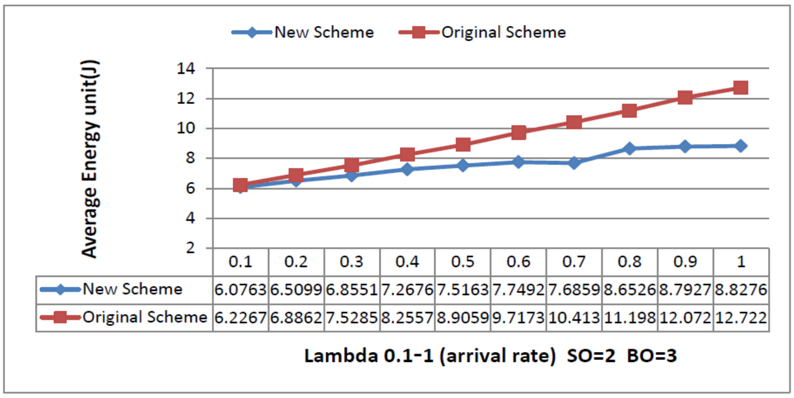


Fig. 5 Data packet transmission path



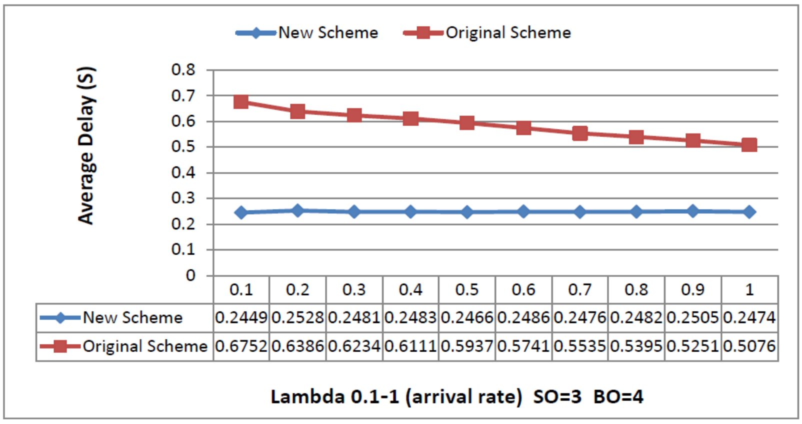
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
New Scheme	0.0867	0.0793	0.0782	0.0768	0.0814	0.0772	0.0788	0.0797	0.0802	0.0796
Original Scheme	0.3009	0.2968	0.2835	0.272	0.2697	0.2642	0.2653	0.2598	0.2607	0.2591

Fig. 6 Packet average transmission delay (SO=2 BO =3)



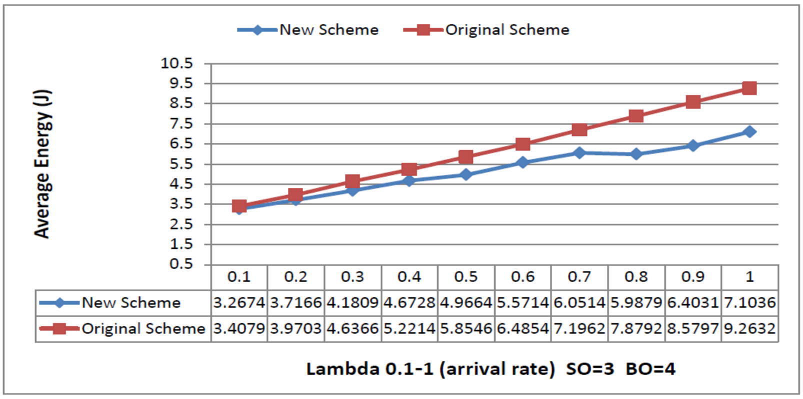
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
New Scheme	6.0763	6.5099	6.8551	7.2676	7.5163	7.7492	7.6859	8.6526	8.7927	8.8276
Original Scheme	6.2267	6.8862	7.5285	8.2557	8.9059	9.7173	10.413	11.198	12.072	12.722

Fig. 7 Average energy consumption (SO=2 BO =3)



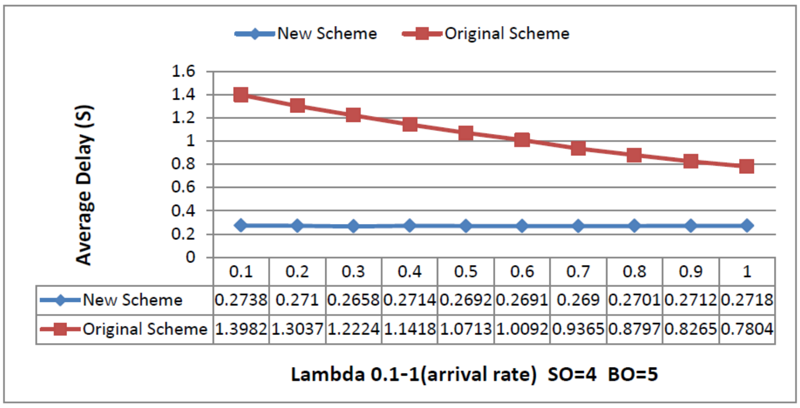
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
New Scheme	0.2449	0.2528	0.2481	0.2483	0.2466	0.2486	0.2476	0.2482	0.2505	0.2474
Original Scheme	0.6752	0.6386	0.6234	0.6111	0.5937	0.5741	0.5535	0.5395	0.5251	0.5076

Fig. 8 Packet average transmission delay (SO=3 BO =4)



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
New Scheme	3.2674	3.7166	4.1809	4.6728	4.9664	5.5714	6.0514	5.9879	6.4031	7.1036
Original Scheme	3.4079	3.9703	4.6366	5.2214	5.8546	6.4854	7.1962	7.8792	8.5797	9.2632

Fig. 9 Average energy consumption (SO=3 BO =4)



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
New Scheme	0.2738	0.271	0.2658	0.2714	0.2692	0.2691	0.269	0.2701	0.2712	0.2718
Original Scheme	1.3982	1.3037	1.2224	1.1418	1.0713	1.0092	0.9365	0.8797	0.8265	0.7804

Fig. 10. Packet average transmission delay (SO=4 BO =5)

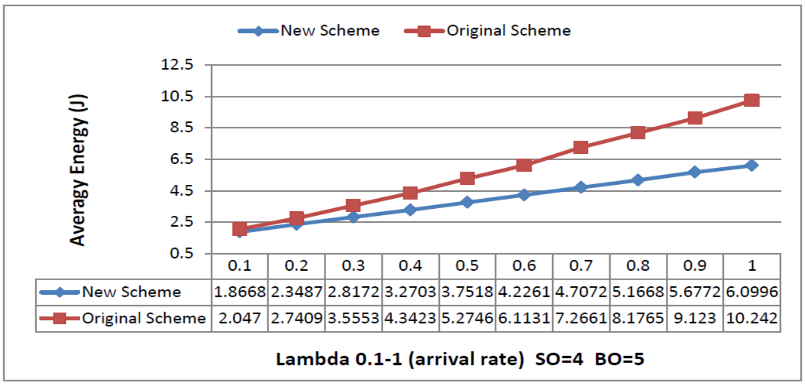


Fig. 11 Average energy consumption (SO=4 BO =5)

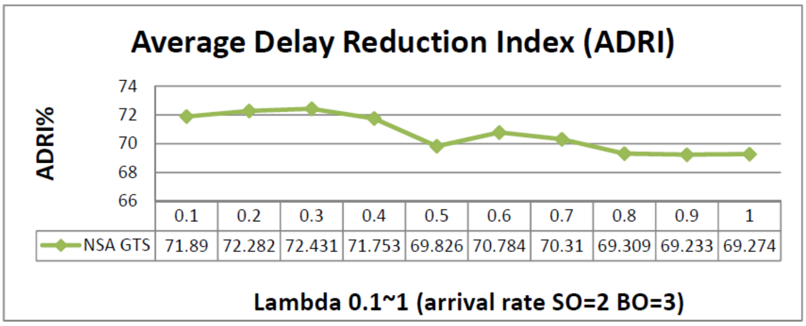


Fig. 12 SO=2 BO=3 ADRI

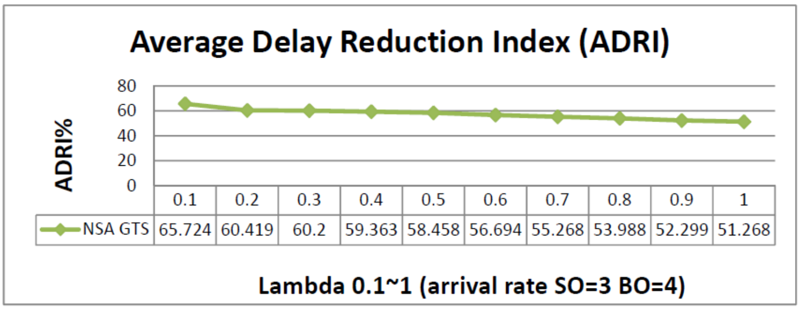


Fig. 13 SO=3 BO=4 ADRI

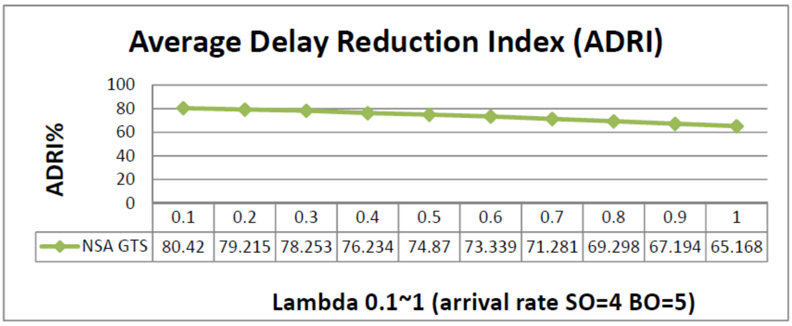


Fig. 14 SO=4 BO=5 ADRI

5. Conclusions

This paper proposes a new pre-allocation mechanism to resolve the drawbacks of traditional time slot access mechanism in the IEEE 802.15.4 specification. This method ensures each device to allocate a fix bandwidth based on the pre-allocation scenario. Our proposed method doesn't need control mechanism to obtain guarantee time slot such that the control packet can be reduced to decrease delay and power consumption. We adopts pre-allocation schema to allocate the time slot in advance to increase the utilization of bandwidth and keep data transmission in real-time manner. Based on the experimental results, the proposed GTS mechanism is better than the IEEE 802.15.4 for the delay effect and energy consumption. To further enhance the performance of our method, we will propose an algorithm to improve the counting of sensor node number more precisely so that the power consumption and transmission delay can be optimized.

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