Clustered Coordinator SABTS (CC-SABTS) for Beacon Transmission in IEEE802.15.4 LR-WPAN

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***Abstract*—IEEE802.15.4 standard for Wireless Sensor Network (WSN) provides low-power transmission in the low-rate wireless personal area network (WPAN). It has three types of topology: star, peer-to-peer and cluster tree. Star topology has limit to expand network. Peer-to-peer topology has a complex multihop routing during network expansion due to the large number of full-function devices. A full-function device can act as coordinator and personal area network coordinator (PAN-C). Cluster tree topology is preferable because it can expand networks using less number of full-function devices and thus reduces complexity in routing messages. A cluster tree topology consists of a wireless PAN-C, several cluster coordinators and a number of end devices. The coordinators periodically transmit beacon frames to one another to allow synchronization and communication. However, collision will happen if the coordinators transmit beacon frames at the same time and will degrade the network performance. Different mechanisms have been introduced to solve the collision problem and one of the mechanisms is superframe adjustment and beacon transmission scheme (SABTS). SABTS calculates the precise time for beacon transmission by assigning an accurate value of beacon order and superframe order for PAN-C, cluster coordinators and end devices. As the number of cluster coordinator increases, SABTS method reiterates the calculation for beacon transmission time numerously. Hence, in order to decrease the iteration, this paper introduces clustered coordinator SABTS (CC-SABTS) by clustering coordinator nodes that are separated by two length radius. The performance of CC-SABTS is simulated and evaluated using NS2 simulation software. Result shows that CC-SABTS provides better average throughput, packet delivery ratio and end-to-end delay compared to the conventional SABTS.**

***Index Terms*—Wireless Sensor Network; IEEE802.15.4; Beacon Collision; ZigBee; WPAN.**

I. INTRODUCTION

Wireless Sensor Network (WSN) is a distribution of wireless devices (denoted as nodes) which can configure themselves in a network. They monitor and sense the physical surrounding. An example of WSN is the IEEE802.15.4 low-rate wireless personal area network (LR-WPAN). IEEE802.15.4 LR-WPAN defines the specification for ZigBee,that includes Medium Access Control (MAC) enhancement in beacon scheduling and synchronization of broadcast messages in beacon-enabled network PAN [1]. A beacon-enabled network provides a low-power sleep mode for PAN-C and cluster coordinators [2] during the inactive period and hence gives benefit for energy-restrained network environments [1]. Also, the transmitted beacon frames allow nodes to identify the PAN-C and synchronize the wireless devices.

IEEE802.15.4 LR-WPAN has three types of topology which is star, peer-to-peer and cluster tree. A cluster tree topology consists with several clusters of nodes. Each cluster contains a cluster coordinator. Compared to star topology, cluster tree topology allows network to be extended because more nodes can join PAN-C to form the network. Peer-to-peer topology consists of full-function devices (FFDs). A full-function device is a network device that can act as a coordinator and PAN-C. As more complex network are formed, the multihop to route messages will become more complicated. Thus, cluster tree is chosen to reduce the multihop complexity and at the same time can expand the network.

It is possible to implement a beacon enabled network in a cluster tree topology. However, the network suffers beacon frame collision when coordinators transmit their beacon frames at the same time. This problem degrades the network performance. Consequently, it is crucial to provide effective mechanisms to avoid beacon frame collision in a cluster tree topology.

This paper introduces an enhanced method of SABTS [3] called Clustered Coordinator SABTS (CC-SABTS). CC-SABTS allows more coordinator nodes transmit their beacon at the same time in a cluster tree topology, without having a beacon collision. The cluster coordinators, which are separated by two length radius are clustered together to have the same beacon transmission time. The proposed method reduces the iteration to get beacon transmission time and also improves the average throughput, packet delivery ratio and end-to-end delay.

From this point forward, the paper is structured as follows. Section 2 explains related work on beacon frame collision avoidance mechanism. Section 3 gives an overview of IEEE802.15.4 LR-WPAN. Section 4 explains the method for CC-SABTS. In Section 5, performance evaluation results are presented. Finally, conclusions and future works are drawn.

II. RELATED WORK

Various mechanisms have been formulated to overcome the beacon frame collision problem. Time division beacon scheduling (TDBS) with Superframe Duration Scheduling

(SDS) algorithm [2] is one of well-known mechanism. SDS algorithm sums the duty cycle of coordinators in the network to determine if they can be scheduled. If the sum of duty cycle is less than 1, then the algorithm will return a schedulable notification for the set of coordinators. Also, research in [2] has introduced coordinator clustering in large scale networks that allow coordinators that are far enough to transmit their beacon frames simultaneously. However, scheduling the beacon frames transmission which have different superframe length is a challenging task, especially when there are numerous of beacon frames.

Research in [4] presents a MeshMAC protocol that introduces two new primitives; MLME-NEIGHBOUR_SCAN and MLME_LIST, to enable new associating nodes to find an empty slot for beacon transmission. This is achieved by obtaining the neighbours and neighbours' neighbours beacon frame transmission list. Based on the list, the first empty slot found by the new full function device nodes will be selected. However, MeshMac was designed to suit network in Mesh topology and method on how the node selects the empty slot from the broadcast list is yet to be elaborated.

Researchers in [5] and [3] have introduced different approaches, where it will determine a pre-calculated slot for the beacon frame transmission offset. The main different between both work is: research in [5] shifts the beacon transmission offset for each cluster head in the network and modified the standard beacon frame format while research in [3] maintains the original beacon frame format and determines the exact value of macBeaconOrder (BO) and macSuperframeOrder (SO) to gain the beacon transmission offset for each coordinators including PAN-C. Both formulated mechanisms are very straight forward and practical, however the growth of cluster coordinators in a network will increase the iteration to obtain the beacon transmission offset.

The scheduling mechanism does not restrict on scheduling the time, but also includes a multichannel technique such as work in [6] and [7]. Both introducing ways to manipulate the channels in the IEEE802.15.4 LR-WPAN to enable multiple cluster transmits beacon frames at different channels without acquiring additional hardware. Although the methods seem appealing but both techniques do not address other issues such as hidden nodes and deaf nodes [8].

Based on the mentioned researches, time based beacon scheduling such in [3] and [5] is more likable to be used due to their simplicity. Research in [3] has the upper hand because it maintains the original beacon frame format and thus less complexity. Therefore, this paper focuses on improving the research gap in [3].

III. OVERVIEW OF IEEE802.15.4/ZIGBEE

The IEEE802.15.4 LR-WPAN has two network modes: beacon-enabled network and non-beacon enabled network [9]. PAN-C may use either mode during data transfer to, or from coordinator and a peer to peer data transfer. In a beacon-enabled network, beacons are periodically sent by the PAN-C to allow nodes to synchronize in the network [9]. A beacon-enabled network also provides a low-power sleep mode for both PAN-C and its nodes [10] during the inactive period and therefore offers benefit for energy-restrained network environments [9]. Figure 1 illustrates how superframe duration (SD) bounded by the beacon which contains a Contention Access Period (CAP), and a Contention Free Period (CFP) with guaranteed time slot (GTS) in the active portion [9].

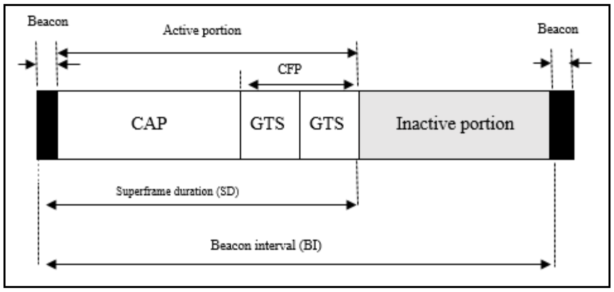

Figure 1: Superframe structure

There are TWO (2) important parameters in beacon-enabled network: BO and SO. BO determines the beacon interval (denoted as BI) where:

$$BI = aBaseSuperframeDuration \times 2^{macBeaconOrder} \quad (1)$$

for: $0 \leq macBeaconOrder \leq 14$

SO determines the superframe duration (denoted as SD) where:

$$SD = aBaseSuperframeDuration \times 2^{macSuperframeOrder} \quad (2)$$

for: $0 \leq macSuperframeOrder \leq macBeaconOrder \leq 14$

aBaseSuperframeDuration is fixed to 960 symbols which denotes the minimum number of symbols in active period.

Node uses the slotted version of CSMA-CA algorithm for transmission during CAP in a beacon-enabled network. There are three parameters needed to be maintained during transmission: NB, CW and BE which denotes the number of backoff (initial value = 0), contention window length (initial value = 2) and backoff exponential (initial value = 3), respectively. Nodes delay randomly by a unit backoff period (UBP) between 0 and 2BE – 1 UBP. Then, these nodes perform the channel clear assessment (CCA) to monitor idle or busy channel. If the channel is idle, the value of CW is decreased by 1 and another CCA will be performed until the CW become 0. Transmission will start after two CCAs, and the channel is confirmed idle.

However, if the channel is not idle, NB will be increased by 1, and CW will be reset back to 2 and BE will be increased by 1, up to the maximum BE (macMaxBE = 5). The node will repetitively take random delay until the value of NB reach macMaxCSMABackoff, which is equal to 4. The transmission is considered fail if NB value is larger than the macMaxCSMABackoffs value [9].

IV. CLUSTERED COORDINATOR SABTS (CC-SABTS)

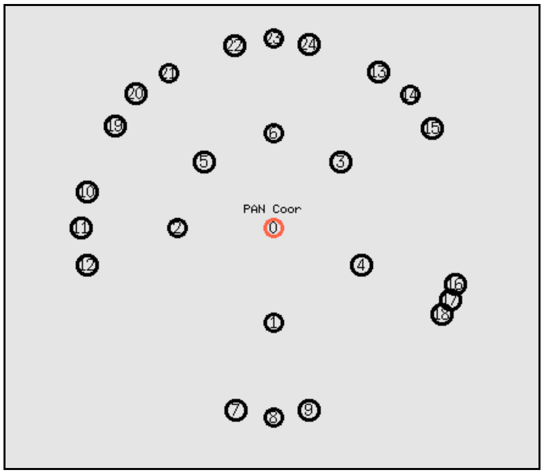

Figure 2: Example of topology scenario

This paper proposes *clustered coordinator* in superframe adjustment and beacon transmission scheme (CC-SABTS) as enhancement for the conventional SABTS to reduce the number of beacon transmission offset that needs to be obtained due to the growth of the network. CC-SABTS clusters coordinator nodes that are separated by two length radius (2*r*) without compromising the network performance. The idea for clustering comes from the extended TDBS approach introduced by [2] which suggest that coordinators that are far enough can transmit their beacons simultaneously because of the non-overlapping transmission range.

Before the beacon transmission offset can be calculated, existing coordinator nodes are clustered with their 2*r* node neighbour's. This will reduce the number of coordinators' beacon transmission time ($TxOffset_i$) that need to be obtained. For example, in Figure 2, there are six coordinator nodes (denoted as number 1 until 6). These coordinator nodes (N_{coord} = 6) require six $TxOffset_i$ to be obtained using the conventional SABTS. CC-SABTS will find the 2r neighbours coordinator to be clustered the coordinators together. The clustered coordinators are assumed to be far enough such that their transmission range does not overlap [2]. Therefore, only two $\mathrm{TxOffset}_i$ shall be obtained as there are three coordinators that can transmit their beacon at the same time.

Table 1
Two length radius neighbor

Coordinator node number	2r neighbour
1	3,5
2	4,6
3	1,5
4	2,6
5	1,3
6	2,4

Table 2
Clustering beacon transmission

Coordinator node number	TxOffset1	TxOffset2
1	X	
2		X
3	X	
4		X
5	X	
6		X

After implementing coordinator clustering, the exact value of beacon order and superframe order for PAN coordinator (BO_{PAN} and SO_{PAN}, respectively) , beacon order and superframe order for coordinator node (BO_{coord} and SO_{coord}, respectively) and the beacon order and superframe order for end device (BO_{dev} and SO_{dev}, respectively) needs to be calculated using the conventional SABTS formula[3]. After determining the BO_{PAN}, SO_{PAN}, BO_{coord}, SO_{coord}, BO_{dev} and SO_{dev}, the exact time of beacon transmission offset for PAN-C ($TxOffset_{PAN}$) and coordinators ($TxOffset_i$) can be obtained to avoid beacon collisions between the coordinators. Below are the related equations [3] applied in CC-SABTS:

$$BO_{PAN} = \left(\log_2 \left(\frac{N_{coord} \times INTV \times R_s}{B_s \times N_s} \right) \right) \tag{3}$$

where: BO_{PAN} = Beacon Order for PAN
N_{coord} = number of coordinator nodes
Rs = symbol rate =62,500symbols/s
Bs= aBaseSlotDuration = 60 symbols
Ns= aNumSuperframeSlots = 16 slots

$$BO_{coord} = BO_{PAN} - 1 \tag{4}$$

$$SO_{PAN} = BO_{PAN} \tag{5}$$

$$SD_{coord} = \frac{B_s \times N_s \times 2^{BO_{coord}}}{N_{coord}} + 190 \tag{6}$$

where: SD_{coord} = superframe duration for coordinator

$$SO_{coord} = \left[\log_2 \left(\frac{2^{BO_{coord}}}{N_{coord}} + 0.2 \right) \right] \tag{7}$$

$$BO_{dev} = SO_{coord} ; SO_{dev} = SO_{coord} \tag{8}$$

$$TxOffset_i = \begin{cases} TxOffset_{PAN} + \frac{L_{beacon}}{R_s} & , i = 1 \\ TxOffset_{i-1} + \frac{L_{beacon}}{R_s} + SD_{coord} & , 2 \leq i \leq N_{coord} \end{cases} \tag{9}$$

where: L_{beacon} = 190 symbols

In order to simplify CC-SABTS, a pseudo-code is proposed as shown in Figure 3.

```
BEGIN
{
    Get the number of coordinator nodes (N);
    Get the two radius length neighbor nodes;
    Cluster node with two radius length neighbor nodes;
    Update the number of coordinator nodes;
    (N=maximum cluster number)
    Get beacon transmission offset;
}
END
```

Figure 3: Proposed pseudo-code of CC-SABTS

V. SIMULATION AND ANALYSIS

In this section, a network topology consists of 1 PAN-C, 10 coordinator nodes and 30 end devices is considered to determine the network performance of CC-SABTS and conventional SABTS. The packet interarrival rate (INTV) is varied from 0.1 to 1 which follows the Poisson distribution. Simulations are performed using NS2 simulator software. AWK programming analyzes all the trace file output. The following metrics: throughput, packet delivery ratio and end-to-end delay are used to determine the performance of conventional SABTS and CC-SABTS.

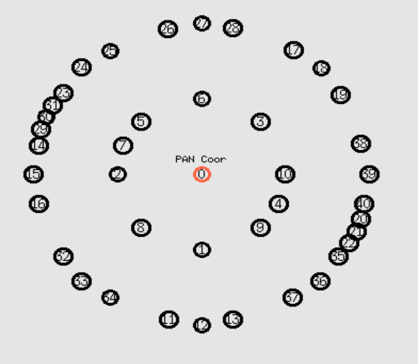

Figure 4: Simulated network topology

Average throughput is defined as the measure of total packet received within an observed duration where it can be mathematically defined as:

$$Average\ Throughput = \frac{\sum bytes\ received\ at\ destination\ nodes}{simulation\ time} \quad (10)$$

Based on the simulation, the average throughput for CC-SABTS is higher than the conventional SABTS. This is due to the increased number of coordinators that can transmit their data frames at the same time. When the traffic load is lower (i.e., INTV is equal to 1 and 0.9), CC-SABTS obviously outperforms conventional SABTS for average throughput performance. The beacon interval (BI) time is lower with CC-SABTS and beacon frames are transmitted more frequent.

Another performance metric: packet delivery ratio (PDR) represents the ratio between the number of packet received by all nodes and number of packet sent by the sources. It can be mathematically defined as:

$$Average\ PDR = \frac{\sum no\ of\ packet\ received}{\sum no\ of\ packet\ sent} \quad (11)$$

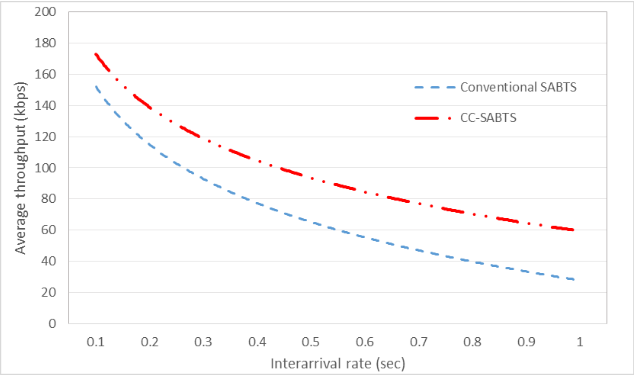

Figure 5: Average throughput

Simulation result shows that PDR for CC-SABTS follows same pattern as the average throughput. CC-SABTS has a better PDR compared to the conventional SABTS. As the traffic load increases, the PDR also increases.

Average end-to-end delay defines the average of total difference delay between packet received at the sending nodes and the transmitting nodes.

$$Average\ end\ to\ end\ delay = \frac{\sum (arrived\ time - sent\ time)}{\sum no\ of\ connections} \quad (12)$$

As expected, the average of end-to-end delay is lower with CC-SABTS compared to conventional SABTS. Clustering mechanism applied in CC-SABTS allows more coordinator nodes transmit their beacon frames at the same time and thus reduces time queue.

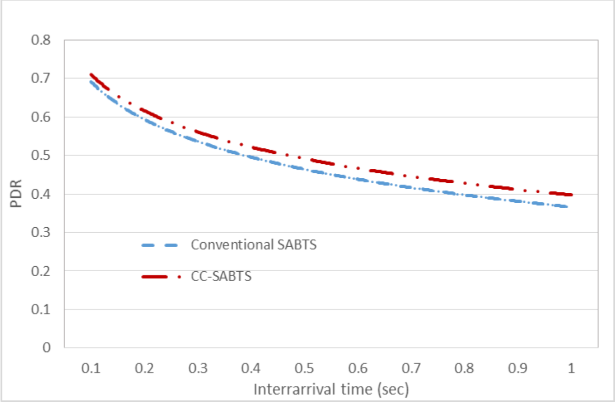

Figure 6: Average PDR

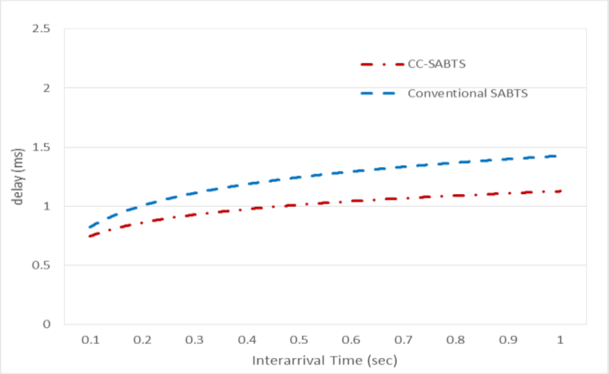

Figure 7: Average end-to-end delay

VI. CONCLUSION AND FUTURE WORKS

This paper has proposed an improved method of conventional SABTS called CC-SABTS. CC-SABTS reduces the iteration to obtain the beacon transmission offset in conventional SABTS and improves the network performances. Analysis results shows that the proposed method performs 39.5% higher in throughput and 5.6% better in packet delivery ratio. The average end-to-end delay decreases by 22.4% with CC-SABTS compared to the conventional SABTS. For further study, CC-SABTS shall be tested in a different network scenario where the best node location must be taken into consideration. Effect of hidden nodes problem in the network scenario can also be considered to improve this research work.

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