Effect of Clustered Coordinator Superframe Adjustment and Beacon Transmission Scheme (CC-SABTS) in IEEE802.15.4 LR-WPAN Cluster Tree Topology with Varied Network Density and Traffic Model

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Abstract-- This paper examines and evaluates the performances of clustered coordinator superframe adjustment and beacon transmission scheme (CC-SABTS) in a cluster tree network with different network density and traffic model. A cluster tree topology network consists of a Personal Area Network Coordinator (PAN-C), a few clusters of coordinators and several end device nodes at each coordinators. Coordinators need to transmit a periodic beacon in order to synchronize and communicate with PAN-C. Transmitting beacons simultaneously causes beacon collisions while CC-SABTS is designed provides method to reduce these collisions. Nonetheless, the performances of CC-SABTS in denser network has yet to be investigated and evaluated. Therefore, a simulation is carried out using NS2 simulation software to study the scheme. In the simulation, one PAN-C is used while the number of the coordinator nodes are increased between the ranges of 10 to 100. Two different traffic models are deployed: Poisson traffic and Constant Bit Rate (CBR) traffic. Results showed that CC-SABTS has 41% better throughput, 30% higher packet delivery ratio (PDR), 41% lower end-to-end delay and 27% lower of packet loss in CBR traffic model compared to conventional SABTS. In Poisson traffic model, CC-SABTS improves up to 18% higher throughput, 17% higher PDR, 44% lower of end-to-end delay and 33% lower packet loss compared to conventional SABTS. Between both traffic, CC-SABTS shows higher throughput and packet delivery ratio in CBR traffic however end-to-end delay and packet loss are better in Poisson traffic.

Index Term-- CC-SABTS, LR-WPAN, beacon scheduling, 802.15.4, network density, traffic model

1. Introduction

IEEE 802.15.4 Low –Rate Wireless Personal Area Network (LR-WPAN) [1] is one of the standards that defines functions and protocol to deploy a Wireless Sensor network (WSN). It defines the specification of physical and MAC layer for ZigBee [2]. Within the IEEE802.15.4 network, the only existing devices are the full function device (FFD) and reduced function device (RFD). While FFD can act as a PAN-C or coordinators which has the ability to transmit periodic beacons, RFD can only act as an end device. The standard also states that IEEE802.15.4 can operate either in star topology or peer-to-peer topology. If the established communication happens only between end devices and a PAN-C, then the network is operating in a star topology. A peer-to-peer topology becomes a mesh topology or a tree topology depending on the restriction on the devices used in the network. If there is no restrictions at all which means all the devices in the network are FFDs, then the topology will become a mesh topology. For tree topology, there must be a combination of FFDs and RFDs. The PAN-C will start the network and other coordinators will associate with the PAN-C and form branches. The RFDs will associate with the coordinators to become an end-devices which act like leaves to the tree topology.

The IEEE802.15.4 LR-WPAN operates in two modes: the beacon enabled and non-beacon enabled. Beacon is a periodic signal sent by PAN-C or coordinators in a network in order for new devices to identify a personal area network (PAN) and synchronize with the attached devices in the PAN. Beacons are also periodically sent by the PAN-C to allow devices competing for channel. Unfortunately, a simultaneous beacons transmission from two or more adjacent coordinators will result in beacon collisions. The end devices that are located within the overlapped transmission range of coordinators will be unable to receive beacons. This may cause devices to lose synchronization and keep listening for beacons. Data transfer activities will not happen and none of the coordinators are aware of these beacons conflict.

CC-SABTS [3] is an enhanced method to avoid beacon collision in a cluster tree topology. It provides better throughput, packet delivery ratio and end-to-end delay compared to the conventional SABTS [4]. It introduces a clustering method that groups coordinators with their two length radius neighbour to share beacon transmission offset. Compared to conventional SABTS, CC-SABTS shifts the beacon transmission earlier when number of coordinators are increased and as a result, reduces delay [3]. However, in static network, the growth of coordinators for a multi hop communication will increase traffic load of coordinators which are nearer to the PAN-C [5]. This paper, therefore, examines the effect of network density for CC-SABTS by increasing the number of coordinators in different traffic model scenarios. Only CBR traffic and Poisson traffic are considered in this paper. The network simulation is carried out using the NS2.35 simulation software [6].

The remainder of this paper is structured as follows. Section 2 covers related research in this area. Section 3 explains the two traffic models used in the simulation. In Section 4, the simulation environment are presented. Results
are presented in Section 5 and finally, conclusion are drawn in Section 6.

2. Related work

Various researches have been carried out to examine the effect of network density and traffic distribution to a network. These researches are necessary to obtain some expectations before a real time application can be implemented. Several network performance indicators such as throughout, packet delivery ratio (PDR) and end-to-end delay are mostly used to measure the quality of service (QoS) in a network.

Research in [7] uses OPNET [8] to simulate the effect of increasing load on Wireless Local Area Network (WLAN). Load is increased in three different scenarios. In one of the scenarios, the number of nodes is increased in three diverse routing protocols: Ad Hoc On Demand Distance Vector (AODV), Optimized Link State Routing (OLSR), and Temporally Ordered Routing Algorithm (TORA). Simulation results show that network with less nodes give better throughput, lower packet drop and delay; for all routing protocols. However, this research only focuses on the traffic load and traffic density. Only a maximum of 20 nodes are involved and FTP traffic is deployed in each simulation. It does not cover other traffic models such as CBR and Poisson which may affect the performance of the WLAN network.

Another similar research, such as in [9] also examines the effect of routing protocols (AODV and DSDV) in different network topologies. The study focuses on the performance of IEEE802.15.4 LR-WPAN. One of the variable includes number of nodes in the network. The study uses the NS2 simulation software to set up the scenarios. Results reveal that PDR and throughput are higher when AODV protocol is deployed. The end-to-end delay for the network shows the opposite. However, in case of congested network, AODV gives better overall performances. This research only uses CBR traffic as its traffic model hence, does not cover ON-OFF traffic scenarios.

Research in [10] compares the WPAN network performance in constant bit rate (CBR), Poisson and FTP traffic models. In the study, Scatternet, PicoNet and peer-to-peer topologies are deployed in NS2 simulation software. The PicoNet and peer-to-peer operate in beacon enabled mode. In the first scenario, 10 to 50 nodes are set up in a Scatternet topology. There are no significant differences of performances when nodes are increased from 10 to 30. However, the performances are worst in FTP traffic as the number of nodes are increased to 50. In the second scenario, 7 nodes are involved in the PicoNet topology including PAN-C. Results show that WPAN performs worst in FTP traffic model. The last scenario uses 21 devices including PAN-C and was simulated in a peer-to-peer topology. As expected, WPAN also performs worst in FTP traffic model. This research covers most of the common traffic models used in simulation. However, it only focuses on the general performance of WPAN and not on specific issues for each topology such as mentioned in [11]. These issues need to be studied in order to increase network performances.

The next research [12] also uses NS2 to study the network performance of LR-WPAN in different topologies but only 40 nodes were involved in the network study. The simulation uses CBR, Poisson and FTP traffic models in each network topology. The results reveal that the Star topology has better PDR when modelled in CBR and Poisson traffic. In mesh topology, the network achieves better PDR in Poisson traffic. For tree topology, CBR and Poisson traffic produces the best PDR compared to FTP traffic. Nevertheless, the research in [12] only limits the network density up to 40 nodes. It does not study the effect of dense network where the number of hops may increase. This will reduce the efficiency AODV and thus affect the network performances [13].

Another related research [14] focuses on the goodput of IEEE802.11g multi hop wireless networks. The research compares the effect of Poisson, CBR, Pareto and Exponential traffic load to the routing process which include the hidden terminal scenario. All of the studies are simulated using NS2 simulation software. 127 nodes were placed hexagonally to provide a dense network and the traffic load is set to low, moderate and high. Results conclude that Pareto and Exponential give the best goodput under light traffic load and CBR performs worst in light traffic load. However, for high traffic load, CBR gives highest goodput and Poisson presents the worst. This research uses a planned nodes deployment [15] in the simulation. Unfortunately, the planned nodes deployment may not reflect the real time situation especially in a large area [16] where random deployment is preferred.

These researches provide a basis to study the effect of network density and traffic distribution in a certain network topologies. Hence, this paper will focus on cluster tree topology which applies CC-SABTS method to reduce beacon collision problem. Furthermore, this paper will study the performance of CC-SABTS in a dense network by using different traffic models. By considering these issues, optimum network performance can be achieved for CC-SABTS.

3. Methodology

In this section, the beacon scheduling methods, simulation environment, traffic model and performance metrics are explained.

3.1 CC-SABTS

CC-SABTS [3] has contributed to increase the network performance in a cluster tree network. It was an enhanced method which had included a coordinator clustering mechanism in the conventional SABTS [4]. Coordinators that separated by two length radius (2r) are clustered to share the beacon transmission offset to avoid beacon collision. Table 1 simplifies the process of CC-SABTS.

The process can be explained based on network scenario shown in Figure 1. In Figure 1, a network consisting of 10 coordinator nodes (denoted as number 1 until 10) was set up in NS2.35 simulation software. The 2r neighbour for the coordinators were obtained according to Table 2 and clustered to share TOffset set such in Table 3. The clustered coordinators were assumed to be far enough such that transmission range does not overlap [17]. The number of
TxOffset that needs to be obtained will be updated. Before obtaining the TxOffset, the exact value of beacon order \((BO_{PAN})\) and superframe order \((SO_{PAN})\) for PAN-C, beacon order and superframe order for coordinators and end devices (denoted as \(BO_{coord}\), \(SO_{coord}\), \(BO_{dev}\) and \(SO_{dev}\)) need to be calculated using below formulas [4].

\[
BO_{PAN} = \left[ \log \left( \frac{N_{coord} \times \text{INTV} \times R_s}{B_s \times N_t} \right) \right]
\]

(1)

\[
BO_{coord} = BO_{PAN} - 1
\]

(2)

\[
SO_{PAN} = BO_{PAN}
\]

(3)

\[
SD_{coord} = \frac{B_s \times N_t \times 2^{BO_{coord}}}{N_{coord}} + 190
\]

(4)

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

(5)

\[
BO_{dev} = SO_{coord}; SO_{dev} = SO_{coord}
\]

(6)

\[
TxOffset_i = \begin{cases} 
\text{TxOffset}_{PAN} + \frac{L_{beacon}}{R_s}, & i = 1 \\
TxOffset_{i-1} + \frac{L_{beacon}}{R_s} + SD_{coord}, & 2 \leq i \leq N_{coord} 
\end{cases}
\]

(7)

where:

\(BO_{PAN}\) = Beacon Order for PAN

\(N_{coord}\) = number of coordinator nodes

\(R_s\) = symbol rate = 62,500 symbols/s

\(B_s\) = aBaseSlotDuration = 60 symbols

\(N_c\) = aNumSuperframeSlots = 16 slots

\(SD_{coord}\) = superframe duration for coordinator

\(L_{beacon}\) = 190 symbols

### Table I
The pseudo Code of CC-SABTS [3]

<table>
<thead>
<tr>
<th>BEGIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>/</td>
</tr>
<tr>
<td>Get the number of coordinator nodes ((N));</td>
</tr>
<tr>
<td>Get the two radius length neighbour nodes;</td>
</tr>
<tr>
<td>Cluster node with two radius length neighbor nodes;</td>
</tr>
<tr>
<td>Update the number of coordinator nodes; ((N=\text{maximum cluster number}))</td>
</tr>
<tr>
<td>Get beacon transmission offset;</td>
</tr>
<tr>
<td>/</td>
</tr>
<tr>
<td>END</td>
</tr>
</tbody>
</table>

### Table II
2r neighbors

<table>
<thead>
<tr>
<th>Coordinator no</th>
<th>2r neighbor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>4, 6</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>6, 2</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>6, 8</td>
</tr>
</tbody>
</table>

### Table III
Clustering coordinators

<table>
<thead>
<tr>
<th>Coordinator number</th>
<th>Beacon transmission slot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
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</tr>
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<td>6</td>
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<tr>
<td>7</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

### Table IV
Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Terrain size</td>
<td>1000m²</td>
</tr>
<tr>
<td>Number of coordinator nodes</td>
<td>10, 20, 30, 40, 50, 60, 70, 80, 90, 100</td>
</tr>
<tr>
<td>Number of end devices</td>
<td>10, 20, 30, 40, 50, 60, 70, 80, 90, 100</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Poisson, CBR</td>
</tr>
<tr>
<td>Routing protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>Simulation time</td>
<td>1000 s</td>
</tr>
<tr>
<td>Beacon mode</td>
<td>Beacon enabled</td>
</tr>
<tr>
<td>Beacon scheduling method</td>
<td>Conventional SABTS, CC-SABTS</td>
</tr>
</tbody>
</table>
3.3 Traffic models

This research uses two traffic models; Poisson and CBR. Both traffics were frequently mentioned in the literature. Poisson is suitable for network with data traffic that is not bursty [20]. The generated packets for each nodes in the network increases with mean λ packets per slot following an independent process. The inter arrival rate are also exponentially distributed with mean $1/\lambda$ [21].

CBR is one of the simplest traffic model [21] and is mostly used in real time application [22]. It provides guaranteed delivery of traffic [9]. Unlike Poisson, packets are generated at constant rate. User Datagram Protocol (UDP) [23] is used as the transport agent.

3.4 Performance metrics

There are four network performance metrics used in this research, namely average throughput, average packet delivery ratio (PDR), average end-to-end delay and packet loss. Average throughput can be defined as the sum of received packet within a simulated time. Average PDR is the ratio between all received packet and sent packet from all nodes in the simulation. The average end-to-end delay can be defined as the total delay between packets arrival time and sending time for every existing connection in the simulated network. Lastly, packet loss can be defined as the difference between total generated packet and received packet in the designated network.

4. Results and analysis

In this section, simulation results are presented. The results compare the average throughput, average PDR, average end-to-end delay and packet loss for conventional SABTS and CC-SABTS in two traffic models.

4.1 Average Throughput

Figure 2 shows the average throughput performance for conventional SABTS and CC-SABTS in Poisson and CBR network. As the number of coordinators increase, the throughput decreases. In CBR and Poisson traffic, CC-SABTS outperforms conventional SABTS up to 41% and 18%, respectively. However, from Figure 2, CC-SABTS shows higher in throughput in CBR traffic compared to Poisson traffic within the simulation time. The results are supported by research in [14] and [21] which is due to the nature of CBR traffic that generates packet constantly in the network compared to Poisson traffic.

4.2 Average PDR

CC-SABTS also outperforms conventional SABTS in CBR and Poisson traffic models for average PDR which is up to 30% and 17%, respectively. Figure 3 also reveals that CC-SABTS gives better average PDR performance when simulated in CBR traffic. Overall performance shows the PDR decreases when the network density increases. Similar result for PDR can be seen in [9] whereby PDR decreases as the number of nodes increase regardless of the type of routing protocol used in the simulated network.

4.3 Average end to end delay

Simulation results show an increase of average end-to-end delay as the network becomes denser. Compared to conventional SABTS, CC-SABTS gives 41% and 44% lower average end-to-end delay in CBR traffic and Poisson traffic, respectively. Notably from Figure 4, Poisson traffic contributes lowest average end-to-end delay in the higher number of coordinators network when CC-SABTS are applied. The reason for better average end-to-end delay in Poisson traffic is due to the inability of UDP agent used in CBR traffic to handle traffic congestion [18, 22].
congestion in CBR traffic [18, 22] and the failure to detect bursty network in Poisson traffic [21].

Other significance outcome from the simulation results is how CC-SABTS outperformed conventional SABTS in varied network density. Although performing better, all the performance metric shows that network with CC-SABTS method will degrade with the increase of nodes. The pattern of the performance is similar in [27] and [28]. The increased number or nodes contribute to bottleneck in delivering packet at nodes nearest to PAN-C [29]. The congested packets need to compete for channel during superframe duration [30, 31]. Since the congested packets may not fully transmitted in the same superframe, the later will need to wait for another superframe to access the transmission channel [32]. There is possibility packets will be dropped and lost [33]. All of these factors lead to the network degradation.

6. Conclusions
This paper compared the performance of conventional SABTS and CC-SABTS in two different traffic models: Poisson and CBR. CC-SABTS performs better in average throughput, PDR, end-to-end delay and packet loss in both traffic. Although the average throughput and average PDR degrade as the network becomes denser, analysis reveals that CC-SABTS performs up to 67% and 18% higher throughput and PDR, respectively in CBR traffic compared to Poisson traffic. On the contrary, Poisson traffic gives CC-SABTS 30% and 69% lower average end-to-end delay and packet loss, respectively as the network becomes denser. These results provide options to network developer to choose between a high throughput and PDR or lower delay and packet loss for WSN that applies CC-SABTS. For future work, the performance of CC-SABTS in a mixed traffic model will be studied as it reflects more to real network scenarios. The impact of node deployment can also be taken into consideration in order to ensure that CC-SABTS can perform optimally either in large area or limited space.

REFERENCES
Topologies under CBR Traffic Pattern,” vol. 124, no. 11, pp. 5–12, 2015.


