Distributed Beacon Synchronization Mechanism for 802.15.4 Cluster-Tree Topology

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Abstract. Lack of synchronization mechanism in IEEE 802.15.4 standard for cluster-tree topology has restricted its use to non-beacon mode. Initial works in this direction are more centralized in nature whereas more recent works follow the distributed way. The former way of achieving synchronization have performance limitations in terms of scalability and overhead. In this paper, we propose a distributed beacon synchronization scheme that requires lesser transmissions and results in improved channel utilization. Apart from that, the proposed scheme also minimizes the number of collisions during beacon transmissions thus lowering the number of orphan nodes. Analytical and simulation studies corroborate our findings.

1 Introduction

The IEEE 802.15.4 standard [1] has emerged as a de facto standard for low-power wireless personal area networks (WPAN). It defines multiple physical layer (PHY) technologies and medium access control sub-layer for such low data-rate devices. IEEE 802.15.4 networks support both star and cluster-tree topologies. They can operate in either beacon-enabled (BEM) or non beacon-enabled (NBE) modes. In BEM, beacon synchronization allows attached devices to detect any pending messages or to track the beacon. In addition, as the structure of superframe is described in beacon, synchronization becomes important. In BEM, medium access control is achieved through slotted CSMA/CA. In addition, a guaranteed time slot (GTS) can be obtained for transmission that are assigned by a coordinator using an optional superframe. In presence of multiple end-devices and multiple coordinators, synchronization among coordinators reduces collisions.

In a star network, achieving synchronization is straight forward as all nodes are within communication range of central PAN coordinator (PANC). All communications are through the central coordinator. On the other hand, devices in a cluster-tree network can communicate with any other node provided they are within range of each other. This allows the network to scale whereby other

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devices can also act as coordinators by providing services to its attached devices. Many commercial and industrial applications need such a topology. However, the operation of such a network comes with its own set of challenges. Synchronization is difficult as multiple coordinators are involved and overlapping beacon schedules result in frequent collisions and orphan nodes.

This problem has been addressed in [2–13]. But, majority of them are centralized in nature where a central coordinator computes beacon schedules and transmits to each coordinator with the help of a routing protocol. Nodes that actively participate in message relay run out of battery power resulting in network disconnections. Furthermore, distributed schemes like [9,10,14] are constrained by their own set of limitations like the need to shift between radio channels and maintaining tree routes. This motivated us to design a beacon scheduling scheme with low-overhead for a cluster-tree network. The main contributions of this paper are summarized as follows.

- We propose a distributed beacon synchronization scheme for a cluster-tree network that uses available channel slots effectively, incurs fewer transmissions and in turn consumes less energy.
- We present the collision probability analysis of the proposed synchronization mechanism.

A preliminary version of this work has been published in [15]. The rest of the paper is organized as follows. Section 2 provides brief overview of IEEE 802.15.4 MAC superframe as the proposed work uses beacon order (BO) and superframe order (SO) parameters. The proposed synchronization mechanism and its analytical evaluation is presented in Sect. 3. Simulation results are presented in Sect. 4. Finally, conclusion and future scope is presented in Sect. 5.

2 Overview of Superframe in 802.15.4 MAC

The superframe is bounded by two successive beacons that are separated by beacon interval (BI). It consists of an active period (contention access period and contention free period) followed by an optional inactive period. The superframe structure is divided into 16 equal duration slots. Slots in the contention access period (CAP) are accessed through slotted CSMA/CA, whereas, dedicated access is possible in contention free period (CFP) through GTSs. The active period of the superframe beginning from the beacon transmission is called superframe duration (SD). Nodes sleep during the inactive period and wakes up marking the beginning of the next superframe cycle. Two parameters namely `macBeaconOrder` (BO) and `macSuperframeOrder` (SO) together defines the structure of superframe as,

$$BI = \texttt{aBaseSuperframeDuration}.2^{\mathrm{BO}}$$

$$SD = \texttt{aBaseSuperframeDuration}.2^{\mathrm{SO}}$$

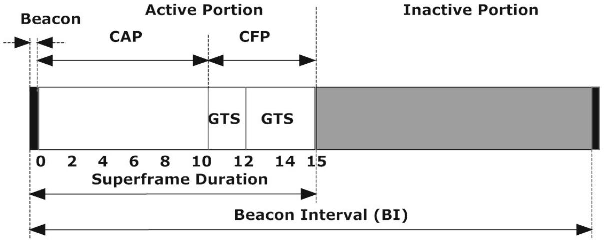

Fig. 1. IEEE 802.15.4 superframe structure.

where, SO and BO refer to the duration of active period along with beacon transmission time and the cyclic time period when the coordinator communicates using beacons, respectively. The structure of the superframe is shown in Fig. 1. The `aBaseSuperframeDuration` is the number of symbols constituting a superframe when the SO is set to zero. It gives us the time period between two beacon frame transmission. With $0 \leq \text{SO} \leq \text{BO} \leq 14$ and $\text{BO} = 15$ implies non-beacon mode.

3 Proposed Distributed Beacon Synchronization Scheme

3.1 Network Model

We consider a cluster-tree network, comprised of coordinators and end devices, as shown in Fig. 2. One of the selected coordinators acts as overall network coordinator. Coordinators are entrusted with additional functionality of synchronizing associated nodes with the help of periodic beacons. An end device associates with a coordinator and all data is routed via the parent. Clusters are formed among a group of coordinators and end devices, that executes a common function. A cluster head is chosen among the coordinators in each cluster for operational simplicity. The main notations in this paper are summarized in Table 1.

3.2 2-hop Distributed Beacon Synchronization (2-hop DBS)

The proposed scheme emphasizes on reducing the number of transmissions required to achieve beacon synchronization in a network and to restrict beacon collisions between neighboring coordinators. We focus on striking a balance between reducing the number of orphaned devices when beacons of multiple coordinators collide, and the synchronization simplicity. The proposed mechanism is presented below.

2-hop Distributed Beacon Synchronization: Following the designed synchronization scheme, a coordinator that aims to compute a synchronized schedule needs the *BO* and *SO* values of the parent coordinator (i.e. the coordinator to which it is associated) and all its (parent's) relatives. The first part of the information can be retrieved from the beacon frame received from the parent.

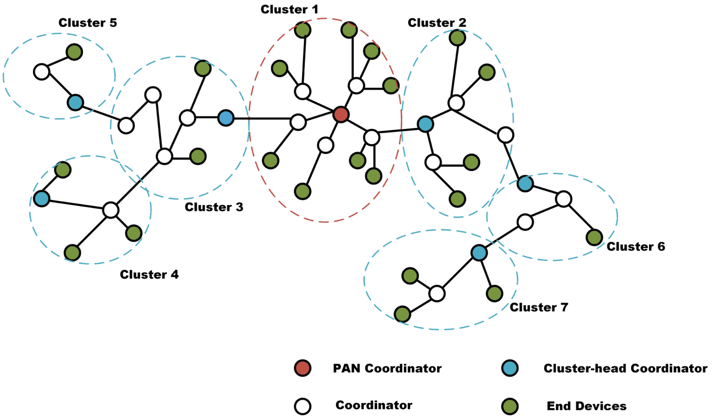

Fig. 2. Cluster-tree topology.

Table 1. Main notation definition

Symbols	Definition
N	Total number of coordinators in neighbor list (both 1-hop and 2-hop)
n	Number of coordinators in transmission range + N
ρ_N	The probability of $n = N$
ρ_n	The probability that $n > N$
p_t	The probability that a node chooses a slot t_l that do not overlap with any of the coordinators in its neighbor list
P_c	The collision probability

The relatives information is provided by the parent coordinator in the form of a neighbor list. To simply put, a node requires information about its parent and all the coordinators associated to it, which may include all the coordinators grand parent and peers if any. The payload part of the beacon carries this additional information comprising of short addresses of respective coordinators followed by their BO and SO, and an association field that is of two bits. The association field allows a coordinator to determine the relative ranking which are by default *0* for a grand parent, *1* for the parent and $\{2, 3 \text{ or } 4\}$ for the peers sorted based on their association time. These values are set by a coordinator (read parent) in accordance to their association times. This allows a coordinator to schedule accordingly based on its priority with respect its peers.

Algorithm 1 lists the steps involved in computing a synchronized schedule. First, a coordinator awaits the reception of a beacon frame from its parent that contains all the required BO and SO information. Based on this, it determines the respective BI and SD for each neighboring coordinator. For an agreed BO and SO, the coordinator also calculates its BI and SD. The goal is to estimate neighboring coordinators schedules and synchronize with them. Based on the information realized in the first part, a coordinator sorts all *BI* based on the order of association and selects the maximum *BI* ($BI_{\max}$) to fix a time cycle. This time cycle is divided into slots, where each slot equals minimum *SD*. Now, the superframe duration of a coordinator i, given as SD_i, is allocated based on first empty time slot. Based on BI_i, the duration of SD_i is set until $BI_{\max}$ is reached. This allows a coordinator to recreate a map of beacon transmissions of all its neighbors and thus synchronize its own transmissions avoiding collisions. The gathered two hop neighborhood information prevents collisions between coordinators whose transmission ranges overlap. The probability of such an occurrence is estimated in the following sub-section.

Algorithm 1. Distributed beacon synchronization algorithm

```
From parent beacon, obtain $BO$, $SO$, and association order.
Compute $BI$ for all received $BO$, $SO$, represented by set $B$, for all $BI_{\mathrm{i}}$.
Compute $BI_{\min} = 2^{BO_{\min}}$ and $BI_{\max} = 2^{BO_{\max}}$.
Sort $B$ based on association order for each $BI$.
Set $time - line = BI_{\max}$, where slot $= \min(SD_i), 1 \leq i \leq N$
for each $i$ in $B$ do
    find the first available consecutive time slots $\geq SD_i$
    fix $(i)$ of $SD_i$ in consecutive time slots beginning with first empty slot
end for
return The coordinators time slot.
```

3.3 Illustrative Example of 2-hop DBS

To illustrate the 2-hop DBS algorithm, assume a simple hierarchy where a coordinator c2 is associated with coordinator c1, and coordinators c3 and c4 are associated to c2. That is, c1 is parent of c2 and grand parent of c3 and c4. Let {c1, c2, c3} be already synchronized and transmitting beacons. Now, node c4 that needs to compute its schedule, retrieves the required *BO*, *SO* and association order parameters from its parent (c2's) beacon payload. Table 2 shows the configuration of c4. Based on received parameters, c4 computes corresponding *BI* and *SD* for each coordinator. Then, it chooses the maximum *BI*, $BI_{\max} = 16$, and minimum *BI*, $BI_{\min} = 8$, where each time slot corresponds to a base superframe duration, $SO = 0$. BI values are further arranged to form a ordered set $B = \{16(\text{c1}), 8(\text{c2}), 16(\text{c3}), 8(\text{c4})\}$ with respect to their order of association.

Next, from the set B, c4 schedules each instance of *SD* of the corresponding coordinator in the first available slot of size *SD* time slots in such a way that it does not overlap with other superframe durations. Subsequent instances are placed at a distance equal to a multiple of $BI_{\min} = 8$ time slots from the first instance corresponding to its *BI*. We place *SD* of c1 in first horizontal line. Then c2 is placed after the instance of c1. Afterward, c3 is placed in the third horizontal line after the c2. Finally c4 is placed after the instance of coordinator c3. The instances are repeated according to the coordinators' *BI*. The schedule is periodically repeated after a slotted timeline of 16 slots ($BI_{\max}$). The final beacon schedule computed by c4 is shown in Fig. 3 upto 32 timeslots.

Table 2. Configuration of c4

Coordinator	SD	BI	Association order
c1 (grand parent)	2	16	0
c2 (parent)	2	8	1
c3 (sibling)	1	16	2
c4	2	8	3

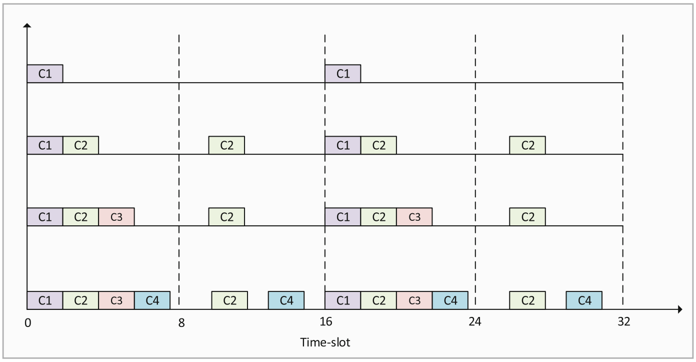

Fig. 3. Beacon schedule for coordinator c4.

3.4 Collision Probability with 2-hop Information

Consider an all probable scenario where all n devices of coordinator A aim for beacon transmission. Relying on N (obtained from the proposed scheme), A can compute a non overlapping transmission schedule. But, in case of $n > N$, a set of k coordinators ($k < n$) exist that are within *A's* reach but not accounted while realizing schedule. This issue can be categorized as the problem of overlapping schedules with one of $n_1, n_2, ..., n_k$ coordinators. Inherently, this can be viewed as $N \subset n$. That is, we need to account for transmission of those $(n - N)$ nodes. For simplicity, let us assume that all the devices that are within the range of A are also present in the neighbor list obtained by A. That is $n = N$. Consider the probability of such an occurrence is ρ_N. Alternatively, for the case of $n > N$, the probability be ρ_n. Also, $\rho_N = (1 - \rho_n)$. In a given scenario of $n > N$, device A determines a time slot t_l with p_t probability. This time line avoids collisions with all devices in the neighbor list but may still collide with unaccounted $(n - N)$ nodes. The probability of non-occurrence of such an event is given by

$$(1 - p_t)^{n-N} \tag{1}$$

This means that the remaining $(n - N)$ devices have not chosen the same time slot as A. It in turn means that a node A has chosen a collision free time slot t_l with probability $p_t(1 - p_t)^{2(n-N)}$. Let P_c be the collision probability with one of $(n - N)$ if it selects same slot t_l. So,

$$P_c = 1 - (1 - p_t)^{2(n-N)}. \tag{2}$$

To account for a scenario of $n = N$, let a device select a time slot t_l with a probability p_t based on the proposed scheme. Accordingly, the rest of the $(N-1)$ nodes not selecting the same slot t_l is given by $(1-p_t)^{N-1}$. Since, the proposed scheme makes sure that no two coordinators select the same t_l, the probability of collision P_c in this case is 0. This is achieved with the help of association order that is assigned by the coordinators parent resolving colliding beacon schedules between neighbouring coordinators.

4 Simulation Results and Discussion

In this section, we compare the proposed algorithm with the centralized and distributed schemes presented in [7,10], respectively. We have used the network simulator NS-2.34 [16] to evaluate the aforementioned protocols. Parameters that are used in the experiments are listed in Table 3. An 802.15.4 cluster tree network consisting of seven clusters, where 23 devices act as coordinators and another 24 devices are associated with these coordinators as end devices. Figure 2 represents the network set up. The protocols performance is distinguished in terms of number of transmissions, energy consumed and utilization of the channel. For simplicity, we do not consider any battery model and assume one unit of energy is spent per byte transmission.

To achieve synchronization, all the coordinators need to transmit messages and this forms the basis of our first experiment. In other words, we measure the transmission count that is necessary for synchronization. Each coordinator exchanges beacons with the neighboring devices to determine their respective slots of transmission. More the number of such transmissions more the network overhead. Figure 4 shows a linear increase in number of transmissions for a centralized scheme like [7], as the size of the network grows. It is due to the fact that the overall central coordinator determines the beacon schedules of all other coordinators in the network and transmits these to respective coordinators that may be located multiple hops away. To achieve this a routing protocol like ZigBee [17] can be used. On the contrary, distributed mechanism like MeshMAC achieves synchronization within fewer number of transmissions as it depends on all the neighboring coordinators. However, this is still higher compared to the proposed algorithm, as the 2-hop DBS relies only on the neighbor list from the parent coordinator thus restricting the transmission count to 2 for each coordinator. Thus, the proposed mechanism achieves synchronization with 30% lesser transmissions when compared to MeshMAC making it more scalable.

Next, we evaluate aforementioned schemes for average energy consumption with respect to the height of cluster-tree. Since, energy consumed is directly proportional to transmission count, and as SDS is shown to incur more transmissions, we mainly focus on the other two schemes. Figure 5 shows the comparison graph. The proposed scheme consumes lesser energy over MeshMAC as

Table 3. Simulation parameters

Parameters	Values
Frequency of operation	2.4 GHz
Total nodes	48
Tx range	50 m
Tx Power	−7 dBm
BO	8
SO	4
BI	245760 symbols
SD	15360 symbols

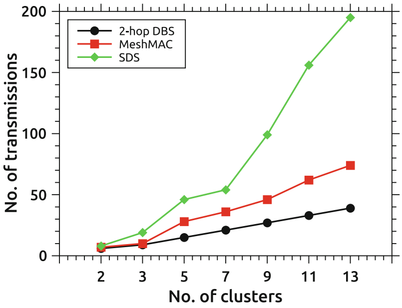

Fig. 4. Comparison of transmission overhead.

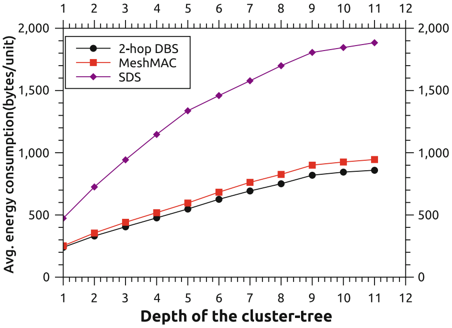

Fig. 5. Comparison of energy consumption.

the transmissions related to computation of beacon offset are kept to minimum. Conversely, in case of MeshMAC it varies with the degree of a coordinator. In other words, it depends on the number of neighboring coordinators that a node has to consider to compute its offset. Lesser dependencies contribute to energy efficiency in case of our scheme.

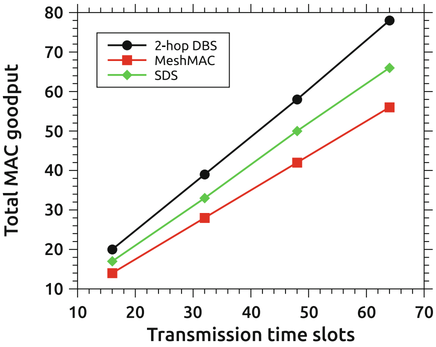

Fig. 6. Channel utilization of the schemes.

Beacon synchronization results in effective channel utilization in the network. This forms the basis of our final experiment that is to evaluate the channel utilization of all three synchronization mechanisms. The results are presented in Fig. 6. For a given BO and SO, the centralized scheme computes non-overlapping beacon schedules for all the coordinators in the network. This results in non optimal allocation as the central coordinator aims to assign completely non overlapping schedules even though the coordinators in contention are not in collision range of each other. Similarly, depending on superframe duration SD MeshMac also reports sub-optimal schedule, especially if the coordinator needs a shorter SD. On the other hand, the proposed scheme resolves synchronization transmission conflicts based on the cumulative information provided by the parent, it registers better channel utilization. In a dynamic network setting where different clusters may resort to different BO and SO parameter settings (based on the requirements of associated devices), the proposed mechanism has a near optimal solution. The increase in channel utilization compared to other two schemes respectively are 15% and 28%. The point to be noted is that even though the centralized scheme incurs higher transmission overhead, it offers better channel utilization.

5 Conclusion and Future Scope

In this paper, we presented a distributed beacon synchronization mechanism named 2-hop DBS, designed for peer-to-peer cluster-tree topologies. The proposed mechanism uses beacon information of 2-hop coordinators to compute a non-overlapping beacon schedule. The required information is provided by a parent coordinator as part of the beacon payload. This scheme is shown to perform 28% better in terms channel utilization compared to MeshMAC. Further, it does not need an active routing protocol that adheres to device constraints by minimizing the complexity of synchronization. This process may be further simplified for sparse topologies where the probability of beacon collisions is low.

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