On the Synchronization of Co-Located IEEE 802.15.4 Networks for IoT Applications

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***Abstract*—With the coming wide-spread deployment of Internet of Things (IoT) applications, particularly robustness of the wireless transmissions becomes an issue. We focus on the IEEE 802.15.4 MAC protocol, which has been widely adopted for a variety of Wireless Personal Area Network (WPAN) applications. IEEE 802.15.4 defines a node synchronization strategy using beacons for achieving robust and real-time capable low energy communication within the WPAN. However, problems arise when there are many co-located networks within the same transmission area. This problem has been identified in the literature considering the many possible configuration options for the protocols' superframe structure. In this paper, we propose a novel scheme that enables WPANs to overhear beacon information from neighboring networks in order to mitigate interference by adjusting the beacon transmission time. We analyzed the scheme in an extensive set of simulations and can confirm its ability to overcome a majority of the collision-prone situations.**

I. Introduction

We address the problem of necessary de-synchronization of co-located wireless networks in the scope of Internet of Things (IoT) applications. In particular, we focus on Wireless Personal Area Networks (WPANs) based on the IEEE 802.15.4 protocol [1]–[3]. This protocol started as a standard designed for WPANs, which focuses on short range operation, low data rate, and energy efficiency. Being designed for such scenarios, IEEE 802.15.4 quickly became a *de facto* standard in the field of sensor networks as well as healthcare and industrial applications.

In the mentioned application domains, however, the deployment of multiple WPANs operating on the same channel within the same transmission range becomes unavoidable. In the scope of this paper, we call such WPANs *multi-WPANs* or *co-located WPANs*. Whenever timing is an issue, IEEE 802.15.4 is operated in the co-called *beacon enabled* mode. That is, the network gets synchronized by means of a fixed superframe structure that is initiated using a beacon sent by the WPAN coordinator.

In a multiple co-located scenarios, due to the uncoordinated and independent nature of the WPANs, packet collisions are inevitable. As beacons are sent without carrier sensing, collisions involving beacons could easily result in loss of synchronization. The inability to synchronize affects the network performance as the nodes are not able to send packets during its superframe. Furthermore, as co-located WPANs are not managed by a central entity, their different beacon transmission times might result in superframe overlaps. This further aggravates the impact on performance as increased overlaps result in increased packet collisions [4]–[6].

In such situations, in order to optimize throughput, one of the WPANs should be able to adjust its active time to start within the inactive time of the other WPAN [4], [7], [8]. Taking that into consideration, we present a new strategy, which tries to adjust the beacon transmission time so that a WPAN is able operate with the least amount of interference from a nearby networks. We study this beacon offset strategy that takes into account the configuration of the interfering WPANs. This strategy builds upon the approaches made by 802.15.4 Task Group 15.4b, which recommends the coordinator to adjusts its active period to coincide with the inactive period of the nearby network.

Our main contributions can be summarized as follows:

- We study the advantages and open issues of related approaches to identify open issues and potential challenges (Section II).
- We outline a novel coordination scheme for co-located WPANs that takes the configuration of the interfering networks into account (Section III).
- Using a fairness index, we evaluate the effectiveness proposed solution in an extensive set of simulation experiments (Section IV).

II. Related Work

A. IEEE 802.15.4 Overview

In order to synchronize the communication at the MAC layer, IEEE 802.15.4 can operate in a *beacon enabled* mode using a well-defined superframe structure. Each *superframe* is bounded by periodically transmitted beacon frames, which allow nodes to synchronize to the coordinator. Each superframe consists of two parts: an active period and an inactive period. The superframe structure (cf. Figure 1) is defined by two configuration parameters: the Beacon Order (BO) specified by the parameter *macBeaconOrder* and the Superframe Order (SO) specified by *macSuperframeOrder*. They determine the length of the Beacon Interval (BI) and the length of the active portion of the superframe, Superframe Duration (SD), respectively. The inner structure is not that relevant for our investigations; in short, the protocol supports both a contention based access (Contention Access Period, CAP) as well as a TDMA based access (Contention Free Period, CFP).

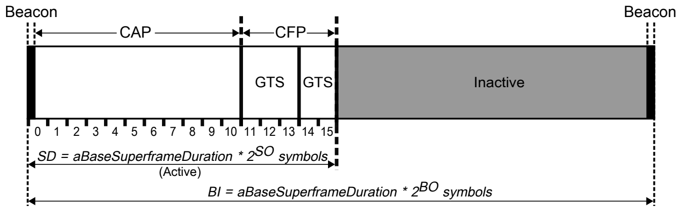

Figure 1. IEEE 802.15.4 superframe structure

The typical configuration for energy and time sensitive applications is the *beacon enabled* mode in which the network is synchronized by a WPAN coordinator. In this setup, significant energy savings could be achieved – if nodes could be synchronized. Unfortunately, the IEEE 802.15.4 standard does not foresees how to manage multiple WPANs operating in the same interference range, i.e., how to schedule beacons and how to adapt the superframe between multiple WPAN coordinators.

B. Co-Located Networks

The IEEE 802.15.4 Task Group 15.4b proposed two approaches for beacon scheduling. The first approach was adjust their inactive periods to start during the inactive period the other WPANs. This is in line with our findings in earlier work [5], [6]. Unfortunately, details on its execution was not specified. As an initial concept, a beacon scheduling mechanism was proposed in [7]. This strategy applies to new coordinators that wish to join the network. If their BO and SO values are schedulable, then it is admitted. Otherwise, it is forbidden from joining the network. This strategy works best for newly-formed WPANs, however, for existing disjointed networks where a WPAN coordinator has little control over another WPAN coordinator, this strategy does not work effectively.

The second approach, called the beacon-only period approach, specifies that all superframes should start at the same time and that a portion of time at the beginning of all superframes should be dedicated only for the transmissions of beacons, which contain information on the starting time for each respective WPAN. Nonetheless, as mentioned in [7], [9], the same problems may occur and there might also be insufficient resources for all WPANs in the shared active period.

C. Mitigating Synchronization Problems

In the literature, we find several work focusing on beacon scheduling in multi-WPANs. One notable work is a scheme proposed in [8], where the superframes of multiple WPANs that operate within the same space are dynamically scheduled within the inactive period of other WPANs. The scheduling is determined by first estimating the throughput which was done by analyzing the overlap of two superframes. However, the approach is limited to scenarios in which all nodes of all involved WPANs are in each others communication range. Partially overlapping networks are not supported.

In [4], a collision avoidance strategy has been proposed that requires the coordinators to adjust the start time of their superframe depending on the amount of detected superframe overlap. The coordinator first obtains the amount of overlap at the beginning, which is denoted by $b[t]$, and the end of its superframe, $e[t]$. The difference between $b[t]$ and $e[t]$ determines whether the coordinator will delay or advance its next superframe. However, the approach shows only little impact if all superframe sizes are similar and using a 50 % duty cycle. In this case, collisions will be unavoidable. This concept has been extended in [10] by introducing a guard time at the end of the neighbors' beacon intervals. Conceptually, the approach is limited to scenarios in which all WPANs share the same BI and the total active time of all networks is smaller than the inactive time.

In [9], [11], a complementary strategy has been presented for avoiding beacon collisions. Multiple groups have been introduced using a multiple channels in order to avoid beacon collisions. However, as the 2.4 GHz band is also used by other technologies such Wi-Fi and Bluetooth, only 4 non-overlapping channels are available for IEEE 802.15.4. Therefore, the limited number of channels may not be able to support rather crowded scenarios.

III. Proposed Scheme

In our study, we consider the IEEE 802.15.4 wireless technology with beacon-enabled mode. As we assume that the co-located WPANs have similar configurations, we try to leverage on this information in order to reduce superframe overlap, thus allowing both WPANs to operate as though they are not in range of one another. We also assume that associations between the child node and its coordinator are already made before the WPAN comes into contact with another WPAN and that child nodes always have packets to send during each superframe. This is in line with many applications that require periodic data reporting to the coordinator.

A. Concept and Algorithm

The beacon rescheduling algorithm for our strategy is shown in Algorithm 1. The coordinator is required to keep track of the number of packets sent by its child nodes. At the end of

Algorithm 1 Beacon rescheduling

```
if No packets received from child node during superframe then
    Randomly decide to hold the next beacon transmission and listen for
    other beacons
    if Hold next beacon transmission then
        Hold next beacon transmission (minimum 1 BI + inactive time)
        if Detect beacons coming from another coordinator then
            Get the WPAN IDs, BO, SO and the beacon reception times
            if Only one WPAN detected then
                Set beacon transmission time to start at the inactive period of
                the detected WPANs
            else
                Sort WPANs according to their IDs; reset time for the next
                beacon transmission.
            end if
        end if
    else
        Maintain the current settings
    end if
end if
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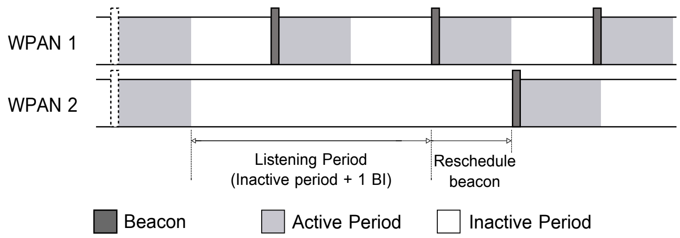


Figure 2. Illustration of beacon offsetting

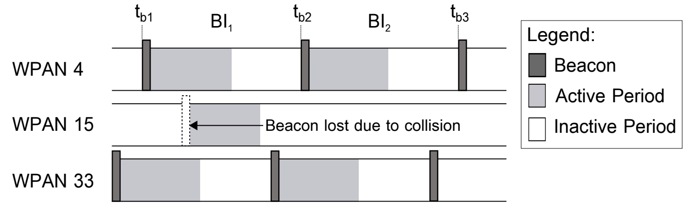
each superframe, the coordinator will get the total number of packets. If it finds that no packet is sent by any of its child nodes, it will assume that the previous beacon is lost due to a collision with an interfering WPAN. Therefore, the coordinator will randomly generate a new beacon transmission time within the inactive period. The decision to generate a new transmission time on a random basis is to counter the effect both WPANs offsetting their beacon transmission times to the same time should they both experience beacon collision, which would lead to further beacon collisions.

Until the coordinator is due to transmit the next beacon, it overhears beacons transmitted by other WPAN coordinators. If there is only one, then it takes the BO and SO from the beacon and offsets the transmission time of the its beacon to the inactive time of that interfering WPAN as illustrated in Figure 2. Otherwise, it sorts the all the WPAN IDs (including its own WPAN IDs) that it detects during the period that it pauses its BI in an ascending order. If its WPAN IDs is found to be the smallest, it will continue transmitting its beacon by using the same settings. Otherwise, it divides the BI by the number of detected WPANs, which we denote by ρ. It then uses its position index i in the sorted WPAN ID list and sets a new beacon transmission time that is offset from the beacon transmission time of the smallest WPAN IDs by $i \times \rho$.

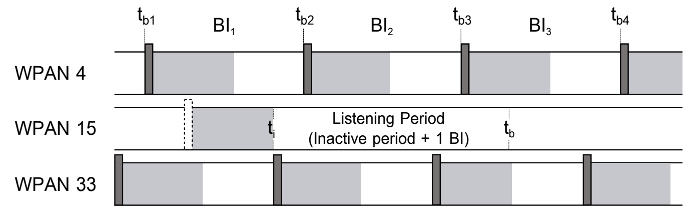
B. Special Cases

As the pause time includes the inactive time, the overall time that the coordinator listens for other beacon becomes longer than one BI. Thus, there could be instances where more than one beacon has been sent by the same coordinator, but only the first one is detected as the subsequent ones got lost due to collision. In this circumstance, the calculated offset time could be less than the current time, in which case, it will not be executed as the beacon transmission time has already passed. To avoid this problem, the coordinator will add an extra offset time which equals the BI length. This would ensure that the subsequent beacon that the coordinator sends still corresponds to the transmission time of the beacon sent by the coordinator with the smallest WPAN IDs.

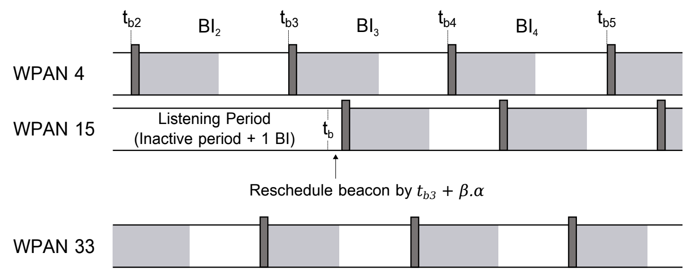
On the other hand, the child node shall keep track of the beacon sent by its coordinator. If the beacon does not arrive at the expected time, the child node will keep its receiver enabled until it receives it and start tracking the new beacon after the it receives it. If the coordinator receives a beacon originating from an interfering WPAN, the coordinator will try to obtain



(a) WPAN 15 experiences beacon loss



(b) WPAN 15 stops beaconing and tries to detect other WPANs' beacons



(c) WPAN 15 reschedules the next beacon

Figure 3. Example of the proposed scheme

the BO and SO of the interfering WPAN and adjusts its next beacon transmission time to start during the inactive period of the interfering WPAN. If it finds that it is able to receive packets from its child in the subsequent superframe, it will enable its original settings and disable its receiver during its inactive period in order to save energy.

C. Example

An illustration of this scheme is shown in Figure 3. As shown in Figure 3a, WPAN 15 experiences a beacon collision during WPAN 4's active period. As a result, the coordinator of WPAN 15 does not receive any packets from its child nodes. Therefore, in the next inactive period (Figure 3b), it will turn on its receiver and tries detect beacons sent by other coordinators. At the end of the listening period, it will sort the beacons by the WPAN IDs and reschedule the new beacon transmission time accordingly as shown in Figure 3c.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

In order to evaluate the performance of the proposed strategy, we performed an extensive set of simulations using the OMNeT++ simulator with INET framework and the IEEE 802.15.4 model [12].

We used a network of two, three, five, or ten WPANs to be in communication range as shown in Figure 4. The WPANs

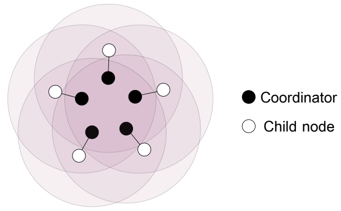


Figure 4. Five WPANs in communication range

Table I
SIMULATION PARAMETERS

Transmission range	10.5 m
Interference range	15 m
Channel bit rate	250 kbps
Duty cycle	50%
Packet size	10 bytes
Mean interarrival time	4 ms

were configured with a duty cycle of 50 % using a BO/SO combination of 2/1 (0.061 44 s / 0.030 72 s) to simulate a time sensitive application. The key parameters of the model are shown in Table I, otherwise we used a typical configuration as used, e.g., in [12]. We assume that all child nodes belong to only one WPAN and the associations with their own coordinators were predetermined. The starting time of all WPANs were randomly set and each simulation was run for 3600 s. For statistical evaluation, all runs were repeated 100 times.

B. Goodput

Figure 5 shows the achieved goodput comparing our adaptive approach with the original IEEE 802.15.4 protocol. As can be seen, our approach clearly improves the overall average goodput for the case of two or three co-located networks) as these WPANs are able to avoid from experiencing a superframe overlap when the scheme is employed. We also found that, generally, only one of the WPANs needs to experience a beacon loss in order to detect an interfering WPAN, adjusts its beacon transmission time and subsequently, avoid subsequent beacon collisions. This is because by being able to detect beacons from a nearby WPAN, a coordinator would be able to obtain the WPAN's BO and SO values that it can use to offset the time of its next beacon transmission.

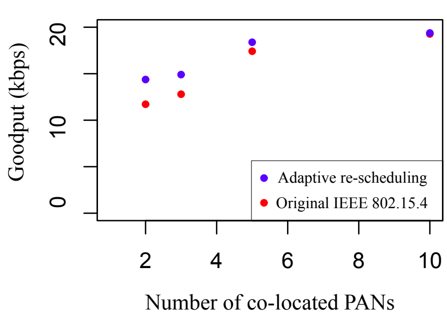


Figure 5. Goodput (adaptive re-scheduling vs. original IEEE 802.15.4)

On the other hand, our approach becomes more and more useless when many WPANs are located within the same communication range. Here, less or no improvements at all can be observed – please note that our system never performs worse compared to the standard protocol. This is because according to the IEEE 802.15.4 MAC protocol, at the time that some WPANs are experiencing and resolving collisions, other WPANs are using that opportunity to use the medium for data transfer. The same also applies when the proposed scheme is applied, thus, the amount of improvements that can be achieved is limited.

C. Fairness

Although the scheme does not improve average throughput significantly in case of a larger number of involved WPANs, it is able to distribute access relatively fairly. In order to measure fairness, we used Raj Jain's fairness index [13], which is calculated as

$$F = \frac{(\sum_{i=1}^{n} v_i)^2}{n \sum_{i=1}^{n} v_i^2}, \quad (1)$$

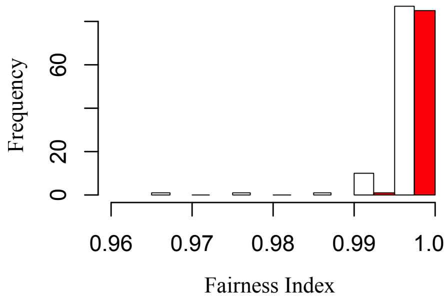
where v_i represents the throughput of sender flow i and n the total number of nodes. The fairness index represents the distribution of throughput gained by all competing nodes. An index value of 1.0 signifies that all nodes are given equal amount of access to the channel.

Figure 6 shows the fairness index for our measurements in form of a histogram. As can be seen, without our scheme, the minimum index is at about 0.96 for a two WPAN scenario. This is due to the packets losses that the WPANs experience during the recurring superframe overlaps. When the scheme is employed, both WPANs are able to operate with minimal interference with minimum fairness index being close to 1.

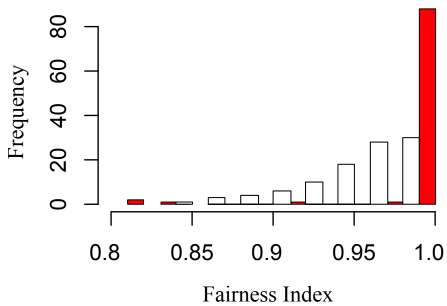
As we increase the number of WPANs, without the beacon adjustment, the fairness index can be as low as 0.8. However, with our proposed scheme, we manage to maintain a fairness larger than 0.95 for the majority of the simulation runs. Nonetheless, due to the randomness in deciding whether to postpone beacon transmissions and the larger number of senders, it is more difficult to ensure that all WPANs get the same amount overlaps. As a result, a fairness less than 1 is achieved as we increase the number of co-located WPANs.

V. CONCLUSION AND FUTURE WORK

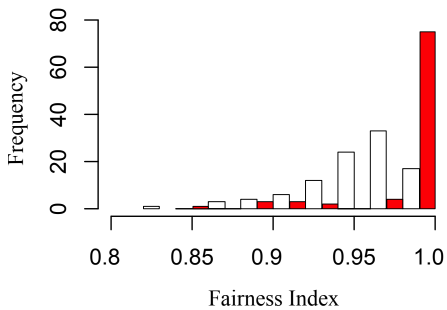
We presented a novel scheme for beacon re-synchronization in the presence of co-located Wireless Personal Area Networks (WPANs). The proposed scheme is able to slightly improve the goodput without requiring major changes to the standard IEEE 802.15.4 MAC protocol. Even more importantly, our scheme is able to support a fair sharing of the medium for multiple co-located WPANs. This is a substantial improvement compared to the original protocol in which single networks may be able to fully use the network while other are starved from medium access. For our future work, we plan to conduct simulations involving more WPANs and enhancing the strategy by obtaining and utilizing information about the co-located WPANs in order to improve the overall network performance.



(a) Fairness index for 2 WPANs



(b) Fairness index for 5 WPANs



(c) Fairness index for 10 WPANs

Figure 6. Fairness Index (adaptive re-scheduling in red and the original IEEE 802.15.4 in white)

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