Effects and Implications of Beacon Collisions in Co-located IEEE 802.15.4 Networks

Noorsalwati Nordin and Falko Dressler
Computer and Communication Systems, Institute of Computer Science, University of Innsbruck, Austria
{noorsalwati.nordin,falko.dressler}@uibk.ac.at

Abstract—**Beacon-synchronized operation allows wireless networks to operate very efficiently, in particular focusing on energy requirements. It is, however, unclear, to what extend this beacon-based synchronization suffers in case of independently operating networks with overlapping communication ranges. We study the effects and implications of beacon collisions in co-located IEEE 802.15.4 networks. This protocol has become the de-facto standard in many areas of wireless communications including wireless sensor and body area networks, but also in industrial network domains. IEEE 802.15.4 defines a node synchronization strategy using beacons for achieving robust and real-time capable low energy communication. Nonetheless, collisions are inevitable as some packets, e.g., the synchronization beacons indicating the start of a new superframe, are sent without carrier sensing. Consequently, co-located networks may substantially suffer from beacon collisions. In an extensive set of simulation experiments of co-located networks, we found that the number of lost beacons is independent of the amount of superframe overlap, but is a major cause of performance degradations.**

I. Introduction

Besides Wireless Local Area Networks (WLANs), one of the more frequently used wireless networking technology is IEEE 802.15.4 [1], which started as a standard designed for Low-Rate Wireless Personal Area Networks (LR-WPANs). In contrast to WLAN, which is standardized within the IEEE 802.11 family, LR-WPANs focus 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 Wireless Sensor Networks (WSNs) and, more recently, also in the research domain of Body Area Networks (BANs) [2], [3]. This domain is rapidly growing, especially driven by applications in the healthcare sector.

Furthermore, the IEEE 802.15.4 standard has become a recognized industry standard and, thus, has been well accepted by industrial users [4]. An increasing number of industrial applications are focusing on wireless networks as a core technology. In this context, especially industrial automation is of interest due to the specific requirements w.r.t. transmission latency and reliability [5]–[7]. For example, the Siemens Industry Automation Devision is currently evaluating such wireless technologies for use in automation environments.

The practicality of the IEEE 802.15.4 based LR-WPAN technology will enable a multitude of additional use cases. Thus, the deployment of multiple Wireless Personal Area Networks (WPANs) operating on the same channel within the same transmission range will soon become unavoidable. In the scope of this paper, we call such WPANs *multi-WPANs* or *co-located WPANs*. Several IEEE 802.15.4 packets, e.g., beacons and acknowledgments, are sent without carrier sensing. Thus, the existence of co-located WPANs that are independent and unsynchronized will result in collisions, and subsequently in the overall degradation of those WPANs' performance.

In this paper, we aim for a better understanding of the effects of multiple co-located WPANs operating within one another's transmission and interference ranges, and to quantify the impact on the WPAN performances. Our results provide first insights into the effects of beacon collisions in co-located WPANs. We see this simulation study as a major step towards developing adaptive beacon strategies.

In our earlier work, we studied the general performance behavior of IEEE 802.15.4 networks [8]. Similar work was also done, for example, by Zheng et al., who presented a comprehensive performance study of IEEE 802.15.4 [9], and Koubaa et al., who came up with a simulation model for the IEEE 802.15.4 beacon-enabled mode for evaluating the performance of the slotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism [10].

Apart from the more generic performance metrics, the communication reliability also needs to be seriously considered [4], [11]. Reliability is especially of interest w.r.t. signal distribution and channel properties [4], [6]. These studies helped to get a better understanding of how IEEE 802.15.4 behaves and led to significant performance improvements by means of slight protocol modifications.

Yet, in all those investigations, only a single network controlled and synchronized by a WPAN coordinator has been considered. In this paper, we go one step further, investigating effects in co-located networks – extending our earlier work in [12]. This situation was not considered in the protocol design of IEEE 802.15.4. However, this is a typical scenario, which is particularly related to applications in the body area networking and industrial automation domains, where multiple administratively disjunct networks have to be operated and mobility of entire networks is an issue.

Our key contributions can be summarized as follows:

- We extensively investigate the effects of beacon collisions in co-located WPANs, especially caring for different overlaps of the active periods in each participating network.
- We also look into the performance impact caused by mobility, e.g., BANs carried by two persons, slowly geting into communication and interference range.

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II. Related Work

There has not been much work focusing on beacon collisions in multi-WPANs. One notable work is a scheme proposed in [13], where the superframes of multiple WPANs that operate within the same space are scheduled within the inactive period of certain WPANs. The scheme works by creating several logical channels that are used by the different WPANs. The scheduling is determined by first estimating the throughput which was done by analyzing the overlap of two superframes. In their analysis, the authors mainly focused on the effect of complete overlapping of two WPANs where all nodes are within each other's range. They did not analyze scenarios where only parts of the involved WPANs are overlapping.

The IEEE802.15.4 Task Group 15.4b is also working on approaches for beacon scheduling. One interesting solution is called the beacon-only period approach, which 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 contains information on the starting time for each respective WPAN. Nonetheless, as mentioned in [14] and [15], there are still outstanding problems such as an inadequate inactive period or a beacon-only period that may get too long, especially if the number of co-located WPANs gets too high.

Another study on beacon scheduling was also conducted in [16] where the authors proposed another scheme which adjusts the beacon interval. According to their scheme, nodes are required to obtain information about the communication frequency in order for the coordinators to decide on the most optimal BO which will determine the BI and the duty cycle. Their scheme is able to reduce the energy consumption, however, it is at the expense of packet delay. In [17], the authors proposed a strategy for avoiding beacon collision which also reduces energy consumption. Their strategy covers the whole architecture of IEEE 802.15.4 where changes are required to be made on the addressing scheme, network frame, scheduling technique etc. Their architecture was found to be energy-efficient, however, it requires a lot of modification to the current protocol which may not be feasible for actual implementation. Multiple groups proposed using multichannels in order to avoid beacon collisions [7], [15], [18]. However, as the 2.4 GHz band is also used by other technologies such IEEE 802.11 and Bluetooth, this would leave only 4 non-overlapping channels for IEEE 802.15.4. Therefore, the limited number of channels may no longer suffice should an areas gets too crowded, and those schemes may no longer be practical. Besides increasing the reliability, real-time communication became one of the utmost challenges in the industrial automation domain [6].

The effect of beacon losses resulting in degraded network performance has become a concern especially in the area of inter-network interference in BANs [3]. Unlike cellular and sensor networks where movements may involve several independent nodes, movements in such BANs could involve a whole network consisting of several nodes. The challenges that might arise will be different from those in typical IEEE 802.11 or IEEE 802.15.4 networks that will require careful study. Several studies have been conducted on the performance of IEEE 802.15.4 in BAN applications. One notable work is [19] where the authors compared the performance of IEEE 802.15.4 and Bluetooth in various BAN scenarios. They found that while Bluetooth performs better at delivering bigger packets, IEEE 802.15.4 is more efficient at power consumption. In [20], the authors found that non-beacon mode outperformed beacon-mode in BAN scenarios, however they only simulated a static network. Similarly, schemes for transmission power control strategies that aim at extending the lifetime of the network have been proposed [21]–[23].

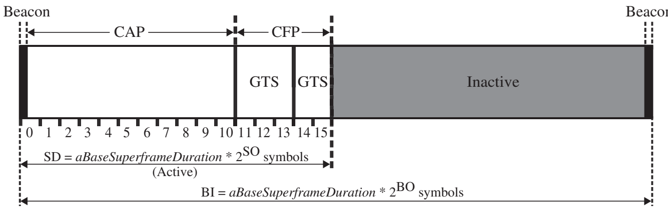


Figure 1: IEEE 802.15.4 Superframe Structure

To the best of our knowledge, there has been no work focusing on analyzing beacon collisions in multi-WPAN scenarios. Thus, we hope this study can help us to understand better the underlying problems that can take place so that a better solution can be formulated.

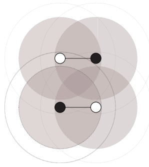
III. Performance Issues in Co-located WPANs

In a first step, we carefully analyzed the performance behavior due to beacon collisions in a stationary setup with well-defined properties. This represents a very synthetic environment, in which the most interesting effects can be investigated.

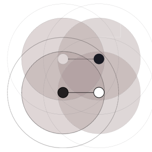
A. Protocol Overview

In order to synchronize the communication at the Medium Access Control (MAC) layer, IEEE 802.15.4 can operate in the so called *beacon-enabled* mode using a well-defined superframe structure as shown in Figure 1. Each *superframe* is bounded by periodically transmitted beacon frames, which allow nodes to synchronize with the coordinator. Each superframe consists of two parts: an active period and an inactive period. In order to save energy, nodes may enter a low-power (sleep) mode during the inactive period. The superframe structure is defined by two MAC attributes; *macBeaconOrder* (Beacon Order (BO)) and *macSuperframeOrder* (Superframe Order (SO)). They determine the length of the *beacon interval* (BI) and the length of the active portion of the superframe, *superframe duration* (SD), respectively.

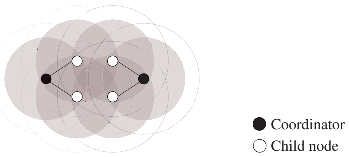
The active portion of the superframe is divided into 16 equally spaced slots, which are called *superframe slots*. The duration of one superframe slot is calculated as $2^{SO} \times$ *aBaseSlotDuration*, where the default value of *aBaseSlotDuration* is 60 symbols. There are three parts in the active portion: a beacon, a Contention Access Period (CAP), and a Contention-Free Period (CFP). In the CAP, all data transmissions rely on a slotted CSMA/CA algorithm. For application scenarios



(a) Two networks in interference range



(b) Two networks in transmission range



(c) Larger scenario: Two networks with three nodes each

Figure 2: Simulation scenarios for co-located WPANs

requiring real-time operation, a maximum of seven Guaranteed Time Slots (GTSs) are available in the CFP for a superframe. GTS transfer mode is only applicable in star networks.

The typical application scenario 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 among multiple WPAN coordinators.

B. Simulation Setup

In our study, we simulated two scenarios with topologies as shown in Figure 2. In the first scenario, we evaluated the impact of beacon collisions in a two-WPAN scenario. We used two networks, each consisting of two nodes, a WPAN coordinator sending beacons and a node sending data to the coordinator. A first experiment was used as a benchmark, where both networks were not in each other's interference range. In two additional experiments, we placed both networks in communication range (Figures 2a and 2b) and swapped the order of nodes to either have both WPAN coordinators in transmission range or the coordinator and a node from different networks. The second scenario is also based on two networks but we used three nodes per network (Figure 2c). This allows to study different beacon collision scenarios.

In this study, we simulated the WPAN networks using OMNeT++ with the INET framework and the IEEE 802.15.4

Table I: Parameters used in the simulation

Beacon Order, BO	6
Superframe Order, SO	5
Duty cycle	50%
Packet size	10 bytes
Mean Interarrival Time	4 miliseconds
Transmission Range	10.5 m
Interference Range	15 m
Channel Bit rate	250 kbps

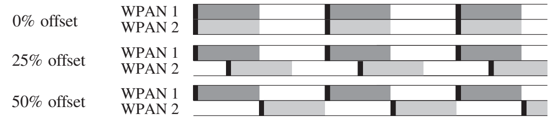


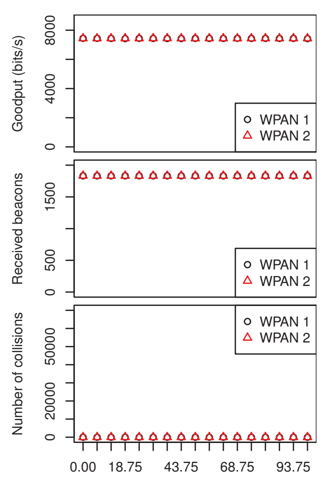
Figure 3: Time offset

model developed by Chen et al. [24], [25]. We chose the beacon-enabled mode as we want to understand the losses due to corrupted beacons. We configured a duty cycle of 50 % using a BO/SO combination of 6/5. All the key parameters of the model have been used as in [25]. We assume that all child nodes belong to only one WPAN and the associations between the nodes and their respective coordinators were predetermined.

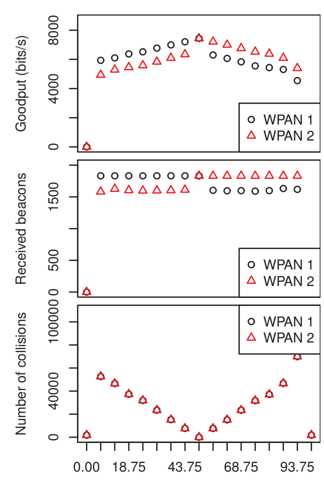
Table I lists the parameters used in the simulation, while the default values specified by the IEEE standard can be found in [1]. The starting times for both WPANs were varied with WPAN 1 starting at 0 s while WPAN 2 starting at $0\,\mathrm{s} + n/16$ of the superframe length as depicted in Figure 3. This allows us to analyze the effect of different degrees of superframe overlaps. Each simulation was run for 30 min and the results shown were taken over 5 runs.

C. Results and Discussion

We start with discussing results for the first scenario. As a baseline, we evaluated the performance of two independent WPANs (Figure 4a). As expected, 100 % of the beacons were successfully received. The resulting goodput shows a stochastic behavior. However, when there is an overlap of the WPANs' superframes, collisions that occur result in a loss of beacons and data packets as both WPANs will behave as two non-overlapping WPANs at 50 % of the time offset and achieve similar level of goodput as seen at the 50 % measure in Figure 4b. As for the increasing and the decreasing goodput, this can be attributed to the amount of overlap

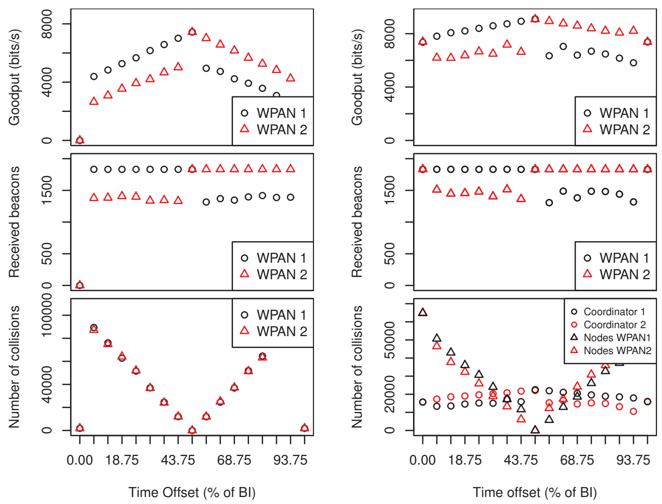


(a) Baseline scenario, WPANs with no common interference range



(b) First scenario, WPANs with coordinator/node in interference range

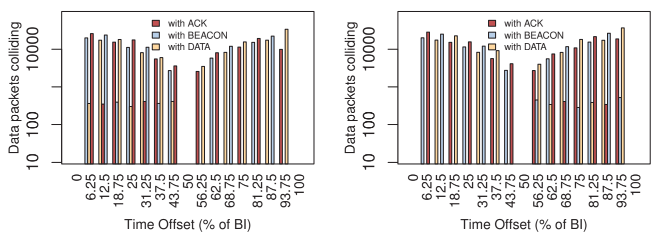
Figure 4: Simulation results: not in communication range



(a) First scenario, WPANs with coordinator/node interference

(b) Second scenario: WPANs with coordinator/node interference

Figure 5: Simulation results: in communication range



(a) WPAN 1

(b) WPAN 2

Figure 6: Collision with data packets

between the superframes belonging to both WPANs. As the overlap increases, although the number of beacons colliding does not proportionally increase, the number of successfully transmitted data packet still decreases as a wider window of overlap allows for more collisions to occur (Figure 4b).

Similar results (Figure 5a) can be observed in the setup where both coordinators are in communication range, the situation is even more aggravated as more collisions occur due to the overlap of both interference and transmission ranges of both WPANs. In this setup, more beacon collisions are experienced by the WPAN that starts later. This is because, due to the WPAN's late starting time, its beacons are transmitted during the active period of another WPAN, and could subsequently result in a beacon collision. As a result of the lost beacon, the node is unable to synchronize itself with its coordinator for the whole duration of the superframe and is forced to wait for the next beacon in order to gain access to the channel. This is clearly shown in Figure 6 where the packets that collide with each WPAN's data packets are plotted. In this figure, it can be observed that prior to 50 % time overlap, WPAN 2's beacons mainly collide with WPAN 1's data packets, and vice versa after the 50 % time overlap.

We further simulated the scenario involving two WPANs, each comprising the coordinator and two child nodes with nodes in a particular WPAN interfering with nodes from the other WPAN (Figure 2c). The results are shown in Figure 5b. As predicted, collisions involving DATA-DATA coming from each respective WPAN occurred at both coordinators. Collisions involving ACK-DATA and BEACON-DATA took place at all nodes. Similar to the previous experiments, goodput increases as the amount of overlap decreases, where it reaches the maximum rate at 50 %. At this point, each WPAN is able to operate as though it is not sharing the same medium due to the the same superframe size and a duty cycle of 50 %.

IV. Beacon Collisions in Mobile WPANs

We also extended the earlier scenario by making WPAN 2 moving past WPAN 1 at two different speeds as outlined in Figure 7. While still applying the time overlaps, we measured the result of the simulation when WPAN 2 is moving at normal walking speeds of 1.5 m/s and 2.5 m/s. This scenario reflects a typical Body Area Network configuration where multiple persons are carrying their own networks but spontaneously get into communication and interference range if meeting each other. In the simulation for both speeds, the measurement was taken from the same starting and ending point. The results are shown in Figure 8. For each data set, a box is drawn from the first quartile to the third quartile, and the median is marked with a thick line. Outliers are drawn as small circles.

We observe that the total collision at 2.5 m/s is slightly lower than at 1.5 m/s as shown in Figure 8b. This is because faster speed allows WPAN 2 to move away quicker from WPAN 1, thus allowing it to escape from being interfered by WPAN 1. We also observe that at low speeds, as shown in Figure 8a, the number of collisions mainly depends on the time overlap, i.e., on the configuration of both the superframe format and the occasional cross-network synchronization. Although the mean collisions for both speeds are relatively similar (as this is influenced by the collisions within each respective WPAN), the effects of the time overlaps can still be observed by the increase of outliers as the time overlaps increase as they approach the 0 % and 100 % marks.

Furthermore, although it seems that the mean number of collisions do not change much across all time overlaps. On further inspection, it is found that it gradually increases when WPAN 2 was moving closer to WPAN 1 while entering WPAN 1's interference range, and gradually decreases as it moves away from WPAN 1, thus slightly affecting each network's goodput. This effect is illustrated in Figure 9. Here, a time series plot is shown for collisions experienced in both networks for a 0 %, i.e., fully overlapping, and a 50 %, i.e., non-overlapping active periods.

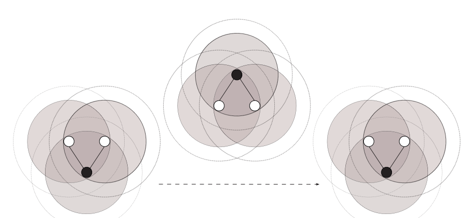
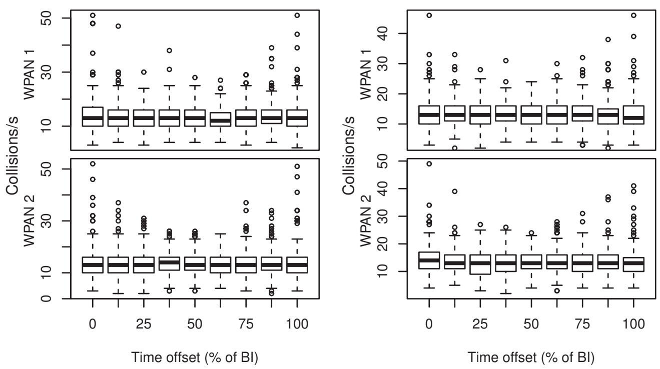
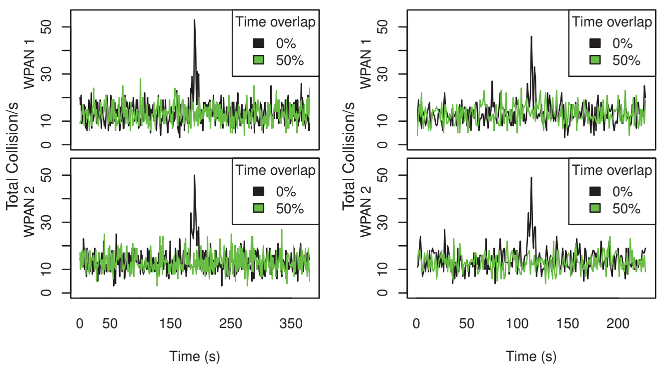


Figure 7: Simulation scenario for co-located WPANs



(a) WPAN 2 moving at 1.5 m/s (b) WPAN 2 moving at 2.5 m/s

Figure 8: Experienced collisions



(a) WPAN 2 moving at 1.5 m/s (b) WPAN 2 moving at 2.5 m/s

Figure 9: Collision as WPAN 2 moves into WPAN 1's interference range

V. Conclusion and Future Work

The proliferation of industrial automation and healthcare applications would increase the occurrence of co-located WPANs. Both domains require them to perform in a robust manner. From our simulations, we found that that could be an issue as there is a substantial performance degradation due to beacon collisions that needs to be addressed by adaptive inter-network beacon coordination schemes. As expected, the amount of superframe overlap has an inverse effect on the goodput in co-located networks. Nonetheless, it does not have a direct effect on the beacon collisions. That is because the packets that the beacons collide with have a randomness property due to the number of random backoff slots that the nodes generate for accessing the channel. In our ongoing future work, we will validate the simulations by running actual experiments and analytically analyzing the simulated models. In addition, due to the uncoordinated and independent nature of multiple co-located WPANs, we find it essential to formulate a strategy to adaptively coordinate the multi-PANs in a distributed fashion.

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