Efficient Beacon Collision Resolution Procedure for IEEE 802.15.4 /Zigbee Wireless Personal Area Networks

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ABSTRACT

While IEEE 802.15.4/Zigbee is a promising technology for Wireless Personal Area Networks, several transmission problems are not yet resolved. In particular, the problem of beacon transmission interferences is causing the device connection loss to the network. In order to resolve this problem, we present a new distributed and reactive procedure for beacon collision resolution. It is an extension of the alignment procedure to reorganize randomly the beacon transmission time when a collision has occurred. The detail of the proposed procedure will be fully described and analyzed. The performance of our approach is performed by simulations. The results show that our approach reduces the collision probability and the device disconnections consequently.

Keywords: Beacon collisions, IEEE 802.15.4/Zigbee, beacon interference, Wireless Sensor Networks.

1. INTRODUCTION

IEEE 802.15.4/Zigbee is considered as a universal solution for low-cost, low-power wirelessly connected monitoring and control devices [13] [14] [15]. It has gained an exponentially increasing interest from industry. This interest is mainly driven by emerging applications including smart home, health care monitoring, surveillance, industrial automation and environmental monitoring.

IEEE 802.15.4 is a standard for wireless sensor network operating in the ISM spectrum band of 2.4 GHz with low rate and low power [11]. It can be defined in a start topology or cluster tree topology with multi-hope links. For these topologies, synchronization is needed by the way of the beacon-enabled mode. In fact, the PAN (Personal Area Network) Coordinator sends periodically beacon frames to synchronize the transmission of the member devices. This beacon is spread by routing devices called coordinators to the end devices. This beacon frame is used for establishing and maintaining links between devices and their coordinators.

In deploying IEEE 802.15.4 networks in the real context, some problems are detected related to transmission interferences [7] [6] [2]. These networks are not always free from the danger of collisions. The beacon frame collisions can be held due to the simultaneous transmissions from neighbor coordinators. In this case, devices/nodes that wait for the periodic beacon frames will lose synchronization with their coordinators, and consequently with the network, which will prevent them to communicate [10]. In some situations, this problem can persist which leads to device disconnection to the network even if it is in the transmission range of coordinators.

To resolve the problem of beacon collision, most related works go in the way of creating proactive actions with global and centralized scheduling. But these solutions are not flexible especially with dynamic topology and node mobility. That is why in this paper, we propose a new collision resolution procedure that can be adapted to the topology changing. This procedure is defined in distributed manner that resolves the problem only on the corresponding coordinator that causes the collision. We extend the alignment procedure defined by the standard IEEE 8012.15.4 in order to reach a better probability of beacon collision resolution. This new procedure will defer the beacon transmission related to the specific coordinator when collisions have occurred.

The rest of paper is organized as follows. First, in Section 2, we present the IEEE 802.15.4 standard basics that help to understand the presented approaches. In Section 3, related works about beacon collision problems for IEEE 802.15.4 network are provided. In Section 4, we present our approach for beacon collision resolution with related models. Then, in Section 5, simulation results are presented. Finally, this paper is concluded in Section 6.

2. IEEE 802.15.4 STANDARD BASICS

An IEEE 802.15.4 WPAN is composed of one PAN coordinator and a set of devices. The PAN coordinator is the primary controller of the network. It is responsible for initiating the network operations. It sends a beacon that is received from devices to be then associated to their network.

Two main types of network topology are considered in IEEE 802.15.4, namely, the star topology and the peer-to-peer topology for multi-hope communication [5]. In the peer-to-peer topology with the use of beacon network, the cluster tree is the most interesting network structuring. In this topology the devices are associated to coordinators (FFD: Full-Function Device) considered as parent nodes and router to forward communications. The FFD devices are also connected to other until reaching the PAN coordinator. To synchronize the transmission, the coordinator sends beacons to their associated devices (child nodes).

Concerning the topology formation, the PAN coordinator starts a new WPAN network, and scan, association procedures are used to allow devices to join a WPAN. That's a new device scan the channel to find an active coordinator, then it tries to associate this one by the way of the association procedure. To maintain the association to this coordinator, it needs that it receives their beacons. When it could not receive them, it will try to be associated again with the realignment procedure. Thus, the maintaining of network links is ensured by the beacon transmission from the PAN coordinator, to the intermediary coordinators (FFD devices) to the end devices. This beacon defines the superframe periods of transmissions to be used by the associated devices.

The IEEE 802.15.4 superframe is divided in an active period (with a long SD) and inactive period (figure 1). In the active period, there are the CAP (Contention access period) and CFP (Contention-free period). In this paper, we are concerned about the CAP (Contention access period) which is slotted in *aBaseSuperframeDuration* for sending messages with contention access using a slotted CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) mechanism to access the channel.

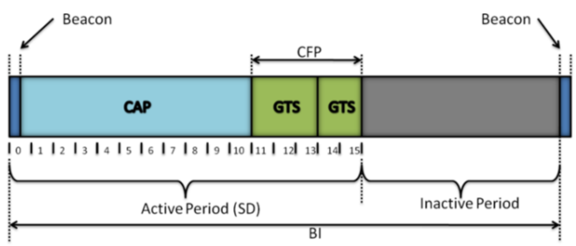


Figure 1— The IEEE 802.15.4 superframe

All beacon frames shall be transmitted at the beginning of each superframe at an interval equal to BI depending on the value of the Beacon Order (*BO*). The activity period (*SD*) will be also computed depending on the activity order (SO). Thus, the computing equation of the frame intervals:

$$\begin{cases} BI = aBaseSuperframeDuration \cdot 2^{BO} \text{ symbols} \\ SD = aBaseSuperframeDuration \cdot 2^{SO} \text{ symbols} \end{cases} \quad \textbf{(1)}$$

To acquire beacon synchronization, a device shall enable its receiver and search for at most *BI* interval. If a beacon frame is not received, it shall repeat this search. Once the number of missed beacons reaches *aMaxLostBeacons*, it shall notify the synchronization lost from the coordinator.

The beacon is one of the keys of the creation and updating of the network topology based on the beacon-enabled PAN. So, it is used for the device transmission synchronization, the support for low latency devices, and the network discovery. That is when the beacon is found, the device synchronizes to the superframe structure. At the appropriate time, the device transmits its data frame to the coordinator. Furthermore, when the coordinator wishes to transfer data to a device, it indicates in the network beacon that the data message is pending. The device periodically listens to the network beacon and, if a message is pending, transmits a MAC command requesting the data.

The use of the beacon is not limited to the transmission synchronization but is used also for network topology maintenance. It is used in channel scan is for a device that needs to connect or to change the association to a coordinator. There are an active or passive channel scan allows a device to locate any coordinator transmitting beacon frames within its radio communications range. An active scan uses the beacon request command to extract the beacon from a coordinator. In a passive scan, the beacon request command is not transmitted.

In some situations of transmission trouble as the beacon collision problem, the device will lose communication with its coordinator and becomes then an orphan device without a coordinator. In this case and in order to rejoin the network again, the device performs an orphan channel scan which is an active channel scan to find another coordinator. This involves sending an orphan notification command in the hope that its Coordinator will detect the broadcast and respond with a Coordinator Realignment command. Then a realignment procedure will be executed as the association procedure to join again the coordinator.

3. RELATED WORKS

The inconsistency of 802.15.4 especially for beacon collision has been discussed by the Task Group 15.4b [11]. This group is created to improve some inconsistencies of the original specification. They present some recommendations to resolve the problem of beacon collisions [12]. To resolve the collision, the idea is to schedule specific periods (called: Time Division/TD approach) or starting beacon transmission (called: Beacon Only Period/BOP approach) approaches that not overlaps with other beacons. For that, two alternatives have been discussed: the proactive and the reactive approaches.

Note that these approaches proposed by the Task Group 15.4b are global strategies and there is no penetration of how to implement such solutions in IEEE 802.15.4. Indeed, there are no included algorithms to schedule beacon frames transmission. Further related works are inspired from the recommendation of Task Group 15.4b and tries to find the way to implement their proposed strategies in IEEE 802.15.4 networks.

The authors of the paper [5] propose a multi-channel window scheduling method for preventing beacon collisions and interference in cluster-tree type IEEE 802.15.4 wireless networks. In the tree building, a node joins the parent node in such a way that its window schedule does not collide with the window schedules of the parent node. This approach is limited to the treatment of only the collision between the coordinator and child device which can be also another coordinator. It does not consider beacon collisions between coordinators which are not directly related.

The authors of the paper [10] propose two collision-free beacon frame scheduling scheme. This scheme adjusts the Beacon

Interval (*BI*) and Superframe Duration (*SD*) for each device according to the problem of collision avoidance. However, this approach changes the beacon periods especially the activity period (SD) which is used in other optimization purposes as the node activity adjustment for energy consumption optimization [1].

The Adaptive and Distributed Collision-Free Medium Access Control (called: ADCF MAC) is presented in the paper [8]. It is a Beacon Only Period/BOP approach. It computes the starting beacon transmission and the beacon only period according to the maximum number of hops in the network, the maximum number of neighbors within 2 hops and the time interval between two beacons. All these parameters are assumed to be fixed values and defined by the application.

The main drawback of these solutions is the lack of flexibility, especially regarding the topology changing and the inconstancy of the wireless medium.

4. PROPOSED APPROACH

We propose a new procedure for resolving the beacon collisions called BCR (Beacon Collision resolution). This procedure aims to react without changing the superframe period parameters which can be used for other optimization issues. It is also adapted to the network topology changing as in the mobility case or in load balancing re-associations [4] [3]. Our approach is a reactive procedure that resolves the collisions by changing and differing the starting beacon periods. This procedure is a totally distributed solution in which each coordinator will react separately without a global synchronization or centralized scheduling. Thus, after a beacon collision is detected by the device, it will request the coordinator to change their starting beacon period to remove the problem of collision interference. This procedure is more detailed in the next sub-section.

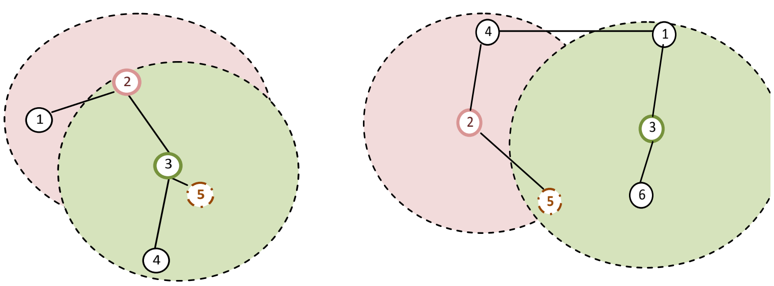


Figure 2— Beacon interference situations

BCR Description

Most of the related works provide solutions to the beacon collision in the case of direct interference. This situation happens in one hope interference as in the figure 2.a where the coordinators 2 and 3 can send simultaneously their beacons and consequently the collision will be held in the node 5. Then, this node will lose the synchronization to its coordinator. There is a need of changing the beacon starting times to differ their transmissions. However many other situations are not treated by these related works. For instance, we consider what we called the indirect beacon collision which can hold between coordinators that have no direct link either within more that 2 hops. The figure 2.b illustrates this situation where collisions can occur in the node 5 between the simultaneous transmission between the coordinators 2 and 3. In this situation, the centralized and limited hop approaches are not able to resolve efficiently the problem of beacon collisions. From that point, we propose a new distributed approach centered on the devices (child nodes) instead of the coordinators (parent nodes). One of reasons is that beacon collisions or interferences could not be detected by coordinators. However, the device that needs to be synchronized to the coordinator can know if a beacon is in a collision after successive beacon lost. After that, they can request the associated coordinator to change it beacon timing in order to find no collide instant.

Our approach is an extension of the realignment procedure defined in the IEEE 802.15.4 standard. This procedure is executed if we have a synchronization loss from the coordinator. The main reasons of that are beacon interferences, coordinator break or mobility. However, with persistence of interferences, the realignment procedure is unable to resolve the beacon collisions.

Firstly, we present the realignment procedure and then the whole collision resolution procedure. The realignment procedure starts with a device sending an orphan notification command (after beacon lost) to the coordinator. The Network layer of the coordinator verifies the address of the orphan device, and in its response, the Network layer confirms whether the device was previously associated with this coordinator. If the device was previously associated with this coordinator, the coordinator sends the realignment command to the orphaned device. The realignment command is used to deliver network settings (figure 3).

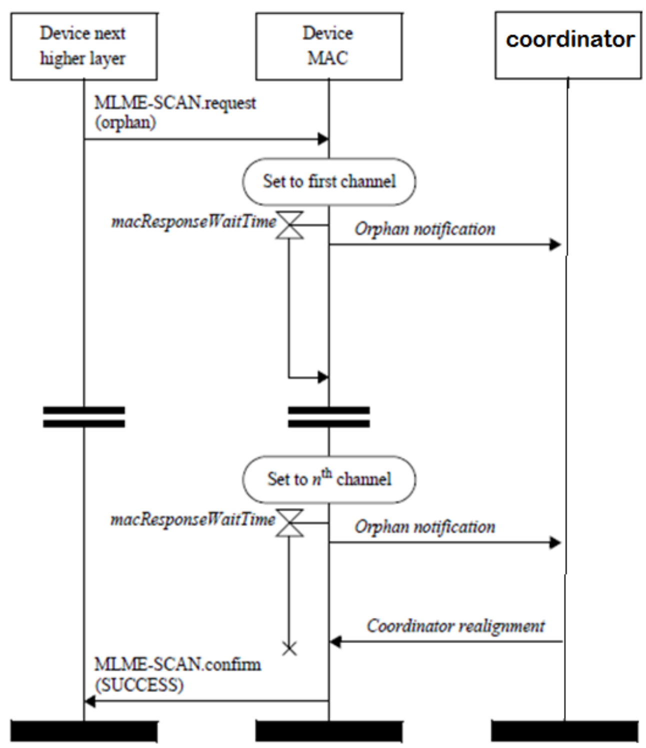


Figure 3— Realignment message sequence chart

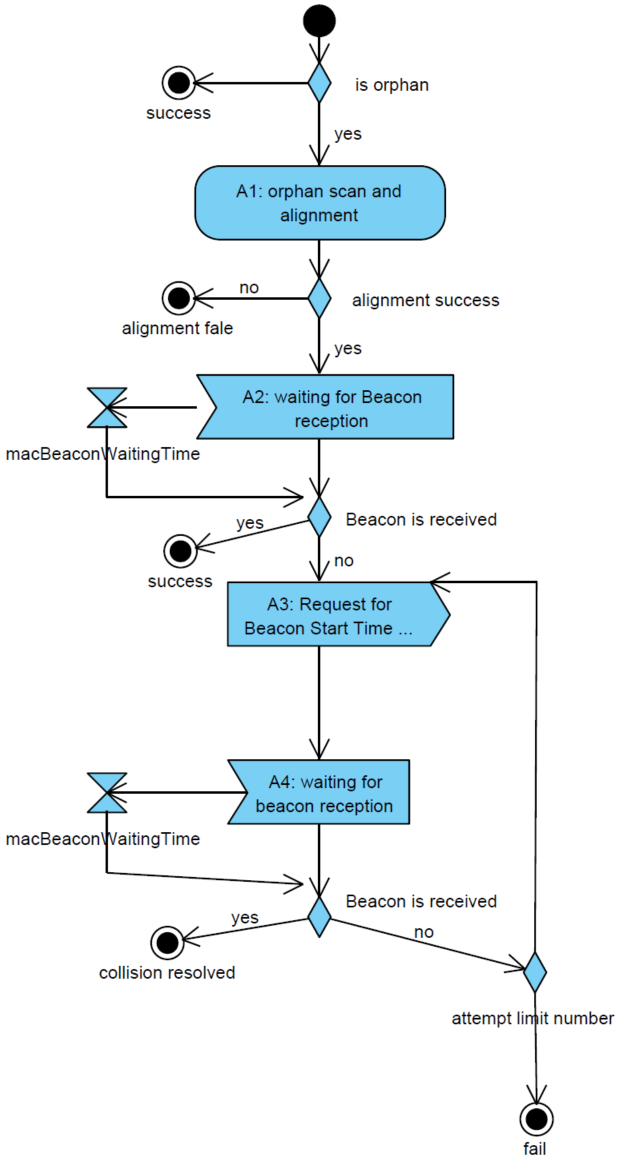


Figure 4—Activity diagram of the Beacon Collision resolution

The procedure of realignment can lead to transmission fail if no action is on beacon timing. That is after the step of alignment, our procedure will check if there is a success of beacon reception (A2 figure 4). If the collision persists, the action of the device request to change the timing from the correspond coordinator (A3 figure 4). This one will have the task to randomly select a different starting time for the next attempts of beacon transmission and reception. With a high probability, the collision will be resolved. If the beacon is not received an iterative selection will be held to find a free starting time for the collided beacon transmission (A3 and A4 figure 4).

Collision probability model

In this section, we present the beacon collision model in order to evaluate the efficiency of our procedure. Therefore, we deduce the success probability and the estimated average response time of the collision resolution procedure.

Beacon Collision Probability

We consider two cases depending on the Beacon Intervals (*BI*) selection from Zigbee devices settings. In the first case, we refer to the default setting where all devices have the same Beacon intervals. The second case will be for devices with different beacon intervals.

In the first case of the selection of the same *BI* intervals for all coordinator devices, the probability of beacon collision will be computed as:

$$\begin{cases} P_{Beaco\ nCollision} = \sum_{i=2}^{N} C_N^i \cdot \left(\frac{1}{2^{BO}}\right)^{(i-1)} & if\ N < BO \\ P_{Beaco\ nCollision} = 1 & \text{otherwise} \end{cases} \quad (2)$$

Where C_N^i is the combination function and *N* is the number of devices that are in the same transmission range and can have beacon collisions.

Proof:

The beacon collision can be held between the coordinator devices in the same transmission range. The set of devices in transmission range is $\{1,2,..,N\}$. The collision can happen between 2 until *N* devices. So, the beacon collision probability will be computed as the sum of the probabilities of collision between 2 until N devices and relative to the device combinations.

$$P_{BeaconCollision} = C_N^2 \cdot P_{BeaconCollision}(2) + C_N^3 \cdot P_{BeaconCollision}(3) + \dots + C_N^N \cdot P_{BeaconCollision}(N)$$

Where $P_{BeaconCollision}(i)$ is the collision between *i* nodes.

The probability of collision between 2 nodes is determined as the chance to select the same beacon starting time from the *BO* index interval, so: $P_{BeaconCollision}(2) = \frac{1}{2^{BO}}$. For i device collisions the probability will be: $P_{BeaconCollision}(i) = (\frac{1}{2^{BO}})^{i-1}$

Thus, the total beacon collision probability will be:

$$P_{BeaconCollision} = \sum_{i=2}^{N} C_N^i \cdot (\frac{1}{2^{BO}})^{(i-1)}$$ □

In the second case where the devices select different Beacon intervals, the probability of collision will be bounded by the following formula:

$$P_{BeaconCollision}(time = t) \leq \frac{\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\left\lfloor \frac{t_{slot}(t)}{LCM\ (2^{BO_i}, 2^{BO_j})}\right\rfloor}{t_{slot}(t)} \quad (3)$$

Where *LCM* is the *Least Common Multiple* function and $t_{slot}(t) = \left\lfloor \frac{t}{aBaseSlotDuration} \right\rfloor$.

We can deduce that:

$$P_{BeaconCollision} \leq \frac{N^2}{2^{\min_{i\in[1,N]}(BO_i)}} \quad (4)$$

Proof:

$$P_{BeaconCollision}(time = t) \leq \frac{\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\left\lfloor \frac{t_{slot}(t)}{LCM\ (2^{BO_i}, 2^{BO_j})}\right\rfloor}{t_{slot}(t)}$$

$$\leq \frac{\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N} \frac{t_{slot}(t)}{LCM\ (2^{BO_i}, 2^{BO_j})}}{t_{slot}(t)} \leq \sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N} \frac{1}{LCM(2^{BO_i}, 2^{BO_j})}$$

Then, we can deduce that:

$$P_{BeaconCollision} \leq \sum_{i=1}^{N} \sum_{j=1,j\neq i}^{N} \frac{1}{LCM\,(BO_i, BO_j)}.$$

As $LCM\left(2^{BO_i}, 2^{BO_j}\right) = 2^{\max(BO_i, BO_j)}$, we obtain:

$$P_{BeaconCollision} \leq \sum_{i=1}^{N} \sum_{j=1,j\neq i}^{N} \frac{1}{2^{\max(BO_i, BO_j)}}$$
$$\leq \frac{1}{2^{\min_{i\in[1,N]}(BO_i)}} \cdot \sum_{i=1}^{N} \sum_{j=1,j\neq i}^{N} 1 .$$

Thus $P_{BeaconCollision} \leq \frac{N^2}{2^{\min_{i\in[1,N]}(BO_i)}}$ □

From the Beacon collision probability, we can also deduce the probability of success of collision resolution procedure with the limit to *n* attempts (attempts limit number in figure 4):

$$P_{ResolutionSuccess} = \sum_{i=1}^{n} \overline{P_{BeaconCollision}} \cdot P_{BeaconCollision}{}^{i} \quad (5)$$

Average response time

The average response time (called: *R*) of the procedure of beacon collision resolution depends especially on the repetitive waiting for beacon until it is transmitted correctly. If collision occurs, retransmission of the beacon will be held with different starting time. Thus, the response time will depend on the probability of beacon collisions. The response time (called: R_i) according to i attempts to transmit the beacon upon the success at the last time can be held with the probability of (*i*-1) fails (due to collisions) and then a success which is equal to: $P_{BeaconCollision}{}^{i-1} \cdot \overline{P_{BeaconCollision}}$. From that, we deduce the average response time according to the probability of collision and the retransmissions:

$$R = \sum_{i=1}^{\infty} \left(P_{BeaconCollision}{}^{i-1} \cdot \overline{P_{BeaconCollision}}\right) \cdot R_i \quad (6)$$

We assume that beacon retransmission is not infinite. So, we have *K* attempts as a limit after it the beacon retransmission will be considered as fails. The average response time can be estimated as:

$$R = \frac{\sum_{i=1}^{K} \left(P_{BeaconCollision}{}^{i-1} \cdot \overline{P_{BeaconCollision}}\right) \cdot R_i}{\sum_{i=1}^{K} \left(P_{BeaconCollision}{}^{i-1} \cdot \overline{P_{BeaconCollision}}\right)} \quad (7)$$

5. EVALUATION

We evaluate the proposed procedure through simulations. Based on the analytical model, we developed the simulation for proposed scheme to perform the results about collisions, transmission fail and collision resolution procedure response time.

For the frame parameter durations are select as in the IEEE 802.15.4 standard and the CC2430 - Texas Instruments which is a System-on-Chip solution for 2.4 GHz IEEE 802.15.4/ ZigBeeTM [9]. So, by default, the *aBaseSuperframeDuration* is equal to 960 µs and each symbol is 16 µs. Also, the superframe Beacon Order (*BO*) is 7 and consequently the superframe interval *BI* is equal to 1.966 seconds (equation 1).

The figure 5 shows the beacon probability collision according to the number of devices in a neighborhood (transmission range). We note that with a low value of *BO* associated to the beacon interval, the probability will be important with just some neighbors in the transmission range. So, the probability is equal to 1 for 6 neighbors and with *BO* low than 8. However, we have low collision probability with high values of the beacon interval.

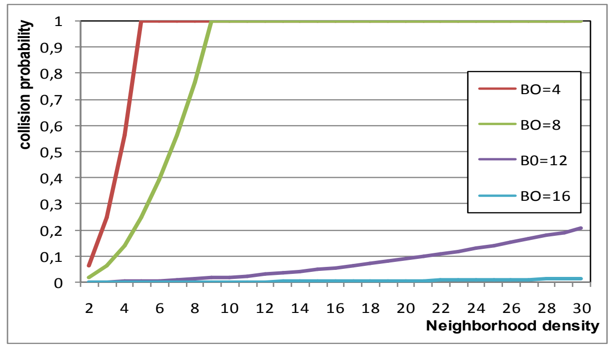


Figure 5— The Beacon Collision probability according to the neighborhood density

For the simulation illustrated by the figure 6, we compare our approach (BCR) with ADCF MAC approach according to the probability of collision resolution success and relative to the number of neighbors in the transmission range. We use the default value of the beacon order (BO) which is 7. The BCR use 4 attempt limit for resolution and BCR(16) is with 16 attempts. It is clear that our approach performs better success for collision resolution, especially with 16 attempts.

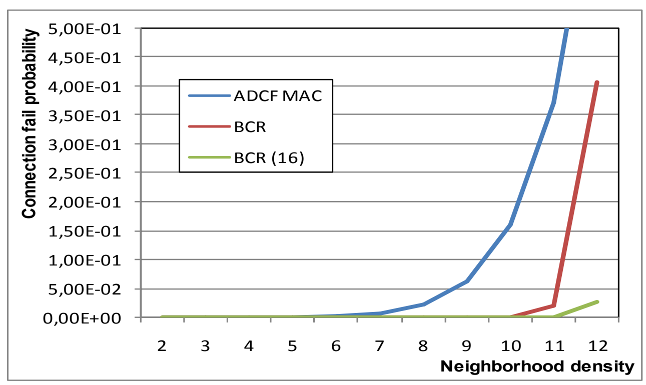
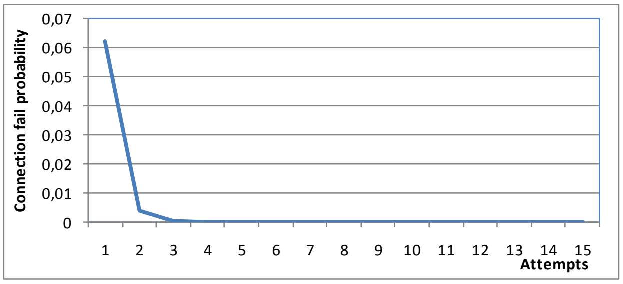
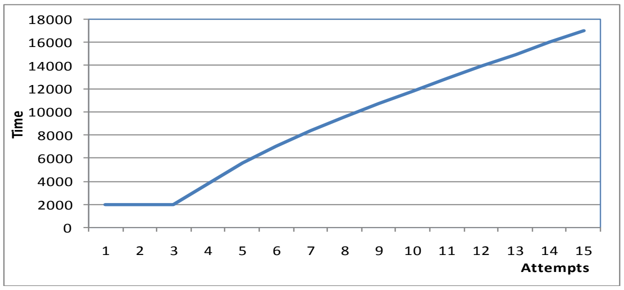


Figure 6— Fail probability comparison between BCR and ADCF MAC

The high connection fail probability of ADCE MAC is due to its centralized approach centered coordinator scheduling. It is a proactive approach that schedules the beacon transmission period with the objective of no collision. However, in many situations, it is hard to predict situations of collisions as in the case of indirect collision (figure 2). So, in these situations, the ADCF MAC as in the IEEE 802.15.4, after 4 successive Beacon losses the connection will fail. Even a re-association will be again established, the transmission conditions will be the same and the beacon collisions will not be resolved. These situations are better treated with our approach. It reacts to the beacon loss for any indirect collisions and reorganizes the beacon starting with a different value in order to reduce the probability of collisions.



a. BCR Fail probability



b. BCR average execution time (*ms*)

Figure 7— The BCR efficiency according to the attempt number limits

In the last simulation of figure 7, we want to show how to setup the proposed procedure (BCR). We need to make the compromise between the probability of collision resolution success and the time that take the procedure with Beacon transmission attempts. That is with more attempts the success probability will be better but on the other side, the response time of resolution procedure will be more important. Thus, depending on the optimization objective either delay or reliability, we can select the best value of the limits of Beacon retransmission attempts.

6. CONCLUSIONS

In this paper, we have proposed a new beacon collision resolution procedure. This procedure finds randomly the free time for beacon transmission to avoid collisions. This procedure is trigged by the device that fails to receive the beacon from its coordinator. It will then request the coordinator to change their beacon timing in order to avoid collisions. The proposed procedure is a device centered instead of being trigged by coordination which is unable to detect beacon lost. Moreover, our procedure can be easily implemented as the extension of the alignment procedure of the IEEE 802.15.4 standard. Different from the related works, this procedure will have no effect on beacon timing periods related to the activity and sleeping times which can be used for other purposes.

By simulations, we have proved the efficiency of our approach to reduce the beacon collision probability and consequently the probability of device disconnections.

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