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STUDY OF BEACON MODE COLLISION PROBLEM IN THE IEEE 802.15.4/ZIGBEE

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ABSTRACT

ZigBee is a specification for a suite of high level communication protocols using small, low-power digital radios based on an IEEE 802 standard for personal area networks. The IEEE 802.15.4 standard provide two modes of connections: beacon enabled mode and non-beacon enabled mode. In beacon-enabled networks, the special network nodes called ZigBee Routers transmit periodic beacons to confirm their presence to other network nodes i.e. it can offer transmission determinism. The non-beacon enabled mode does not offer any guarantee on traffic determinism In this networks an unslotted CSMA/CA channel access mechanism is used. Contrary to the non-beacon enabled mode, the beacon enabled mode does not allow us to form mesh topology in order to interconnect several beacon networks. In this paper, we compare the beacon-enabled mode with the non-beacon enabled mode. A beacon aware device acts as an interface between a mesh network and in range beacon network. Unlike a non-beacon device, a beacon aware device gives priority to the in range beacon traffic, in order to avoid any perturbations. This priority is obtained with a modification of the slotted CSMA/CA algorithm, implemented on the beacon aware device. When enabling its beacon mode, the protocol makes possible real-time guarantees by using its Guaranteed Time Slot (GTS) mechanism and it provides reliability of the network.

KEYWORDS: ZigBee, IEEE 802.15.4, Beacon, Non-Beacon, Signal Perception, MAC

INTRODUCTION

The IEEE 802.15.4 standard [1] was approved in 2003 as a multiple access control (MAC) and physical (PHY) layer standard for low cost, low power, and low data rate wireless personal area networks (WPANs). IEEE standard 802.15.4, which defines the physical layer (PHY) and media access control (MAC) for low-rate WPANs, restricts the data rate to 250 kbps in the global 2.4-GHz Industrial, Scientific, Medical (ISM) band, while also specifying low power consumption and cost. Taking the low-level PHY and MAC layers as their base, the Zigbee Alliance developed Zigbee – the network protocol, security, and application layers for low-rate[3] WPANs.

The ZigBee Alliance [4] is a rapidly growing association of companies working together to enable lowpower, cost-effective, reliable, wirelessly networked monitoring and control applications. ZigBee is a wireless network protocol specifically designed for low data rate sensors and control networks. There are a number of applications that can benefit from the ZigBee protocol: remote metering, home security systems, industrial control networks, building PC peripherals and automation networks are some of the many possible applications. In Comparison to other wireless protocols, the ZigBee wireless protocol offers reduced resource requirements, low complexity and most importantly, a standard set of specifications. ZigBee is a set of specifications created specifically for control and sensor networks. Built on IEEE 802.15.4, the standard for low data rate wireless personal area networks (WPANs), it was developed by the ZigBee Alliance[2][4].

ZIGBEE PROTOCOL OVERVIEW

ZigBee is a standard wireless network protocol designed for low data rate control networks. It is layered on top of the IEEE 802.15.4 specification and provides a standard methodology for functions such as including messaging, network formation and device discovery. At the physical layer, IEEE 802.15.4 defines 27 channels of data rates 20 kb/s, 40 kb/s and250 kb/s. At the MAC layer, IEEE 802.15.4 access to the radio channel using the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism.. Based on IEEE 802.15.4, the ZigBee Alliance specifies the standards for network and application sublayer, as shown in Figure 1.

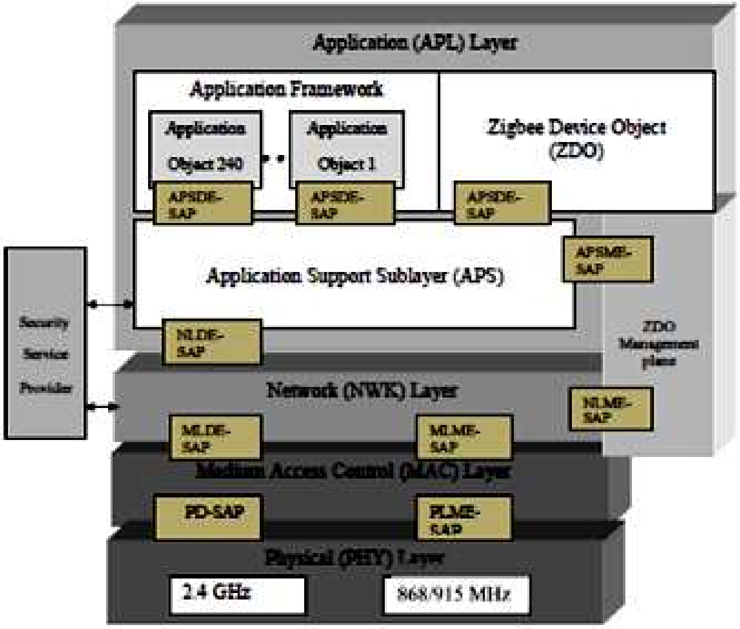

Figure 1: 802.15.4/Zigbee Protocol Stack

The responsibilities of network layer [3] include joining/leaving a network, storing neighbor information, security, discovering 1-hop neighbors, and routing. The ZigBee network layer builds a hierarchical tree topology and assigns addresses. A coordinator is responsible for starting a new ZigBee WPAN and setting network parameters such as the maximum allowable number of children nm of each device and the maximum level dm of the logical tree. When a new device is willing to join a network, its MAC layer scans the available WPANs and notifies the network layer. After the upper layer selects a suitable WPAN, MAC layer and the network perform the association process with an existing device in the selected WPAN.

If the existing device has enough address space, it will assign a free network address to the new device and make it one of its children. In case a child loses the association with its parent, it can initiate a rejoining process, called orphaning, and its parent will respond to resume the association. IEEE 802.15.4 defines two types of devices: reduced function device (RFD) and full function device (FFD) [9], [10] and [11]. An RFD is a simple device that associates and communicates only with an FFD. An FFD can serve as a coordinator or a regular device. It can communicate with any other device. A FFD implements all the standard's functions. A device of this kind may operate as a coordinator, as a router or as a simple device. A coordinator is the device responsible for starting and maintaining the network. A RFD device implements only a part of the functions defined in the standard. For example, RFD cannot start a network, cannot route packets, etc. This kind of devices can only operate as simple devices associated to a coordinator.

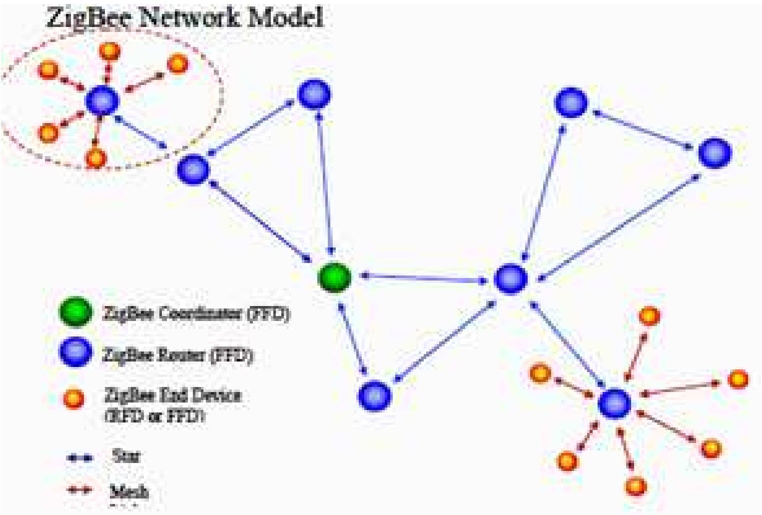

Figure 2: Zigbee Network Model

NETWORK CONFIGURATIONS

A ZigBee protocol wireless network may assume many types of configurations. In all network configurations, there are at least two main components:

- Coordinator node
- End device

A third and optional component, the ZigBee protocol router, is present in some network configurations.

Star Network Configuration

A star network configuration consists of one of one ZigBee protocol coordinator node and one or more end devices. In this network, all end devices communicate only with the coordinator.

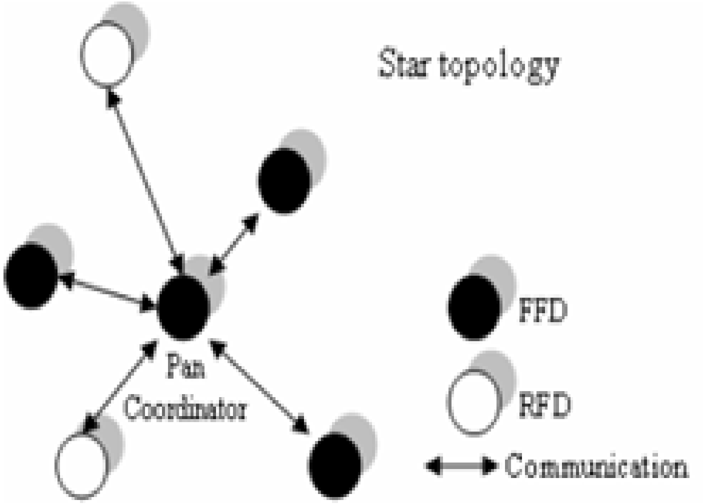

Figure 3: Start Topology

If an end device needs to transfer data to another end device, it sends its data to the coordinator. The coordinator, in turn, forwards the data to the intended recipient.

Cluster Tree Topology

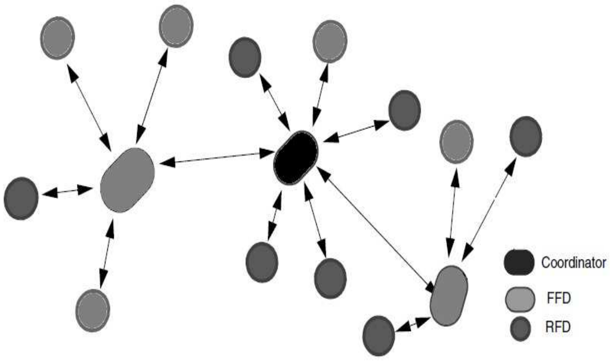

Figure 4: Cluster Tree Topology

Another network configuration is a cluster tree topology [5]. In this configuration, end devices may join either to the ZigBee protocol coordinator or to the ZigBee protocol routers. Routers serve two functions, one is to increase the number of nodes that can be on a network and the other is to extend the physical range of the network. All messages in a cluster tree topology are routed along the tree.

Mesh Network

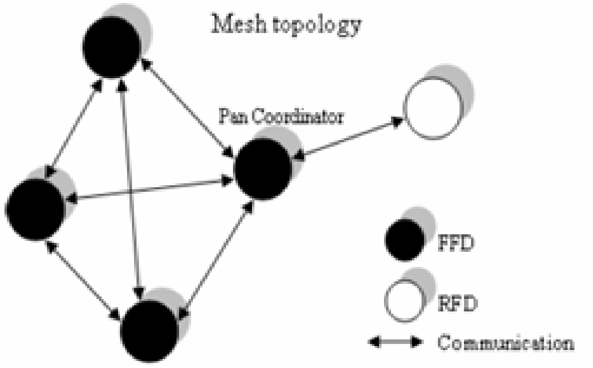

Figure 5: Mesh Topology

A mesh network is similar to a cluster tree configuration, except that FFDs can route messages directly to other FFDs instead of following the tree structure. Messages to RFDs must still go through the RFD's parent. The advantages of mesh topology are that message latency can be reduced and reliability is increased.

The mesh topologies and cluster tree are also known as multi-hop networks due to their abilities to route packets through multiple devices, while the star topology is a single-hop network.

OVERVIEW OF THE IEEE 802.15.4 PROTOCOL

The IEEE 802.15.4 MAC protocol supports two operational modes that may be selected by a central node called PAN coordinator:

- The non-beacon enabled mode[14], in which the MAC is ruled by non-slotted CSMA/CA;
- The beacon enabled mode, in which beacons are periodically sent by the PAN coordinator to identify it's PAN and synchronize nodes that are associated with it.

Non-Beacon Enabled Network

In a non-beacon mode, the two topologies mesh and star can be used. This mode assumes that every node can communicate directly with other nodes without passing by the coordinator and without any synchronization requirements. A node can transmit at any time, and can go to sleep at any time following its own energy consumption policy. All transmissions are done after performing the unslotted CSMA/CA algorithm to check if the channel is clear for a transmission or not. A non-beacon device transmits the beacon frame only as a response to a beacon request command. Devices operating in this mode do not need to synchronize with other devices.

Beacon Enabled Network

In a beacon enabled mode, the coordinator plays a crucial role. It defines periods of time in which transmissions can be done and intervals of time where all nodes associated to it must go to sleep. In this mode, time is divided into a succession of Super frames. A Super frame is a time interval that contains an active period and an inactive period. The Beacon Interval (BI) parameter indicates the interval of transmitting the beacon frame and at the same time indicates the length of the super frame.

The length of the active period is indicated by SD (Super frame Duration) parameter[6]. The active period is divided into a fixed number of 16 equally time slots. All beacon network communications are done within this period. The active period is divided into a contention access period (CAP) and a contention free period (CFP). The CAP is the period where all nodes compete for channel access using the slotted CSMA/CA algorithm. The CFP gathers GTSs {Guaranteed Time Slots}). A GTS is one or more slots of time reserved for a particular node. A GTS is directional i.e. only for receptions or only for transmissions. The coordinator starts allocating GTSs from the last time slot to the first slots respecting a maximum size of the CFP. GTS transmissions do not need the use of CSMA/CA algorithm for channel access since the slots are reserved for one node.

In **beacon-enabled mode** [10], the *Beacon Interval* (BI) defines the time between two consecutive beacons, and includes an active period and, optionally, an inactive period. The active period, called *superframe*, is divided into 16 equally-sized timeslots, during which frame transmissions are allowed. During the inactive period (if it exists), all nodes may enter in a sleep mode, thus saving energy. Figure 1 illustrates the beacon interval and the superframe structure. The lengths of the Beacon Interval and the *Superframe Duration* (SD) are determined by two parameters, the *Beacon Order* (BO) and the *Superframe Order* (SO), respectively.

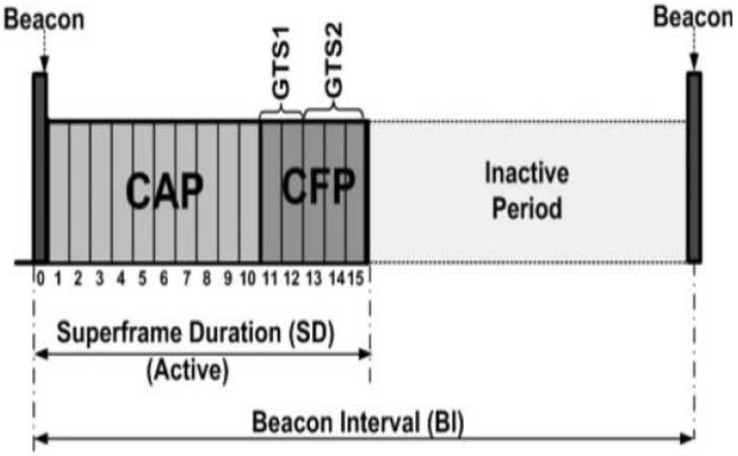

Figure 6: Beacon Interval and Superframe Structure

The active portion consists of a Contention Access Period (CAP) and Contention Free Period (CFP). Any device wishing to communicate during the CAP competes with other devices using a slotted CSMA/CA mechanism. On the other hand, the CFP contains Guaranteed Time Slots (GTSs). The GTSs always appear at the end of the active Super frame starting at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven of these GTSs and a GTS can occupy more than one slot period. The minimum CAP length is fixed by the standard to 440 symbols.

The *Beacon Interval* (*BI*) and the *Super frame Duration* (*SD*) are determined by two parameters, the *Beacon Order* (*BO*) and the *Super frame Order* (*SO*), respectively. The Beacon Interval is defined as follows:

$$BI = a\ Base\ Super frame\ Duration \cdot 2BO\ ,for\ 0 \leq BO \leq 14 \qquad \textbf{(1.1)}$$

The Super frame Duration, which corresponds to the active period, is defined as follows:

$$SD = a\ Base\ Super frame\ Duration \cdot 2SO\ ,for\ 0 \leq SO \leq BO \leq 14 \qquad \textbf{(1.2)}$$

In Eqs.(1.1) and (1.2), *a Base Super frame Duration* denotes the minimum duration of the Super frame, corresponding to $SO = 0$. This duration is fixed to 960 symbols [IEEE 802.15.4] corresponding to 15.36 ms, assuming 250 kbps in the 2.4 GHz frequency band. In this case, each time slot has a duration of 15.36/16 = 0.96 ms.

BEACON COLLISIONS IN IEEE 802.15.4

In large-scale IEEE 802.15.4/Zigbee networks, the flexibility given by the beacon-enabled mode is counterbalanced by the beacon collision problem[10]. In the case of cluster-tree PANs, having several coordinators generating beacons to provide local synchronization to their children may increase the probability of beacon collisions, since IEEE 802.15.4 does not support a mechanism to avoid these conflicts. Actually, the IEEE 802.15.4/ZigBee protocol introduced the cluster-tree topology but did not describe the way to make it functional. Two types of beacon collisions in such topologies can be distinguished: (1) **direct beacon frame collisions** (2) **indirect frame beacon collisions**.

Direct Beacon Frame Collisions

Direct beacon frame collisions occur when two or more coordinators are in the transmission range of each other (*direct neighbors* or parent-to-child relation) and send their beacon frames at approximately the same time, as shown in Figure 7. Assume that node N1 is associated with C1 and C2 is a coordinator of another PAN. In this case, if C1 and C2 transmit their beacon frames at approximately the same time, node N1 may lose the beacon information due to the collision of the two beacons.

If the super frame duration of the two PANs is the same, their beacons will be continuously in conflict with each other. Unfortunately, these two coordinators will not be aware of the collisions. The authors in proposed a collision-free super frame duration scheduling algorithm, which efficiently organizes the super frame durations of different coordinators in a non-overlapping manner, based on their super frame orders and beacon orders.

In addition, to overcome the limited channel availability of IEEE 802.15.4 LR-WPANs, the authors in [3] proposed the Virtual Channel, a novel concept to increase the number of available channels when various WPAN applications coexist. A virtual channel is basically created via super frame scheduling within the inactive periods in a logical channel preoccupied by other WPANs.

To maximize the coexistence capability of WPANs using virtual channels, they propose the Least Collision super frame scheduler (LCscheduler), less complex heuristics, and the Virtual Channel Selector to efficiently manage the multiple available logical channels.

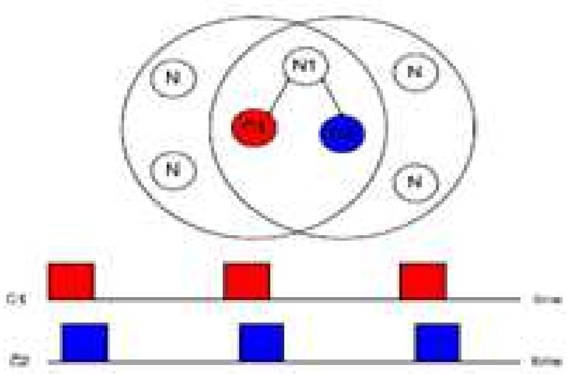

Figure 7: Direct Beacon Frame Collision Problem

Indirect Beacon Frame Collisions

In contrast to direct beacon collisions, indirect beacon frame collisions occur when two or more coordinators cannot hear each other, but have overlapped transmission ranges (*indirect neighbors*) and transmit their beacon frames at approximately the same time, as shown in Figure 8 Assume that node N1, which is located in the overlapped region of the transmission ranges of C1 and C2, will not be able to correctly receive the beacon frames from either coordinator, since the beacons will collide with each other. Task Group 15.4b [4] has been working on an improved version of the IEEE 802.15.4 standard. They proposed a solution to address direct and indirect beacon conflicts between coordinators in different WPANs. The approaches discussed in Task Group 15.4b were not included in the IEEE 802.15.4-2006 release.

However, the approaches in [4] do not address how to choose the proper time offset of different beacons. Moreover, these approaches only focus on how to avoid conflicts between beacons. Collisions between beacon frames and data frames may also occur, because while the time of beacon transmissions was considered, the super frame duration of other PANs was not.

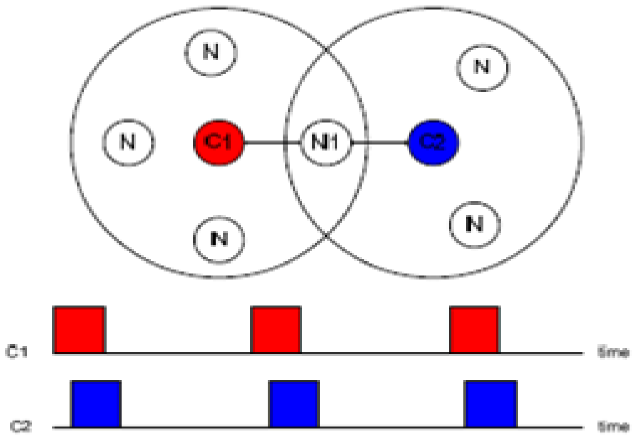

Figure 8: Indirect Beacon Frame Collision Problem

In addition, if a beacon frame and a data frame collide again after adjusting the time of the beacon transmission, the PAN coordinator (PC) has to adjust the transmission time of the beacon frame again. The disadvantage of the reactive solution that is proposed in reference [4] is that the recovery procedure may take a long time. On the other hand, a proactive solution cannot be applicable in the environment such as that shown in Figure 8 because the coordinators cannot listen to each other's beacon information.

Two scenarios are possible

- **Case 1:** N1 is associated to C1. C2 joins the PAN and starts sending its beacons at approximately the same time as C1. In this case N1 loses its synchronization with its parent (C1).
- **Case2:** C1 and C2 belong to the PAN. They cannot hear each other and may send beacons almost the same time. Then N1 wants to join the PAN and there are no other coordinators within N1's transmission range to allow it to associate. N1 conducts active or passive scans but cannot get any beacons correctly due to indirect beacon conflicts.

Proposals for Beacon Collision Avoidance

Since no mechanism was implemented in IEEE 802.15.4 to avoid beacon collisions, some solutions and enhancements were proposed by the IEEE 02.15.4b Task Group. To the author's best knowledge, these proposals are basic approaches that are not detailed yet. They were proposed as pattern ideas or mechanisms to trigger the design of a solution for beacon conflicts. No technical details or implementation guidelines were proposed to these solutions.

Proposals for the "Direct Beacon Frame Collisions" Problem

Time-Division Approach

This is an approach added to the Zigbee specification. This approach presents a solution to schedule beacon transmission avoiding direct beacon collisions. In this approach, each coordinator selects a starting time (referred to as Beacon Tx_Offset) for its beacon transmission and Super frame duration during the sleeping periods of other coordinators. Before starting sending beacons, a coordinator must obtain the Beacon_Tx_Offset of its neighbors and their parents and then choose a different one. The limitation of this approach is that it imposes low duty cycles and the direct communication between sibling nodes is not possible. Moreover, this approach requires that, each coordinator wakes up both in its own active period and also its parent's active period.

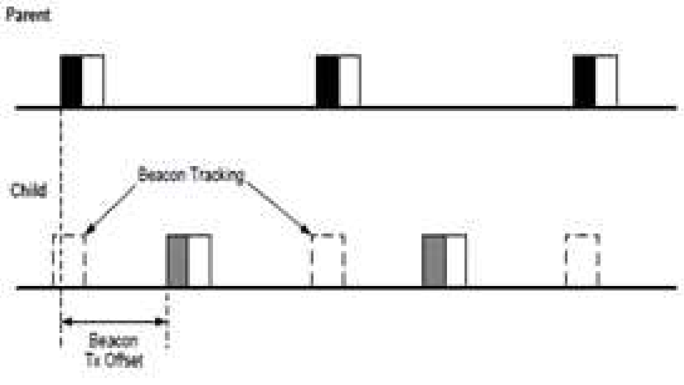

Figure 9: Beacon Tracking [ZigBee]

The Beacon-Only Period

In this approach, the Super frame structure of the PAN, each coordinator starts with a Beacon- Only-Period in which beacon frames from different coordinators are sent in a contention free manner. Each coordinator chooses a sending time offset (also referred to as *Contention-Free Time Slot*) in this Beacon-Only-Period such that its beacon does not collide with beacons sent by its neighbors. In this case, all the active periods start at the same time, which enables direct communications between sibling nodes from different clusters. Also, there is no constraint on the duty cycle with this approach, contrarily to the previous solution.

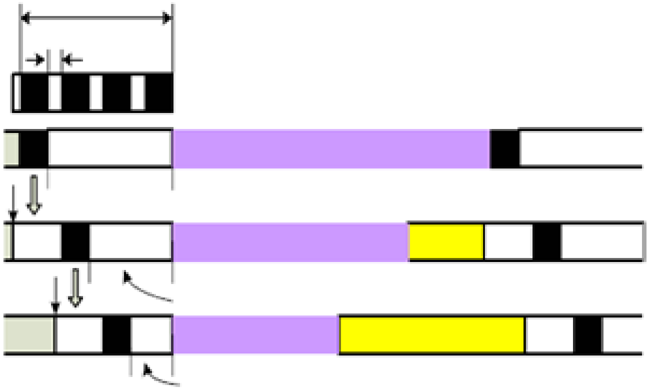

Figure 10: The Beacon-Only-Period

The basic limit of this approach is that no implementation detail was presented to make it a practical approach easy to implement and especially the way to make the coordinators share the Beacon-Only Period. Another difficulty inherent to this approach is how to dimension the Beacon-Only Period.

Proposals for the "Indirect Beacon Frame Collision" Problem

There are two kinds of solutions for indirect conflicts: the reactive and the proactive methods.

The Reactive Approach

This method is the easiest to implement. A coordinator does not carry out any specific procedure to avoid the indirect beacon collisions during its association stage. If an indirect beacon collision is detected, the nodes in question try to resolve it. This method needs a long time to resume normal operation.

The Proactive Approach

This approach tackles the indirect beacon conflict at the association stage. During the association, a coordinator will try its best to avoid the indirect conflict by collecting specific data to characterize the beacon transmissions in its neighborhood. In this method, any device (FFD or RFD) needs to have the capability of forwarding its parent coordinator's beacon time information to its neighbors. In this approach, it is complicated to maintain the neighboring coordinator table (because it needs frequent updates), but it eliminates the possibility of indirect beacon collisions. To enable different kinds of two-way data traffic ZigBee operates in two main modes: non-beacon mode and beacon mode. The beacon mode is for battery-powered coordinators and so saves maximum energy, whereas the non-beacon mode serves mains-powered coordinators. In beacon-enabled networks, the coordinator periodically wakes up and sends beacons to the routers in its network. The beacons wake up other nodes to check whether there is any incoming message. If there is none, both the nodes and the coordinators go back to sleep.

Beacon-oriented networks use guaranteed time slots – in other words, devices are active only when a beacon is being transmitted. The result? Shorter duty cycles and longer battery lives.

In non-beacon mode, some devices are always active and others sleep. The coordinator and routers' receivers do not sleep because any node can wake up and talk to it. Although the non-beacon mode requires a robust power supply (mains) and uses more energy, its overall power consumption is low because most of the network devices can remain inactive over long periods. In short, ZigBee devices are either awake or asleep. Its two modes may be set against Bluetooth's multiple modes, dictated by latency and power requirements – e.g. sniff, park, hold, active. ZigBee's beacon and non-beacon operating modes can seamlessly manage different data types, whether periodic, intermittent, or repetitive low latency. Although “[e]ach of these traffic types mandates different attributes from IEEE802.15.4 MAC, the MAC is flexible enough to handle each of these types”. The beaconing system can manage periodic data like sensor data, whereas intermittent data (e.g. light switches) is handled in the beaconless mode. Intermittent data traffic can, however, also be managed in a disconnected way whereby a device joins the network only when it needs to communicate – an operating mode that, once again, saves significant amounts of energy. Low latency usage – typically, computer mice – make use of guaranteed time slots (GTS), whereby devices are active only when beacons are being transmitted.

CONCLUSIONS

In this paper, we have studied the non beacon and beacon mode and becon collision problem in the IEEE 802.15.4/Zigbee protocol stack, which is a suitable protocol for Wireless Sensor Networks. We have mainly focused on becon collision problem in both direct frame and indirect frame. Also we have outlined some proposals suggested to fix this problem. We have proposed two solutions for both type of collison. In case of direct becon collision we have proposed time division and becon only period solution. For indirect collision reactive and proactive approach has explained.

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