1.4 IEEE 802.15.4 MAC

The Institute of Electrical and Electronics Engineers (IEEE) finalized the IEEE 802.15.4 standard in October 2003. The standard covers the physical layer and the MAC layer of a low-rate Wireless Personal Area Network (WPAN). Sometimes, people confuse IEEE 802.15.4 with ZigBee5, an emerging standard from the ZigBee alliance. ZigBee uses the services offered by IEEE 802.15.4 and adds network construction (star networks, peer-to-peer mesh networks, cluster-tree networks), security, application services, and more.

The targeted applications for IEEE 802.15.4 are in the area of wireless sensor networks, home automation, home networking, connecting devices to a PC, home security, and so on. Most of these applications require only low-to-medium bitrates (up to some few hundreds of kbps), moderate average delays without too stringent delay guarantees, and for certain nodes it is highly desirable to reduce the energy consumption to a minimum. The physical layer offers bitrates of 20 kbps (a single channel in the frequency range 868–868.6 MHz), 40 kbps (ten channels in the range between 905 and 928 MHz) and 250 kbps (16 channels in the 2.4 GHz ISM band between 2.4 and 2.485 GHz with 5-MHz spacing between the center frequencies). There are a total of 27 channels available, but the MAC protocol uses only one of these channels at a time; it is not a multichannel protocol.

The MAC protocol combines both schedule-based as well as contention-based schemes. The protocol is asymmetric in that different types of nodes with different roles are used.

Network architecture and types/roles of nodes

The standard distinguishes on the MAC layer two types of nodes:

- A Full Function Device (FFD) can operate in three different roles: it can be a PAN coordinator (PAN = Personal Area Network), a simple coordinator or a device.
- A Reduced Function Device (RFD) can operate only as a device. A device must be associated to a coordinator node (which must be a FFD) and communicates only with this, this way forming a star network. Coordinators can operate in a peer-to-peer fashion and multiple coordinators can form a Personal Area Network (PAN). The PAN is identified by a 16-bit

PAN Identifier

PAN Identifier and one of its coordinators is designated as a PAN coordinator. A coordinator handles among others the following tasks:

- It manages a list of associated devices. Devices are required to explicitly associate and disassociate with a coordinator using certain signalling packets.

- It allocates short addresses to its devices. All IEEE 802.15.4 nodes have a 64-bit device address. When a device associates with a coordinator, it may request assignment of a 16-bit short address to be used subsequently in all communications between device and coordinator. The assigned address is indicated in the association response packet issued by the coordinator.
- In the beaconed mode of IEEE 802.15.4, it transmits regularly frame beacon packets announcing the PAN identifier, a list of outstanding frames, and other parameters. Furthermore, the coordinator can accept and process requests to reserve fixed time slots to nodes and the allocations are indicated in the beacon.
- It exchanges data packets with devices and with peer coordinators. In the remainder of this section, we focus on the data exchange between coordinator and devices in a star network; a possible protocol for data exchange between coordinators is described. We start with the beaconed mode of IEEE 802.15.4.

Super frame structure

The coordinator of a star network operating in the beaconed mode organizes channel access and data transmission with the help of a super frame structure displayed in Figure 14. All super frames have the same length. The coordinator starts each super frame by sending a frame beacon packet. The frame beacon includes a super frame specification describing the length of the various components of the following super frame:

- The super frame is subdivided into an active period and an inactive period. During the inactive period, all nodes including the coordinator can switch off their transceivers and go into sleep state. The nodes have to wake up immediately before the inactive period ends to receive the next beacon. The inactive period may be void.
- The active period is subdivided into 16 time slots. The first time slot is occupied by the beacon frame and the remaining time slots are partitioned into a Contention Access Period (CAP) followed by a number (maximal seven) of contiguous Guaranteed Time Slots (GTSs).

  The length of the active and inactive period as well as the length of a single time slot and the usage of GTS slots are configurable.

  The coordinator is active during the entire active period. The associated devices are active in the GTS phase only in time slots allocated to them; in all other GTS slots they can enter sleep mode. In the CAP, a device can shut down its transceiver if it has neither any own data to transmit nor any data to fetch from the coordinator.

It can be noted already from this description that coordinators do much more work than devices and the protocol is inherently asymmetric. The protocol is optimized for cases where energy constrained sensors are to be attached to energy-unconstrained nodes.

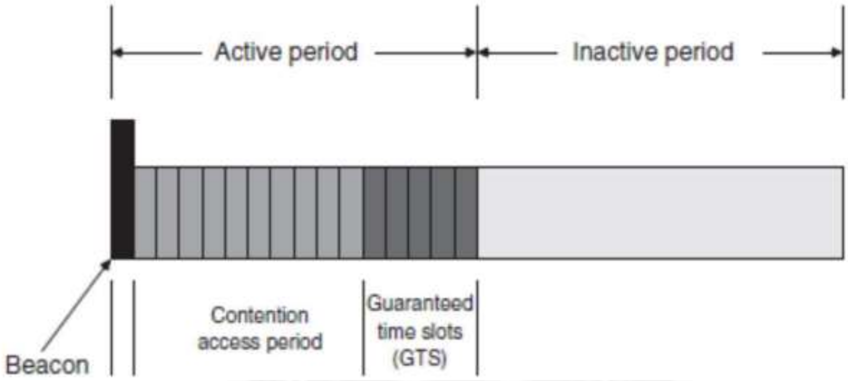


Fig 1.4.1 Super frame structure of IEEE 804.15.4

GTS management

The coordinator allocates GTS to devices only when the latter send appropriate request packets during the CAP. One flag in the request indicates whether the requested time slot is a transmit slot or a receive slot. In a transmit slot, the device transmits packets to the coordinator and in a receive slot the data flows in the reverse direction. Another field in the request specifies the desired number of contiguous time slots in the GTS phase.

The coordinator answers the request packet in two steps: An immediate acknowledgment packet confirms that the coordinator has received the request packet properly but contains no information about success or failure of the request.

After receiving the acknowledgment packet, the device is required to track the coordinator's beacons for some specified time. When the coordinator has sufficient resources to allocate a GTS to the node, it inserts an appropriate GTS descriptor into one of the next beacon frames. This GTS descriptor specifies the short address of the requesting node and the number and position of the time slots within the GTS phase of the super frame. A device can use its allocated slots each time they are announced by the coordinator in the GTS descriptor. If the coordinator has insufficient resources, it generates a GTS descriptor for (invalid) time slot zero, indicating the available resources in the descriptors length field. Upon receiving such a descriptor, the device may consider renegotiation. If the device receives no GTS descriptor within a GTS Desc Persistence Time time after sending the request, it concludes that the allocation request has failed.

A GTS is allocated to a device on a regular basis until it is explicitly deallocated. The deallocation can be requested by the device by means of a special control frame. After sending this frame, the device shall not use the allocated slots any further. The coordinator can also trigger deallocation based on certain criteria. Specifically, the coordinator monitors the usage of the time slot: If the slot is not used at least once within a certain number of super frames, the slot is deallocated. The coordinator signals deallocation to the device by generating a GTS descriptor with start slot zero.

Data transfer procedures

Let us first assume that a device wants to transmit a data packet to the coordinator. If the device has an allocated transmit GTS, it wakes up just before the time slot starts and sends its packet immediately without running any carrier-sense or other collision-avoiding operations. However, the device can do so only when the full transaction consisting of the data packet and an immediate acknowledgment sent by the coordinator as well as appropriate InterFrame Spaces (IFSs) fit into the allocated time slots. If this is not the case or when the device does not have any allocated slots, it sends its data packet during the CAP using a slotted CSMA protocol, described below. The coordinator sends an immediate acknowledgment for the data packet.

The other case is a data transfer from the coordinator to a device. If the device has allocated a receive GTS and when the packet/acknowledgment/IFS cycle fits into these, the coordinator simply transmits the packet in the allocated time slot without further coordination. The device has to acknowledge the data packet.

The more interesting case is when the coordinator is not able to use a receive GTS. The handshake between device and coordinator is sketched in Figure 15. The coordinator announces a buffered packet to a device by including the devices address into the pending address field of the beacon frame. In fact, the device’s address is included as long as the device has not retrieved the packet or a certain timer has expired. When the device finds its address in the pending address field, it sends a special data request packet during the CAP. The coordinator answers this packet with an acknowledgment packet and continues with sending the data packet. The device knows upon receiving the acknowledgment packet that it shall leave its transceiver on and prepares for the incoming data packet, which in turn is acknowledged. Otherwise, the device tries again to send the data request packet during one of the following super frames and optionally switches off its transceiver until the next beacon.

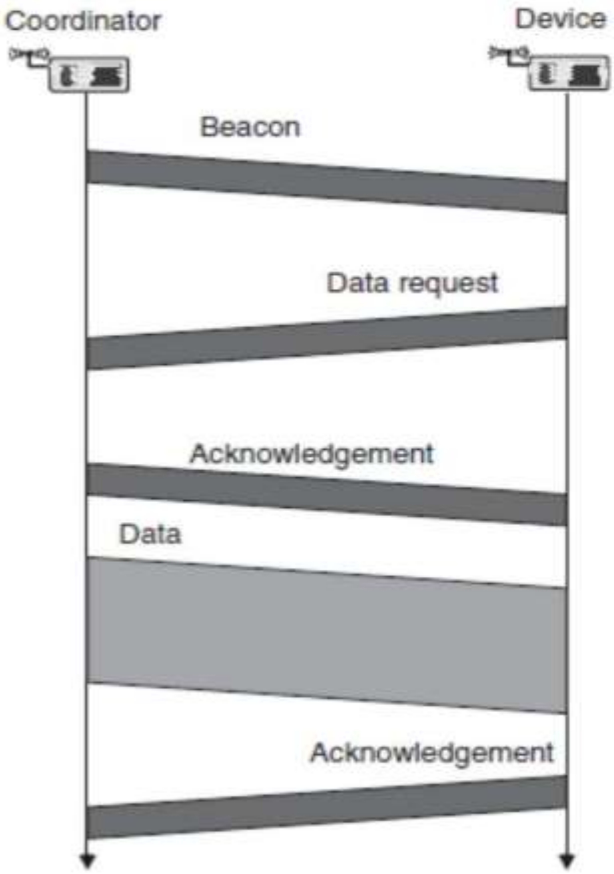


Fig 1.4.2 Handshake between coordinator and device when the device retrieves a packet

Slotted CSMA-CA protocol

When nodes have to send data or management/control packets during the CAP, they use a slotted CSMA protocol. The protocol contains no provisions against hidden-terminal situations, for example there is no RTS/CTS handshake. To reduce the probability of collisions, the protocol uses random delays; it is thus a CSMA-CA protocol (CSMA with Collision Avoidance). Using such random delays is also part of the protocols described. The time slots making up the CAP are subdivided into smaller time slots, called back off periods. One back off period has a length corresponding to 20 channel symbol times and the slots considered by the slotted CSMA-CA protocol are just these back off periods.

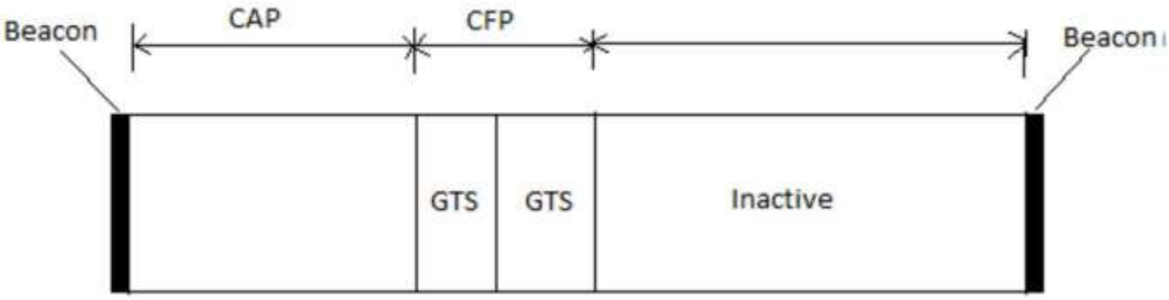
Nonbeaconed mode

The IEEE 802.15.4 protocol offers a nonbeaconed mode besides the beaconed mode. Some important differences between these modes are the following:

- In the nonbeaconed mode, the coordinator does not send beacon frames nor is there any GTS mechanism. The lack of beacon packets takes away a good opportunity for devices to acquire time synchronization with the coordinator.
- All packets from devices are transmitted using an unslotted (because of the lack of time synchronization) CSMA-CA protocol. As opposed to the slotted CSMA-CA protocol, there is no synchronization to back off period boundaries and, in addition, the device performs only a single CCA operation. If this indicates an idle channel, the device infers success.
- Coordinators must be switched on constantly but devices can follow their own sleep schedule. Devices wake up for two reasons:
    - To send a data/control packet to the coordinators,
    - To fetch a packet destined to itself from the coordinator by using the data request/acknowledgment/ data/acknowledgment handshake (fetch cycle) discussed above. The data request packet is sent through the unslotted CSMA-CA mechanism and the following acknowledgment is sent without any further ado. When the coordinator has a data packet for the device, it transmits it using the unslotted CSMA-CA access method and the device sends an immediate acknowledgment for the data. Therefore, the device must stay awake for a certain time after sending the data request packet. The rate by which the device initiates the fetch cycle is application dependent.

ZigBee MAC PROTOCOL

ZigBee MAC protocol uses CSMA/CA or TDMA for accessing the shared medium. In ZigBee MAC data is packed into super frame. Super frame structure is shown in figure. The super frame may have an active and an inactive portion. During the inactive portion, the coordinator will not interact with its PAN and may enter a lowpower mode.



The active portion consists of contention access period (CAP) and contention free period (CFP). Any device that communicates during the CAP will compete with other devices using a slotted CSMA/CA mechanism. On the other hand, the CFP contains guaranteed time slots (GTSs), a TDMA approach. The GTSs always placed at the end of the active super frame starting at a slot boundary just following the CAP. The network coordinator may allocate up to seven of these GTSs. A GTS can occupy more than one slot period. Synchronization is provided by beacon management. If TDMA mechanism is applied, device uses CFP field that contains GTSs. ZigBee MAC protocol while using CSMA/CA mechanism listen the channel continuously hence energy consumption is high. When it uses GTS management by providing a time slot to a device for transmission, only in period of time slot device has to transmit and for rest of the period it goes in sleep mode. Thus the energy consumption is reduced considerably.

After observing the simulation results it is obvious that ZigBee MAC protocol with GTS management is better if energy efficiency and throughput are more dominating factors. On the other hand T-MAC dominates ZigBee with GTS at low data rates in terms of energy consumption. But at low data rates throughput of T-MAC is lower than that of ZigBee with GTS. ZigBee with GTS has a problem of latency at higher data rates and synchronization, however many solution for resolving these problems are provided. So as per overall performance ZigBee MAC protocol is better for WBAN