



IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 m, for Both Stationary and Mobile Devices

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

IEEE Std 802.15.13™-2023

STANDARDS

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Approved 15 February 2023
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Abstract: The protocol and compatible network equipment for optical wireless communications and its operation as an optical wireless personal area network (OWPAN), supporting data rates of multiple Gbit/s for wireless specialty applications, are defined in this standard. A medium access control (MAC) sublayer, supporting scheduled and polled medium access, as well as two physical layers (PHYs), enabling low complexity, low power, and high throughput are included.

Keywords: DC-biased OFDM, distributed MIMO, IEEE 802[®], IEEE 802.15.13[™], mobility support, optical wireless communication, pulsed modulation

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Introduction

This introduction is not part of IEEE Std 802.15.13-2023, IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 m, for Both Stationary and Mobile Devices.

IEEE Std 802.15.13 was developed to provide gigabit optical wireless communication (OWC) over short-range wireless links with applications in industrial wireless, fixed wireless access, home and office scenarios. Main requirements are the provision of high data rates in fixed and mobile scenarios with the additional support of robustness and low latency. A properly designed network interface for integration with existing radio technologies was another important design criterion.

Original ideas for a new OWC standard were presented in March 2015 together with other ideas, to develop optical camera communications (OCC), as a tutorial at the IEEE 802 Plenary in Berlin, Germany. Initially, the IEEE decided to consider both technologies in a joint revision of IEEE Std 802.15.7™-2011. While IEEE Std 802.15.7r1 continued to add OCC, a new task group IEEE P802.15.13 started in May 2017 to create IEEE Std 802.15.13 focusing on OWC.

IEEE Std 802.15.13 aims to support a ceiling-mounted infrastructure serving stationary and mobile devices as well as point-to-point links. To support time-sensitive transmission, the standard defines scheduled or polled medium access. For industrial use cases, distributed MIMO allows leveraging diversity and mobility support through dynamic selection of optical frontends. To increase data rates for devices that have a poor link quality with the coordinator, IEEE Std 802.15.13 allows relaying via other devices. To achieve multi-gigabit throughputs, the standard uses aggregation to reduce per-packet overhead. Rate adaptation aids reliable data transport in varying channel conditions based on two PHYs for energy-efficiency and spectral efficiency, respectively.

Overall, work towards IEEE Std 802.15.13 led to the conclusion that it is more efficient to follow a wavelength-agnostic approach and handle lighting and communication separately. As a result, IEEE Std 802.15.13 handles optical wireless communication similar to radio communication.

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IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 m, for Both Stationary and Mobile Devices

1. Overview

1.1 Scope

This standard defines a physical layer (PHY) and medium access control (MAC) sublayer using light wave-lengths from 10 000 nm to 190 nm in optically transparent media for optical wireless communications (OWC). The standard is capable of delivering data rates up to 2.192 Gb/s at distances in the range of 200 m unrestricted line-of-sight. It is designed for point-to-point and point-to-multipoint communications and adaptation to varying channel conditions.

1.2 Purpose

The purpose of this standard is to define OWC specifications in optically transparent media enabling high data rate transfer among end points at data rates up to 2.192 Gb/s and ranges up to 200 m unrestricted line-of-sight and that are capable of meeting the needs of industrial and similar classes of applications requiring secure, high performance, high data rate communications that are very robust, have low latency, and are not interfering with existing radio-frequency (RF) systems.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall equals is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should equals is recommended that*).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60825-1:2014, Ed. 3.0, Safety of Laser Products—Part 1: Equipment Classification and Requirements.⁸

IEEE Std 802[®], IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture.^{9, 10}

IEEE Std 802.1AC[™], IEEE Standard for Local and metropolitan area networks—Media Access Control (MAC) Service Definition.

IEEE Std 802.1Q[™], IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks.

IEEE Std 802.3[™], IEEE Standard for Ethernet.

IEEE Std 802.15.4[™]-2020, IEEE Standard for Low-Rate Wireless Networks.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

association: The service used to establish membership for a device in an optical wireless personal area network (OWPAN).

coordinator: A device that supports additional functionality to coordinate an optical wireless personal area network (OWPAN) and actively maintains an OWPAN.

device: An entity that implements an IEEE 802.15.13 conformant media access control (MAC) and physical layer (PHY) interface to the wireless medium.

fragment: An individual contiguous subset of a MAC protocol data unit (MPDU).

⁸ IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

⁹ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁰ The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

¹¹ *IEEE Standards Dictionary Online* is available at <https://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

frame: The format of aggregated bits from a medium access control (MAC) sublayer entity that are transmitted together in time.

fronthaul: A connection between the coordinator and its optical frontend(s).

MAC address: A media access control address.

member: A device that is associated with an optical wireless personal area network (OWPAN) and does not act as a coordinator.

optical frontend (OFE): The interface to the optical wireless channel. It consists of a single optical transmitter and receiver.

optical wireless personal area network (OWPAN): A group of at least one coordinator and one or more members that allows connectivity between the participating devices.

payload: The contents of a frame that is being transmitted.

relay device: A member that is used to forward data from a coordinator to another member and from another member to the coordinator.

relayed device: A member whose frames are being relayed by a relay device.

relay link: An indirect connection between a member and the coordinator through a relay device.

superframe number: A consecutive number, assigned to each superframe in the scheduled medium access mode.

3.2 Acronyms and abbreviations

2-PAM	binary pulse-amplitude modulation
AID	association identifier
BAT	bit allocation table
CID	Company ID
CRC	cyclic redundancy check
CSI	channel state information
CSS	cyclic section shift
dc	direct current
DME	device management entity
FCS	frame check sequence
FEC	forward error correction
GTS	guaranteed time slice
HB-PHY	high bandwidth PHY

HCS	header check sequence
IDFT	inverse discrete Fourier transformation
IoT	Internet of things
LDPC	low-density parity-check code
LED	light-emitting diode
LFSR	linear feedback shift register
LSB	least significant bit
MAC	medium access control
MD-SAP	MAC data service access point
MCS	modulation and coding scheme
MIFS	minimum interframe space
MIMO	multiple-input multiple-output
MLME	MAC layer management entity
MLME-SAP	MLME service access point
MPDU	MAC protocol data unit
MSB	most significant bit
MSDU	MAC service data unit
OFDM	orthogonal frequency division multiplexing
OFE	optical frontend
OUI	Organizationally Unique Identifier
OWC	optical wireless communication
OWPAN	optical wireless personal area network
OWPAN ID	optical wireless personal area network identifier
PD-SAP	PHY data service access point
PHY	physical layer
PIB	PAN information base
PLME-SAP	PHY management entity service access point
PM-PHY	pulsed modulation PHY
PPDU	PHY protocol data unit
PSDU	PHY service data unit
QAM	quadrature amplitude modulation

QC-LDPC-BC	quasi-cyclic low-density parity-check block-code
RANDOP	random access opportunity
RS	Reed-Solomon
RTS	random time slice
SAP	service access point
SNR	signal-to-noise ratio
TDMA	time-division multiple access

4. Conventions

4.1 Names

The names of constants and PAN information base (PIB) attributes are written in italics and without spaces. Constants have a prefix of “a”, e.g., *aMinFragmentSize*. Variable PIB attributes of the MAC start with the prefix “mac”, e.g., *macOwpanId*. Variable PIB attributes of the PHY start with the prefix “phy”, e.g., *phyClockRate*.

Names of frames, elements, or fields are capitalized and written in italics. They might contain whitespaces, e.g., *Association Request* element.

4.2 Frame and element representation

Frames and elements in this standard are represented as figures in table format. The top line specifies the width of a field. The second (middle) line provides the name of the field or a reference to an element specified elsewhere in the standard. The third (bottom) line is optional and provides an alternative description of the fields or elements corresponding to its columns. Figure 1 depicts an example with two fields.

Width	Width
Field description	Field description
Optional alternative description	

Figure 1—Frame or element representation example

Field widths are given by their number of bits or octets. The corresponding notion includes the number of bits or octets followed by the word “Bits” or “Octets” as shown in *Field 2*, *Field 3*, and *Field 5* of Figure 2. If a field contains different numbers of bits or octets, the discrete set of possible numbers might be listed, separated by forward slashes. Alternatively, a range of possible values might be indicated by a dash.

Bit 0–3	4 Bits	2 Octets	variable	5/7 Octets
Field 1	Field 2	Field 3	Field 4	Field 5

Figure 2—Width specification example

In consecutive fields that include no variable widths from the start of the parent frame or element, the field width might be given by the first and last bit in the field. The corresponding notion reads the word “Bit” and successively the specification of the first and last denoted bit. This is demonstrated for *Field 1* of Figure 2.

If an element or set of consecutive fields has a variable width, its width is specified by the word “variable.” If between the field and the start of the frame or element lies a variable width field, the absolute bit specification is not used.

4.3 Byte order and representation

Figures in this standard sometimes represent information contained in fields of MAC protocol data units (MPDUs) and PHY protocol data units (PPDUs).

Figures in the context of the MAC sublayer depict whole MPDUs, elements, or fields. Elements are groups of fields for usage through multiple MAC functions. Elements aid the readability of the standard enabling groups of fields to be reused in different MPDUs. MPDUs consist of an ordered sequence of octets with given values.

The bit order within each octet for transmission is determined by the used PHY. MPDUs are commonly handed to the PHY or received from it.

The relationship between processing (that means transmitting or interpreting to and from the PHY) of MAC frames and their representation in this standard is as follows: bits, fields, and elements are processed in their order of representation in figures from left to right. This relationship is depicted in Figure 3.

Fields in PPDUs are depicted in their processing order from left to right. Elements are not used in PPDUs.

If a field exceeds the length of an octet, i.e., is a multi-byte field, it is depicted in big endian representation. Hence, the octet containing the most significant byte of the numeric value is processed first and presented leftmost.

If a field contains a bitmap, the first bit, i.e., bit 0, is the least significant bit (LSB) of the first octet. The eighth bit, i.e., bit 7, is the most significant bit (MSB) of the first octet. The ninth bit is the LSB of the second octet and so on.

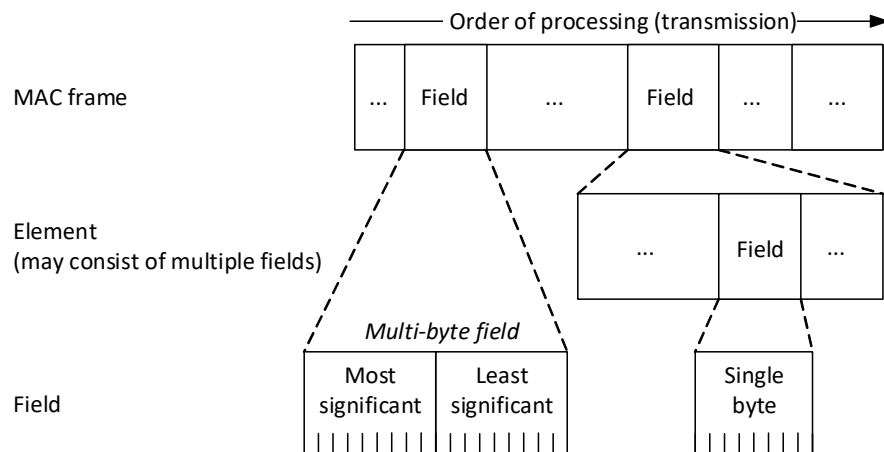


Figure 3—Fields and elements in the MAC frame

4.4 Numbers

Numbers are represented in decimal (nnn), binary (0bnnn), or hexadecimal (0xnnn) notation with the number of digits indicated by n. For example, 0b001 is a three-digit binary number with the value one and 0x001 is a three-digit hexadecimal number with the value one. Numbers encoded in fields are signed or unsigned integers. Unless otherwise stated in the definition of a field, a number in a field is formatted as an unsigned integer.

MAC addresses use the IEEE 802 hexadecimal representation (six hexadecimal octets separated with hyphens).

Other formats (e.g., a field containing a floating point number) are stated in the field definition where applicable.

4.5 Reserved fields and values

Fields that are “reserved” do not carry meaningful information in the current version of the standard. It is possible that the meaning of such fields changes in later versions of the standard. Fields that are reserved shall be set to all zeros for transmission and shall be ignored on reception.

In addition, certain values for fields are reserved. Reserved values shall not be used in outgoing frames. If a frame or element is received with one or more fields carrying a reserved value, the corresponding frame shall be dropped.

5. General description

5.1 Introduction

OWC transmits data by modulating optical sources, such as light-emitting diodes (LEDs) and laser diodes, faster than the perception of the human eye. OWC can merge lighting infrastructures and data communications in applications such as area lighting, signboards, streetlights, vehicles, and traffic signals.

This standard describes the use of OWC for wireless specialty networks. Some of the characteristics found in this standard are as follows:

- Star topology supporting point-to-point, broadcast, and multiple-input multiple-output (MIMO) operation
- EUI-48 MAC addresses
- Scheduled or polled medium access with random initial access
- Flexible medium access schedules allowing for the support of isochronous traffic
- Acknowledgment and retransmission protocol for transfer reliability

5.2 Components of IEEE 802.15.13 networks

An optical wireless personal area network (OWPAN) is comprised of two or more devices conformant with this standard. Devices constitute of a standards-conformant MAC implementation and make use of a conformant PHY defined in the standard. Devices have a MAC address for identification and addressing in the network. During association with the network, 16-bit association identifiers (AIDs) are allocated to devices.

Devices that support additional functionality to coordinate an OWPAN are also referred to as “coordinator-capable devices” or “coordinators” when they actively maintain an OWPAN. In each OWPAN, a single coordinator-capable device assumes the role of the coordinator. The coordinator is responsible for starting, maintaining, and finally stopping the OWPAN. The coordinator is furthermore involved in all data transmissions in the OWPAN.

Devices associated with an OWPAN that do not act as coordinator, hereafter referred to as “members,” implement partially different functionality than coordinators. Members associate with an OWPAN in order to establish a connection with the network.

Each OWPAN has an optical wireless personal area network identifier (OWPAN ID) and an OWPAN name. The OWPAN ID serves as a unique identifier and the OWPAN name serves as a human-readable name and is not necessarily unique. Both are described in 6.5.3.

5.3 Network topologies

5.3.1 Logical topology

All IEEE 802.15.13 OWPANs have a logical star topology. A single coordinator is involved in all data transmission between devices or between external peers and the devices associated with the OWPAN as illustrated in Figure 4. The coordinator offers the MAC service at its MAC data service access point (MD-SAP). Data transmissions between two members of the same OWPAN are forwarded by the coordinator.

IEEE 802.15.13 networks operate independently from other IEEE 802.15.13 networks in operation. This is achieved by choosing an OWPAN identifier that is not currently used by any other network within the coverage area. Once the OWPAN identifier is chosen, the coordinator allows other devices to join its network.

Depending on the application, the star topology is used to realize different physical topologies as described in the following subclauses.

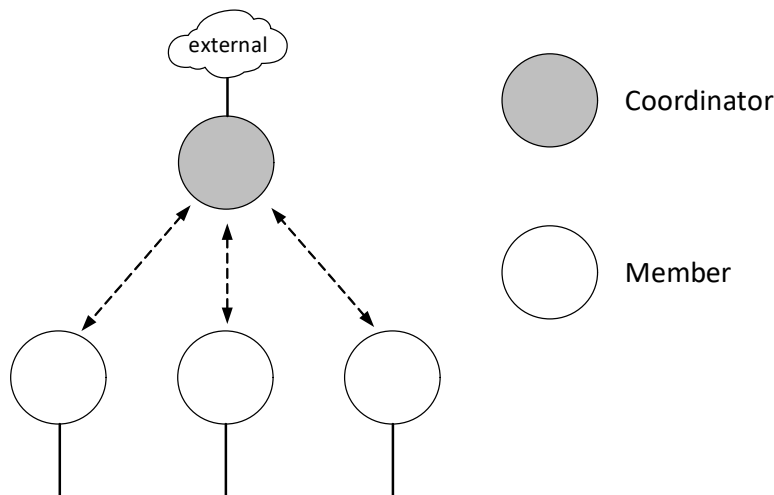


Figure 4—Basic star topology

5.3.2 Distributed MIMO star topology

To improve robustness of transmissions and enhance mobility support, the star topology is able to support MIMO principles. The distributed MIMO star topology is illustrated in Figure 5.

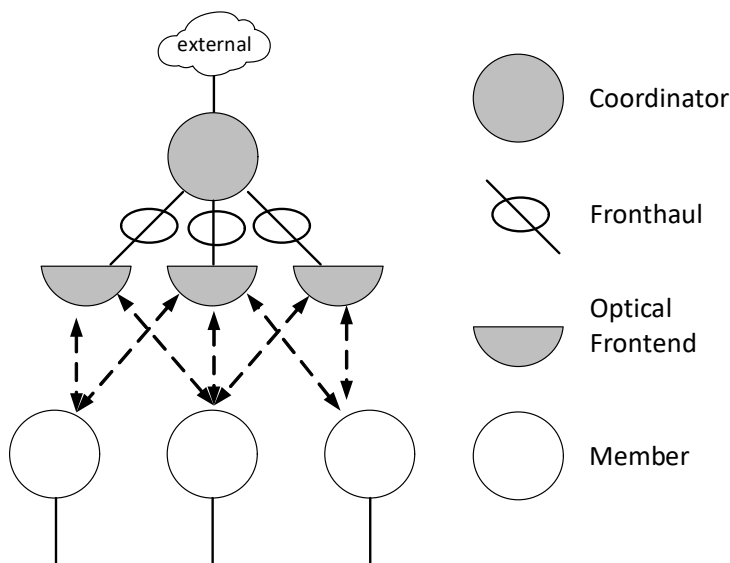


Figure 5—Distributed MIMO star topology

In the MIMO star topology, the coordinator has more than one optical frontend (OFE) for transmission and reception connected with its PHY. Over each OFE, the coordinator is able to transmit the same or different signals via multiple transmit and receive chains. Individual OFEs are transparent to members. Members observe a single logical coordinator.

The realization of the distributed MIMO star topology is out of scope of this standard. For example, the OFEs could be distributed in space and connected to the single central coordinator instance via fronthaul technology, e.g., according to IEEE Std 802.1CM™ [B3].¹² To account for such possibilities, the standard

¹² The numbers in brackets correspond to those of the bibliography in Annex A.

defines means that are helpful for realization. These are, among others, the possibility to transmit explicit MIMO pilot signals from each OFE at the PHY and measure them at the PHY in the receiving device. The MAC supports MIMO transmissions through a medium access mechanism that is able to cope with fronthaul delays for individual OFEs. This includes scheduled medium access as well as the possibility for delayed acknowledgment.

5.3.3 Broadcast topology

In the broadcast topology, the OWPAN comprises only the coordinator. The broadcast topology is depicted in Figure 6. The coordinator in broadcast mode transmits MPDUs with the broadcast address as receiver address. Such MPDUs are received and possibly parsed by any device, even if not associated to any OWPAN.

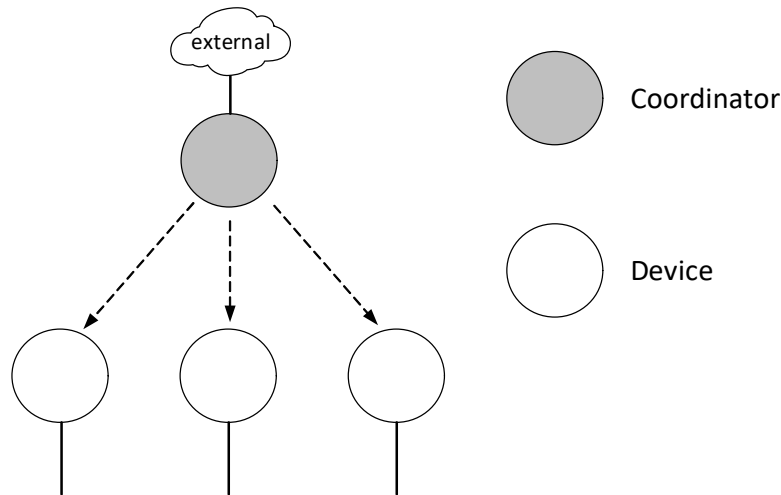


Figure 6—Broadcast topology

5.3.4 Relay topology

In the relay topology, the OWPAN includes at least one relay device. The relay topology is depicted in Figure 7. Relaying is supported within the coverage of the OWPAN. Relaying requires direct connectivity between the coordinator, the relay device and the relayed device.

In the downlink, if the coordinator decides that connectivity via the relay would be better than via the direct link, the coordinator sets up a relay link via the relay device. Similarly in the uplink, the relayed device may choose to transmit its frames via the relay device to the coordinator.

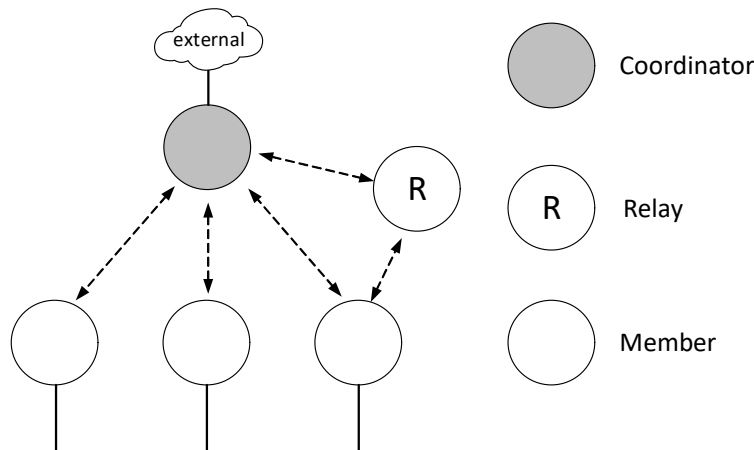


Figure 7—Relay topology

5.4 Coexistence

Light does not interfere with radio communication but operates in an orthogonal part of the electromagnetic spectrum. The propagation of light is confined within the illuminated area, typically spanning a few meters in diameter. In addition, the directivity of light helps to reduce interference with neighboring networks. To further prevent interference, coordinators only start a new OWPAN if no overlapping OWC networks in operation were detected, as described in 6.5.3.

The current standards and standardization projects in the light spectrum are as follows:

- Infrared remote controls: Remote controls usually emit narrowband signals and their modulation spectrum is not relevant for IEEE Std 802.15.13, which operates at higher modulation frequencies on all its PHYs.
- IrDA in various variants up to GigaIR [B12]: IrDA operates in the infrared spectrum and has found mass market adoption in the 1990s. Modern devices replaced IrDA by Bluetooth and IEEE Std 802.11. Given the rapid replacement of mobile devices, IrDA is no longer relevant in the market, i.e., there is no need to consider coexistence with IEEE Std 802.15.13.
- IEEE Std 802.15.7™ [B5]: IEEE 802.15.7 defined wireless communication in the optical spectrum. It can be operated in PHY I-PHY III with photodiode receivers and in PHY IV, V, and VI using optical cameras. PHY I and PHY IV-VI operate at lower modulation frequencies, which are not relevant for IEEE Std 802.15.13. PHY II and PHY III were never adopted by the market. Hence, there is no need to consider coexistence with IEEE Std 802.15.13.
- ITU-T G.9991 [B7]: Both standards support multiple optical bands for transmission but do not require use of a specific one. Hence, for a given installation, coexistence can be ensured by choosing the wavelengths of both systems so that they do not overlap.
- IEEE Std 802.11bb™-2023 [B4]: Coexistence between the two systems can be ensured by spatial separation or by using different optical wavelengths.

5.5 Device architecture

5.5.1 Overview

The IEEE 802.15.13 device architecture is defined in terms of layers. The standard includes a specification of the PHY and MAC sublayer and their exposed interfaces. Each layer is responsible for one part of the

standard and offers its services to the next higher layer. Layers make use of service access points (SAPs) based on primitives, as described in the 5.8 of IEEE Std 802.15.4-2020.¹³

Figure 8 depicts the architecture of a single device. The MAC sublayer and the PHY are described in more detail in 5.6 and 5.7, respectively.

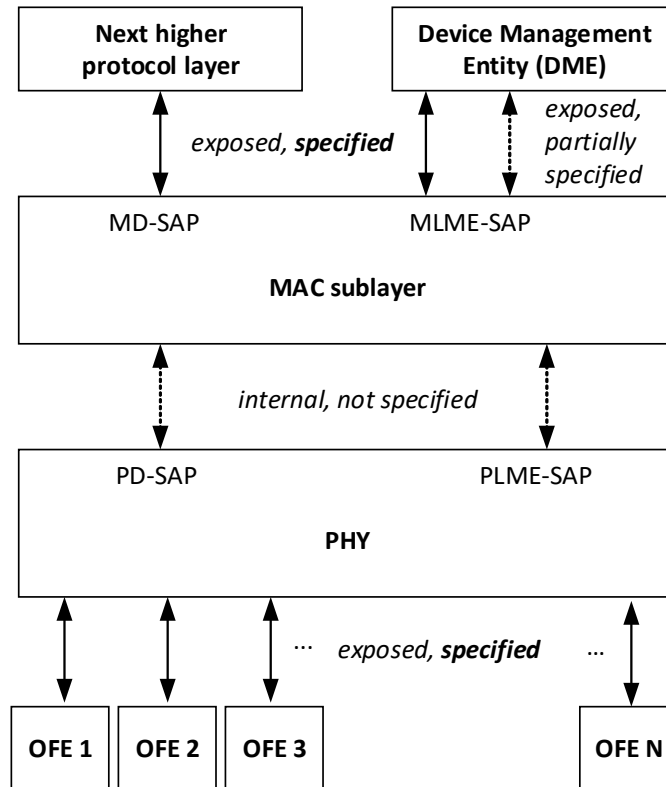


Figure 8—OWPAN device architecture

Each device has a device management entity (DME), responsible for managing the device and, in case the device is a coordinator, the OWPAN. The DME invokes MAC layer management entity (MLME) functionality through the MLME service access point (MLME-SAP). The MLME-SAP defines a set of essential primitives for network operation. Further functionality is potentially provided by the MAC sublayer to the DME in an implementation specific manner.

The IEEE 802.15.13 MAC sublayer controls access to the medium for all types of transfers. It provides the MD-SAP and MLME-SAP to the higher layers. Its MD-SAP allows the next higher protocol layer to transmit MAC service data units (MSDUs) between peer IEEE 802.15.13 devices by supporting the MAC service defined by IEEE Std 802.1AC. The higher layers are a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. The definition of these higher layers is outside the scope of this standard.

The PHY contains the optical wireless transceiver, which is responsible for turning a PHY service data unit (PSDU) into a PPDU for transmission. PSDUs are MPDUs from the MAC sublayer that are transferred through the PHY data service access point (PD-SAP) of the PHY. To yield the PPDU, a PSDU is supplemented with various fields, needed by each respective PHY for reception. Thereafter, the PPDU is

¹³ Information on references can be found in Clause 2.

output to one or more OFEs as an analog signal. Management functions of the PHY are invoked through the PHY management entity service access point (PLME-SAP).

The relationship between data units of the different layers is depicted in Figure 9.

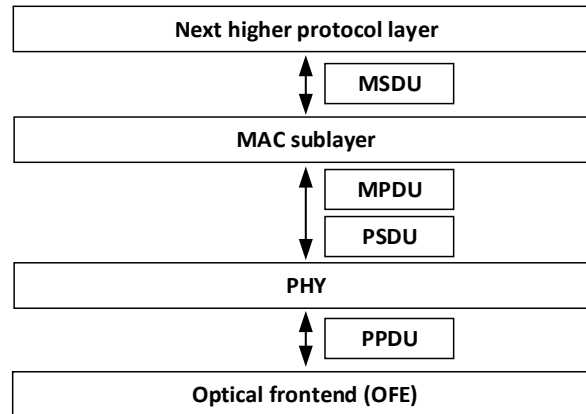


Figure 9—Relationship between data units of the different layers

5.5.2 Dimming support

In this standard, illumination and dimming is considered to be independent of the communication functionality. The receiver is not required to know what dimming level is used while communication is ongoing. For further information, refer to Annex C.

5.5.3 Flicker mitigation support

In this standard, flickering is avoided through waveform design and possibly selection of invisible wavelengths. Flickering is not perceivable by the human eye if the average light intensity is constant. Therefore, light is modulated at a very high speed while the average modulation is zero. In this way, changes in light intensity are so fast that they are not perceivable by the human eye.

The waveforms of all PHYs are designed so that they do not contain frequencies that are perceivable by the human eye. Moreover, waveforms are direct current (dc)-free and balanced around the bias. This is achieved, for example, by using 8B10B line codes or dc-biased orthogonal frequency division multiplexing (OFDM) with zero amplitude of the dc subcarrier.

5.6 MAC sublayer overview

5.6.1 General

This clause provides a brief overview of the general functions of an OWPAN MAC sublayer. IEEE 802.15.13 OWPANs have characteristics that are not common in other wireless networks, due to directionality and visibility when using the optical spectrum. Unlike in RF-based wireless networks, optical signals do not propagate through opaque media such as walls. In addition, signals are significantly weaker when the line-of-sight between the transmitter and the receiver is blocked.

5.6.2 Data transfer model

The following two types of data transfer transactions exist:

- a) The data transfer to a coordinator, in which a member transmits the data.
- b) The data transfer from a coordinator, in which a member receives the data.

Direct communication between members is only allowed for relaying frames between the coordinator and a member, as described in 6.11.

MSDUs originating from a member and destined to another member are delivered by the coordinator to the higher layers. To support communication between members, coordinators need to implement bridging functionality based on IEEE Std 802.1Q.

The standard provides deterministic transmission schedules for the support of real-time data streams through its medium access mechanism as described in 5.6.6. The configuration of data streams is out-of-scope of the standard and requires implementation-specific interfaces. Coordinators support registered streams by scheduling resources for transmissions accordingly.

The reliability of data transfers over the wireless medium is increased through multiple measures, such as forward error correction (FEC) and retransmissions.

5.6.3 Data transfer through a relay device

Direct communication between members is not intended except in cases where relaying is used. Relaying is supported within the coverage of the OWPAN. Relaying requires direct connectivity between the coordinator, the relay device and the relayed device and aims to improve throughput for the relayed device.

A relay device listens to other members in its environment being associated to the same coordinator and informs the coordinator about its neighborhood connectivity. In the downlink, if the coordinator decides that connectivity via the relay would be better than via the direct link, the coordinator has the possibility to setup the link via the relay device. Similarly in the uplink, the relayed device chooses whether to transmit its frames via the relay device to the coordinator.

5.6.4 Adaptive transmission

The standard supports multiple bandwidths in order to accommodate a wide variety of optical sources and receivers. Variable bandwidths as well as different modulation and coding rates are used to support varying channel conditions.

5.6.5 MAC frames

The standard defines elements to convey information between peer devices in the various protocol routines. A single MAC frame format, i.e., MPDU, is defined to encapsulate elements for transmission via the PHY. To aid frame differentiation and parsing, the MPDU header indicates the type of contained information. There are three distinct types of frames:

- a) Data frames, used to transfer MSDUs between to MACs.
- b) Management frames, used for all transfers of OWPAN management information between two MLMEs.
- c) Control frames, which are used to convey control information between two MACs layers to assist the delivery of data frames.

This allows to determine potentially different paths and priorities for handling the MPDU in an implementation. The presence of some header fields in the MPDU is determined by the frame type and other contents of the *Frame Control* field.

For each element, the type of MPDU in which it is transported is specified. If multiple elements need to be transmitted in a single MPDU, this is done by using container elements.

5.6.6 Medium access mechanism

IEEE 802.15.13 OWPANs apply one of two medium access mechanisms. The scheduled medium access relies on special frames to synchronize members with the coordinator. The coordinator allocates channel time for different ways of medium access. Deterministic medium access is supported in guaranteed time slices (GTS) and random medium access is supported in random time slices (RTS).

NOTE—RTS are only used for certain purposes such as association and requesting additional channel time resources.¹⁴

The polled medium access relies on the coordinator to poll members to access the channel. The polled medium access consists of two periods for random access and contention-free access, referred to as random access polling period (RAPP) and dedicated polling period (DPP), respectively. Devices may communicate with the coordinator in the RAPP to request a transmission. In the DPP, the coordinator polls members.

5.6.7 Frame acknowledgment and retransmission

A successful reception and validation of a data or management frame is optionally confirmed with an acknowledgment. If the originator does not receive an acknowledgment after a configurable period, it assumes that the transmission was unsuccessful. When the acknowledgment is not required, the originator assumes the transmission was successful. MPDUs that were not successfully transmitted are retransmitted.

5.6.8 Data verification

Cyclic redundancy check (CRC) is used to detect corrupt data.

5.6.9 Security

Security is not included in this standard and assumed to be handled by the higher layers for data transmissions.

5.7 Physical layer overview

5.7.1 Overview

This standard includes the following PHYs:

- a) Pulsed modulation PHY (PM-PHY) introduced in 5.7.2.
- b) High bandwidth PHY (HB-PHY) introduced in 5.7.3.

5.7.2 PM-PHY introduction

The PM-PHY, specified in Clause 10, is intended for moderate data rates between ~9 Mb/s and ~100 Mb/s, low power and low latency. It allows fast adaptation to the time-varying channel in mobile scenarios. The unique approach of the PM-PHY is to use a high clock rate and modulation with low spectral efficiency. This approach offers enhanced reach in applications where power efficiency is an issue, e.g., the Internet of Things (IoT).

¹⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Binary pulse-amplitude modulation (2-PAM) with 8B10B line coding, as defined in 10.3.5, is supported. It is combined with Reed-Solomon (RS) FEC.

Moreover, the PM-PHY provides means to estimate the channel impulse response of multiple LED lights simultaneously. The PM-PHY supports MIMO transmissions via multiple OFEs.

5.7.3 HB-PHY introduction

The HB-PHY, specified in Clause 11, is intended for low latency and very high data rates, between 23 Mb/s and 2.192 Gb/s. It allows fast adaptation to the time-varying channel in mobile scenarios. The unique approach of the HB-PHY is to combine a high bandwidth with a high spectral efficiency.

For modulation of the LED, multiple bandwidths are used. DC-biased OFDM is used in combination with adaptive bitloading, applying quadrature amplitude modulation (QAM) with variable constellation sizes on each subcarrier or subcarrier group. Low-density parity-check codes (LDPC) with variable code rates and different block sizes are used for FEC.

Moreover, the HB-PHY provides means to estimate the channel impulse response of multiple LED lights simultaneously. The HB-PHY supports MIMO transmissions via multiple OFEs.

6. MAC functional specification

6.1 Overview

This clause specifies functions and procedures of the MAC sublayer. Procedures may be initiated by the MAC or as a consequence of a MLME-SAP primitive invocation. The MAC makes use of the PHY service and is responsible for the following tasks:

- Medium access and transmission in correspondence with the OWPAN's configuration
- Start and maintenance of an OWPAN
- Association with an OWPAN
- Disassociation from an OWPAN
- Fragmentation and reassembly of MSDUs
- Data transfer between two devices
- Adaptation to varying channel conditions

The MAC frame formats supporting the function of the MAC are specified in Clause 7. Capabilities are specified in 8.6.

6.2 General device functions

6.2.1 General

This subclause provides an overview of basic functionality that is common to all devices. It covers procedures for frame transmission, as initiated through the MD-DATA.request primitive until the start of PSDU processing through the PHY. Similarly, procedures for frame reception, starting after the successful reception of a PSDU through the PHY until the triggering of a MD-DATA.indication primitive are described. Transmission and reception of other frames that support control and management functions is described as well.

6.2.2 Addressing

Each device conforming to this standard shall have a MAC address that is a EUI-48 as specified by IEEE Std 802.¹⁵ The MAC address shall be sent in the canonical format defined in IEEE Std 802. The MAC address value FF-FF-FF-FF-FF-FF shall be used as the broadcast address.

Each device has an AID assigned as part of the association process. Table 1 specifies the use of certain AIDs.

Table 1—AID uses

AID(s)	Use
0x0000	Assigned to coordinator
0x0001 – 0xEFFF	Allocated to members through the coordinator
0xF000 – 0xFFFFD	Reserved
0xFFFFE	Allocated to members that have no unique AID
0xFFFFF	Reserved to address all devices (broadcast)

Each OWPAN is identified through its OWPAN ID. The OWPAN ID corresponds to the MAC address of the coordinator.

MPDUs in this standard have a receiver address and a transmitter address that identify the intended receiving device and the device transmitting the MPDU, respectively.

MSDUs that are transferred via an IEEE 802.15.13 network have a destination address and a source address that identify the intended destination and the source of the MSDU, respectively.

IEEE 802.15.13 devices select the receiver address of MPDUs based on the destination address of the MSDU. MSDUs that have a destination address that has the multicast bit set in the MD-DATA.request shall be treated as if the destination address was the broadcast address.

NOTE—MSDUs that have a multicast address as destination address therefore result in the receiver address of the MPDU being the broadcast address.

6.2.3 Transmitting an MPDU

A transmit process starts when the transmission of MSDUs from the MD-SAP, management elements, or control elements is required. The transmit process for MSDUs is illustrated in Figure 10.

¹⁵ EUI-48 assignments are administered by the IEEE Registration Authority at: <http://standards.ieee.org/regauth>.

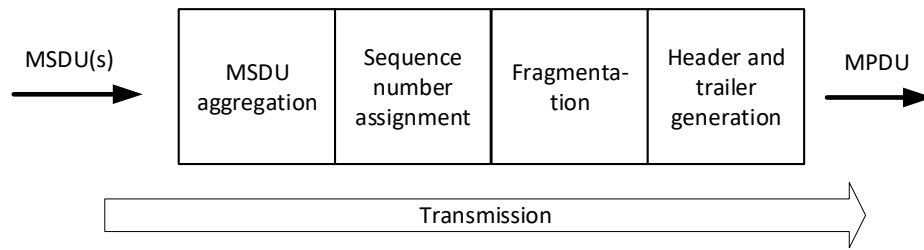


Figure 10—The MAC transmit process for MSDUs

A device prepares MPDUs for transmission in accordance with the requirements of the medium access procedure. This includes generation of the appropriate MAC header fields and limiting the MPDU size to the maximum size that can be transferred within the available transmission time. The MPDU size is furthermore limited to the maximum PSDU size of the PHY.

If multiple elements are to be transmitted in one MPDU, they may be grouped in a single container element such as defined in 7.2.4 or 7.2.5. The MPDU generation process involves optional aggregation of multiple MSDUs as described in 6.7.

MPDUs may optionally be fragmented as described in 6.6. Sequence numbers are assigned to MPDUs as described in 6.2.6. Outgoing MPDUs with acknowledgment request are buffered to allow later retransmission.

Finally, the medium access mechanism, as defined in 6.3 or 6.4, determines when to transmit the resulting MPDU via the PHY as a PPDU.

Devices shall stay silent for a certain time after each PPDU transmission. That time is called “interframe space.” The minimum interframe space (MIFS) depends on the PHY used for transmission. It shall be equal to the *aPhyMifsDuration* constant of each PHY.

6.2.4 Receiving an MPDU

After a PSDU was successfully received by the PHY, the corresponding MPDU enters the MAC through the PD-SAP.

Devices shall check the integrity of incoming frames based on the frame check sequence (FCS) in the *FCS* field of the frame. The *FCS* field is described in 7.1.9. If the calculated FCS over the received MPDU does not match the received *FCS* field, the device shall discard the MPDU.

The MAC shall discard frames that have an unsupported value in the *Frame Version* field of the *Frame Control* field as defined in 7.1.2.

A device may discard frames that have a receiver address other than its own or the broadcast address and frames that do not belong to its associated OWPAN. Devices shall handle MPDUs with the receiver and transmitter address set to the broadcast address to support the broadcast topology described in 5.3.3.

NOTE—Since all addresses that have the multicast bit set are treated as broadcast addresses, MPDUs with such addresses are handled by all devices.

Received MPDUs should be regarded as duplicates if they carry the same sequence and fragment number. This does not apply if the receiver received more than *aAckWindow* unique sequence numbers since the reception of the first of the potential duplicate MPDUs. If a duplicate is detected, the receiver shall discard the last received duplicate.

The MAC shall generate an acknowledgment for each successfully received MPDU for that an acknowledgment was requested as described in 6.8.

The reordering of MSDUs at a receiving device is implementation specific. However, MSDUs should be passed to the higher layers following the order indicated through the corresponding MPDU's sequence number.

6.2.5 Sequence numbering

Each device shall maintain an outgoing sequence number counter for transmissions towards every peer device it exchanges MPDUs with. The sequence number is a 12-bit wide unsigned integer, which wraps to zero after the highest possible value. All MPDUs except control frames shall be assigned a sequence number. The first sequence number shall be zero. The sequence number shall be incremented for each outgoing MPDU on a per receiver device basis. Rules for MPDUs carrying fragments are described in 6.6.

Each device shall maintain an incoming sequence number counter for receptions from each peer device with which it exchanges MPDUs.

6.2.6 Transmission of management information

Elements that are part of management routines and thus need to be transmitted in MPDUs with the type management shall be wrapped in a *Management Procedure Container* element. This allows to group different elements that belong to the same management exchange.

The *Invocation ID* field of the *Management Procedure Container* element shall contain a monotonically increasing index that identifies the invocation of the corresponding procedure. The index shall wrap to zero after reaching the highest representable value. *Management Procedure Container* elements that are a response to a preceding *Management Procedure Container* element shall include the same invocation ID as the *Management Procedure Container* element they respond to.

6.3 Scheduled medium access

6.3.1 Overview

In scheduled medium access mode, time is divided into superframes. Superframes are further divided into consecutive groups of one or more slots, called “time slices.”

Time slices may be unassigned, assigned to one or more devices as GTS, or designated as RTS. Assigning time slices is done by an implementation specific scheduler that is part of the coordinator. The scheduler assigns time slices for transmissions to the coordinator and to members.

During a GTS, devices shall perform deterministic medium access according to the rules described in 6.3.5. During an RTS, members shall perform random medium access according to the rules described in 6.3.4.

When maintaining an OWPAN with scheduled medium access, the coordinator shall send frames containing the *Sync* element as described in 6.3.4.

6.3.2 Superframe structure

A superframe consists of *NumSuperframeSlots* superframe slots in total. *NumSuperframeSlots* is a variable determined by the OWPAN coordinator and announced to members in the *Sync* element as described in 6.3.4.

The superframe slot with the number zero shall be the first slot in the superframe.

The maximum number of superframe slots within a superframe is 65535. Each superframe slot has a duration of *aSuperframeSlotDuration*. The number of superframe slots determines the total duration of each superframe.

The standard makes use of integer numbers of superframe slots to specify durations within the superframe, e.g., the duration of a GTS or RTS.

A coordinator defines the superframe structure for its OWPAN by assigning slots to devices for different purposes. See Figure 11. Slots in the superframe are in one of the following states:

- Unassigned: No device shall transmit in these slots.
- Assigned as GTS: The time slice was assigned to a device by the coordinator using a *GTS Descriptor* element as described in 6.3.7. The corresponding device shall transmit during the GTS as described in 6.3.6.
- Assigned as RTS: These slots were assigned as RTS by the coordinator using an *RTS Descriptor* element. During the RTS, devices may access the medium randomly by means of slotted ALOHA, as defined in 6.3.4.4.

Devices shall not transmit in superframe slots that were not assigned to it.

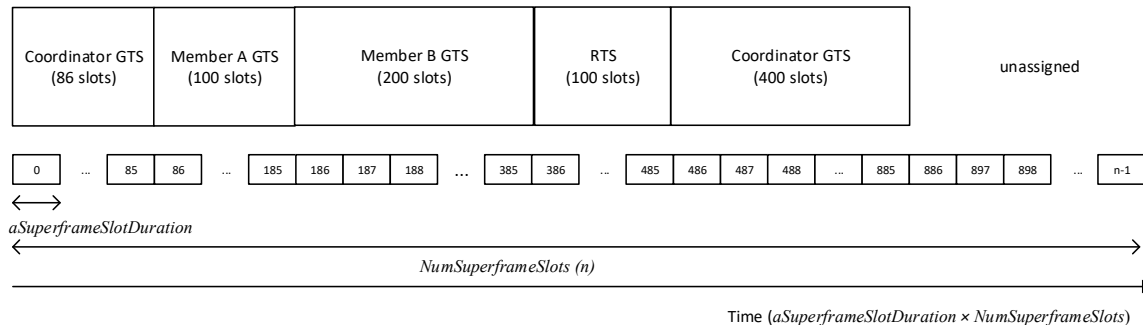


Figure 11—Example of a superframe structure

6.3.3 Synchronization

All members, whether they are associated with an OWPAN operating in scheduled medium access mode or attempting association with one shall be synchronized to the coordinator's clock before they start transmission. The frame that contains a *Sync* element enables synchronization of devices in the scheduled OWPAN through time of arrival synchronization.

Members shall assume that the start of the preamble of the PPDU that carries a *Sync* element corresponds to the start time of the slot with the number *Sync Slot* as specified in the *Sync* element. This is illustrated in Figure 12 and Figure 13. Therefore, the superframe starts *Sync Slot* slots before the start of the preamble. All superframe slots and hence timings within the superframe are relative to the calculated start of the superframe.

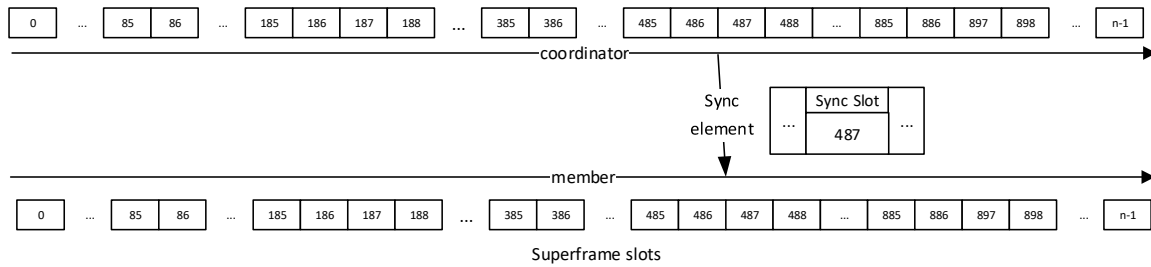


Figure 12—Relation of the coordinator's and the member's superframe slots when synchronizing via the Sync element



Figure 13—Timing relative to the PPDU reception

Devices shall maintain the accuracy of the local time to be at least as accurate as *aClockAccuracy*.

The coordinator shall maintain a superframe number and increment it by one for every started superframe. The superframe number value wraps to zero after reaching the maximum value of 65535.

The coordinator shall transmit a frame containing a *Sync* element via each OFE in a suitable time slice with an implementation specific rate but at least every *aMaxSyncInterval*. The frame's receiver address shall be the broadcast address. The *Sync* element shall contain the current superframe number, the number of slots contained in the superframe, and the number of the slot in which the frame containing the *Sync* element was transmitted in. The coordinator shall start transmitting the frame at the start of the superframe slot.

NOTE—As defined for each PHY, the real transmit time does not deviate by more than *aPhyOfeSyncAccuracy* from the nominal transmit time.

If the coordinator supports the *capExplicitMimoEstimation* capability, it shall embed an explicit MIMO pilot in the frame containing the *Sync* element, as detailed in 6.10.

Upon reception of a *Sync* element, members shall set their value of the superframe number and *NumSuperframeSlots* to the value contained in the *Total Superframe Slots* field in the received *Sync* element. Moreover, members shall synchronize their clocks to the coordinator's clock using the received *Sync* element. Devices shall reduce the offset between their local clock and the time indicated through the *Sync Slot* and the *Superframe Number* fields within the *Sync* element to less than *aPhyOfeSyncAccuracy*.

If no *Sync* element is received within a superframe, devices shall assume that the value specified for *NumSuperframeSlots* in the last received *Sync* element is still valid and increase their value of the superframe number at the time the next expected superframe starts.

If a *Sync* element is not received within *aMaxSyncInterval*, devices shall keep listening for the next *Sync* element in order to synchronize. Members are considered not synchronized after more than

$$2 \times aMaxSyncInterval$$

has passed without reception of a *Sync* element.

NOTE—The transmission of *Sync* elements does not depend on the superframe duration. Therefore, multiple elements or no *Sync* element may be transmitted in one superframe.

6.3.4 Medium access in GTS

6.3.4.1 General medium access in an RTS

RTS shall only be used for transmissions from devices to the coordinator in the following:

- a) Association procedure, described in 6.3.4.3
- b) GTS request procedure, described in 6.3.4.4

The slotted ALOHA scheme is used for contention-based medium access in RTS. Superframe slots in RTS are grouped in so-called random access opportunities (RANDOPs), which comprise of a certain number of superframe slots each. The number of superframe slots per RANDOP determines the slot size for the slotted ALOHA scheme and hence the effectiveness of collision prevention. The value of number of superframe slots is advertised in the *RANDOP Length* field of the *RTS Descriptor* element, defined in 7.2.10.

RTS are signaled through *RTS Descriptor* elements, transmitted from the coordinator to other devices. For each received *RTS Descriptor* element, the corresponding RTS shall start with the superframe slot given in the *RTS Descriptor* element and end after the number of slots given in the *RTS Length* field have passed.

The number and duration of RTS may be varied over time by the coordinator's scheduler in order to allow more or less random-access transmissions in a superframe.

NOTE—The coordinator should transmit a frame containing an *RTS Descriptor* element regularly in order to allow associations. In case a member does not have sufficient GTS allocated, it may use the random medium access to request more resources.

Transmissions of MPDUs in RTS shall happen sequentially, and there shall at most be one RTS transmission process at a time. Before transmitting a frame in an RTS, a device shall choose a random number *BS* of RANDOPs as backoff slots. The random numbers shall be uniformly distributed in

$$[0, CW]$$

where *CW* is a variable representing the current contention window.

CW shall be equal to *aInitialRtsCw* for the first attempt to transmit an MPDU in an RTS. Random number generators for determining *BS* should be designed with the goal to reduce correlation with random number generators in other devices. The device shall let *BS* RANDOPs pass before attempting transmission. The waiting process may extend over multiple superframes, until a total of *BS* RANDOPs have passed. The transmission shall then be performed at the starting boundary of the next RANDOP.

If the PPDU of the MPDU to be transmitted exceeds the RTS, the prospective transmitter shall wait for the next RANDOP that provides sufficient length in the RTS to contain the whole transmission and start transmission in that RANDOP.

6.3.4.2 Failed transmissions in RTS

Detection of a failed transmission in an RTS varies with the procedure and does not rely on the acknowledgment procedure defined in 6.8. How to detect a failed transmission is defined in 6.3.4.3 and 6.3.4.4, respectively.

If a device detects that an RTS transmission failed, the device shall increment the variable *RC*, representing the retry count, by one, and double the *CW*. *RC* shall initially be zero. *CW* shall be less or equal to *macMaxRtsCw*. The device may retry the failed transmission with *BS* being newly selected as described in

6.3.4.1. The RTS transmission shall ultimately considered as failed, once RC exceeds the value of maximum allowed retries as defined in the respective procedure.

Figure 14 shows the generic RTS transmission procedure.

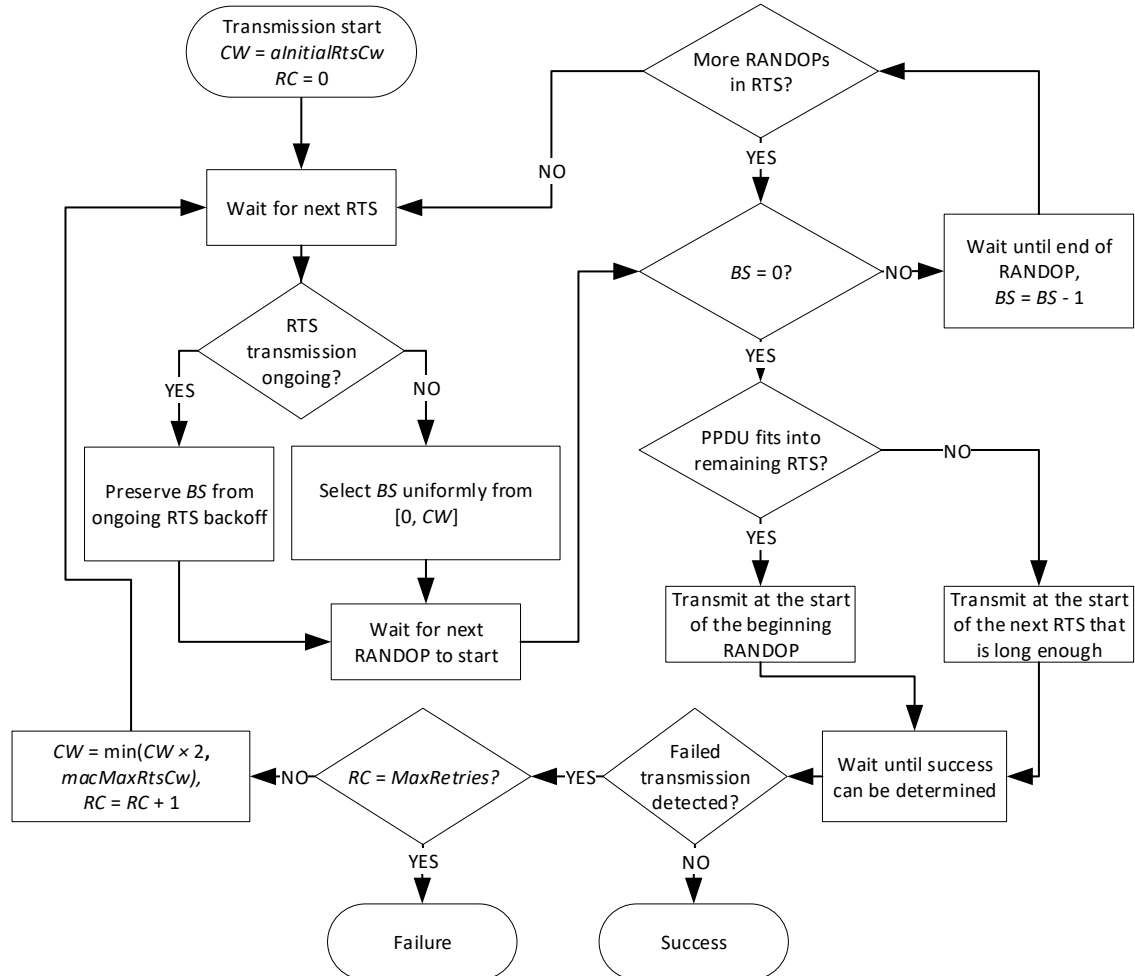


Figure 14—Generic RTS transmission procedure

6.3.4.3 Association procedure in RTS

Since a device has no GTS allocated prior to association, the *Association Request* element shall be transmitted in an RTS. Hence, the requesting device begins the RTS transmission procedure after preparing an MPDU containing the *Association Request* element as described in 6.5.6.

If no *Association Response* element was received as described in 6.5.6.1, the transmission of the *Association Request* element shall be considered to have failed. In this case, the device may reattempt association through sending the MPDU again as described in 6.3.4.2.

6.3.4.4 Queue report procedure in RTS

Members request additional resources during a GTS through transmitting a *Queue Report* element to the coordinator. However, when a member does not have any or only insufficient GTS time allocated to perform a GTS request, it may make use of an RTS to transmit a *Queue Report* element to the coordinator.

For example, this may be the case after the connectivity with the coordinator was interrupted and the coordinator stopped allocating GTSs for the member.

In that case, the member may transmit a *Queue Report* element in an RTS to signal the requirement for GTS time to the coordinator. After transmitting the *Queue Report* element, the member shall await updated GTS assignments from the coordinator. If the member does not receive sufficient GTS resources after *macQueueReportTimeout* superframes, it shall consider the queue report failed. In that case, it may transmit a new queue report according to the rules in 6.3.4.2.

6.3.5 Medium access in GTS

GTS allow medium access based on the time-division multiple access (TDMA) principle. In GTS, a group of adjacent superframe slots is reserved on a per-device basis in order to allow contention-free medium access. The first superframe slot and an integer number of superframe slots define the position and length of a GTS in the superframe as described in 7.2.10.

Devices shall keep a list of all upcoming GTS that were assigned to it.

Devices should prevent transmitted signals from interfering with transmissions in other GTS at any other device. This includes, for example, regarding for the total transmit delay introduced by the used PHY and the assumed propagation delay and range. Transmissions shall adhere to the rules for interframe spaces, as described in 6.2.3.

A device with a GTS may make use of all the allocated time duration within the GTS or only a subset thereof. The selection of an MPDU for transmission is determined locally by the device depending on the number of pending frames in its queue and the value of their user priority fields and potentially other criteria.

A member shall only transmit in GTS that were assigned to it by the coordinator of the OWPAN that the member is associated with.

A transmitting device shall finish its transmissions at least MIFS before the end of the GTS in order to enable all receiving devices to utilize their GTSs from the beginning.

The coordinator may perform transmissions to a member at any point in the superframe, except when the member has a time slice assigned (half-duplex).

If the *capFullDuplex* was negotiated during association, the coordinator may also transmit to the member when they have a time slice assigned.

6.3.6 GTS allocation and assignment

Only the OWPAN coordinator is entitled to assign GTSs. If the coordinator has multiple spatially distributed OFEs, it may allocate the same superframe slots in different GTS or RTS for multiple members that are served by spatially distant OFEs in order to facilitate spatial reuse of superframe slots within the OWPAN's coverage area. The coordinator should allocate GTS and RTS with the goal to keep interference between parallel transmissions low.

NOTE—If members are mobile, the coordinator should allocate GTS not too far in the future so that moving members do not cause unexpected interference.

Members aid the coordinator's scheduler in the GTS allocation process through providing information about their queue states over the wireless medium. For that purpose, members may transmit *Queue Report* elements to the coordinator.

GTS for relay devices shall not overlap with GTS or RTS allocated to other devices.

If the *capFullDuplex* capability was negotiated, superframe slots may be assigned to the coordinator and a member at the same time for transmission.

If *capExplicitMimoEstimation* was negotiated during association, members aid the coordinator at allocating GTSs in an interference-free manner through providing information about the signal strengths that they receive from the nearest OFEs. For this purpose, members shall transmit *Explicit MIMO Feedback* elements to the coordinator.

The coordinator may move GTSs within the superframe on a superframe-by-superframe basis. This allows the coordinator the flexibility to rearrange GTS assignments, optimize the utilization of resources, and prevent collisions of GTSs if visibility and signal strength varies among OFEs and members due to mobility.

GTS assignments shall be signaled from the coordinator to the corresponding members via *GTS Descriptor* elements or *GTS Descriptor List* elements. The containing frames shall be unicasts and only be processed by the members for that the GTS assignments are designated. Members shall infer that a GTS assignment belongs to themselves based on the receiver address of the frame.

A GTS assignment is only valid in the superframe that is indicated in the *Valid Superframe* field of the *GTS Descriptor* element.

The *Valid Superframe* field shall only contain superframe numbers that are *aMacSuperframeLookahead* in the future. Members shall ignore GTS assignments that are outside of that range.

A coordinator may signal GTS allocations to multiple members within the same MPDU by wrapping them in a *Multiple Device Element Container* element.

6.3.7 Guard time

In a TDMA system, guard times are required to keep transmissions in adjacent GTS from colliding when local clocks of devices are imperfectly synchronized, e.g., through drift caused by frequency inaccuracy of local oscillators in devices. A GTS is defined by the start time and the duration, as specified in the *GTS Descriptor* element, defined in 7.2.10. Guard time is the time between the end of one GTS and the start of the next GTS. Guard time is counted in superframe slots. For that purpose, the guard time shall be rounded up to the next integer number of superframe slots.

Figure 15 depicts an illustration of the guard time such that consecutive transmissions are separated by at least a MIFS if the owners of adjacent GTS have drift towards the other GTSs.

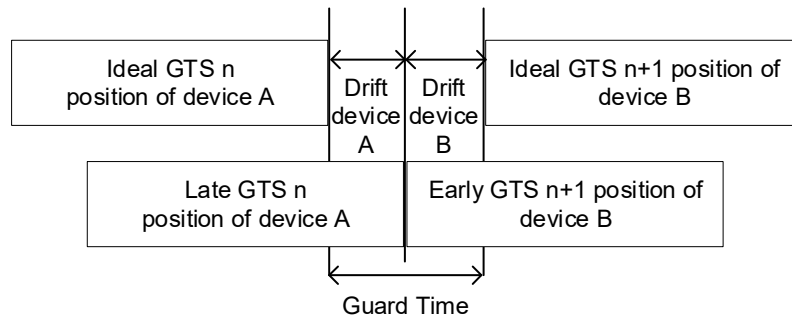


Figure 15—Application of the guard time between adjacent GTSs

The required guard time depends on the maximum drift $MaxDrift$ between the device's local time and the reference time. This drift is a function of the time elapsed since a synchronizing reference event, i.e., the reception of a *Sync* element, and the precision of local oscillators in OFEs and devices defining the local sampling clock. In an IEEE 802.15.13 OWPAN, the synchronizing event is the start of the preamble of a PPDU that contains a *Sync* element. The maximum drift $MaxDrift$ is calculated as shown in Equation (1):

$$MaxDrift = aClockAccuracy \times SyncInterval \quad (1)$$

Where $aClockAccuracy$ is a MAC constant and $SyncInterval$ is the interval between *Sync* element transmissions and hence the periodicity of the synchronizing event.

The coordinator shall allocate GTSs with the constraint that a guard time of at least

$$2 \times (MaxDrift + aPhyOfeSyncAccuracy) \quad (2)$$

lies between two subsequent GTS that are not orthogonal in space. See Equation (2).

6.4 Polled medium access

6.4.1 Overview

The polling mechanism enables low-complexity synchronization of transmission slots and enables the coordinator to dynamically adapt and assign slots for transmissions. The polled medium access consists of two periods, namely RAPP and DPP. The RAPP starts with the transmission of a *Random Access* element from the coordinator. During the RAPP, devices compete by sending *Random Access Response* elements to the coordinator.

In the DPP, based on the previous state (i.e., members already associated), and the *Random Access Response* elements received during RAPP, the coordinator polls one or multiple devices through transmission of a single PPDU. In the DPP, devices are allowed to transmit once they recognize the beginning of a frame that contains a *Poll* element. An example of a full polled medium access cycle is given in Figure 16. Here, device A is working in the full-duplex mode, while device B is working in the half-duplex mode.

The specific polling algorithm and order is outside the scope of this specification and is left as a system designer's choice.

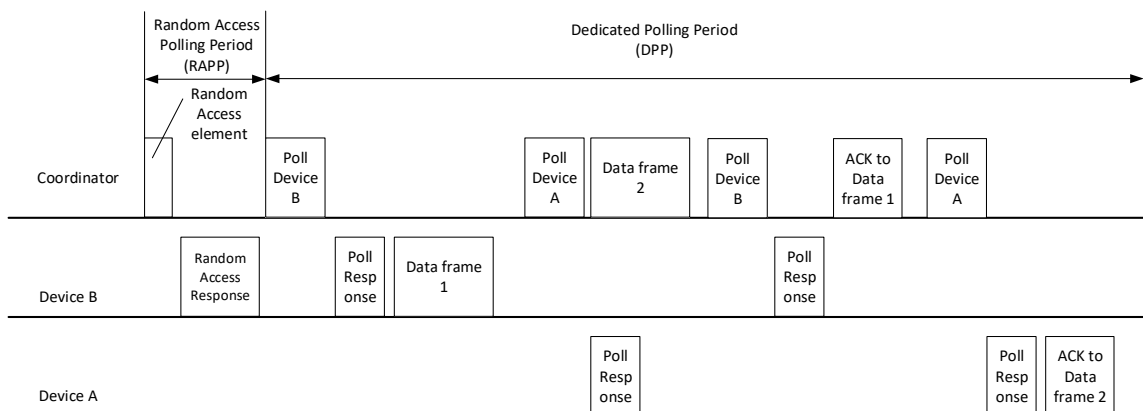


Figure 16—Example of one cycle of the polled medium access

6.4.2 Medium access duplex

The basis for all medium access shall be half-duplex. The coordinator needs to wait for a *Poll Response* element from the polled device before sending any other frames. The polled devices are allowed to send additional frames after the frame containing the *Poll Response* element within the period they request in the *Duration* field of the *Poll Response* element. The coordinator shall use the information of the duration field in the *Poll Response* element to derive the time to start transmission of any other frames following the transmission from the polled device. An example is given in Figure 17.

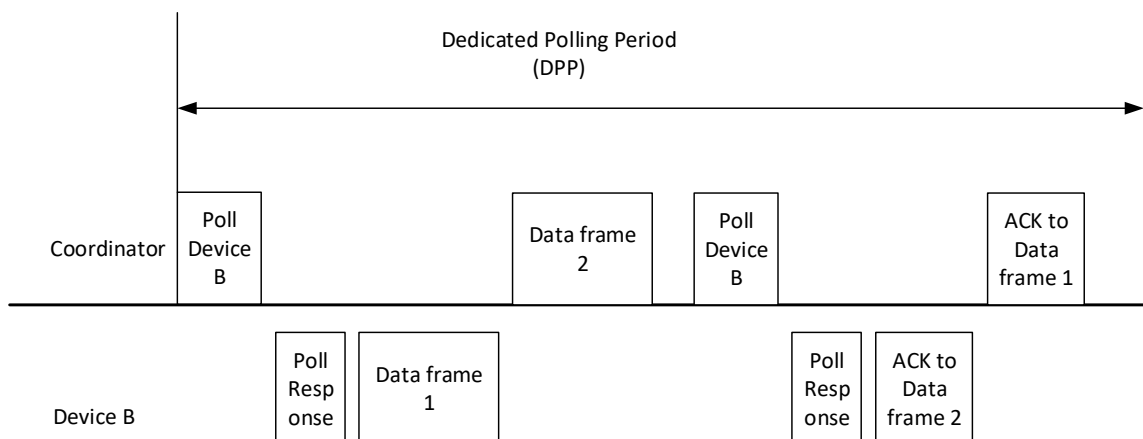


Figure 17—Example of half-duplex medium access

If the *capFullDuplex* is negotiated during the association process, devices may perform full duplex medium access. Thus, devices may transmit and receive at the same time. The coordinator may send any frames after the *Poll* element before the finish of transmission of *Poll Response* element and / or any other frames that are sent by devices. Devices may also send all intended frames before the finish of transmission of frames other than *Poll* element from the coordinator. An example is given in Figure 18.

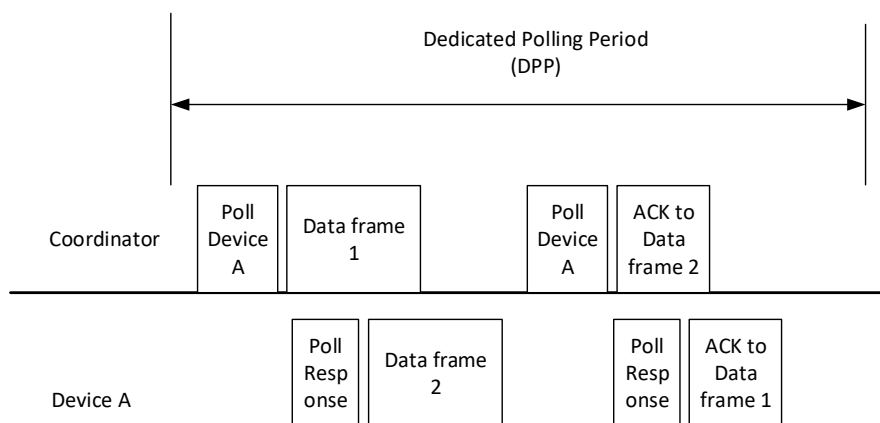


Figure 18—Example of full-duplex medium access

6.4.3 Random access polling period (RAPP)

At the beginning of a RAPP, the coordinator shall send a control frame carrying a *Random Access* element. All stations that have already been associated with the coordinator shall ignore any polling during the RAPP. After receiving the *Random Access* element, the device may send a frame carrying the *Random Access Response* element. Then, the coordinator may start polling the device in the next polling round after successfully receiving the *Random Access Response* element. Figure 19 shows an example of the process without any collision from devices.

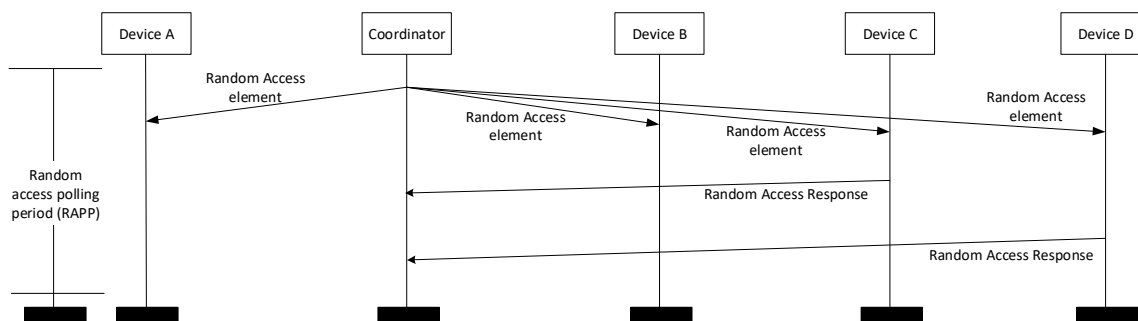


Figure 19—Random access polling period without collisions

However, if multiple devices send frames containing *Random Access Response* elements at the same time or with little offset of each other *Random Access Response*, there may be collisions among the devices, which may cause *Random Access Response* elements to be not decodable by the coordinator. Figure 20 shows an example of the process with collisions from devices.

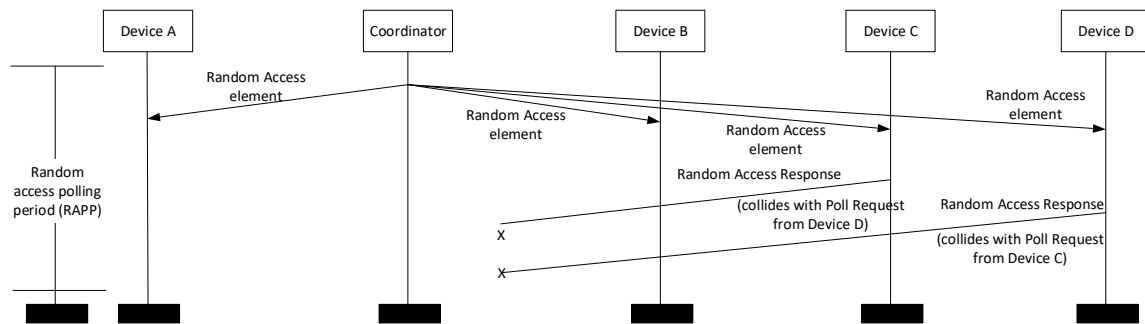


Figure 20—Random access polling period with collisions

If a device is not polled during the next DPP, the device may assume the *Random Access Response* element it sent was not received by the coordinator. Then, the random backoff is introduced. The device shall randomly select a number N between one and five. The device shall retry to establish a connection after N cycles of RAPPs. Upon a successful polling request (the coordinator has successfully received the device's request and has polled the station within the next transmission round), a device exchanges the necessary association information with the coordinator via association and authentication control frames.

6.4.4 Dedicated polling period (DPP)

The DPP starts when the coordinator sends the first *Poll* element. During the dedicated polling period, each device is required to respond to a *Poll* element received from a coordinator.

When a device is polled by the coordinator, it replies with a *Poll Response* element to the coordinator to announce its availability and append one data frame if any are queued. The device shall transmit only one MPDU. The coordinator shall stop polling a device provided it does not receive any response from the device for more than *macDeviceTimeout*. An example of the process is given in Figure 21.

The coordinator shall not start another polling request before the current polled device finishes its transmission. Hence, no collisions on the channel from devices to the coordinator are possible.

The *Cycle Interval* field in the *Random Access* element contains the length of a full cycle, which consists of a RAPP and DPP. Polled devices and the coordinator calculate the time left in the current cycle and compare with the transmission time required with the other device / coordinator. If there is not enough time to finish the transmission, devices shall only respond with a *Poll Response* without any additional package. The coordinator, on the other hand, shall not initiate another poll if there is not enough time to finish an intended transmission.

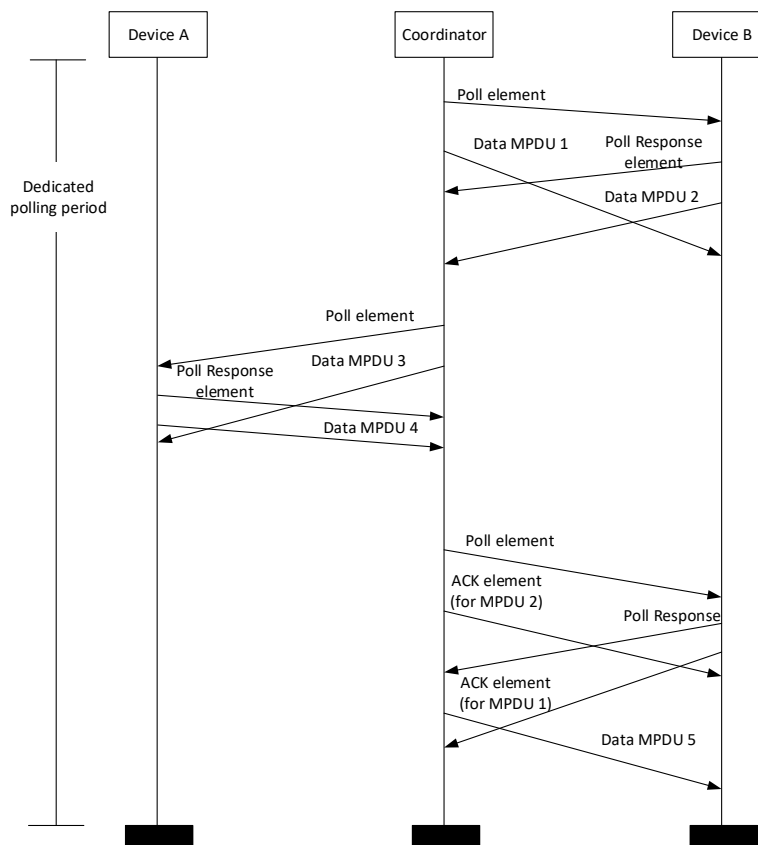


Figure 21—Example of dedicated polling period of full-duplex medium access

6.5 OWPAN management

6.5.1 Overview

This subclause describes the scanning for existing OWPANs, starting of new OWPANs as well as the association and disassociation of devices with / from existing OWPANs.

6.5.2 Scanning for OWPANs

A scan procedure is performed by a device to detect OWPANs that are operating in its vicinity. In this standard, only a single frequency range in the baseband is utilized for all transmissions. Hence, scanning for existing OWPANs only requires scanning of a single frequency channel. Devices shall support passive scanning for OWPANs during which the device listens for signals without performing any transmissions itself. If a device makes use of multiple OFEs, it shall listen on all frontends.

A scan may be initialized by the MAC itself or based on a request from the DME through the MLME-SCAN.request primitive, as shown in Figure 22.

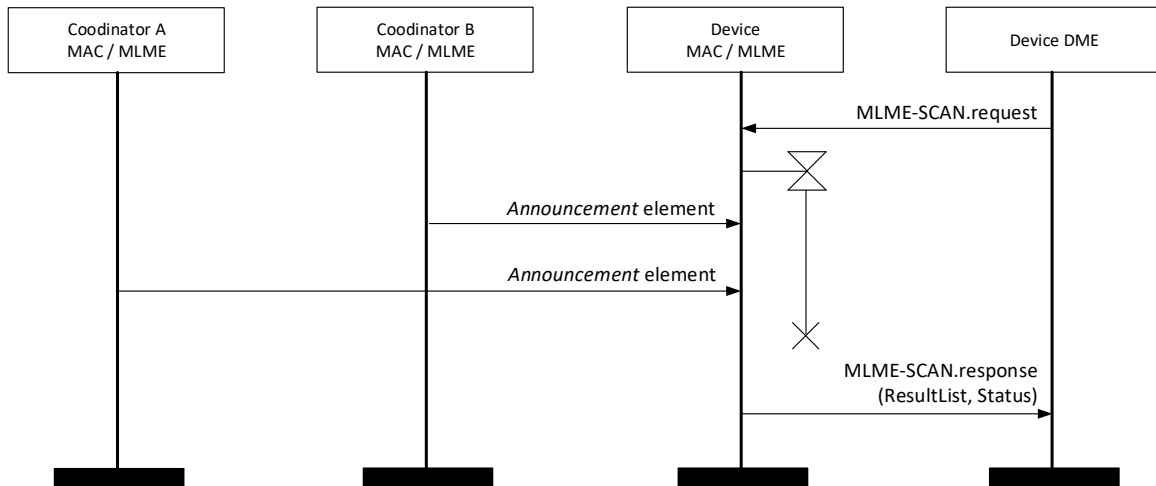


Figure 22—Scanning for OWPANs

The device performing a passive scan for OWPANs shall decode all received frames and store the contents of any contained *Announcement* elements until the end of the scan. Furthermore, it shall consider received signals whose power exceeds an implementation specific threshold while the signal is not decodable. Distinction of these signals is implementation specific.

If the scan was initiated through the MLME-SCAN.request primitive, the results of the scan shall be returned via the MLME-SCAN.confirm primitive as follows. For every successfully decoded *Announcement* element in the scan period, the device shall add the corresponding OWPAN ID to the scan result list. It shall furthermore add the received electrical signal-to-noise ratio (SNR) to the result list. The returned list shall not contain duplicate entries. If a device detects at least one non-decodable signal during the scan time, the device shall add an entry with OWPAN ID = ff-ff-ff-ff-ff with the received power level of the strongest received signal to the scan result list.

6.5.3 Starting an OWPAN

A coordinator-capable device shall start a new OWPAN and become its coordinator upon receipt of the MLME-START.request primitive through the MLME-SAP. If the device maintained an OWPAN before, it shall stop the OWPAN, according to 6.5.5, prior to starting a new OWPAN in order to reset all MAC and PHY state and disassociate potentially associated members.

The parameters for starting and maintaining the OWPAN shall be obtained from the device's PIB attribute database. Thus, the DME of the prospective coordinator should set the intended parameters prior to issuing the MLME-START.request.

The DME of the prospective coordinator selects a MAC address for the coordinator through setting *macMacAddress* to the given value. Upon reception of the MLME-START.request primitive, the MAC shall set *macOwpanId* to its MAC address and use it as the OWPAN ID.

If the PIB attributes contain an invalid configuration, the device shall issue a MLME-START.confirm primitive with the Status parameter set to FAIL_INVALID_CONFIGURATION.

The prospective coordinator shall perform a scan immediately before attempting to start a new OWPAN as described in 6.5.2. The prospective coordinator shall only proceed to start an OWPAN if the scan found no other networks or non-decodable optical signals. Otherwise, the prospective coordinator shall issue a MLME-START.confirm primitive with the Status parameter set to FAIL_OTHER_NETWORK_FOUND.

If the device is not able to start acting as a coordinator for another reason, it shall issue an MLME-START.confirm primitive with the Status parameter set to FAIL_OTHER.

When all preconditions are met, the prospective coordinator shall start to transmit *Announcement* elements in accordance with the implemented medium access mechanism. It shall furthermore begin to handle requests for association and other coordinator functionality. Finally the new coordinator shall issue an MLME-START.confirm primitive with the Status parameter set to SUCCESS.

The coordinator shall start transmitting an *Announcement* element in a suitable time slice at least every *aMaxAnnouncementInterval*. The receiver address of the frame containing the *Announcement* element shall be the broadcast address. The *Announcement* element shall contain the current values of the *OWPAN Name* and *OWPAN Name Length*, as configured in *macOwpanName* of the coordinator.

If the coordinator requires unassociated devices to set one or more PIB attributes to a specific value prior to association, it shall transmit one *Attribute Change Request* element for each of these PIB attributes in the same frame as the transmitted *Announcement* element. Devices attempting to join the OWPAN shall set their values of the respective PIB attributes to the values contained in the respective *Attribute Change Request* element prior to pursuing association. Members that are already associated with the OWPAN shall ignore any *Attribute Change Request* element that is contained in the frame that carries the *Announcement* element.

If multiple OFEs are used by the coordinator, frames containing *Announcement* elements shall be transmitted over all OFEs.

6.5.4 Maintaining an OWPAN

After successfully starting an OWPAN, the coordinator and associated members shall support the primitives of the MD-SAP and the corresponding MAC data path functionality as well as the primitives of the MLME-SAP that implemented and part of the supported capabilities.

A coordinator may change parameters of a running OWPAN such that members of the OWPAN need to modify their respective PIB attributes. To control PIB attributes of a member, the coordinator may transmit an *Attribute Change Request* element to that member. The *Attribute Change Request* element shall contain the corresponding PIB attribute ID and the new value to be set.

A member receiving the *Attribute Change Request* element shall modify the value of the indicated attribute to reflect the requested change. Subsequently, it shall respond to the coordinator with an *Attribute Change Response* element, indicating the result of the attempted attribute change.

6.5.5 Stopping an OWPAN

To stop a running OWPAN, the DME of a coordinator issues the MLME-STOP.request through the MLME-SAP. Upon reception of the primitive, the coordinator should disassociate all associated members. It shall furthermore stop transmitting *Announcement* elements as well as handling new association requests. Furthermore, it shall reset all state that was introduced while the OWPAN was active.

The MAC shall respond to the MLME-STOP.request with a MLME-STOP.confirm. It shall set the Status parameter to SUCCESS upon successful stopping of the OWPAN.

It shall set the Status parameter to FAIL_TIMEOUT if the OWPAN could not be stopped because some of the associated members were not successfully disassociated. It shall set the Status parameter to FAIL_OTHER if the OWPAN could not be stopped due to other reasons.