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information exchange between
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area networks — Specific
requirements —**

**Part 15-7:
Short-range optical wireless
communications**

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Exigences pour les réseaux locaux et métropolitains —*

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IEEE Std 802.15.7™-2018
(Revision of
IEEE Std 802.15.7-2011)

**IEEE Standard for
Local and metropolitan area networks—**

**Part 15.7: Short-Range
Optical Wireless Communications**

Sponsor

**LAN/MAN Standards Committee
of the
IEEE Computer Society**

Approved 5 December 2018

IEEE-SA Standards Board

Abstract: A physical layer (PHY) and medium access control (MAC) sublayer for short-range optical wireless communications (OWC) in optically transparent media using light wavelengths from 10 000 nm to 190 nm are defined. The standard is capable of delivering data rates sufficient to support audio and video multimedia services and also considers mobility of the optical link, compatibility with various light infrastructures, impairments due to noise and interference from sources like ambient light, and a MAC sublayer that accommodates the unique needs of visible links as well as the other targeted light wavelengths. It also accommodates optical communications for cameras where transmitting devices incorporate light-emitting sources and receivers are digital cameras with a lens and image sensor. The standard adheres to applicable eye safety regulations.

Keywords: IEEE 802.15.7™, laser diode, LD, LED, light-emitting diode, OCC, optical camera communications, OWC, short-range optical wireless communications, visible light, visible-light communication, VLC

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Introduction

This introduction is not part of IEEE Std 802.15.7-2018, IEEE Standard for Local and metropolitan area networks—Part 15.7: Short-Range Optical Wireless Communications.

This edition is a revision of IEEE Std 802.15.7-2011 and broadens the standard's scope to include more optical wireless communications (OWC) technologies. This revision adds new clauses for physical layer (PHY) types IV, V, and VI (see Clause 13, Clause 14, and Clause 15) and several related annexes (see Annex G through Annex N).

In OWC, data is transmitted by intensity modulating optical sources, such as light-emitting diodes (LEDs) and laser diodes (LDs), faster than the persistence of the human eye. OWC merges lighting and data communications in applications such as area lighting, signboards, streetlights, vehicles, traffic signals, status indicators, displays, LED panel, and digital signage. This standard describes the use of OWC for optical wireless personal area networks (OWPANs) and covers topics such as network topologies, addressing, collision avoidance, acknowledgment, performance quality indication, dimming support, visibility support, colored status indication, and color stabilization.

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IEEE Standard for Local and metropolitan area networks—

Part 15.7: Short-Range Optical Wireless Communications

1. Overview

1.1 Scope

This standard defines a physical layer (PHY) and medium access control (MAC) sublayer for short-range optical wireless communications (OWC) in optically transparent media using light wavelengths from 10 000 nm to 190 nm. The standard is capable of delivering data rates sufficient to support audio and video multimedia services and also considers mobility of the optical link, compatibility with various light infrastructures, impairments due to noise and interference from sources like ambient light, and a MAC sublayer that accommodates the unique needs of visible links as well as the other targeted light wavelengths. It also accommodates optical communications for cameras where transmitting devices incorporate light-emitting sources and receivers are digital cameras with a lens and image sensor. The standard adheres to applicable eye safety regulations.

1.2 Purpose

This standard provides a global standard for short-range OWC. The standard provides the following:

- Access to several hundred terahertz of unlicensed spectrum.
- Immunity to electromagnetic interference and noninterference with radio frequency systems.
- For visible light systems, additional security by allowing the user to see the communication channel.
- Communication augmenting and complementing existing services (e.g., illumination, display, indication, decoration).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used; therefore, each referenced document is cited in text, and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI/INCITS 373: Fiber Channel Framing and Signaling Interface (FC-FS).¹

IEEE Std 802.15.4™-2015, IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements—Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).^{2,3}

ITU-T I.432.1, Series I: Integrated Services Digital Network, ISDN user-network interfaces—Layer 1 RecommendationsB-ISDN user-network interface—Physical layer specification: General characteristics, <http://www.itu.int/rec/T-REC-I.432.1-199902-I/en>.⁴

3. Definitions, acronyms, and abbreviations

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.⁵

3.1 Definitions

blending: The disproportional merging of two different images as a single image.

color function: A function that provides information, such as device status and channel quality, to the human eye via color.

color stabilization: A control loop for the stabilization of the color emitted by color-shift keying (CSK) transmitters.

color visibility dimming (CVD) frame: A frame used for color, visibility, and dimming support.

compensation time: The idle time inserted in the idle pattern or in the data frame, where the light is turned ON or OFF with the appropriate ratio to meet dimming requirements.

dimming: Reducing the radiant power of a transmitting light.

idle pattern: A pattern whose duty cycle variation results in a change of brightness for dimming support.

image sensor: A sensor that captures an image and translates it into a light-coded output signal.

macro cell: An aggregate cell formed using all the cells available at the optical media.

¹ ANSI publications are available from the American National Standards Institute (<http://www.ansi.org>).

² IEEE publications are available from The Institute of Electrical and Electronics Engineers, Inc. (<http://standards.ieee.org>).

³ The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

⁴ ITU-T publications are available from the International Telecommunications Union (<http://www.itu.int/>).

⁵ *IEEE Standards Dictionary Online* is available at <http://dictionary.ieee.org>.

modulation-domain spectrum: The spectrum observed at the output of the receiver's photodetector.

optical clock rate: The frequency at which the data is clocked out to the optical source.

photodetector: A device that captures optical power and translates it into an output signal.

PHY switch: A switch at the transmission interface between the physical layer (PHY) and the optical service access point (SAP), used to send and receive data to and from a single or multiple optical sources and photodetectors in a selective manner.

point-and-shoot: The alignment of devices by the transmission of a color visibility dimming (CVD) frame to illuminate the target receiving device.

region of interest (ROI): An interesting subset of an image region.

switching level: A distinct amplitude level that defines ON and OFF of the light source for communications.

visibility pattern: An in-band idle pattern used in the payload of a color visibility dimming (CVD) frame.

watermarking: The process of hiding digital information in a digital image.

3.2 Acronyms and abbreviations

2D	two-dimensional
2-PSK	two-phase shift keying
AB	average brightness
ACK	acknowledgment
AES	advanced encryption standard
AM	amplitude modulation
A-QL	asynchronous quick link
AR	acknowledgment request
B-ACK	block acknowledgment
BE	backoff exponent
BP	beacon period
BSN	beacon-sequence number
CAP	contention access period
CC	convolutional coding
CCA	clear channel assessment
CCM*	extension of CBC-MAC [i.e., cipher block chaining message authentication code]
CFP	contention-free period
CIE	Commission internationale de l'Eclairage (International Commission on Illumination)
CM-FSK	camera m-ary frequency-shift keying
C-OOK	camera ON-OFF keying
CRC	cyclic redundancy check
CS	compensation symbols
CSK	color-shift keying
CSMA/CA	carrier sense multiple access with collision avoidance
CVD	color visibility dimming
D/A	digital-to-analog converter
DC	direct current
DCT	discrete cosine transform
DME	device management entity
DP	data packet

DS8-PSK	dimmbable spatial eight-phase shift keying
DSN	data-sequence number
ENC	encryption mode
FCS	frame check sequence
FDM	frequency division multiplexing
FEC	forward error correction
FER	frame-error ratio
FLP	fast locking pattern
FP	FEC packet or frame pending
FSK	frequency shift keying
GF	Galois field
GTS	guaranteed time slot
HA-QL	hidden asynchronous quick link
HCS	header check sequence
HP	hopping pattern
HS-PSK	hybrid spatial phase shift keying
Hybrid-MPSK	hybrid m-ary phase-frequency shift keying
ID	identifier
IDE	invisible data embedding
IE	information element
IFS	interframe space
LAN	local area network
LD	laser diode
LED	light-emitting diode
LIFS	long interframe space
LLC	logical link control
LPDU	LLC protocol data unit
LSB	least significant bit
M-FSK	m-ary frequency shift keying
M-PSK	m-ary phase shift keying
MAC	medium access control
MCPS	MAC common-part sublayer
MCS	modulation and coding scheme
MFR	MAC footer
MFTP	maximum flickering-time period
MHR	MAC header
MIC	message integrity code
MLME	MAC (sub)layer management entity
MIMO	multiple-input, multiple-output
MPM	mirror pulse modulation
MPDU	MAC protocol data unit
MPPM	mirror pulse position modulation
MPWM	mirror pulse width modulation
MSDU	MAC service data unit
NB	number of backoffs
OCC	optical camera communications
Offset-VPWM	offset variable pulse width modulation
OOK	ON-OFF keying
OWC	optical wireless communications
OWPAN	optical wireless personal area network
PAN	personal area network
PD	PHY data
PHR	PHY header
PHY	physical layer

PIB	PAN information base
PLCP	physical layer conversion protocol
PLME	physical layer management entity
PPDU	physical protocol data unit
PSDU	PHY service data unit
PWM	pulse width modulation
RGB	red, green, blue
RIFS	reduced interframe space
RLL	run-length limited
ROI	region of interest
RS	Reed-Solomon
RS-FSK	rolling shutter frequency shift keying
RX	receiver
SAP	service access point
S2-PSK	spatial two-phase shift keying
SD	symbol delimiter
SFD	start frame delimiter
SHR	synchronization header
SIFS	short interframe space
SPDU	SSCS protocol data unit
SS2DC	sequential scalable two-dimensional color
SS	spread spectrum
SSCS	service-specific convergence sublayer
SSID	service set identifier
TDP	topology-dependent pattern
TRX	transceiver
TX	transmitter
UFSOOK	undersampled frequency shift ON-OFF keying
VPPM	variable pulse position modulation
VTASC	variable transparent amplitude-shape-color
WQI	wavelength quality indicator
ZCD	zero-correlation duration

4. General description

4.1 Introduction

In optical wireless communications (OWC), data is transmitted by intensity modulating optical sources, such as light-emitting diodes (LEDs) and laser diodes (LDs), faster than the persistence of the human eye. OWC merges lighting and data communications in applications such as area lighting, signboards, streetlights, vehicles, traffic signals, status indicators, displays, LED panel, and digital signage. This standard describes the use of OWC for optical wireless personal area networks (OWPANs) and covers topics such as network topologies, addressing, collision avoidance, acknowledgment, performance quality indication, dimming support, visibility support, colored status indication, and color stabilization.

Some of the characteristics found in this standard are as follows:

- a) Star, peer-to-peer, or broadcast operation
- b) 16-bit short or 64-bit extended addresses
- c) Scheduled or slotted random access with collision avoidance transmission
- d) Fully acknowledged protocol for transfer reliability
- e) Wavelength quality indication
- f) Dimming support
- g) Visibility support
- h) Color function support
- i) Color stabilization support

4.2 Network topologies

As shown in Table 1, three classes of devices are considered for OWC: infrastructure, mobile, and vehicle.

Table 1—Device classification

	Infrastructure	Mobile	Vehicle
Fixed coordinator	Yes	No	No
Power supply	Ample	Limited	Moderate
Form factor	Unconstrained	Constrained	Unconstrained
Light source	Intense	Weak	Intense
Physical mobility	No	Yes	Yes
Range	Short/long	Short	Long
Data rates	High/low	High	Low

This standard for OWPAN maps the intended applications to three topologies: peer-to-peer, star, and broadcast. See Figure 1.

In the star topology, the communication is established between devices and a single central controller, called the coordinator. In the peer-to-peer topology, one of the two devices in an association takes on the role of the coordinator.

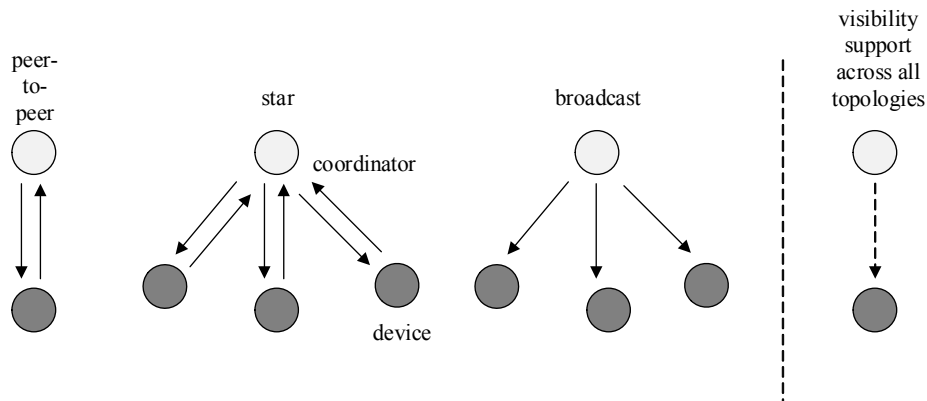


Figure 1—MAC topologies

Each device or coordinator has a unique 64-bit address. When a device associates with a coordinator node it is allowed to be allocated a short 16-bit address. Either address is allowed to be used for communication within the OWPAN managed by the coordinator. The coordinator may often be mains powered, while the devices will often be battery powered.

Each independent OWPAN has an identifier, as defined in 5.2.1.3 and 5.2.1.5. This OWPAN identifier allows communication between devices within a network using short addresses. The mechanism by which OWPAN identifiers are chosen is outside the scope of this standard.

The network formation is performed by the higher layer, which is not part of this standard. Apart from the peer-to-peer and star topologies, devices compliant to this standard are also allowed to operate in a broadcast-only topology without being part of a network, i.e., without being associated to any device or having any devices associated to them. A brief overview on how each supported topology may be formed is provided in 4.2.1, 4.2.2, and 4.2.3.

In case illumination function is required, visibility support is also provided in the absence of communication or in the idle or receive modes of operation. The purpose of this mode is to maintain illumination and mitigate flicker.

4.2.1 Peer-to-peer topology

The basic structure of a peer-to-peer topology is illustrated in Figure 1. In a peer-to-peer topology, each device is capable of communicating with any other device within its coverage area. In a peer-to-peer topology, one of the peers acts as a coordinator. One peer defaults as the coordinator, for instance, by virtue of being the first device to communicate on the channel.

4.2.2 Star topology

The basic structure of a star topology is illustrated in Figure 1. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a 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. The higher layer is allowed to use the procedures described in 5.1.2 and 5.1.4 to form a star network.

4.2.3 Broadcast topology

The basic structure of a broadcast topology is illustrated in Figure 1. The device in a broadcast mode can transmit a signal to other devices without forming a network. The communication is unidirectional and the destination address is not required.

4.3 Modulation-domain spectrum

Figure 2 illustrates the concept of the modulation-domain spectrum in which $+V$ is the bias supply voltage and F_m is the modulation spectral line. In Figure 2, the optical light source is “always on”; hence, the output of the photodetector, which could be a discrete diode or part of the camera receiver, can be observed for performing clear channel assessment (CCA). Prior to time $t = T_1$, the spectrum is all at DC. After $t = T_1$, the spectrum is split between DC and the modulating signal.

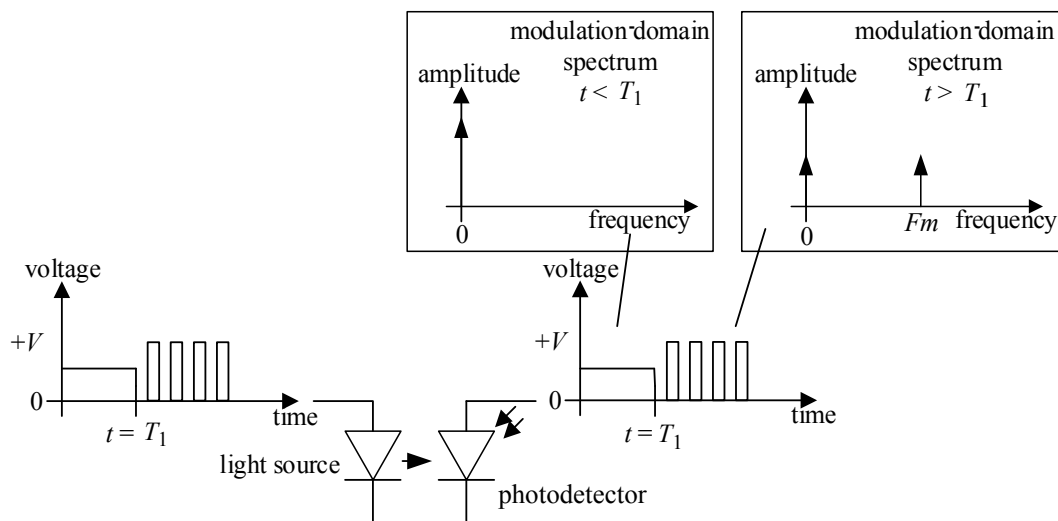


Figure 2—Illustration of modulation-domain spectrum

4.4 Architecture

This standard defines an architecture in terms of a number of layers and sublayers in order to simplify the standard. Each layer is responsible for one part of the standard and offers services to the higher layers. The interface between the layers serves to define the logical links that are described in this standard.

An OWPAN device comprises a PHY, which contains the light transceiver along with its low-level control mechanism, and a MAC sublayer that provides access to the physical channel for all types of transfers. Figure 3 shows these layers in a graphical representation, and the layers are described in more detail in 4.4.1 and 4.4.2.

The upper layers, shown in Figure 3, consist of 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 upper layers is outside the scope of this standard. A logical link control (LLC) layer can access the MAC sublayer through the service-specific convergence sublayer (SSCS), defined in Annex B.

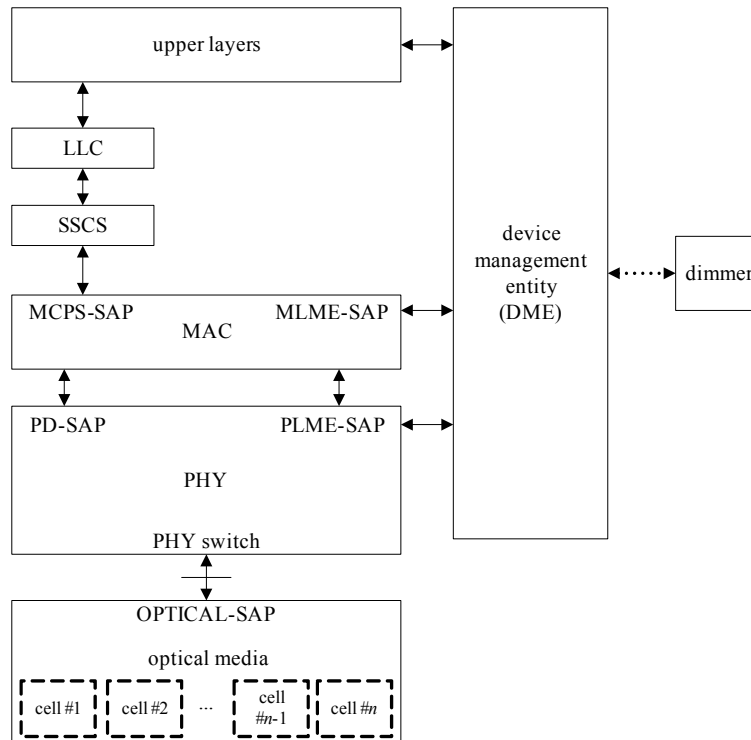


Figure 3—OWPAN device architecture

A device management entity (DME) is also supported in the architecture. The DME can talk to the physical layer management entity (PLME) and MAC (sub)layer management entity (MLME) to interface the MAC and PHY with a dimmer. The DME can access certain dimmer-related attributes from the MLME and PLME in order to provide dimming information to the MAC and PHY. The DME can also control the PHY switch using the PLME for selection of the optical sources and photodetectors. The details of the DME are outside the scope of this standard. The PHY switch interfaces to the optical service access point (SAP) and connects to the optical media, which may consist of a single or multiple optical sources and photodetectors. Multiple optical sources and photodetectors are supported in this standard for PHY III and for OWC cell mobility. The PLME controls the PHY switch in order to select a cell. The line going to the optical SAP from the PHY switch is a vector. The number of lines comprising the optical SAP has the dimension of $n \times m$, where n is the number of cells and m is the number of distinct data streams from the PHY. The value of m is three for PHY III.

4.4.1 PHY types

The PHY supports multiple PHY types.

- PHY I: This PHY type is intended for outdoor usage with low data rate applications. This mode uses ON-OFF keying (OOK) and variable pulse position modulation (VPPM) with data rates in the tens to hundreds of kbps, as defined in Table 76.
- PHY II: This PHY type is intended for indoor usage with moderate data rate applications. This mode uses OOK and VPPM with data rates in the tens of Mbps, as defined in Table 77.
- PHY III: This PHY type is intended for applications using color-shift keying (CSK) that have multiple light sources and detectors. This mode uses CSK with data rates in the tens of Mbps, as defined in Table 78.

- d) PHY IV: This PHY is intended for use with discrete light sources with data rates up to 22 kbps using various modulations, as defined in Table 79.
- e) PHY V: This PHY is intended for use with diffused surface light sources with data rates up to 5.71 kbps using various modulations, as defined in Table 79.
- f) PHY VI: This PHY is intended for use with video displays with data rates in kbps using various modulations, as defined in Table 79.

4.4.1.1 PHY frame structure

The MAC protocol data unit (MPDU) at the output of the MAC sublayer passes through the PHY and becomes the PHY service data unit (PSDU) at the output of the PHY after being processed via the various PHY blocks such as channel coding and line coding. The PSDU is prefixed with a synchronization header (SHR), containing the Preamble field; and a PHY header (PHR), which, among other things, contains the length of the PSDU in octets. The preamble sequence enables the receiver to achieve synchronization. The SHR, PHR, and PSDU together form the PHY frame or physical protocol data unit (PPDU). The format of the PHY frame is shown in Figure 124.

Use of over-the-air PHY frame configuration is forbidden for PHY IV, PHY V, and PHY VI. It is mandatory that PHY frame configuration be done via the PHY PAN information base (PHY PIB). This is due to the fact that unlike traditional wireless local area networks (LANs) and personal area networks (PANs), the data rates associated with optical camera communications (OCC) are such that the configuration overhead cannot be tolerated. In other words, there is no “base default” transmission mode. In addition, it is anticipated that configuration will be with application layer “APPs” that are specifically loaded to support a particular OCC PHY mode. The PHY PIB is not transmitted; rather, it is written by the DME and is read by the PHY.

4.4.1.2 Interoperability and coexistence between PHY types

The PHY types coexist but do not interoperate. PHY I and PHY II occupy different spectral regions in the modulation-domain spectrum, which enables frequency division multiplexing (FDM) as a coexistence mechanism, as shown in Figure 4. PHY I and PHY III also occupy different spectral regions in the modulation-domain spectrum, with different data rates and different optical rate support, providing coexistence. However, the optical clock frequencies used for PHY II and PHY III overlap, causing significant overlap in the frequency domain spectrum. In addition, not all devices support multiple optical frequency bands needed for PHY III. Hence, all PHY III devices use a PHY II device for device discovery to support coexistence with PHY II. PHY IV, PHY V, and PHY VI are spectrally located below PHY I and use highly directive receivers (e.g., cameras) to coexist via spatial division multiplexing.

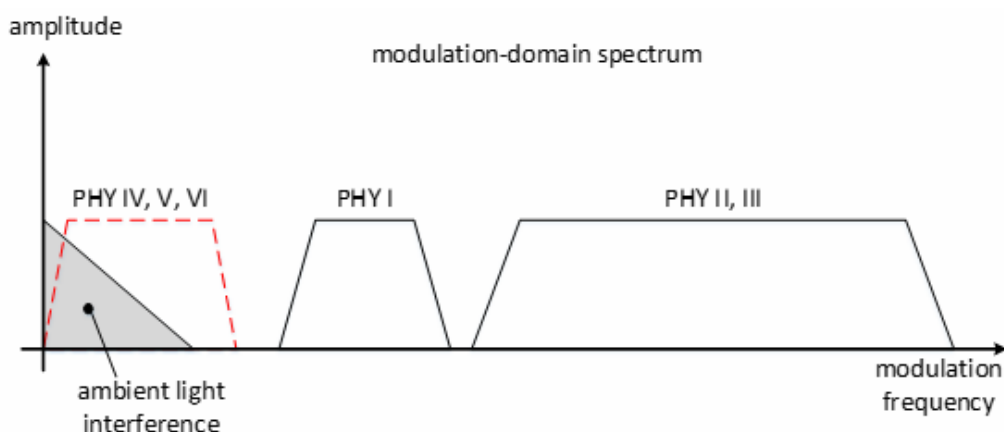


Figure 4—FDM separation of the PHY types in the modulation domain

4.4.2 MAC sublayer

The MAC sublayer provides two services accessed through two SAPs. MAC data is accessed through the MAC common part sublayer SAP (MCPS-SAP), while MAC management is accessed through the MAC (sub)layer management entity SAP (MLME-SAP). The MAC data service enables the transmission and reception of MPDUs across the PHY data service.

The features of the MAC sublayer are beacon management, channel access, guaranteed time slot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. The MAC sublayer provides hooks for implementing application-appropriate security mechanisms. The MAC sublayer also provides color function, visibility, color stabilization, and dimming support.

Clause 5 describes the specifications for the MAC sublayer.

Use of over-the-air MAC frame configuration is forbidden for PHY IV, PHY V, and PHY VI. It is mandatory that MAC frame configuration be done via the MAC PAN information based (MAC PIB). This is due to the fact that unlike traditional wireless LAN/PAN, the data rates associated with OCC are such that the configuration overhead cannot be tolerated. In other words, there is no “base default” transmission mode. In addition, it is anticipated that configuration will be with application layer “APPs” that are specifically loaded to support a particular OCC PHY mode. The MAC PIB is not transmitted; rather, it is written by the DME and is read by the MAC sublayer.

4.4.3 Dimming and flicker-mitigation support

This subclause outlines the methods for dimming and flicker-mitigation support. For PHY I, PHY II, and PHY III, an idle pattern can be transmitted during MAC idle or RX states for infrastructure light sources for dimming support. This is important since it is desired to maintain visibility and flicker-free operation during idle or RX periods at the infrastructure. The idle pattern has the same duty cycle that is used during the active data communication so that there is no flicker seen during idle periods. This idle pattern and its dependence on the dimmer setting is shown in Figure 5. The transition of active operation and idle/RX operation can be in large time-scale (block active/idle/RX) or in a small time-scale (within a communication session). In the large time-scale block session activity, when the OWC activity is ON, there can be a small time-scaled transition of active mode and idle/RX mode. Dimmer setting for high brightness, in Figure 5a, illustrates a higher duty cycle for higher brightness. Dimmer setting for low brightness, in Figure 5b, illustrates a lower duty cycle for lower brightness. The data and the idle pattern should have the same duty cycle in order to minimize flicker.

4.4.3.1 Flicker mitigation

Flicker is the temporal modulation of lighting at frequencies higher than the critical fusion frequency that can affect human efficiency in diverse ways. This standard strives for the mitigation of flicker that may be caused due to modulation of the light sources for communication. The maximum flickering time period (MFTP) is defined as the maximum time period over which the light intensity can be changing, but for which the resulting flicker is not perceivable by the human eye (Berman et al. [B1]).⁶ To avoid flicker, any brightness changes over periods longer than MFTP must be avoided.

The flicker in OWC is classified into two categories according to its generation mechanism: intraframe flicker and interframe flicker. Intraframe flicker is defined as the perceivable brightness fluctuation within a frame. Interframe flicker is defined as the perceivable brightness fluctuation between adjacent frame transmissions.

⁶ Number in brackets correspond to the numbers in the bibliography in Annex A.

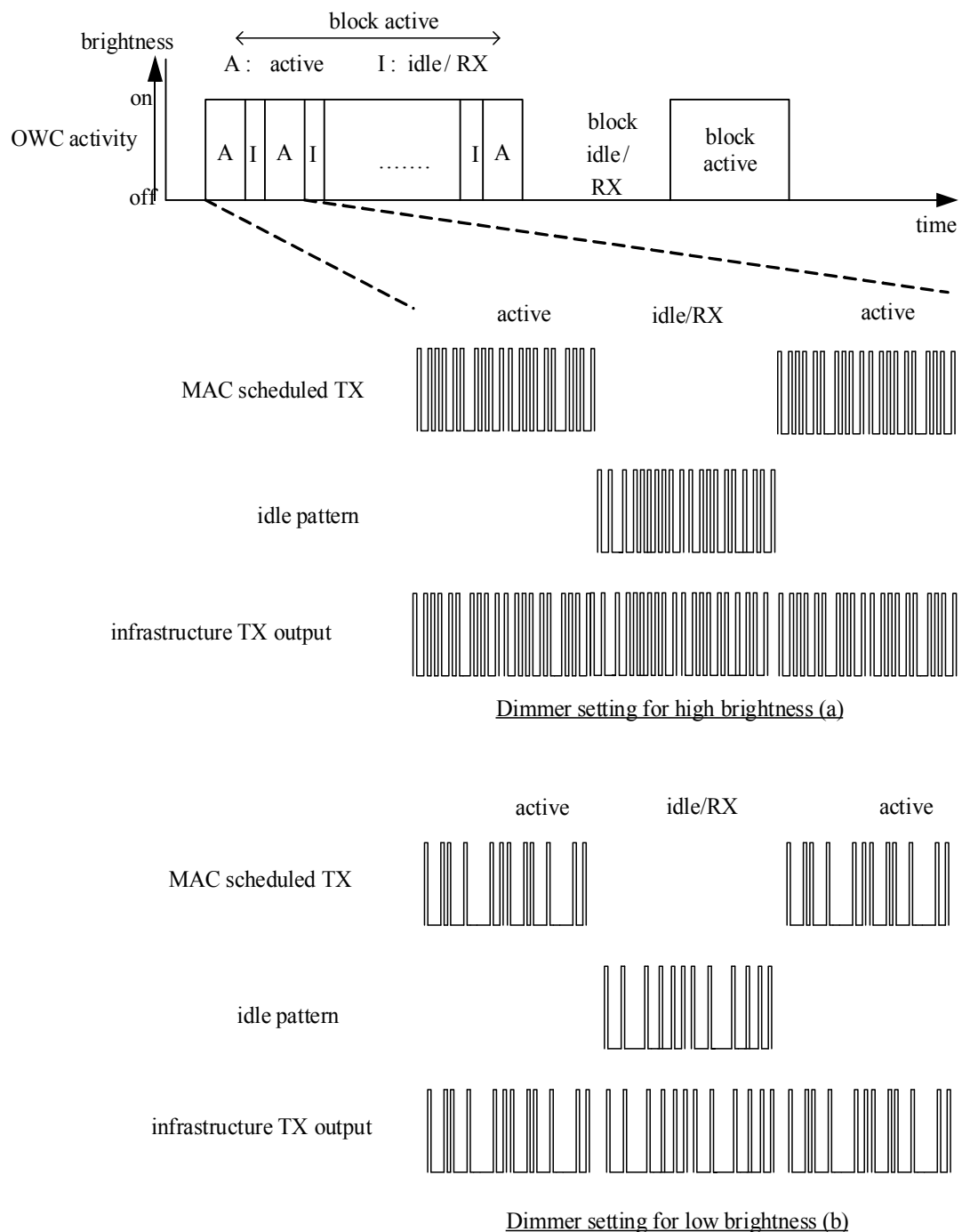


Figure 5—Adapting dimmer pattern and data duty cycle depending on dimmer setting

4.4.3.1.1 Intraframe flicker mitigation

Intraframe flicker mitigation is accomplished by either the use of run-length limited (RLL) coding, modulation scheme, or both.

4.4.3.1.2 Interframe flicker mitigation

The scheme used for interframe flicker mitigation is the transmission of an idle pattern between data frames whose average brightness is equal to that of the data frames, as defined in 8.5.1.1. See Figure 6.

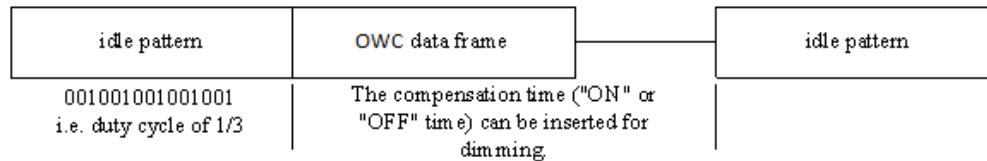


Figure 6—Example of idle pattern and compensation time dimming

4.4.3.2 Light dimming

Light dimming is defined as controlling the perceived brightness of the light source according to the user's requirement and is a cross layer function between the PHY and MAC. The details on the light dimming function of MAC sublayer are discussed in 5.3.10.

Three major dimming methods can be applied to control the light brightness: (1) adding compensation symbols, (2) controlling pulse width, and (3) controlling the amplitude of the signal. The selection of a proper dimming method follows the selection of the modulation. Details on dimming during data transmission of individual modulation is described in 8.5.

4.4.3.2.1 Dimming by adding compensation symbols

Since OOK modulation and mirror pulse modulation (MPM) are always sent with a constant brightness within a symbol (e.g., a symmetric Manchester symbol or MPM symbol), compensation time may need to be inserted into the data frame to adjust the average intensity of the perceived source. The frame structure for the dimming method of inserting compensation symbols is as shown in Figure 7.

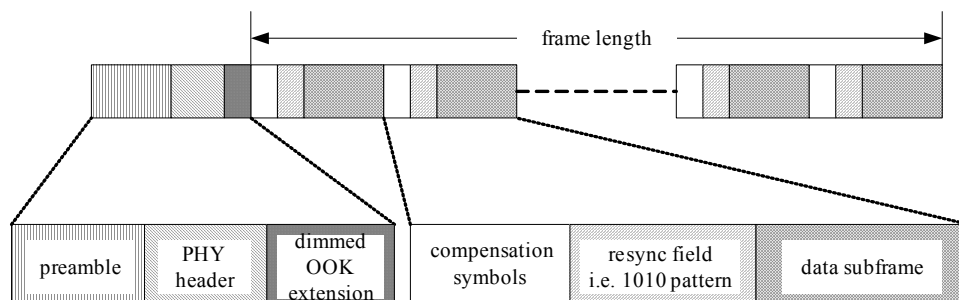


Figure 7—OOK dimming structure

This process breaks the frame into subframes, and each subframe can be preceded by a resync field that aids in readjusting the data clock after the compensation time. The data frame is fragmented into subframes of the appropriate length after the frame check sequence (FCS) has been calculated and the forward error

correction (FEC) has been applied. An example of OOK dimming to increase average brightness (AB) by $N\%$ by adding compensation symbols is as shown in Figure 8.

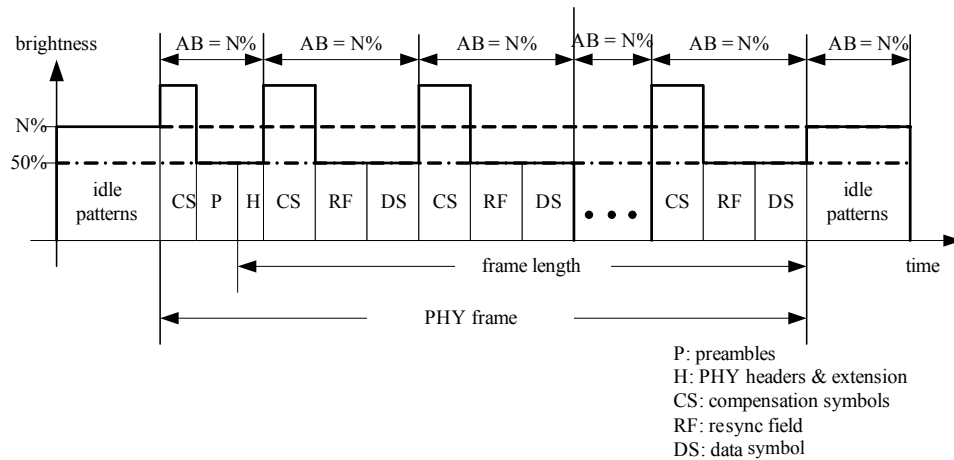


Figure 8—Example of OOK dimming to increase brightness

An example of MPM dimming to increase average brightness (AB) by adding compensation symbols (CS) is as shown in Figure 9.

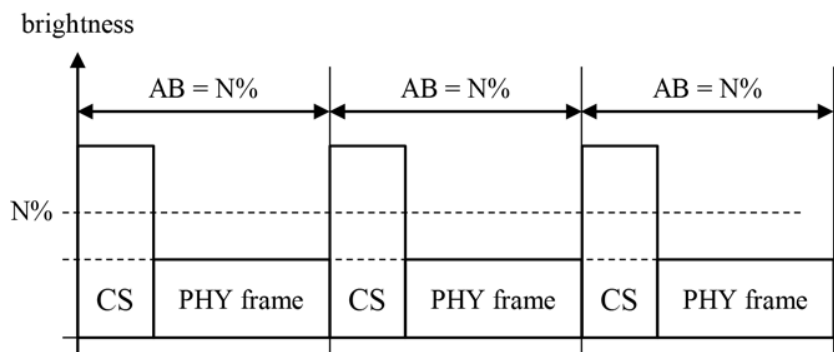


Figure 9—Example of MPM dimming by adding compensation symbols

4.4.3.2.2 Dimming by controlling pulse width

Dimming by controlling the pulse width is illustrated in Figure 10.

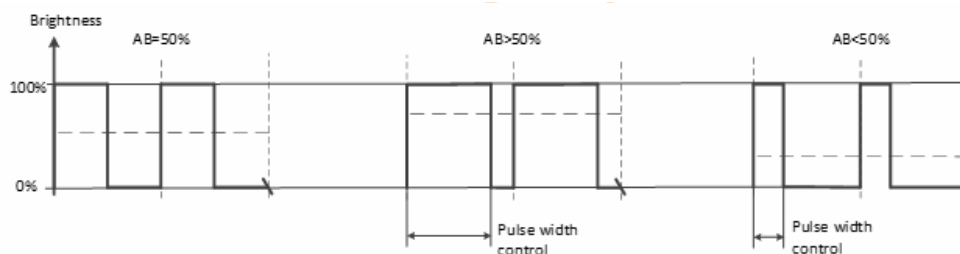


Figure 10—Pulse width dimming

VPPM is adapted for pulse-width-based light dimming and offers protection from intraframe flicker. The pulse amplitude in VPPM is always constant, and the dimming control is performed by the pulse width, not the amplitude. An example of VPPM dimming to increase brightness by controlling pulse width modulation (PWM) is as shown in Figure 11.

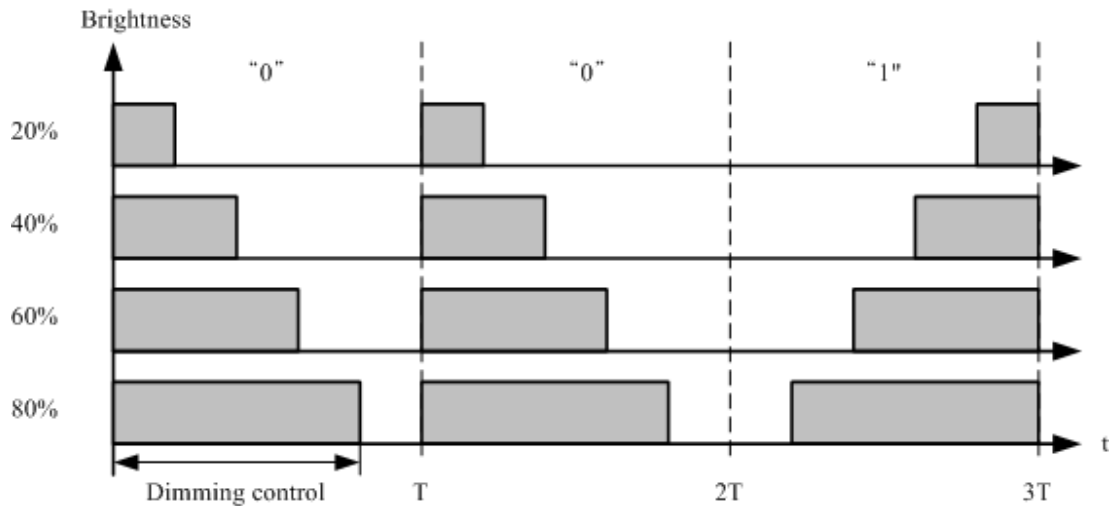


Figure 11—Example of VPPM dimming

Frequency shift keying (FSK) at a frequency that does not cause flicker during a symbol time uses a constant pulse amplitude during the transmission of symbols and performs dimming by controlling the duty cycle of the signal, as shown in Figure 12.

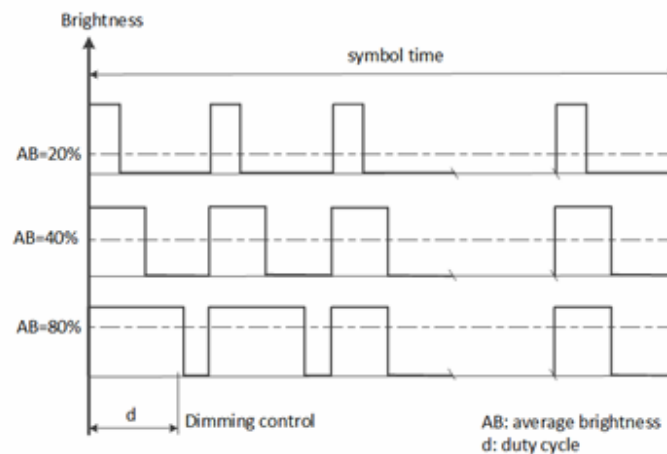


Figure 12—Example of FSK dimming by controlling pulse width

4.4.3.2.3 Dimming by controlling pulse amplitude

The dimming is performed by controlling the amplitude of ones or zeros or both, as shown in Figure 13.

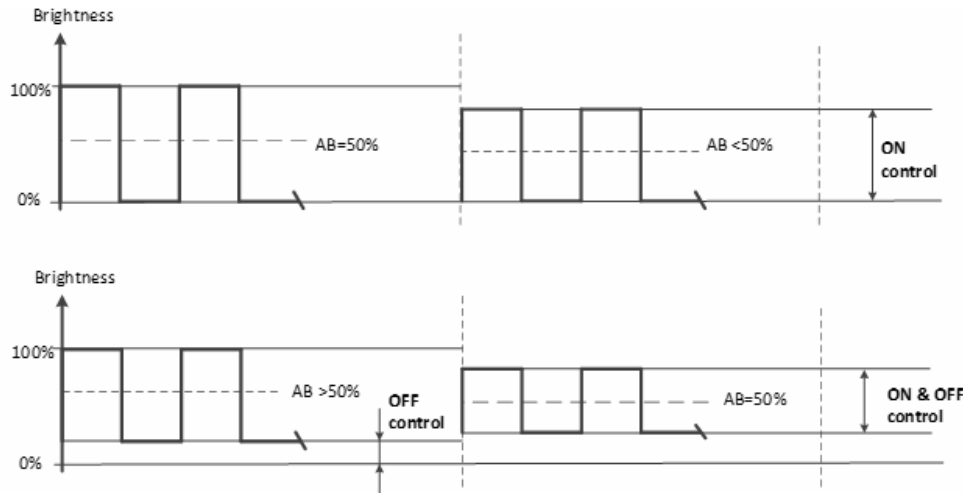


Figure 13—Mechanism for amplitude dimming

4.4.3.2.4 Dimming by controlling brightness in out-of-band frequency

The apparent average pulse brightness can be controlled by representing the pulse as a high-frequency, controllable duty cycle waveform, as shown in Figure 14. The frequency is selected so that only the amplitude envelop survives the signal processing with the duty cycle controlling the pulse average.

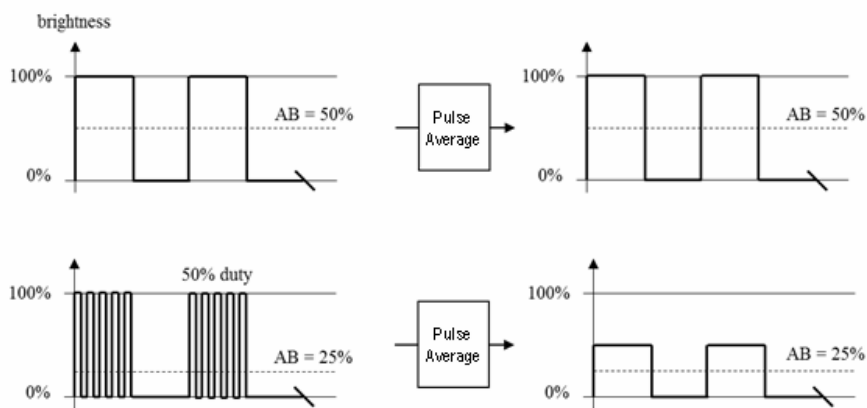


Figure 14—Out-of-band dimming

4.5 Functional overview

This subclause provides a brief overview of the general functions of a OWPAN MAC sublayer and includes information on the superframe structure, data transfer model, data frame structure, acknowledgments, and security.

4.5.1 Superframe structure

This standard allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator and varies with the network topologies. The superframe is bounded by beacons sent by the coordinator, as shown in Figure 15a, and is divided into slots of equal size. Optionally, the superframe can have an active and an inactive portion, as shown in Figure 15b. The beacon frame is transmitted in the first slot of each superframe. If a coordinator does not wish to use a superframe structure, it will turn off the beacon transmissions. Each superframe can have two or three portions: beacon period (BP), contention access period (CAP) and optional contention-free period (CFP), as shown in Figure 15. The beacons are sent in the BP and are used to synchronize the attached devices, to identify the OWPAN, and to describe the structure of the superframes. Any device wishing to communicate during the CAP between two beacons competes with other devices via slotted random access. The standard defines four random access methods: unslotted random access, slotted random access, unslotted carrier sense multiple access with collision avoidance (CSMA/CA), and slotted CSMA/CA. These methods are described in 5.1.2.2.

All transactions are completed by the time of the next BP.

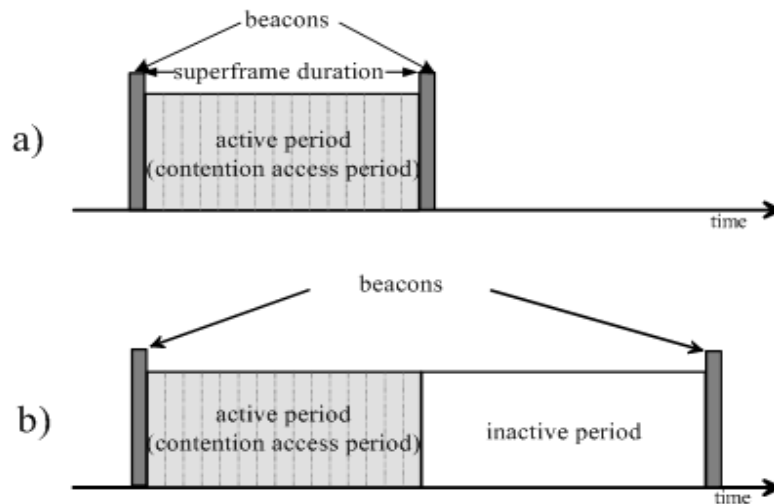


Figure 15—Superframe structure without GTSs

For low-latency applications or applications requiring specific data bandwidth, the coordinator is allowed to dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the CFP, which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP. More information on the GTS structure is provided in Figure 17. The coordinator is allowed to allocate a number of these GTSs, and a GTS may occupy more than one slot period. More information on the GTS slots and the maximum number available can be found in 5.2.2.1. All contention-based transactions are completed before the CFP begins. Also each device transmitting in a GTS determines that its transaction is complete before the time of the next GTS or the end of the CFP. More information on the superframe structure is described in 5.1.1.1.

4.5.2 Data transfer model

Three types of data transfer transactions exist:

- The data transfer to a coordinator in which a device transmits the data.
- The data transfer from a coordinator in which the device receives the data.
- The data transfer between two peer devices.

In a star or broadcast topology, only the first two transaction types are used, while in a peer-to-peer topology, all three transaction types are allowed.

The mechanisms for each transfer type depend on whether the network supports the transmission of beacons. A beacon-enabled OWPAN is used in networks that require either synchronization or support for low-latency devices. If the network does not need synchronization or support for low-latency devices, it can elect not to use the beacon for normal transfers. However, the beacon is still required for network discovery. The structure of the frames used for data transfer is specified in 5.2.

4.5.2.1 Data transfer to a coordinator

When a device wishes to transfer data to a coordinator in a beacon-enabled OWPAN, it first listens for the beacon. When the beacon is found, the device synchronizes to the superframe structure. At the appropriate time, the device transmits its data frame, using slotted random access, to the coordinator. The coordinator has the option to acknowledge the successful reception of the data by transmitting an acknowledgment frame.

When a device wishes to transfer data in a nonbeacon-enabled OWPAN, it simply transmits its data frame, using unslotted random access, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame. The transaction is now complete.

4.5.2.2 Data transfer from a coordinator

When the coordinator wishes to transfer data to a device in a beacon-enabled OWPAN, it indicates in the beacon that the data message is pending. The device periodically listens to the beacon and, if a message is pending, transmits a MAC command requesting the data, using slotted random access. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. The pending data frame is then sent using slotted random access, or, if possible, immediately after the acknowledgment as described in 5.1.7.3. The device is allowed to acknowledge the successful reception of the data by transmitting an optional acknowledgment frame. The transaction is now complete. Upon successful completion of the data transaction, the message is removed from the list of pending messages in the beacon.

When a coordinator wishes to transfer data to a device in a nonbeacon-enabled OWPAN, it stores the data and waits for the appropriate device to make contact and request the data. A device is allowed to make contact by transmitting a MAC command requesting the data, using unslotted random access, to its coordinator. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. If a data frame is pending, the coordinator transmits the data frame, using unslotted random access to the device. If a data frame is not pending, the coordinator indicates this fact either in the acknowledgment frame following the data request or in a data frame with a zero-length payload as described in 5.1.7.3. If requested, the device acknowledges the successful reception of the data frame by transmitting an acknowledgment frame.

4.5.2.3 Peer-to-peer data transfers

In a peer-to-peer OWPAN, every device is allowed to communicate with every other device in its coverage area. In order to do this effectively, the devices wishing to communicate will need to either receive constantly or synchronize with each other. In the former case, the device can simply transmit its data using unslotted random access. In the latter case, other measures need to be taken in order to achieve synchronization. Such measures are beyond the scope of this standard.

4.5.3 Clock-rate selection

This standard supports multiple optical clock rates in order to accommodate a wide variety of optical sources and receivers. The standard also supports the use of asymmetric clock rates between two devices since the transmitter and receiver in a device are independent and may support different clock-rate ranges. As an example, the infrastructure transmitter may be unable to switch rapidly but may be able to transmit with high power and require lower error correction, while the mobile device transmitter may be able to switch rapidly but may require higher error correction support due to its lower transmit power. The optical clock rate for communication is established using the MAC and can be communicated to the receiver prior to data transfer. The clock-rate selection and negotiation procedure is described in 6.5.

4.5.4 Frame structure

The frame structures have been designed to keep the complexity to a minimum while providing for error protection for transmission on a noisy channel. Each successive protocol layer adds to the structure with layer-specific headers and footers.

- a) A beacon frame, used by a coordinator to transmit beacons.
- b) A data frame, used for all transfers of data.
- c) An acknowledgment frame, used for confirming successful frame reception.
- d) A MAC command frame, used for handling all MAC peer entity control transfer.
- e) A color visibility dimming (CVD) frame, used to maintain the proper light intensity between data frames, to support dimming, and to visually provide information such as communication status and channel quality to the user.

4.5.5 Improving probability of successful delivery

This standard employs various mechanisms to improve the probability of successful data transmission. These mechanisms are random access, frame acknowledgment, and data verification.

4.5.5.1 Random access mechanism

This standard uses four types of channel access mechanism, depending on the network configuration. Nonbeacon-enabled OWPANs use an unslotted random channel access mechanism, with or without CSMA/CA, as described in 5.1.2.2. Each time a device wishes to transmit data frames or MAC commands, it waits for a random backoff period. Following the random backoff, the device transmits its frame of data. If the optional carrier sense mechanism is active and the channel is found to be busy following the random backoff, the device waits for another random period before trying to access the channel again. Acknowledgment frames are sent without using a random access mechanism (i.e., scheduled).

Beacon-enabled OWPANs use a slotted random channel access mechanism, with or without CSMA/CA, where the backoff slots are aligned with the start of the beacon transmission. Each time a device wishes to transmit data frames during the CAP, it locates the boundary of the next backoff slot and then waits for a random number of backoff slots. If the optional collision avoidance mechanism is active and the channel is busy, following this random backoff, the device waits for another random number of backoff slots before trying to access the channel again. If the channel is idle or the optional carrier sense mechanism is not active, the device begins transmitting on the next available backoff slot boundary. Acknowledgment and beacon frames are sent without using a random access mechanism (i.e., scheduled).

If the device transmits and receives on the same spectrum and the device is within coverage of any other device, CSMA/CA can be optionally implemented.

4.5.5.2 Frame acknowledgment

A successful reception and validation of a data or MAC command frame can be optionally confirmed with an acknowledgment, as described in 5.1.7.4. If the receiving device is unable to handle the received data frame for any reason, the message is not acknowledged.

If the originator does not receive an acknowledgment after some period, it assumes that the transmission was unsuccessful. When the acknowledgment is not required, the originator assumes the transmission was successful.

4.5.5.3 Data verification

A cyclic redundancy check (CRC) is included in the MAC frame and the PHY header, as defined in Annex C, to verify the validity of the received data.

4.6 Security

From a security perspective, this standard is slightly different from other wireless networks, due to the fact that the signal will not travel across media such as walls, unlike other radio-frequency-based wireless networks. However, security algorithms are still provided in the standard for features such as data confidentiality, authentication, and replay protection.

Devices can be low-cost and have limited capabilities in terms of computing power, available storage, and power drain; it cannot always be assumed they have a trusted computing base nor a high-quality random number generator aboard. Communications cannot rely on the online availability of a fixed infrastructure and might involve short-term relationships between devices that may never have previously communicated. These constraints limit the choice of cryptographic algorithms and protocols and influence the design of the security architecture because the establishment and maintenance of trust relationships between devices need to be addressed with care. In addition, battery lifetime and cost constraints can put severe limits on the security overhead these networks can tolerate, something that is of far less concern with higher bandwidth networks. Most of these security architectural elements can be implemented at higher layers and may, therefore, be considered to be outside the scope of this standard.

The cryptographic mechanism in this standard is based on symmetric-key cryptography and uses keys that are provided by higher layer processes. The establishment and maintenance of these keys is outside the scope of this standard. The mechanism assumes a secure implementation of cryptographic operations and secure and authentic storage of keying material.

The cryptographic mechanism provides particular combinations of the following security services:

- a) *Data confidentiality*: Assurance that transmitted information is only disclosed to parties for whom it is intended.
- b) *Data authenticity*: Assurance of the source of transmitted information (and, thereby, that information was not modified in transit).
- c) *Replay protection*: Assurance that duplicate information is detected.

The actual frame protection provided can be adapted on a frame-by-frame basis and allows for varying levels of data authenticity (to minimize security overhead in transmitted frames where required) and for optional data confidentiality. When nontrivial protection is required, replay protection is always provided.

Cryptographic frame protection is allowed to use a key shared between two peer devices (link key) or a key shared among a group of devices (group key), thus allowing some flexibility and application-specific tradeoff between key storage and key maintenance costs versus the cryptographic protection provided. If a

group key is used for peer-to-peer communication, protection is provided only against outsider devices and not against potential malicious devices in the key-sharing group.

The cryptographic security mechanisms used for protected MAC frames are described in Clause 7.

4.7 Concept of primitives

This subclause provides a brief overview of the concept of service primitives. The services of a layer are the capabilities it offers to the next higher layer or sublayer by building its functions on the services of the next lower layer. This concept is illustrated in Figure 16, showing the service hierarchy and the relationship of the two correspondent users and their associated layer (or sublayer) peer protocol entities.

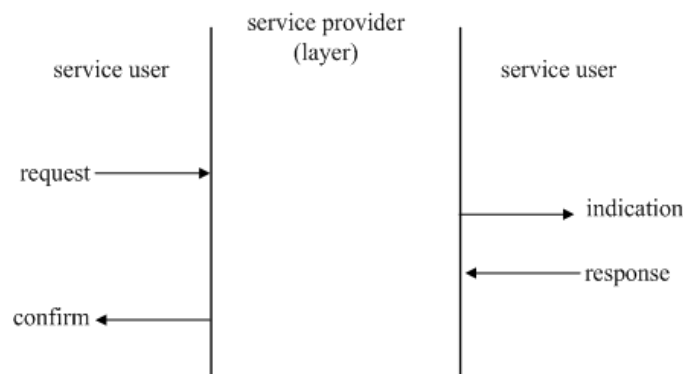


Figure 16—Service primitives

The services are specified by describing the information flow between the user and the layer. This information flow is modeled by discrete, instantaneous events, which characterize the provision of a service. Each event consists of passing a service primitive from one layer to the other through a layer SAP associated with an user. Service primitives convey the required information by providing a particular service. These service primitives are an abstraction because they specify only the provided service rather than the means by which it is provided. This definition is independent of any interface implementation.

Services are specified by describing the service primitives and parameters that characterize it. A service may have one or more related primitives that constitute the activity that is related to that particular service. Each service primitive may have zero or more parameters that convey the information required to provide the service.

A primitive can be one of the following four generic types:

- a) *Request*: The request primitive is used to request a service to be initiated.
- b) *Confirm*: The confirm primitive is used to convey the results of one or more associated previous service requests.
- c) *Indication*: The indication primitive is used to indicate the next higher layer of an internal event.
- d) *Response*: The response primitive is used to complete a procedure previously invoked by an indication primitive.

4.8 Some media access mechanisms by PHY types

The following transmitter schemes use unslotted ALOHA:

- Undersampled frequency shift ON-OFF keying (UFSOOK)
- Twinkle variable pulse position modulation (Twinkle VPPM)
- Offset variable pulse width modulation (Offset-VPWM)
- Mirror pulse modulation (MPM)
- Variable transparent amplitude-shape-color (VTASC)
- Sequential scalable two-dimensional (2D) color (SS2DC)
- Invisible data embedding (IDE)

In other words, when the transmitter has a packet to send, it just sends it. There is no beacon, and the transmitter does not do a listen-before-talk channel activity check. The superframe structure as shown in Figure 17 (in 5.1.1.1) consists of only the CAP.

4.9 Decoding

This standard defines PHY and MAC sublayer protocols; how to decode them is not in the normative scope of the standard.

5. MAC protocol specifications

This clause specifies the MAC sublayer of this standard. The MAC sublayer handles all access to the physical layer and is responsible for the following tasks:

- a) Generating network beacons if the device is a coordinator
- b) Synchronizing to network beacons
- c) Supporting OWPAN association and disassociation
- d) Supporting color function
- e) Supporting visibility
- f) Supporting dimming
- g) Flicker-mitigation scheme
- h) Supporting visual indication of device status and channel quality
- i) Supporting device security
- j) Providing a reliable link between two peer MAC entities
- k) Supporting mobility

Peer-to-peer, star, and broadcasting, as shown in Figure 1, are provided with a single MAC frame structure.

Constants and attributes that are specified and maintained by the MAC sublayer are written in the text of this clause in italics. Constants have a general prefix of “a”, e.g., *aBaseSlotDuration*, and are listed in Table 61 (see 6.4.1). Attributes have a general prefix of “mac”, e.g., *macAckWaitDuration*, and are listed either in Table 62 (see 6.4.2) or in Table 69 (see 7.5.1).

5.1 MAC functional description

This subclause provides a detailed description of the MAC functionality. Subclause 5.1.1 describes the following two mechanisms for channel access: contention based and contention free. Contention-based access allows devices to access the channel in a distributed fashion using an unslotted random access backoff algorithm. Contention-free access is controlled entirely by the coordinator through the use of GTSS.

The mechanisms used for starting and maintaining a OWPAN are respectively described in 5.1.2 and 5.1.3. Channel scanning is used by a device to assess the current state of a channel (or channels), locate all beacons within its operating space, or locate a particular beacon with which it has lost synchronization. Before starting a new OWPAN, the results of a channel scan can be used to select an appropriate logical channel, as well as a OWPAN identifier that is not being used by any other OWPAN in the area. Because it is still possible for the operating space of two OWPANs with the same OWPAN identifier to overlap, a procedure exists to detect and resolve this situation. Operation as a coordinator commences following a channel scan and suitable OWPAN identifier selection. Also described in the subclause is a method to allow coordinator beaconing to discover other such devices during normal operations, i.e., when not scanning.

The mechanisms to allow devices to join or leave a OWPAN are defined in 5.1.4. The association procedure describes the conditions under which a device may join a OWPAN and the conditions necessary for a coordinator to permit devices to join. Also described is the disassociation procedure, which can be initiated by the associated device or its coordinator.

The mechanisms to allow devices to acquire and maintain synchronization with a coordinator are described in 5.1.5. Synchronization on a beacon-enabled OWPAN is described after first explaining how a coordinator generates beacon frames. Following this explanation, synchronization on a nonbeacon-enabled OWPAN is described. Also described is a procedure to reestablish communication between a device and its coordinator, as it is possible that a device may lose synchronization in the case of either a beacon-enabled or a nonbeacon-enabled OWPAN.

This standard has been designed so that application data transfers can be controlled by the devices on a OWPAN rather than by the coordinator. The procedures the coordinator uses to handle multiple transactions while preserving this requirement are described in 5.1.6.

The mechanisms for transmitting, receiving, and acknowledging frames, including frames sent using indirect transmission, are described in 5.1.7. In addition, methods for retransmitting frames are also described.

The mechanisms for allocating and deallocating a GTS are described in 5.1.8. The deallocation process may result in the fragmentation of the GTS space, i.e., an unused slot or slots. The subclause describes a mechanism to resolve fragmentation.

The MAC sublayer uses the mechanisms described in Clause 7 for all incoming and outgoing frames.

Throughout this subclause, the receipt of a frame is defined as the successful receipt of the frame by the PHY and the successful verification of the FCS by the MAC sublayer, as described in 5.2.1.9.

The mechanisms to allow devices to recover quickly in case of temporary interference using a fast link recovery process are defined in 5.1.9. The fast link recovery process also enables devices to save power by letting the infrastructure initiate the link recovery.

The mechanisms to allow devices to use multiple channels in case of limited time resources or interference are defined in 5.1.10. Multiple channel resource assignment uses information about multiple channel support and band hopping in order to support more users or improve performance.

The mechanisms to support mobility of the device under an infrastructure that supports multiple optical elements over a wide coverage area are defined in 5.1.11. The concept of a cell is introduced and the support for mobility across multiple cells supported by the infrastructure is presented.

The mechanisms to visually indicate to the user the various states using various colors are defined in 5.1.12. The various states such as device discovery (scan, association, disassociation), file transfer status, wavelength quality indication and acknowledgments can be visually indicated to the user to help with device alignment for communication.

The mechanisms to stabilize the optical color emitted by the transmitter are defined in 5.1.13. The CVD frames are used to estimate the change in color and this information can be provided as feedback to the transmitter to stabilize its color.

The mechanisms for using the visibility and dimming information in the MAC are defined in 5.1.14. Features such as an extended preamble mode for providing visibility with improved synchronization performance, dimming overrides, adjusting the MAC sublayer transmission schedule to accommodate dimming, association and link adaptation in the presence of dimming are provided.

5.1.1 Channel access

This subclause describes the mechanisms for accessing the physical optical channel. The standard provides a single OWC MAC frame structure that can be configured for multiple modes. The frame is composed of a variable number of slots. A slot can be defined as the fixed minimum time needed to communicate to send the smallest data to a device and is fixed.

5.1.1.1 Superframe structure

A coordinator on a OWPAN can optionally bound its channel time using a superframe structure. A superframe is bounded by the transmission of a beacon frame and can have an active portion and an inactive portion. The coordinator may enter a low-power (sleep) mode during the inactive portion.

The structure of this superframe is controlled by the values of *macBeaconOrder* and *macSuperframeOrder*. The MAC PIB attribute *macBeaconOrder*, describes the interval at which the coordinator transmits its beacon frames when a coordinator is using a superframe structure, it shall transmit beacon frames based on the value of *macBeaconOrder*. The value of *macBeaconOrder*, *BO*, and the beacon interval, *BI*, are related as follows: for $0 \leq BO \leq 14$, $BI = aBaseSuperframeDuration \times 2^{BO}$ optical clocks. When *macBeaconOrder* is set to 15, superframe structure shall not be used and the value of *macSuperframeOrder* shall be ignored.

The MAC PIB attribute *macSuperframeOrder* describes the length of the active portion of the superframe, which includes the beacon frame. The value of *macSuperframeOrder*, *SO*, and the superframe duration, *SD*, are related as follows: for $0 \leq SO \leq BO \leq 14$, $SD = aBaseSuperframeDuration \times 2^{SO}$ optical clocks. If *SO* = 15, the active period of the superframe shall be zero duration. If *BO* = 15, the superframe shall not exist (the value of *macSuperframeOrder* shall be ignored), and when *macRxOnWhenIdle* is TRUE, the receiver shall be capable of receiving an incoming frame during periods of transceiver inactivity.

The active portion of each superframe shall be divided into *aNumSuperframeSlots* equally spaced slots of duration $2^{SO} \times aBaseSlotDuration$ and is composed of three parts: a beacon, a CAP, and a CFP. The beacon frame initiating a superframe shall be transmitted without use of the random access algorithm defined in 5.1.1.3. If BP exists, beacon is transmitted without the use of any random access, in one beacon slot of BP. The CAP shall commence immediately following the beacon. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. Any allocated GTSS shall be located within the CFP.

The MAC sublayer maintains the integrity of the superframe by compensating for clock drift error, etc.

OWPANs that wish to use the superframe structure (referred to as beacon-enabled OWPANs) shall set *macBeaconOrder* to a value between 0 and 14, both inclusive, and *macSuperframeOrder* to a value between 0 and the value of *macBeaconOrder*, both inclusive.

OWPANs that do not wish to use the superframe structure (referred to as nonbeacon-enabled OWPANs) shall set both *macBeaconOrder* and *macSuperframeOrder* to 15. In this case a coordinator shall not transmit periodic beacons; all transmissions in a nonbeacon-enabled OWPAN, with the exception of acknowledgment frames and any data frame that quickly follows the acknowledgment of a data request command (see 5.1.7.3), shall use an unslotted random access mechanism to access the channel (see 5.1.1.3).

An example of a superframe structure is shown in Figure 17. In this case, the beacon interval, *BI*, is twice as long as the active superframe duration, *SD*, and the CFP contains two GTSS.

Figure 18 provides an example usage of superframe structure configuration for multiple topologies such as peer-to-peer, star, broadcast, and visibility modes. The beacon slots are used for the beacons and the contention slots are used in the CAP. The uplink and downlink GTS slots are used in the CFPs. Visibility or idle patterns can be sent in the visibility slots during idle or RX modes of the infrastructure to provide continuous output and mitigate flicker and are also used for point-and-shoot mode to provide visibility.

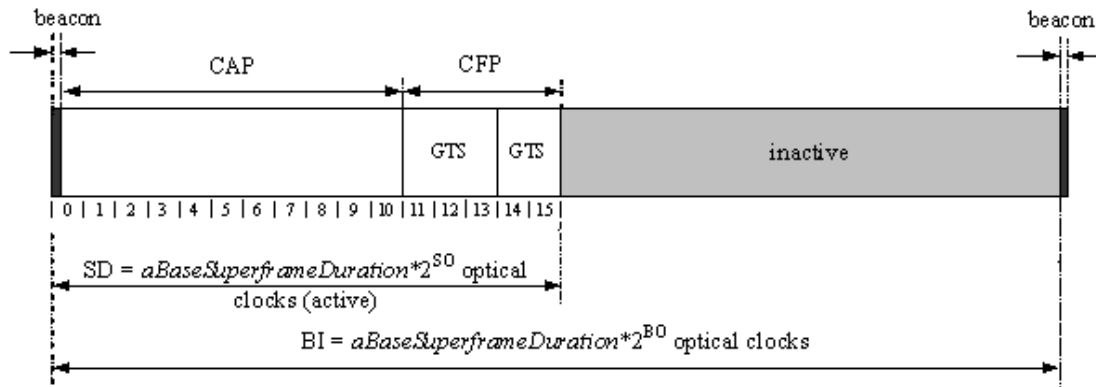


Figure 17—An example of the superframe structure

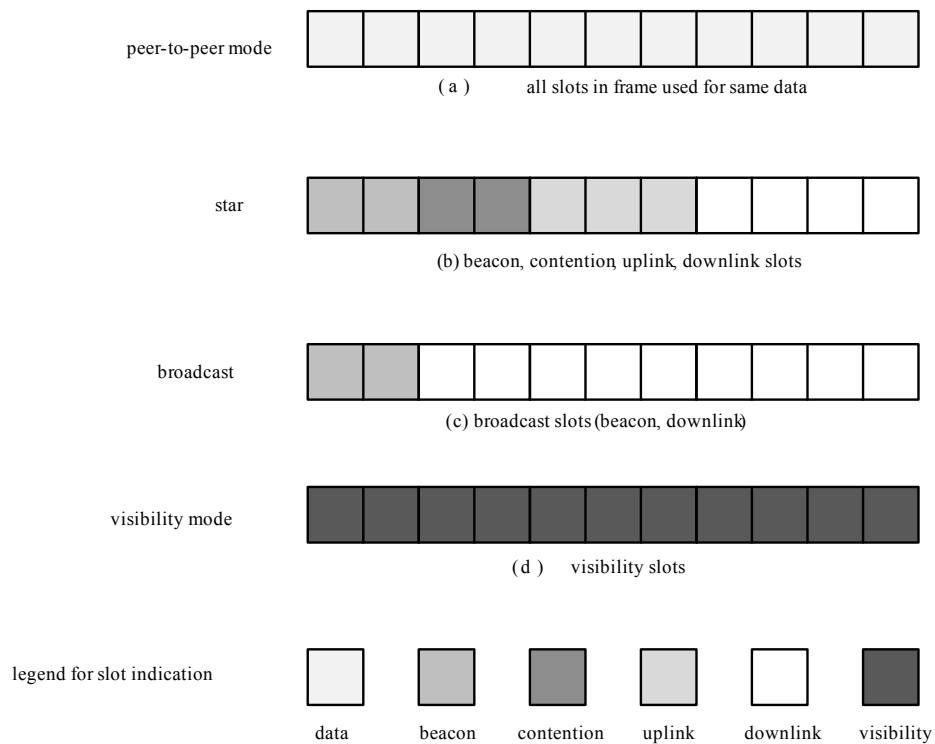


Figure 18—Example usage of frame structure for multiple topologies

5.1.1.1.1 Visibility support during channel access

The visibility slots can be used during contention and uplink slots in star topology mode and unused slots in all modes to maintain visibility, reduce flicker and keep the transmitter always ON for the infrastructure. This is shown in Figure 19. Visibility support is a very important distinguishing feature for OWC. One may need to transmit idle patterns during receive and idle modes. This can be done by simultaneous reception of data and the transmission of visibility or idle patterns. This is possible due to spatial separation of the light source and the receiving circuitry. As shown in Figure 19, idle patterns are sent during contention, uplink slots and unused downlink slots by the infrastructure to maintain visibility. Idle patterns are also sent during unused slots by the mobile device to help with pointing and alignment for optimal data transfer.

If the continuous visibility bit is set in the Capabilities Information field shown in Table 18 (in 5.3.19.1.1), then infrastructure devices shall provide continuous visibility.

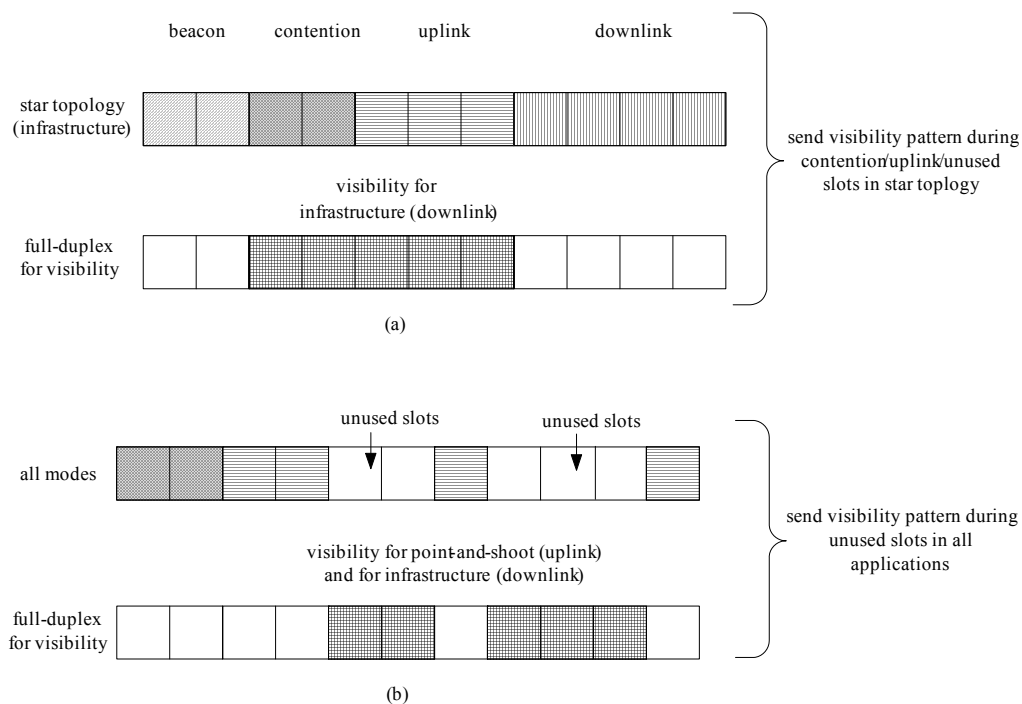


Figure 19—Usage of CVD frames during idle or RX modes of operation

5.1.1.2 Interframe space (IFS)

The MAC sublayer needs a finite amount of time to process data received by the PHY. To allow for this, two successive frames transmitted from a device shall be separated by at least an IFS period; if the first transmission requires an acknowledgment, the separation between the acknowledgment (ACK) frame and the second transmission shall be at least an IFS period. The length of the IFS period is dependent on the size of the frame that has just been transmitted. Frames (i.e., MPDUs) of up to *aMaxSIFSFrameSize* octets in length shall be followed by a short interframe space (SIFS) period of a duration of at least *macMinSIFSPeriod* optical clocks. Frames (i.e., MPDUs) with lengths greater than *aMaxSIFSFrameSize* octets shall be followed by a long interframe space (LIFS) period of a duration of at least *macMinLIFSPeriod* optical clocks. Burst frames shall have a reduced interframe space (RIFS) given by *macMinRIFSPeriod*. The IFS for the different modes are defined in 8.3.4, and the concepts are illustrated in Figure 20.

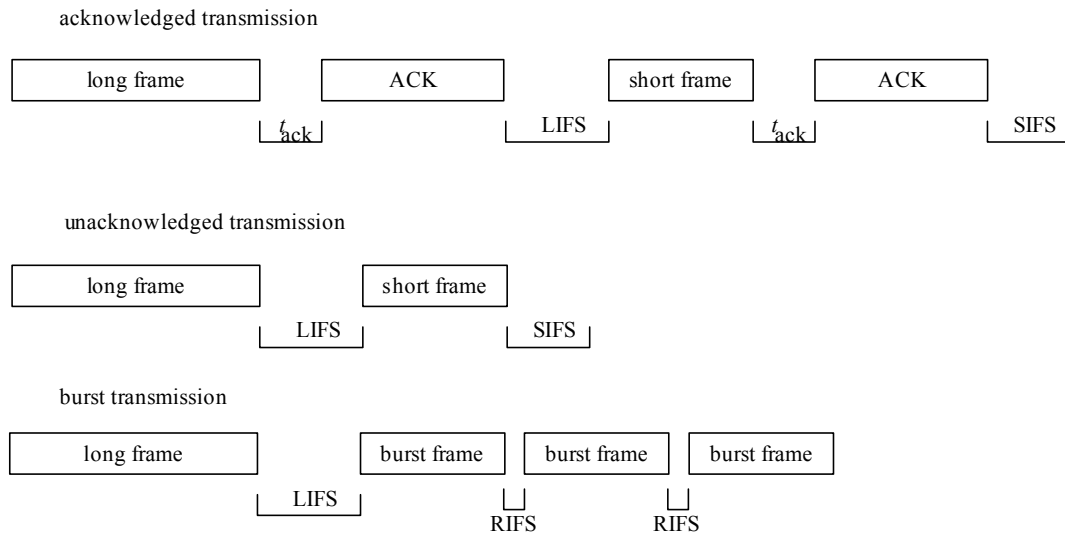


Figure 20—Interframe spacing

5.1.1.3 Random access algorithm

The slotted random access algorithm shall be used before the transmission of data or MAC command frames transmitted within the CAP, unless the frame can be quickly transmitted following the acknowledgment of a data request command (as defined in 5.1.7.3 for timing requirements) or periodic beacons are being used. None of the random access algorithms shall be used for the transmission of beacon frames in a beacon-enabled OWPAN, acknowledgment (ACK) frames, or data frames transmitted in the CFP.

If periodic beacons are being used in the OWPAN, the MAC sublayer shall employ the slotted version of the random access algorithm for transmissions in the CAP of the superframe. Conversely, if periodic beacons are not being used in the OWPAN or if a beacon could not be located in a beacon-enabled OWPAN, the MAC sublayer shall transmit using the unslotted version of the random access algorithm. In both cases, the algorithm is implemented using units of time called backoff periods, where one backoff period shall be equal to *aUnitBackoffPeriod* optical clocks.

In slotted random access, the backoff period boundaries of every device in the OWPAN shall be aligned with the superframe slot boundaries of the coordinator, i.e., the start of the first backoff period of each device is aligned with the start of the beacon transmission. In slotted random access, the MAC sublayer shall determine that the PHY commences all of its transmissions on the boundary of a backoff period. In unslotted random access, the backoff periods of one device are not related in time to the backoff periods of any other device in the OWPAN. When a polling mechanism is used, each poll by the coordinator node simultaneously addressed to all device nodes will indicate the beginning of the next transmission slot.

Each device shall maintain two variables for each transmission attempt: *NB* and *BE*. *NB* is the number of times the access algorithm was required to backoff while attempting the current transmission; this value shall be initialized to zero before each new transmission attempt. The variable *BE* is the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to access/assess a channel. *BE* shall be initialized to the value of *macMinBE*.

Figure 21 illustrates the steps of the access algorithm.

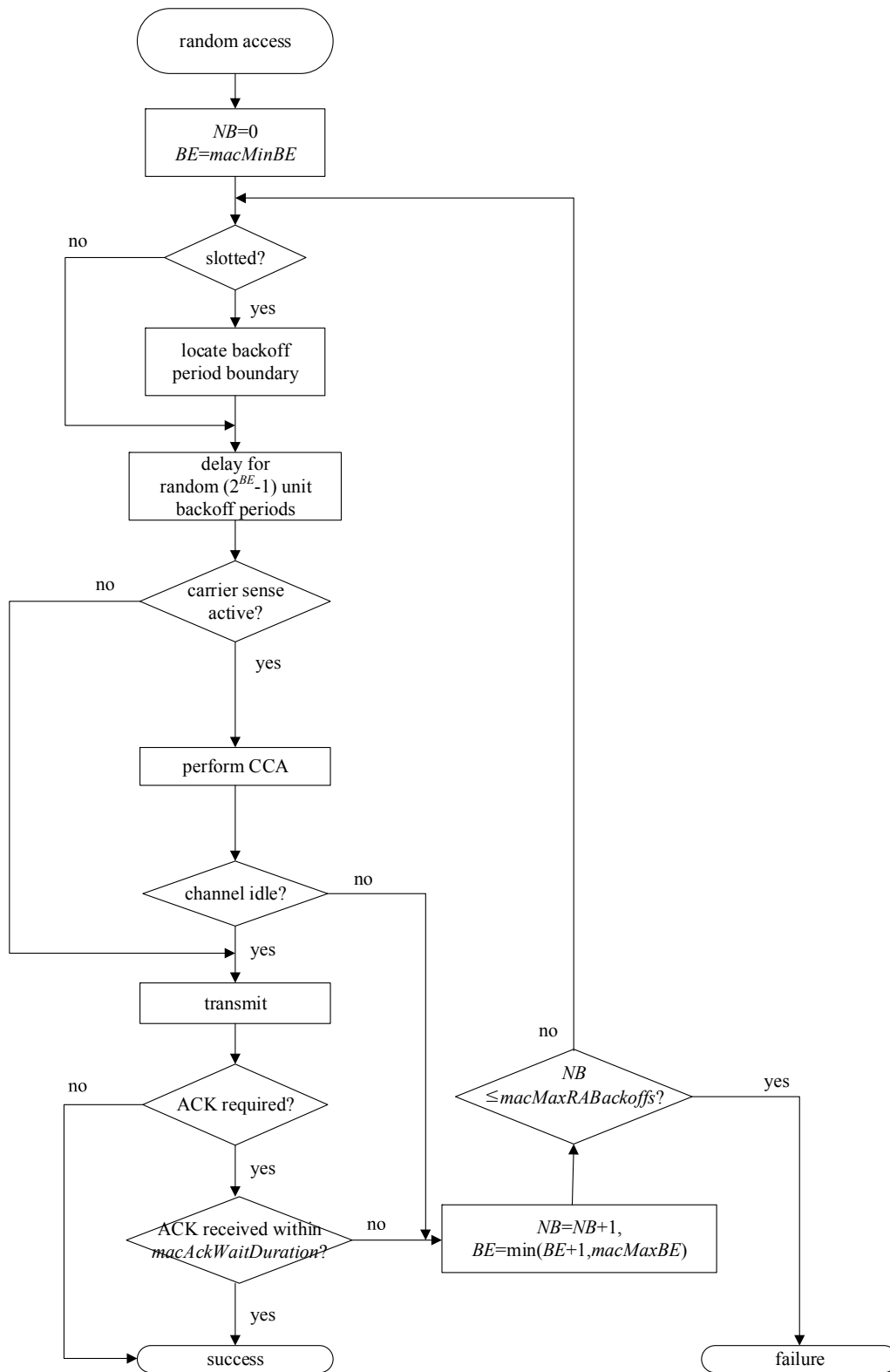


Figure 21—Random access flowchart

The MAC sublayer shall first initialize *NB* and *BE* for slotted random access then locate the boundary of the next backoff period. The MAC sublayer shall delay for a random number of complete backoff periods in the range 0 to $2^{BE} - 1$ [step (2)] and then request that the PHY perform a transmission or optionally a CCA. In a slotted random access system, the transmission, or CCA if active, shall start on a backoff period boundary. In an unslotted system, the transmission, or CCA if active, shall start immediately.

In a slotted random access system, the MAC sublayer shall determine that, after the random backoff, the remaining slotted random access operations can be undertaken and the entire transaction can be transmitted before the end of the CAP. Calculation of the transaction duration shall include any bit padding that may be added by the chosen PHY. If the number of backoff periods is greater than the remaining number of backoff periods in the CAP, the MAC sublayer shall pause the backoff countdown at the end of the CAP and resume it at the start of the CAP in the next superframe. If the number of backoff periods is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer shall apply its backoff delay and then evaluate whether it can proceed. The MAC sublayer shall proceed if the remaining unslotted random access algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP. If the MAC sublayer can proceed and CCA is active, it shall request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and apply a further random backoff delay before evaluating whether it can proceed again.

If CCA is active and the channel is assessed to be busy, the MAC sublayer shall increment both *NB* and *BE* by one, ensuring that *BE* shall be no more than *macMaxBE*. If the value of *NB* is less than or equal to *macMaxRABackoffs*, the access algorithm shall return to perform a random backoff as shown in Figure 21. If the value of *NB* is greater than *macMaxRABackoffs*, the access algorithm shall terminate with a channel access failure status.

5.1.2 Starting a OWPAN

5.1.2.1 Scanning through channels

All devices shall be capable of performing passive scans across a specified list of channels. In addition, a coordinator shall be able to perform active scans. A device is instructed to begin a channel scan through the MLME-SCAN.request primitive. For the duration of the scan, the device shall suspend beacon transmissions, if applicable, and may accept frames received over the PHY data service that are relevant to the scan being performed. Upon the conclusion of the scan, the device shall recommence beacon transmissions. The results of the scan shall be returned via the MLME-SCAN.confirm primitive.

5.1.2.1.1 Active channel scan

It is anticipated that the active channel scan is used with the peer-to-peer topology.

An active scan allows a device to locate any coordinator transmitting beacon frames within its coverage area. This could be used by a prospective OWPAN coordinator to select a OWPAN identifier prior to starting a new OWPAN, or it could be used by a device prior to association.

During an active scan, the MAC sublayer may discard all frames received over the PHY data service that are not beacon frames. If a beacon frame is received that contains the address of the scanning device in its list of pending addresses, the scanning device shall not attempt to extract the pending data.

Before commencing an active scan, the MAC sublayer shall store the value of *macOWPANId* and then set it to 0xffff for the duration of the scan. This enables the receive filter to accept all beacons rather than just the beacons from its current OWPAN (see 5.1.7.2). On completion of the scan, the MAC sublayer shall restore the value of *macOWPANId* to the value stored before the scan began. An active scan over a specified set of logical channels is requested using the MLME-SCAN.request primitive with the ScanType parameter set to indicate an active scan. For each logical channel, the device shall first switch to the channel, by setting

phyCurrentChannel accordingly, and send a beacon request command (see 5.3.6). Upon successful transmission of the beacon request command, the device shall enable its receiver for at most $[aBaseSuperframeDuration \times (2^n + 1)]$ optical clocks, where n is the value of the *ScanDuration* parameter. During this time, the device may reject all nonbeacon frames and record the information contained in all unique beacons in a OWPAN descriptor structure (see 6.3.3.1), including the channel information and the preamble code. If a beacon frame is received when *macAutoRequest* is set to TRUE, the list of OWPAN descriptor structures shall be stored by the MAC sublayer until the scan is complete; at this time, the list shall be sent to the next higher layer in the OWPANDescriptorList parameter of the MLME-SCAN.confirm primitive. A device shall be able to store between one and an implementation-specified maximum number of OWPAN descriptors. A beacon frame shall be determined to be unique if it contains both a OWPAN identifier and a source address that has not been seen before during the scan of the current channel. If a beacon frame is received when *macAutoRequest* is set to FALSE, each recorded OWPAN descriptor is sent to the next higher layer in a separate MLME-BEACON-NOTIFY.indication primitive. A received beacon frame containing one or more octets of payload shall also cause the OWPAN descriptor to be sent to the next higher layer via the MLME-BEACON-NOTIFY.indication primitive. If a protected beacon frame is received, i.e., the Security Enabled subfield in the Frame Control field is set to one, the device shall perform the unsecuring process described in 7.2.3. The security-related elements of the OWPAN descriptor corresponding to the beacon (see 6.3.3.1) shall be set to the corresponding parameters returned by the unsecuring process. The SecurityFailure element of the OWPAN descriptor shall be set to SUCCESS if the status from the unsecuring process is SUCCESS and set to one of the other status codes indicating an error in the security processing otherwise. The information from the unsecured frame shall be recorded in the OWPAN descriptor even if the status from the unsecuring process indicated an error. If a coordinator of a beacon-enabled OWPAN receives the beacon request command, it shall ignore the command and continue transmitting its periodic beacons as usual. If a coordinator of a nonbeacon-enabled OWPAN receives this command, it shall transmit a single beacon frame using unslotted random access or unslotted CSMA-CA.

If *macAutoRequest* is set to TRUE, the active scan on a particular channel shall terminate when the number of beacons found equals the implementation-specified limit or the channel has been scanned for the full time, as specified in 5.1.2.1.1. If *macAutoRequest* is set to FALSE, the active scan on a particular channel shall terminate when the channel has been scanned for the full time. If a channel was not scanned for the full time, it is considered to be unscanned.

If *macAutoRequest* is set to TRUE, the entire scan procedure shall terminate when the number of OWPAN descriptors stored equals the implementation-specified maximum or every channel in the set of available channels has been scanned. If *macAutoRequest* is set to FALSE, the entire scan procedure shall only terminate when every channel in the set of available channels has been scanned.

5.1.2.1.2 Passive channel scan

It is anticipated that the passive channel scan is used with the star or broadcast topology.

A passive scan, like an active scan, allows a device to locate any coordinator transmitting beacon frames within its coverage area. The beacon request command, however, is not transmitted. This type of scan could be used by a device prior to association. During a passive scan, the MAC sublayer may discard all frames received over the PHY data service that are not beacon frames. If a beacon frame is received that contains the address of the scanning device in its list of pending addresses, the scanning device shall not attempt to extract the pending data.

Before commencing a passive scan, the MAC sublayer shall store the value of *macOWPANId* and then set it to 0xffff for the duration of the scan. This enables the receive filter to accept all beacons rather than just the beacons from its current OWPAN (see 5.1.7.2). On completion of the scan, the MAC sublayer shall restore the value of *macOWPANId* to the value stored before the scan began. A passive scan over a specified set of logical channels is requested using the MLME-SCAN.request primitive with the *ScanType* parameter set to indicate a passive scan. For each logical channel, the device shall first switch to the channel, by setting