

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

**Part 15.7: Short-Range Wireless Optical
Communication Using Visible Light**

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

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Part 15.7: Short-Range Wireless Optical Communication Using Visible Light

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IEEE Computer Society**

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Abstract: A PHY and a MAC layer for short-range optical wireless communications using visible light in optically transparent media are defined. The visible light spectrum extends from 380 nm to 780 nm in wavelength. The standard is capable of delivering data rates sufficient to support audio and video multimedia services and also considers mobility of the visible link, compatibility with visible-light infrastructures, impairments due to noise and interference from sources like ambient light and a MAC layer that accommodates visible links. The standard adheres to applicable eye safety regulations.

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

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IEEE Standard for Local and metropolitan area networks—

Part 15.7: Short-Range Wireless Optical Communication Using Visible Light

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1. Overview

1.1 Scope

This standard defines a PHY and MAC layer for short-range optical wireless communications using visible light in optically transparent media. The visible light spectrum extends from 380 nm to 780 nm in wavelength. The standard is capable of delivering data rates sufficient to support audio and video multimedia services and also considers mobility of the visible link, compatibility with visible-light infrastructures, impairments due to noise and interference from sources like ambient light and a MAC layer that accommodates visible links. The standard adheres to applicable eye safety regulations.

1.2 Purpose

The purpose of this standard is to provide a global standard for short-range optical wireless communication using visible light. The standard provides (i) access to several hundred THz of unlicensed spectrum; (ii) immunity to electromagnetic interference and noninterference with Radio Frequency (RF) systems; (iii) additional security by allowing the user to see the communication channel; and (iv) communication augmenting and complementing existing services (such as illumination, display, indication, decoration, etc.) from visible-light infrastructures.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so 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™-2006, 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 Recommendations B-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

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be consulted for terms not defined in this clause.⁵

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

color-shift keying (CSK): A modulation scheme for visible-light communication involving multiple light sources, which keeps the average emitted optical color and the total optical power constant during communication.

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

color visibility dimming (CVD) frame: A frame used for color, visibility and dimming support. The color visibility dimming frame visually provides information such as communication status and channel quality to the user via various colors. The color visibility dimming frame may also be sent during idle or receive modes of operation for continuous visibility and dimming support. During the color visibility dimming frame transmission, the device is still emitting light while not communicating, and it is thus able to fulfill its lighting function. The payload of the frame consists of visibility patterns of appropriate intensity and color.

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.

¹ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

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⁴ITU-T publications are available from the International Telecommunications Union, Place des Nations, CH-1211, Geneva 20, Switzerland/Suisse (<http://www.itu.int/>).

⁵*The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

dimming: Reducing the radiant power of a transmitter while preserving the color of the transmitted light.

field of view (FOV): The angular extent of coverage for the optical transmitter or receiver.

idle pattern: A pattern whose duty cycle variation results in a change of brightness for dimming support and may be transmitted during idle or receive mode.

macro cell: An aggregate cell formed using all the cells available at the optical media and is used for device discovery and association.

modulation-domain spectrum: The spectrum observed at the output of the receiver's photodetector; typically measured at the output of the trans impedance amplifier

on-off keying (OOK): A simple modulation technique that represents digital data as the presence ('ON') or absence ('OFF') of a signal. Note that 'ON' and 'OFF' are simply two logic levels or two distinct amplitude levels for the purposes of communication and does not necessarily require that the light source be turned OFF completely.

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

photodetector: A photodetector captures optical power and translates it into an output signal. Most photodetectors convert optical power into an electrical current or an electrical voltage.

PHY switch: A switch at the transmission interface between the PHY and the optical 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 frame for the purpose of illuminating the target receiving device.

switching level: A distinct amplitude level that defines 'ON' and 'OFF' of the light source for the purpose of communications and does not necessarily require that the light source be turned off completely.

variable pulse-position modulation (VPPM): A modulation scheme for visible-light communication that allows pulse-width control for light dimming support, mitigating intra-frame flicker.

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

3.2 Acronyms and abbreviations

A/D	analog-to-digital converter
ACK	acknowledgment
AES	advanced encryption standard
AR	acknowledgment request
BE	backoff exponent
BI	beacon interval
BO	beacon order
BSN	beacon-sequence number
CAP	contention access period
CC	convolutional code
CCA	clear channel assessment
CDR	clock and data recovery
CFP	contention-free period
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)

CRC	cyclic redundancy check
CSK	color-shift keying
CSMA/CA	carrier sense multiple access with collision avoidance
CVD	color visibility dimming
D/A	digital-to-analog converter
D/L	downlink
DC	direct current
DME	device management entity
DSN	data-sequence number
ED	energy detection
ENC	encryption mode
FCS	frame check sequence
FDM	frequency division multiplexing
FEC	forward error correction
FER	frame-error ratio
FLP	fast locking pattern
FLR	fast link recovery
FOV	field of view
GF	Galois field
GTS	guaranteed time slot
HCS	header-check sequence
HP	hopping pattern
IFS	interframe space
ID	identifier
IE	information element
LD	laser diode
LED	light-emitting diode
LIFS	long interframe space
LLC	logical link control
LPDU	logical link control protocol data unit
LOS	line of sight
MAC	medium access control
MCPS	medium-access-control common-part sublayer
MCS	modulation and coding scheme
MD	mobile device
MFR	medium-access-control footer
MFTP	maximum flickering-time period
MHR	medium-access-control header
MIC	message-integrity code
MLME	medium-access-control link-management entity
MPDU	medium-access-control protocol-data unit
MSDU	medium-access-control service-data unit
NB	number of backoffs
OOK	on-off keying
PAN	personal-area network
PD	physical-layer data
PHR	physical-layer header
PHY	physical layer
PIB	physical-layer personal-area-network information base
PID	personal-area-network identifier
PLME	physical-layer management entity
PPDU	physical-layer data unit
PSDU	PHY service data unit
PWM	pulse-width modulation

P2MP	point-to-multipoint
P2P	peer-to-peer
QoS	quality of service
RIFS	reduced interframe space
RLL	run-length limited
RS	Reed-Solomon
RX	receiver
SAP	service access point
SHR	synchronization header
SIFS	short interframe space
SPDU	session-protocol data unit
SO	superframe order
SSCS	service-specific convergence sublayer
TDP	topology dependent pattern
TRX	transceiver
TX	transmitter
U/L	uplink
VPAN	visible-light communication personal area network
VLC	visible-light communication
VPPM	variable pulse-position modulation
WPAN	wireless personal area network
WQI	wavelength quality indication

4. General description

4.1 Introduction

Visible-light communication (VLC) transmits data by intensity modulating optical sources, such as light-emitting diodes (LEDs) and laser diodes (LDs), faster than the persistence of the human eye. VLC merges lighting and data communications in applications such as area lighting, signboards, streetlights, vehicles, and traffic signals. This standard describes the use of VLC for wireless personal area networks (WPAN). 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 (WQI)
- 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 VLC: infrastructure, mobile, and vehicle.

The IEEE 802.15.7 visible-light communication personal area network (VPAN) standard maps the intended applications to three topologies: peer-to-peer, star, and broadcast, as shown in Figure 1.

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

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.

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

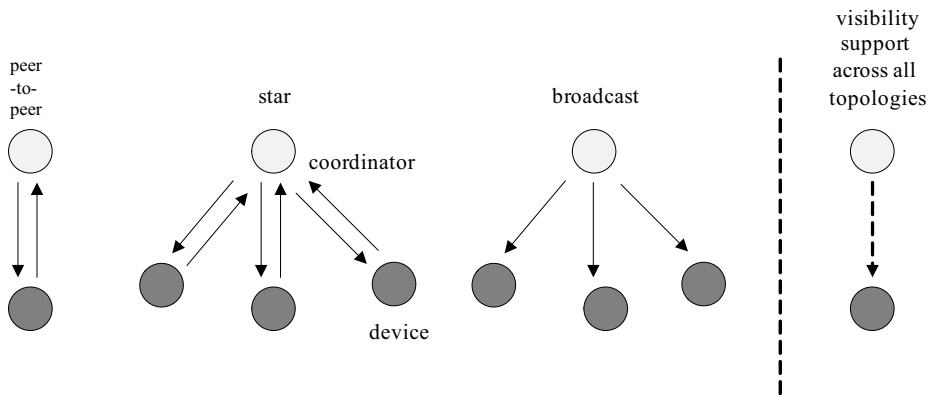


Figure 1—Supported MAC topologies

Each independent VPAN has an identifier, as defined in 5.2.1.3 and 5.2.1.5. This VPAN identifier allows communication between devices within a network using short addresses. The mechanism by which VPAN 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, IEEE 802.15.7 devices 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.

Visibility support is also provided across all topologies to maintain the illumination function 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 VPAN identifier that is not currently used by any other network within the coverage area. Once the VPAN 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 uni-directional and the destination address is not required.

4.3 Modulation-domain spectrum

Figure 2 illustrates the concept of the modulation-domain spectrum. In Figure 2, the visible light source is “always on”; hence, the output of the photodetector 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.

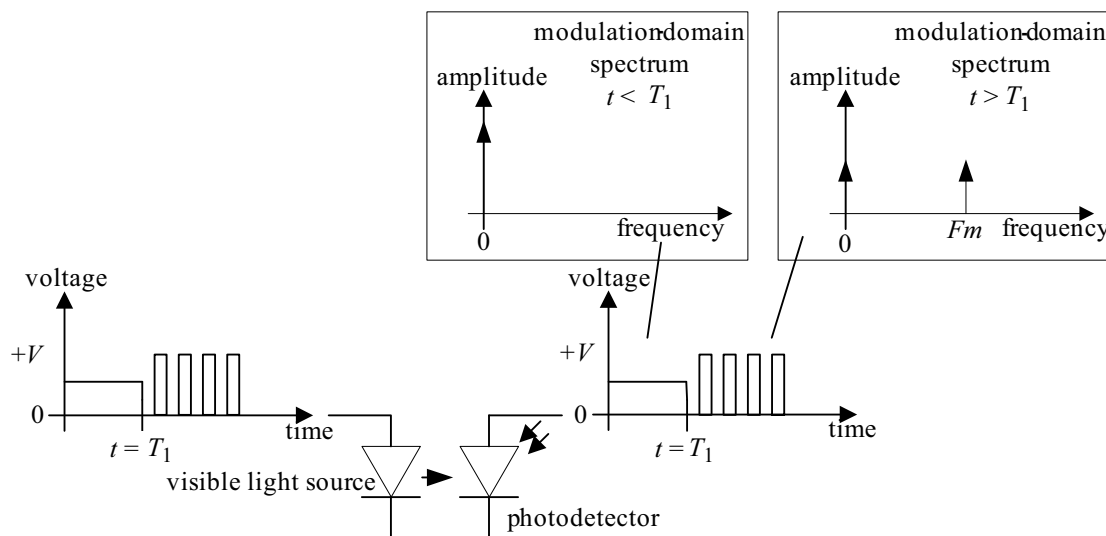


Figure 2—Illustration of modulation-domain spectrum

4.4 Architecture

The IEEE 802.15.7 architecture is defined 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 serve to define the logical links that are described in this standard.

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

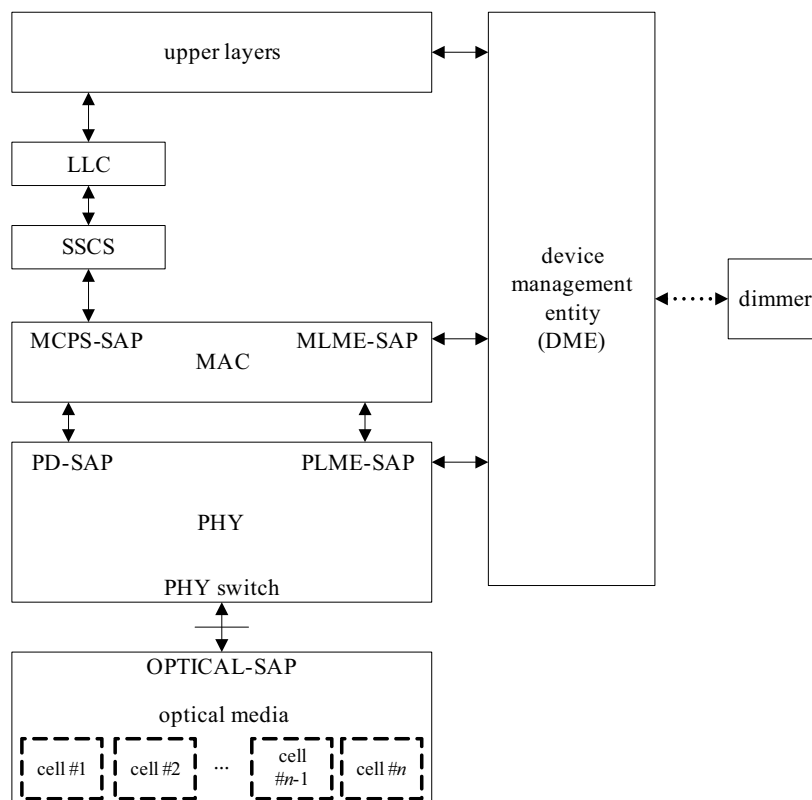


Figure 3—VPAN device architecture

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.

A device management entity (DME) is also supported in the architecture. The DME can talk to the PLME and MLME for the purposes of interfacing 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 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 the

standard for PHY III as well for VLC 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 layer

The PHY layer supports multiple PHY types.

- a) 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 kb/s, as defined in Table 73.
- b) 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 Mb/s, as defined in Table 74.
- c) 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 Mb/s, as defined in Table 75.

4.4.1.1 PHY frame structure

The MAC protocol data unit (MPDU) at the output of the MAC sublayer passes through the PHY layer and becomes the PHY service data unit (PSDU) at the output of the PHY layer 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 sequence 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 PHY layer data unit (PPDU). The format of the PHY frame is shown in Figure 118.

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.

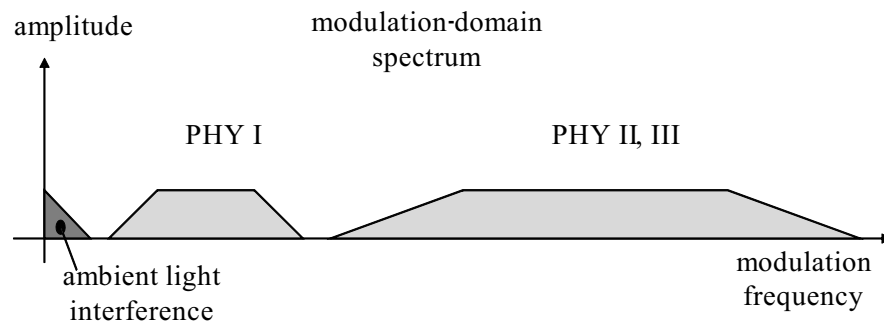


Figure 4—FDM separation of the PHY types in the modulation domain

4.4.2 MAC sublayer

The MAC sublayer provides two services accessed through two service access points (SAPs). MAC data is accessed through the MAC common part sublayer SAP (MCPS-SAP) while MAC management is accessed through the MAC sublayer 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 contains the specifications for the MAC sublayer.

4.4.3 Dimming and flicker-mitigation support

This subclause outlines the methods for dimming and flicker-mitigation support. 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 VLC activity is “ON”, there can be small time scaled transition of active mode and idle/RX mode. Dimmer setting for high brightness (a) in Figure 5 illustrates a higher duty cycle for higher brightness. Dimmer setting for low brightness (b) 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.

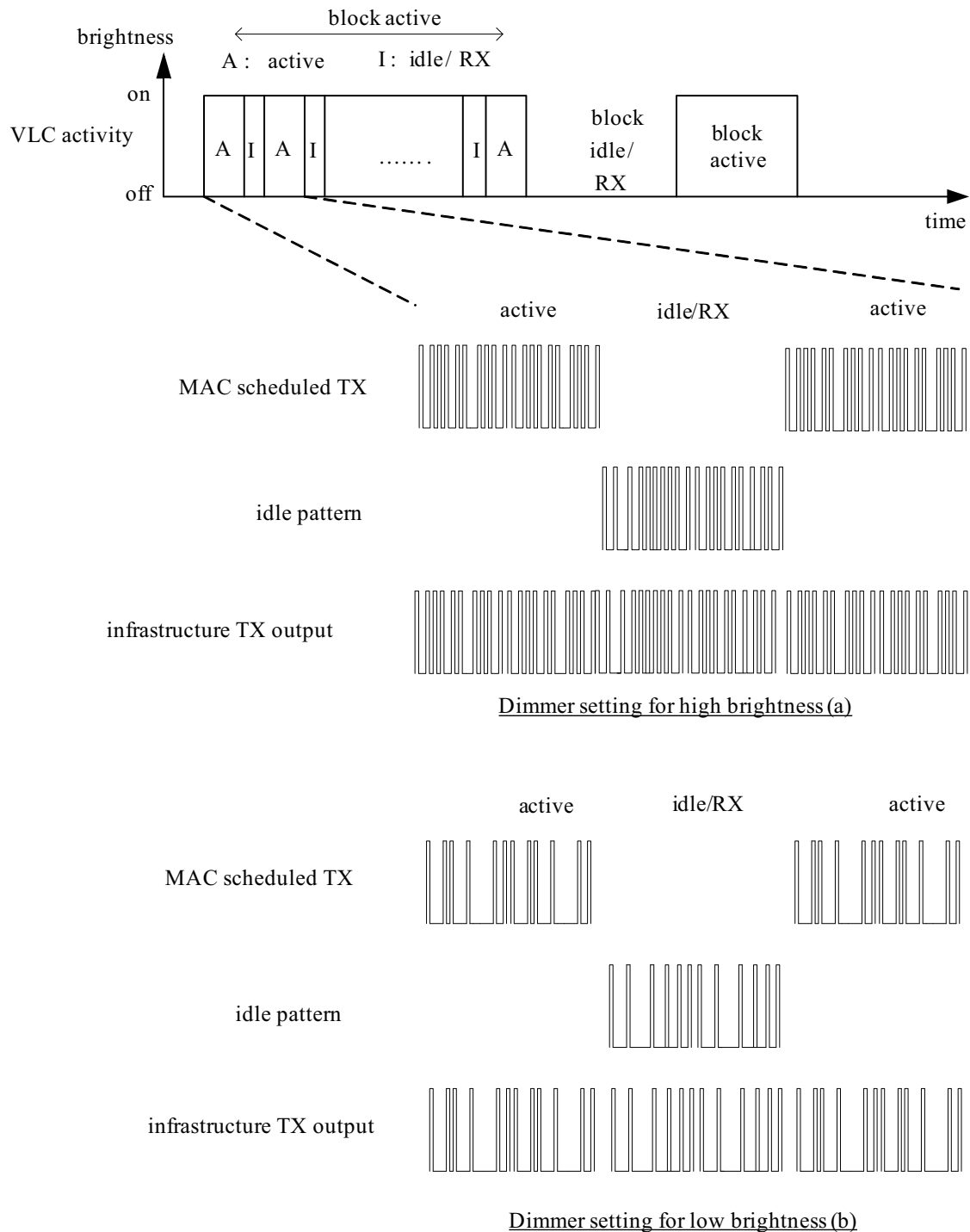


Figure 5—Adapting dimmer pattern and data duty cycle depending on dimmer setting

4.4.3.1 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.

4.4.3.1.1 Idle pattern and compensation time dimming

The standard allows an idle pattern to be inserted between the data frames for light dimming, as shown in Figure 6. The duty cycle of the idle pattern can be varied to provide brightness variation. The idle pattern selection is not specified in this standard. An idle pattern can either be in-band or out-of-band as defined by the modulation-domain spectrum and both types of idle patterns are supported in this standard. An in-band idle pattern does not require any change in the clock and can be seen by the receiver. An out-of-band idle pattern is typically sent at a much lower optical clock rate (including the option of maintaining visibility via a DC bias only) and is not seen by the receiver (i.e., it does not lie in the receiver’s modulation-domain bandpass). The standard also allows a compensation time (“ON” or “OFF” time of a light source) to be inserted into either the idle pattern or into the data frame to reduce or increase the average brightness of a light source.

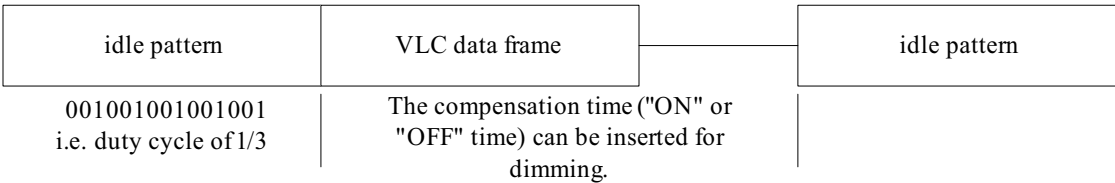


Figure 6—Example of idle pattern and compensation time dimming

4.4.3.1.2 Visibility pattern dimming

Visibility patterns are in-band idle patterns that are used in the payload of a CVD frame. The visibility patterns are used for supporting features such as flicker mitigation, continuous visibility, device discovery, and color stabilization. The visibility patterns are not encoded in the PHY layer and do not have a frame check sequence (FCS) associated with them. In order to generate high resolution visibility patterns from 0% to 100% in steps of 0.1%, there are certain constraints that need to be used in the design criteria for visibility patterns.

- a) The number of transitions between ones and zeros can be maximized to provide high-frequency switching in order to avoid flicker and to help the clock and data recovery (CDR) circuit at receiver for synchronization purposes, if used.
- b) Visibility pattern generation can be made in a simple manner. Designing a thousand patterns to support low resolutions (as low as 0.1% resolution) is not practical and makes visibility pattern generation and use very complex.
- c) Since visibility patterns are transmitted without changing the clock frequency (in-band), the patterns avoiding conflicts with existing RLL code words are recommended.

The generation of the visibility patterns and their usage is defined in 8.5.1.2.

4.4.3.1.3 Color-shift keying (CSK) dimming

CSK supports VLC using multi-color light sources and photo detectors. CSK has the following advantages:

- a) Information is provided by the color coordinates: CSK channels are defined by mixed colors that are allocated in the color coordinate plane; therefore, the connectivity is facilitated by the color coding.
- b) Total average power is constant: The total average power of all CSK light sources is constant; therefore, the envelope of the sum of all light signals is constant.
- c) Variable bit rate: CSK enables variable bit rate due to higher order modulation support; that is, the raw bit rate equals the optical clock rate times the bits per CSK symbol.

CSK dimming employs amplitude dimming and controls the brightness by changing the current driving the light source. However, a color shift of the light source may arise from improper control of driving current for amplitude dimming. For a given dimmer setting, the average optical power from the light sources is constant. This implies that the center color of the color constellation is constant.

4.4.3.1.4 OOK dimming

Since OOK modulation is always sent with a symmetric Manchester symbol, compensation time may need to be inserted into the data frame to adjust the average intensity of the perceived source. The structure for the OOK dimming frame is as shown in Figure 7. 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 FCS has been calculated and the forward error correction (FEC) has been applied. An example of OOK dimming to increase brightness by adding compensation symbols is as shown in Figure 8.

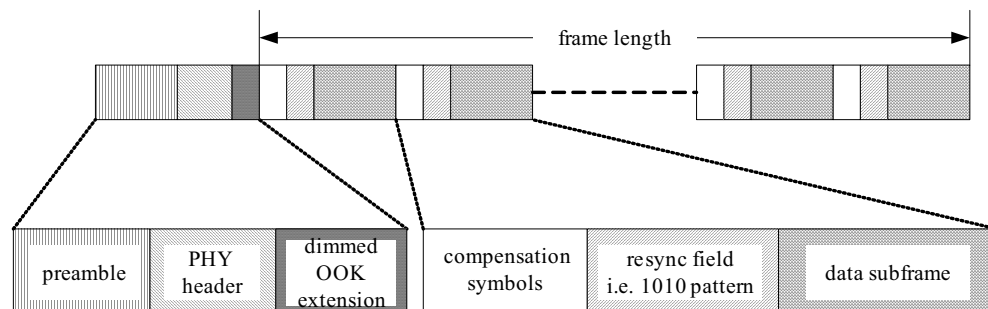


Figure 7—OOK dimming structure

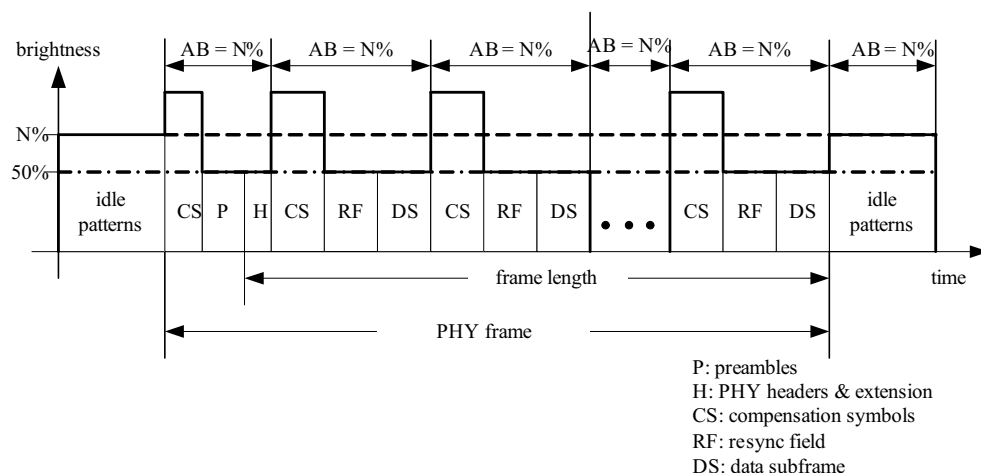


Figure 8—Example of OOK dimming to increase brightness

4.4.3.1.5 VPPM dimming

VPPM is a modulation scheme adapted for pulse width based light dimming and offers protection from intra-frame flicker. It does not create a color-shift in the light source that can arise from amplitude dimming because the pulse amplitude in VPPM is always constant and the dimming control is performed by the pulse width, not the amplitude.

VPPM makes use of the characteristics of 2-PPM (pulse position modulation) for non-flicker and PWM (pulse-width modulation) for dimming control and full brightness. Bits “1” and “0” in VPPM are distinguished by the pulse position within a unit period and have the same pulse width within their respective unit periods. The non-flicker characteristic in VPPM is obtained from the property that the average brightness on bits “1” and “0” is constant.

Dimming and full brightness in VPPM is achieved by controlling the “ON” time pulse width. Figure 9 describes the dimming control mechanism by VPPM. It is possible to adjust the pulse width for VPPM based on the dimming requirements. Therefore, a user can achieve the full brightness that can be provided by the light source.

As shown in Figure 10, the light intensity for the payload can be adjusted by adapting the pulse width of VPPM symbols. The light intensity for the preamble and header can be adjusted by inserting compensation symbols of the appropriate length and intensity before the frame. The details on high resolution dimming using VPPM are described in 8.5.2.3.

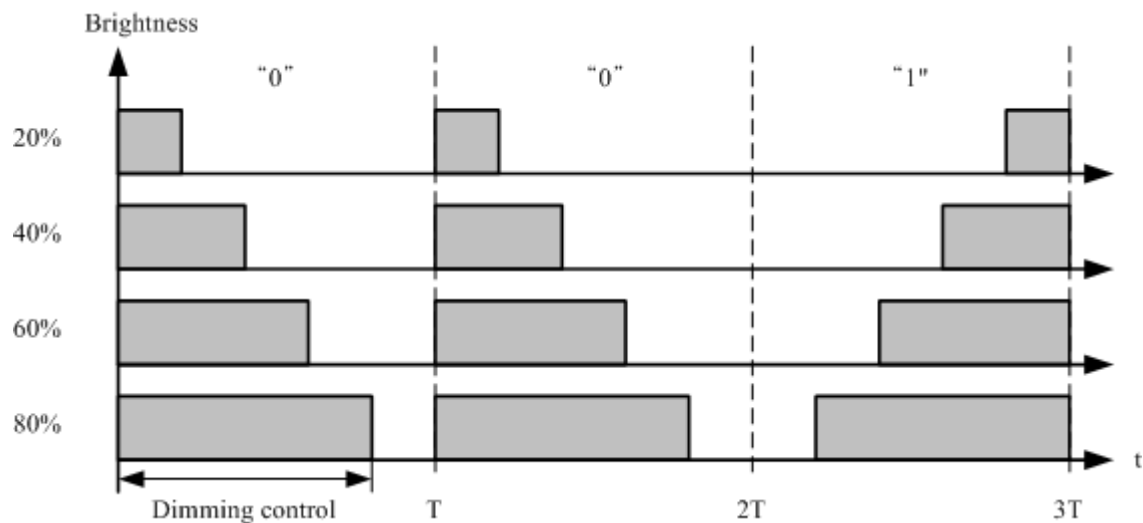


Figure 9—Schematic mechanism for VPPM dimming

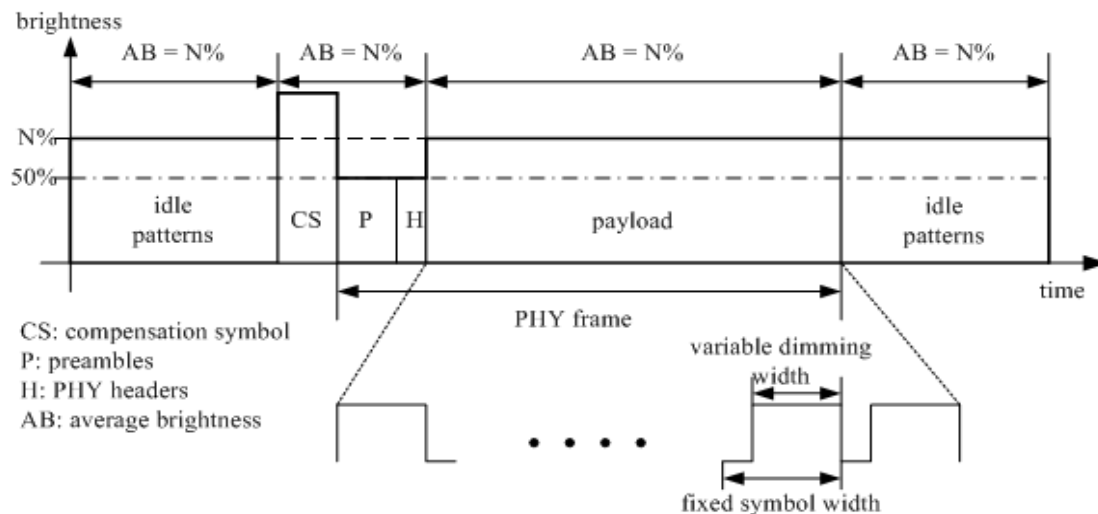


Figure 10—Example of VPPM dimming

4.4.3.2 Flicker mitigation

Flicker is defined as the fluctuation of the brightness of light that can cause noticeable physiological changes in humans. 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. [B13]). To avoid flicker, the brightness changes over periods longer than MFTP must be avoided.

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

4.4.3.2.1 Intra-frame flicker mitigation

Intra-frame flicker mitigation is accomplished by either the use of run length limiting coding, modulation scheme, or both. Specifically, these schemes are manchester encoding as specified in 10.5.2, 4B6B encoding as specified in 10.5.1, 8B10B encoding as specified in 11.3, or VPPM as specified in 10.6.

4.4.3.2.2 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.

4.5 Functional overview

This clause provides a brief overview of the general functions of a VPAN 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. The superframe is bounded by beacons sent by the coordinator, as shown in Figure 11a, and is divided into equally sized slots. Optionally, the superframe can have an active and an inactive portion, as shown in Figure 11b. 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. The beacons are used to synchronize the attached devices, to identify the VPAN, and to describe the structure of the superframes. Any device wishing to communicate during the contention access period (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 CSMA/CA, and slotted CSMA/CA. These methods are described in 5.1.1.3.

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

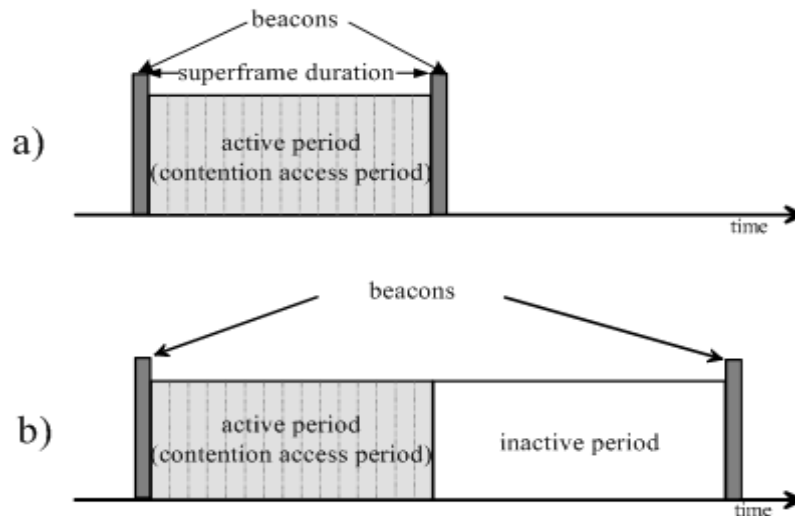


Figure 11—Superframe structure without GTSs

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 contention-free period (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 13. 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 ensures that its transaction is complete before the time of the next GTS or the end of the CFP. More information on the superframe structure as described in 5.1.1.1.

4.5.2 Data transfer model

Three types of data transfer transactions exist:

- a) The first transaction type is the data transfer to a coordinator in which a device transmits the data.
- b) The second transaction type is the data transfer from a coordinator in which the device receives the data.
- c) The third transaction type is 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 VPAN is used in networks that either require 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 VPAN, 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 is allowed to acknowledge the successful reception of the data by transmitting an optional acknowledgment frame.

When a device wishes to transfer data in a non beacon-enabled VPAN, 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 VPAN, 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 non beacon-enabled VPAN, 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 VPAN, 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

The 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 CVD frame, used to maintain the proper light intensity between data frames, support dimming and for visually providing information such as communication status and channel quality to the user.

4.5.5 Improving probability of successful delivery

The IEEE 802.15.7 VPAN 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

The IEEE 802.15.7 VPAN uses four types of channel access mechanism, depending on the network configuration. Non-beacon-enabled VPANs use an unslotted random channel access mechanism, with or without CSMA/CA, as described in 5.1.1.3. Each time a device wishes to transmit data frames or MAC commands, it waits for a random back off period. Following the random back off, 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 back off, 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 VPANs use a slotted random channel access mechanism, with or without CSMA/CA, where the back off 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 back off slot and then waits for a random number of back off slots. If the optional collision avoidance mechanism is active, and the channel is busy, following this random back off the device waits for another random number of back off 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 back off slot boundary. Acknowledgment and beacon frames are sent without using a random access mechanism (i.e., scheduled).

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 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, IEEE 802.15.7 VPAN is slightly different from other wireless networks, due to directionality and visibility because of the choice of the visible optical spectrum. Because of directionality and visibility, if an unauthorized receiver is in the path of the communication signal, it can be recognized. Also, the signal will not travel across medium 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; and 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 trade-off 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 is 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 12, showing the service hierarchy and the relationship of the two correspondent users and their associated layer (or sublayer) peer protocol entities.

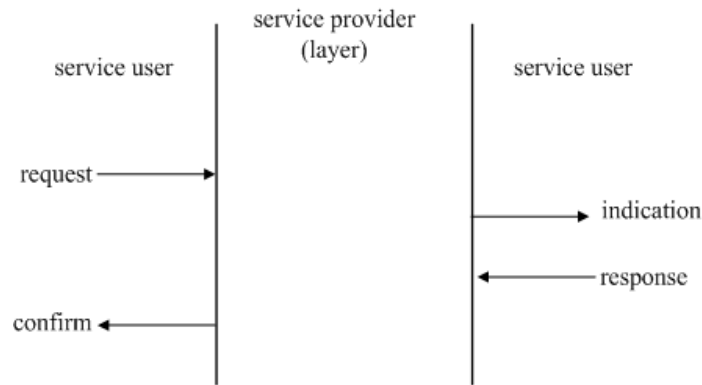


Figure 12—Service primitives

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 service access point (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.

5. MAC protocol specification

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 VPAN 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 capabilities, as shown in Figure 1, are provided with a single MAC frame structure. All of these diverse modes are supported via a single low complexity integrated 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 59 (see 6.4.1). Attributes have a general prefix of “mac”, e.g., *macAckWaitDuration*, and are listed in Table 60 (see 6.4.2), while the security attributes are listed in Table 66 (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 GTSSs.

The mechanisms used for starting and maintaining a VPAN 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 VPAN, the results of a channel scan can be used to select an appropriate logical channel, as well as a VPAN identifier that is not being used by any other VPAN in the area. Because it is still possible for the operating space of two VPANs with the same VPAN identifier to overlap, a procedure exists to detect and resolve this situation. Following a channel scan and suitable VPAN identifier selection, operation as a coordinator shall commence. 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 VPAN are defined in 5.1.4. The association procedure describes the conditions under which a device may join a VPAN 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 VPAN is described after first explaining how a coordinator generates beacon frames. Following this explanation, synchronization on a nonbeacon-enabled VPAN 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 VPAN.

This standard has been designed so that application data transfers can be controlled by the devices on a VPAN 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 layer 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 VLC 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 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 VPAN 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 described by the values of *macBeaconOrder* and *macSuperframeOrder*. The MAC PIB attribute *macBeaconOrder*, describes the interval at which the coordinator shall transmit its beacon frames. 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. If $BO = 15$, the coordinator shall not transmit beacon frames except when requested to do so, such as on receipt of a beacon request command. The value of *macSuperframeOrder* shall be ignored if $BO = 15$.

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 superframe shall not remain active after the beacon. If $BO = 15$, the superframe shall not exist (the value of *macSuperframeOrder* shall be ignored), and *macRxOnWhenIdle* shall define whether the receiver is enabled 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 shall be transmitted, without the use of any random access, at the start of slot 0, and the CAP shall commence immediately following the beacon. The start of slot 0 is defined as the point at which the first bit of the beacon PPDU is transmitted. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. Any allocated GTSSs shall be located within the CFP.

The MAC sublayer shall ensure that the integrity of the superframe timing is maintained, e.g., compensating for clock drift error.

VPANs that wish to use the superframe structure (referred to as a beacon-enabled VPAN) 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.

VPANs that do not wish to use the superframe structure (referred to as a nonbeacon-enabled VPAN) shall set both *macBeaconOrder* and *macSuperframeOrder* to 15. In this case, a coordinator shall not transmit beacons, except upon receipt of a beacon request command; all transmissions, 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. In addition, GTSSs shall not be permitted.

An example of a superframe structure is shown in Figure 13. In this case, the beacon interval, BI , is twice as long as the active superframe duration, SD , and the CFP contains two GTSs.

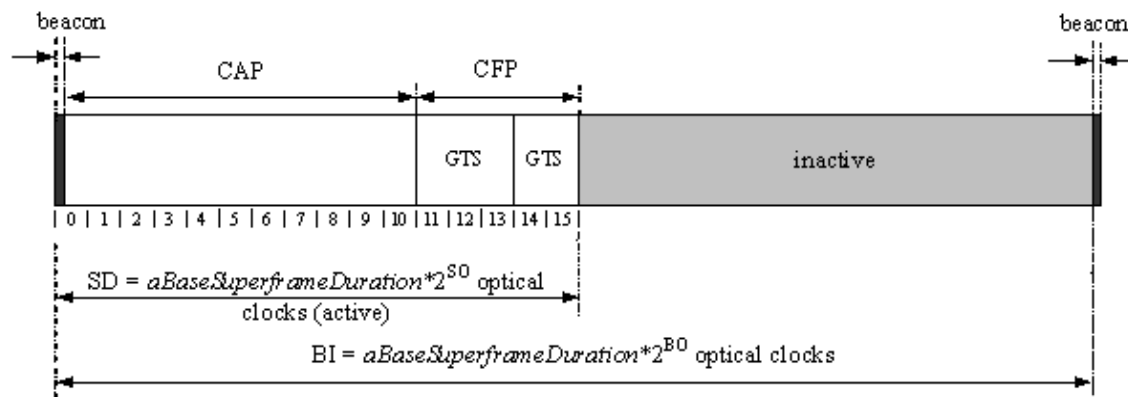


Figure 13—An example of the superframe structure

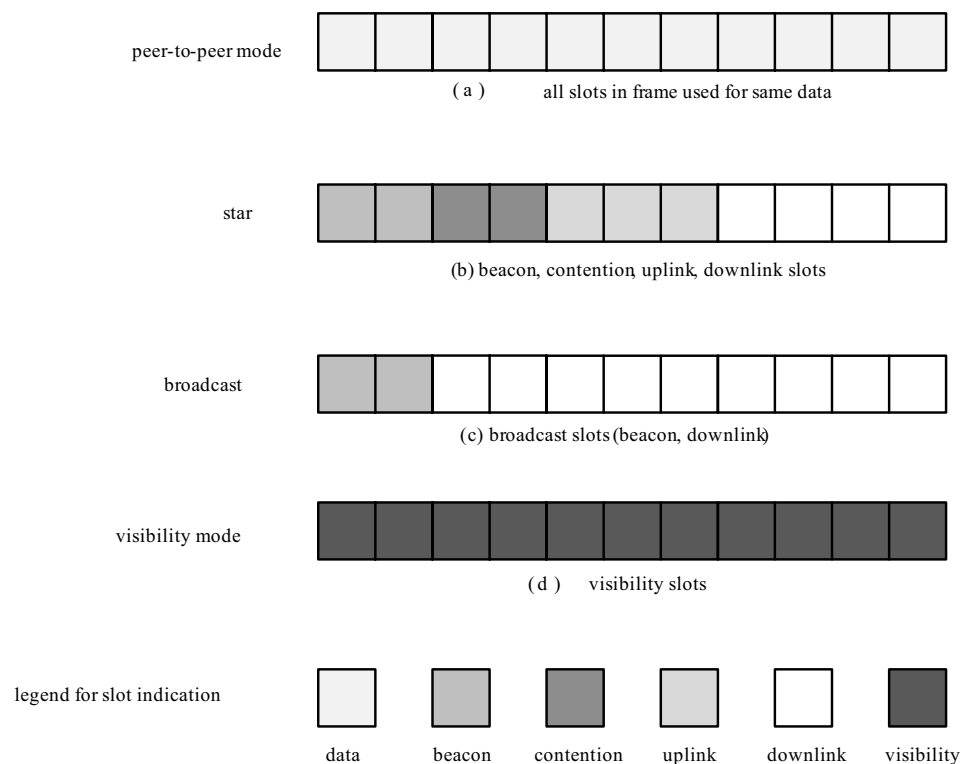


Figure 14—Example usage of frame structure for multiple topologies

Figure 14 provides an example usage of frame 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 period. The uplink and downlink GTS slots are used in the CFP periods. Visibility or idle patterns can be sent in the visibility slots during idle or RX modes of the infrastructure to ensure continuous output and mitigate flicker and are also used for point-and-shoot mode to ensure visibility.

5.1.1.1.1 Contention access period (CAP)

The CAP shall start immediately following the beacon and complete before the beginning of the CFP on a superframe slot boundary. If the CFP is zero length, the CAP shall complete at the end of the active portion of the superframe. The CAP shall be at least $aMinCAPLength$ optical clocks, unless additional space is needed to temporarily accommodate the increase in the beacon frame length needed to perform GTS maintenance (see 5.2.2.1.3) and shall shrink or grow dynamically to accommodate the size of the CFP.

All frames, except acknowledgment frames and any data frame that quickly follows the acknowledgment of a data request command (see 5.1.7.3) transmitted in the CAP shall use a slotted random access mechanism to access the channel. A device transmitting within the CAP shall ensure that its transaction is complete (i.e., including the reception of any acknowledgment) one interframe space (IFS) period (see 5.1.1.2) before the end of the CAP. If this is not possible, the device shall defer its transmission until the CAP of the following superframe.

5.1.1.1.2 Contention-free period (CFP)

The CFP shall start on a slot boundary immediately following the CAP and it shall complete before the end of the active portion of the superframe. If any GTSS have been allocated by the coordinator, they shall be located within the CFP and occupy contiguous slots. The CFP shall therefore grow or shrink depending on the total length of all of the combined GTSS. Communication between devices can take a variable number of slots. A single device or user can have access to more than a single slot for sustained data transfer in the frame, if there are slots available.

No transmissions within the CFP shall use a unslotted random access mechanism to access the channel. A device transmitting in the CFP shall ensure that its transmissions are complete one IFS period (see 5.1.1.2) before the end of its GTS.

5.1.1.1.3 Visibility support during channel access

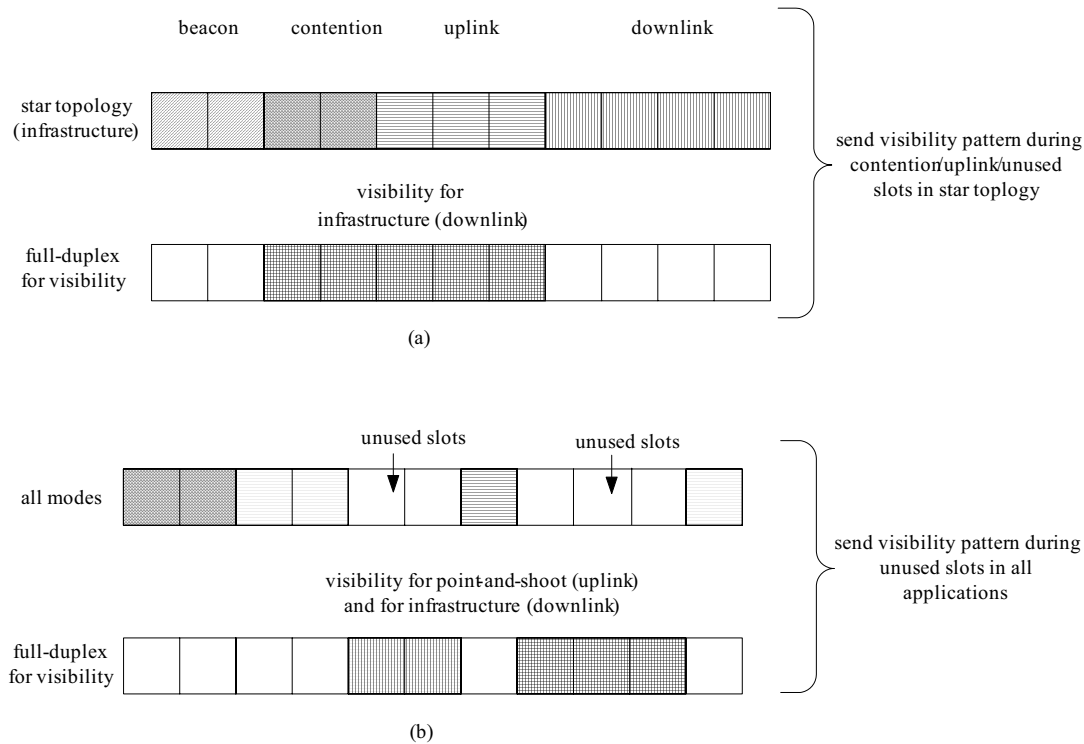


Figure 15—Usage of CVD frames during idle or RX modes of operation

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 15. Visibility support is a very important distinguishing feature for VLC. 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 15, 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 field shown in Table 16, then infrastructure devices shall provide continuous visibility.

5.1.1.2 Interframe spacing (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 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 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 an RIFS of exactly *macMinRIFSPeriod*. The IFS for the different modes are defined in 8.3.4 and the concepts are illustrated in Figure 16.