

IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC)

IEEE Computer Society

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LAN/MAN Standards Committee

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Abstract: Physical layer (PHY) and medium access control (MAC) mechanisms are defined in this standard for wireless personal area networks (WPANs) peer aware communications (PAC) optimized for peer-to-peer and infrastructure-less communications with fully distributed coordination. PAC features include discovery for peer information without association, discovery signaling rate typically greater than 100 kb/s, discovery of the number of devices in the network, scalable data transmission rates typically up to 10 Mb/s, group communications with simultaneous membership in multiple groups typically up to 10, relative positioning, security, and operation in selected globally available unlicensed/licensed bands below 11 GHz capable of supporting these requirements.

Keywords: D2D, device-to-device communications, distributed network synchronization, group communications, IEEE 802.15.8™, infrastructure-less, peer aware communications

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Introduction

This introduction is not part of IEEE Std 802.15.8-2017, IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC).

This standard defines physical layer (PHY) and medium access control (MAC) mechanisms for peer-to-peer or device-to-device (D2D) communications. It offers to improve the delivery and monitoring of ever-growing data services ranging from social networking, gaming, advertisement, and emergency communications, especially when infrastructure-based systems such as base stations or access points have been knocked down by natural disasters. Indeed, in mission-critical communications from public safety to highly reliable wireless systems in scenarios where access to infrastructure does not exist or was shut down due to natural disasters, D2D communications can offer real-time communication services infrastructure-less. Depending on the use case, this standard defines an orthogonal frequency division multiplexing (OFDM) PHY, orthogonal frequency division multiple access (OFDMA) PHY, and ultra-wide band (UWB) PHY operating under a contention access period (CAP) with carrier sense multiple access with collision avoidance (CSMA-CA) or contention free period (CFP) MAC layer.

A motivation for this standard is that current solutions still rely on infrastructure for network synchronization and/or discovery and management. This standard defines ad hoc peer-to-peer and infrastructure-less communications with fully distributed coordination. Peer aware communications (PAC) network features supported by this standard include discovery of peer information without association, scalable number of devices, scalable data transmission rates, multi-group communications, multiple antennas, and two-way ranging.

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IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC)

1. Overview

1.1 General

Peer aware communications (PAC) networks are wireless personal area networks (WPAN) used for direct communication among PAC devices (PDs). Unlike conventional wireless networks, PAC networks use fully distributed coordination where connections are established without involving any infrastructure. This allows efficient direct communication among PDs to support a wide range of peer-to-peer communication scenarios.

1.2 Scope

This standard defines physical layer (PHY) and medium access control (MAC) layer specifications for Wireless Personal Area Networks (WPAN) Peer Aware Communications (PAC) optimized for peer-to-peer and infrastructure-less communications with fully distributed coordination. PAC network features include discovery of peer information without association, discovery signaling rate typically greater than 100 kb/s, discovery of PDs in the neighborhood, scalable data transmission rates, typically up to 10 Mb/s, group communications with simultaneous membership in multiple groups, relative positioning, operation in selected globally available unlicensed/licensed bands below 11 GHz, and security.

1.3 Purpose

The standard provides for scalable, low power, highly reliable wireless communications for emerging services such as social networking, advertising, gaming, streaming, and emergency services. Multiple PHYs are specified to support a variety of frequency bands and requirements.

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.

FIPS 197, Advanced Encryption Standard (AES).¹

FIPS 180-4, Secure Hash Standard.

FIPS 186-4, Digital Signature Standard.

NIST Special Publication 800-56C, Revision 1, Draft.²

IEEE Registration Authority Ethertype values.³

¹ FIPS publications are available at <http://csrc.nist.gov/publications>.

² NIST Special Publications are available at <http://csrc.nist.gov/publications>.

³ IEEE Registration Authority Ethertype values are available at <https://standards.ieee.org/develop/regauth/ethertype/eth.csv>.

3. Definitions, acronyms, abbreviations, and word usage

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this subclause.⁴

authentication: The procedure used to verify the authenticity of a message.

burst: A group of ultra-wide band (UWB) pulses occurring at consecutive chip periods, or the transmission of a set of consecutive frames without requesting an Ack frame for other PHYs.

carrier aggregation: This refers to combining two contiguous channels of 10 MHz in order to increase the transmission bandwidth.

channel scan: The procedure to probe a channel or a number of channels.

complex channel: A combination of a channel [radio frequency (RF) center frequency] and a code sequence.

contention access period: A period of time during which access to the wireless medium is based on contention.

contention free period: A period of time during which access to the wireless medium is free of contention.

cyclic-superframe: A periodic time interval comprising multiple superframes with specified active and inactive periods repeated in a specified sequence.

de-peering: The termination of the link(s) established by peering.

device ID: The unique ID of a PD, i.e., its MAC address.

discovery: Detection of the presence of other PDs and their services (discovery information).

ED channel scan: A channel scan performed by measuring the peak energy in a channel or a number of channels.

frame: The format of aggregated bits from a medium access control layer entity that is transmitted together in time.

idle power indicator (IPI): A physical layer (PHY) indication of the total channel power (noise and interference) as measured in the channel at the receiving antenna connector while the PD is idle, i.e., neither transmitting nor receiving a frame.

mean pulse repetition frequency (PRF): The total number of pulses within a symbol divided by the symbol duration.

network synchronization: The coordination of timing among PDs.

⁴ *IEEE Standards Dictionary Online* is available at <http://dictionary.ieee.org>.

PAC device (PD): Any entity containing an implementation of IEEE 802.15.8™.

packet: The formatted, aggregated bits that are transmitted together in time across the physical medium.

peak pulse repetition frequency: The maximum rate at which an ultra-wide band physical layer emits pulses.

peer aware communications (PAC) network: A peer-to-peer wireless proximity network in which devices implementing IEEE 802.15.8™ communicate with other peer devices.

peering: The establishment of communication links among PDs subsequent to discovery.

ranging frame: An ultra-wide band frame having the ranging bit set in the physical layer header.

ranging marker: The start of the first symbol of the physical layer header of a ranging frame.

reference or pilot signal: A signal containing pilot symbols inserted into the PPDU that is used to perform channel estimation.

reference timing: A reference that represents the beginning of a superframe and is used by a PD to achieve network synchronization.

resource element: A unit of OFDM resources of a bandwidth of 90 kHz and duration of 0.5 ms.

superframe: A periodic time interval comprising the synchronization period, the discovery period, the peering period, and the communication period.

TDD frame: A physical layer frame consisting of two switching slots and eight data slots.

3.2 Acronyms and abbreviations

AES	advanced encryption standard
AGC	automatic gain control
AOA	angle of arrival
AR	acknowledgment request
BER	bit error rate
BJ	beam jittering
BPM	burst position modulation
BPSK	binary phase-shift keying
BW	bandwidth
CAP	contention access period
CCA	clear channel assessment
CFP	contention free period
CP	cyclic prefix
CQI	channel quality indicator
CRC	cyclic redundancy check
CS	carrier sense
CSI	channel state information
CSMA/CA	carrier sense multiple access with collision avoidance
CTS	clear to send
CW	contention window
CWIF	contention window indication field
DFT	discrete Fourier transform
DIP	discovery information present
DP	discovery period
DPS	dynamic preamble selection
DRB	discovery resource block

DRS	discovery resource block signal
DSN	data sequence number
DS-TWR	double-sided two-way ranging
EC	elliptic curve
ECDSA	elliptic curve digital signature algorithm
ED	energy detection
E-DH	Extended Diffie-Hellman
EIED	exponential increase exponential decrease
EIRP	effective isotropic radiated power
EK	ephemeral key
EVM	error vector magnitude
FCS	frame check sequence
FEC	forward error correction
FFT	fast Fourier transform
FIPS	federal information processing standard
FSK	frequency-shift keying
GCMP	Galois counter mode protocol
GK	group key
GMAC	Galois message authentication code
GPSK	Gaussian phase-shift keying
HCS	header check sequence
HKDF	hash-based key derivation function
IFFT	inverse fast Fourier transform
IFS	inter-frame space
IK	identity key
IPI	idle power indicator
ITU	international telecommunications union
LFSR	linear feedback shift register
LIFS	long inter-frame space
LSB	least significant bit
LBT	listen before talk
LTF	long training field
MAC	medium access control
MLDE	MAC layer data entity
MCS	modulation and coding scheme
MHR	MAC header
MIAT	measured inter-arrival time
MIC	message integrity code
MIFS	minimum inter-frame space
MIMO	multiple input multiple output
MLME	MAC layer management entity
MSB	most significant bit
NAV	network allocation vector
NF	noise figure
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOK	on off keying
OPK	one-time pre-key
PAC	peer aware communications
PAPR	peak-to-average power ratio
PCO	pulse coupled oscillator
PD	PAC device
PDME	PD management entity
PER	packet error rate
PHR	PHY header
PHY	physical layer
PIB	PAC network information base
PLME	physical layer management entity
PN	packet number
PP	peering period
PPDU	PHY protocol data unit
PRBS	pseudo-random binary sequence

PRF	pulse repetition frequency
PSD	power spectral density
PSDU	PHY service data unit
PSR	preamble symbol repetition
QAM	quadrature amplitude modulation
QC-LDPC	quasi-cyclic low density parity check code
QoS	quality of service
QPSK	quadrature phase-shift keying
RCPI	received channel power indicator
REs	resource elements
RF	radio frequency
RFRAME	ranging frame
RI	rank indicator
RMARKER	ranging marker
RMS	root-mean-square
RS	Reed-Solomon
RSC	receive sequence count
RSSI	received signal strength indicator
RTD	round-trip delay
RTS	request to send
SAP	service access point
SBPSK	spread binary phase-shift keying
SECDED	single error correct double error detect Hamming code
SFD	start-of-frame delimiter
SHA	secure hash algorithm
SHR	synchronization header
SINR	signal to interference-plus-noise ratio
SK	secret key
SKF	security key frame
SNR	signal-to-noise ratio
SP	synchronization period
SPK	signed pre-key
STF	short training field
SYNC	synchronization
TDD	time division duplex
TK	temporal key
TOF	time of flight
TOIF	timing-offset indication field
TPDRI	target packet delivery ratio indicator
ULA	uniform linear array
UWB	ultra-wide band
XOR	exclusive OR
ZC	Zadoff-Chu

3.3 Word usage

In this document, the word *shall* is used to indicate a mandatory requirement. The word *should* is used to indicate a recommendation. The word *may* is used to indicate a permissible action. The word *can* is used for statements of possibility and capability.

4. Format conventions

4.1 General

Throughout this standard, unless otherwise stated, data structures exposed in interfaces (SAPs) through primitives are represented using the serial bit convention and format specified in this clause. However, vendors may implement such interfaces in other forms, e.g., 4- or 8-bit parallel. Within a PHY frame using the serial bit convention, the size of a MAC frame shall be less than the maximum PSDU size supported by the PHY in use. A PHY frame using the serial bit convention represents the over-the-air messages in this standard.

4.2 Fields

4.2.1 Overview

The general format of a data structure is shown in Figure 1. Each field is represented by a column with a row indicating the size of the field in either octets or bits; and another row below indicating the name of the field with the convention to begin every word with a capital letter. This data structure is recursive such that a field may contain a data structure, which is in turn composed of fields.

Octets: 2	Bits: 0–5	6–7	Octets: 1	Variable	...
Field Name A	Field Name B	Reserved	Field Name C Length	Field Name C	...

Octets: 2	Bits: 0–5	6–7	Octets: 1	Variable	...
Field Name D	Field Name E	Reserved	Field Name F Length	Field Name F	...

Figure 1—General data structure format

The form “Octets: **n**” means the field is **n** octets long. The form “Bits: **n**” or “Bits: **m–n**” means bit number **n** or bits **m** to **n** of an octet. If a field uses the “Bits:” form, a complete octet shall be described as illustrated in Figure 1. If a field length appears without either Octets or Bits, then the preceding units apply as illustrated in Figure 1.

The form “Octets: **n/m/l**” means the field can be **n**, **m** or **l** octets long. The form “**Variable**” means the size in octets of the field changes and an exact value cannot be written. In that case, an extra field may be added to indicate the length of the “**Variable**” size field for a particular MAC frame as illustrated in Figure 1. In this example, the size in octets range from 0 to 255.

When the number of fields is such they cannot be fitted in one row, additional rows are used as illustrated in Figure 1. The order of representation is strict from the upper row to the lower row with the leftmost field occurring before the next field to its right, and subsequently until the lower rightmost field is reached and occurring last.

4.2.2 Numbers

Numbers are represented in decimal (nnn) or binary (0bnnn) notation with the number of digits indicated, or hexadecimal (0xmm) notation. For example, 0b001 is a 3 digit binary number of value 1 and 0x01 is the hexadecimal number of value 1. Numbers specified in fields, tables, and parameters of service primitives can be integers or single-precision floating-point numbers. Numbers specified as “b-bit integers” denote b-bit unsigned integers, where b is a positive integer number. For simplicity, 8-bit unsigned integers are specified as “Integers”. “Signed integers” are 32-bit signed integers with two’s complement for negative numbers. Single-precision floating-point numbers are specified as “Float”.

4.2.3 Strings

The term string is used when the field’s content is not interpreted as a number specified in 4.2.2, but rather mapped onto another format. For example, the octet 0b01000001 represents the letter “A” in the extended ASCII format, or cryptographic keys.

4.2.4 Transmission order

For every field, the bit transmission order shall be performed from the leftmost octet (LMO) to the rightmost octet (RMO) in the field, and inside an octet from the least significant bit (LSB) to the most significant bit (MSB); as shown in Figure 2, where the content’s field is assumed as AC-DE-48-23-45-67 for illustration.

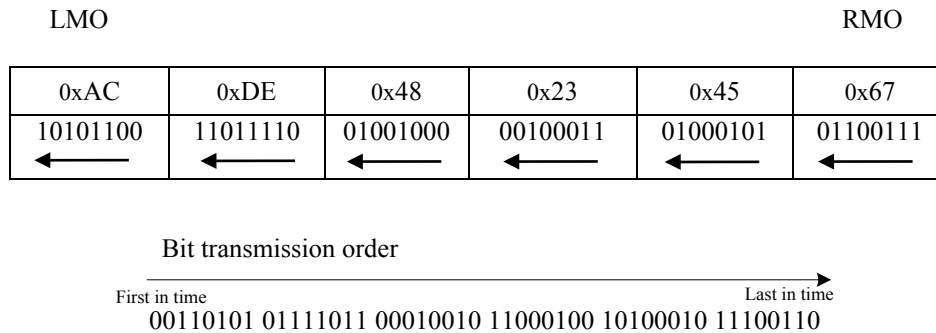


Figure 2—Bit transmission order

4.2.5 Reserved fields

Each bit within any Reserved field shall be set to zero on transmission and shall be ignored on reception.

4.2.6 Data rate units

The data rate units in terms of symbols and abbreviations are specified in Table 1.

Table 1—Data rate units

Decimal multiples of bits	Symbol	Abbreviation
kilo-bits per second	kb/s	Kbps
Mega-bits per second	Mb/s	Mbps
Decimal multiple of symbols		
kilo-symbols per second	kilo-symbols/s	Ksps
Mega-symbols per second	Mega-symbols/s	Msps

5. General description

5.1 General

A PAC network is a fully distributed communication network that allows direct communication among PDs. The main objectives of a PAC network are scalability, low power consumption, highly reliable wireless communications for emerging services with fully distributed coordination not relying on infrastructure. In addition, PAC networks allow fast peer discovery and scalable peer group communications.

Some of the capabilities provided by this standard are as follows:

- Communication can be unicast (one-to-one), or multicast (one-to-many or many-to-many) or broadcast.
- Fully distributed coordination
- Fully distributed synchronization
- Discovery of peer information before peering
- Group communication with concurrent membership in multiple groups
- Relative positioning
- Carrier sense multiple access with collision avoidance (CSMA/CA) or ALOHA channel access
- Low power consumption
- Channel quality indication (CQI)
- Scalable data rates up to 320 Mb/s

This standard defines multiple PHYs operating in a variety of frequency bands, as described in Clause 11, Clause 12, and Clause 13.

5.2 Components of an IEEE 802.15.8 PAC network

A system conforming to this standard consists of two or more PDs. PDs operating on the same physical channel constitute a PAC network. All PDs in a PAC network are equal in terms of operation.

5.3 Network topologies

Several topologies, such as mesh topology or star topology, may be used to support interactions among PDs for various services. One-to-one, one-to-many, and many-to-many topologies can be formed.

This standard can supports simultaneous communication sessions for different applications and participation in multiple independent communication sessions with different peers at the same time. See Figure 3.

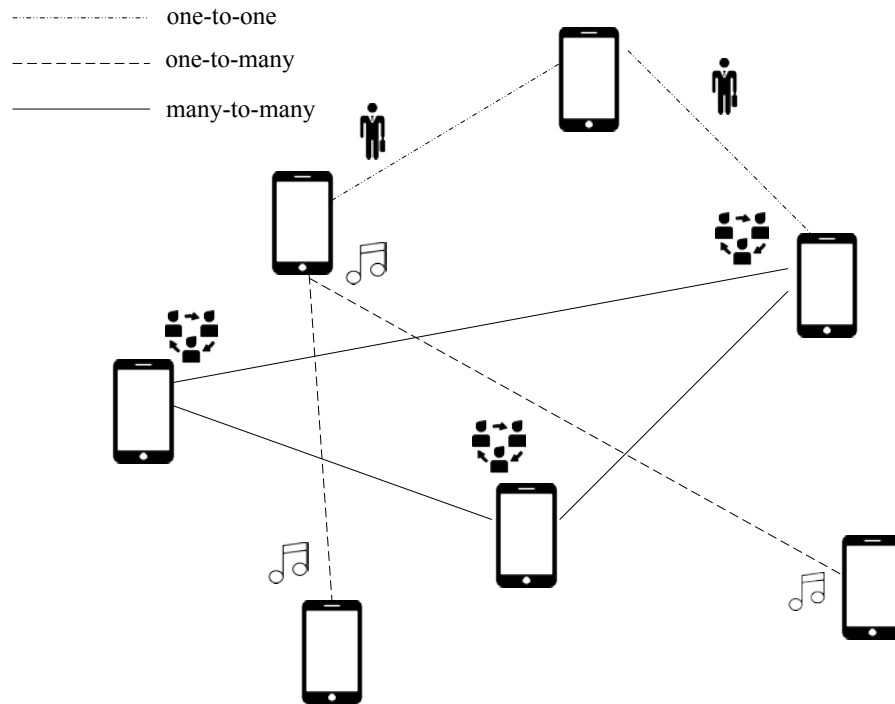


Figure 3—Example of concurrent communication

5.4 Architecture

5.4.1 Overview

The IEEE 802.15.8 architecture is specified in terms of a number of layers in order to simplify the standard. Each layer is responsible for one part of the standard and offers services to the higher layers.

The interfaces between the layers serve to define the SAPs that are described in this standard.

A PD shall support at least one PHY, which contains the radio frequency (RF) transceiver along with its low-level control mechanism, and a MAC layer that provides access to the physical channel for all types of data transfer. Figure 4 shows these layers in a graphical representation, which are described in 5.4.2, 5.4.3 and 8.1. The next higher layers typically consist of a network layer, which provides network configuration, IP routing if applicable, etc., and an application layer that provides the intended function of the device. The definition of these higher layers is outside the scope of this standard.

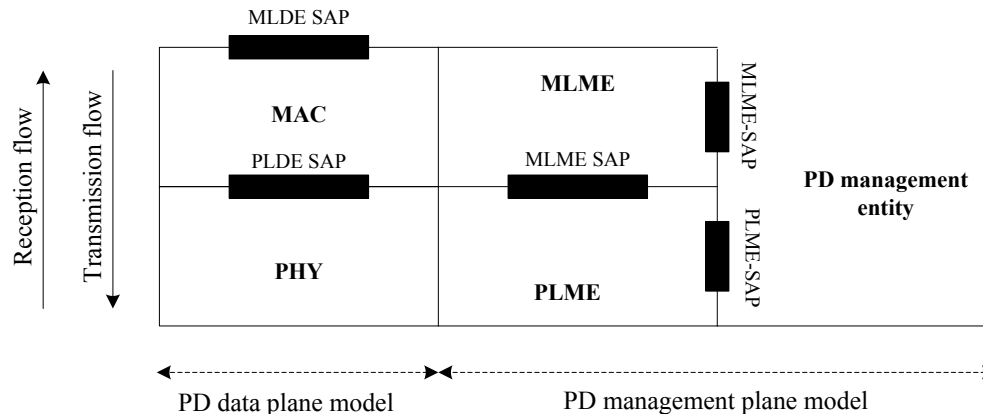


Figure 4—PAC device architecture

5.4.2 Physical layer (PHY)

The PHY provides two services: the PHY layer data entity (PLDE) service and the PHY layer management entity (PLME) service with interfaces PLDE-SAP and PLME-SAP, respectively. The PLDE service enables the transmission and reception of PHY protocol data units (PPDUs) across the physical radio channel. The general PHY requirements are described in Clause 9 and the PHY services are described in Clause 10.

The features of the PHY are activation and deactivation of the radio transceiver, energy detection (ED), channel quality indicator (CQI), channel switching, clear channel assessment (CCA), and transmitting and receiving packets across the physical medium. The UWB PHY supports precision ranging.

A discussion of the coexistence of the various IEEE 802.15.8 PHYs with other wireless systems is given in Hernandez et al. [B1].⁵

5.4.3 MAC layer

The MAC layer provides two services: the MAC layer data entity (MLDE) service and the MAC layer management entity (MLME) service with interfaces MLDE-SAP and MLME-SAP, respectively. The MLDE enables the transmission and reception of MAC frames across the PHY layer. The MAC functional description is detailed in Clause 6.

The features of the MAC layer are channel scan, distributed synchronization, resource elements management, acknowledged frame delivery, discovery, peering, de-peering, and support of relative positioning. In addition, the MAC layer provides security mechanisms.

5.5 Functional overview of the general functions of PAC networks

5.5.1 Superframe structure

The operation of the PAC network as specified by this standard is based on a superframe structure that repeats continuously in back-to-back time periods. The superframe consists of the synchronization period,

⁵ The numbers in brackets correspond to the numbers of the bibliography in Annex H.

the discovery period, the peering period and a communication period that is subdivided into a contention access period (CAP), and a contention free period (CFP). The detailed superframe structure is specified in 6.2.

5.5.2 Cyclic-superframe

For efficient synchronized group communication, the PAC MAC superframe uses a period of fixed length. For the application to choose a duty-cycle of activity to suit the particular traffic needs of its peer group and to reduce interference between adjacent PDs or PAC groups, the cyclic-superframe is specified. The cyclic-superframe is a periodic time interval comprising multiple superframes with specified active and inactive periods repeated in a specified sequence. During inactive periods, a PD may turn off its receiver, etc., to conserve power. The cyclic superframe shall be overridden when the next higher layer requests to use a given period of the superframe in the current and subsequent superframes if required (the MAC layer does not need to wait until the change of cyclic-superframe configuration is completed). Once the cyclic-superframe configuration is completed, the MAC layer shall resume operation with the new cyclic superframe configuration. The details of the cyclic-superframe structure are specified in 6.3.1.

The support of cyclic superframe is mandatory for the OFDM PHY (Clause 11) and optional for the UWB PHY (Clause 13).

5.5.3 Communication types

Communication types used in this standard are categorized as unicast, multicast and broadcast transmission.

- Unicast is a one-to-one data communication between a pair of PDs.
- Multicast is a one-to-many or many-to-many data communication to specific PDs in a group.
- Broadcast is a one-to-many data communication to all PDs within reachable range.

5.5.4 Synchronization

Synchronization is the procedure to acquire reference timing of the MAC superframe for PDs to discover other PDs and to communicate with them. When first started, a PD uses the initial synchronization procedure to synchronize its reference timing specified in 6.8.2. After completing the initial synchronization procedure, the PD follows the maintaining synchronization procedure specified in 6.8.3. If a PD loses synchronization it uses the re-synchronization procedure to reestablish it.

The Synchronization procedures for PAC networks with UWB PHY are specified in 6.14.4.2 and 6.14.4.3.

5.5.5 Discovery

Discovery is the procedure for a PD to detect other PDs in the surroundings. The MAC supports one-way discovery, untargeted two-way discovery, and targeted two-way discovery for Clause 11 and Clause 12. For UWB PHY, discovery is based on using the sync frame as per 6.14.5.

For one-way discovery, the discovery information is transmitted in a time-frequency matrix, which is divided into a set of discovery resource elements of 21 octets each. The PD's next higher layer selects a discovery resource element to transmit its discovery information, or scans such discovery resource elements to detect other PDs' discovery information.

For untargeted two-way discovery, the PD's next higher layer broadcasts the Discovery Request command frame in the CAP, and expects responses from the PDs' next higher layer that have received the Discovery Request command frame and agreed to send a Discovery Response command frame.

For targeted two-way discovery, the PD's next higher layer multicasts the Discovery Request command frame in the CAP, and expects responses from the PDs' next higher layer that have received the Discovery Request command frame and agreed to send a Discovery Response command frame.

5.5.6 Peering

Peering is the procedure to establish a communication link among discovered PDs. The MAC supports one-to-one peering, one-to-many peering, and many-to-many peering. The peering procedure is specified in 6.10.

6. MAC functional description

6.1 Overview

The MAC layer handles all access to the physical radio channels and is responsible for the following tasks:

- Network synchronization
- Supporting device discovery
- Supporting peering and de-peering
- Supporting security at MAC level
- Employing mechanisms for channel access
- Providing reliable unicast between peer MAC entities
- Providing multicast group communication as well as broadcast and unicast

Throughout this standard the reception of a MAC frame is specified as successful, if it passes through the receive frame filtering specified in 6.7.2.

The PAC information base (PIB), consisting of variables and constants required to manage the MAC and PHY layers, are written in italics (see 8.5).

The next higher layer accesses the services provided by the MAC through the MAC layer management entity service access point (MLME-SAP) on behalf of the PD management entity (ME) as described in Clause 8, and the MAC layer data entity service access point (MLDE-SAP) as described in Clause 8. The primitives for the MLME-SAP are written in all capital letters prefixed with MLME, e.g., MLME-SCAN.confirm. The primitives for the MLDE-SAP are written in all capital letters prefixed with MLDE, e.g., MLDE-DATA.request.

6.2 Superframe structure

6.2.1 General

The superframe structure is illustrated in Figure 5. The superframe is divided into 5 periods in the following order: synchronization period (SP), discovery period (DP), peering period (PP), contention access period (CAP), and contention free period (CFP). The duration of the superframe shall be set to *aSuperframeDuration* specified in Table 87.

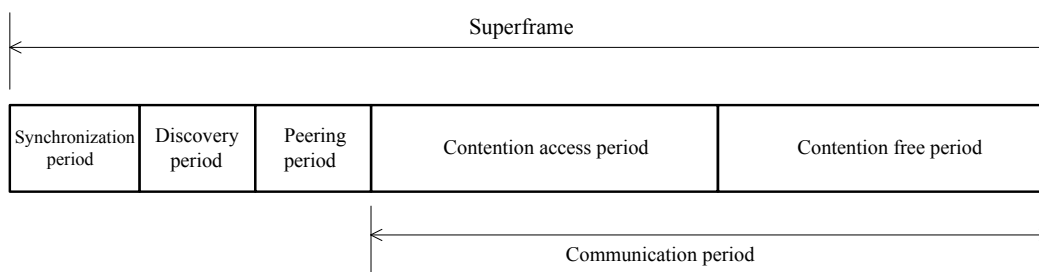


Figure 5—The superframe structure

6.2.2 Synchronization period

The synchronization period shall start at the beginning of each superframe and shall have a fixed length of *aSyncPeriodDuration*. The synchronization signals, specified in Figure 72, are transmitted within the synchronization period using a contention based random access mechanism for initial network synchronization and for ongoing maintenance of synchronization, as described in 6.8.

6.2.3 Discovery period

The discovery period shall start immediately following the synchronization period and shall have a fixed length of *aDiscoveryPeriodDuration*. Discovery information specified in 6.6.5 is transmitted within the discovery period. Transmission and reception within the discovery period shall use the mechanism described in 6.9.4.1.

6.2.4 Peering period

The peering period shall start immediately following the discovery period and shall have a fixed length of *aPeeringPeriodDuration*. Transmission and reception within the peering period shall use the same contention based random access mechanism designed for CAP, which is described in 6.12.2 and 6.5.1.1.

6.2.5 CAP

The CAP shall start immediately following the peering period and shall have a fixed length of *aCapDuration*. Transmission and reception within the CAP shall use the contention based random access mechanism described in 6.5.1.1. The CAP can be used for the transmission of management messages, including discovery management messages, as well as data packets.

6.2.6 CFP

The CFP shall start immediately following the CAP and shall have fixed length of *aCfpDuration*. Transmission and reception within the CFP shall be performed as described in 6.5.2.

Transmissions within the CFP shall be performed without a CSMA-CA contention mechanism to access the channel.

6.3 Cyclic-superframe

6.3.1 Cyclic-superframe structure

A cyclic-superframe is a periodic time interval comprising superframes. A cyclic-superframe contains multiple superframes with active and inactive periods. During an inactive period, a PD may turn off its transceiver, etc., in order to conserve power and reduce interference. Each period of every superframe, except the synchronization period, may be configured to be either active or inactive. A superframe of a cyclic-superframe shall use one of 16 possible combinations of active and inactive periods, which are illustrated in Figure 6.

A cyclic-superframe shall be formed with the superframes using two patterns of active and inactive periods: pattern A and pattern B, each of which can be one of 16 types. The cyclic-superframe consists of a number

of repetitions of pattern a superframe, followed by a number of repetitions of pattern B superframe, as shown in Figure 7 The maximum cyclic-superframe size is 4096 superframes. If a cyclic-superframe size is one, the cyclic-superframe is formed only with the pattern a superframe.

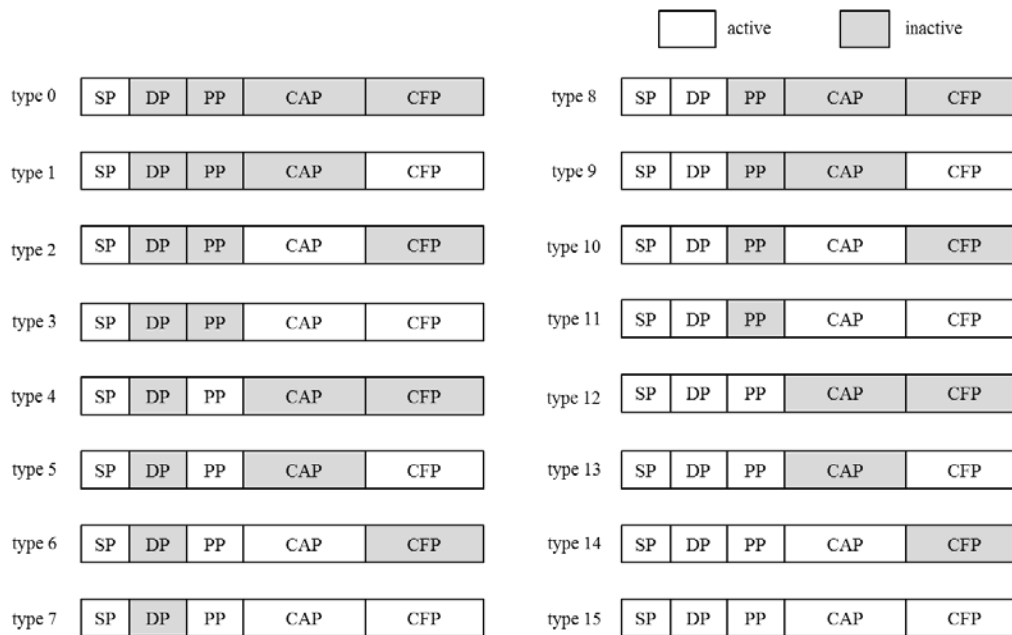


Figure 6—Combinations of active and inactive periods of a superframe

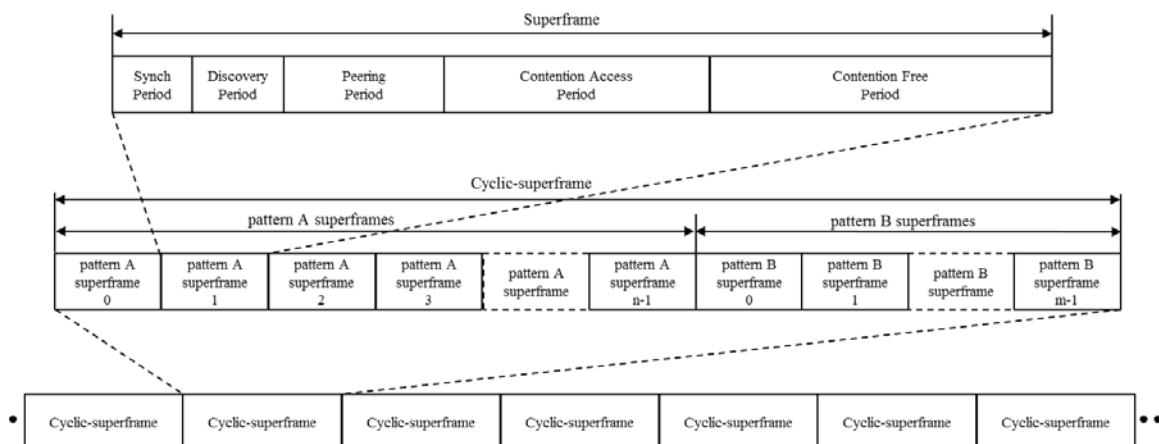
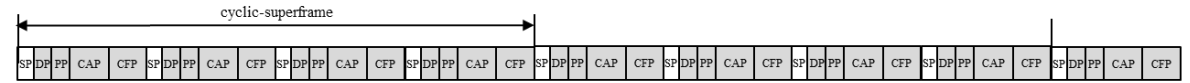


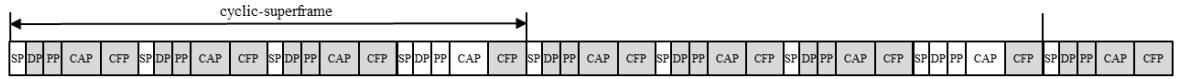
Figure 7—The cyclic-superframe structure

The next higher layer is responsible for configuring the appropriate cyclic-superframe structure for its application(s) usage, via the cyclic-superframe descriptors present in the *macCyclicSuperframeStructureList* PIB attribute.

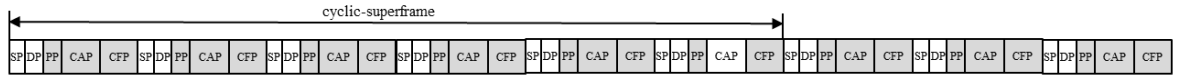
Several examples of a cyclic-superframe structure are shown in Figure 8.



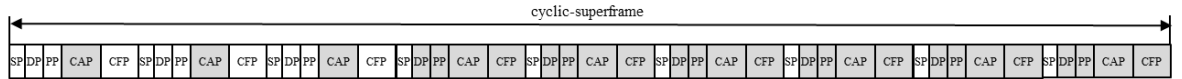
a) cyclic-superframe size = 4, number of pattern A superframe = 2, type of pattern A superframe = 0b0000, type of pattern B superframe = 0b0000



b) cyclic-superframe size = 4, number of pattern A superframe = 3, type of pattern A superframe = 0b0000, type of pattern B superframe = 0b1110



c) cyclic-superframe size = 6, number of pattern A superframe = 5, type of pattern A superframe = 0b1000, type of pattern B superframe = 0b1010



d) cyclic-superframe size = 9, number of pattern A superframe = 3, type of pattern A superframe = 0b1101, type of pattern B superframe = 0b0000

Figure 8—Example of cyclic-superframe structures

Figure 8a) shows a cyclic-superframe with two pattern A superframes each with the SP active (0b0000), followed by two pattern B superframes, each with the SP active (0b0000). This example cyclic-superframe could be used during synchronization.

Figure 8b) shows a cyclic-superframe with three pattern A superframes each with the SP active (0b0000), followed by one pattern B superframe with SP, DP, PP and CAP active (0b1110). This example cyclic-superframe could be used for supporting discovery every four superframes.

Figure 8c) shows a cyclic-superframe with five pattern A superframes, each with SP and DP active (0b1000), followed by one pattern B superframe with SP, DP and CAP active (0b1010). This example cyclic-superframe could be used for supporting energy efficient data transmission by transmitting a Data frame over the CAP every six superframes.

Figure 8d) shows a cyclic-superframe with three pattern A superframes each with SP, DP, PP and CFP active (0b1101), followed by six pattern B superframes with SP active (0b0000). This example cyclic-superframe could be used for supporting reliable data transmission by using three consecutive Data frames transmissions over the CFP, before sleeping for the duration of six superframes.

6.3.2 Maintaining cyclic-superframe structure

6.3.2.1 General

If the PIB *macCyclicSuperframeEnabled* is set to TRUE, the MAC layer shall maintain the cyclic-superframe structure and manage the reception and transmission frames accordingly. The MAC layer may operate the multiple cyclic-superframes concurrently. The next higher layer configures a cyclic-superframe for providing an application service. The next higher layer configures the background cyclic-superframe that instructs the MAC layer to turn the transceiver on periodically for providing active periods to receive or transmit Cyclic-superframe Advertise Request command frames. The background cyclic-superframe is always present and may be updated when adding or deleting a cyclic-superframe for an application service.

The cyclic-superframe configuration is stored in the Cyclic-Superframe Descriptor of the PIB *macCyclicSuperframeStructureList*. The cyclic-superframe configuration is identified with the MAC address of a PD starting the cyclic-superframe and the cyclic-superframe identifier selected by the PD's MAC layer. The cyclic-superframe identifier of the background cyclic-superframe is zero.

At any time it wishes, the next higher layer may modify the cyclic-superframe structure using the MLME-CYCLICSUPERFRAME.request primitive to add, update, or delete any of cyclic-superframe descriptors in the PIB *macCyclicSuperframeStructureList*.

6.3.2.2 Maintaining cyclic-superframe structure after starting a PD

After starting a PD, the MAC layer maintains the cyclic-superframe structure as shown in Figure 9.

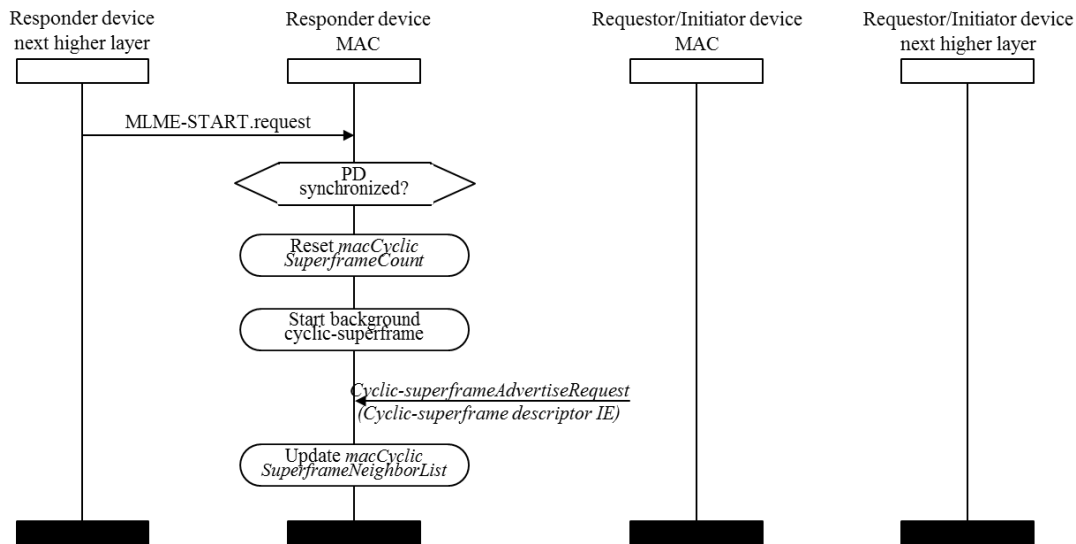


Figure 9—Sequence chart for maintaining cyclic-superframe after starting a PD

- After synchronization, the MAC layer shall reset *macCyclicSuperframeCount* and start to control the PHY according to the background cyclic-superframe. The background cyclic-superframe has default value defined in the *macCyclicSuperframeStructureList* of Table 87.
- Irrespective of the cyclic superframe configuration, the MAC layer listens during the peering period for *aCyclicSuperframeAdvWindow* consecutive superframes to collect neighbor PAC groups' cyclic-superframe structures by receiving the Cyclic-superframe Advertise Request command frames. The received cyclic-superframe configurations of neighbor PAC groups are added to the *macCyclicSuperframeNeighborList*. Based on *macCyclicSuperframeNeighborList*, the next higher layer may select a start time of a cyclic-superframe avoiding interference with neighbor running PAC groups when starting a new PAC group.

6.3.2.3 Maintaining cyclic-superframe structure for discovery

For discovery or for being discovered, the MAC layer maintains the cyclic-superframe structure as shown in Figure 10.

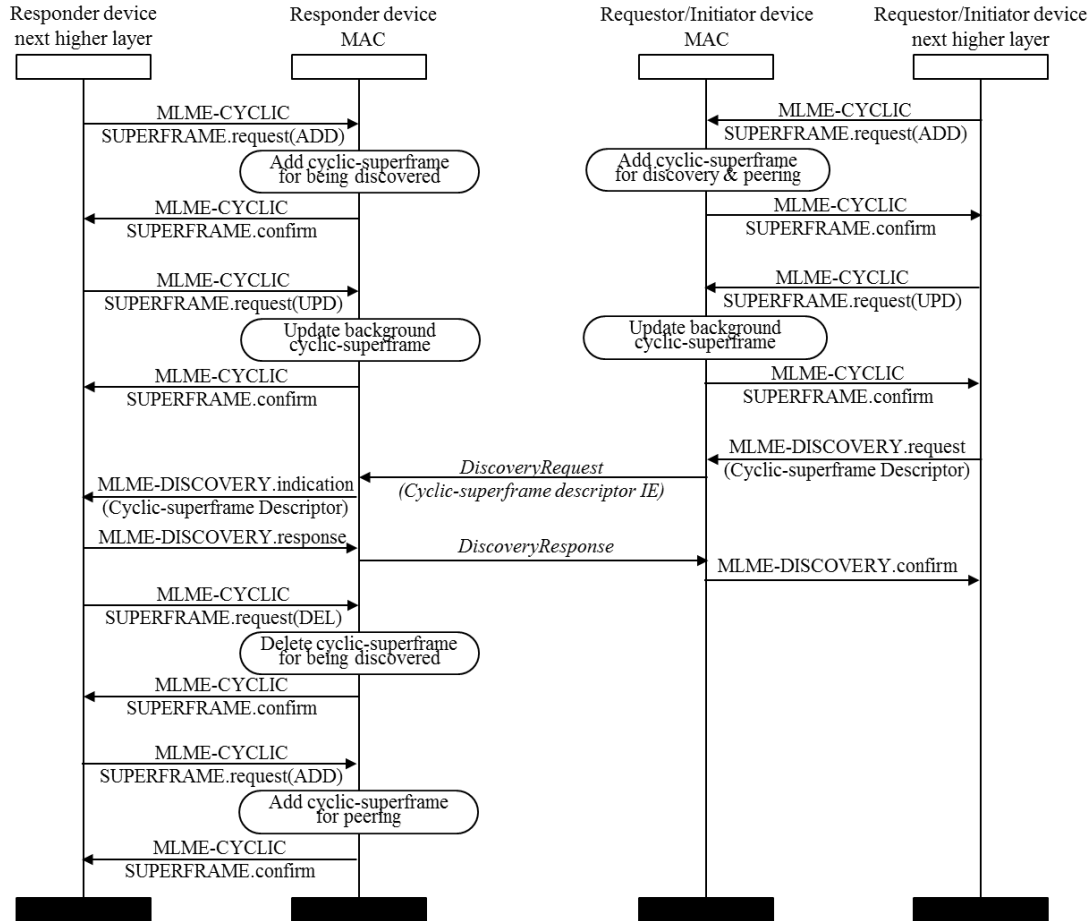


Figure 10—Sequence chart for maintaining cyclic-superframe for discovery

- If a PD intends to be discovered, the next higher layer may select the cyclic-superframe configuration adequate to support being discovered procedure. The new cyclic-superframe for being discovered is added by the MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to ADD and the Cyclic-superframe Descriptor parameters: Initiator PD address set to the PD MAC address, Cyclic-superframe Identifier selected by the next higher layer for registering the cyclic-superframe descriptor to the PIB *macCyclicSuperframeStructureList*, Cyclic-superframe size, Number of pattern A superframes, Number of pattern B superframes, Type of pattern A superframe, Type of pattern B superframe, and Start time of cyclic-superframe. The MAC layer shall add a cyclic-superframe descriptor to *macCyclicSuperframeStructureList* and start the operation of the new cyclic-superframe for being discovered at the Start time of cyclic-superframe of the Cyclic-superframe Descriptor parameter.

- The next higher layer may update the background cyclic-superframe to adapt to the changing cyclic-superframe structure by the MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to UPDATE and the Cyclic-superframe Descriptor parameters: Initiator PD address set to the PD MAC address, Cyclic-superframe Identifier set to zero, modified Cyclic-superframe structure configuration, and Start time of cyclic-superframe set to the Start time of the Cyclic-superframe Descriptor parameter of MLME-CYCLICSUPERFRAME.request primitive requested for adding a new cyclic-superframe for being discovered procedure.
- If multiple cyclic-superframes are already operated, newly added cyclic-superframe structure is merged over the currently operating cyclic-superframes, as described in 6.3.3.
- When the next higher layer wants to initiate two-way untargeted discovery or two-way targeted discovery, or many-to-many group discovery, it may do so by first issuing MLME-CYCLICSUPERFRAME.request primitive to add a new cyclic-superframe for the discovery procedure and peering procedure, and then using the MLME-DISCOVER.request primitive with Discovery Type, Discovery Resource, Discovery Range Min, Discovery Range Max, Destination Address, Multicast Address, Address Mode, and Cyclic-Superframe Descriptor parameter, where the Cyclic-Superframe Descriptor are identical in both primitives. The Cyclic-Superframe Descriptor parameter of the MLME-DISCOVER.request primitive is copied into the content field of a Cyclic-superframe descriptor IE included in the Discovery Request command, as described in 7.4.3.2.
- As shown in Figure 10, the MAC layer of responder PD receiving the Discovery Request command shall report its reception via the MLME-DISCOVERY.indication primitive with Discovery Type and Cyclic-superframe Descriptor parameters. The Cyclic-superframe Descriptor parameter is copied from Cyclic-superframe descriptor IE content field of the received Discovery Request command.
- If the next higher layer of the responder PD wishes to be discovered, it responds using the MLME-DISCOVERY.response primitive, as described in 8.3.4.5.
- The next higher layer of the responder PD may then instruct the MAC layer to use the cyclic-superframe of the requestor PD by deleting the cyclic-superframe structure used for being discovered and adding the cyclic-superframe structure provided by the requestor PD. The deletion is achieved by issuing an MLME-CYCLICSUPERFRAME.request with the Manipulation Type parameter set to DELETE and the Cyclic-superframe Descriptor parameters: Initiator PD address set to the PD MAC address, Cyclic-superframe Identifier set to the registered cyclic-superframe identifier, and Start time of cyclic-superframe selected by the next higher layer. The addition the cyclic-superframe for peering by the MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to ADD and the Cyclic-superframe Descriptor parameter that is identical with the Cyclic-superframe Descriptor parameter of MLME-DISCOVERY.indication primitive. The MAC layer shall update the cyclic-superframe descriptor of the *macCyclicSuperframeStructureList*. The MAC layer shall start the operation of the updated cyclic-superframe structure at the Start time of cyclic-superframe of the Cyclic-superframe Descriptor parameter of the MLME-CYCLICSUPERFRAME.request primitive.

6.3.2.4 Maintaining cyclic-superframe structure for peering

For peering, the MAC layer maintains the cyclic-superframe structure as shown in Figure 11.

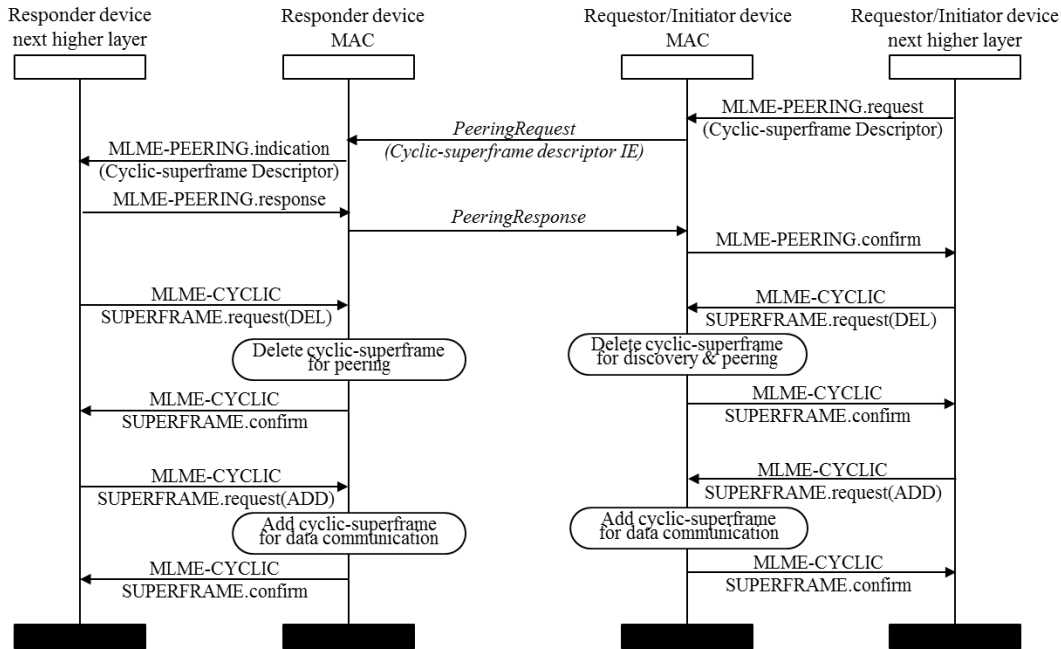


Figure 11—Sequence chart for maintaining cyclic-superframe during peering

- If the next higher layer of initiator PD intends to configure the cyclic-superframe structure for data communication, it may provide the cyclic-superframe configuration in the MLME-PEERING.request primitive with the Request Type, Channel Page, Channel Number, Group ID, Application ID, Destination Address, Multicast Address, PD List, PHY Capability List, Elliptic Curve, Key Descriptor, and Cyclic-Superframe Descriptor. The Cyclic-Superframe Descriptor parameter of the MLME-PEERING.request primitive is copied into Cyclic-superframe descriptor IE content field of the Peering Request command, as described in 7.4.3.2.
- After completing the peering procedure, the upper layer of the initiator PD may start the new cyclic-superframe structure for data communication (i.e., with the Cyclic-superframe Descriptor it used for the MLME-PEERING.request) by issuing a MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to ADD and the Cyclic-superframe Descriptor parameters, which causes the MAC layer to update the cyclic-superframe descriptor of the *macCyclicSuperframeStructureList*. If multiple cyclic-superframes are operating, the newly requested cyclic-superframe is merged into the currently operating cyclic-superframe structures. The MAC layer shall start the operation of the updated cyclic-superframe at the Start time specified by the Cyclic-superframe Descriptor parameter.
- If the next higher layer of the initiator PD intends not to continue the discovery and peering procedure, the next higher layer may delete the cyclic-superframe structure for discovery and peering procedure by MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to DELETE and the Cyclic-superframe Descriptor parameters: Initiator PD address set to the PD MAC address, Cyclic-superframe Identifier set to the registered cyclic-superframe identifier, and Start time of cyclic-superframe selected by the next higher layer.
- As shown in Figure 11, the MAC layer of responder PD receiving the Peering Request command shall report the reception by the MLME-PEERING.indication primitive with Request Type, Source Address, Channel Page, Channel Number, Group ID, Application ID, PHY Capability List, and Cyclic-superframe Descriptor parameters. The Cyclic-superframe Descriptor parameter is copied

from Cyclic-superframe descriptor IE content field of the Peering Request command. If the next higher layer of the responder PD wishes to be peered, the next higher layer may respond to the requester PD by the MLME-PEERING.response primitive.

- The next higher layer of the responder PD may then instruct its MAC layer to use the cyclic-superframe of the requestor PD by deleting the cyclic-superframe structure for peering and adding the cyclic-superframe for data communication. The deletion is achieved by issuing an MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to DELETE and the Cyclic-superframe Descriptor parameters: Initiator PD address set to the requestor PD MAC address, Cyclic-superframe Identifier set to the registered cyclic-superframe identifier, and Start time of cyclic-superframe selected by the next higher layer. The addition the cyclic-superframe for data communication is achieved using the MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to ADD and the Cyclic-superframe Descriptor parameter matching the Cyclic-superframe Descriptor parameter of MLME-PEERING.indication primitive. The MAC layer shall update the cyclic-superframe descriptor of the *macCyclicSuperframeStructureList*. If multiple cyclic-superframes are operating, newly added cyclic-superframe is merged with the currently operating cyclic-superframe structures. The MAC layer shall start the operation of the updated cyclic-superframes at the Start time specified in the Cyclic-superframe Descriptor parameter of the MLME-CYCLICSUPERFRAME.request primitive.

6.3.2.5 Advertising and deleting cyclic-superframe structure

The cyclic-superframe configuration of a PAC group is advertised by a requestor PD or an initiator PD of discovery or peering. The cyclic-superframe configuration of a PAC group is shared with PDs of neighbor PAC groups as follows:

- The MAC layer of a requestor PD or an initiator PD shall send the Cyclic-superframe Advertise Request command frame periodically every *aCyclicSuperframeAdvWindow* superframes, in the peering period of the superframe, starting at a randomly selected superframe within the period of the *aCyclicSuperframeAdvWindow*. The Cyclic-superframe Advertise Request command frame shall be transmitted, irrespective of whether the selected peering periods are marked as inactive in the cyclic superframe structure..
- The MAC layer of a PD listens during the peering period for duration of *aCyclicSuperframeAdvWindow* superframes to collect neighbor PAC groups' cyclic-superframe structures by receiving the Cyclic-superframe Advertise Request command frames. The received cyclic-superframe descriptor of a neighbor PAC group updates the *macCyclicSuperframeNeighborList*. If the Cyclic-superframe Advertise Request command frame for any particular PAC group is not heard for five consecutive *aCyclicSuperframeAdvWindow* periods, the MAC layer shall remove the cyclic-superframe descriptor from the *macCyclicSuperframeNeighborList*.

The cyclic-superframe descriptor is deleted from the *macCyclicSuperframeStructureList* as follows:

- When the discovery procedure or peering procedure, or data communication is terminated, the next higher layer may delete the cyclic-superframe structure by the MLME-CYCLICSUPERFRAME.request primitive with the Manipulation Type parameter set to DELETE and the Cyclic-superframe Descriptor parameter. The cyclic-superframe descriptor identified with the Initiator PD MAC address and Cyclic-superframe identifier is deleted from the *macCyclicSuperframeStructureList*. The currently operating cyclic-superframe structure is reconfigured at Start time specified by the Cyclic-superframe Descriptor parameter of the MLME-CYCLICSUPERFRAME.request primitive.

6.3.3 Access control with cyclic-superframe structure

The cyclic-superframe specifies when a PAC group is able to communicate. Each PD in a PAC group maintains the start time of its cyclic-superframe as follows.

- With reference to the `macCyclicSuperframeNeighborList`, the next higher layer of an initiator PD selects the start time of cyclic-superframe to minimize the likelihood that the new PAC group interferes with its neighbor PAC groups. The `macCyclicSuperframeNeighborList` is obtained using the `MLME-GET.request` primitive.
- The MAC layer maintains the `macCyclicSuperframeCount`, which is a modulo-4096 counter of the number superframes since synchronization. When receiving the Cyclic-superframe descriptor IE, the start time of the cyclic-superframe is given by the following expression:

$$\{(\text{macCyclicSuperframeCount} - \text{Superframe Sequence Number}) + n * \text{Cyclic-superframe Size}\},$$

where n is the smallest integer that lets $\{(\text{macCyclicSuperframeCount} - \text{Superframe Sequence Number}) + n * \text{Cyclic-superframe Size}\}$ be larger than zero.

- A PD can join multiple PAC groups having different cyclic-superframe configurations. Different cyclic-superframe size and different start time of cyclic-superframes cause cyclic-superframes overlapping and some period may be shared with multiple PAC groups. To know which period of a superframe is active for receiving and transmitting a frame, all active cyclic-superframe configurations are considered together, and a period is only considered inactive, when it is inactive in all configurations

The frames transmitted are scheduled for accessing medium as follows:

- Before requesting to receive or transmit a frame, the appropriate period of the cyclic-superframe should be activated. The next higher layer is responsible for selecting a cyclic-superframe structure to satisfy its applications' requirements.
- The MAC layer transmits the Cyclic-superframe Advertise Request command frame at the selected PP.
- The Discovery Request command frame or the Discovery Response command frame is transmitted in the active CAP of the cyclic-superframe configured by the Requestor PD or the Initiator PD.
- The Peering Request command frame or the Peering Response command frame is transmitted in the active PP of the cyclic-superframe configured by the Requestor PD or the Initiator PD.
- The Data frame is transmitted in the active CFP of the cyclic-superframe of the destination PAC group, if the `CFPTx` parameter of `MLME-DATA.request` primitive is set. Otherwise, the Data frame is transmitted in the nearest active CAP of the destination PAC group.

6.4 IFS

6.4.1 General

The time interval between frames is called the inter-frame space (IFS). Three different IFSs are specified.

- MIFS minimum inter-frame space
- DIFS distributed inter-frame space
- EIFS extended inter-frame space

The different IFSs shall be independent of the PD bit rate. The IFS timings are specified as time gaps on the medium, and the IFS timings are fixed for each PHY during the CAP. The MIFS is variable during the

CFP, where the DIFS and EIFS are not applicable. Figure 12 shows some of IFS relationships. Timings are referenced from occurrence of the PHY interface primitives (see 10.7): PLDE-TXEND.confirm, PLDE-TXSTART.confirm, PLDE-RXSTART.indication, and PLDE-RXEND.indication.

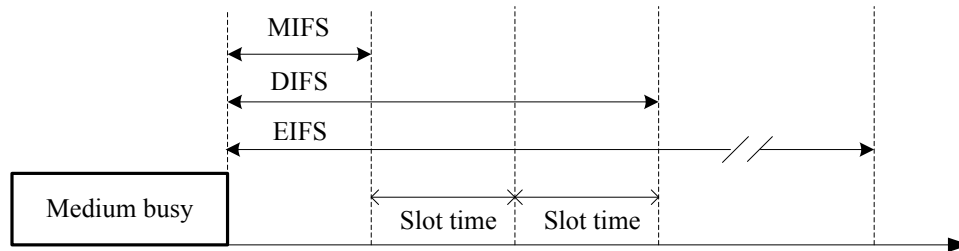


Figure 12—IFS relationships

6.4.2 MIFS

The MIFS is the time from the end of the last symbol of the previous frame to the beginning of the first symbol of the subsequent frame as seen at the air interface.

The MIFS shall be used prior to transmission of an Immediate Ack, Enhanced Ack frame, or a CTS frame.

The MIFS timing shall be achieved when the transmission of the subsequent frame is started at the beginning of the Rx/Tx slot as specified in 6.4.5.

An IEEE 802.15.8 implementation shall not allow the space between frames that is specified to be separated by the MIFS, as measured on the medium, to vary from the nominal MIFS value by more than $\pm 10\%$ of MIFS for the PHY in use.

6.4.3 DIFS

The DIFS shall be used by PDs operating under *p*-EIED to transmit MAC frames. A PD using *p*-EIED shall be allowed to contend to transmit if the following conditions met:

- Its CS mechanism determines that the medium is idle at the beginning of the Rx/Tx slot of the second slot time as specified in 6.4.5 after a correctly received frame;
- The PD's backoff time has expired.

6.4.4 EIFS

The EIFS shall be used by PDs operating under *p*-EIED before transmission, when it determines that the medium is idle following reception of a frame for which the PLDE-RXEND.indication primitive contained an error or a frame for which the FCS value was not correct. The duration of an EIFS is specified in 6.4.5.

The EIFS interval shall begin following the indication by PHY layer that the medium is idle after detection of the erroneous frame, without regard to the virtual CS mechanism. The PD shall not begin a transmission until the expiration of NAV or EIFS whichever comes later.

The EIFS is specified to provide enough time for another PD to acknowledge what was, to this PD, an incorrectly received frame before this PD commences transmission. Reception of an error-free frame

6.4.5 Timing relations

The end of a transmission is referenced from the end of the last symbol of the PPDU. The beginning of a transmission refers to the start of the first symbol of the next PPDU. All MAC timings are referenced from the PLDE-TXEND.confirm, PLDE-TXSTART.confirm, PLDE-RXSTART.indication, and PLDE-RXEND.indication primitives specified in 10.7.

$$\text{MIFS} = \text{RxPHYDelay} + \text{MACProcessingDelay} + \text{RxTxTurnAroundTime} \quad (1)$$

$$\text{SlotTime} = \text{AirPropagationTime} + \text{CCATime} + \text{MACProcessingDelay} + \text{RxTxTurnAroundTime} \quad (2)$$

$$\begin{aligned} M &= \text{MACProcessingDelay} \\ R_x/T_x &= aR_xT_x\text{TurnAroundTime} = T_x\text{PHYDelay} + R_xT_x\text{SwitchTime} + T_x\text{RampOnTime} \\ D1 &= R_x\text{PHYDelay} \\ D2 &= D1 + \text{AirPropagationTime} \\ CCAd &= CCATime - D1 \end{aligned}$$


AirPropagationTime describes variations in actual propagation time that are accounted for in a PD and specified in Table 2. AirPropagationTime together with the maximum transmit power level allow to control the coverage area.

Table 2—AirPropagationTime parameters

<i>n</i>	AirPropagationTime (μs)
0–30	<i>n</i>
31–255	Reserved

Radio waves propagate approximately at 300 m/μs in free space. For instance, 1 μs would be the upper limit for a PD maximum one-way distance of 150 m (300 m round trip).

The DIFS and EIFS are derived by Equation (3) and Equation (4).

$$\text{DIFS} = \text{MIFS} + 2 \text{ SlotTime} \quad (3)$$

$$\text{EIFS} = \text{MIFS} + \text{AckTxTime} + \text{DIFS} \quad (4)$$

where AckTxTime is the time required to transmit an Ack frame at the lowest PHY mandatory rate.

6.5 Channel access

6.5.1 Random access

6.5.1.1 CSMA/CA algorithm

6.5.1.1.1 Overview

The random access scheme used for contention shall be slotted CSMA/CA (carrier sense multiple access with collision avoidance) with EIED (exponential increase exponential decrease) backoff algorithm, if the PD operates with the OFDM PHY or OFDMA PHY.

6.5.1.1.2 Basic access

Basic access refers to the core mechanism a PD uses to determine whether it may transmit. In general, a PD may transmit a pending MAC frames when it is operating under *p*-EIED access method, when the PD determines that the medium is idle for greater than or equal to a DIFS period, or an EIFS period if the immediately preceding medium-busy event was caused by the detection of a collision. If, under these conditions, the medium is determined by the CS mechanism to be busy when a PD desires to transmit a frame, the backoff procedure described in 6.5.1.1.3 shall be followed. The basic access mechanism is illustrated in Figure 14.

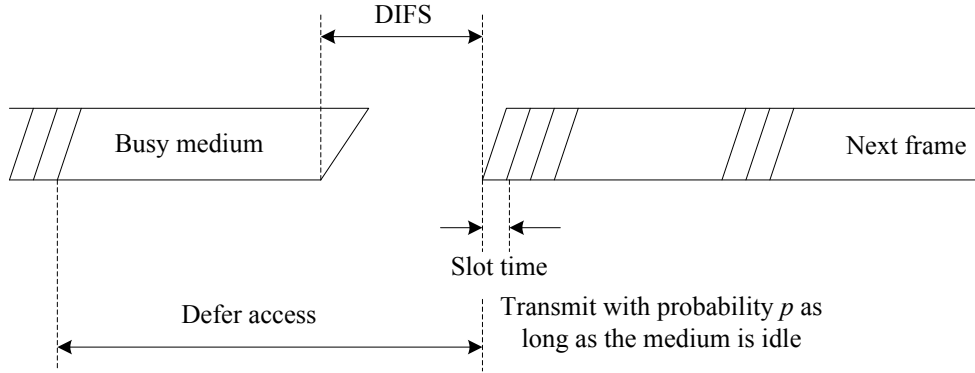


Figure 14—Basic access model

6.5.1.1.3 Backoff procedure for p -EIED

This subclause describes backoff procedure that is to be invoked when p -EIED is used. The behavior of p -EIED is governed by four parameters: persistence level p , the average persistence level of neighboring PDs p_{avg} , measured average inter-arrival time T_M , and target inter-arrival time T_T .

- The persistent level p is used to regulate the transmission of Data frames. PDs update their persistence level p so that the average transmission rate in the network remains constant regardless of the PD density, and the variation of p among PDs is maintained to a low value. If channel becomes idle, after DIFS period, a PD attempts to transmit a Data frame in each backoff slot with probability p .
- The average persistence level of neighboring PDs p_{avg} is used to provide fairness among PDs.
- Each PD measures the average inter-arrival time T_M , where inter-arrival time is specified as the number of consecutive idle slots between transmissions. T_M represents the channel condition, i.e., the contention, and is highly correlated with the average packet transmission rate in the network. T_M as a measure of channel condition can be used even when unicast messages are mixed with broadcast and multicast messages that are not acknowledged by an ACK.
- T_T is the target inter-arrival time optimized for predetermined packet length l_{basic} . If T_M is smaller than T_T , a PD increases its persistence level p to make T_M converge to the value of T_T . On the other hand, if T_M is larger than T_T , a PD decreases its persistence level p .

When a PD receives a packet, it updates T_M and p_{avg} . T_M is updated by Equation (5).

$$T_M := \beta T_M + (1 - \beta) T_s \quad (5)$$

where $:=$ is the assignment operator, T_s is the measured inter-arrival time between the last two packets, and $0 < \beta < 1$. The value of p_{avg} is updated by Equation (6).

$$p_{avg} := \frac{Q}{R} \quad (6)$$

where Equation (7) and Equation (8) are true.

$$Q := \beta Q + \left((1 - \beta) \frac{1}{\gamma_r} \right) \quad (7)$$

$$R := \beta R + \left((1 - \beta) \frac{1}{\gamma_r p_r} \right) \quad (8)$$

p_r is the persistence level contained in the latest packet received, γ_r is a scaling factor. The value of β is implementation dependent. Recommended value for β is 0.99. The scaling factor γ_r is specified as shown in Equation (9).

$$\gamma_r = \left(\frac{l_r}{l_{basic}} \right)^{\frac{1}{2}} \quad (9)$$

where l_r is the length corresponding to the length of payload plus EIFS in case of basic access, and the length of RTS packet plus EIFS in case of access mechanism with RTS/CTS handshaking.

The optimal target inter-arrival time T_T is obtained when the channel utilization $U(p)$ reaches a maximum value, which is specified by Equation (10).

$$U(p) = \frac{P_{succ}}{P_{idle} T_{slot} + P_{succ} T_{succ} + P_{coll} T_{coll}} \quad (10)$$

where N is the number of PDs, $P_{succ} = N p (1-p)^{N-1}$, $P_{coll} = 1 - P_{succ} - P_{idle}$, $P_{idle} = (1-p)^N$, T_{slot} is the length of a backoff slot, T_{succ} is the duration that the channel is used by a successful transmission, and T_{coll} is the duration that the channel is wasted by an unsuccessful transmission. T_{succ} and T_{coll} are determined by l_{basic} and the protocol overhead, and they are specified as shown in Equation (11) and Equation (12).

$$T_{succ} = \begin{cases} l_{basic} + SIFS + ACK + DIFS, & \text{Basic access} \\ RTS + 3SIFS + CTS + l_{basic} + ACK + DIFS, & \text{RTS/CTS access} \end{cases} \quad (11)$$

$$T_{coll} = \begin{cases} l_{basic} + EIFS, & \text{Basic access} \\ RTS + EIFS, & \text{RTS/CTS access} \end{cases} \quad (12)$$

Maximizing channel utilization is equivalent to minimizing the cost of collision $C(p)$, where Equation (13) is true.

$$C(p) = \frac{P_{idle} T_{slot} + P_{coll} T_{coll}}{P_{succ}} \quad (13)$$

The target inter-arrival time T_T that reduces $C(p)$ shall be obtained numerically for asymptotically large N for a given value of l_{basic} . For instance, when $l_{basic} = 1.367$ ms, the target inter-arrival time is given as $T_T = 8.55362$.

Each PD maintains its own persistence level p_{basic} , and updates p_{basic} every time a packet is received using the rule described in Table 3. p_{basic} is the persistence level if the cost of collision is l_{basic} .

Table 3— p_{basic} update rule

	$p_{basic} < p_{avg} / \sqrt{2}$	$p_{avg} / \sqrt{2} \leq p_{basic} < \sqrt{2} p_{avg}$	$\sqrt{2} p_{avg} \leq p_{basic}$
$T_M \leq T_T$	$p_{basic} := p_{basic}$	$p_{basic} := p_{basic} / \sqrt{2}$	$p_{basic} := p_{basic} / 2$
$T_T < T_M$	$p_{basic} := 2 p_{basic}$	$p_{basic} := \sqrt{2} p_{basic}$	$p_{basic} := p_{basic}$

Since the cost of collision is different from l_{basic} , the actual persistence level p that a PD uses to transmit a packet needs to be calculated for p_{basic} as shown in Equation (14).

$$p = \frac{p_{basic}}{\sqrt{T_{coll} / l_{basic}}} \quad (14)$$

6.5.1.1.4 Access with RTS/CTS

PDs receiving a valid frame shall update their NAV with the information received in the Duration field for all frames where the new NAV value is greater than the current NAV value. If the new NAV value is not greater than the current NAV value, PDs shall not update their NAV. Figure 15 indicates the NAV in the Duration field of RTS, CTS, and Ack frame.

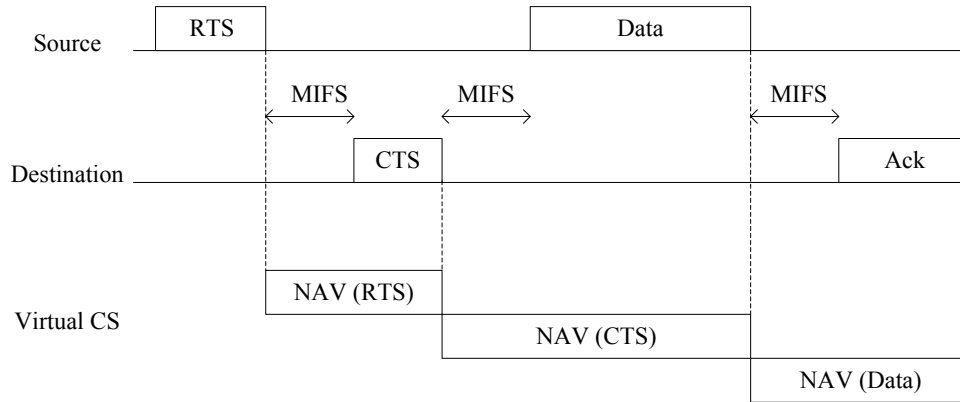


Figure 15—NAV setting mechanism

6.5.1.2 Aloha

If the PD operates with the UWB PHY, the contention access shall use Aloha. As specified in 9.13, Aloha shall be CCA in mode 4: CCA shall report an idle medium.

6.5.2 Contention free access

6.5.2.1 General

Slotted resource elements (REs) allow a PD to operate on a channel within a portion of the superframe that is dedicated exclusively to that PD. REs are used during the CFP. REs are allocated provided there is sufficient capacity in the superframe. REs may extend over one or more superframes.

REs shall be allocated when a Requestor PD and Responder PD agree to allow data transfer over a communication link l using such REs, henceforth referred to as the scheduling of link l . The scheduling of link l shall be based on the requirements of the RE Request command, like traffic priority, the current available capacity in the superframe, reported potential SINR degradation (interference) cause to already scheduled links and potential SINR degradation (interference) to the requested communication link caused by the already scheduled links.

The total number of REs during the CFP is NM , where N is the number of blocks of 6 subcarriers as specified in 12.5.18 and M is the number of blocks of 0.5 ms as specified in 12.5.18. The REs in the CFP are indexed as RE_{i+Mj} where $i=0, 1, \dots, M-1$ and $j=0, 1, \dots, N-1$.

PDs using the CFP shall use the *macCFPtable* specified in Table 88 and part of the PIB for management of resources.

The allocation of REs shall be strictly contiguous. If a PD deallocates REs, such PD shall adjust the *macCFPtable* to have sequentially available REs and shall broadcast the *macCFPtable* using the RE Notification command frame as specified in 7.5.10.

Each RE shall be deallocated when the RE is no longer required. A PD operating in the CFP may operate in the CAP.

6.5.2.2 Resource allocation

The resource allocation flow is illustrated in Figure 16. The MAC layer of the Requestor PD shall send the RE Request command frame as describe in 7.5.8 to the Responder PD during the CAP or scheduling reservation of the superframe (see 6.12.3). The Allocation field shall be set to one (allocation), the length (number of REs) and direction fields shall be set according to the desired characteristics of the required REs, and the current *macCFPtable*.

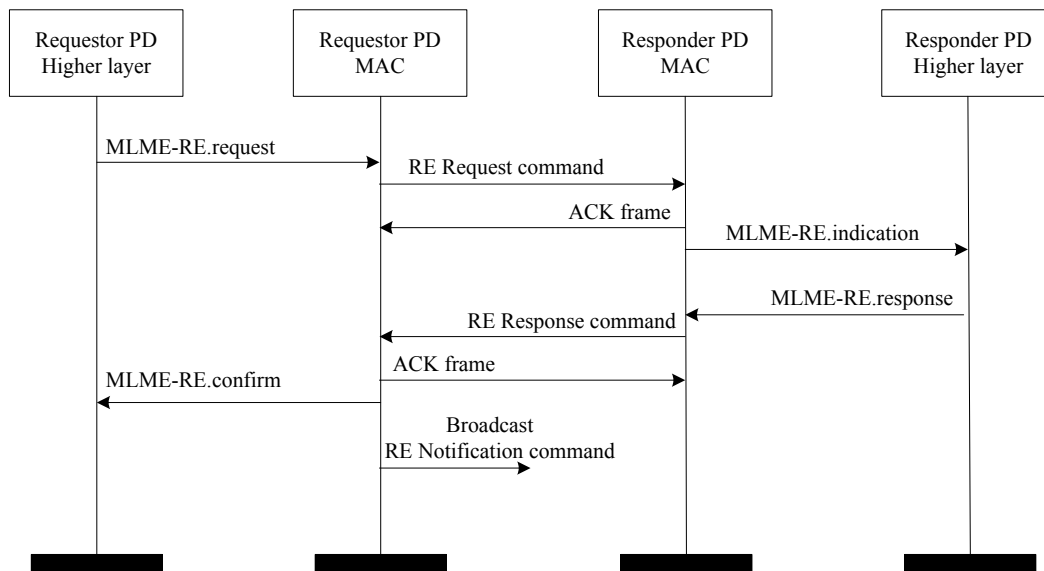


Figure 16—Flow chart for RE allocation

On receipt of a RE Request command frame, the Responder PD shall send an Immediate Ack frame, the MLME shall update the *macCFPtable* and shall issue a MLME-RE.indication primitive to inform the next higher layer. The MLME shall allocate the REs required according to the resources available in the

macCFPtable. If enough REs are available, the MLME selects the start index $(i,j)_{\text{start}}$ and finish index $(i,j)_{\text{finish}}$ and a *LinkIndex* value, and the MLME shall store them in the *MacCFPtable*. If there was not sufficient capacity to allocate the requested REs, the MLME shall set the Allocation field to zero, the start of the RE index field shall be set to zero as well as the number of allocated REs field. After the allocation process is finished, the MLME shall send a RE Response command frame.

On receipt of a RE Response command frame, the Requestor PD shall send an Immediate Ack frame and shall issue a MLME-RE.confirm primitive to inform the next higher layer. If the Status field of the RE Response command frame indicates success, the MLME shall update the *macCFPtable* and shall broadcast a RE Notification command frame with the updated *macCFPtable* to inform other PDs of the status of the CFP allocation.

On receipt of a RE Notification command frame, PDs using the CFP shall update their *macCFPtable*, or ignore if PDs are not operating in the CFP.

If the CFP or CAP is inactive during the current cyclic-superframe configuration, the MAC layer shall override such cyclic-superframe configuration to have the CFP and CAP active.

6.5.2.3 Scheduling maintenance

The requestor PD shall keep the scheduling of a communication link with *LinkIndex*, if the following conditions are met:

- $SINR_{\text{LinkIndex}} > \gamma_T$
- There is no higher traffic priority requesting resources and capacity is not available.

Otherwise, the requestor shall issue a De-Peering request primitive to the PDs with communication index *LinkIndex* that do not satisfy the above mentioned conditions. The value of γ_T shall be selected such that the PER $\leq 10\%$.

6.5.2.4 Rate adaptation

PDs in transmission mode and in already scheduled links shall send pilot signals after the scheduling reservation for the first half of the TDD frame (see 12.3.3.2). PDs in reception mode shall estimate SINR. During the second half of the TDD frame, PDs in transmission mode shall send the SINR and CQI based on the estimated SINR. In that manner, PDs can determine the best coding and modulation schemes to employ (the CQI is calculated in the next higher layer, and consequently the selection of coding and modulation scheme based on CQI is done in the next higher layer).

6.5.2.5 RE usage

When the MAC layer of a PD receives an MLDE-DATA.request primitive, as described in 8.4.2.2, with the CFPTx parameter indicating a RE transmission, it shall determine whether it has a valid scheduled link indicated previously after reception of a RE Response command frame, with a valid transmit RE parameter and a valid receive RE parameter for the Responder PD. If a valid scheduled link is determined, the MAC layer shall transmit the data during the allocated REs, provided the requested transaction can be completed before the end of the allocated REs. If the requested transaction cannot be completed before the end of the allocated REs, the MAC layer shall defer the transmission of the remaining data for the next superframe over the allocated REs.

For all allocated REs for a PD, its MAC layer shall verify that its receiver or transmitter is enabled, accordingly, at a time prior to the start and for the duration of each allocated RE. Before commencing transmission in a RE, the PD scheduled to transmit shall verify that the data transmission, the immediate acknowledgment, if requested, and the IFS, suitable to the size of the Data frame, can be completed before the end of the allocated REs. If a PD misses the synchronization condition, it shall not use the CFP until it achieves the synchronization condition again. If a loss of synchronization occurs, the PD's next higher layer should consider deallocating its REs over the CFP.

6.5.2.6 RE deallocation

As illustrated in Figure 17, when a PD stops using REs in the CFP, the next higher layer shall issue the MLME-DEALLOCATION.request primitive. Upon reception of the MLME-DEALLOCATION.request primitive, the MAC layer shall broadcast the RE Notification command frame with the updated CFP Table with the available RE resources. Upon reception of the RE Notification command frame, the MAC layer shall issue the MLME-DEALLOCATION.indication primitive to notify the next high layer of the updated CFP Table.

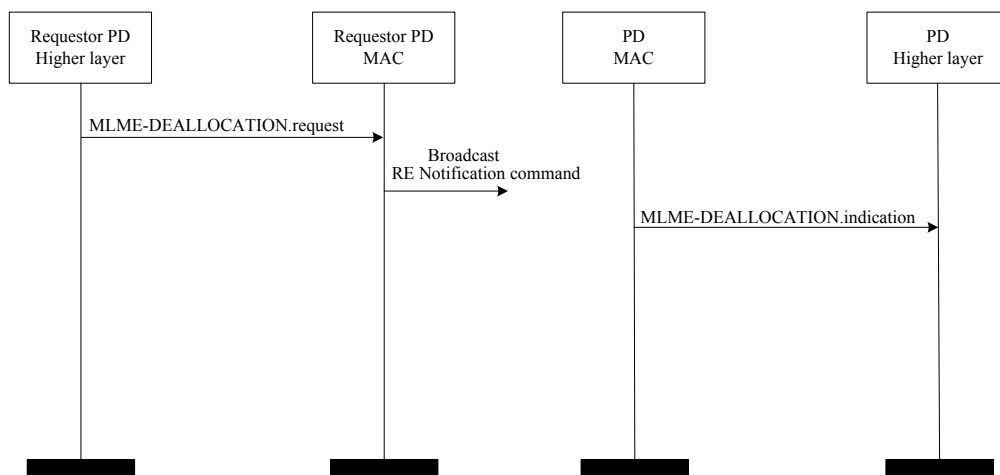


Figure 17—Flow chart for RE deallocation

6.5.2.7 REs allocation expiration

A PD may attempt to detect when a *LinkIndex* has stopped using its allocated REs by broadcasting a RE Request command frame with parameter AllocationLive set to 1. The PDs that return an Immediate Ack frame are considered their allocation is still being used. If PDs do not return an Immediate Ack frame, the PD should consider the deallocation of their REs.

6.6 Starting and maintaining PAC networks

6.6.1 Overview

This subclause describes how to start and maintain a PAC network. The procedure of starting a PAC network proceeds in the following order: channel scanning, synchronization, discovery, and peering.

6.6.2 Channel scanning

6.6.2.1 General

All PDs shall be capable of performing ED across a specified list of channels. The next higher layer should submit a scan request for a particular channel page containing a list of channels taken from the channels specified in Table 91 for that particular channel page.

A PD shall be instructed to begin a channel scan through the MLME-SCAN.request primitive, as described in 8.3.11.2. Channels are scanned first starting from the common channel as specified in 6.6.3 and then in the order from the lowest channel number to the highest channel number. For the duration of the scan, the PD shall suspend transmissions. For UWB PHYs, each preamble code appropriate to the specified channel is used for scanning. The results of the scan shall be returned via the MLME-SCAN.confirm primitive as described in 8.3.11.3.

6.6.2.2 ED channel scan

An ED scan allows a PD to obtain a measure of the peak energy in each requested channel. This could be used by a prospective PD to select a channel on which to operate prior to starting a new PAC network. During an ED scan, the MAC layer shall discard all frames received over the PHY data service.

An ED scan over a specified set of channels is requested using the MLME-SCAN.request primitive. For each channel, the MLME shall first switch to the channel, by setting *ScanChannels* and *ChannelPage* accordingly, and then repeatedly perform an ED measurement for a length of the *ScanDuration* parameter in the MLME-SCAN.request primitive. The maximum ED measurement obtained during this period shall be recorded before moving on to the next channel in the channel list. A PD shall be able to store at least one channel ED measurement. The ED scan shall terminate when either the number of channel ED measurements stored equals the implementation-specified maximum or energy has been measured on each of the specified channels.

6.6.3 Common mode and channel access order

6.6.3.1 Common mode

This standard defines a common mode at each frequency band in order to facilitate distributed synchronization among neighboring PDs.

The common mode shall be assigned with a fixed RF channel and fixed PHY parameters to achieve immediate distributed synchronization. There shall be one and only one common mode specified at each channel page of a frequency band, as shown in Table 4.

Table 4—Common mode parameters

PHY clause	Frequency band (GHz)	Channel page	Channel number	Data rate (Mb/s)
11	2.4	2	4	2
12	2.4	5	3	1
11	5.7	4	6	2
12	5.7	7	7	1

Table 5 presents the common mode channel band options for the UWB PHY including a nominated preamble code to be used depending on the modulation mode supported. The choice of which band to use depends on local regulations and the capability of the PD to support it.

Table 5—Common modes for UWB PHY

Channel Index	Mandatory frequency (GHz)	BPM-BPSK modulation mode	OOK modulation mode
2	4.0	Preamble Sequence ID = 45	Gold sequence code $i = 0$
5	6.5		
8	8.0		

For interoperability, any PD shall attempt to synchronize in the common mode. If it fails to synchronize in the common mode, it may attempt to synchronize in other RF channels.

6.6.3.2 Use of common mode

- At start up, the PD shall perform synchronization, one-way discovery, and peering in the common channel.
- During normal operation, the PD shall perform synchronization and one-way discovery in the common channel; while 2-way discovery, peering and communication may be performed in another channel.
- For PAC networks with UWB PHY, the PD shall perform synchronization, discovery, peering and communication in the common channel.

6.6.4 Synchronization

The synchronization allows PDs to acquire common reference timing. The synchronization procedure includes initial synchronization, maintaining synchronization, and re-synchronization. Synchronization procedure is described in 6.8.

6.6.5 PD discovery

- One-way discovery: A PD either indicates its presence to other PDs by transmitting its discovery information during the discovery period, or discovers the presence of other PDs by detecting their discovery information during the discovery period (PDs are half duplex), where PDs are not necessarily peered.
- Two-way discovery: A PD requests the discovery information of another PD or PAC group by issuing the Discovery Request command frame, including its own discovery information, which is sent during the CAP. PDs are assumed peered already.

PD discovery information shall contain PD MAC address and the high level IDs: Group ID and Application ID as indicated in Table 6.

Table 6—Discovery information

Discovery information	Octets
PD MAC address	6
Group ID	2
Application ID	13

6.6.6 Peering and de-peering

6.6.6.1 Peering

The next higher layer requests to peer when the discovery information of PDs has been obtained successfully. This standard offers three possible mechanisms for peering: one-to-one peering, one-to-many peering and many-to-many peering procedure. Those are described in 6.10.

6.6.6.2 De-peering

The de-peering procedure of PDs or the termination of a peering among PDs in a PAC network is described in 6.11.1.

6.6.7 Managing dynamic preamble selection (DPS)

It is anticipated that typical ranging traffic will take place using the same preamble code as selected for normal data traffic by the *phyPreambleCode*. Therefore, even if the messages are encrypted, a hostile device can monitor traffic, and turn on its transmitter to generally disrupt the ranging. To defeat this attack, this standard offers the DPS option, allowing the PDs participating in the ranging exchange to change preamble codes during the ranging exchange.

The coordination of DPS is beyond the scope of this standard; however it may be achieved by encrypted messages so that any hostile devices are denied knowledge of the preambles that will be used. To defeat a “jam and spoof the retry” attack the preambles used should be changed for each ranging attempt.

The *DPSIndexDuration* parameter of the MLME-DPS.request primitive described in 8.3.15.2 ensures that the PDs are returned to an interoperable data state in the event of not receiving an expected message. PDs that do not implement DPS do not sacrifice any other ranging capabilities.

Figure 18 shows a suggested message sequence employing DPS for the three-message double-sided two-way ranging exchange. The messages exchange in the box is a suggestion of how the DPS use and its preamble codes could be selected. The MLME-DPS.request primitive is described in 8.3.15.2, and the MLME-DPS.confirm is described in 8.3.15.3.

Upon the generation of the MLME-DPS.confirm primitive, as illustrated in Figure 18, both of the PHYs have switched to use the TxDPSIndex and RxDPSIndex codes for their preamble symbols and MAC layers on both sides have started timers of the *DPSIndexDuration* value. The changing of preamble code is intended to help protect against attack, but as a side effect neither PHYs can communicate with the rest of its peers. The *DPSIndexDuration* value serves to prevent this situation persisting any longer than is necessary. If this timer duration is exceeded before the MAC layer issues the MLDE-DATA.confirm (for the initiator) or the MLDE-DATA.indication primitive (for the recipient), then the MAC layer shall initiate the MLME-DPS.indication to the next higher layer as described in 8.3.15.4.

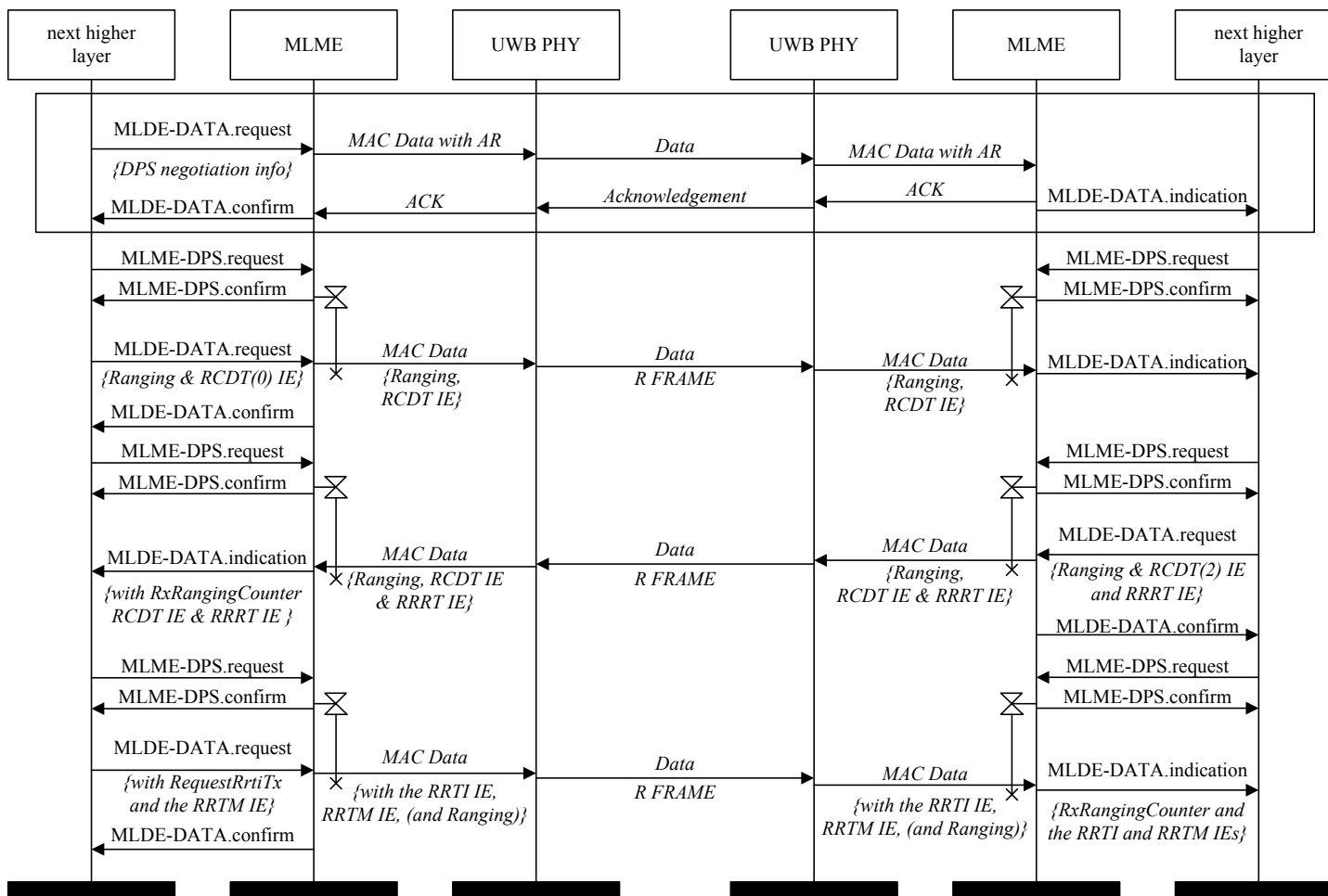


Figure 18—Message sequence chart for the three message DS-TWR using DPS

6.7 Transmission, reception, and acknowledgment

6.7.1 Transmission

Each PD shall store its current Data Sequence Number (DSN) value in the PAC network Information Base (PIB) attribute *macDSN* and initialize it to a random value; the algorithm for choosing a random number is outside the scope of this standard. Each time a data or a MAC command frame is generated, the MAC layer shall copy the value of *macDSN* into the Sequence Number field of the MAC Header (MHR) of the outgoing frame and then increment it by one. When the Sequence Number field is suppressed, the *macDSN* is not copied into the frame and shall not be incremented. Each PD shall maintain exactly one DSN regardless of the number of unique devices with which it wishes to communicate. The value of *macDSN* shall be permitted to roll over.

The Destination Address field, if present, shall contain either an IEEE 48-bit MAC address (see 7.1), or a 16-bit multicast group address (see 7.1).

The Source Address field, if present, shall contain either an IEEE 48-bit MAC address of the PD sending the frame, or where the Destination Address is an IEEE 48-bit MAC address and the destination PD has provided a link ID (via a Link ID Assignment IE), the link ID may be used in the Source Address field. For link ID values less than 256 the 8-bit form of link ID may be used.

If the transmission originates due to a primitive issued by the next higher layer and the CSMA-CA algorithm fails, the next higher layer shall be notified.

The PD's MAC layer shall process the frame using the outgoing frame security procedure described in Clause 16.

6.7.2 Reception and rejection

Each PD may choose whether the MAC layer is to enable its receiver during idle mode. During the idle mode, the MAC layer shall be ready for transceiver task requests from the next higher layer. A transceiver task shall be specified as a transmission request with acknowledgment reception, if required, or a reception request. On completion of each transceiver task, the MAC layer shall request that the PHY enables or disables its receiver, depending on the values of *macRxOnWhenIdle*.

Due to the nature of radio communications, a PD with its receiver enabled will be able to receive and decode transmissions from all PDs complying with this standard that are currently operating on the same channel and are in its radio communications range, along with interference from other sources. The MAC layer shall, therefore, be able to filter incoming frames and present only the frames that are of interest to the next higher layers.

For the first level of filtering, the MAC layer shall discard all received frames that fail the CRC verification by either recalculating the purported FCS over the MHR and MAC payload of the received frame and by subsequently comparing this value with the received FCS field. The FCS field of the received frame shall be considered to be correct if these values are the same and incorrect otherwise; or by computing the CRC over the entire MAC frame plus FCS. If they are correct, the CRC result is zero and the received frame shall be considered to be correct; and incorrect otherwise.

The second level of filtering shall be dependent on whether the MAC layer is currently operating in promiscuous mode. In promiscuous mode, the MAC layer shall pass all frames received after the first filter directly to the next higher layers without applying any more filtering or processing. The MAC layer shall be in promiscuous mode if *macPromiscuousMode* is set to TRUE.