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Electricity metering data exchange — Lower layer PLC profile using Adaptive Multi Carrier Spread-Spectrum (AMC-SS) modulation

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**Electricity metering data exchange - Lower layer PLC profile
using Adaptive Multi Carrier Spread-Spectrum (AMC-SS)
modulation**

This Technical Specification was approved by CENELEC on 2014-11-11.

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Foreword

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1 Scope

This Technical Specification specifies the physical layer, medium access control layer and logical link control layer for communication on an electrical distribution network between a master node and one or more slave nodes using a compatibly extendable form (CX1) of Adaptive Multi-Carrier Spread Spectrum (AMC-SS) technique. The adaptive cellular communication network technology provided in this specification may be used for automated meter reading as well as for other distribution network applications.

The physical layer provides a modulation technique that efficiently utilizes the allowed bandwidth within the CENELEC A band (3 kHz – 95 kHz), offering a very robust communication in the presence of narrowband interference, impulsive noise, and frequency selective attenuation. The physical layer of AMC-SS is defined in Clause 5 of CLC/TS 50590:2015.

The data link (DL) layer consists of three parts, the 'Medium Access Control' (MAC) sub-layer, the Logical Link Control (LLC) sub-layer and the 'Convergence' sub-layer. The data link layer allows the transmission of data frames through the use of the power line physical channel. It provides data services, frame integrity control, routing, registration, multiple access, and cell change functionality. The MAC sub-layer and the LLC sub-layer of AMC-SS are defined in Clause 6 of CLC/TS 50590:2015. The Convergence sub-layer is defined in this document.

2 Normative references

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

EN 50065-1, *Signaling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz – Part 1: General requirements, frequency bands and electromagnetic disturbances*

DIN 43863–5:2012-04, *Identification number for measuring devices applying for all manufacturers*

3 Terms, definitions and acronyms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1

device identifier

property that universally identifies a node

3.1.2

frame forwarding

procedure of PHY frame retransmission by a slave node or simultaneously by several slave nodes

3.1.3**higher layer entity**

entity of the layer or sub-layer in OSI model, which is situated above the layer or sub-layer of the entity offering the services. A possible convergence sub-layer between the higher layer entity and the entity offering the services may be a null layer, which is as simple as possible without a special convergence capability

3.1.4**MAC frame**

MAC sub-layer Protocol Data Unit (MPDU)

3.1.5**master node**

node which controls and manages the resources of a network cell

3.1.6**message**

LLC sub-layer Protocol Data Unit (MPDU)

3.1.7**network**

set of network nodes that can communicate by complying with this specification and are identified by the same value of N_NIN

3.1.8**network cell**

set of network nodes that can communicate by complying with this specification and share a single master node, which is identified by the CIN

3.1.9**node**

any one element of a network cell which is able to transmit to and receive from other network elements

3.1.10**slave node**

any node of a network cell which is not operating as a master node

3.1.11**PHY frame**

a PHY Layer Protocol Data Unit (PPDU)

3.1.12**registration**

procedure of master node assignment to a slave node

3.1.13**slave node registration**

assignment of dynamic address information to a slave node

3.1.14**symbol**

waveform used in the communication channel that persists for a fixed period of time

3.2 Acronyms

AC	Alternating Current
ACK	Acknowledgement
AGC	Automatic Gain Control
AMC-SS	Adaptive Multi-Carrier Spread-Spectrum
BNC	Backbone Network Connection
BTO	Beacon Time-Out Period
CCV	Code Connection Vector
CENELEC	European Committee for Electrotechnical Standardization
CFL	Carrier Frequency List
CIN	Channel Identification Number
CL	Convergence Sub-Layer
CONV	Convolutional Code
COSEM	Companion Specification for Energy Metering
CRC	Cyclic Redundancy Check
CRCINITVAL	CRC Initialization Value
CWD	Contention Window Duration
CX1	Compatibly extendable form [JK3] of AMC-SS PLC
D_ACK	Data Acknowledgement
DB	Data Block
DBL	Data Block Length
DFC	Data Flow Control
D8PSK	Differential Eight Phase Shift Keying
DBPSK	Differential Binary Phase Shift Keying
DID	Device Identifier
DL	Data Link
DLL	Data Link Layer
DLMS	Device Language Message Specification
DLS	Data Link Services
DP	Data Priority
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
FCB	Frame Count Bit
FCS	Frame Check Sequence
FCV	Frame Count Bit Valid
FEC	Forward Error Correction
FH	Frequency Hopping
FHCS	Frame Header Check Sequence
FMS	Frequency mapping schemes
FX	Frame Forwarding
FXDC	Frame Forwarding Down-Counter
FXS	Frame Forwarding Sector Address
FXT	Total Number of Frame Retransmissions
HLE	Higher Layer Entity
HTB	Header Tail Bits
Hz	Hertz
IEC	International Electrotechnical Commission
IFI	Interframe Interval
ITD	Initial Transmission Delay
kHz	kilo Hertz
L_FC	Link Function Code
L_NIN	Lower Byte of Network Identification Number
LA	Link Address
LCN	Link Channel Number
LLC	Logical Link Control
LLCF	Logical Link Control Field
LPDU	LLC Sub-Layer Protocol Data Unit
LSB	Least Significant Byte
LTS	Length of Training Sequence

N_NIN	Node Network Identification Number
M_CIN	Master Channel Identification Number
MAC	Medium Access Control
MA	Multicast Link-Address
MCN	Multicast Number
MN	Master Node
MPDU	MAC Protocol Data Unit
MSB	Most Significant Byte
NIN	Network Identification Number
NLA	New Link Address
NMAx	New Multicast Addresses
NSC	Network with Spreading/Shrinking Cells
p-MN	Primary Master Node
OSI	Open System Interconnection
PDDTH	Power-Down Duration Threshold
PDS	PHY Data Symbol
PDU	Protocol Data Unit
PDZ	PHY Data Zero Symbol
PHS	PHY Header Symbol
PHY	Physical Layer
PHZ	PHY Header Zero Symbol
PPDU	PHY Protocol Data Unit
PRM	Primary Bit
PRMB	Preamble
PSDU	PHY Service Data Unit
PSK	Phase Shift Keying
RC	Repetition Code
RES	Reserved
RN	Relaying Node
RZCO	Reference Zero-Crossing Offset
s-MN	Secondary Master Node
SCA	Scrambling Code Array
SCL	Scrambling Code Length
SN	Slave Node
SYNC	Synchronization Sequence
SYNCR	Synchronization Sequence Reference Symbols
SYNCS	Synchronization Sequence Symbols
S_CIN	Slave Channel Identification Number
S_FXENA	Slave Frame Forwarding Enable
S_FXS	Slave Frame Forwarding Sector
S_MAx	Slave Multicast Addresses
S_LA	Slave Link-Address
TB	Tail Bits
TLA	Temporary Link Address
TM	Transmit Mode
TNCW	Total Number of Contention Windows
TNS	Total Number of Symbols
TS	Training Sequence
TSS	Training Sequence Symbol
TSA	Training Sequence Array
TSL	Training Sequence Length

4 General description

Layers 1 and 2 transport the higher layer messages between the nodes of a low voltage distribution network. Layer 1 (physical layer, PHY) generates a physical signal that is sent over the medium. The data link layer (DLL, layer 2) is split up into three sub-layers: medium access control sub-layer (MAC, sub-layer 2a), logical link control sub-layer

(LLC, sub-layer 2b) and convergence sub-layer (CL, sub-layer 2c). The first two sub-layers of the data link layer perform the formatting of the frames, handle channel access and frame forwarding procedures, provide data integrity checks and are responsible for addressing, segmentation and message retransmission. The convergence layer provides adaptation to the specific higher layer protocol and may be transparent. The convergence layer is not part of this document but is defined in the profile specification. The convergence sub-layer provides a mapping between the primitives that are used by the higher layer entity, and the primitives of the logical link control sub-layer. Layer 2 also provides functionality of multiplexing and prioritization between different higher layer entities or applications (within a network node) and layer-2 networking. Furthermore, multiplexing of different protocol elements with DLMS/COSEM elements is specified herein. The structure of the lower layer PLC profile is shown in Figure 1.

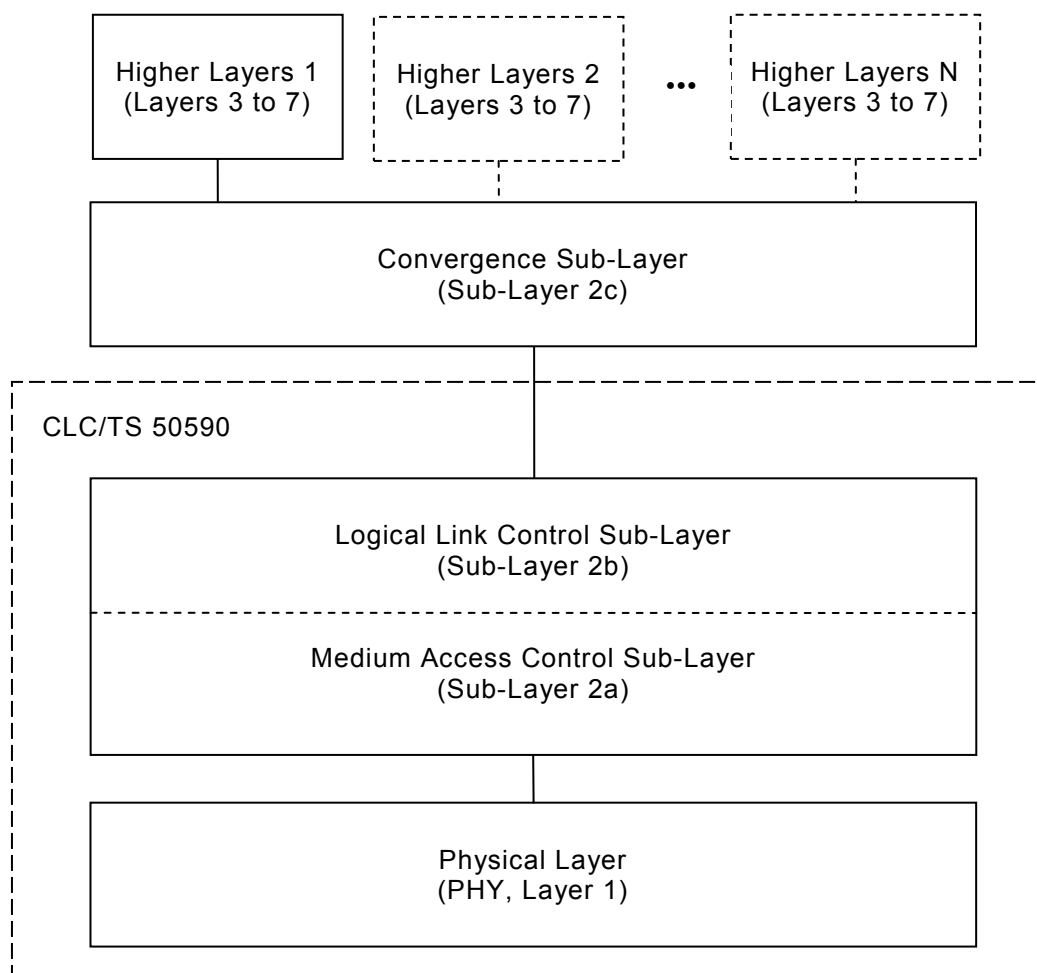


Figure 1 – Layers of AMC-SS profile

Information between layers is exchanged via primitives (see Figure 2). The following primitives are used for the communication between the logical link control sub-layer and the convergence sub-layer: DL_data.request, DL_data_identifier.confirm, DL_data.indication, DL_data.response, DL_data.confirm, DL_data_ack.response, DL_data_ack.confirm and DL_control.indication. For communication between the data link layer (LLC + MAC) and the physical layer the primitives P_data.request and P_data.indication are used.

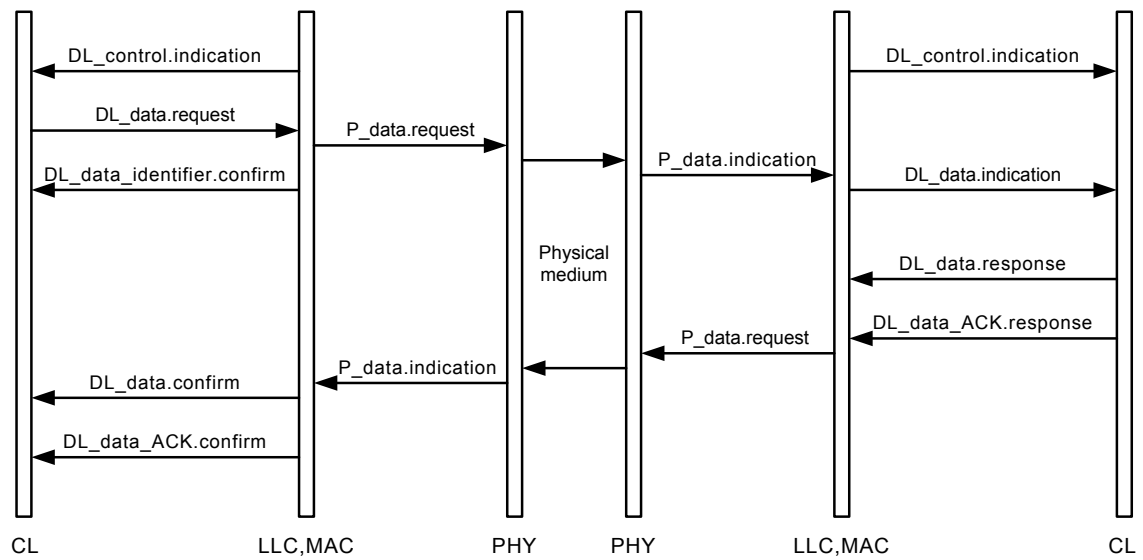


Figure 2 – Primitives

5 PHY layer specification

5.1 Overview

To generate physical signals, the AMC-SS physical layer uses a multi-carrier spread spectrum technique in combination with Differential Phase Shift Keying (DPSK) and forward-error-correction (FEC) coding.

This technique provides the following advantages:

- Robustness against time–frequency-selective fading;
- Robustness against pulse and narrowband interference, pulsating non-gaussian noise and combinations of them;
- Robustness against unwanted intermodulation effects;
- Lower linearity requirements for the analogue front end;
- High power efficiency as a result of low peak-to-average power ratio of the transmitted signal;
- Good electromagnetic compatibility between neighbouring systems.

The Figure 3 shows the block diagram of different data processing steps performed by the physical layer during the transmission of a PHY protocol data unit (PPDU).

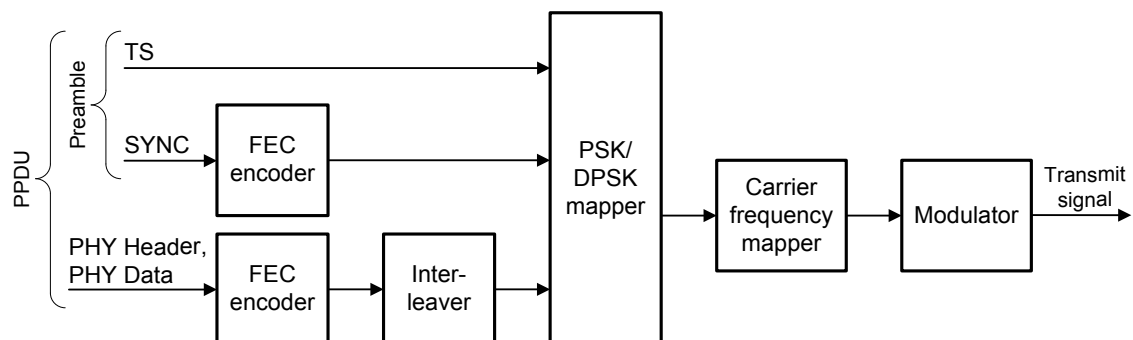


Figure 3 – PHY layer processing steps during PPDU transmission

Neither FEC-encoding nor interleaving is performed on the training sequence (TS). The bits of the synchronisation sequence (SYNC), the PHY header and PHY data are encoded with a FEC code. Encoded bit-sequences of the PHY header and PHY data are additionally interleaved. The training sequence and the encoded and interleaved bit sequences are mapped to the carrier phase angles depending on a PSK or a DPSK scheme and then to the carrier frequencies. The result of the PSK/DPSK and carrier frequency mapping is a sequence of unmodulated symbols containing modulation parameter. In the modulator these symbols are modulated and combined to a transmit signal, which is coupled into the physical channel – power-line.

The PHY layer processing steps during the reception of the PPDU are implementation specific and out of scope of this specification.

5.2 PHY protocol data unit

5.2.1 PPDU structure

5.2.1.1 General

The PPDU (i. e. PHY frame) consists of the preamble, the PHY header and the PHY data field. The preamble contains a training sequence (TS) and the synchronisation sequence SYNC. The PSK encoded elements of the TS are defined by the parameter TSL and the parameter array TSA (see Annex D).

Figure 4 below shows the bit-oriented structure of the PPDU (except training sequence), which is defined in Table 1 below.

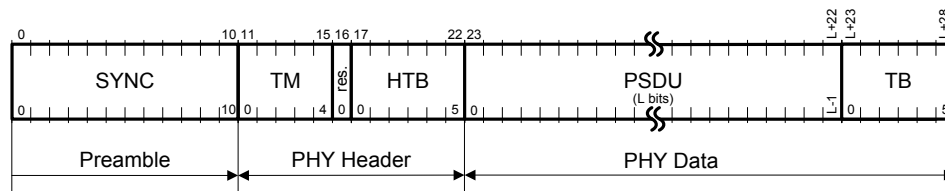


Figure 4 – Bit-oriented PPDU structure without TS

The bits of the PPDU (except TS) are numbered from 0 to L+28, where L is the length of PSDU in bits. In the following these bits are denoted as $d_0, d_1, \dots, d_k, \dots, d_{L+28}$.

Table 1 – PPDU structure without TS

		Field	Bit number	Bits	Name	Value
Part of PPDU	Preamble	SYNC	10 to 0	11	Synchronisation bit sequence	0x247 - allowed value; 0x000 to 0x246 - unused; 0x248 to 0x7FF - unused.
	PHY Header	TM ^a	15 to 11	5	PHY data transmit mode number ^a	0x00 to 0x14 - TM0 to TM20; 0x15 to 0x1F – reserved for future use.
		res.	16	1	Reserved bit for future use	0x0 - allowed value; 0x1 - not allowed.
		HTB	22 to 17	6	PHY header tail bits	0x00 - allowed value; 0x01 to 0x3F - not allowed.
	PHY Data	PSDU	23 to L+22	L ^a	PHY service data unit	PSDU = MPDU (cf. Table 9).
		TB ^b	L+23 to L+28	6	PHY data tail bits ^b	0x00 - allowed value; 0x01 to 0x3F - not allowed.

^a L is the length of PSDU in bits. The value of L is handed over to the PHY layer from MAC sub-layer together with MPDU = PSDU and the value of TM using the primitive P_data.request defined in Sub-section 5.5.

^b PPDU does not contain TB if TM = 16 to 20

For the transmission of the TS, SYNC, PHY header and PHY data different transmit modes are used (see Table 2 below).

Figure 5 shows symbolically the transmit signal (corresponding transmitted PHY frame) consisting of overlapped modulated symbols at the output of the modulator (cf. Figure 7 and Figure 8). The detailed PHY frame structure is described in the following sub-sections.

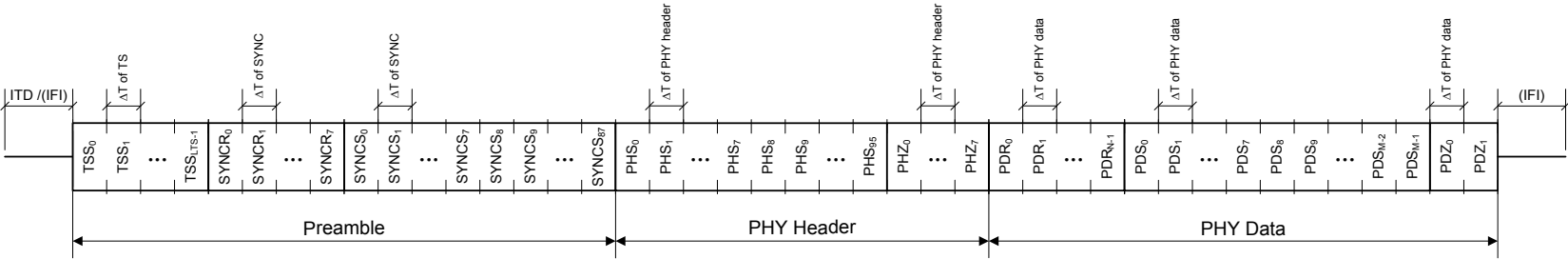


Figure 5 – Structure of transmit signal (PHY frame) consisting of overlapped modulated symbols

5.2.1.2 Preamble

Each PHY frame starts with the preamble, which is used for bit and block synchronization and for automatic gain control (AGC) adaptation. As shown in Figure 5, the preamble starts with a training sequence (TS) of symbols TSS_0 to TSS_{LTS-1} , followed by reference symbols $SYNCR_0$ to $SYNCR_7$ and symbols $SYNCS_0$ to $SYNCS_{87}$ of the synchronisation sequence.

The modulated TS symbols TSS_0 to TSS_{LTS-1} are generated using the corresponding parameters from Table 2 and the parameter TLS and TSA (see Annex D), that are defining the PSK encoding of the TS. Note that neither FEC-encoding nor interleaving is performed on the TS (see Table 2).

The modulated symbols of the synchronisation sequence $SYNCS_i$, $i = 0, \dots, 87$ are generated by repetition encoding and differential modulation of SYNC, which is defined as the following bit sequence (cf. Table 1):

$$SYNC = (d_0, \dots, d_{10}) = (1, 1, 1, 0, 0, 0, 1, 0, 0, 1, 0).$$

The symbols $SYNCR_0$ to $SYNCR_7$ serve as initial reference symbols for differential modulation of the first eight symbols $SYNCS_0$ to $SYNCS_7$ respectively. The initial carrier frequency phases of the modulated symbols $SYNCR_0$ to $SYNCR_7$ are defined by the parameter array RPA0 (see Annex D).

5.2.2 PHY header

The PHY header starts with the bits of the transmit mode (TM) field. These bits are denoted as $d_{11}, d_{12}, \dots, d_{15}$. They indicate the number of the transmission mode, which is used to transmit data contained within the field PHY Data. The bits d_{11} to d_{22} (fields TM, Res. and HTB) of the PHY header are convolutionally encoded with the rate 1/8, which is defined in the sub-section 5.3.2.3. The purpose of the zero PHY header tail bits (HTB) d_{17} to d_{22} , is to return the encoder to its initial state. The encoded bit sequence is interleaved and mapped to the phase angles and then to the carrier frequencies according to the DBPSK rule and the frequency mapping scheme FMS1 respectively. The preamble symbols $SYNCS_{80}$ to $SYNCS_{87}$ are used as references for differential modulation of the first eight symbols PHS_0 to PHS_7 respectively.

At the end of the PHY header, eight zero symbols PHZ_0 to PHZ_7 are inserted in order to ensure that the modulated symbols of the PHY header and PHY data do not overlap in time. This is necessary because the PHY data may be transmitted in a different transmission mode than the PHY header. A zero symbol is a symbol which consists of all zero samples for the duration of T_s , where T_s is defined in Table 2 (cf. Figure 8). The transmit mode for the PHY data is defined by the field TM in the PHY header and can be any of transmit modes TM0 to TM20 from Table 2. The parameter of the transmit mode used for the PHY header are the same as of the PHY data transmit mode TM0 (cf. Table 2).

5.2.3 PHY data

The PHY-data field always contains a PHY service data unit (PSDU). Furthermore, for transmit modes TM0 to TM16, it also contains six zero tail bits (TB) in order to return the convolutional encoder to its initial state. For TM16 to TM20 there is no TB field because a repetition block code is used, see Table 2. It needs to be noted that the total size of PSDU can vary between 96 bits and 2152 bits.

As explained in the previous chapter, the transmit mode of the PHY data is defined by the TM field of the PHY header.

The bits d_{23} up to d_{L+28} (fields PSDU and, if available, TB) of the PHY data are FEC encoded. The encoded bit sequence is interleaved and mapped to the phase angles and then to the carrier frequencies according to the used DPSK rule and the frequency mapping scheme respectively.

The first N symbols of PDR_0 to PDR_{N-1} serve as initial reference symbols for differential modulation of the corresponding carrier of the first N symbols PDS_0 to PDS_{N-1} respectively. The number N is equal to the length of the frequency hopping cycle, which is the number of modulated symbols contained therein (N_{fhc}). It depends on the number of used carrier frequencies (N_{cf}) and the number of simultaneously used carriers (N_{suc}) in the PHY data transmission mode. The value of N_{fhc} is defined as: $N_{fhc} = N_{cf} / N_{suc} = 1, 3, 5, 7$ or 8 (cf. Table 2). The initial carrier frequency phases of the modulated symbols PDR_0 to PDR_{N-1} , $N = 1, 3, 5, 7$ or 8 are user-specific.

At the end of the PHY data two additional zero symbols PDZ_0 and PDZ_1 are transmitted (see zero symbol definition in Sub-section 5.2.2). This ensures a complete transmission of the previous symbols PDS_{M-2} and PDS_{M-1} (see Figure 8).

5.3 PHY frame transmission

5.3.1 General

The PHY layer of the AMC-SS allows the transmission of the PSDU using one of the 21 transmit modes TM0 to TM20. They differ from each other by the used FEC code, type of DPSK, frequency hopping scheme etc. (see Table 2 below), allowing a flexible trade-off between bit-rate and noise immunity. This is necessary for the adaptation of the MAC layer to the conditions of the communication channel.

The TS and SYNC of the preamble (PRMB) and the PHY header are transmitted in the predefined transmit modes. The transmit mode for the PHY data field is determined by the MAC entity using the primitive `P_data.request` (see Sub-section 5.5). The number of this mode is transmitted in the TM field of the PHY header to indicate it to the receiver for a correct reception of the PHY data.

The following Table 2 contains the parameters of the transmit modes for the preamble, PHY header and PHY data field. The transmit modes TM0 to TM15 are arranged by increasing data bit rate. The additionally defined transmission modes TM16 to TM20 use more simple transmission schemes allowing a low-cost implementation of the receiver.

The PHY layer processing steps during the transmission of the PHY frame as shown in Figure 3 are described in following sub-sections.

Table 2 – Parameter of preamble, PHY header and PHY data transmit modes

		Nominal data bit rate bit/s	Lower -3dB- frequency of TX-signal kHz	Upper -3dB- frequency of TX-signal kHz	Carrier frequency spacing kHz	Number of carrier frequencies	Number of simultaneously used carriers	Frequency hopping cycle length symbols	Frequency mapping scheme (see Annex A)	Symbol-to symbol shift ΔT (samples)	Symbol duration T_s (samples)	Window function W (see Annex A)	Type of modulation	Forward error correction code	Code rate	Interleaving block length L_{INTL} (see also A.2) bits
PRMB	TS	4800	39.0	89.5	6.764	8	1	8	FMS0	72	154	W0	PSK	--	1	--
	SYNC	600	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DBPSK	RC	1/8	--
PHY header		600	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DBPSK	CONV	1/8	96
PHY data	TM0	600	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DBPSK	CONV	1/8	96
	TM1	850	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	DBPSK	CONV	1/7	120
	TM2	1200	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DQPSK	CONV	1/8	192
	TM3	1600	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DQPSK	CONV	1/6	192
	TM4	2400	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	DQPSK	CONV	1/5	240
	TM5	3200	41.5	88.7	10.850	8	1	8	FMS1	72	154	W0	DQPSK	CONV	1/3	192
	TM6	4000	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	DQPSK	CONV	1/3	240
	TM7	4800	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DQPSK	CONV	1/2	180
	TM8	6000	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	DQPSK	CONV	1/2	150
	TM9	8000	44.2	88.7	2.7125	16	2	8	FMS3	58	128	W1	DQPSK	CONV	1/3	224
	TM10	9000	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	D8PSK	CONV	1/2	225
	TM11	12000	44.2	88.7	2.7125	16	2	8	FMS3	58	128	W1	DQPSK	CONV	1/2	224
	TM12	18000	44.2	88.7	2.7125	16	2	8	FMS3	58	128	W1	D8PSK	CONV	1/2	336
	TM13	27000	41.5	88.7	5.425	9	3	3	FMS4	58	128	W1	D8PSK	CONV	1/2	486
	TM14	32000	46.9	88.7	5.425	8	8	1	FMS5	128	128	W2	D8PSK	CONV	1/2	480
	TM15	64000	33.3	88.7	2.7125	20	20	1	FMS6	163	179	W3	D8PSK	CONV	1/2	600
	TM16	600	39.0	89.5	6.764	8	1	8	FMS1	72	154	W0	DBPSK	RC	1/8	128
	TM17	900	39.6	90.0	7.773	7	1	7	FMS7	55	134	W4	DBPSK	RC	1/7	98
	TM18	1200	41.5	88.7	10.850	5	1	5	FMS2	58	128	W1	DBPSK	RC	1/5	50
	TM19	1800	39.6	90.0	7.773	7	1	7	FMS7	55	134	W4	DQPSK	RC	1/7	192
	TM20	3000	40.1	87.4	10.629	5	1	5	FMS8	46	98	W5	DQPSK	RC	1/5	100

5.3.2 Forward error correction encoding

5.3.2.1 General

Two types of FEC are used by AMC-SS based on repetition block codes (RC) and convolutional codes (CONV). The bits d_0 to d_{10} of the synchronisation sequence SYNC are encoded using the repetition code with code rate 1/8. The PHY header bits d_{11} to d_{22} are encoded by the rate 1/8 convolutional encoder with constraint length $K = 7$, see Table 3. Depending on the used transmission mode, the PHY data bits are encoded by convolutional encoder (TM0 to TM15) or repetition encoder (TM16 to TM20). If repetition encoder is used, the PHY data block does not contain tail bits.

5.3.2.2 Repetition encoding

The repetition encoder uses the repetition block code $(N,1,N)_2$ with a rate of $1/N$, with N being the number of used carrier frequencies (Ncf). The encoder repeats every bit d_k of the SYNCS or PHY data N times creating the code word of encoded bits $C_k = c_{k,0}, \dots, c_{k,n}, \dots, c_{k,N-1}$, $n = 0..N-1$, where C_k is defined as:

$$C_k = \begin{cases} c_{k,n} = 0, n = 0, \dots, N-1 & | d_k = 0 \\ c_{k,n} = 1, n = 0, \dots, N-1 & | d_k = 1 \end{cases}$$

The resulting encoded bits are denoted as $c_i = c_{k,n}$, $i = N \cdot k + n$, $n = 0, 1, \dots, N-1$.

5.3.2.3 Convolutional encoding

The six convolutional encoders that are based on binary convolutional codes with constraint length $K=7$ and code rates $1/N = 1/8, 1/7, 1/6, 1/5, 1/3$ and $1/2$ that are used for different transmission modes (see Table 2). The general structure of the convolutional encoder is shown in Figure 6.

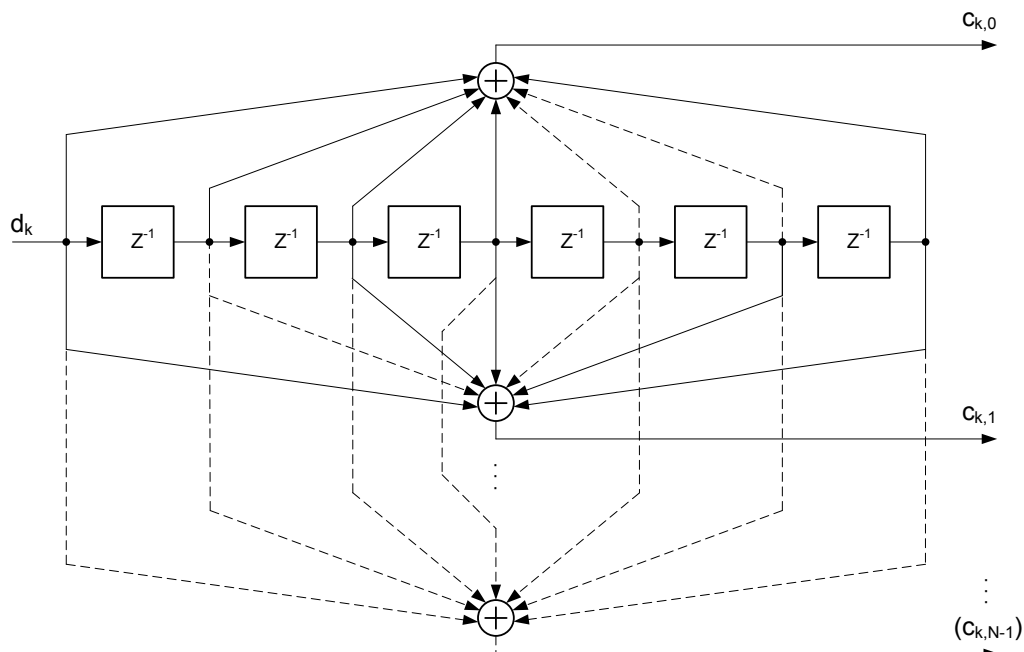


Figure 6 –General structure of a convolutional encoder with constraint length 7, used in this particular example (solid connections) for rate $\frac{1}{2}$ encoder

Before the encoding of the PHY header, the initial state of the shift register in the encoder is zero. The code construction of each rate 1/N convolutional encoder is defined by the code connection vectors listed in Table 3.

Table 3 – Code connection vectors for convolutional encoder

		Code rate = 1/N					
		1/8	1/7	1/6	1/5	1/3	1/2
Code connection vectors (CCV _n) for output $c_{k,n}$ $n = 0, 1, \dots, N-1$ of encoder	CCV ₀	1101011	1110101	1111011	1111101	1011011	1111001
	CCV ₁	1001001	1100111	1101001	1011001	1100101	1011011
	CCV ₂	1110101	1111011	1011101	1011101	1111101	--
	CCV ₃	1111011	1011101	1011101	1011101	--	--
	CCV ₄	1011101	1011101	1110011	1100111	--	--
	CCV ₅	1011101	1100111	1011111	--	--	--
	CCV ₆	1100111	1011111	--	--	--	--
	CCV ₇	1011111	--	--	--	--	--

Depending on the code connection vectors, the shift register taps are connected to N modulo2-summer generating the code word $C_k = (c_{k,0}, \dots, c_{k,n}, \dots, c_{k,N-1})$, $n = 0, 1, \dots, N-1$ from the bit d_k at the input of the encoder and bits d_{k-1} to d_{k-6} in the shift register stages. The solid connections in the encoder structure in Figure 6 correspond to the rate $\frac{1}{2}$ encoder defined in Table 3. The dashed connections symbolise possible code connections in the encoder for other code rates.

The code words from the output of the encoder are serialised into a stream of encoded bits $c_i = c_{k,n}$, $i = N \cdot k + n$, $n = 0, 1, \dots, N-1$.

With the shift of the last header tail bit d_{22} or the last tail bit d_{L+28} into the register, the encoder returns to its initial state finishing the encoding of the PHY header or PHY data respectively (i.e., c_{183} is the last encoded bit of the PHY header). For encoding of the PHY data, the convolutional encoder shall be reinitialised according to a used transmit mode and with all zero in the shift register.

5.3.3 Interleaving

The encoded bits of PHY header and PHY data are segmented into input blocks of the length L_{INTL} ($sc_0, \dots, sc_i, \dots, sc_{L_{INTL}-1}$), where $sc_0 = c_i, \dots, sc_{L_{INTL}-1} = c_{i+L_{INTL}-1}$. Padding bits shall be added, if needed, to fill up the final block. Padding bits are generated by a pseudo-noise sequence generator shown in Figure 12 starting with all ones as initial state.

In the input block an intra-block interleaving is performed. The result is an output block ($oc_0, \dots, oc_p, \dots, oc_{L_{INTL}-1}$) containing the interleaved bits. Table 2 and Annex A.2 define the values of L_{INTL} and the corresponding bit interleaving schemes for the encoded PHY header and for the encoded PHY data in each transmit mode. Each cell of an interleaving scheme (i. e. interleaving table) defines the index i of the encoded bit sc_i from the input block ($sc_0, \dots, sc_i, \dots, sc_{L_{INTL}-1}$), which is put as the interleaved bit oc_p in the output block ($oc_0, \dots, oc_p, \dots, oc_{L_{INTL}-1}$). The cells of the interleaving scheme that are

linked with the interleaved bits in the output block $(oc_0, \dots, oc_p, \dots, oc_{L_{INTL}-1})$, are sequentially arranged in rows starting in the 1st row from left to right and continuing from the left position in the next row. E.g., the 1st cell in the 1st row of an interleaving table is linked with the interleaved bit oc_0 in the output block. The interleaved bits are serialized as the bit sequence $(ic_0, ic_1, \dots, ic_i, \dots)$.

The bits of the encoded synchronisation sequence are not interleaved, i. e.: $(c_0, \dots, c_{87}) = (ic_0, \dots, ic_{87})$.

The encoded PHY header $c_{88}, \dots, c_{183}$ is considered as one 96-bit-block interleaved according to the bit interleaving scheme defined in Annex A.2.

The interleaving schemes in Annex A.2 also show how the interleaved bits are mapped to the carrier frequencies.

5.3.4 PSK / DPSK mapping

The elements of the training sequence $(ts_0, ts_1, \dots, ts_{LTS-1})$ and its length LTS are defined by the parameter array TSA and parameter TSL (see Annex D). An element of the TS is a nibble, which is defined as $(tsb3, tsb2, tsb1, tsb0)_i$, $i = 0, \dots, LTS - 1$. It contains an encoded phase value for PSK. Using the phase mapping scheme for PSK from Table 4, the sequence $(ts_0, ts_1, \dots, ts_{LTS-1})$ is transformed into the PSK-encoded training sequence $(ts\varphi_0, ts\varphi_1, \dots, ts\varphi_{LTS-1})$.

After the PSK-encoded training sequence the reference-phase sequence $(\varphi_0, \varphi_1, \dots, \varphi_7)$ is inserted. This sequence contains the use-defined values φ , $\varphi \in \{0, \pi/8, \pi/4, 3\pi/8, \pi/2, 5\pi/8, 3\pi/4, 7\pi/8, \pi, 9\pi/8, 5\pi/4, 11\pi/8, 3\pi/2, 13\pi/8, 7\pi/4, 15\pi/8\}$. It is necessary for DBPSK of the bit sequence $(ic_0, ic_1, \dots, ic_i, \dots, ic_{183})$ containing the encoded SYNC and PHY header, which is transmitted using eight carrier frequencies (see Table 2). Each bit of this bit sequence is considered in the DPSK mapper as the bit b0 in the Table 5 and mapped first to the corresponding value of $\Delta\varphi$, (i. e.: ic_i , $i = 0, \dots, 183$ is mapped to $\Delta\varphi_i$). Then the DPSK mapper generates the PSK encoded sequence $(\varphi_0, \varphi_1, \dots, \varphi_{i+8}, \dots, \varphi_{191})$ by extending the reference-phase sequence $(\varphi_0, \varphi_1, \dots, \varphi_i, \dots, \varphi_7)$ with PSK elements $\varphi_8, \varphi_9, \dots, \varphi_{i+8}, \dots, \varphi_{191}$ that are calculated as $\varphi_i = \varphi_{i-8} + \Delta\varphi_i$, $i = 0, \dots, 183$.

At the end of this sequence eight additional PSK elements $(\varphi_{192}, \varphi_{193}, \dots, \varphi_{199})$ with the phase value $\pi/2$ are added to generate zero symbols PHZ₀ to PHZ₇ in the modulator.

Table 4 – Phase mapping scheme for PSK

tsb_3	tsb_2	tsb_1	tsb_0	φ
0	0	0	0	0
0	0	0	1	$\pi/8$
0	0	1	0	$\pi/4$
0	0	1	1	$3\pi/8$
0	1	0	0	$\pi/2$
0	1	0	1	$5\pi/8$
0	1	1	0	$3\pi/4$
0	1	1	1	$7\pi/8$
1	0	0	0	π
1	0	0	1	$9\pi/8$
1	0	1	0	$5\pi/4$
1	0	1	1	$11\pi/8$
1	1	0	0	$3\pi/2$
1	1	0	1	$13\pi/8$
1	1	1	0	$7\pi/4$
1	1	1	1	$15\pi/8$

Then the DPSK mapper is reinitialised with the parameter of the transmit mode, which is used for the transmission of the remaining bit sequence $(ic_{184}, ic_{185}, \dots, ic_i, \dots)$ containing the encoded PHY data. Depending on the used transmit mode (DBPSK, DQPSK or D8PSK) the elements of this sequence are considered as single bits $ic_n = ic_i$ or grouped to bit duplets $(ic_i, ic_{i+1})_n$ or bit triplets $(ic_i, ic_{i+1}, ic_{i+2})_n$ respectively, where n is a consecutive number starting with 184.

In case of DBPSK, each single bit of this bit sequence is considered in the DPSK mapper as the bit b0 in the Table 5 and mapped first to the corresponding value of $\Delta\varphi$.

If DQPSK or D8PSK is used, each grouped bit duplet $(ic_i, ic_{i+1})_n$ or bit triplet $(ic_i, ic_{i+1}, ic_{i+2})_n$ of this bit sequence is considered in the DPSK mapper as the bit duplet (b0,b1) in

Table 6 or as the bit triplet (b0,b1,b2) in Table 7 respectively and mapped first to the corresponding value of $\Delta\varphi$.

Because the bit sequence $(ic_{184}, ic_{185}, \dots, ic_i, \dots)$ is transmitted without referencing to the PSK encoded sequence $(\varphi_0, \varphi_1, \dots, \varphi_{i+8}, \dots, \varphi_{199})$, an additional reference-phase sequence $(\varphi_{200}, \varphi_{201}, \dots, \varphi_{Ncf+199})$ is inserted, where Ncf is the number of carrier frequencies in the used transmit mode. This sequence contains values of φ , $\varphi \in \{0, \pi/8, \pi/4, 3\pi/8, \pi/2, 5\pi/8, 3\pi/4, 7\pi/8, \pi, 9\pi/8, 5\pi/4, 11\pi/8, 3\pi/2, 13\pi/8, 7\pi/4, 15\pi/8\}$ that are user-

defined. Each of this phase values serves as reference for DPSK of the corresponding N_{FC} carrier frequencies in the used transmit mode.

As the next step the DPSK mapper generates the PSK encoded sequence $(\varphi_{200}, \varphi_{201}, \dots, \varphi_{N_{cf}+199}, \varphi_{N_{cf}+200}, \dots, \varphi_n, \dots)$ by extending the reference-phase sequence $(\varphi_{200}, \varphi_{201}, \dots, \varphi_{N_{cf}+199})$ with PSK elements of the sequence $(\varphi_{N_{cf}+200}, \varphi_{N_{cf}+201}, \dots, \varphi_n, \dots)$ that are calculated as $\varphi_n = \varphi_{n-N_{cf}} + \Delta\varphi_n$.

Table 5 – Phase difference mapping scheme for DPSK

b0	$\Delta\varphi$
0	0
1	π

Table 6 – Phase difference mapping scheme for DQPSK

b1	b0	$\Delta\varphi$
0	0	$5\pi/4$
0	1	$7\pi/4$
1	0	$3\pi/4$
1	1	$\pi/4$

Table 7 – Phase difference mapping scheme for D8PSK

b2	b1	b0	$\Delta\varphi$
0	0	0	$11\pi/8$
0	0	1	$9\pi/8$
0	1	0	$13\pi/8$
0	1	1	$15\pi/8$
1	0	0	$5\pi/8$
1	0	1	$7\pi/8$
1	1	0	$3\pi/8$
1	1	1	$\pi/8$

5.3.5 Carrier frequency mapping

During the transmission of the PPDU four frequency mapping schemes (FMS) are applied: FMS0 to the training sequence, FMS1 to the synchronisation sequence and PHY header, FMS1 to FMS8 to PHY data depending on the used transmit mode (see Table 2) and zero carrier frequency values to the zero symbols PHZ₀ to PHZ₇, PDZ₀ and PDZ₁. In the carrier frequency mapper the carrier frequency mapping the PSK-encoded training sequence $(ts\varphi_0, ts\varphi_1, \dots, ts\varphi_{LTS-1})$ and the subsequent PSK-encoded sequence $(\varphi_0, \varphi_1, \dots, \varphi_n, \dots)$ of the remaining part of the PPDU are converted to a sequence of the unmodulated symbols $(V_0, V_1, \dots, V_m, \dots, V_{TNS-1})$, TNS is the total number of symbols in the PHY frame. The value of TNS depends on the length of the PSDU and the transmit mode, which is used for its transmission.

Depending on the used frequency mapping scheme (see A.3) and carrier window function an unmodulated symbol V_m is defined as:

$$V_m = \{N_{suc}, W, c\varphi_{m,1}, cf_{m,1}, c\varphi_{m,2}, cf_{m,2}, \dots, c\varphi_{m,N_{suc}}, cf_{m,N_{suc}}\}_m,$$

where: $N_{suc} = 1, 2, 3, 8$ or 20 is the number of simultaneously used carrier frequencies in the symbol; $c\varphi_{m,1}, c\varphi_{m,2}, \dots, c\varphi_{m,N_{suc}}$ are the phases of this carriers, that are shaped by the window function W , and have the carrier frequencies $cf_{m,1}, cf_{m,2}, \dots, cf_{m,N_{suc}}$ respectively; W indicates to the modulator which window function respectively symbol duration T_s and symbol-to-symbol shift ΔT are used.

For the preamble and PHY header $N_{cf} = 8$, $N_{suc} = 1$, $N_{fhc} = 8$ and $W = W_0$ is used (cf. 5.2.3). The unmodulated symbols V_0 to V_{TSL-1} of the training sequence in the preamble are built by the cyclic assigning of the carrier frequency values according to the carrier frequency mapping scheme FMS0 to the PSK-encoded elements of the training sequence $(ts\varphi_0, ts\varphi_1, \dots, ts\varphi_{TSL-1})$. The built sequence is denoted as $(V_0, \dots, V_m, \dots, V_{TNS-1})$,

where: $V_m = \{1, W_0, c\varphi_{m,1}, cf_{m,1}\}_m$, $m = 0, \dots, LTS - 1$, $c\varphi_{0,1} = ts\varphi_0, \dots, c\varphi_{LTS-1,1} = ts\varphi_{LTS-1}$, $cf_{0,1} = f_3$, $cf_{1,1} = f_6$, $\dots$, $cf_{7,1} = f_8$, $cf_{8,1} = f_3$, $cf_{9,1} = f_6$, $\dots$, $cf_{LTS-1,1} = f_8$.

Continuing the frequency mapping of the remaining part of the preamble and PHY header the carrier frequency values according to the carrier frequency mapping scheme FMS1 are cyclically assigned to the PSK-encoded sequence $(\varphi_0, \varphi_1, \dots, \varphi_{191})$ and zero frequency values to the sequence $(\varphi_{192}, \varphi_{193}, \dots, \varphi_{199})$. This is necessary to generate zero symbols PHZ₀ to PHZ₇ in the modulator. The continued sequence on the output of the carrier frequency mapper is denoted as: $(V_{LTS}, \dots, V_m, \dots, V_{LTS+199})$, where $V_m = \{1, W_0, c\varphi_{m,1}, cf_{m,1}\}_m$, $m = LTS, \dots, LTS + 199$,

$c\varphi_{LTS,1} = \varphi_0, \dots, c\varphi_{LTS+191,1} = \varphi_{191}$, $c\varphi_{LTS+192,1} = \pi/2$, $c\varphi_{LTS+193,1} = \pi/2$, $\dots, c\varphi_{LTS+199,1} = \pi/2$, $cf_{LTS,1} = f_1$, $cf_{LTS+1,1} = f_4$, $\dots$, $cf_{LTS+7,1} = f_6$, $cf_{LTS+8,1} = f_1$, $cf_{LTS+9,1} = f_4$, $\dots$, $cf_{LTS+191,1} = f_6$, $cf_{LTS+192,1} = 0$, $cf_{LTS+193,1} = 0$, $\dots$, $cf_{LTS+199,1} = 0$.

The carrier frequency mapping of the PHY data consist of the following three steps:

Step 1: Depending on the transmit mode carrier frequency $f_j \in \{f_1, f_2, \dots, f_{N_{cf}}\}$ from the used FMS is cyclically, with the period N_{cf} , assigned to each element of the PSK-encoded sequence $(\varphi_{200}, \varphi_{201}, \dots, \varphi_{N_{cf}+199}, \varphi_{N_{cf}+200}, \dots, \varphi_n, \dots)$. As result a new sequence of duplets $\{\varphi_n, f_j\}_n$, $n = 200, 201, \dots$ is built.

If, e.g., TM13 with FMS4, $N_{cf} = 9$, $N_{suc} = 3$, $N_{fhc} = 3$ and $W = W_0$ is used, this new sequence may be denoted as:

$(\{\varphi_{200}, f_1\}_{200}, \{\varphi_{201}, f_4\}_{201}, \{\varphi_{202}, f_7\}_{202}, \{\varphi_{203}, f_2\}_{203}, \{\varphi_{204}, f_5\}_{204}, \{\varphi_{205}, f_8\}_{205}, \dots, \{\varphi_{206}, f_3\}_{206}, \{\varphi_{207}, f_6\}_{207}, \{\varphi_{208}, f_9\}_{208}, \{\varphi_{209}, f_1\}_{209}, \dots, \{\varphi_{217}, f_9\}_{217}, \{\varphi_{218}, f_1\}_{218}, \dots)$.

Step 2: Within each carrier frequency cycle of N_{cf} duplets, the groups of N_{suc} duplets are built and assigned cording to the used FMS to unmodulated symbols in the

sequence $(V_{LTS+200}, V_{LTS+201}, \dots, V_m, \dots, V_{TNS-3})$. Therefore each carrier frequency cycle contains $N_{fhc} = N_{cf} / N_{suc}$ symbols.

In previous example the sequence on the output of the carrier frequency mapper would contain the unmodulated symbols

$V_m = \{3, W1, c\varphi_{m,1}, cf_{m,1}, c\varphi_{m,2}, cf_{m,2}, c\varphi_{m,3}, cf_{m,3}\}_m$, where:

$m = LTS + 200, \dots, TNS(L, TM13) - 3$;

$c\varphi_{LTS+200,1} = \varphi_{200}, c\varphi_{LTS+200,2} = \varphi_{201}, c\varphi_{LTS+200,3} = \varphi_{202},$

$c\varphi_{LTS+201,1} = \varphi_{203}, c\varphi_{LTS+201,2} = \varphi_{204}, c\varphi_{LTS+201,3} = \varphi_{205},$

$c\varphi_{LTS+202,1} = \varphi_{206}, c\varphi_{LTS+202,2} = \varphi_{207}, c\varphi_{LTS+202,3} = \varphi_{208},$

$c\varphi_{LTS+203,1} = \varphi_{209}, \dots, c\varphi_{LTS+205,3} = \varphi_{217}, \dots$;

$cf_{LTS+200,1} = f_1, cf_{LTS+200,2} = f_4, cf_{LTS+200,3} = f_7,$

$cf_{LTS+201,1} = f_2, cf_{LTS+201,2} = f_5, cf_{LTS+201,3} = f_8,$

$cf_{LTS+202,1} = f_3, cf_{LTS+202,2} = f_6, cf_{LTS+202,3} = f_9,$

$cf_{LTS+203,1} = f_1, \dots, cf_{LTS+205,3} = f_9, \dots$;

$TNS(L, TM13)$ is the number of unmodulated symbols in the PPDU transmitting a PSDU of L bit in the transmit mode TM13.

If, for example, TM14 with FMS5, $N_{cf} = 8$, $N_{suc} = 8$, $N_{fhc} = 1$ and $W = W3$ is used for the transmission of the PHY data, then each carrier frequency cycle consist of only one symbol containing all eight carrier frequencies. It is denoted as:

$V_m = \{8, W3, c\varphi_{m,1}, cf_{m,1}, c\varphi_{m,2}, cf_{m,2}, c\varphi_{m,3}, cf_{m,3}, c\varphi_{m,4}, cf_{m,4}, c\varphi_{m,5}, cf_{m,5}, c\varphi_{m,6}, cf_{m,6},$

$c\varphi_{m,7}, cf_{m,7}, c\varphi_{m,8}, cf_{m,8}\}_m, m = LTS + 200, \dots, TNS(L, TM14) - 3$;

Step 3: As the last symbols V_{TNS-2} and V_{TNS-1} of the PHY data two unmodulated zero symbols are inserted. This ensures a complete transmission of the previous symbols in the modulator. They are denoted as:

$V_{TNS-2} = \{1, W, \pi/2, 0\}_{TNS-2}, V_{TNS-1} = \{1, W, \pi/2, 0\}_{TNS-1}$, where: W is a window function used in the transmit mode; TNS is the total number of symbols in the PHY frame.

5.3.6 Modulation

The transmit signal in the modulator is defined as a sequence of consecutive samples with the rate $f_{Tx} = 347200$ samples/s respectively the sampling interval $\Delta t_{Tx} = 1/f_{Tx}$. The sample rate may be an integer multiples of $f_{Tx}/2$, if it is required for the carrier frequency values in the parameter lists CFL0 to CFL8. In this case the window functions W0 to W5 shall be resampled. The over-all sample rate accuracy shall be better than ± 25 ppm.

Usually the PPDU transmission procedure starts with an initial transmission delay (ITD). It is defined by the parameter ITDD, which contains a value of N_{ITD} in multiples of the sampling interval $\Delta t = 1/347200$ s. During the ITD zero-samples $s(i) = 0$, $i = 1$ to N_{ITD} are transmitted.

In the modulator each unmodulated symbol V_m from the sequence $(V_0, V_1, \dots, V_m, \dots, V_{TNS-1})$ is first transformed to the corresponding modulated symbol

S_m , $m = 0, \dots, TNS - 1$. The modulated symbols of the PHY frame shown in Figure 5 correspond to the symbols S_m , $m = 0, \dots, TNS - 1$ as follows:

$$\begin{aligned} (S_0 \text{ to } S_{LTS-1}) &= (TSS_0 \text{ to } TSS_{LTS-1}), \\ (S_{LTS} \text{ to } S_{LTS+7}) &= (SYNCR_0 \text{ to } SYNCR_7), \\ (S_{LTS+8} \text{ to } S_{LTS+95}) &= (SYNCS_0 \text{ to } SYNCS_{87}), \\ (S_{LTS+96} \text{ to } S_{LTS+191}) &= (PHS_0 \text{ to } PHS_{95}), \\ (S_{LTS+192} \text{ to } S_{LTS+199}) &= (PHZ_0 \text{ to } PHZ_7), \\ (S_{LTS+200} \text{ to } S_{LTS+Nfhc+199}) &= (PDR_0 \text{ to } PDR_{Nfhc}), \\ (S_{LTS+Nfhc+200} \text{ to } S_{TNS-3}) &= (PDS_0 \text{ to } PDS_{M-1}), \\ (S_{TNS-3}, S_{TNS-1}) &= (PDZ_0, \text{ to } PDZ_1). \end{aligned}$$

Where: LTS is the length of the training sequence in symbols; Nfhc is the length of the frequency hopping cycle in the PHY data transmit mode; TNS is the total number of symbols in the frame.

A symbol S_m consists of the consecutive samples $s_m(i)$, $i = 1, \dots, Ts$. Ts is the duration of the modulated symbol respectively window function W in samples. Using the modulation parameter $Nsuc$, W , $cf_{m,1}, cf_{m,2}, \dots, cf_{m,NSUC}$, $c\phi_{m,1}, c\phi_{m,2}, \dots, c\phi_{m,NSUC}$ contained in the corresponding unmodulated symbol V_m (cf. Table 2) the sampling values $s_m(i)$ are defined as:

$$s_m(i) = \frac{-1}{Nsuc} \cdot \sum_{j=1}^{Nsuc} \left[w(i) \cdot \cos(2\pi \cdot cf_{m,j} \cdot \frac{i-0.5}{Ts} + c\phi_{m,j}) \right], \quad i = 1, \dots, Ts,$$

where: $Nsuc = 1, 2, 3, 8$ or 20 is the number of simultaneously used carrier frequencies in the symbol $cf_{m,1}, cf_{m,2}, \dots, cf_{m,NSUC}$ with the phases $c\phi_{m,1}, c\phi_{m,2}, \dots, c\phi_{m,NSUC}$; $w(i)$ are samples of the window W ; Ts is the duration of the symbol corresponding to the used W .

The samples of the resulting transmit signal are generated by summing up the samples of consecutive modulated symbols S_m , $m = 0, \dots, TNS - 1$, that are shifted by ΔT samples against each other. The first sample $s_0(1)$ of the preamble follows the last zero sample of ITD. Figure 7 shows symbolically how the overlapped modulated symbols are combined with each other. As shown in this Figure, up to 3 modulated symbols can overlap.

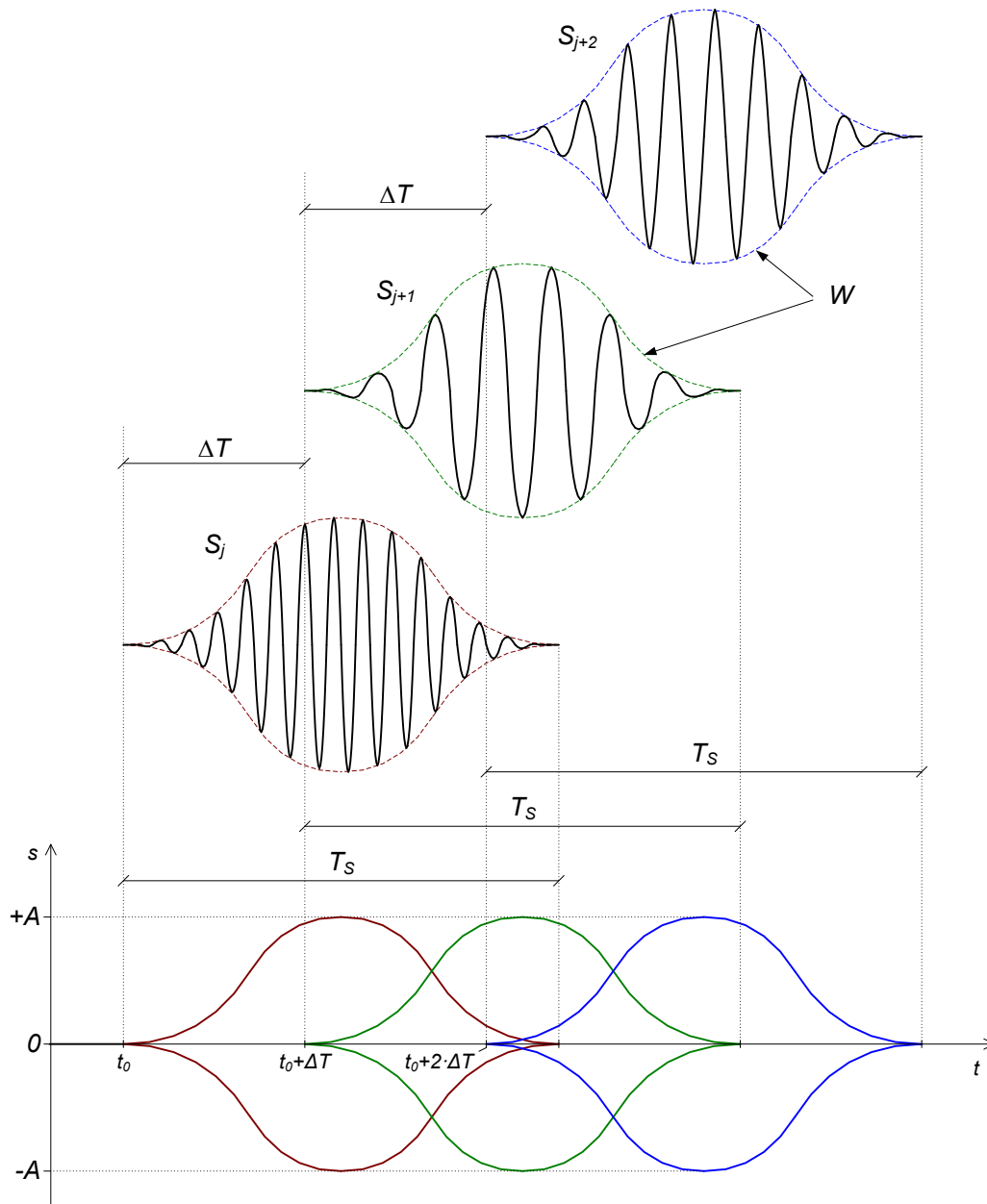


Figure 7 – Combining of overlapped modulated symbols

An interframe interval (IFI) of N_{IFI} sampling intervals $\Delta t = 1/347200$ s follows the last zero sample of the PDZ_1 symbol, if is requested by the MAC sub-layer entity. N_{IFI} is defined by the parameter IFID. During the IFI zero samples $s(i) = 0$, $i = 1$ to N_{ITD} are transmitted. In this case the next PHY frame shall be transmitted without ITD. Its first sample $s_0(1)$ of the preamble follows the last zero sample of IFI. Figure 8 shows symbolically how the last three PHY data symbols PDS_{M-3} to PDS_{M-1} of an PHY frame are combined with the zero symbols PDZ_0 , to PDZ_1 , IFI and the first TSS₀ symbol of the next PHY frame.

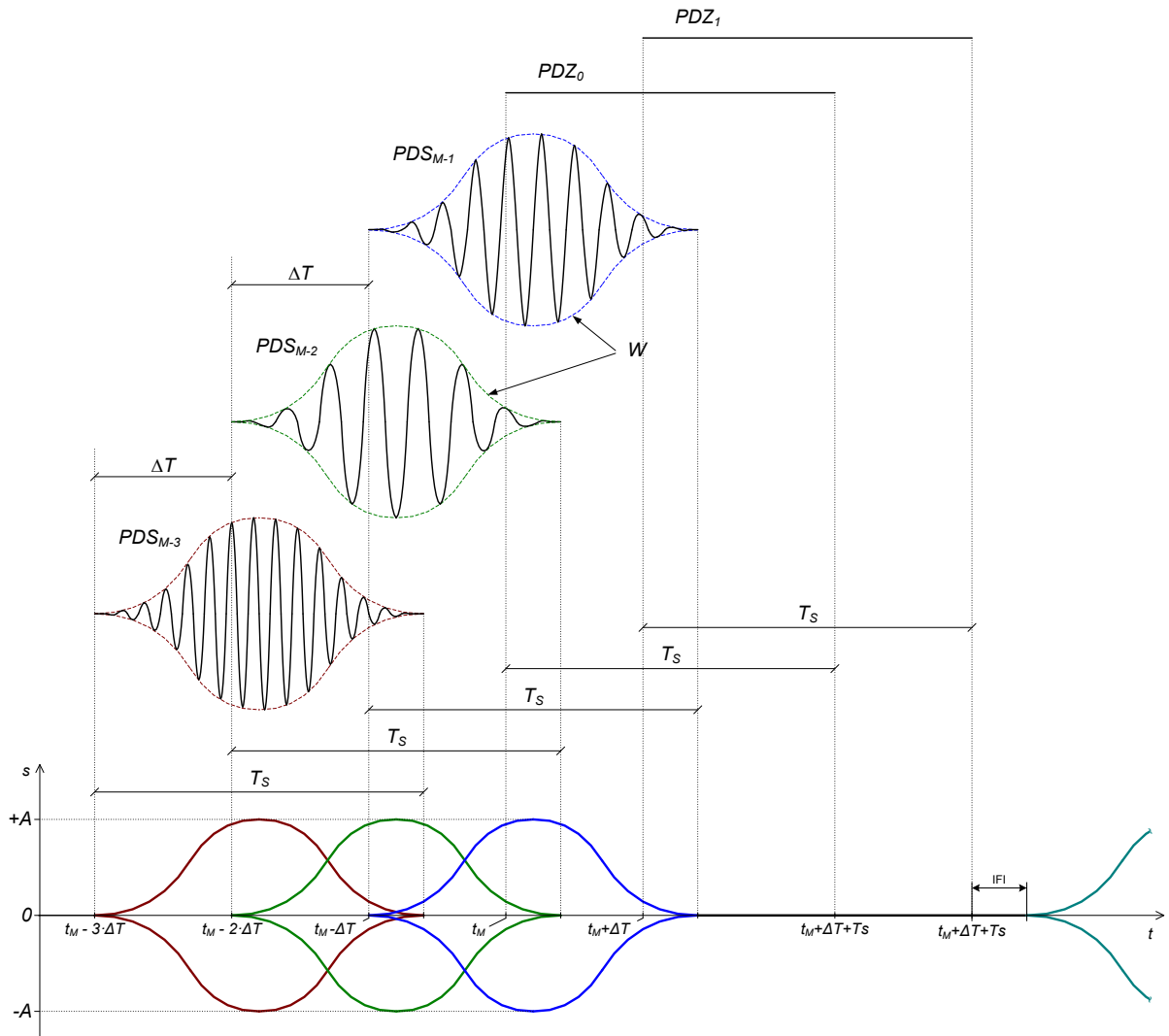


Figure 8 – Combining of overlapped modulated symbols followed by IFI

Finally the sampled transmit signal converted to the analogue signal and coupled into the physical channel – power-line.

5.4 EMC requirements

The emission requirements of EN 50065-1 shall be met.

5.5 PHY layer services

5.5.1 General

The PHY layer offers to the layer 2 only SEND/NO REPLY service.

As shown in Figure 9, the primitives P_data.request and P_data.indication are used to exchange information between the MAC sub-layer of layer 2 and the physical layer.

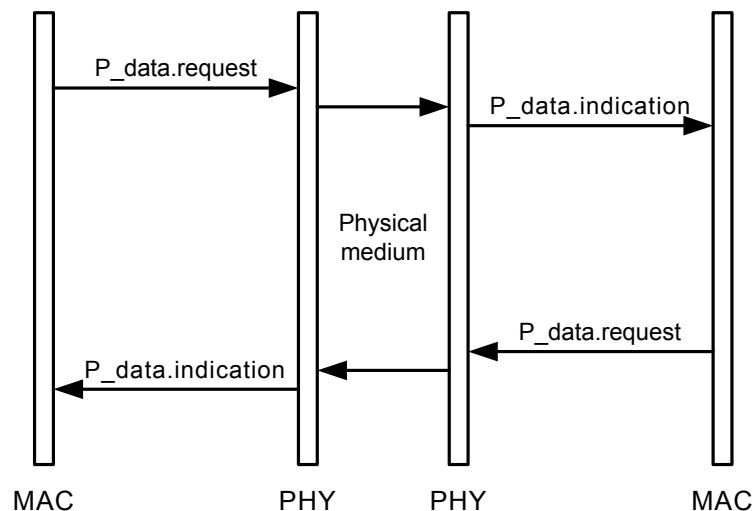


Figure 9 – Primitives between layer 2 and layer 1

The PHY layer primitive are described in the following sub-sections.

5.5.2 P_data.request

The *P_data.request* primitive is used by MAC sub-layer entity to initiate a PHY frame transmission procedure.

This primitive has following structure:

P_data.request{*TransmitTimingType*, *TransmitMode*, *DataLength*, *Data*}

The *TransmitTimingType* parameter specifies the type of the timing during the required PHY frame transmission procedure. The parameter may have one of the following values:

- 0: PHY frame shall be transmitted with ITD but without IFI;
- 1: PHY frame shall be transmitted with ITD and IFI at the end;
- 2: PHY frame shall start after the last zero sample of the last IFI. At the end of the frame the next IFI shall be transmitted;
- 3: PHY frame shall start after the last zero sample of the last IFI. At the end of the frame no IFI shall be transmitted.

The *TransmitMode* parameter specifies the transmit mode, which shall be used for the PSDU transmission in the PHY frame. The parameter may have one of the values 0 to 20 corresponding to the TM0 to TM20 respectively.

The *DataLength* parameter is the length of the *Data* parameter in bits. It may have any value in the range from 96 to 2152.

The *Data* parameter is a block of bits, which contains a MPDU to be transmitted.

5.5.3 P_data.indication

The *P_data.indication* primitive is used by a PHY layer entity to inform the MAC sub-layer entity about the reception of a PHY frame.

This primitive has following structure:

`P_data.indication{TransmitTimingType, TransmitMode, DataLength, Data}`

The *TransmitTimingType* parameter specifies the type of the PHY frame transmission timing. The parameter may have one of the following values:

- 0: PHY frame has been transmitted with ITD but without IFI;
- 1: PHY frame has been transmitted with ITD and IFI at the end;
- 2: PHY frame has been started after the last zero sample of the last IFI. At the end of the frame the IFI has been transmitted;
- 3: PHY frame has been started after the last zero sample of the last IFI. At the end of the frame no IFI has been transmitted.

The *TransmitMode* parameter specifies the transmit mode, which has been used for the PSDU transmission in the PHY frame. The parameter may have one of the values 0 to 20 corresponding to the TM0 to TM20 respectively.

The *DataLength* parameter is the length of the *Data* parameter in bits. It may have any value in the range from 96 to 2152.

The *Data* parameter is a block of bits, which contains the received PSDU = MPDU.

6 Data link layer specification

6.1 Overview

The MAC and LLC sub-layer of the data link layer provide point-to-multi-point and point-to-point communication on the low voltage distribution network between a master node and one or more slave nodes. The transmitted information is protected by CRC sequences. The MAC layer provides a simultaneous forwarding procedure in order to extend the achievable transmission range and to improve the transmission quality.

6.2 MAC protocol data unit

6.2.1 MPDU structure

An overview of the MPDU is shown in the Table 8.

Table 8 – Structure of MPDU

	Field name												
	Reserved bits	Frame forwarding sector number (FXS)	CIN of source node	NIN of source node	Link address (LA)	Data block length (DBL)	Total number of frame retransmission (FXT)	Frame retransmission down-counter (FXDC)	Reference-zero-crossing offset (RZCO)	LLC field (LLCF)	Frame header check sequence (FHCS)	Data block (DB)	Frame check sequence (FCS)
short frame (data block length = 0)	+	+	+	+	+	+	+	+	+	+	+	--	--
data frame (data block length ≠ 0)	+	+	+	+	+	+	+	+	+	+	+	+	+
A paragraph containing a requirement.													
NOTE “+”: frame contains the field; “-”: frame does not contain the field													

A detailed structure of the MPDU, as shown in Figure 10, is defined in Table 9 and described in the following sub-sections.

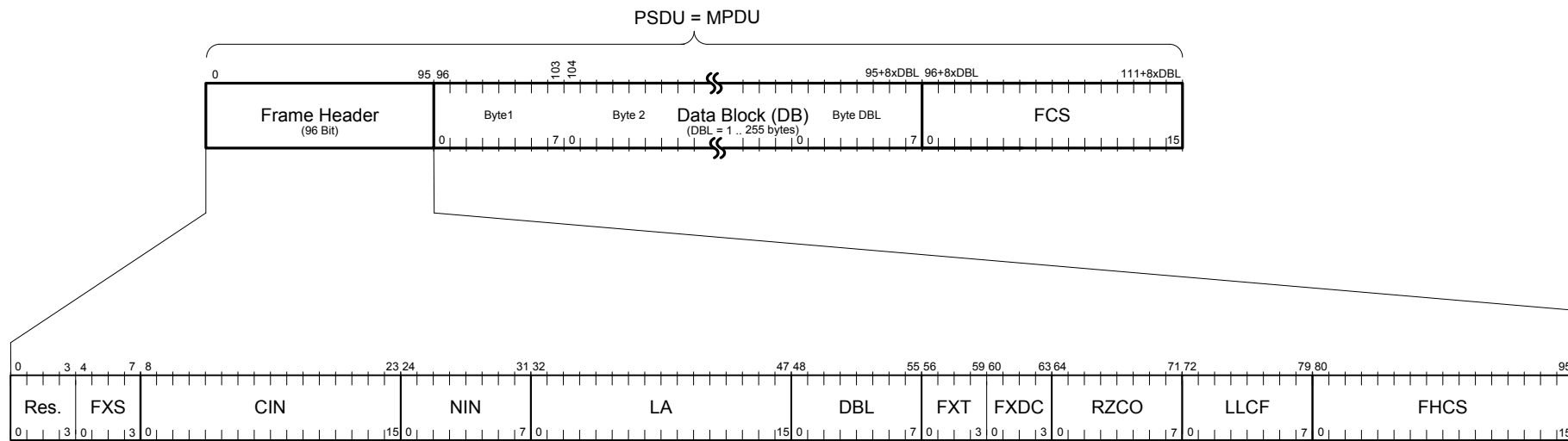


Figure 10 – MPDU structure

Table 9 – Description of MPDU

Field	Bit number	Bits	Full name of field	Value
Res.	3 to 0	4	Reserved bits for future use	0x0 - allowed value; 0x1 to 0xF - not allowed values.
FXS	7 to 4	4	Frame forwarding sector number	0x0 to 0xE – Fx-sector 0 to 14; 0xF – frames shall be forwarded in all Fx-sectors.
CIN	23 to 8	16	MAC-channel identification number (CIN) of source node	0x0000 to 0xFFFFE - allowed CIN values; 0xFFFF - broadcast to all network nodes with the same N_NIN.
NIN	31 to 24	8	Lower byte of the network identification number (NIN) of source node	0x00 to 0xFF - allowed values.
LA	47 to 32	16	Link address (LA)	0x0000 to 0xFFFFD - valid link addresses; 0xFFFFE - wait-state address; 0xFFFFF - broadcast-address, which is used for broadcasts to all nodes with the same S_CIN within a network cell or, together with CIN = 0xFFFFF for broadcast to all nodes with the same N_NIN within a network.
DBL	55 to 48	8	Data block length (DBL) in bytes	0x00 to 0xFF - allowed values.
FXT	59 to 56	4	Total number of frame retransmissions (FXT)	0x0 to 0xF - allowed values.
FXDC	63 to 60	4	Frame retransmission down-counter (FXCD)	0x0 to 0xF – allowed values if FXDC ≤ FXT.
RZCO	71 to 64	8	Reference-zero-crossing offset (RZCO)	0x00 to 0xFE - possible values; 0xFF – no RZCO available.
LLCF	79 to 72	8	Logical link control field (LLCF)	0x00 to 0xFF - possible values.
FHCS	95 to 80	16	Frame header check sequence	0x0000 to 0xFFFF - possible values.
DB	96 to 95+8xDBL	8xDBL	Data block (available if DBL ≠ 0)	0x00 to 0xFF - allowed values for each data block byte. The data block starts with the bit 0 of first byte and ends with the bit 7 of last byte.
FCS	111+8xDBL to 96+8xDBL	16	Frame check sequence (FCS) is based on CRC16 sequence., and is available if DBL ≠ 0	0x0000 to 0xFFFF - possible values.

6.2.2 Frame forwarding sector number

The field FXS contains the number of a frame forwarding sector. The frames with FXS ≠ 0xF are simultaneously forwarded only by nodes from this sector. The value 0xF is reserved for frame forwarding in all sectors simultaneously. The settings of the slave node contain a parameter S_FXS (Slave Frame Forwarding Sector) for its assignment to a frame forwarding sector. A group of the slave nodes, registered on a dedicated master node, with the same setting S_FXS ≠ 0xF, form a frame forwarding sector. Frames are forwarded/retransmitted only in one frame forwarding sector, if FXS = S_FXS ≠ 0xF. Frames with FXS = 0xF are forwarded by all slave nodes in a network cell independently from the value of S_FXS. The s-MN, alternatively acting as a slave, uses its own parameter S_FXS.

6.2.3 MAC-channel identification number

The field CIN contains the MAC-channel identification number. CIN≠0xFFFF identifies a dedicated master in the network. It is also used by slave nodes to address their master node. The CIN value 0xFFFF is reserved for broadcast from a master node to other master nodes within the same network. The settings of the master node contain a parameter 'Master MAC-channel identification number (M_CIN)', which is preconfigured with a unique 16 bit CIN≠0xFFFF. A Slave node contains a non-preconfigured dynamic parameter 'Slave MAC-Channel identification number (S_CIN)'. During the registration (log-in) procedure the slave node receives from the master a new S_CIN. Registered slave nodes together with their master node create a network cell. S_CIN ≠ 0xFFFF is stored in a fail-safe memory as long as the slave node is registered with the master node. The current value of S_CIN is discarded (S_CIN=0xFFFF) after the slave's registration with the current master has been lost or it becomes registered with another master with a new S_CIN. The s-MN can alternately act as master or slave using its own preconfigured M_CIN or an additional dynamic S_CIN respectively.

6.2.4 Network identification number

The field NIN contains the lower 8 bits of the 16 bit Network Identification Number of the Node (N_NIN) transmitting the frame. The same N_NIN value is preconfigured in all the nodes of the network.

6.2.5 Link address

The field LA contains the link address, which is used for layer 2 addressing. The value 0xFFFFE is reserved for the wait-state address of a slave node. The value 0xFFFF is reserved for the broadcast address. With a LA ≠ 0xFFFF either one dedicated slave node or a group of slave nodes in a network cell (a so-called multicast group) is addressed by the master node. A slave node contains a non-preconfigured dynamic parameter 'Slave link address (S_LA)'. Additionally the slave node may contain a non-preconfigured dynamic parameter array 'Slave multicast addresses (S_MAx)' with up to 31 slave multicast addresses: S_MA1 to S_MA31. The values of S_LA ≠ 0xFFFF and, if available, the values of S_MAx are assigned to the slave node by a master node during slave's registration (log-in) procedure with the master. Note, that the value of S_LA shall be unique in a network cell. The (new) values of S_LA and S_MAx are stored in a fail-safe memory as long as the slave node is registered with the master node. The values of S_LA and S_MAx are discarded becoming = 0xFFFF after the slave's registration with the current master has been lost. If the slave node becomes registered with another master with new S_LA and S_MAx values, the previous values of these parameters are discarded as well. A node acting as master does not have its own S_LA and S_MAx. An s-MN can alternatively act as slave node using its own S_LA and S_MAx assigned to it by the master node it is registered with.

6.2.6 Data block length

The field DBL determines the length of the data block in the frame in octets. If DBL = 0 the frame does not contain DB and FCS.

6.2.7 Total number of frame retransmissions

The field FXT provides the number of frame retransmissions in total. It is not changed when a frame is transmitted. If FXT = 0 the frame is transmitted only once without retransmissions.

6.2.8 Frame retransmission down counter

The field FXDC contains a value from 0 to 15. The FX down counter contains the number of remaining frame retransmissions. If $FXDC \neq 0$, it is decremented before each frame retransmission by 1. A frame containing $FXDC = 0$, is transmitted only once without further retransmissions. For their initial transmission (before their retransmission), frames have to contain $FXDC = FXT$.

6.2.9 Reference zero-crossing delay

The field contains a value from 0 to 255. The Reference zero-crossing delay field contains a factor, which is multiplied with 34/347.2 ms to determine the duration from the last voltage zero-crossing on a predefined AC-line to the start of each frame transmission procedure. It may be analysed by slave or master nodes for AC-phase recognition. $RZCO = 255$ indicates that no reference zero-crossing delay is available.

6.2.10 Logical link control field

The field LLCF has two different formats, that depend on bit 7 of this field defining the frame transmission direction. Both formats of LLCF are shown in Figure 11.

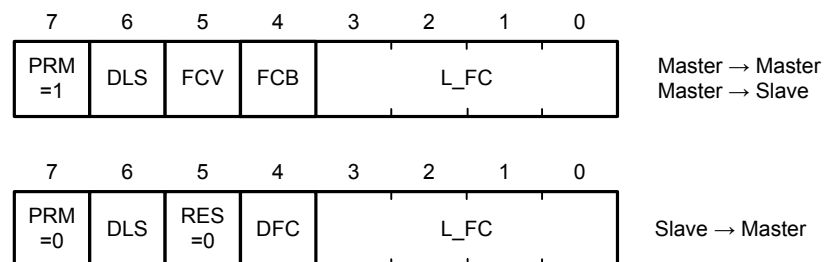


Figure 11 – Formats of logical link control field

Elements of LLCF are defined in Table 10 to Table 14.

Table 10 – Description of LLCF (cf. IEC 60870-5-2)

LLCF element	Full name of element	Values
PRM	Primary bit	PRM=1 – message from master node; PRM=0 – message from slave node.
DLS	Data link service	DLS=0 - L_FC field contains function codes for data link control functions; DLS=1 - L_FC field contains function codes for higher layer servicing.
FCV	Frame count bit valid	FCV=1 - alternating function of the FCB bit is valid and can be analysed by slave node; FCV=0 - alternating function of the FCB bit is invalid. SEND/NO REPLY messages, MULTICAST or BROADCAST messages or other transmission services, that ignore the deletion of duplication or loss of information, do not alternate the FCB bit and indicate this by cleared FCV bit.
FCB	Frame count bit	0, 1 = alternating bit for successive SEND/CONFIRM or REQUEST/RESPOND messages directed to the same destination. The frame count bit is used to delete losses and duplication of information transfers. The master node alternates the FCB bit for each new SEND/CONFIRM or REQUEST/RESPOND message transmission directed to the same destination: to a slave node if DLS = 0 or to one of the link channels of the slave node if DLS = 1. Thus the master node keeps an own copy of the frame count bit for each of the destinations (each data link channel or data link control channel of a slave node). If an expected reply is timed out (missing) or garbled, then the same SEND/CONFIRM or REQUEST/RESPOND message is repeated with the same frame count bit. In case of 'Clear transmit buffer messages (L_FC = 0, DLS = 0,1) the FCB bit is always zero, and upon the receipt of these messages the data link control channel (DLS = 0) or one of link channels (DLS = 1, LCN = 0 to 15) of the addressed slave node will always be set to expect from the master node the next message, addressing the same channel, with FCV = 1 to have an opposite setting of FCB, it is FCB = 1.
RES	Reserved	RES=0 – valid value; RES=1 – invalid value
DFC	Data flow control	DFC=0 - further messages are acceptable; DFC=1 – indicates to the master node that an immediately following messages may cause buffer overflow in the slave node.
L_FC	Link function code	See Table 11 to Table 14 below for valid values

Table 11 – Link function codes if PRM=1 and DLS=0

Master node messages for data link control functions (PRM=1, DLS=0). See B.1.			
L_FC	Type of message or service	Function	FCV
0	SEND/NO REPLY expected	Generate temporary link address (BROADCAST)	0
1	SEND/CONFIRM expected	Clear transmit buffer	0
2	SEND/NO REPLY expected	Master node beacon (BROADCAST)	0
3	SEND/NO REPLY expected	Master node deactivated (BROADCAST)	0
4	SEND/NO REPLY expected	Clock synchronisation command (BROADCAST)	0
5	SEND/NO REPLY expected	Reuse link address (BROADCAST)	0
6	SEND/CONFIRM expected ^a	Perform PHY link test	1 / 0 ^a
7	SEND/NO REPLY expected	MN PHY link test	0
8	REQUEST/RESPOND expected	Request to node with temporary link address (BROADCAST)	0
9	REQUEST/RESPOND expected	Assign new address	1 / 0 ^b
10	REQUEST/RESPOND expected	Status enquiry	1
11	REQUEST/RESPOND expected	Node enquiry	1
12	REQUEST/RESPOND expected	Data availability enquiry (BROADCAST)	0
13, 14	-	Reserved for future use	-
15	REQUEST/RESPOND expected	Link quality enquiry	1
^a The frame may be sent as a none-confirmed broadcast/multicast. In this case no reply is expected and FCV bit is zero. ^b The frame may be sent with LA=0xFFFF. In this case FCV bit is zero.			

Table 12 – Link function codes if PRM=0 and DLS=0

Slave node messages for data link control functions (PRM=0, DLS=0). See B.3.		
L_FC	Type of message or service	Function
0	CONFIRM	ACK: Positive acknowledgement
1 to 6	-	Reserved for future use
7	RESPOND	SN PHY link test
8	RESPOND	Status response
9	RESPOND	Node response
10	RESPOND	Response from node with temporary link address
11	-	Reserved for future use
12	RESPOND	Data availability status
13, 14	-	Reserved for future use
15	RESPOND	Link quality response

Table 13 – Link function codes if PRM=1 and DLS=1

Master node messages for higher layer servicing (PRM=1, DLS=1). See B.2.			
L_FC	Type of message or service	Function	FCV
0	-	Reserved for future use	-
1	SEND-CONFIRM expected	Clear transmit buffer	0
2	-	Reserved for future use	-
3	SEND-CONFIRM expected	Data transmission	1
4	SEND-NO-REPLY expected	Data multicast (MULTICAST / BROADCAST)	0
5	SEND-CONFIRM expected	Segmented data transmission	1
6	SEND-NO-REPLY expected	Segmented data multicast (MULTICAST / BROADCAST)	0
7 to 10		Reserved for future use	-
11	REQUEST-RESPOND expected	Data enquiry	1
12 to 15	-	Reserved for future use	-

Table 14 – Link function codes if PRM=0 and DLS=1

Slave node messages for higher layer servicing (PRM=0, DLS=1). See B.4		
L_FC	Type of message or service	Function
0	CONFIRM	D_ACK: positive data reception acknowledgement
1 to 8	-	Reserved for future use
9	RESPOND	Data response
10 to 15	-	Reserved for future use

6.2.11 Frame header check sequence

The MAC header CRC sequence is calculated from the successive bits 11 to 16 of PPDU and bits 0 to 79 of MPDU and added at the end of the frame header. For calculation of a 16-bit CRC sequence, a polynomial $P_{CRC}(x) = x^{16} + x^{12} + x^5 + 1$ (also known as CRC CCITT-16) is used, together with a 16-bit CRC initial value defined by parameter CRCINITVAL. The default value of CRCINITVAL = 0xFFFF.

6.2.12 Data block and frame check sequence

The Data block and the frame check sequence are available in the frame, if the data block length (DBL) is greater than zero. The frame check sequence is calculated from the data block bits, starting with the 1st bit of the 1st byte, as the second CRC sequence using the same polynomial as for the header CRC. The initial value for the frame check sequence calculation is the value of the frame header check sequence, meaning that CRC calculation just continues, with the header check sequence being an intermediate result. The frame check sequence is added immediately after the data block.

6.2.13 Scrambling

Before transmission, the MPDU is scrambled by a bit sequence SC with the length L_{SC} . MPDU and, if necessary, cyclic extended SC are bitwise combined using XOR operation starting with the 1st bit each. The bit sequence SC and its length are defined by parameter array SCA and the parameter SCL respectively.

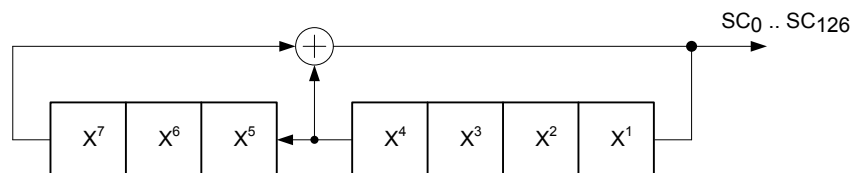


Figure 12 – Pseudo-noise sequence generator

Default values of SC are bits of a pseudo-noise sequence with the length $L_{SC} = 127$ generated at the output of a linear feedback shift register as shown in Figure 12, which is defined by the polynomial $P_{SC}(x) = x^7 + x^4 + 1$ and all ones as initial value of the register.

6.3 MAC frame transmission

The frames are retransmitted FXT times. The total number of retransmissions FXT, the transmission mode TM and, perhaps, the forwarding sector FXS are dynamically defined by the master node for each slave node. The retransmission improves the range and the frame transmission quality. Before the start of the frame transmission procedure by a master or a slave node, the FXT and FXDC in the frame shall have the same value. If this value is equal to zero, then the frame is sent only once. Otherwise the frame is retransmitted FXT times. Before every retransmission, the FXDC-value in the frame shall be decremented by 1 and the CRC-sequences FHCS and FCS shall be recalculated. An example of the frame transmission procedure of a SEND/NO REPLY-message is shown in Figure 13. In the example three copies of the same message have been received by the slave node. During the frame transmission procedure usually only the 1st received message copy is used. The others are discarded.

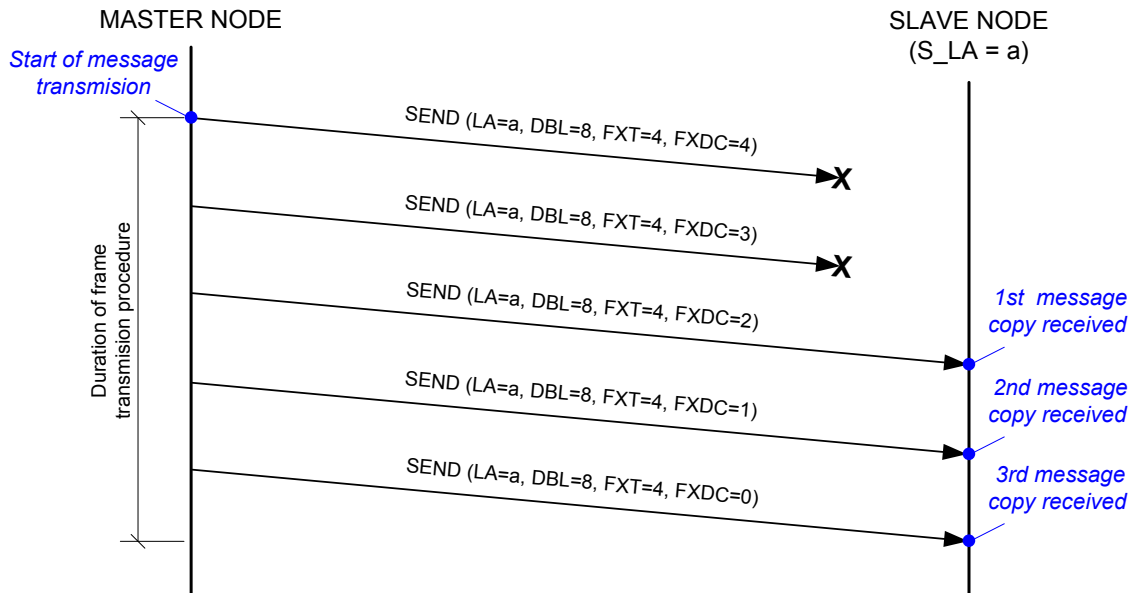


Figure 13 – Frame transmission procedure used by SEND/NO REPLY service.

Every frame transmission procedure in the MAC layer starts with an initial transmission delay (ITD) defined by the parameter ITDD. Between frame retransmissions lies an interframe interval (IFI). Its duration is defined by the parameter IFIT. Both parameters contain values in multiples of the sampling interval $\Delta t = 1/347200$ s.

For multi-hop transmission of the frames, the MAC layer provides a simultaneous forwarding procedure, where all involved nodes retransmit received frames simultaneously (synchronously). When a master node can reach a slave node without frame retransmission, this is called direct communication or communication in the hop plane 0. Each retransmission creates an additional hop plane. A slave node, which can be reached by the master node only via one slave node, is located on hop plane 1. Up to 16 hop planes (0 to 15 frame retransmissions) are possible.

Depending on the values of the parameters N_NIN, S_FXENA, S_FXS, S_CIN, S_LA, S_MAx, $x = 1$ to 31 and the values of FXS, CIN, NIN, LA, FXDC each network node acting as a slave node can forward a frame to other nodes. A network node acting as master node shall not forward frames from other network nodes. It retransmits a frame only during a transmission procedure initiated by itself.

If the value of the FX-decrement-counter in a MPDU received by a slave node is greater than zero, then the FX-down-counter shall be decremented by 1 and the frame shall be (re)transmitted until the FX-decrement-counter has reached a zero value. Only FXDC-values not greater than FXT are valid in received frames.

Transmission of frames with $NIN \neq L_NIN$, L_NIN is lower byte of N_NIN value, is not allowed. A node discards frames with $NIN \neq L_NIN$ when received.

Usually nodes acting as slaves discard frames if $S_CIN \neq CIN \neq 0xFFFF$, but they may receive them, if it is necessary for the hand-off procedure.

A correctly received frame may only be forwarded by a slave node if at least one of the following conditions is true:

- $(S_FXENA = 1)$ AND $(FXDC \neq 0x0)$ AND $(CIN = 0xFFFF)$;

- $(S_FXENA = 1) \text{ AND } (FXDC \neq 0x0) \text{ AND } (S_CIN \neq 0xFFFF) \text{ AND } (S_LA \neq 0xFFFF) \text{ AND } (CIN \neq 0xFFFF) \text{ AND } (S_CIN = CIN) \text{ AND } (LA = 0xFFFF);$
- $(S_FXENA = 1) \text{ AND } (FXDC \neq 0x0) \text{ AND } (S_CIN \neq 0xFFFF) \text{ AND } (S_LA \neq 0xFFFF) \text{ AND } (CIN \neq 0xFFFF) \text{ AND } (S_CIN = CIN) \text{ AND } (S_LA \neq LA) \text{ AND } (FXS = 0xF);$
- $(S_FXENA = 1) \text{ AND } (FXDC \neq 0x0) \text{ AND } (S_CIN \neq 0xFFFF) \text{ AND } (S_LA \neq 0xFFFF) \text{ AND } (CIN \neq 0xFFFF) \text{ AND } (S_CIN = CIN) \text{ AND } (S_LA \neq LA) \text{ AND } (S_FXS = FXS).$

An example of simultaneous frame forwarding is shown in Figure 14. The transmission procedure was initiated by a master with a total number of frame retransmissions $FXT=4$ and $FXDC=4$. It means that the frame has been transmitted 5 times during this forwarding procedure: 4 frame retransmissions by other nodes follow the initial frame transmission from master node.

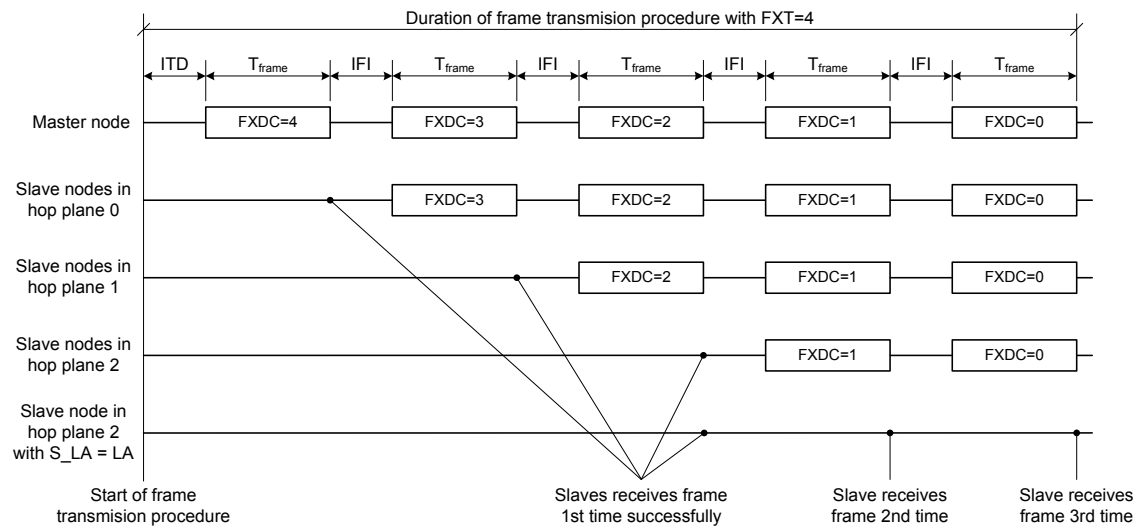


Figure 14 – Frame transmission procedure with simultaneous forwarding

For the first time the addressed slave node with $S_LA = LA$ receives the frame already with $FXDC=2$. Two further frame receptions can follow until the end of the last frame retransmission with $FXDC=0$.

Only after the completion of the current frame transmission procedure, the slave node may answer by initiating a new frame transmission procedure to the master node.

Figure 15 shows an example of how the frame transmission procedure with simultaneous forwarding is used by REQUEST/RESPOND service in the LLC layer.

For the response the slave nodes use usually the same value of TM , FXS , CIN , NIN , LA and FXT as in the frame received from the master.