IEEE P802.15
Wireless Personal Area Networks

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Abstract	A partial specification of newly proposed 802.15.7r1 PHY modes is provided. A generalized PHY specification is proposed and logically separated into: 1) Low-bandwidth (low-complexity) mode; 2) High-bandwidth mode.
Purpose	Proposal
Notice	
Release	

6. Generic PHY

6.1. Adaptive OFDM Concept

The OFDM concept adopted in the current specification enables a highly adaptive modular implementation, which supports both a high-efficiency PHY mode designed to enable very high data rates up to 10 Gb/s as well as a low-complexity PHY mode designed to enable high energy efficiency in mobile applications. Furthermore, the specification enables the adaptive and modular introduction of energy-efficient waveforms such as enhanced unipolar OFDM (eU-OFDM), performance enhancing waveforms such as single-carrier OFDM (SC-OFDM) and waveforms designed for improved illumination control such as reverse polarity optical OFDM (RPO-OFDM). In addition, the specification supports the application of multiple-input multiple-output (MIMO) techniques which can leverage the additional communication capacity of multiple light sources as well as the additional communication capacity introduced by the utilization of different optical wavelengths for communication. A DC-biased optical OFDM (DCO-OFDM) waveform is the basic foundation of all concepts, which are specified as optional features and can be applied in a non-conflicting manner.

The adaptive OFDM concept enables different parameters of the OFDM modulation scheme to be adjusted in response to the changing channel conditions. In particular, the robustness, efficiency and complexity of the implementation can be controlled by selection of the PHY mode, which in turn enables the optimization of specific modulation parameters.

6.2. Frame Structure

The fields of the presented PHY frame are specified in terms of their generic functionality. Different specific values for each field can be specified, supporting the individual implementations of the different PHY modes. The different parts of the PHY frame structure in Fig. 6.2.1. are envisioned to occupy different OFDM frames in order to achieve a modular PHY frame design, which can be augmented easily based on the functionality which the specific PHY implementation supports.

6.2.1.Preamble

The function of the preamble is to enable the PHY to identify the existence of a packet and its beginning. The specific value for this sequence is specified in Section 7 for the different PHY modes.

6.2.2. Channel Estimation

A sequence of OFDM training symbols is used to estimate the channel impulse response. The sequence can also be used for additional synchronization. The specific value for this sequence is specified in Section 7 for the different PHY modes.

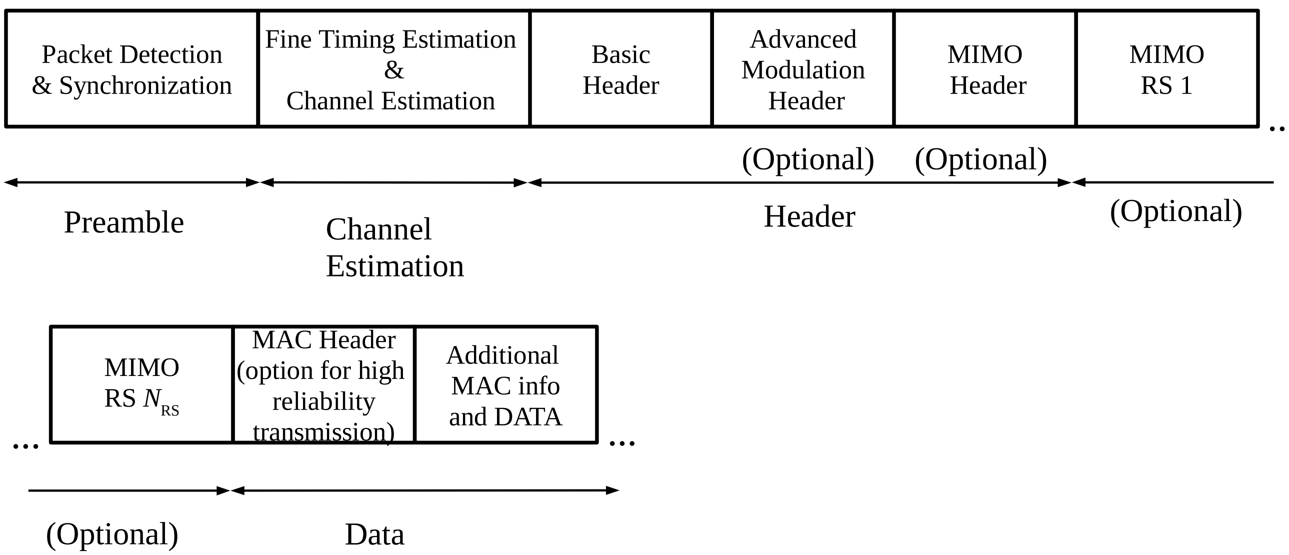

Figure 6.2.1: Generic PHY frame structure.

6.2.3. Header

The Header contains all information necessary for demodulating the subsequent frame payload. The header is logically split into three sections, which are encoded in separate OFDM frames (each part can be encoded in more than one OFDM frame) in order to achieve a modular PHY frame design.

6.2.3.1. Basic Header

The basic header contains the minimum information required for demodulating the subsequent payload. In the low-bandwidth PHY mode, this header includes information such as the constellation size, the FEC rate and the payload size. In the high-bandwidth PHY mode, this header contains further information such as what BAT is used. The Basic Header also indicates whether an Advanced Modulation Header (containing further information regarding the modulation format) is used. If no advanced modulation header is used, then the DATA portion of the PHY frame is expected to appear after the basic header. The basic header is encoded in the most robust modulation format. The exact values of this frame field are described in clause 7 for the different PHY modes.

6.2.3.2. Advanced Modulation Header

The advanced modulation header is encoded in separate OFDM frames from the Basic Header, so that the overall structure becomes more modular, i.e., when certain parts of the general PHY structure are not required, they can be easily excluded. The Advanced Modulation Header is encoded in the most robust modulation format. The exact values of this frame field are described in clause 7 for the different PHY modes.

6.2.3.3. MIMO Header

The MIMO Header like the Advanced Modulation Header is encoded in separate OFDM frames, so that the overall structure becomes more modular, i.e., when certain parts of the general PHY structure are not required, they can be easily excluded. The MIMO Header is encoded in the most robust modulation format. The exact values of this frame field are described in clause 7 for the different PHY modes.

6.2.4. Data

This field contains the MPDU transferred from the higher layer. The size of this field is specified in the PHY header. The MPDU is encoded according to the modulation format specified in the PHY header. The MAC header portion of the MPDU can be encoded separately using a more robust modulation format.

6.2.4.1. High-reliability MAC Header

The MAC header (alternatively, just the part of the header required for polling and acknowledgments) is encoded in the lowest data-rate (most robust) modulation format. The exact format is specified in clause 7 for the different PHY modes.

6.2.4.2. General Payload Data

The MPDU is encoded according to the modulation format specified in the PHY header. The exact format is specified in clause 7 for the different PHY modes.

6.3. Waveform

6.3.1. Adaptive OFDM signal generation

The adaptive OFDM concept adopted in the current PHY specification allows for adaptive adjustment of the waveform parameters including the carrier mapping, the DFT size, the cyclic prefix as well as for the application of sophisticated signal processing techniques such as single-carrier pre-coding and unipolar modulation for improved transmission rates and efficiency. The individual features of the adaptive signal generation approach as described as follows.

6.3.2. Carrier mapping

The High-bandwidth PHY mode employs variable carrier mapping, whereas the Low-bandwidth PHY mode employs fixed carrier mapping. The exact carrier mapping schemes are specified in clause 7 for the different PHY modes.

6.3.3. IDFT

The IDFT size is variable in the High-bandwidth PHY mode to enable optimal utilization of the communication channel resources. The IDFT size is fixed in the Low-bandwidth PHY mode to enable lower implementation complexity. The exact values of the IDFT size are specified in clause 7 for the different PHY modes.

6.3.4. Cyclic prefix

The cyclic prefix is a cyclic extension of the time-domain information signal in the duration of a single OFDM frame/symbol. The cyclic prefix size is variable in the High-bandwidth PHY mode to enable optimal utilization of the communication channel resources. The cyclic prefix size is fixed in the Low-bandwidth PHY mode to enable lower implementation complexity. The exact values of the cyclic prefix size are specified in clause 7 for the different PHY modes.

6.3.5. Single-carrier modulation (optional)

6.3.6. Unipolar modulation (optional)

6.3.7. Dimming

6.4. MIMO

6.4.1. Modified frame structure

6.4.2. Reference symbols for MIMO channel estimation

6.4.3. MIMO transmission modes

6.5. Channel coding

6.5.1. Channel coding for the header

6.5.2. Channel coding for the data

6.5.3. Channel coding for MIMO

6.6. Relaying

6.6.1. Modified frame structure

6.6.2. Amplify and forward

6.6.3. Decode and forward

6.7. Coordinated Network

6.7.1. Modified frame structure

6.7.2. Reference symbols for CO channel estimation

6.7.3. CO transmission modes

7. Numerology

7.1. Low-bandwidth PHY mode

The low-bandwidth PHY mode covers communication bandwidth up to 20 MHz. The timings described in this subclause and shown in subsection 7.1 are for communication bandwidth of 20 MHz. They are increased by 4/3 for communication bandwidth of 15 MHz, doubled for a communication bandwidth of 10 MHz and are quadrupled for a quarter-clocked (i.e., 5 MHz) communication system.

7.1.1. Bandwidth Specification

To be decided.

7.1.2. Frame Structure

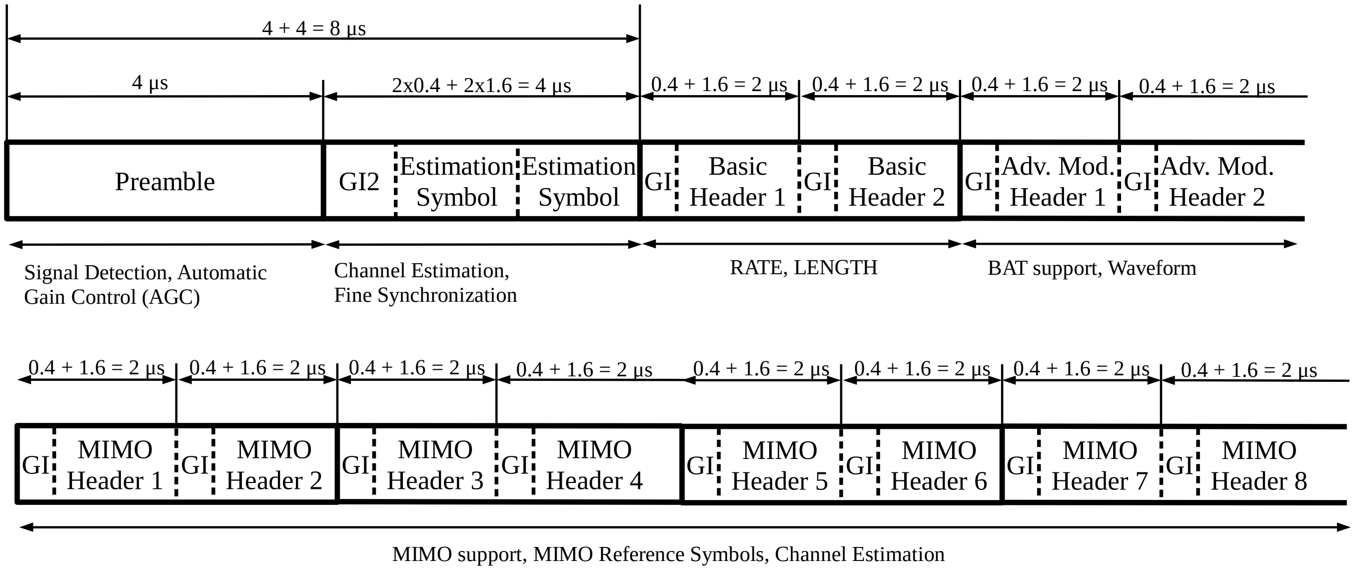

Figure 7.1.2.1: PHY control information.

7.1.2.1. Preamble

The preamble sequence, used for signal detection and automatic gain control (AGC), is the following 160-sample time domain sequence (having the duration equivalent of two OFDM frames), which has been normalized by the factor 1/√78 in order to ensure an average energy level of 1 in agreement with the average energy levels in the information signal:

S_{160} = {1 -1 -8 -2 15 15 13 4 -7 -1 6 0 -12 -14 -14 -5 5 2 7 3 -12 -13 -13 -4 7 0 -6 0 12 14 13 4 -5 -2 -7 -3 12 13 13 4 -6 -2 -7 -3 12 13 13 4 -7 0 6 0 -12 -14 -14 -4 5 2 7 3 -13 -13 -14 -4 7 0 -6 0 12 14 14 4 -7 -1 6 0 -12 -15 -14 -4 7 1 -6 0 12 14 14 5 -6 -2 -7 -3 12 13 13 4 -6 -2 -7 -3 12 14 13 4 -8 0 6 0 -13 -14 -14 -4 7 1 -6 0 12 15 13 4 -7 0 6 0 -12 -14 -13 -5 5 2 7 3 -12 -13 -13 -4 5 2 7 3 -12 -13 -13 -5 6 2 7 3 -12 -13 -13 -5 6 2 7 3 -12 -13 -13 -4} / √78

7.1.2.2. Channel Estimation

The channel estimation sequence contains the following values on all subcarriers of two identical OFDM frames:

$E_{0\text{ to }63}$ = {0 0 0 -1 -1 1 -1 1 -1 -1 1 1 1 -1 -1 -1 1 -1 1 1 1 1 1 -1 -1 1 1 -1 1 0 0 0 0 0 0 0 1 -1 1 1 -1 -1 1 1 1 1 1 -1 1 -1 -1 -1 1 1 1 -1 -1 1 -1 1 -1 -1 0 0}

The sequence is Hermitian symmetric in order to satisfy the requirement for a real time-domain signal after the IDFT and has very good auto-correlation properties. In Fig. 7.1.2.1, the channel estimation OFDM symbol is transmitted twice in two identical copies of the time-equivalent signal of the frequency-domain modulation sequence $E_{0\ \text{to}\ 63}$. The time-domain signal is obtained after an IDFT operation. The guard interval GI2 is a cyclic extension of this same time-domain signal and has a duration of 32 samples (twice the length of the typical cyclic extension for this PHY mode specification).

7.1.2.3. Header

The three components of the header in the current PHY take the following form.

7.1.2.3.1. Basic Header

The basic header is encoded using 1/2 rate FEC coded BPSK. It contains 24 bits and fits within 2 OFDM frames of the current PHY mode. The field contains the information and is structured as follows (Fig. 7.1.2.3.1.1).

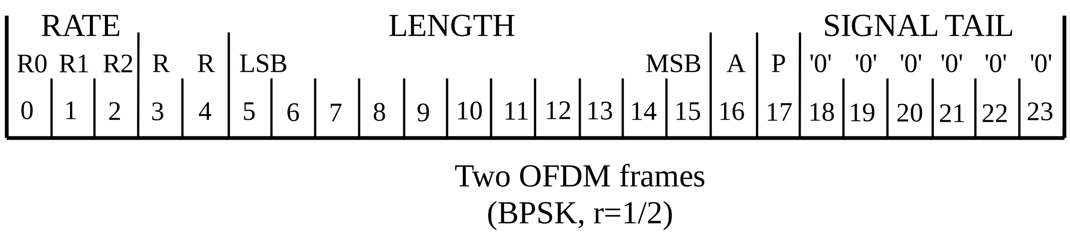

Figure 7.1.2.3.1.1: Structure of the Basic Header.

7.1.2.3.1.1. RATE

The RATE field consists of three bits and indicates the QAM constellation size and the FEC rate used for the subsequent payload. The values specified in Table 5 are valid for the RATE field.

Table 5: Valid RATE values

R1-R4	Modulation	FEC rate	Data rate (Mb/s) (20 MHz)	Data rate (Mb/s) (15 MHz)	Data rate (Mb/s) (10 MHz)	Data rate (Mb/s) (5 MHz)
110	BPSK	1/2	6	4.5	3	1.5
111		3/4	9	6.75	4.5	2.25
010	4-QAM	1/2	12	9	6	3

011		3/4	18	13.5	9	4.5
100	16-QAM	1/2	24	18	12	6
101		3/4	36	27	18	9
000	64-QAM	2/3	48	36	24	12
001		3/4	54	40.5	27	13.5

Two bits are reserved for introducing additional transmission rates in future modifications of the standard.

7.1.2.3.1.3. LENGTH

An 11-bit field which indicates the size of the payload in octets. Hence, the size of the payload is between 0 and 2048 octets.

7.1.2.3.1.3. Advanced Modulation Header Bit (A)

One bit indicating whether an Advanced Modulation Header is included in the next OFDM frame:

1 → The next OFDM frame is an Advanced Modulation Header.
0 → The next OFDM frame is part of the DATA portion (payload) of the PHY frame.

7.1.2.3.1.5. Parity Check Bit (P)

A parity check bit for the information in bits 0 – 16.

7.1.2.3.1.6. SIGNAL TAIL

Six bits set to zero complete the Basic Header. These bits re-set the state machine of the convolutional encoder used in the current PHY mode.

7.1.2.3.2. Advanced Modulation Header

The Advanced Modulation Header is an optional field which contains the information necessary for demodulating the subsequent waveform. It contains information necessary to identify if a bit allocation table is used, and which bit allocation table is used for encoding the payload. It also contains commands for the PHY necessary for estimating the channel quality indicators (CQIs), necessary for constructing a BAT during the real-time operation of the system. The format is presented in Fig. 7.1.2.3.2.1.

																		SIGNAL TAIL					
B	BAT					C	HC	eU	STR		SC	RP	R	R	R	M	P	'0'	'0'	'0'	'0'	'0'	'0'
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

Figure 7.1.2.3.2.1: Advanced Modulation Header format.

7.1.2.3.2.1. Bit Allocation Table Use (B)

One bit indicating whether a Bit Allocation Table is used to encode the subsequent payload:

1 → A Bit Allocation Table is used.
0 → A Bit Allocation Table is not used. In this case, the subsequent payload is encoded with the default loading scheme and the rate specified in the Basic Header.

The low-bandwidth PHY mode is not required to support a BAT update or a BAT in general, so this bit can be used to signal this information. If a PHY which does not support BATs encounters a packet which has this bit set to 1, it will ignore it, since it will no be able to demodulate it.

7.1.2.3.2.2. Bit Allocation Table Number (BAT)

Five bits, which allow up to 32 BATs to be specified. This field indicates which BAT is used to encode the payload in the current PHY frame. If B is set to '0', then this field is irrelevant.

7.1.2.3.2.3. Estimate CQIs (C)

One bit indicating whether the CQIs should be calculated in the PHY for the current transmission frame. The channel estimation symbols preceding the PHY header are used for the estimation of the CQIs.

1 → the CQIs should be estimated
0 → the CQIs should not be estimated

7.1.2.3.2.4. High-reliability CQIs (HC)

Indicates whether there are CQIs in the payload, encoded as high-reliability data, i.e., using the lowest modulation format 1/2 rate BPSK.

1 → the DATA (payload) field contains CQIs encoded in 1/2 rate BPSK.
0 → the DATA (payload) field does not contain CQIs encoded in 1/2 rate BPSK. In this case, any CQI transmission is part of the standard payload (encoded in the same format as the payload,

using the BAT specified in the Advanced Modulation Header or the rate specified in the Basic Header).

The high-reliability transmission is made optional so that higher efficiency can be achieved with higher order modulation.

7.1.2.3.2.5. Use of eU-OFDM

Indicates whether the PHY DATA (payload) field is encoded using eU-OFDM.

1 → the DATA (payload) is encoded using eU-OFDM.
0 → the DATA (payload) is not encoded using eU-OFDM.

Note that the use of an alternative waveform can be negotiated in advance using control/management frames. Furthermore, the use of eU-OFDM encoding does not prohibit the use of any additional advanced waveforms such as SC-OFDM or RPO-OFDM.

7.1.2.3.2.6. Number of Streams in eU-OFDM (STR)

Two bits indicating the number of U-OFDM streams superimposed in the signal encoding procedure. The valid values for this field are:

Table 7.1.2.3.2.6.1: Valid STR values

STR	Number of Streams
00	1
10	2
01	3
11	4

7.1.2.3.2.7. Use of Single-carrier OFDM

Indicates whether the PHY DATA (payload) field is encoded using SC-OFDM.

1 → the DATA (payload) is encoded using SC-OFDM.
0 → the DATA (payload) is not encoded using SC-OFDM.

Note that the use of an alternative waveform can be negotiated in advance using control/management frames. Furthermore, the use of SC-OFDM encoding does not prohibit the use of any additional advanced waveforms such as eU-OFDM or RPO-OFDM.

7.1.2.3.2.8. Use of Reverse Polarity Optical OFDM

Indicates whether the PHY DATA (payload) field is encoded using RPO-OFDM.

1 → the DATA (payload) is encoded using RPO-OFDM.
0 → the DATA (payload) is not encoded using RPO-OFDM.

Note that the use of an alternative waveform can be negotiated in advance using control/management frames. Furthermore, the use of RPO-OFDM encoding does not prohibit the use of any additional advanced waveforms such as eU-OFDM or SC-OFDM.

7.1.2.3.2.9. Reserved bits (R)

Three bits are reserved for introducing additional transmission rates in future modifications of the standard. Some of these bits are likely to be occupied by additional functionality specifications for the advanced modulation waveforms.

7.1.2.3.2.10. MIMO Header Bit (M)

One bit indicating whether a MIMO Header is included in the next OFDM frame:

1 → The next OFDM frame is a MIMO Header.
0 → The next OFDM frame is part of the DATA portion (payload) of the PHY frame.

7.1.2.3.2.11. Parity Check Bit (P)

A parity check bit for the information in bits 0 – 16.

7.1.2.3.2.12. SIGNAL TAIL

Six bits set to zero complete the Advanced Modulation Header. These bits re-set the state machine of the convolutional encoder used in the current PHY mode.

7.1.2.3.3. MIMO Header

The MIMO Header is an optional field which contains the information necessary for demodulating the subsequent waveform in case MIMO techniques are used. It contains information necessary to identify the number of MIMO channels in use, the encoding that is used for each channel, as well as any information necessary to conduct a CQI estimation technique for each channel.

C	HC	CH				BAT 1					BAT 2					BAT 3					BAT 4		
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

		BAT 5					BAT 6					BAT 7					BAT 8						
24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47

BAT 9			BAT 10					BAT 11					BAT 12					BAT 13					
48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71

BAT 14				BAT 15					BAT 16					RS	R	R	P	SIGNAL TAIL '0'	'0'	'0'	'0'	'0'	'0'
72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95

Figure 7.1.2.3.3.1: MIMO Header Format.

7.1.2.3.3.1. Estimate CQIs (C)

Indicates whether the PHY should estimate the channel quality indicators (CQIs) for the current transmission. The reference symbols following the MIMO header will be used for the estimation of the CQIs. If the implementation does not support MIMO and/or the CQIs should not be estimated, no reference symbols will be present and the next OFDM frame will contain the payload / high-reliability MAC header.

1 → the CQIs should be estimated
0 → the CQIs should not be estimated

7.1.2.3.3.2. High-reliability CQIs (HC)

Indicates whether there are CQIs in the payload encoded in the most robust modulation format.

7.1.2.3.3.3. Number of MIMO channels (CH)

Indicates the number of MIMO channels used in the current transmission. The size of this field allows for up to 16 parallel communication channels to be used.

7.1.2.3.3.4. Bit Allocation Table Numbers (BAT#)

Indicates the BAT used to encode the information in the respective MIMO channel used for communication.

7.1.2.3.3.5. Reference Symbols Format (RS)

Indicates the format of the reference symbols used for CQI estimation.

7.1.2.3.3.6. Reserved Bits (R)

Two bits are reserved for introducing additional transmission rates in future modifications of the standard. Some of these bits are likely to be occupied by additional functionality specifications for the MIMO mode.

7.1.2.3.3.7. Parity Check (P)

A parity check bit for the information in bits 0 – 88.

7.1.2.3.3.8. SIGNAL TAIL

Six bits set to zero complete the Basic Header. These bits re-set the state machine of the convolutional encoder used in the current PHY mode.

7.1.2.4. MIMO Reference Symbols

The MIMO reference symbols constitute N OFDM frames (or the time-frame equivalent of that many OFDM frames) for N transmitters, where N = # of MIMO channels.

7.1.2.5. Data

This field contains the MPDU transferred from the higher layer. The size of this field is specified in 7.1.2.3.1.3. The DATA field begins with a 16-bit SERVICE field, where the first seven bits are set to zero for descrambler initialization at the receiver and the remaining nine bits are reserved for future use. Following the SERVICE field is the FEC-encoded PPDU data followed by a SIGNAL TAIL of six zero bits for resetting the convolutional decoder. In case the DATA field does not fit within an exact number of OFDM frames, padding bits will be introduced.

7.1.2.5.1.High-reliability MAC Header

The MAC header (at least the portion necessary for polling and acknowledgements) will be encoded in the beginning of the payload using the coding rate of the PHY header (1/2 rate BPSK). This part can be optional in order to ensure compatibility with implementations in which the PHY passes the MAC header as part of the payload. Such an approach would decouple the MAC and the PHY layer.

Making the polling and acknowledgement information robust ensures avoiding a lot of unnecessary retransmissions. Furthermore, when this information is encoded separately from the rest of the payload, errors in the payload (especially for long payloads) which cause the packet to be discarded (and retransmitted) do not influence the polling and acknowledgement mechanism.

7.1.2.5.2. General Payload Data

The general payload in the Data field consists of the rest of the PPDU (excluding the data already encoded in the High-reliability MAC Header).

7.1.3. Waveform

7.1.3.1. Adaptive OFDM signal generation

The current PHY mode supports adaptive bit and energy loading by means of BATs, advanced modulation waveforms, as well as MIMO functionality. These features are optional. The IDFT size, the cyclic prefix and the default carrier mapping are fixed. The valid values which these fields can obtain are described as follows.

7.1.3.2. Carrier mapping

In the current PHY mode, all subcarriers are designated for information transfer by a single communication node in an allocated time interval. No special carrier designation for multiple access techniques exists, and no special carriers are designated for control information. Depending on whether the current PHY implementation supports BATs for carrier mapping, the mapping procedure can be described as follows.

7.1.3.2.1. PHY does not support BATs.

The QAM modulation symbols to which the binary information has been mapped are divided into groups of 24 symbols, where the original order at the output of the QAM modulation encoder is preserved. Each ordered group of 24 symbols is mapped to the ordered set of subcarrier indices [3,4,5,6,8,9,10,11,12,13,14,15,16,17,18,19,20,22,23,24,25,26,27,28], where indices 7 and 21 are assigned to fixed pilot values of 1 and -1, respectively. Zeros are assigned to subcarrier indices [0,1,2,29,30,31,32,33,34,62,63]. The Hermitian symmetric sequence of the 26 symbols assigned to indices [3–28] is assigned to subcarrier indices [35–61].

7.1.3.2.2. PHY supports BATs.

If the PHY mode supports adaptive bit loading, the carrier mapping is determined by means of a bit allocation table.

The description will be completed after the standardization partners agree on the BAT format.

7.1.3.3. IDFT

The modulation of the different frequency-domain subcarriers is achieved through an IDFT operation, described as follows:

$$\sum_{k=0}^{63} S[k] e^{\frac{-j2\pi k}{64}} \quad (7.1.3.3.1)$$

where $S[k]$ is the symbol mapped to subcarrier index k, as described in 7.1.3.2. Conventionally, the inverse Fourier transform, as shown in Equation (7.1.3.3.1), is implemented with an IFFT algorithm. The DFT/IDFT size in the current PHY mode is fixed to 64. The DC subcarrier (subcarrier index 0 in the IFFT operation) and the 180-degree subcarrier (subcarrier index 32 in the IFFT operation) are set to 0. The information and pilot symbols with coefficients 1 to 26 are mapped to IFFT inputs 3 to 28, while the Hermitian symmetry symbols are mapped onto IFFT inputs 35 to 61. The high-frequency subcarriers, at inputs 29 to 34, form a guard interval and are set to 0. The low-frequency subcarriers, at inputs 0-2 and 62-63, are set to 0 in order to avoid possible low-frequency distortion in the system due to baseline wandering and background light interference. The mapping is illustrated in Figure 7.1.3.3.1. After performing an IFFT, the output is cyclically extended to the desired length as described in 7.1.3.4.

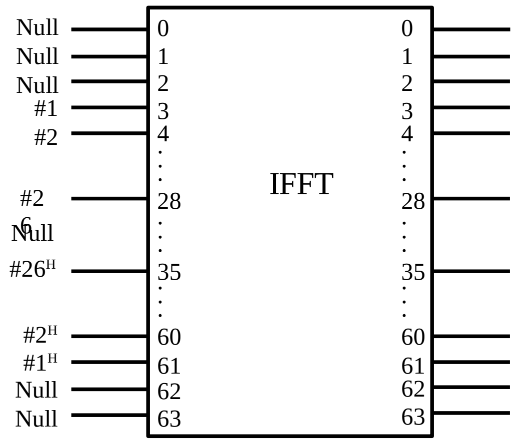

Figure 7.1.3.4.1: IDFT realization by means of an IFFT algorithm.

7.1.3.4. Cyclic prefix

The cyclic prefix/guard interval (GI) is a cyclic extension of the IDFT result in each OFDM frame, where the cyclic prefix is formed by the last 16 samples of the IDFT result, appended in front of the 64-sample IDFT result. In the current PHY mode, the cyclic prefix size is not variable and cannot be changed.

7.1.3.5. Single-carrier modulation (optional)

7.1.3.6. Unipolar modulation (optional)

7.1.3.7. Dimming

7.2. High-bandwidth PHY mode