19. High-throughput (HT) PHY specification

19.1 Introduction

19.1.1 Introduction to the HT PHY

Clause 19 specifies the PHY entity for a high-throughput (HT) orthogonal frequency division multiplexing (OFDM) system. In addition, a variant capability PHY based on the HT PHY ("Class 2 HT PHY") is defined in this clause.

In addition to the requirements found in Clause 19, an HT STA shall be capable of transmitting and receiving frames that are compliant with the mandatory PHY specifications defined as follows:

- In Clause 17 when the HT STA is operating in a 20 MHz channel width in the 5 GHz band
- In Clause 16 and Clause 18 when the HT STA is operating in a 20 MHz channel width in the 2.4 GHz band

An HT STA that operates in the 5 GHz band shall comply with all normative requirements of Clause 17. An HT STA that operates in the 2.4 GHz band shall comply with all normative requirements of Clause 18.

The HT PHY is based on the OFDM PHY defined in Clause 17, with extensibility up to four spatial streams, operating in 20 MHz bandwidth. Additionally, transmission using one to four spatial streams is defined for operation in 40 MHz bandwidth. These features are capable of supporting data rates up to 600 Mb/s (four spatial streams, 40 MHz bandwidth).

The HT PHY data subcarriers are modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), or 64-QAM. Forward error correction (FEC) coding (convolutional coding) is used with a coding rate of 1/2, 2/3, 3/4, or 5/6. LDPC codes are added as an optional feature.

Other optional features at both transmit and receive sides are 400 ns (short) guard interval (GI), transmit beamforming, HT-greenfield format, and STBC.

The maximum HT PSDU length is 65 535 octets.

A non-AP STA is a Class 2 HT STA if it satisfies all of the following requirements and is not an HT STA:

1) The STA shall operate in the 2.4 GHz band, and shall have operating channel width 20 MHz.
2) The STA shall support transmission and reception of DSSS 1 Mb/s and 2 Mb/s.
3) The STA shall support transmission and reception of ERP-OFDM 6 Mb/s.
4) If the STA supports HR/DSSS 11 Mb/s, then it shall support HR/DSSS 5.5 Mb/s.
5) If the STA supports ERP-OFDM 24 Mb/s, then it shall support ERP-OFDM 12 Mb/s.
6) If the STA supports any $N_{SS} = 1$ HT-MCS > 0, then it shall support all $N_{SS} = 1$ HT lower HT-MCSs and all lower ERP rates.
7) Except as noted in 4), 5), and 6), each (non-DSSS) HR/DSSS and ERP-OFDM data rate and each HT-MCS is optional.
8) The STA shall support DSSS long preamble and short preamble.
9) The STA shall support short slot time.
10) The CCA functionality for ERP-OFDM in 18.4.6 a) and b) and for HT in 19.3.19.5.4 shall be supported.
11) The minimum receiver sensitivity requirements of Clause 15, Clause 16, Clause 18, and Clause 19 shall apply to all supported modes.

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12) A Class 2 HT STA shall indicate support in the Supported Rates and BSS Membership Selectors element, and, if applicable, the Extended Supported Rates and BSS Membership Selectors element, during association and reassociation, and in probe requests, for
    - 1, 2, 5.5, 11, 6, 12, and 24 Mb/s (whether it supports all of these rates of not), and
    - All ERP rates from the set 9, 18, 36, 48, and 54 Mb/s that the Class 2 HT STA supports, and shall not indicate support for other ERP rates.
13) A Class 2 HT STA shall transmit the HT Capabilities element during association and reassociation, and in probe requests, and shall indicate in the Supported MCS Set field support for HT-MCSs 0-7 (whether it supports all of these HT-MCSs or not).
14) A Class 2 HT STA shall transmit the Supplemental Class 2 Capabilities element.
15) In all other respects the STA shall follow the requirements of the ERP and the HT PHY.

NOTE—A Class 2 HT STA will not be able to operate in a BSS whose AP includes in the basic rate/HT-MCS set, and uses for transmission of group-addressed frames, only rates/HT-MCSs that the STA does not support.

19.1.2 Scope of HT PHY services

The services provided to the MAC by the HT PHY consist of the following protocol functions:

a) A function that defines a method of mapping the PSDUs into a framing format (PPDU) suitable for sending and receiving PSDUs between two or more STAs.
b) A function that defines the characteristics and method of transmitting and receiving data through a wireless medium between two or more STAs. Depending on the PPDU format, these STAs support a mixture of HT PHY and Clause 15, Clause 17, Clause 16, or Clause 18 PHYs.

19.1.3 HT PHY functions

19.1.3.1 General

The HT PHY contains two functional entities: the PHY and the layer management function (i.e., the PLME). Both of these functions are described in detail in 19.3 and 19.4.

The HT PHY service is provided to the MAC through the PHY service primitives defined in Clause 8.

19.1.3.2 PHY management entity (PLME)

The PLME performs management of the local PHY functions in conjunction with the MLME.

19.1.3.3 Service specification method

The models represented by figures and state diagrams are intended to be illustrations of the functions provided. It is important to distinguish between a model and a real implementation. The models are optimized for simplicity and clarity of presentation, but do not necessarily reflect any particular implementation. The service of a layer or sublayer is the set of capabilities that it offers to a user in the next higher layer (or sublayer). Abstract services are specified here by describing the service primitives and parameters that characterize each service. This definition is independent of any particular implementation.

19.1.4 PPDU formats

The structure of the PPDU transmitted by an HT STA is determined by the TXVECTOR FORMAT, CH_BANDWIDTH, CH_OFFSET, and MCS parameters as defined in Table 19-1. The effect of the CH_BANDWIDTH, CH_OFFSET, and MCS parameters on PPDU format is described in 19.2.4.

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The FORMAT parameter determines the overall structure of the PPDU as follows:

— *Non-HT format* **(NON_HT):** Packets of this format are structured according to the Clause 17 (OFDM) or Clause 18 (ERP) specification. Support for non-HT format is mandatory.
— *HT-mixed format* **(HT_MF):** Packets of this format contain a preamble compatible with Clause 17 and Clause 18 receivers. The non-HT-STF (L-STF), the non-HT-LTF (L-LTF), and the non-HT SIGNAL field (L-SIG) are defined so they can be decoded by non-HT Clause 17 and Clause 18 STAs. The rest of the packet cannot be decoded by Clause 17 or Clause 18 STAs. Support for HT-mixed format is mandatory.
— *HT-greenfield format* **(HT_GF):** HT packets of this format do not contain a non-HT compatible part. Support for HT-greenfield format is optional. An HT STA that does not support the reception of an HT-greenfield format packet shall be able to detect that an HT-greenfield format packet is an HT transmission (as opposed to a non-HT transmission). In this case, the receiver shall decode the HT-SIG and determine whether the HT-SIG cyclic redundancy check (CRC) passes.

19.2 HT PHY service interface

19.2.1 Introduction

The PHY interfaces to the MAC through the TXVECTOR, TXSTATUS, RXVECTOR, and PHYCONFIG_VECTOR. Using the TXVECTOR, the MAC supplies the PHY with per-PPDU transmit parameters. Status of the transmission is reported from PHY to MAC by parameters within TXSTATUS. Using the RXVECTOR, the PHY informs the MAC of the received packet parameters. Using the PHYCONFIG_VECTOR, the MAC configures the PHY for operation, independent of frame transmission or reception.

This interface is an extension of the generic PHY service interface defined in 8.3.4.

19.2.2 TXVECTOR and RXVECTOR parameters

The parameters in Table 19-1 are defined as part of the TXVECTOR parameter list in the PHY-TXSTART.request primitive and/or as part of the RXVECTOR parameter list in the PHY-RXSTART.indication primitive.

Table 19-1—TXVECTOR and RXVECTOR parameters

Parameter	Condition	Value	TXVECTOR	RXVECTOR
			See NOTE 1	
FORMAT		Determines the format of the PPDU. Enumerated type: NON_HT indicates DSSS, HR/DSSS, OFDM or ERP PPDU formats or non-HT duplicates PPDU format. In this case, the modulation is determined by the NON_HT_MODULATION parameter. HT_MF indicates HT-mixed format. HT_GF indicates HT-greenfield format.	Y	Y

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR	RXVECTOR
			See NOTE 1	
NON_HT_ MODULATION	FORMAT is NON_HT	Enumerated type: ERP-DSSS ERP-CCK ERP-OFDM OFDM NON_HT_DUP_OFDM	Y	Y
	Otherwise	Not present		
L_LENGTH	FORMAT is NON_HT	Indicates the length of the PSDU in octets in the range 1 to 4095. This value is used by the PHY to determine the number of octet transfers that occur between the MAC and the PHY.	Y	Y
	FORMAT is HT_MF	Indicates the value in the Length field of the L-SIG in the range 1 to 4095. This use is defined in 10.27.4.	Y	Y
	FORMAT is HT_GF	Not present	N	N
L_DATARATE	FORMAT is NON_HT	Indicates the rate used to transmit the PSDU in megabits per second. Allowed values depend on the value of the NON_HT_MODULATION parameter as follows: ERP-DSSS: 1 and 2 ERP-CCK: 5.5 and 11 ERP-OFDM, NON_HT_DUP_OFDM: 6, 9, 12, 18, 24, 36, 48, and 54 OFDM: 6, 9, 12, 18, 24, 36, 48, and 54	Y	Y
	FORMAT is HT_MF	Indicates the data rate value that is in the L-SIG. This use is defined in 10.27.4.	Y	Y
	FORMAT is HT_GF	Not present	N	N
LSIGVALID	FORMAT is HT_MF	true if L-SIG Parity is valid false if L-SIG Parity is not valid	N	Y
	Otherwise	Not present	N	N
SERVICE	FORMAT is NON_HT and NON_HT_MODULATION is one of — ERP-OFDM — OFDM	Scrambler initialization, null	Y	N
	FORMAT is HT_MF or HT_GF	Scrambler initialization, null	Y	N
	Otherwise	Not present	N	N

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR	RXVECTOR
			See NOTE 1	
TXPWR_LEVEL_INDEX		The allowed values for the TXPWR_LEVEL_INDEX parameter are in the range 1 to 8. This parameter is used to indicate which of the available TxPowerLevel attributes defined in the MIB shall be used for the current transmission.	Y	N
RSSI		The allowed values for the RSSI parameter are in the range 0 to 255. This parameter is a measure by the PHY of the power observed at the antenna connector used to receive the current PPDU. RSSI shall be measured during the reception of the PHY preamble. In HT-mixed format, the reported RSSI shall be measured during the reception of the HT-LTFs. RSSI is intended to be used in a relative manner, and it shall be a monotonically increasing function of the received power.	N	Y
PREAMBLE_TYPE	FORMAT is NON_HT and NON_HT_MODULATION is one of — ERP-DSSS — ERP-CCK	Enumerated type: SHORTPREAMBLE LONGPREAMBLE	Y	Y
	Otherwise	Not present	N	N
MCS	FORMAT is HT_MF or HT_GF	Selects the modulation and coding scheme used in the transmission of the packet. The value used in each MCS is the index defined in 19.5. Integer: range 0 to 76. Values of 77 to 127 are reserved. The interpretation of the MCS index is defined in 19.5.	Y	Y
	Otherwise	Not present	N	N
REC_MCS	FORMAT is HT_MF or HT_GF	Indicates the MCS that the STA's receiver recommends.	N	O
	Otherwise	Not present	N	N
CH_BANDWIDTH	FORMAT is HT_MF or HT_GF	Indicates whether the packet is transmitted using 40 MHz or 20 MHz channel width. Enumerated type: HT_CBW20 for 20 MHz and 40 MHz upper and 40 MHz lower modes HT_CBW40 for 40 MHz	Y	Y
	FORMAT is NON_HT	Enumerated type: NON_HT_CBW40 for non-HT duplicate format NON_HT_CBW20 for all other non-HT formats	Y	Y

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR (See NOTE 1)	RXVECTOR (See NOTE 1)
CH_OFFSET		Indicates which portion of the channel is used for transmission. Refer to Table 19-2 for valid combinations of CH_OFFSET and CH_BANDWIDTH. Enumerated type: CH_OFF_20 indicates the use of a 20 MHz channel (that is not part of a 40 MHz channel). CH_OFF_40 indicates the entire 40 MHz channel. CH_OFF_20U indicates the upper 20 MHz of the 40 MHz channel CH_OFF_20L indicates the lower 20 MHz of the 40 MHz channel.	Y	N
LENGTH	FORMAT is HT_MF or HT_GF	Indicates the length of an HT PSDU in the range 0 to 65 535 octets. A value of 0 indicates a NDP that contains no data symbols after the HT preamble (see 19.3.9).	Y	Y
	Otherwise	Not present	N	N
SMOOTHING	FORMAT is HT_MF or HT_GF	Indicates whether frequency domain smoothing is recommended as part of channel estimation. (See NOTE 2.) Enumerated type: SMOOTHING_REC indicates that smoothing is recommended. SMOOTHING_NOT_REC indicates that smoothing is not recommended.	Y	Y
	Otherwise	Not present	N	N
SOUNDING	FORMAT is HT_MF or HT_GF	Indicates whether this packet is a sounding PPDU. Enumerated type: SOUNDING indicates this is a sounding PPDU. NOT_SOUNDING indicates this is not a sounding PPDU.	Y	Y
	Otherwise	Not present	N	N
AGGREGATION	FORMAT is HT_MF or HT_GF	Indicates whether the PSDU contains an A-MPDU. Enumerated type: AGGREGATED indicates this PSDU has A-MPDU aggregation. NOT_AGGREGATED indicates this PSDU does not have A-MPDU aggregation.	Y	Y
	Otherwise	Not present	N	N
STBC	FORMAT is HT_MF or HT_GF	Indicates the difference between the number of space-time streams (N_{STS}) and the number of spatial streams (N_{SS}) indicated by the MCS as follows: 0 indicates no STBC ($N_{STS} = N_{SS}$). 1 indicates $N_{STS} - N_{SS} = 1$. 2 indicates $N_{STS} - N_{SS} = 2$. Value of 3 is reserved.	Y	Y
	Otherwise	Not present	N	N

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR	RXVECTOR
			See NOTE 1	
FEC_CODING	FORMAT is HT_MF or HT_GF	Indicates which FEC encoding is used. Enumerated type: BCC_CODING indicates binary convolutional code. LDPC_CODING indicates low-density parity check code.	Y	Y
	Otherwise	Not present	N	N
GI_TYPE	FORMAT is HT_MF or HT_GF	Indicates whether a short guard interval is used in the transmission of the packet. Enumerated type: LONG_GI indicates short GI is not used in the packet. SHORT_GI indicates short GI is used in the packet.	Y	Y
	Otherwise	Not present	N	N
NUM_EXTEN_SS	FORMAT is HT_MF or HT_GF	Indicates the number of extension spatial streams that are sounded during the extension HT-LTFs in the range 0 to 3.	Y	Y
	Otherwise	Not present	N	N
ANTENNA_SET	FORMAT is HT_MF or HT_GF	Indicates which antennas of the available antennas are used in the transmission. The length of the field is 8 bits. A 1 in bit position *n,* relative to the LSB, indicates that antenna *n* is used. At most 4 bits out of 8 may be set to 1. This field is present only if ASEL is applied.	O	N
	Otherwise	Not present	N	N
N_TX	FORMAT is HT_MF or HT_GF	The N_TX parameter indicates the number of transmit chains.	Y	N
	Otherwise	Not present	N	N
EXPANSION_MAT	EXPANSION_MAT_TYPE is COMPRESSED_SV	Contains a set of compressed beamforming feedback matrices as defined in 19.3.12.3.6. The number of elements depends on the number of spatial streams and the number of transmit chains.	Y	N
	EXPANSION_MAT_TYPE is NON_COMPRESSED_SV	Contains a set of noncompressed beamforming feedback matrices as defined in 19.3.12.3.5. The number of complex elements is $N_{ST} \times N_r \times N_c$ where N_{ST} is the total number of subcarriers, N_c is the number of columns, and N_r is the number of rows in each matrix.	Y	N
	EXPANSION_MAT_TYPE is CSI_MATRICES	Contains a set of CSI matrices as defined in 19.3.12.3.2. The number of complex elements is $N_{ST} \times N_r \times N_c$ where N_{ST} is the total number of subcarriers, N_c is the number of columns, and N_r is the number of rows in each matrix.	Y	N
	Otherwise	Not present	N	N

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR (See NOTE 1)	RXVECTOR (See NOTE 1)
EXPANSION_MAT_TYPE	EXPANSION_MAT is present	Enumerated type: COMPRESSED_SV indicates that EXPANSION_MAT is a set of compressed beamforming feedback matrices. NON_COMPRESSED_SV indicates that EXPANSION_MAT is a set of noncompressed beamforming feedback matrices. CSI_MATRICES indicates that EXPANSION_MAT is a set of channel state matrices.	Y	N
	Otherwise	Not present	N	N
CHAN_MAT	CHAN_MAT_TYPE is COMPRESSED_SV	Contains a set of compressed beamforming feedback matrices as defined in 19.3.12.3.6 based on the channel measured during the training symbols of the received PPDU. The number of elements depends on the number of spatial streams and the number of transmit chains.	N	Y
	CHAN_MAT_TYPE is NON_COMPRESSED_SV	Contains a set of noncompressed beamforming feedback matrices as defined in 19.3.12.3.5 based on the channel measured during the training symbols of the received PPDU. The number of complex elements is $N_{ST} \times N_r \times N_c$ where N_{ST} is the total number of subcarriers, N_c is the number of columns, and N_r is the number of rows in each matrix.	N	Y
	CHAN_MAT_TYPE is CSI_MATRICES	Contains a set of CSI matrices as defined in 19.3.12.3.2 based on the channel measured during the training symbols of the received PPDU. The number of complex elements is $N_{ST} \times N_r \times N_c$ where N_{ST} is the total number of subcarriers, N_c is the number of columns, and N_r is the number of rows in each matrix.	N	Y
	Otherwise	Not present	N	N
CHAN_MAT_TYPE	FORMAT is HT_MF or HT_GF	Enumerated type: COMPRESSED_SV indicates that CHAN_MAT is a set of compressed beamforming vector matrices. NON_COMPRESSED_SV indicates that CHAN_MAT is a set of noncompressed beamforming vector matrices. CSI_MATRICES indicates that CHAN_MAT is a set of channel state matrices.	N	Y
	Otherwise	Not present	N	N
SNR	CHAN_MAT_TYPE is CSI_MATRICES	Is a measure of the received SNR per chain. SNR indications of 8 bits are supported. SNR shall be the decibel representation of linearly averaged values over the tones represented in each receive chain as described in 9.4.1.27	N	Y
	CHAN_MAT_TYPE is COMPRESSED_SV or NON_COMPRESSED_SV	Is a measure of the received SNR per stream. SNR indications of 8 bits are supported. SNR shall be the sum of the decibel values of SNR per tone divided by the number of tones represented in each stream as described in 9.4.1.28 and 9.4.1.29	N	Y

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Table 19-1—TXVECTOR and RXVECTOR parameters *(continued)*

Parameter	Condition	Value	TXVECTOR (See NOTE 1)	RXVECTOR (See NOTE 1)
NO_SIG_EXTN	FORMAT is HT_MF or HT_GF Or FORMAT is NON_HT and NON_HT_MODULATION is NON_HT_DUP_OFDM	Indicates whether signal extension needs to be applied at the end of transmission. Boolean values: true indicates no signal extension is present. false indicates signal extension may be present depending on other TXVECTOR parameters (see 19.2.2).	Y	N
	Otherwise	Not present	N	N
TIME_OF_DEPARTURE_REQUESTED		Enumerated type: true indicates that the MAC entity requests that the PHY entity measures and reports time of departure parameters corresponding to the time when the first frame energy is sent by the transmitting port. false indicates that the MAC entity requests that the PHY entity neither measures nor reports time of departure parameters.	O	N
RX_START_OF_FRAME_OFFSET		0 to $2^{32}-1$. An estimate of the offset (in 10 ns units) from the point in time at which the start of the preamble corresponding to the incoming frame arrived at the receive antenna connector to the point in time at which this primitive is issued to the MAC.	N	O

NOTE 1—In the TXVECTOR and RXVECTOR columns, the following apply:
Y = Present; N = Not present; O = Optional.

NOTE 2—Setting the Smoothing bit is defined in 19.3.11.11.2.

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19.2.3 PHYCONFIG_VECTOR parameters

The PHYCONFIG_VECTOR carried in a PHY-CONFIG.request primitive for an HT PHY contains an OPERATING_CHANNEL parameter, which identifies the operating or primary channel. The PHY shall set dot11CurrentPrimaryChannel to the value of this parameter.

The PHYCONFIG_VECTOR carried in a PHY-CONFIG.request primitive for an HT PHY contains a SECONDARY_CHANNEL_OFFSET parameter, which takes one of the following values:

— SECONDARY_CHANNEL_NONE if no secondary channel is present; in this case the PHY shall set dot11CurrentSecondaryChannel to 0.
— SECONDARY_CHANNEL_ABOVE if the secondary channel is above the primary channel; in this case the PHY shall set dot11CurrentSecondaryChannel to dot11CurrentPrimaryChannel + 4.
— SECONDARY_CHANNEL_BELOW if the secondary channel is below the primary channel; in this case the PHY shall set dot11CurrentSecondaryChannel to dot11CurrentPrimaryChannel – 4.

19.2.4 Effect of CH_BANDWIDTH, CH_OFFSET, and MCS parameters on PPDU format

The structure of the PPDU transmitted by an HT STA is determined by the TXVECTOR FORMAT, CH_BANDWIDTH, CH_OFFSET, and MCS parameters as defined in Table 19-1. The effect of the FORMAT parameter is described in 19.1.4.

The operation of the PHY in the frequency domain is determined by the FORMAT, CH_BANDWIDTH, and CH_OFFSET parameters. Table 19-2 shows the valid combinations of FORMAT, CH_BANDWIDTH, and CH_OFFSET and the corresponding PPDU format. Other combinations are reserved.

Table 19-2—Interpretation of FORMAT, CH_BANDWIDTH, and CH_OFFSET parameters

FORMAT	CH_BANDWIDTH	CH_OFFSET
HF_MF, HF_GF	HT_CBW20	CH_OFF_20: *20 MHz HT format*—The STA has a 20 MHz operating channel width and transmits an HT-mixed or HT-greenfield format PPDU of 20 MHz bandwidth. CH_OFF_20U: *40 MHz HT upper format*—The STA transmits an HT-mixed or HT-greenfield format PPDU of 20 MHz bandwidth in the upper 20 MHz of a 40 MHz channel. CH_OFF_20L: *40 MHz HT lower format*—The STA transmits an HT-mixed or HT-greenfield format PPDU of 20 MHz bandwidth in the lower 20 MHz of a 40 MHz channel.
HT_MF, HT_GF	HT_CBW40	CH_OFF_40: *40 MHz HT format*—The STA transmits an HT-mixed or HT-greenfield format PPDU of 40 MHz bandwidth.
NON_HT	NON_HT_CBW20 and the SECONDARY_CHANNEL_OFFSET parameter of the PHYCONFIG_VECTOR is SECONDARY_CHANNEL_NONE	CH_OFF_20: *20 MHz non-HT format*—The STA has a 20 MHz operating channel width and transmits an ERP-DSSS, ERP-CCK, ERP-OFDM, or OFDM format PPDU.

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Table 19-2—Interpretation of FORMAT, CH_BANDWIDTH, and CH_OFFSET parameters *(continued)*

FORMAT	CH_BANDWIDTH	CH_OFFSET
NON_HT	NON_HT_CBW20 and the SECONDARY_CHANNEL_OFFSET parameter of the PHYCONFIG_VECTOR is SECONDARY_CHANNEL_BELOW	CH_OFF_20U: *40 MHz non-HT upper format*—The STA transmits an ERP-DSSS, ERP-CCK, ERP-OFDM, or OFDM format PPDU, in the upper 20 MHz of a 40 MHz channel.
NON_HT	NON_HT_CBW20 and the SECONDARY_CHANNEL_OFFSET parameter of the PHYCONFIG_VECTOR is SECONDARY_CHANNEL_ABOVE	CH_OFF_20L: *40 MHz non-HT lower format*—The STA transmits an ERP-DSSS, ERP-CCK, ERP-OFDM, or OFDM format PPDU, in the lower 20 MHz of a 40 MHz channel.
NON_HT	NON_HT_CBW40	CH_OFF_40: *Non-HT duplicate format*—The STA transmits an ERP-OFDM or OFDM format PPDU in each of the 20 MHz channels of a 40 MHz channel. The upper channel (higher frequency) is rotated by +90° relative to the lower channel. See 19.3.11.12.

19.2.5 Support for NON_HT formats

When the FORMAT parameter is equal to NON_HT, the behavior of the HT PHY is defined in other clauses as shown in Table 19-3, dependent on the operational band. In this case, the PHY-TXSTART.request primitive is handled by mapping the TXVECTOR parameters as defined in Table 19-3 and following the operation as defined in the referenced clause. Likewise the PHY-RXSTART.indication primitive emitted when a non-HT PPDU is received is defined in the referenced clauses, with mapping of RXVECTOR parameters as defined in Table 19-3.

Table 19-3—Mapping of the HT PHY parameters for NON_HT operation

HT PHY parameter	2.4 GHz operation defined by Clause 15	2.4 GHz operation defined by Clause 16	2.4 GHz operation defined by Clause 18	5.0 GHz operation defined by Clause 17
L_LENGTH	LENGTH	LENGTH	LENGTH	LENGTH
L_DATARATE	DATARATE	DATARATE	DATARATE	DATARATE
LSIGVALID	—	—	—	—
TXPWR_LEVEL_INDEX	TXPWR_LEVEL_INDEX	TXPWR_LEVEL_INDEX	TXPWR_LEVEL_INDEX	TXPWR_LEVEL_INDEX
RSSI	RSSI	RSSI	RSSI	RSSI

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Table 19-3—Mapping of the HT PHY parameters for NON_HT operation *(continued)*

HT PHY parameter	2.4 GHz operation defined by Clause 15	2.4 GHz operation defined by Clause 16	2.4 GHz operation defined by Clause 18	5.0 GHz operation defined by Clause 17
FORMAT	—	—	—	—
PREAMBLE_TYPE	—	—	PREAMBLE_TYPE	—
NON_HT_MODULATION	—	—	MODULATION	—
SERVICE	SERVICE	SERVICE	SERVICE	SERVICE
MCS	—	—	—	—
CH_BANDWIDTH	—	—	—	—
CH_OFFSET	—	—	—	—
LENGTH	—	—	—	—
SMOOTHING	—	—	—	—
SOUNDING	—	—	—	—
AGGREGATION	—	—	—	—
STBC	—	—	—	—
FEC_CODING	—	—	—	—
GI_TYPE	—	—	—	—
NUM_EXTEN_SS	—	—	—	—
ANTENNA_SET	—	—	—	—
EXPANSION_MAT	—	—	—	—
EXPANSION_MAT_TYPE	—	—	—	—
CHAN_MAT	—	—	—	—
CHAN_MAT_TYPE	—	—	—	—
N_TX	—	—	—	—
RCPI	RCPI	RCPI	RCPI	RCPI
REC_MCS	—	—	—	—
NO_SIG_EXTN	—	—	—	—
TIME_OF_DEPARTURE_REQUESTED	TIME_OF_DEPARTURE_REQUESTED	TIME_OF_DEPARTURE_REQUESTED	TIME_OF_DEPARTURE_REQUESTED	TIME_OF_DEPARTURE_REQUESTED
NOTE—A dash (—) in an entry above indicates that the related parameter is not present.				

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Non-HT format PPDUs structured according to Clause 15, Clause 17, Clause 16, or Clause 18 are transmitted

— Within the limits of the transmit spectrum mask specified in the respective clauses, or
— As non-HT duplicate PPDUs within the limits of the 40 MHz transmit spectrum mask defined in 19.3.18.1, or
— As 20 MHz format non-HT PPDUs, within the limits of the 40 MHz transmit spectrum mask defined in 19.3.18.1, in the upper (CH_BANDWIDTH of value NON_HT_CBW20 and CH_OFFSET of value CH_OFF_20U) or lower (CH_BANDWIDTH of value NON_HT_CBW20 and CH_OFFSET of value CH_OFF_20U) 20 MHz of the 40 MHz channel.

Non-HT PPDUs transmitted using the 40 MHz transmit spectrum mask are referred to as *40 MHz mask non-HT PPDUs*. Refer to 11.15.9 for CCA sensing rules for transmission of 40 MHz mask non-HT PPDUs.

19.2.6 TXSTATUS parameters

The parameters listed in Table 19-4 are defined as part of the TXSTATUS parameter list in the PHY-TXSTART.confirm service primitive.

Table 19-4—TXSTATUS parameters

Parameter	Value
TIME_OF_DEPARTURE	0 to 2^{32}– 1. The locally measured time when the first frame energy is sent by the transmitting port, in units equal to 1/ TIME_OF_DEPARTURE_ClockRate. This parameter is present only if TIME_OF_DEPARTURE_REQUESTED is true in the corresponding request.
TIME_OF_DEPARTURE_ClockRate	0 to 2^{16}– 1. The clock rate, in units of MHz, is used to generate the TIME_OF_DEPARTURE value. This parameter is present only if TIME_OF_DEPARTURE_REQUESTED is true in the corresponding request.
TX_START_OF_FRAME_OFFSET	0 to 2^{32}– 1. An estimate of the offset (in 10 ns units) from the point in time at which the start of the preamble corresponding to the frame was transmitted at the transmit antenna connector to the point in time at which this primitive is issued to the MAC.

19.3 HT PHY

19.3.1 Introduction

Subclause 19.3 provides a procedure in which PSDUs are converted to and from PPDUs. During transmission, the PSDU is processed (i.e., scrambled and coded) and appended to the PHY preamble to create the PPDU. At the receiver, the PHY preamble is processed to aid in demodulation and delivery of the PSDU.

Two preamble formats are defined. For HT-mixed format operation, the preamble has a non-HT portion and an HT portion. The non-HT portion of the HT-mixed format preamble enables detection of the PPDU and acquisition of carrier frequency and timing by both HT STAs and STAs that are compliant with Clause 17 and/or Clause 18. The non-HT portion of the HT-mixed format preamble also consists of the SIGNAL field defined in Clause 17 and is thus decodable by STAs compliant with Clause 17 and Clause 18 as well as HT STAs.

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The HT portion of the HT-mixed format preamble enables estimation of the MIMO channel to support demodulation of the HT data by HT STAs. The HT portion of the HT-mixed format preamble also includes the HT-SIG field, which supports HT operation. The SERVICE field is prepended to the PSDU.

For HT-greenfield operation, compatibility with Clause 17 and Clause 18 STAs is not required. Therefore, the non-HT portions of the preamble are not included in the HT-greenfield format preamble.

19.3.2 PPDU format

Two formats are defined for the PPDU: HT-mixed format and HT-greenfield format. These two formats are called *HT formats*. Figure 19-1 shows the non-HT format[44] and the HT formats. The HT formats can be used for MCS 32 that provides the lowest rate in a 40 MHz channel (see in 19.3.11.11.5). In addition to the HT formats, there is a non-HT duplicate format (specified in 19.3.11.12) that duplicates the 20 MHz non-HT packet in two 20 MHz halves of a 40 MHz channel.

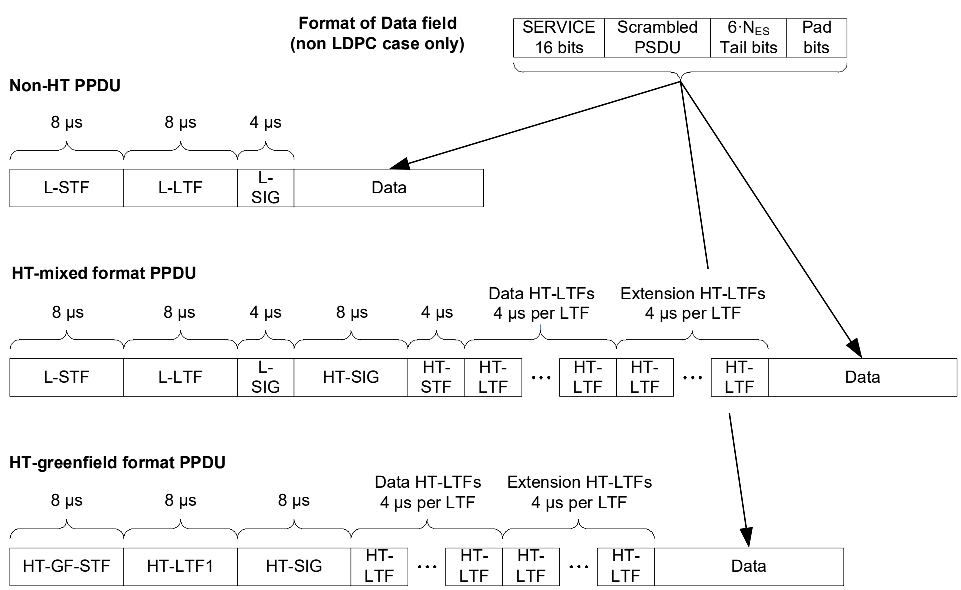

Figure 19-1—PPDU format

The elements of the PPDU are summarized in Table 19-5.

Table 19-5—Elements of the HT PPDU

Element	Description
L-STF	Non-HT Short Training field
L-LTF	Non-HT Long Training field
L-SIG	Non-HT SIGNAL field
HT-SIG	HT SIGNAL field
HT-STF	HT Short Training field

[44] The non-HT format is shown related to the terminology of this subclause. The non-HT PPDU format is defined in 17.3.3 and 17.3.2.

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Table 19-5—Elements of the HT PPDU *(continued)*

Element	Description
HT-GF-STF	HT-Greenfield Short Training field
HT-LTF1	First HT Long Training field (Data)
HT-LTFs	Additional HT Long Training fields (Data and Extension)
Data	The Data field includes the PSDU

The HT-SIG, HT-STF, HT-GF-STF, HT-LTF1, and HT-LTFs exist only in HT packets. In non-HT packets only the L-STF, L-LTF, L-SIG, and Data fields exist.

In both HT-mixed format and HT-greenfield format frames, there are two types of HT-LTFs: Data HT-LTFs (HT-DLTFs) and Extension HT-LTFs (HT-ELTFs). HT-DLTFs are always included in HT PPDUs to provide the necessary reference for the receiver to form a channel estimate that allows it to demodulate the data portion of the frame. The number of HT-DLTFs, $N_{HT\text{-}DLTF}$, may be 1, 2, or 4 and is determined by the number of space-time streams being transmitted in the frame (see Table 19-13). HT-ELTFs provide additional reference in sounding PPDUs so that the receiver can form an estimate of additional dimensions of the channel beyond those that are used by the data portion of the frame. The number of HT-ELTFs, $N_{HT\text{-}ELTF}$, may be 0, 1, 2, or 4 (see Table 19-14). PHY preambles in which HT-DLTFs are followed by HT-ELTFs are referred to as *staggered preambles*. The HT-mixed format and HT-greenfield format frames shown in Figure 19-1 both contain staggered preambles for illustrative purposes.

Transmissions of frames with the TXVECTOR parameter NO_SIG_EXTN equal to false are terminated by a period of no transmission for a duration of aSignalExtension. See 10.3.8.

A signal extension shall be present in a transmitted PPDU, based on the parameters of the TXVECTOR, when the NO_SIG_EXTN parameter is equal to false and either of the following is true:

- The FORMAT parameter is equal to HT_MF or HT_GF.
- The FORMAT parameter is equal to NON_HT, and the NON_HT_MODULATION parameter is equal to ERP-OFDM, or NON_HT_DUP_OFDM.

A signal extension shall be assumed to be present (for the purpose of timing of PHY-RXEND.indication and PHY-CCA.indication primitives, as described below and in 19.3.21) in a received PPDU when either of the following is true, based on the determined parameter values of the RXVECTOR:

- The FORMAT parameter is equal to HT_MF or HT_GF.
- The FORMAT parameter is equal to NON_HT, and the NON_HT_MODULATION parameter is equal to ERP-OFDM, or NON_HT_DUP_OFDM.

A PPDU containing a signal extension is called a *signal extended PPDU*. When transmitting a signal extended PPDU, the PHY-TXEND.indication primitive shall be emitted a period of aSignalExtension after the end of the last symbol of the PPDU. When receiving a signal extended PPDU, the PHY-RXEND.indication primitive shall be emitted a period of aSignalExtension after the end of the last symbol of the PPDU.

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19.3.3 Transmitter block diagram

HT-mixed format and HT-greenfield format transmissions can be generated using a transmitter consisting of the following blocks:

a) *Scrambler* scrambles the data to reduce the probability of long sequences of 0s or 1s; see 19.3.11.3.

b) *Encoder parser*, if binary convolutional code (BCC) encoding is to be used, demultiplexes the scrambled bits among N_{ES} (number of BCC encoders for the Data field) BCC encoders, in a round robin manner.

c) *FEC encoders* encode the data to enable error correction. An FEC encoder may include a binary convolutional encoder followed by a puncturing device, or it may include a low-density parity check (LDPC) encoder.

d) *Stream parser* divides the outputs of the encoders into blocks that are sent to different interleaver and mapping devices. The sequence of the bits sent to an interleaver is called a *spatial stream*.

e) *Interleaver* interleaves the bits of each spatial stream (changes order of bits) to prevent long sequences of adjacent noisy bits from entering the BCC decoder. Interleaving is applied only when BCC encoding is used.

f) *Constellation mapper* maps the sequence of bits in each spatial stream to constellation points (complex numbers).

g) *STBC* encoder spreads constellation points from N_{SS} spatial streams into N_{STS} space-time streams using a space-time block code. STBC is used only when $N_{SS} < N_{STS}$; see 19.3.11.9.2.

h) *Spatial mapper* maps space-time streams to transmit chains. This may include one of the following:
   1) *Direct mapping*: Constellation points from each space-time stream are mapped directly onto the transmit chains (one-to-one mapping).
   2) *Spatial expansion*: Vectors of constellation points from all of the space-time streams are expanded via matrix multiplication to produce the input to all of the transmit chains.
   3) *Beamforming*: Similar to spatial expansion, each vector of constellation points from all of the space-time streams is multiplied by a matrix of steering vectors to produce the input to the transmit chains.

i) *Inverse discrete Fourier transform (IDFT)* converts a block of constellation points to a time domain block.

j) *Cyclic shift (CSD) insertion* is where the insertion of the cyclic shifts prevents unintentional beamforming. CSD insertion may occur before or after the IDFT. There are three cyclic shift types as follows:
   1) A cyclic shift specified per transmitter chain with the values defined in Table 19-9 (a possible implementation is shown in Figure 19-2).
   2) A cyclic shift specified per space-time stream with the values defined in Table 19-10 (a possible implementation is shown in Figure 19-3).
   3) A cyclic shift $M_{CSD}(k)$ that may be applied as a part of the spatial mapper; see 19.3.11.11.2.

k) *GI insertion* prepends to the symbol a circular extension of itself.

l) *Windowing* optionally smooths the edges of each symbol to increase spectral decay.

Figure 19-2 and Figure 19-3 show example transmitter block diagrams. In particular, Figure 19-2 shows the transmitter blocks used to generate the HT-SIG of the HT-mixed format PPDU. These transmitter blocks are also used to generate the non-HT portion of the HT-mixed format PPDU, except that the BCC encoder and interleaver are not used when generating the L-STF and L-LTFs. Figure 19-3 shows the transmitter blocks used to generate the Data field of the HT-mixed format and HT-greenfield format PPDUs. A subset of these transmitter blocks consisting of the constellation mapper and CSD blocks, as well as the blocks to the right

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of, and including, the spatial mapping block, are also used to generate the HT-STF, HT-GF-STF, and HT-LTFs. The HT-greenfield format SIGNAL field is generated using the transmitter blocks shown in Figure 19-2, augmented by additional CSD and spatial mapping blocks.

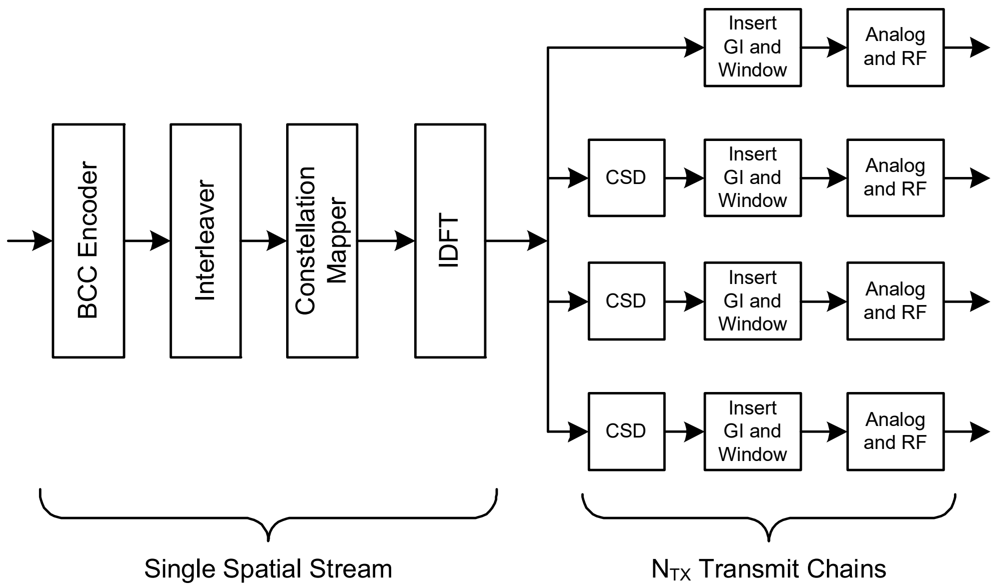
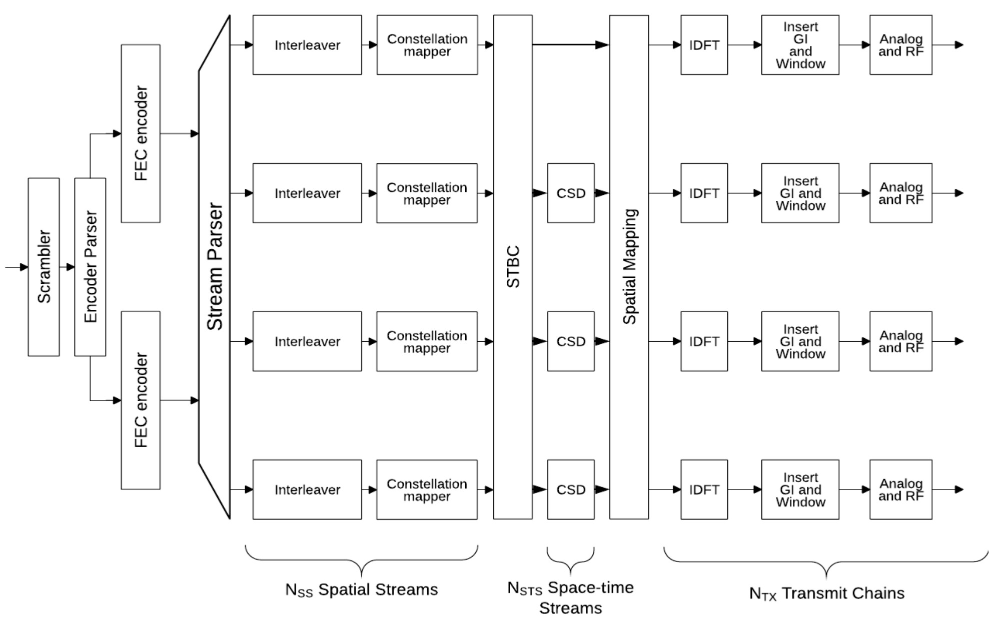


Figure 19-2—Transmitter block diagram 1



NOTE: The particular case shown here has two FEC encoders, four spatial streams, BCC coding, no STBC, and four transmit chains. The actual transmission mode may differ from the one shown here in various ways:
—There might be 1 or 2 FEC encoders when BCC encoding is used.
—The stream parser might have 1, 2, 3 or 4 outputs.
—When LDPC encoding is used, the interleavers are not used.
—When STBC is used, the STBC block has more outputs than inputs (otherwise the ouputs equal the inputs).
—When spatial mapping is used, there might be more transmit chains than space-time streams.
—The number of inputs to the spatial mapper might be 1, 2, 3, or 4.

Figure 19-3—Transmitter block diagram 2

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19.3.4 Overview of the PPDU encoding process

The encoding process is composed of the steps described below. The following overview is intended to facilitate an understanding of the details of the convergence procedure:

a) Determine the number of transmit chains, N_{TX}, from the N_TX field of the TXVECTOR. Produce the PHY preamble training fields for each of the N_{TX} transmit chains based on the FORMAT, NUM_EXTEN_SS, CH_BANDWIDTH, and MCS parameters of the TXVECTOR. The format and relative placement of the PHY preamble training fields vary depending on the frame format being used, as indicated by these parameters. Apply cyclic shifts. Determine spatial mapping to be used for HT-STF and HT-LTFs in HT-mixed format frame and HT-GF-STF and HT-LTFs in HT-greenfield format frame from the EXPANSION_MAT parameter of the TXVECTOR. Refer to 19.3.9 for details.

b) Construct the PHY preamble SIGNAL fields from the appropriate fields of the TXVECTOR by adding tail bits, applying convolutional coding, formatting into one or more OFDM symbols, applying cyclic shifts, applying spatial processing, calculating an inverse Fourier transform for each OFDM symbol and transmit chain, and prepending a cyclic prefix or GI to each OFDM symbol in each transmit chain. The number and placement of the PHY preamble SIGNAL fields depend on the frame format being used. Refer to 19.3.9.3.5, 19.3.9.4.3, and 19.3.9.5.4.

c) Concatenate the PHY preamble training and SIGNAL fields for each transmit chain one field after another, in the appropriate order, as described in 19.3.2 and 19.3.7**.**

d) Use the MCS and CH_BANDWIDTH parameters of the TXVECTOR to determine the number of data bits per OFDM symbol (N_{DBPS}), the coding rate (R), the number of coded bits in each OFDM subcarrier (N_{BPSC}), and the number of coded bits per OFDM symbol (N_{CBPS}). Determine the number of encoding streams (N_{ES}) from the MCS, CH_BANDWIDTH, and FEC_CODING parameters of the TXVECTOR. Refer to 19.3.11.4 for details.

e) Append the PSDU to the SERVICE field (see 19.3.11.2). If BCC encoding is to be used, as indicated by the FEC_CODING parameter of the TXVECTOR, tail bits are appended to the PSDU**.** If a single BCC encoder is used (i.e., when the value of N_{ES} is 1), the bit string is extended by 6 zero bits. If two BCC encoders are used (i.e., when the value of N_{ES} is 2), the bit string is extended by 12 zero bits. The number of symbols, N_{SYM}, is calculated according to Equation (19-32), and if necessary, the bit string is further extended with zero bits so that the resulting length is a multiple of $N_{SYM} \times N_{DBPS}$, as described in 19.3.11. If LDPC encoding is to be used, as indicated by the FEC_CODING parameter of the TXVECTOR, the resulting bit string is padded, if needed, by repeating coded bits rather than using zero bits, as given in the encoding procedure of 19.3.11.7.5. The number of resulting symbols is given by Equation (19-41), and the number of repeated coded bits used for padding is given by Equation (19-42). The resulting bit string constitutes the Data field of the packet.

f) Initiate the scrambler with a pseudorandom nonzero seed, generate a scrambling sequence, and exclusive-OR (XOR) it with the string of data bits, as described in 17.3.5.5.

g) If BCC encoding is to be used, replace the scrambled zero bits that served as tail bits (6 bits if the value of N_{ES} is 1, or 12 bits if the value of N_{ES} is 2) following the data with the same number of nonscrambled zero bits, as described in 17.3.5.3. (These bits return the convolutional encoder to the zero state.)

h) If BCC encoding is to be used and the value of N_{ES} is 2, divide the scrambled data bits between two BCC encoders by sending alternating bits to the two different encoders, as described in 19.3.11.5.

i) If BCC encoding is to be used, encode the extended, scrambled data string with a rate 1/2 convolutional encoder (see 17.3.5.6). Omit (puncture) some of the encoder output string (chosen

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according to puncturing pattern) to reach the coding rate, R, corresponding to the TXVECTOR parameters MCS or L_DATARATE. Refer to 19.3.11.6 for details. If LDPC encoding is to be used, encode the scrambled data stream according to 19.3.11.7.5.

j) Parse the coded bit stream that results from the BCC encoding or LDPC encoding into N_{SS} spatial streams, where the value of N_{SS} is determined from the MCS parameter of the TXVECTOR. See 19.3.11.8.2 for details.

k) Divide each of the N_{SS} encoded and parsed spatial streams of bits into groups of $N_{CBPSS}(i)$ bits. If BCC encoding is to be used, within each spatial stream and group, perform an interleaving (reordering) of the bits according to a rule corresponding to $N_{BPSCS}(i)$, where i is the index of the spatial stream. Refer to 19.3.6 for details.

l) For each of the N_{SS} encoded, parsed, and interleaved spatial streams, divide the resulting coded and interleaved data string into groups of $N_{BPSCS}(i)$ bits, where i is the index of the spatial stream. For each of the bit groups, convert the bit group into a complex number according to the modulation encoding tables. Refer to 17.3.5.8 for details.

m) Divide the complex number string for each of the resulting N_{SS} spatial streams into groups of N_{SD} complex numbers, where the value of N_{SD} is determined from the CH_OFFSET parameter of TXVECTOR and the CH_BANDWIDTH parameter of TXVECTOR. Each such group is associated with one OFDM symbol in one spatial stream. In each group, the complex numbers are indexed 0 to $N_{SD} - 1$, and these indices have an associated one-to-one correspondence with subcarrier indices via the mapping function $M^r(k)$ as described in 19.3.11.11, 19.3.11.11.3, 19.3.11.11.4, 19.3.11.11.5, and 19.3.11.12.

n) If STBC is to be applied, as indicated by the STBC parameter in the TXVECTOR, operate on the complex number associated with each data subcarrier in sequential pairs of OFDM symbols as described in 19.3.11.9.2 to generate N_{STS} OFDM symbols for every N_{SS} OFDM symbols associated with the N_{SS} spatial streams. If STBC is not to be used, the number of space-time streams is the same as the number of spatial streams, and the sequences of OFDM symbols in each space-time stream are composed of the sequences of OFDM symbols in the corresponding spatial stream. In each group of N_{SD} resulting complex numbers in each space-time stream, the complex numbers indexed 0 to $N_{SD} - 1$ are mapped onto OFDM subcarriers via the mapping function $M^r(k)$ as described in 19.3.11.11, 19.3.11.11.3, 19.3.11.11.4, 19.3.11.11.5, and 19.3.11.12.

o) Determine whether 20 MHz or 40 MHz operation is to be used from the CH_BANDWIDTH parameter of the TXVECTOR. Specifically, when CH_BANDWIDTH is HT_CBW20 or NON_HT_CBW20, 20 MHz operation is to be used. When CH_BANDWIDTH is HT_CBW40 or NON_HT_CBW40, 40 MHz operation is to be used. For 20 MHz operation (with the exception of non-HT formats), insert four subcarriers as pilots into positions –21, –7, 7, and 21. The total number of the subcarriers, N_{ST}, is 56. For 40 MHz operation (with the exception of MCS 32 and non-HT duplicate format), insert six subcarriers as pilots into positions –53, –25, –11, 11, 25, and 53, resulting in a total of $N_{ST} = 114$ subcarriers. See 19.3.11.11.5 for pilot locations when using MCS 32 and 19.3.11.12 for pilot locations when using non-HT duplicate format. The pilots are modulated using a pseudorandom cover sequence. Refer to 19.3.11.10 for details. For 40 MHz operation, apply a +90° phase shift to the complex value in each OFDM subcarrier with an index greater than 0, as described in 19.3.11.11.4, 19.3.11.11.5, and 19.3.11.12.

p) Map each of the complex numbers in each of the N_{ST} subcarriers in each of the OFDM symbols in each of the N_{STS} space-time streams to the N_{TX} transmit chain inputs. For direct-mapped operation,

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$N_{TX} = N_{STS}$, and there is a one-to-one correspondence between space-time streams and transmit chains. In this case, the OFDM symbols associated with each space-time stream are also associated with the corresponding transmit chain. Otherwise, a spatial mapping matrix associated with each OFDM subcarrier, as indicated by the EXPANSION_MAT parameter of the TXVECTOR, is used to perform a linear transformation on the vector of N_{STS} complex numbers associated with each subcarrier in each OFDM symbol. This spatial mapping matrix maps the vector of N_{STS} complex numbers in each subcarrier into a vector of N_{TX} complex numbers in each subcarrier. The sequence of N_{ST} complex numbers associated with each transmit chain (where each of the N_{ST} complex numbers is taken from the same position in the N_{TX} vector of complex numbers across the N_{ST} subcarriers associated with an OFDM symbol) constitutes an OFDM symbol associated with the corresponding transmit chain. For details, see 19.3.11.11. Spatial mapping matrices may include cyclic shifts, as described in 19.3.11.11.2.

q) If the CH_BANDWIDTH and CH_OFFSET parameters of the TXVECTOR indicate that upper or lower 20 MHz are to be used in 40 MHz, move the complex numbers associated with subcarriers –28 to 28 in each transmit chain to carriers 4 to 60 in the upper channel or –60 to –4 in the lower channel. Note that this shifts the signal in frequency from the center of the 40 MHz channel to +10 MHz or –10 MHz offset from the center of the 40 MHz channel. The complex numbers in the other subcarriers are set to 0.

r) For each group of N_{ST} subcarriers and each of the N_{TX} transmit chains, convert the subcarriers to time domain using IDFT. Prepend to the Fourier-transformed waveform a circular extension of itself, thus forming a GI, and truncate the resulting periodic waveform to a single OFDM symbol length by applying time domain windowing. Determine the length of the GI according to the GI_TYPE parameter of the TXVECTOR. Refer to 19.3.11.11 and 19.3.11.12 for details. When beamforming is not used, it is sometimes possible to implement the cyclic shifts in the time domain.

s) Append the OFDM symbols associated with each transmit chain one after another, starting after the final field of the PHY preamble. Refer to 19.3.2 and 19.3.7 for details.

t) Upconvert the resulting complex baseband waveform associated with each transmit chain to an RF signal according to the center frequency of the desired channel and transmit. Refer to 19.3.7 for details. The transmit chains are connected to antenna elements according to ANTENNA_SET of the TXVECTOR if ASEL is applied.

19.3.5 Modulation and coding scheme (MCS)

The MCS is a value that determines the modulation, coding, and number of spatial channels. It is a compact representation that is carried in the HT-SIG. Rate-dependent parameters for the full set of MCSs are shown in Table 19-27 to Table 19-41 (in 19.5). These tables give rate-dependent parameters for MCSs with indices 0 to 76. MCSs with indices 0 to 7 and 32 have a single spatial stream; MCSs with indices 8 to 31 have multiple spatial streams using equal modulation (EQM) on all of the streams; MCSs with indices 33 to 76 have multiple spatial streams using unequal modulation (UEQM) on the spatial streams. MCS indices 77 to 127 are reserved.

Table 19-27 to Table 19-30 show rate-dependent parameters for EQM MCSs for one, two, three, and four streams for 20 MHz operation. Table 19-31 to Table 19-34 show rate-dependent parameters for EQM MCSs in one, two, three, and four streams for 40 MHz operation. The same EQM MCSs are used for 20 MHz and 40 MHz operation. Table 19-35 shows rate-dependent parameters for the 40 MHz, 6 Mb/s MCS 32 format.

The remaining tables, Table 19-36 to Table 19-41, show rate-dependent parameters for the MCSs with UEQM of the spatial streams for use with $N_{SS} > 1$.

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UEQM MCSs are detailed in the following tables:

— Table 19-36 to Table 19-38 are for 20 MHz operation.
— Table 19-39 to Table 19-41 are for 40 MHz operation.

An HT STA shall support all equal modulation (EQM) rates for one spatial stream (MCSs 0 to 7) using a 20 MHz channel width. An HT AP that is not a VHT AP shall support all EQM rates for two spatial streams (MCSs 8 to 15) using a 20 MHz channel width. All other MCSs and modes are optional, specifically including transmit and receive support of 400 ns GI, operation in 40 MHz, and support of MCSs with indices 16 to 76.

19.3.6 Timing-related parameters

Table 19-6 defines the timing-related parameters.

Table 19-6—Timing-related constants

Parameter	TXVECTOR CH_BANDWIDTH			
	NON_HT_CBW20	HT_CBW20	HT_CBW40 or NON_HT_CBW40	
			HT format	MCS 32 and non-HT duplicate
N_{SD}: Number of complex data numbers	48	52	108	48
N_{SP}: Number of pilot values	4	4	6	4
N_{ST}: Total number of subcarriers See NOTE 1	52	56	114	104
N_{SR}: Highest data subcarrier index	26	28	58	58
Δ_F : Subcarrier frequency spacing	312.5 kHz (20 MHz/64)	312.5 kHz	312.5 kHz (40 MHz/128)	
T_{DFT}: IDFT/DFT period	3.2 µs	3.2 µs	3.2 µs	
T_{GI}: Guard interval duration	0.8 µs= $T_{DFT}/4$	0.8 µs	0.8 µs	
T_{GI2}: Double guard interval	1.6 µs	1.6 µs	1.6 µs	
T_{GIS}: Short guard interval duration	N/A	0.4 µs = $T_{DFT}/8$	0.4 µs See NOTE 2	
$T_{L\text{-}STF}$: Non-HT short training sequence duration	8 µs=10× $T_{DFT}/4$	8 µs	8 µs	
$T_{HT\text{-}GF\text{-}STF}$: HT-greenfield short training field duration	N/A	8 µs=10× $T_{DFT}/4$	8 µs See NOTE 2	
$T_{L\text{-}LTF}$: Non-HT long training field duration	8 µs=2× $T_{DFT}+T_{GI2}$	8 µs	8 µs	
T_{SYM}: Symbol interval	4 µs= $T_{DFT}+T_{GI}$	4 µs	4 µs	

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Table 19-6—Timing-related constants *(continued)*

Parameter	TXVECTOR CH_BANDWIDTH			
	NON_HT_CBW20	HT_CBW20	HT_CBW40 or NON_HT_CBW40	
			HT format	MCS 32 and non-HT duplicate
T_{SYMS}: Short GI symbol interval	N/A	3.6 µs = T_{DFT}+T_{GIS}	3.6 µs See NOTE 2	
$T_{L\text{-}SIG}$: Non-HT SIGNAL field duration	4 µs= T_{SYM}	4 µs	4 µs	
$T_{HT\text{-}SIG}$: HT SIGNAL field duration	N/A	8 µs= 2T_{SYM}	8 µs See NOTE 2	
$T_{HT\text{-}STF}$: HT short training field duration	N/A	4 µs	4 µs See NOTE 2	
$T_{HT\text{-}LTF1}$: First HT long training field duration	N/A	4 µs in HT-mixed format, 8 µs in HT-greenfield format	4 µs in HT-mixed format, 8 µs in HT-greenfield format See NOTE 2	
$T_{HT\text{-}LTFs}$: Second, and subsequent, HT long training fields duration	N/A	4 µs	4 µs See NOTE 2	

NOTE 1—$N_{ST} = N_{SD} + N_{SP}$ except in the cases of MCS 32 and non-HT duplicate, where the number of data subcarriers differs from the number of complex data numbers, and the number of pilot subcarriers differs from the number of pilot values. In those cases, data numbers and pilot values are replicated in upper and lower 20 MHz portions of 40 MHz signal to make a total of 104 subcarriers.

NOTE 2—Not applicable in non-HT formats.

NOTE 3—N/A = Not applicable.

Table 19-7 defines parameters used frequently in Clause 19.

Table 19-7—Frequently used parameters

Symbol	Explanation
N_{CBPS}	Number of coded bits per symbol
$N_{CBPSS}(i)$	Number of coded bits per symbol per the *i*-th spatial stream
N_{DBPS}	Number of data bits per symbol
N_{BPSC}	Number of coded bits per single carrier
$N_{BPSCS}(i)$	Number of coded bits per single carrier for spatial stream *i*
N_{RX}	Number of receive chains
N_{STS}	Number of space-time streams
N_{SS}	Number of spatial streams
N_{ESS}	Number of extension spatial streams
N_{TX}	Number of transmit chains

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Table 19-7—Frequently used parameters *(continued)*

Symbol	Explanation
N_{ES}	Number of BCC encoders for the Data field
$N_{HT\text{-}LTF}$	Number of HT Long Training fields (see 19.3.9.4.6)
$N_{HT\text{-}DLTF}$	Number of Data HT Long Training fields
$N_{HT\text{-}ELTF}$	Number of Extension HT Long Training fields
R	Coding rate

19.3.7 Mathematical description of signals

For the description of the convention on mathematical description of signals, see 17.3.2.5.

In the case of either a 20 MHz non-HT format (TXVECTOR parameter FORMAT equal to NON_HT, MODULATION parameter equal to one of {ERP-OFDM, OFDM}) transmission or a 20 MHz HT format (TXVECTOR parameter FORMAT equal to HT_MF or HT_GF, CH_BANDWIDTH equal to HT_CBW20) transmission, the channel is divided into 64 subcarriers. In the 20 MHz non-HT format, the signal is transmitted on subcarriers –26 to –1 and 1 to 26, with 0 being the center (dc) carrier. In the 20 MHz HT format, the signal is transmitted on subcarriers –28 to –1 and 1 to 28.

In the case of the 40 MHz HT format, a 40 MHz channel is used. The channel is divided into 128 subcarriers. The signal is transmitted on subcarriers –58 to –2 and 2 to 58.

In the case of 40 MHz HT upper format or 40 MHz HT lower format, the upper or lower 20 MHz is divided into 64 subcarriers. The signal is transmitted on subcarriers –60 to –4 in the case of a 40 MHz HT lower format transmission and on subcarriers 4 to 60 in the case of a 40 MHz HT upper format transmission.

In the case of the MCS 32 and non-HT duplicate formats, the same data are transmitted over two adjacent 20 MHz channels. In this case, the 40 MHz channel is divided into 128 subcarriers, and the data are transmitted on subcarriers –58 to –6 and 6 to 58.

The transmitted signal is described in complex baseband signal notation. The actual transmitted signal is related to the complex baseband signal by the relation shown in Equation (19-1).

$$r_{RF}(t) = \mathrm{Re}\{r(t)\exp(j2\pi f_c t)\} \tag{19-1}$$

where
f_c is the center frequency of the carrier

The transmitted RF signal is derived by modulating the complex baseband signal, which consists of several fields. The timing boundaries for the various fields are shown in Figure 19-4.

The time offset, t_{Field}, determines the starting time of the corresponding field.

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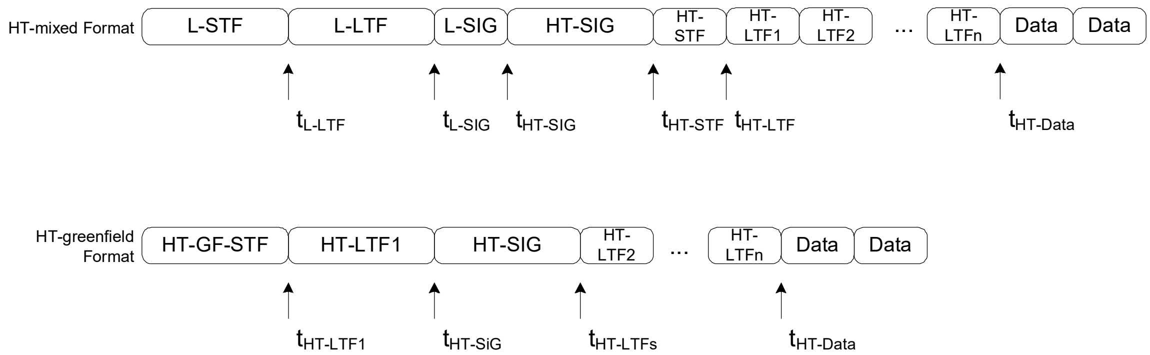

Figure 19-4—Timing boundaries for PPDU fields

In HT-mixed format, the signal transmitted on transmit chain i_{TX} shall be as shown in Equation (19-2).

$$\begin{aligned} r_{PPDU}^{(i_{TX})}(t) &= r_{L\text{-}STF}^{(i_{TX})}(t) + r_{L\text{-}LTF}^{(i_{TX})}(t - t_{L\text{-}LTF}) \\ &+ r_{L\text{-}SIG}^{(i_{TX})}(t - t_{L\text{-}SIG}) + r_{HT\text{-}SIG}^{(i_{TX})}(t - t_{HT\text{-}SIG}) + r_{HT\text{-}STF}^{(i_{TX})}(t - t_{HT\text{-}STF}) \\ &+ \sum_{i_{LTF}=1}^{N_{HTLTF}} r_{HT\text{-}LTF}^{(i_{TX}, i_{LTF})}(t - t_{HT\text{-}LTF} - (i_{LTF} - 1)T_{HT\text{-}LTFs}) + r_{HT\text{-}DATA}^{(i_{TX})}(t - t_{HT\text{-}DATA}) \end{aligned} \tag{19-2}$$

where

$t_{L\text{-}LTF} = T_{L\text{-}STF}$

$t_{L\text{-}SIG} = t_{L\text{-}LTF} + T_{L\text{-}LTF}$

$t_{HT\text{-}SIG} = t_{L\text{-}SIG} + T_{L\text{-}SIG}$

$t_{HT\text{-}STF} = t_{HT\text{-}SIG} + T_{HT\text{-}SIG}$

$t_{HT\text{-}LTF} = t_{HT\text{-}STF} + T_{HT\text{-}STF}$

$t_{HT\text{-}Data} = t_{HT\text{-}LTF} + N_{HT\text{-}LTF} \cdot T_{HT\text{-}LTFs}$

In the case of HT-greenfield format, the transmitted signal on transmit chain i_{TX} shall be as shown in Equation (19-3).

$$\begin{aligned} r_{PPDU}^{(i_{TX})}(t) &= r_{HT-GF-STF}^{(i_{TX})}(t) + r_{HT-LTF1}^{(i_{TX})}(t - t_{HT-LTF1}) \\ &+ r_{HT-SIG}^{(i_{TX})}(t - t_{HT-SIG}) \\ &+ \sum_{i_{LTF}=2}^{N_{HTLTF}} r_{HT-LTF}^{(i_{TX}, i_{LTF})}(t - t_{HT-LTFs} - (i_{LTF} - 2)T_{HT-LTFs}) \\ &+ r_{HT-DATA}^{(i_{TX})}(t - t_{HT-DATA}) \end{aligned} \tag{19-3}$$

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where

$$t_{HT-LTF1} = T_{HT-GF-STF}$$

$$t_{HT\text{-}SIG} = t_{HT\text{-}LTF1} + T_{HT\text{-}LTF1}$$

$$t_{HT\text{-}LTFs} = t_{HT\text{-}SIG} + T_{HT\text{-}SIG}$$

$$t_{HT\text{-}Data} = t_{HT\text{-}LTFs} + (N_{HT\text{-}LTF} - 1) \cdot T_{HT\text{-}LTFs}$$

Each baseband waveform, $r_{\mathrm{Field}}^{(i_{TX})}(t)$, is defined via the discrete Fourier transform (DFT) per OFDM symbol as shown in Equation (19-4).

$$r_{\mathrm{Field}}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{\mathrm{Field}}^{\mathrm{Tone}} \cdot N_{TX}}} w_{T_{\mathrm{Field}}}(t) \sum_k \Upsilon_k X_k^{(i_{TX})} \exp(j2\pi k \Delta_F t) \qquad (19\text{-}4)$$

This general representation holds for all fields. A suggested definition of the windowing function, $w_{T_{\mathrm{Field}}}(t)$, is given in 17.3.2.5. The frequency domain symbols $X_k^{(i_{TX})}$ represent the output of any spatial processing in subcarrier k for transmit chain i_{TX} required for the field.

The function Υ_k is used to represent a rotation of the upper tones in a 40 MHz channel as shown in Equation (19-5) and Equation (19-6).

$$\Upsilon_k = \begin{cases} 1, k \le 0, \text{ in a 40 MHz channel} \\ j, k > 0, \text{ in a 40 MHz channel} \end{cases} \qquad (19\text{-}5)$$

$$\Upsilon_k = 1, \text{ in a 20 MHz channel} \qquad (19\text{-}6)$$

The $1/\sqrt{N_{\mathrm{Field}}^{\mathrm{Tone}} \cdot N_{TX}}$ scale factor in Equation (19-4) causes the total power of the time domain signal as summed over all transmit chains to be either 1 or lower than 1 when required. Table 19-8 summarizes the various values of $N_{\mathrm{Field}}^{\mathrm{Tone}}$.

Table 19-8—Value of tone scaling factor N_{Field}^{Tone}

Field	**N_{Field}^{Tone}, see NOTE 1**	
	20 MHz	**40 MHz**
L-STF	12	24
HT-GF-STF	12	24
L-LTF	52	104
L-SIG	52	104
HT-SIG	52/56, see NOTE 2	104/114, see NOTE 2
HT-STF	12	24

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Table 19-8—Value of tone scaling factor N_{Field}^{Tone} (continued)

Field	N_{Field}^{Tone}, see NOTE 1	
	20 MHz	40 MHz
HT-LTF	56	114
HT-DATA	56	114
MCS 32	—	104
Non-HT Duplicate	—	104
NOTE 1—The numbers in the table refer only to the value of N_{Field}^{Tone} as it appears in Equation (19-4) and in subsequent specification of various fields. This value might be different from the actual number of tones being transmitted. NOTE 2—The values 56 and 114 are for HT-greenfield format; the values 52 and 104 are for HT-mixed format.		

19.3.8 Transmission in the upper/lower 20 MHz of a 40 MHz channel

When transmitting in the upper/lower 20 MHz portion of a 40 MHz channel, the mathematical definition of transmission shall follow that of a 20 MHz channel with f_c in Equation (19-1) replaced by $f_c \pm 10$ MHz .

This rule applies to 20 MHz HT transmission in the upper/lower 20 MHz of a 40 MHz channel (TXVECTOR primitive CH_BANDWIDTH equal to HT_CBW20 and CH_OFFSET primitive equal to CH_OFF_20U or CH_OFF_20L) and to 20 MHz non-HT transmission in the upper/lower 20 MHz of a 40 MHz channel (TXVECTOR primitive CH_BANDWIDTH equal to NON_HT_CBW20 and CH_OFFSET primitive equal to CH_OFF_20U or CH_OFF_20L).

19.3.9 HT preamble

19.3.9.1 Introduction

The HT preambles are defined in HT-mixed format and in HT-greenfield format to carry the required information to operate in a system with multiple transmit and multiple receive antennas.

In the HT-mixed format, to provide compatibility with non-HT STAs, specific non-HT fields are defined so that they can be received by non-HT STAs compliant with Clause 17 or Clause 18 followed by the fields specific to HT STAs.

In the HT-greenfield format, all of the non-HT fields are omitted. The specific HT fields used are as follows:

— One HT-GF-STF for automatic gain control convergence, timing acquisition, and coarse frequency acquisition,
— One or several HT-LTFs, provided as a way for the receiver to estimate the channel between each spatial mapper input and receive chain. The first HT-LTFs (HT-DLTFs) are necessary for demodulation of the HT-Data portion of the PPDU and are followed, for sounding PPDUs only, by optional HT-LTFs (HT-ELTFs) to sound extra spatial dimensions of the MIMO channel,
— HT-SIG, which provides all the information required to interpret the HT packet format.

In the case of multiple transmit chains, the HT preambles use cyclic shift techniques to prevent unintentional beamforming.

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19.3.9.2 HT-mixed format preamble

In HT-mixed format frames, the preamble has fields that support compatibility with Clause 17 and Clause 18 STAs and fields that support HT operation. The non-HT portion of the HT-mixed format preamble enables detection of the PPDU and acquisition of carrier frequency and timing by both HT STAs and STAs that are compliant with Clause 17 or Clause 18. The non-HT portion of the HT-mixed format preamble contains the SIGNAL field (L-SIG) defined in Clause 17 and is thus decodable by STAs compliant with Clause 17 and Clause 18 as well as HT STAs.

The HT portion of the HT-mixed format preamble enables estimation of the MIMO channel to support demodulation of the data portion of the frame by HT STAs. The HT portion of the HT-mixed format preamble also contains the HT-SIG field that supports HT operation.

19.3.9.3 Non-HT portion of the HT-mixed format preamble

19.3.9.3.1 Introduction

The transmission of the L-STF, L-LTF and the L-SIG as part of an HT-mixed format packet is described in 19.3.9.3.2 to 19.3.9.3.5.

19.3.9.3.2 Cyclic shift definition

The cyclic shift values defined in this subclause apply to the non-HT fields in the HT-mixed format preamble and the HT-SIG in the HT-mixed format preamble.

Cyclic shifts are used to prevent unintentional beamforming when the same signal or scalar multiples of one signal are transmitted through different spatial streams or transmit chains. A cyclic shift of duration T_{CS} on a signal $s(t)$ on interval $0 \le t \le T$ is defined as follows, where T is defined as T_{DFT} as referenced in Table 19-6.

With $T_{CS} \le 0$, replace $s(t)$ with $s(t - T_{CS})$ when $0 \le t < T + T_{CS}$ and with $s(t - T_{CS} - T)$ when $T + T_{CS} \le t \le T$. The cyclic-shifted signal is defined as shown in Equation (19-7).

$$s_{CS}(t;T_{CS})\big|_{T_{CS}<0} = \begin{cases} s(t - T_{CS}) & 0 \le t < T + T_{CS} \\ s(t - T_{CS} - T) & T + T_{CS} \le t \le T \end{cases} \tag{19-7}$$

The cyclic shift is applied to each OFDM symbol in the packet separately. Table 19-9 specifies the values for the cyclic shifts that are applied in the L-STF (in an HT-mixed format packet), the L-LTF, and L-SIG. It also applies to the HT-SIG in an HT-mixed format packet.

With more than four transmit chains, each cyclic shift on the additional transmit chains shall be between –200 ns and 0 ns.

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Table 19-9—Cyclic shift for non-HT portion of PPDU

$T_{CS}^{i_{TX}}$ values for non-HT portion of PPDU				
Number of transmit chains	**Cyclic shift for transmit chain 1 (ns)**	**Cyclic shift for transmit chain 2 (ns)**	**Cyclic shift for transmit chain 3 (ns)**	**Cyclic shift for transmit chain 4 (ns)**
1	0	—	—	—
2	0	–200	—	—
3	0	–100	–200	—
4	0	–50	–100	–150

19.3.9.3.3 L-STF definition

The non-HT short training OFDM symbol in the 20 MHz channel width is shown in Equation (19-8).

$$\begin{aligned}S_{-26,26} = {} & \sqrt{1/2} \\ & \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\ & 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}\end{aligned} \tag{19-8}$$

The normalization factor $\sqrt{1/2}$ is the QPSK normalization.

NOTE—Other than the scaling difference, Equation (19-8) represents the same BPSK constellations per subcarrier as those represented in Equation (17-8).

The non-HT short training OFDM symbol in a 40 MHz channel width is given by Equation (19-9), after rotating the tones in the upper subchannel (subcarriers 6–58) by +90° [see Equation (19-10)].

$$\begin{aligned}S_{-58,58} = {} & \sqrt{1/2} \\ & \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\ & 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, \\ & 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, \\ & 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}\end{aligned} \tag{19-9}$$

In HT-mixed format, the L-STF on transmit chain i_{TX} shall be as shown in Equation (19-10).

$$r_{L-STF}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{TX} \cdot N_{L-STF}^{Tone}}} w_{T_{L-STF}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \Upsilon_k S_k \exp(j2\pi k\Delta_F(t - T_{CS}^{i_{TX}})) \tag{19-10}$$

where

$T_{CS}^{i_{TX}}$ represents the cyclic shift for transmit chain i_{TX} and takes values from Table 19-9

Υ_k is defined in Equation (19-5) and Equation (19-6)

The L-STF has a period of 0.8 μs. The entire STF includes ten such periods, with a total duration of $T_{L\text{-}STF} = 8$ μs.

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19.3.9.3.4 L-LTF definition

The non-HT long training OFDM symbol is identical to the Clause 17 long training OFDM symbol. In the 20 MHz channel width, the long training OFDM symbol is given by Equation (19-11).

$$\begin{aligned} L_{-26,26} = \{&1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\} \end{aligned} \tag{19-11}$$

The non-HT long training OFDM symbol in a 40 MHz channel width is given by Equation (19-12), after rotating the tones in the upper subchannel (subcarriers 6–58) by +90° [see Equation (19-13)].

$$\begin{aligned} L_{-58,58} = \{&1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 0, 0, 0, 0, \\ &0, 0, 0, 0, 0, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\} \end{aligned} \tag{19-12}$$

The subcarriers at ± 32 in 40 MHz, which are the dc subcarriers for the non-HT 20 MHz transmission, are both nulled in the L-LTF. Such an arrangement allows proper synchronization of a 20 MHz non-HT STA.

The L-LTF waveform shall be as shown in Equation (19-13).

$$r_{L-LTF}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{TX} \cdot N_{L-LTF}^{Tone}}} w_{T_{L-LTF}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \Upsilon_k L_k \exp(j2\pi k \Delta_F (t - T_{GI2} - T_{CS}^{i_{TX}})) \tag{19-13}$$

where

T_{GI2} is 1.6 µs

$T_{CS}^{i_{TX}}$ represents the cyclic shift for transmit chain i_{TX} and takes values specified in Table 19-9

Υ_k is defined in Equation (19-5) and Equation (19-6)

The entire LTF includes two 3.2 µs IDFT/DFT periods and an additional 1.6 µs double GI. The entire LTF is modulated with the L-LTF waveform.

19.3.9.3.5 L-SIG definition

The L-SIG is used to communicate rate and length information.The structure of the L-SIG is shown in Figure 19-5.

Rate (4 bits)				R	Length (12 bits)												P	Tail (6 bits)					
R1	R2	R3	R4															"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 19-5—L-SIG structure

The value in the Rate field is obtained from the L_DATARATE field of the TXVECTOR. The value in the Length field is obtained from the L_LENGTH field of the TXVECTOR. The Length field is transmitted LSB first.

The reserved bit shall be set to 0.

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The parity field has the even parity of bits 0–16.

The L-SIG shall be encoded, interleaved and mapped, and it shall have pilots inserted following the steps described in 17.3.5.6, 17.3.5.7, and 17.3.5.9. The stream of 48 complex numbers generated by the steps described in 17.3.5.7 is denoted by $d_k, k = 0 \ldots 47$. The time domain waveform of the L-SIG in 20 MHz transmission shall be as given by Equation (19-14).

$$r_{L-SIG}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{TX} \cdot N_{L-SIG}^{Tone}}} w_{T_{SYM}}(t) \sum_{k=-26}^{26} (D_k + p_0 P_k) \exp(j 2\pi k \Delta_F (t - T_{GI} - T_{CS}^{i_{TX}})) \tag{19-14}$$

In a 40 MHz transmission the time domain waveform of the L-SIG shall be as given by Equation (19-15).

$$\begin{aligned} r_{L-SIG}^{(i_{TX})}(t) &= \frac{1}{\sqrt{N_{TX} \cdot N_{L-SIG}^{Tone}}} w_{T_{SYM}}(t) \sum_{k=-26}^{26} (D_k + p_0 P_k) \\ &\cdot (\exp(j 2\pi (k-32) \Delta_F (t - T_{GI} - T_{CS}^{i_{TX}})) + j \exp(j 2\pi (k+32) \Delta_F (t - T_{GI} - T_{CS}^{i_{TX}}))) \end{aligned} \tag{19-15}$$

where

$$D_k = \begin{cases} 0, k = 0, \pm 7, \pm 21 \\ d_{M^r(k)}, \text{ otherwise} \end{cases}$$

$$M^r(k) = \begin{cases} k + 26, -26 \le k \le -22 \\ k + 25, -20 \le k \le -8 \\ k + 24, -6 \le k \le -1 \\ k + 23, 1 \le k \le 6 \\ k + 22, 8 \le k \le 20 \\ k + 21, 22 \le k \le 26 \end{cases}$$

P_k is defined in 17.3.5.10

p_0 is the first pilot value in the sequence defined in 17.3.5.10

N_{L-SIG}^{Tone} has the value given in Table 19-8

$T_{CS}^{i_{TX}}$ represents the cyclic shift for transmit chain i_{TX} and is defined by Table 19-9 for HT-mixed format PPDUs

NOTE—D_k exists for $-N_{SR} \le k \le N_{SR}$ and takes the values from d_k that exists for $0 \le k \le N_{SD} - 1$. $M^r(k)$ is a “reverse” function of the function $M(k)$ defined in 17.3.5.10.

19.3.9.4 HT portion of HT-mixed format preamble

19.3.9.4.1 Introduction

When an HT-mixed format preamble is transmitted, the HT preamble consists of the HT-STF, the HT-LTFs, and the HT-SIG.

All numeric fields are transmitted in unsigned format, LSB first.

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19.3.9.4.2 Cyclic shift definition

The cyclic shift values defined in this subclause apply to the HT-STF and HT-LTFs of the HT-mixed format preamble. The cyclic shift values defined in 19.3.9.3.2 apply to the HT-SIG in an HT-mixed format preamble.

Throughout the HT portion of an HT-mixed format preamble, cyclic shift is applied to prevent beamforming when similar signals are transmitted in different space-time streams. The same cyclic shift is applied to these streams during the transmission of the data portion of the frame. The values of the cyclic shifts to be used during the HT portion of the HT-mixed format preamble (with the exception of the HT_SIG) and the data portion of the frame are specified in Table 19-10.

Table 19-10—Cyclic shift values of HT portion of PPDU

$T_{CS}^{i_{STS}}$ values for HT portion of PPDU				
Number of space-time streams	**Cyclic shift for space-time stream 1 (ns)**	**Cyclic shift for space-time stream 2 (ns)**	**Cyclic shift for space-time stream 3 (ns)**	**Cyclic shift for space-time stream 4 (ns)**
1	0	—	—	—
2	0	–400	—	—
3	0	–400	–200	—
4	0	–400	–200	–600

19.3.9.4.3 HT-SIG definition

The HT-SIG is used to carry information required to interpret the HT packet formats. The fields of the HT-SIG are described in Table 19-11.

Table 19-11—HT-SIG fields

Field	Number of bits	Explanation and coding
Modulation and Coding Scheme	7	Index into the MCS table.
CBW 20/40	1	Set to 0 for 20 MHz or 40 MHz upper/lower. Set to 1 for 40 MHz.
HT Length	16	The number of octets of data in the PSDU. See NOTE.
Smoothing	1	Set to 1 indicates that channel estimate smoothing is recommended. Set to 0 indicates that only per-carrier independent (unsmoothed) channel estimate is recommended. See 19.3.11.11.2.
Not Sounding	1	Set to 0 indicates that PPDU is a sounding PPDU. Set to 1 indicates that the PPDU is not a sounding PPDU.
Reserved	1	Set to 1.

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Table 19-11—HT-SIG fields *(continued)*

Field	Number of bits	Explanation and coding
Aggregation	1	Set to 1 to indicate that the PPDU in the data portion of the packet contains an A-MPDU; otherwise, set to 0.
STBC	2	Set to a nonzero number, to indicate the difference between the number of space-time streams (N_{STS}) and the number of spatial streams (N_{SS}) indicated by the MCS. Set to 00 to indicate no STBC ($N_{STS} = N_{SS}$).
FEC Coding	1	Set to 1 for LDPC. Set to 0 for BCC.
Short GI	1	Set to 1 to indicate that the short GI is used after the HT-LTFs. Set to 0 otherwise.
Number of Extension Spatial Streams	2	Indicates the number of extension spatial streams (N_{ESS}). Set to 0 for no extension spatial stream. Set to 1 for 1 extension spatial stream. Set to 2 for 2 extension spatial streams. Set to 3 for 3 extension spatial streams.
CRC	8	CRC of bits 0–23 in HT-SIG$_1$ and bits 0–9 in HT-SIG$_2$. See 19.3.9.4.4. The first bit to be transmitted is bit C7 as explained in 19.3.9.4.4.
Tail Bits	6	Used to terminate the trellis of the convolution coder. Set to 0.
NOTE—A value of 0 in the HT Length field indicates a PPDU that does not include a data field, i.e., NDP. NDP transmissions are used for sounding purposes only (see 10.36.2). The packet ends after the last HT-LTF or the HT-SIG.		

The structure of the HT-SIG$_1$ and HT-SIG$_2$ fields is defined in Figure 19-6.

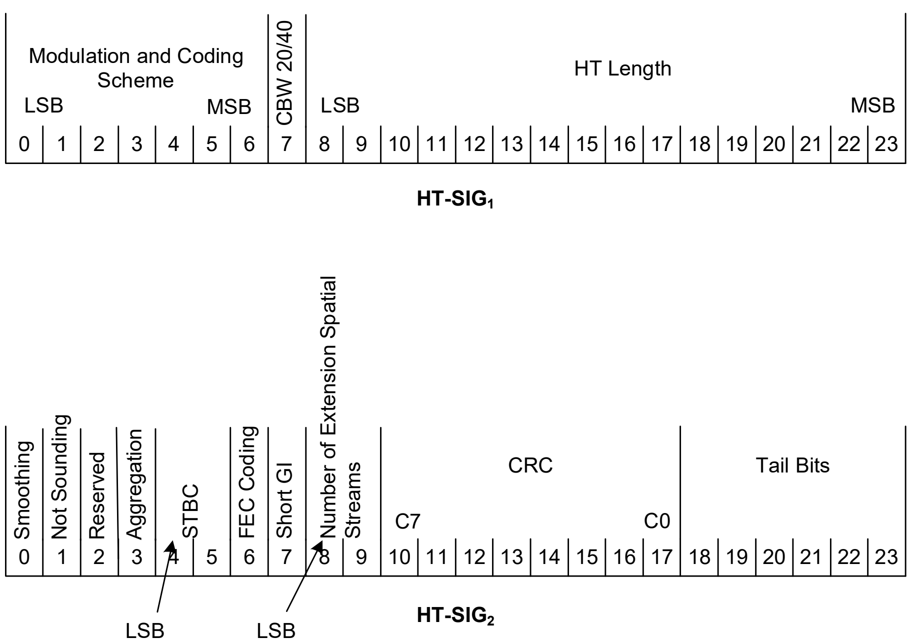

Figure 19-6—Format of HT-SIG$_1$ and HT-SIG$_2$

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The HT-SIG is composed of two parts, HT-SIG$_1$ and HT-SIG$_2$, each containing 24 bits, as shown in Figure 19-6. All of the fields in the HT-SIG are transmitted LSB first, and HT-SIG$_1$ is transmitted before HT-SIG$_2$.

The HT-SIG parts shall be encoded at R = 1/2, interleaved, and mapped to a BPSK constellation, and they have pilots inserted following the steps described in 17.3.5.6, 17.3.5.7, 17.3.5.8, and 17.3.5.9, respectively. The BPSK constellation is rotated by 90° relative to the L-SIG in order to accommodate detection of the start of the HT-SIG. The stream of 96 complex numbers generated by these steps is divided into two groups of 48 complex numbers: $d_{k,n}, 0 \le k \le 47, n = 0, 1$. The time domain waveform for the HT-SIG in an HT-mixed format packet in a 20 MHz transmission shall be as shown in Equation (19-16).

$$
\begin{aligned}
r_{HT-SIG}^{i_{TX}}(t) = & \frac{1}{\sqrt{N_{TX} \cdot N_{HT-SIG}^{Tone}}} \sum_{n=0}^{1} w_{\mathrm{T}_{SYM}}(t - nT_{SYM}) \\
& \cdot \sum_{k=-26}^{26} (jD_{k,n} + p_{n+1}P_k)\exp(j2\pi k\Delta_F(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{TX}}))
\end{aligned}
\tag{19-16}
$$

In a 40 MHz transmission the time domain waveform shall be as shown in Equation (19-17).

$$
\begin{aligned}
r_{HT-SIG}^{i_{TX}}(t) = & \frac{1}{\sqrt{N_{TX} \cdot N_{HT-SIG}^{Tone}}} \sum_{n=0}^{1} w_{\mathrm{T}_{SYM}}(t - nT_{SYM}) \\
& \cdot \sum_{k=-26}^{26} (jD_{k,n} + p_{n+1}P_k)(\exp(j2\pi(k-32)\Delta_F(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{TX}})) \\
& + j\exp(j2\pi(k+32)\Delta_F(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{TX}})))
\end{aligned}
\tag{19-17}
$$

where

$$
D_{k,n} = \begin{cases} 0, & k = 0, \pm 7, \pm 21 \\ d_{M^r(k),n}, & \text{otherwise} \end{cases}
$$

$M^r(k)$ is defined in 19.3.9.3

P_k and p_n are defined in 17.3.5.10

N_{HT-SIG}^{Tone} has the value given in Table 19-8

$T_{CS}^{i_{TX}}$ represents the cyclic shift for transmit chain i_{TX} and is defined by Table 19-9 for HT-mixed format PPDUs

NOTE—This definition results in a quadrature binary phase shift keying (QBPSK) modulation in which the constellation of the data tones is rotated by 90° relative to the L-SIG in HT-mixed format PPDUs and relative to the first HT-LTF in HT-greenfield format PPDUs (see Figure 19-7). In HT-mixed format PPDUs, the HT-SIG is transmitted with the same number of subcarriers and the same cyclic shifts as the preceding non-HT portion of the preamble. This is done to accommodate the estimation of channel parameters needed to robustly demodulate and decode the information contained in the HT-SIG.

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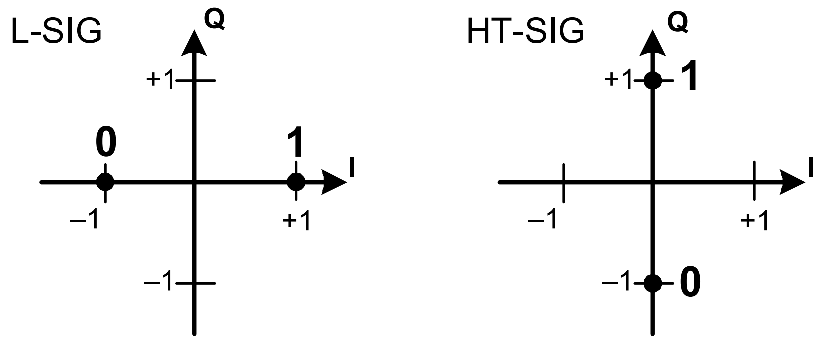

Figure 19-7—Data tone constellations in an HT-mixed format PPDU

19.3.9.4.4 CRC calculation for HT-SIG

The CRC protects bits 0–33 of the HT-SIG (bits 0–23 of HT-SIG$_1$ and bits 0–9 of HT-SIG$_2$). The value of the CRC field shall be the 1s complement of

$$crc(D) = (M(D) \oplus I(D))D^8 \bmod G(D) \tag{19-18}$$

where

$M(D) = m_0 D^{33} + m_1 D^{32} + \ldots + m_{32} D + m_{33}$ is the HT-SIG represented as a polynomial

where

m_0 is bit 0 of HT-SIG$_1$

m_{33} is bit 9 of HT-SIG$_2$

$I(D) = \sum_{i=26}^{33} D^i$ are initialization values that are added modulo 2 to the first 8 bits of HT-SIG$_1$

$G(D) = D^8 + D^2 + D + 1$ is the CRC generating polynomial

$crc(D) = c_0 D^7 + c_1 D^6 + \ldots + c_6 D + c_7$

The CRC field is transmitted with c_7 first.

Figure 19-8 shows the operation of the CRC. First, the shift register is reset to all 1s. The bits are then passed through the XOR operation at the input. When the last bit has entered, the output is generated by shifting the bits out of the shift register, C7 first, through an inverter.

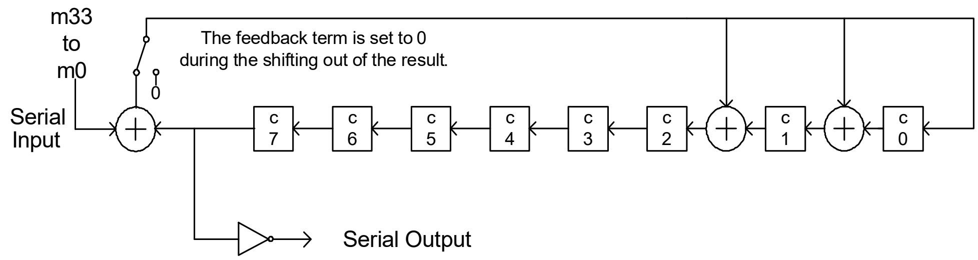

Figure 19-8—HT-SIG CRC calculation

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As an example, if bits $\{m_0 \ldots m_{33}\}$ are given by {1 1 1 1 0 0 0 1 0 0 1 0 0 1 1 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0}, the output bits $\{B_7 \ldots B_0\}$, where B_7 is output first, are {1 0 1 0 1 0 0 0}.

19.3.9.4.5 HT-STF definition

The purpose of the HT-STF is to improve automatic gain control estimation in a MIMO system. The duration of the HT-STF is 4 µs. In a 20 MHz transmission, the frequency sequence used to construct the HT-STF is identical to L-STF. In a 40 MHz transmission, the HT-STF is constructed from the 20 MHz version by duplicating and frequency shifting and by rotating the upper subcarriers by 90°. The frequency sequences are shown in Equation (19-19) and Equation (19-20).

For 20 MHz:

$$\begin{aligned} HTS_{-28,28} = {} & \sqrt{1/2} \\ & \{0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\ & 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0\} \end{aligned} \tag{19-19}$$

For 40 MHz:

$$\begin{aligned} HTS_{-58,58} = {} & \sqrt{1/2} \\ & \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\ & 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, \\ & 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, \\ & 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\} \end{aligned} \tag{19-20}$$

The time domain representation of the transmission in transmit chain i_{TX} shall be as shown in Equation (19-21).

$$\begin{aligned} r_{HT-STF}^{i_{TX}}(t) = {} & \frac{1}{\sqrt{N_{STS} \cdot N_{HT-STF}^{Tone}}} w_{T_{HT-STF}}(t) \\ & \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX}, i_{STS}} \Upsilon_k HTS_k \exp(j2\pi k \Delta_F (t - T_{CS}^{i_{STS}})) \end{aligned} \tag{19-21}$$

where

$T_{CS}^{i_{STS}}$ represents the cyclic shift for the space-time stream i_{STS} and takes the values given in Table 19-10

Q_k is defined in 19.3.11.11.2

Υ_k is defined in Equation (19-5) and Equation (19-6)

19.3.9.4.6 HT-LTF definition

The HT-LTF provides a means for the receiver to estimate the MIMO channel between the set of QAM mapper outputs (or, if STBC is applied, the STBC encoder outputs) and the receive chains. If the transmitter is providing training for exactly the space-time streams (spatial mapper inputs) used for the transmission of the PSDU, the number of training symbols, N_{LTF}, is equal to the number of space-time streams, N_{STS}, except that for three space-time streams, four training symbols are required. If the transmitter is providing

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training for more space-time streams (spatial mapper inputs) than the number used for the transmission of the PSDU, the number of training symbols is greater than the number of space-time streams. This latter case happens in a sounding PPDU.

The HT-LTF portion has one or two parts. The first part consists of one, two, or four HT-LTFs that are necessary for demodulation of the HT-Data portion of the PPDU. These HT-LTFs are referred to as *HT-DLTFs*. The optional second part consists of zero, one, two, or four HT-LTFs that may be used to sound extra spatial dimensions of the MIMO channel that are not utilized by the HT-Data portion of the PPDU. These HT-LTFs are referred to as *HT-ELTFs*. If a receiver has not advertised its ability to receive HT-ELTFs, it shall either issue a PHY-RXEND.indication(UnsupportedRate) primitive upon reception of a frame that includes HT-ELTFs or decode that frame. (When an HT packet includes one or more HT-ELTFs, it is optional for a receiver that has not advertised its capability to receive HT-ELTFs to decode the data portion of the PPDU.)

The number of HT-DLTFs is denoted $N_{HT\text{-}DLTF}$. The number of HT-ELTFs is denoted $N_{HT\text{-}ELTF}$. The total number of HT-LTFs is shown in Equation (19-22).

$$N_{HT\text{-}LTF} = N_{HT\text{-}DLTF} + N_{HT\text{-}ELTF} \tag{19-22}$$

$N_{HT\text{-}LTF}$ shall not exceed 5. Table 19-12 shows the determination of the number of space-time streams from the MCS and STBC fields in the HT-SIG. Table 19-13 shows the number of HT-DLTFs as a function of the number of space-time streams (N_{STS}). Table 19-14 shows the number of HT-ELTFs as a function of the number of extension spatial streams (N_{ESS}). N_{STS} plus N_{ESS} is less than or equal to 4. In the case where N_{STS} equals 3, N_{ESS} cannot exceed one; if N_{ESS} equals one in this case then N_{LTF} equals 5.

Table 19-12—Determining the number of space-time streams

Number of spatial streams (from MCS) N_{SS}	STBC field	Number of space-time streams N_{STS}
1	0	1
1	1	2
2	0	2
2	1	3
2	2	4
3	0	3
3	1	4
4	0	4

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Table 19-13—Number of HT-DLTFs required for data space-time streams

N_{STS}	N_{HTDLTF}
1	1
2	2
3	4
4	4

Table 19-14—Number of HT-ELTFs required for extension spatial streams

N_{ESS}	$N_{HT\text{-}ELTF}$
0	0
1	1
2	2
3	4

The HT-LTF sequence shown in Equation (19-23) is transmitted in the case of 20 MHz operation.

$$\begin{aligned} HT\text{-}LTF_{-28,28} = \{&1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1, -1, -1\} \end{aligned} \tag{19-23}$$

NOTE 1—This sequence is an extension of the L-LTF where the four extra subcarriers are filled with +1 for negative frequencies and –1 for positive frequencies.

In 40 MHz transmissions, including MCS 32 format frames, the sequence to be transmitted is shown in Equation (19-24).

$$\begin{aligned} HT\text{-}LTF_{-58,58} = \{&1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1, -1, -1, -1, 1, 0, \\ &0, 0, -1, 1, 1, -1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, \\ &1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\} \end{aligned} \tag{19-24}$$

NOTE 2—This sequence is also constructed by extending the L-LTF in the following way: first, the L-LTF is duplicated and shifted as explained in 19.3.9.3.4 for the non-HT duplicate format; then the missing subcarriers [–32, –5, –4, –3, –2, 2, 3, 4, 5, 32] are filled with the values [1, –1, –1, –1, 1, –1, 1, 1, –1, 1], respectively.

This sequence, occupying 114 tones, is used even if the data portion is transmitted with MCS 32 format, which uses 104 tones.

NOTE 3—This sequence uses 114 tones when MCS 32 format is used to retain consistency with other 40 MHz formats and to facilitate channel estimation for beamforming and link adaptation.

In an HT-mixed format preamble, each HT-LTF consists of a single occurrence of the sequence plus a GI insertion and has a duration of 4 μs. In case of multiple space-time streams, cyclic shift is invoked as specified in Table 19-10.

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The generation of HT-DLTFs is shown in Figure 19-9. The generation of HT-ELTFs is shown in Figure 19-10. In these figures, and in the following text, the following notational conventions are used:

— $[X]_{m,n}$ indicates the element in row m and column n of matrix X

— $[X]_N$ indicates a matrix consisting of the first N columns of matrix X

— $[X]_{M:N}$ indicates a matrix consisting of columns M to N of matrix X

where
$M \le N$
X is either Q_k or $P_{HT\text{-}LTF}$

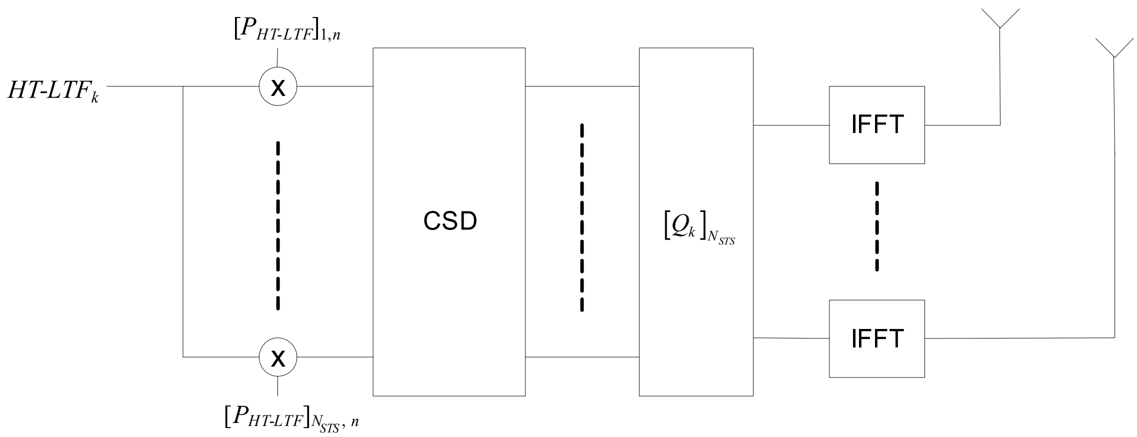

Figure 19-9—Generation of HT-DLTFs

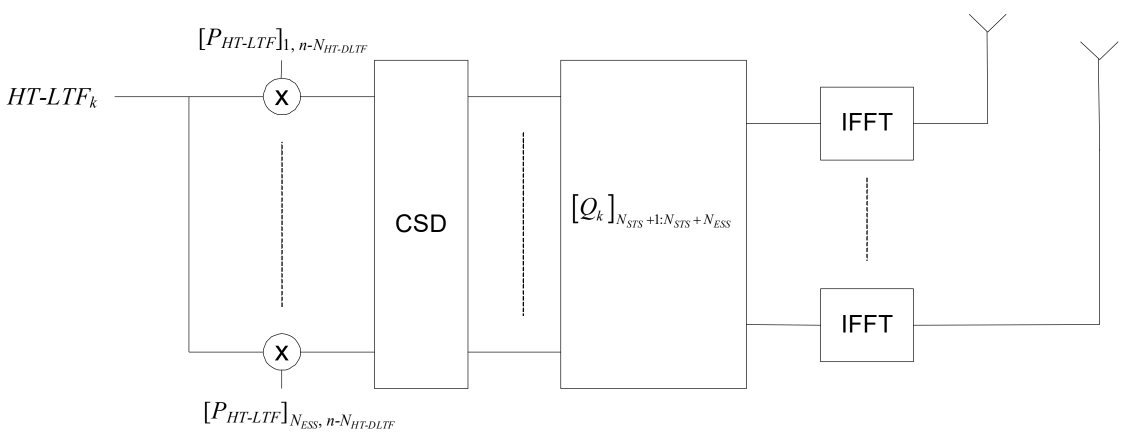

Figure 19-10—Generation of HT-ELTFs

The mapping between space-time streams and transmit chains is defined by the columns of an antenna map matrix Q_k for subcarrier k. The first N_{STS} columns define the space-time streams used for data transmission, and the next N_{ESS} columns (up to $N_{TX} - N_{STS}$ columns) define the extension spatial streams. Thus, for the purpose of defining HT-LTFs, Q_k is an $N_{TX} \times (N_{STS} + N_{ESS})$ dimension matrix. Columns

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$1 \ldots N_{STS}$ of Q_k are excited by the HT-DLTFs, and columns $N_{STS}+1 \ldots N_{STS}+N_{ESS}$ are excited by the HT-ELTFs, where $N_{STS}+N_{ESS} \le N_{TX}$ is the total number of spatial streams being probed by the HT-LTFs.

Possible forms of Q_k and other limitations on Q_k are specified in 19.3.11.11.2. $P_{HT\text{-}LTF}$ is defined in Equation (19-27).

The time domain representation of the waveform transmitted on transmit chain i_{TX} during HT-DLTF n, where $1 \le n \le N_{HT\text{-}DLTF}$, shall be as shown in Equation (19-25).

$$r_{HT-LTF}^{n,i_{TX}}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-LTF}^{Tone}}} w_{T_{HT-LTFs}}(t) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX},i_{STS}} [P_{HT\text{-}LTF}]_{i_{STS},n} \Upsilon_k HT\text{-}LTF_k \exp(j2\pi k \Delta_F (t - T_{GI} - T_{CS}^{i_{STS}})) \tag{19-25}$$

For the HT-ELTFs $(N_{HT\text{-}DLTF} < n \le N_{HT\text{-}LTF})$, it shall be as shown in Equation (19-26).

$$r_{HT-LTF}^{n,i_{TX}}(t) = \frac{1}{\sqrt{N_{HT-LTF}^{Tone} \cdot N_{ESS}}} w_{T_{HT-LTFs}}(t) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{ESS}=1}^{N_{ESS}} \Big([Q_k]_{i_{TX},N_{STS}+i_{ESS}} [P_{HT\text{-}LTF}]_{i_{ESS},n-N_{HTDLTF}} \Upsilon_k HT\text{-}LTF_k \cdot \exp(j2\pi k \Delta_F (t - T_{GI} - T_{CS}^{i_{ESS}})) \Big) \tag{19-26}$$

where

$T_{CS}^{i_{STS}}$	cyclic shift values are given in Table 19-10
$T_{CS}^{i_{ESS}}$	cyclic shift values are given in Table 19-10 with $i_{ESS} = i_{STS}$
Q_k	is defined in 19.3.11.11.2
Υ_k	is defined in Equation (19-5) and Equation (19-6)
$P_{HT\text{-}LTF}$	the HT-LTF mapping matrix, is given by Equation (19-27)

$$P_{HT\text{-}LTF} = \begin{bmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{bmatrix} \tag{19-27}$$

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19.3.9.5 HT-greenfield format preamble

19.3.9.5.1 General

For HT-greenfield operation, compatibility with Clause 17 and Clause 18 STAs is not required. Therefore, the portions of the preamble that are compatible with Clause 17 and Clause 18 STAs are not included. The result is a shorter and more efficient PHY frame format that includes a STF, LTF(s), and an HT-SIG.

19.3.9.5.2 Cyclic shift definition for HT-greenfield format preamble

Throughout the HT-greenfield format preamble, cyclic shift is applied to prevent beamforming when similar signals are transmitted on different spatial streams. The same cyclic shift is applied to these streams during the transmission of the data portion of the frame. The values of the cyclic shift to be used during the HT-greenfield format preamble, as well as the data portion of the HT-greenfield format frame, are specified in Table 19-10.

19.3.9.5.3 HT-GF-STF definition

The HT-GF-STF is placed at the beginning of an HT-greenfield format frame. The time domain waveform for the HT-GF-STF on transmit chain i_{TX} shall be as shown in Equation (19-28).

$$r_{HT-GF-STF}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-GF-STF}^{Tone}}} w_{\mathrm{T}_{HT-GF-STF}}(t) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX}, i_{STS}} [P_{HT\text{-}LTF}]_{i_{STS}, 1} \Upsilon_k S_k \exp(j 2\pi k \Delta_F (t - T_{CS}^{i_{STS}})) \tag{19-28}$$

where

$T_{CS}^{i_{STS}}$	represents the cyclic shift for the space-time stream i_{STS} and takes values from Table 19-10
Q_k	is defined in 19.3.11.11.2
$P_{HT\text{-}LTF}$	is defined in Equation (19-27)
S_k	is defined in non-HT-STF (L-STF), Equation (19-8) for 20 MHz operation and Equation (19-9) for 40 MHz operation
Υ_k	is defined in Equation (19-5) and Equation (19-6)

The waveform defined by Equation (19-28) has a period of 0.8 μs, and the HT-GF-STF includes ten such periods, with a total duration of $\mathrm{T}_{HT-GF-STF} = 8$ μs.

19.3.9.5.4 HT-greenfield format HT-SIG

The content and format of the HT-SIG of an HT-greenfield format frame is identical to the HT-SIG in an HT-mixed format frame, as described in 19.3.9.4.3. The placement of the HT-SIG in an HT-greenfield format frame is shown in Figure 19-1. In HT-greenfield format frames, the HT-SIG is transmitted with the same cyclic shifts and the same spatial mapping as the preceding portions of the preamble. This use of the same cyclic shifts and spatial mapping is done to accommodate the estimation of channel parameters needed to robustly demodulate and decode the information contained in the HT-SIG.

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The time domain waveform for the HT-SIG on transmit chain i_{TX} with 20 MHz operation shall be as shown in Equation (19-29).

$$\begin{aligned} r_{HT-SIG}^{i_{TX}}(t) = & \frac{1}{\sqrt{N_{STS} \cdot N_{HT-SIG}^{Tone}}} \sum_{n=0}^{1} w_{T_{SYM}}(t - nT_{SYM}) \\ & \cdot \sum_{k=-26}^{26} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX}, i_{STS}} [P_{HT\text{-}LTF}]_{i_{STS}, 1} (jD_{k,n} + p_n P_k) \\ & \cdot \exp(j2\pi k \Delta_F (t - nT_{SYM} - T_{GI} - T_{CS}^{i_{STS}})) \end{aligned} \tag{19-29}$$

where

P_k and p_n are defined in 17.3.5.10
$D_{k,n}$ is defined in 19.3.9.4.3
$T_{CS}^{i_{STS}}$ represents the cyclic shift for space-time stream i_{STS} and takes values from Table 19-10
Q_k is defined in 19.3.11.11.2
$P_{HT\text{-}LTF}$ is defined in Equation (19-27)

The time domain waveform for the HT-SIG on transmit chain i_{TX} with 40 MHz operation shall be as shown in Equation (19-30).

$$\begin{aligned} r_{HT-SIG}^{i_{TX}}(t) = & \frac{1}{\sqrt{N_{STS} \cdot N_{HT-SIG}^{Tone}}} \sum_{n=0}^{1} w_{T_{SYM}}(t - nT_{SYM}) \\ & \cdot \sum_{k=-26}^{26} \sum_{i_{STS}=1}^{N_{STS}} [P_{HT\text{-}LTF}]_{i_{STS}, 1} (jD_{k,n} + p_n P_k) \\ & \cdot ([Q_{k-32}]_{i_{TX}, i_{STS}} \exp(j2\pi (k-32) \Delta_F (t - nT_{SYM} - T_{GI} - T_{CS}^{i_{STS}})) \\ & + j[Q_{k+32}]_{i_{TX}, i_{STS}} \exp(j2\pi (k+32) \Delta_F (t - nT_{SYM} - T_{GI} - T_{CS}^{i_{STS}}))) \end{aligned} \tag{19-30}$$

where

p_n and P_k are defined in 17.3.5.10
$D_{k,n}$ is defined in 19.3.9.4.3
$T_{CS}^{i_{STS}}$ represents the cyclic shift for space-time stream i_{STS} and takes values from Table 19-10
Q_k is defined in 19.3.11.11.2
$P_{HT\text{-}LTF}$ is defined in Equation (19-27)

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19.3.9.5.5 HT-greenfield format LTF

The format of the LTF portion of the preamble in an HT-greenfield format frame is similar to that of the HT-LTF in an HT-mixed format frame, as described in 19.3.9.4.6, with the difference that the first HT-LTF (HT-LTF1) is twice as long (8 μs) as the other HT-LTFs. The time domain waveform for the long training symbol on transmit chain i_{TX} for the first HT-LTF in an HT-greenfield format frame shall be as shown in Equation (19-31).

$$r_{HT-LTF}^{1,i_{TX}}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-LTF}^{Tone}}} w_{T_{HT-LTF1}}(t) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX},i_{STS}} [P_{HT\text{-}LTF}]_{i_{STS},1} \Upsilon_k HT\text{-}LTF(k) \exp(j2\pi k\Delta_F(t - T_{GI2} - T_{CS}^{i_{STS}})) \tag{19-31}$$

where

$T_{CS}^{i_{STS}}$ represents the cyclic shift for space-time stream i_{STS} and takes values from Table 19-10

Q_k is defined in 19.3.11.11.2

$P_{HT\text{-}LTF}$ is defined in Equation (19-27)

The first HT-LTF (HT-LTF1) consists of two periods of the long training symbol, preceded by a double-length (1.6 μs) cyclic prefix. The placement of the first and subsequent HT-LTFs in an HT-greenfield format frame is shown in Figure 19-1.

19.3.10 Transmission of NON_HT format PPDUs with more than one transmit chain

When an HT device transmits a NON_HT format PPDU with the MODULATION parameter equal to OFDM or ERP-OFDM using more than one transmit chain, it shall apply the cyclic shifts defined in Table 19-9 to the transmission in each chain.

19.3.11 Data field

19.3.11.1 General

When BCC encoding is used, the Data field consists of the 16-bit SERVICE field, the PSDU, either six or twelve tail bits, depending on whether one or two encoding streams are represented, and pad bits. When LDPC encoding is used, the Data field consists of the 16-bit SERVICE field and the PSDU, processed by the procedure in 19.3.11.7.5.

The number of OFDM symbols in the data field when BCC encoding is used is computed as shown in Equation (19-32).

$$N_{SYM} = m_{STBC} \left\lceil \frac{8 \cdot length + 16 + 6 \cdot N_{ES}}{m_{STBC} \cdot N_{DBPS}} \right\rceil \tag{19-32}$$

where

m_{STBC} is 2 if STBC is used and 1 otherwise (making sure that the number of symbols is even when STBC is used)

length is the value of the HT Length field in the HT-SIG field defined in Table 19-11

N_{DBPS} takes the values defined in Table 19-27 to Table 19-41

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The number of "zero" pad bits is thus $N_{SYM} \times N_{DBPS} - 8 \times length - 16 - 6 \times N_{ES}$. The number of symbols in the data field when LDPC encoding is used is described in 19.3.11.7.

For LDPC encoding, the number of encoded data bits, N_{avbits}, is given by Equation (19-39); the number of OFDM symbols, N_{SYM}, is given by Equation (19-41); and the number of repeated encoded bits for padding, N_{rep}, is given by Equation (19-42), in 19.3.11.7.5.

19.3.11.2 SERVICE field

The SERVICE field is used for scrambler initialization. The SERVICE field is composed of 16 bits, all set to 0 before scrambling. In non-HT PPDUs, the SERVICE field is the same as in 17.3.5.2. In HT PPDUs, the SERVICE field is composed of 16 zero bits, scrambled by the scrambler, as defined in 19.3.11.3.

19.3.11.3 Scrambler

The data field shall be scrambled by the scrambler defined in 17.3.5.5. The Clause 17 TXVECTOR parameters CH_BANDWIDTH_IN_NON_HT and DYN_BANDWIDTH_IN_NON_HT shall not be present; therefore, the initial state of the scrambler shall be set to a pseudorandom nonzero seed.

19.3.11.4 Coding

The Data field shall be encoded using either the BCC defined in 17.3.5.6 or the LDPC code defined in 19.3.11.7. The encoder is selected by the FEC coding field in the HT-SIG, as described in 19.3.9.4.3. A single FEC encoder is always used when LDPC coding is used. When the BCC FEC encoder is used, a single encoder is used, except that two encoders are used when the selected MCS has a PHY rate greater than 300 Mb/s (see 19.5). To determine whether to use one or two BCC FEC encoders, the rate is calculated based on the use of an 800 ns GI. The operation of the BCC FEC is described in 19.3.11.6. The operation of the LDPC coder is described in 19.3.11.7.

Support for the reception of BCC-encoded Data field frames is mandatory.

19.3.11.5 Encoder parsing operation for two BCC FEC encoders

If two BCC encoders are used, the scrambled data bits are divided between the encoders by sending alternating bits to different encoders. Bit with index i sent to the encoder j, denoted $x_i^{(j)}$, is shown in Equation (19-33).

$$x_i^{(j)} = b_{N_{ES} \cdot i + j} \qquad ; \qquad 0 \le j \le N_{ES} - 1 \tag{19-33}$$

Following the parsing operation, 6 scrambled "zero" bits following the end of the message bits in each BCC input sequence are replaced by unscrambled "zero" bits, as described in 17.3.5.3.

The replaced bits are shown in Equation (19-34).

$$x_i^{(j)} \quad : \quad 0 \le j \le N_{ES} - 1 \quad ; \quad \frac{length \cdot 8 + 16}{N_{ES}} \le i \le \frac{length \cdot 8 + 16}{N_{ES}} + 5 \tag{19-34}$$

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19.3.11.6 BCC coding and puncturing

When BCC encoding is used, the encoder parser output sequences $\{x_i^0\}$, and $\{x_i^1\}$ where applicable, are each encoded by the rate 1/2 convolutional encoder defined in 17.3.5.6. After encoding, the encoded data shall be punctured by the method defined in 17.3.5.7 to achieve the rate selected by the MCS.

If rate 5/6 coding is selected, the puncturing scheme is defined in Figure 19-11.

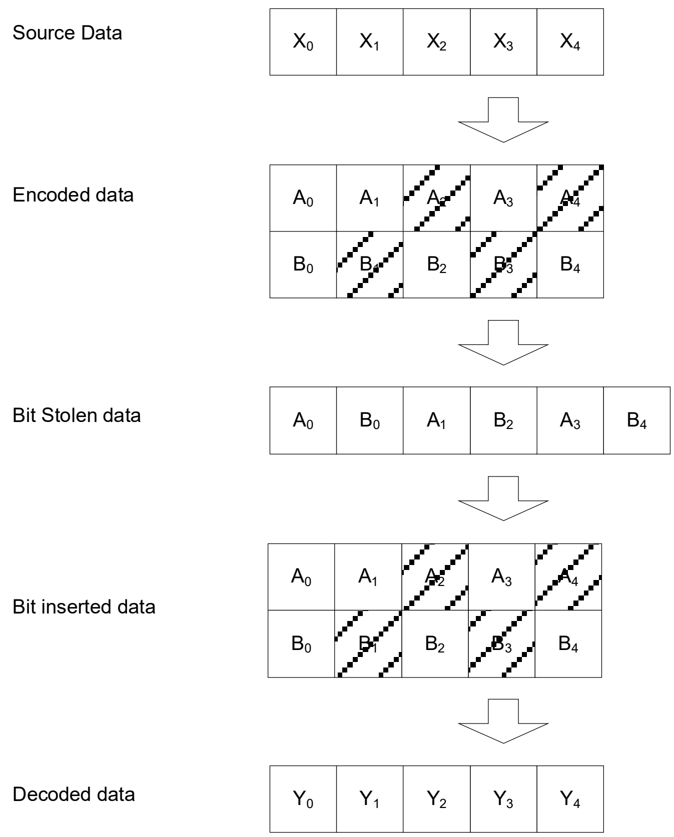

Figure 19-11—Puncturing at rate 5/6

19.3.11.7 LDPC codes

19.3.11.7.1 Introduction

HT LDPC codes are described in 19.3.11.7.2 to 19.3.11.7.6. These codes are optionally used in the HT system as a high-performance error correcting code instead of the convolutional code (19.3.11.6). The LDPC encoder shall use the rate-dependent parameters in Table 19-27 to Table 19-41, with the exception of the N_{ES} parameter.

Support for LDPC codes is optional.

19.3.11.7.2 LDPC coding rates and codeword block lengths

The supported coding rates, information block lengths, and codeword block lengths are described in Table 19-15.

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Table 19-15—LDPC parameters

Coding rate (R)	LDPC information block length (bits)	LDPC codeword block length (bits)
1/2	972	1944
1/2	648	1296
1/2	324	648
2/3	1296	1944
2/3	864	1296
2/3	432	648
3/4	1458	1944
3/4	972	1296
3/4	486	648
5/6	1620	1944
5/6	1080	1296
5/6	540	648

19.3.11.7.3 LDPC encoder

For each of the three available codeword block lengths, the LDPC encoder supports rate 1/2, rate 2/3, rate 3/4, and rate 5/6 encoding. The LDPC encoder is systematic, i.e., it encodes an information block, c=(i_0,i_1,..., $i_{(k–1)}$), of size k, into a codeword, **c,** of size n, **c**=(i_0,i_1,... $i_{(k–1)}$, p_0, p_1,..., $p_{(n–k–1)}$), by adding $n–k$ parity bits obtained so that $\mathbf{H}\times\mathbf{c}^T = \mathbf{0}$, where **H** is an $(n–k)\times n$ parity-check matrix. The selection of the codeword block length (n) is achieved via the LDPC PPDU encoding process described in 19.3.11.7.5.

19.3.11.7.4 Parity-check matrices

Each of the parity-check matrices is partitioned into square subblocks (submatrices) of size $Z \times Z$. These submatrices are either cyclic-permutations of the identity matrix or null submatrices.

The cyclic-permutation matrix P_i is obtained from the $Z \times Z$ identity matrix by cyclically shifting the columns to the right by i elements. The matrix P_0 is the $Z \times Z$ identity matrix. Figure 19-12 illustrates examples (for a subblock size of 8 × 8) of cyclic-permutation matrices P_i.

Table F-1 displays the “matrix prototypes” of parity-check matrices for all four coding rates at block length n=648 bits. The integer i denotes the cyclic-permutation matrix P_i, as illustrated in Figure 19-12. Vacant entries of the table denote null (zero) submatrices.

Table F-2 displays the matrix prototypes of parity-check matrices for block length n=1296 bits, in the same fashion.

Table F-3 displays the matrix prototypes of parity-check matrices for block length n=1944 bits, in the same fashion.

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$$P_0 = \begin{bmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \end{bmatrix}, P_1 = \begin{bmatrix} 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \\ 1&0&0&0&0&0&0&0 \end{bmatrix}, P_5 = \begin{bmatrix} 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \\ 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \end{bmatrix}$$

Figure 19-12—Examples of cyclic-permutation matrices with *Z*=8

19.3.11.7.5 LDPC PPDU encoding process

To encode an LDPC PPDU, step a) to step g) shall be performed in sequence:

a) Compute the number of available bits, N_{avbits}, in the minimum number of OFDM symbols in which the Data field of the packet may fit.

$$N_{pld} = length \times 8 + 16 \tag{19-35}$$

$$N_{avbits} = N_{CBPS} \times m_{STBC} \times \left\lceil \frac{N_{pld}}{N_{CBPS} \times R \times m_{STBC}} \right\rceil \tag{19-36}$$

where

m_{STBC}	is 2 if STBC is used and 1 otherwise
length	is the value of the HT Length field in the HT-SIG field defined in Table 19-11
N_{pld}	is the number of bits in the PSDU and SERVICE field

b) Compute the integer number of LDPC codewords to be transmitted, N_{CW}, and the length of the codewords to be used, L_{LDPC} from Table 19-16.

Table 19-16—PPDU encoding parameters

Range of N_{avbits} (bits)	Number of LDPC codewords (N_{CW})	LDPC codeword length L_{LDPC} (bits)
$N_{avbits} \le 648$	1	1296, if $N_{avbits} \ge N_{pld} + 912 \times (1-R)$ 648, otherwise
$648 < N_{avbits} \le 1296$	1	1944, if $N_{avbits} \ge N_{pld} + 1464 \times (1-R)$ 1296, otherwise
$1296 < N_{avbits} \le 1944$	1	1944
$1944 < N_{avbits} \le 2592$	2	1944, if $N_{avbits} \ge N_{pld} + 2916 \times (1-R)$ 1296, otherwise
$2592 < N_{avbits}$	$\left\lceil \frac{N_{pld}}{1944 \cdot R} \right\rceil$	1944

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c) Compute the number of shortening bits, N_{shrt}, to be padded to the N_{pld} data bits before encoding, as shown in Equation (19-37).

$$N_{shrt} = \max(0, (N_{CW} \times L_{LDPC} \times R) - N_{pld}) \tag{19-37}$$

When $N_{shrt} = 0$, shortening is not performed. (Note that N_{shrt} is inherently restricted to be non-negative due to the codeword length and count selection of Table 19-16). When $N_{shrt} > 0$, shortening bits shall be equally distributed over all N_{CW} codewords with the first N_{shrt} mod N_{CW} codewords shortened 1 bit more than the remaining codewords. Define $N_{spcw} = \lfloor N_{shrt}/N_{CW} \rfloor$. Then, when $N_{shrt} > 0$, the shortening is performed by setting information bits $i_{k - N_{spcw} - 1}, \ldots, i_{k-1}$ to 0 in the first N_{shrt} mod N_{CW} codewords and setting information bits $i_{k - N_{spcw}}, \ldots, i_{k-1}$ to 0 in the remaining codewords. For all values of N_{shrt}, encode each of the N_{CW} codewords using the LDPC encoding technique described in 19.3.11.7.2 to 19.3.11.7.4. When $N_{shrt} > 0$, the shortened bits shall be discarded after encoding.

d) Compute the number of bits to be punctured, N_{punc}, from the codewords after encoding, as shown in Equation (19-38).

$$N_{punc} = \max(0, (N_{CW} \times L_{LDPC}) - N_{avbits} - N_{shrt}) \tag{19-38}$$

If $\left((N_{punc} > 0.1 \times N_{CW} \times L_{LDPC} \times (1 - R)) \text{ AND} \left(N_{shrt} < 1.2 \times N_{punc} \times \frac{R}{1 - R}\right)\right)$ is true OR if $(N_{punc} > 0.3 \times N_{CW} \times L_{LDPC} \times (1 - R))$ is true, increment N_{avbits} and recompute N_{punc} by the following two equations once:

$$N_{avbits} = N_{avbits} + N_{CBPS} \times m_{STBC} \tag{19-39}$$

$$N_{punc} = \max(0, (N_{CW} \times L_{LDPC}) - N_{avbits} - N_{shrt}) \tag{19-40}$$

The punctured bits shall be equally distributed over all N_{CW} codewords with the first N_{punc} mod N_{CW} codewords punctured 1 bit more than the remaining codewords. Define $N_{\mathrm{ppcw}} = \lfloor N_{\mathrm{punc}}/N_{\mathrm{CW}} \rfloor$. When $N_{\mathrm{ppcw}} > 0$, the puncturing is performed by discarding parity bits $p_{n-k-N_{ppcw}-1}, \ldots, p_{n-k-1}$ of the first N_{punc} mod N_{CW} codewords and discarding parity bits $(p_{n-k-N_{ppcw}}, \ldots, p_{n-k-1})$ of the remaining codewords after encoding. The number of OFDM symbols to be transmitted in the PPDU is computed as shown in Equation (19-41).

$$N_{SYM} = N_{avbits} / N_{CBPS} \tag{19-41}$$

e) Compute the number of coded bits to be repeated, N_{rep}, as shown in Equation (19-42).

$$N_{rep} = \max(0, N_{avbits} - N_{CW} \times L_{LDPC} \times (1 - R) - N_{pld}) \tag{19-42}$$

The number of coded bits to be repeated shall be equally distributed over all N_{CW} codewords with one more bit repeated for the first N_{rep} mod N_{CW} codewords than for the remaining codewords.

NOTE—When puncturing occurs, the coded bits are not repeated, and vice versa.

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The coded bits to be repeated for any codeword shall be copied only from that codeword itself, starting from information bit i_0 and continuing sequentially through the information bits and, when necessary, into the parity bits, until the required number of repeated bits is obtained for that codeword. Note that these repeated bits are copied from the codeword after the shortening bits have been removed. If for a codeword the required number of repeated bits are not obtained in this manner (i.e., repeating the codeword once), the procedure is repeated until the required number is achieved. These repeated bits are then concatenated to the codeword after the parity bits in their same order. This process is illustrated in Figure 19-13. In this figure, the outlined arrows indicate the encoding procedure steps, while the solid arrows indicate the direction of puncturing and padding with repeated bits.

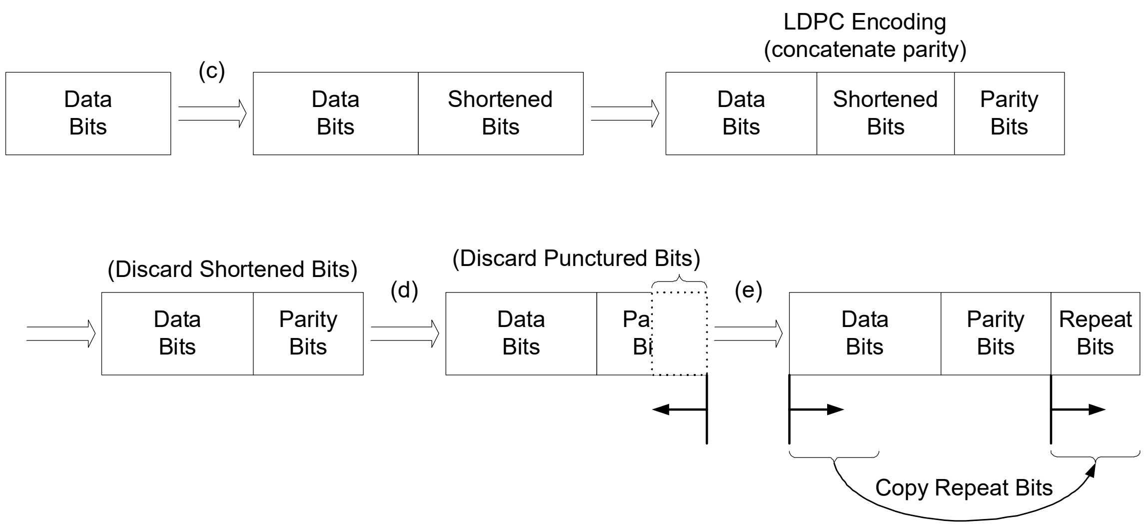

Figure 19-13—LDPC PPDU encoding padding and puncturing of a single codeword

f) For each of the N_{CW} codewords, process the data using the number of shortening bits per codeword as computed in step c) for encoding, and puncture or repeat bits per codeword as computed per step d) and step e), as illustrated in Figure 19-13.

g) Aggregate all codewords and parse as defined in 19.3.11.7.6.

19.3.11.7.6 LDPC parser

The succession of LDPC codewords that result from the encoding process of 19.3.11.7.5 shall be converted into a bitstream in sequential fashion. Within each codeword, bit i_0 is ordered first. The parsing of this encoded data stream into spatial streams shall follow exactly the parsing rules defined for the BCC encoder, as defined in 19.3.11.8.1. However, the frequency interleaver of 19.3.11.8.3 is bypassed.

19.3.11.8 Data interleaver

19.3.11.8.1 Overview

After coding and puncturing, the data bit streams at the output of the FEC encoders are rearranged into blocks of $N_{CBPSS}(i_{SS})$ bits, where $i_{SS} = 1, 2, \ldots N_{SS}$ is the spatial stream index. This operation is referred to as *stream parsing* and is described in 19.3.11.8.2. If BCC encoding was used, each of these blocks is then interleaved by an interleaver that is a modification of the Clause 17 interleaver.

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19.3.11.8.2 Stream parser

The number of bits assigned to a single axis (real or imaginary) in a constellation point in spatial stream i_{SS} is denoted by Equation (19-43).

$$s(i_{SS}) = \max\left\{1, \frac{N_{BPSCS}(i_{SS})}{2}\right\} \tag{19-43}$$

The sum of these over all streams is $S = \sum_{i_{SS}=1}^{N_{SS}} s(i_{SS})$.

NOTE—If equal MCS is used for all spatial streams, this sum becomes $N_{SS} \cdot s$, where s is the number of bits for an axis common to all streams.

Consecutive blocks of $s(i_{SS})$ bits are assigned to different spatial streams in a round robin fashion.

If two encoders are present, the output of each encoder is used alternately for each round robin cycle, i.e., at the beginning *S* bits from the output of first encoder are fed into all spatial streams, and then *S* bits from the output of second encoder are used, and so on.

Input *k* to spatial stream i_{SS} shall be $y_i^{(j)}$, which is output bit *i* of the encoder *j*,

where

$$j = \left\lfloor \frac{k}{s(i_{SS})} \right\rfloor \bmod N_{ES} \tag{19-44}$$

$$i = \sum_{i'=1}^{i_{SS}-1} s(i') + S \cdot \left\lfloor \frac{k}{N_{ES} \cdot s(i_{SS})} \right\rfloor + k \bmod s(i_{SS}) \tag{19-45}$$

$$1 \le i_{SS} \le N_{SS}$$

For $i_{SS} = 1$, the first term in Equation (19-45) has a value of 0.

19.3.11.8.3 Frequency interleaver

MCS 32 interleaving shall be as defined in 17.3.5.7. Interleaving for all other MCSs is defined in this subclause.

The bits at the output of the stream parser are divided into blocks of $N_{CBPSS}(i_{SS})$, $i_{SS} = 1, 2, \ldots N_{SS}$ bits; and if BCC encoding was used, each block shall be interleaved by an interleaver based on the Clause 17 interleaver. This interleaver, which is based on entering the data in rows and reading them out in columns, has a different number of columns and rows depending on whether a 20 MHz channel or a 40 MHz channel is used. Table 19-17 defines the interleaver parameters. If LDPC encoding was used, no frequency interleaving is performed; hence the parsed streams are immediately mapped to symbols as defined in 19.3.11.9.

If more than one spatial stream exists after the operations based on the Clause 17 interleaver have been applied, a third operation called *frequency rotation* shall be applied to the additional spatial streams. The parameter for the frequency rotation is N_{ROT}.

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Table 19-17—Number of rows and columns in the interleaver

Parameter	20 MHz	40 MHz
N_{COL}	13	18
N_{ROW}	$4 \times N_{BPSCS}(i_{SS})$	$6 \times N_{BPSCS}(i_{SS})$
N_{ROT}	11	29

The interleaving is defined using three permutations. The first permutation is defined by the rule shown in Equation (19-46).

$$i = N_{ROW} \times (k \bmod N_{COL}) + \lfloor k / N_{COL} \rfloor, \qquad k = 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \tag{19-46}$$

The second permutation is defined by the rule shown in Equation (19-47).

$$\begin{aligned} j &= s(i_{SS}) \times \lfloor i / s(i_{SS}) \rfloor + (i + N_{CBPSS}(i_{SS}) - \lfloor N_{COL} \times i / N_{CBPSS}(i_{SS}) \rfloor) \bmod s(i_{SS}); \\ i &= 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \end{aligned} \tag{19-47}$$

The value of $s(i_{SS})$ is determined by the number of coded bits per subcarrier as shown in Equation (19-48).

$$s(i_{SS}) = \max(N_{BPSCS}(i_{SS})/2, 1) \tag{19-48}$$

If more than one spatial stream exists, a frequency rotation is applied to the output of the second permutation as shown in Equation (19-49).

$$\begin{aligned} r &= \left(j - \left(((i_{SS} - 1) \times 2) \bmod 3 + 3 \times \left\lfloor \frac{i_{SS} - 1}{3} \right\rfloor\right) \times N_{ROT} \times N_{BPSCS}(i_{SS})\right) \bmod N_{CBPSS}(i_{SS}); \\ j &= 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \end{aligned} \tag{19-49}$$

where

$i_{SS} = 1, 2, \ldots, N_{SS}$ is the index of the spatial stream on which this interleaver is operating

The deinterleaver uses the following operations to perform the inverse rotation. The index of the bit in the received block (per spatial stream) is denoted by *r*. The first permutation reverses the third (frequency rotation) permutation of the interleaver as shown in Equation (19-50).

$$\begin{aligned} j &= \left(r + \left(((i_{SS} - 1) \times 2) \bmod 3 + 3 \times \left\lfloor \frac{i_{SS} - 1}{3} \right\rfloor\right) \times N_{ROT} \times N_{BPSCS}(i_{SS})\right) \bmod N_{CBPSS}(i_{SS}); \\ r &= 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \end{aligned} \tag{19-50}$$

The second permutation reverses the second permutation in the interleaver as shown in Equation (19-51).

$$\begin{aligned} i &= s(i_{SS}) \times \lfloor j / s(i_{SS}) \rfloor + (j + \lfloor N_{COL} \times j / N_{CBPSS}(i_{SS}) \rfloor) \bmod s(i_{SS}); \\ j &= 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \end{aligned} \tag{19-51}$$

where $s(i_{SS})$ is defined in Equation (19-48).

The third permutation reverses the first permutation of the interleaver as shown in Equation (19-52).

$$k = N_{COL} \times i - (N_{CBPSS}(i_{SS}) - 1) \times \lfloor i / N_{ROW} \rfloor \qquad i = 0, 1, \ldots, N_{CBPSS}(i_{SS}) - 1 \tag{19-52}$$

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19.3.11.9 Constellation mapping

19.3.11.9.1 General

The mapping between bits at the output of the interleaver and complex constellation points for BPSK, QPSK, 16-QAM, and 64-QAM follows the rules defined in 17.3.5.8.

The streams of complex numbers are denoted as shown in Equation (19-53).

$$d_{k,l,n},\ 0 \le k \le N_{SD} - 1; 1 \le l \le N_{SS}; 0 \le n \le N_{SYM} - 1 \tag{19-53}$$

19.3.11.9.2 Space-time block coding (STBC)

This subclause defines a set of optional robust transmission formats that are applicable only when N_{STS} is greater than N_{SS}. In this case, N_{SS} spatial streams are mapped to N_{STS} space-time streams, which are mapped to N_{TX} transmit chains. These formats are based on STBC. When the use of STBC is indicated in the STBC field of the HT-SIG, a symbol operation shall occur between the constellation mapper and the spatial mapper (see Figure 19-3) as defined in this subclause.

If STBC is applied, the stream of complex numbers, $d_{k,i,n}; k = 0 \ldots N_{SD} - 1; i = 1 \ldots N_{SS}; n = 0 \ldots N_{SYM} - 1$, generated by the constellation mapper, is the input of the STBC encoder, which produces as output the stream of complex numbers $\tilde{d}_{k,i,n}; k = 0 \ldots N_{SD} - 1; i = 1 \ldots N_{STS}; n = 0 \ldots N_{SYM} - 1$. For given values of k and i, STBC processing operates on the complex modulation symbols in sequential pairs of OFDM symbols so that the value of $\tilde{d}_{k,i,2m}$ depends on $d_{k,i,2m}$ and $d_{k,i,2m+1}$, and $\tilde{d}_{k,i,2m+1}$ also depends on $d_{k,i,2m}$ and $d_{k,i,2m+1}$, as defined in Table 19-18.

Table 19-18—Constellation mapper output to spatial mapper input for STBC

N_{STS}	HT-SIG MCS field (bits 0–6 in HT-SIG$_1$)	N_{SS}	HT-SIG STBC field (bits 4–5 in HT-SIG$_2$)	i_{STS}	$\tilde{d}_{k,i,2m}$	$\tilde{d}_{k,i,2m+1}$
2	0–7	1	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
3	8–15, 33–38	2	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$

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Table 19-18—Constellation mapper output to spatial mapper input for STBC *(continued)*

N_{STS}	HT-SIG MCS field (bits 0–6 in HT-SIG$_1$)	N_{SS}	HT-SIG STBC field (bits 4–5 in HT-SIG$_2$)	i_{STS}	$\tilde{d}_{k,i,2m}$	$\tilde{d}_{k,i,2m+1}$
4	8–15	2	2	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$
				4	$-d^*_{k,2,2m+1}$	$d^*_{k,2,2m}$
4	16–23, 39, 41, 43, 46, 48, 50	3	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$
				4	$d_{k,3,2m}$	$d_{k,3,2m+1}$
NOTE—The '*' operator represents the complex conjugate.						

If STBC is not applied, $\tilde{d}_{k,i,n} = d_{k,i,n}$ and $N_{SS} = N_{STS}$.

NOTE 1—The specific STBC schemes for single spatial streams ($N_{SS} = 1$) with $N_{TX} \geq 3$ are not detailed in this subclause since they are covered through the use of spatial expansion as detailed in 19.3.11.11.2.

NOTE 2—STBC is applied only for the HT-SIG MCS field values specified in Table 19-18 and is not used with MCS 32.

19.3.11.10 Pilot subcarriers

In a 20 MHz transmission four pilot tones shall be inserted in the same subcarriers used in Clause 17, i.e., in subcarriers –21, –7, 7, and 21. The pilot sequence for the n^{th} symbols and $i_{STS}{}^{th}$ space-time stream shall be as shown in Equation (19-54).

$$P^{-28,28}_{(i_{STS},n)} = \{0,0,0,0,0,0,0,\Psi^{(N_{STS})}_{i_{STS},n \bmod 4},0,0,0,0,0,0,0,0,0,0,0,0,0,\Psi^{(N_{STS})}_{i_{STS},(n+1) \bmod 4},0,0,0,0,0,0,0,\\ 0,0,0,0,0,0,\Psi^{(N_{STS})}_{i_{STS},(n+2) \bmod 4},0,0,0,0,0,0,0,0,0,0,0,0,0,\Psi^{(N_{STS})}_{i_{STS},(n+3) \bmod 4},0,0,0,0,0,0,0\} \quad (19\text{-}54)$$

In a 40 MHz transmission (excluding MCS 32; see 19.3.11.11.5), pilot signals shall be inserted in subcarriers –53, –25, –11, 11, 25, and 53. The pilot sequence for symbol n and space-time stream i_{STS} shall be as shown in Equation (19-55).

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$$P_{(i_{STS},\, n)}^{-58,58} = \left\{ 0, 0, 0, 0, 0, \Psi_{i_{STS},\, n \bmod 6}^{(N_{STS})}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \right.$$
$$0, 0, \Psi_{i_{STS},\, (n+1) \bmod 6}^{(N_{STS})}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \Psi_{i_{STS},\, (n+2) \bmod 6}^{(N_{STS})}, 0, 0, 0, 0, 0, 0, 0, 0, 0,$$
$$0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \Psi_{i_{STS},\, (n+3) \bmod 6}^{(N_{STS})}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \Psi_{i_{STS},\, (n+4) \bmod 6}^{(N_{STS})}, \tag{19-55}$$
$$\left. 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \Psi_{i_{STS},\, (n+5) \bmod 6}^{(N_{STS})}, 0, 0, 0, 0, 0 \right\}$$

where the patterns $\Psi_{i_{STS},\, n}^{(N_{STS})}$ are defined in Table 19-19 and Table 19-20.

NOTE—For each space-time stream, there is a different pilot pattern, and the pilot patterns are cyclically rotated over symbols.

The basic patterns are also different according to the total number of space-time streams for the packet.

Table 19-19—Pilot values for 20 MHz transmission

N_{STS}	i_{STS}	$\Psi_{i_{STS},0}^{(N_{STS})}$	$\Psi_{i_{STS},1}^{(N_{STS})}$	$\Psi_{i_{STS},2}^{(N_{STS})}$	$\Psi_{i_{STS},3}^{(N_{STS})}$
1	1	1	1	1	–1
2	1	1	1	–1	–1
2	2	1	–1	–1	1
3	1	1	1	–1	–1
3	2	1	–1	1	–1
3	3	–1	1	1	–1
4	1	1	1	1	–1
4	2	1	1	–1	1
4	3	1	–1	1	1
4	4	–1	1	1	1

Table 19-20—Pilots values for 40 MHz transmission (excluding MCS 32)

N_{STS}	i_{STS}	$\Psi_{i_{STS},0}^{(N_{STS})}$	$\Psi_{i_{STS},1}^{(N_{STS})}$	$\Psi_{i_{STS},2}^{(N_{STS})}$	$\Psi_{i_{STS},3}^{(N_{STS})}$	$\Psi_{i_{STS},4}^{(N_{STS})}$	$\Psi_{i_{STS},5}^{(N_{STS})}$
1	1	1	1	1	–1	–1	1
2	1	1	1	–1	–1	–1	–1
2	2	1	1	1	–1	1	1
3	1	1	1	–1	–1	–1	–1
3	2	1	1	1	–1	1	1
3	3	1	–1	1	–1	–1	1

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Table 19-20—Pilots values for 40 MHz transmission (excluding MCS 32) *(continued)*

N_{STS}	i_{STS}	$\Psi^{(N_{STS})}_{i_{STS},0}$	$\Psi^{(N_{STS})}_{i_{STS},1}$	$\Psi^{(N_{STS})}_{i_{STS},2}$	$\Psi^{(N_{STS})}_{i_{STS},3}$	$\Psi^{(N_{STS})}_{i_{STS},4}$	$\Psi^{(N_{STS})}_{i_{STS},5}$
4	1	1	1	–1	–1	–1	–1
4	2	1	1	1	–1	1	1
4	3	1	–1	1	–1	–1	1
4	4	–1	1	1	1	–1	1

19.3.11.11 OFDM modulation

19.3.11.11.1 General

The time domain signal is composed from the stream of complex numbers as shown in Equation (19-56).

$$\tilde{d}_{k,l,n},\ 0 \le k \le N_{SD} - 1; 1 \le l \le N_{STS}; 0 \le n \le N_{SYM} - 1 \qquad (19\text{-}56)$$

and from the pilot signals. In a 40 MHz transmission, the upper subcarriers are rotated 90° relative to the lower subcarriers.

19.3.11.11.2 Spatial mapping

The transmitter may choose to rotate and/or scale the constellation mapper output vector (or the space-time block coder output, if applicable). This rotation and/or scaling is useful in the following cases:

— When there are more transmit chains than space-time streams, $N_{STS} < N_{TX}$

— As part of (an optional) sounding PPDU

— As part of (an optional) calibration procedure

— When the packet is transmitted using one of the (optional) beamforming techniques

If the data to be transmitted on subcarrier k on space-time stream i_{STS} are $X_k^{(i_{STS})}$, the transmitted data on the transmit chain i_{TX} shall be as shown in Equation (19-57).

$$r_{Field}^{(i_{TX})} = \frac{1}{\sqrt{N_{STS} \cdot N_{Field}^{Tone}}} w_{T_{Field}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX}, i_{STS}} X_k^{(i_{STS})} \exp(j2\pi k \Delta_F (t - T_{CS}^{i_{STS}})) \qquad (19\text{-}57)$$

where

$[Q_k]_{i_{TX}, i_{STS}}$ is the element in row i_{TX} and column i_{STS} in a matrix Q_k with N_{TX} rows and N_{STS} columns; Q_k may be frequency dependent

Field is any field, as defined in 19.3.7, excluding L-STF, L-LTF, L-SIG, and HT-SIG in HT_MF PPDU

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Below are examples of spatial mapping matrices that might be used. There exist many other alternatives; implementation is not restricted to the spatial mapping matrices shown. The examples are as follows:

a) *Direct mapping*: Q_k is a diagonal matrix of unit magnitude complex values that takes one of two forms:

   1) $Q_k = \mathbf{I}$, the identity matrix

   2) A CSD matrix in which the diagonal elements represent cyclic shifts in the time domain: $[Q_k]_{i,i} = \exp(-j2\pi k\Delta_F \tau_{CS}^i)$, where τ_{CS}^i, $i = 1, \ldots, N_{TX}$ represents the CSD applied.

b) *Indirect mapping:* Q_k may be the product of a CSD matrix and a unitary matrix such as the Hadamard matrix or the Fourier matrix.

c) *Spatial expansion:* Q_k is the product of a CSD matrix and a square matrix formed of orthogonal columns. As an illustration:

   1) The spatial expansion may be performed by duplicating some of the N_{STS} streams to form the N_{TX} streams, with each stream being scaled by the normalization factor $\sqrt{N_{STS}/N_{TX}}$. The spatial expansion may be performed by using, for instance, one of the following matrices, denoted D, left-multiplied by a CSD matrix, denoted $M_{CSD}(k)$, and/or possibly multiplied by any unitary matrix. The resulting spatial mapping matrix is then $Q_k = M_{CSD}(k) \cdot D$, where D may take on one of the following values:

      i) N_{TX}=2, N_{STS}=1, $D = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \end{bmatrix}^T$

      ii) N_{TX}=3, N_{STS}=1, $D = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}^T$

      iii) N_{TX}=4, N_{STS}=1, $D = \frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}^T$

      iv) N_{TX}=3, N_{STS}=2, $D = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$

      v) N_{TX}=4, N_{STS}=2, $D = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$

      vi) N_{TX}=4, N_{STS}=3, $D = \frac{\sqrt{3}}{2}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$

   2) Different spatial expansion over subcarriers should be used in HT-mixed format only and with the Smoothing bit equal to 0:

      i) N_{TX}=2, N_{STS}=1, $[Q_k]_{N_{STS}} = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$ or $[Q_k]_{N_{STS}} = \begin{bmatrix} 0 & 1 \end{bmatrix}^T$

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ii) N_{TX}=3, N_{STS}=2, $[Q_k]_{N_{STS}} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$ or $\begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$

iii) N_{TX}=4, N_{STS}=2, $[Q_k]_{N_{STS}} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$ or $\begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$

iv) N_{TX}=4, N_{STS}=3, $[Q_k]_{N_{STS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ or $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

d) *Beamforming steering matrix:* Q_k is any matrix that improves the reception in the receiver based on some knowledge of the channel between the transmitter and the receiver. With transmit beamforming with explicit feedback, the steering matrix Q_k is determined using either H_{eff} for CSI feedback or V_k for noncompressed and compressed matrices feedback from the STA to which the beamformed packet is addressed.

When there are fewer space-time streams than transmit chains, the first N_{STS} columns of the matrices above that are square might be used.

The same matrix Q_k shall be applied to subcarrier *k* during all parts of the packet in HT-greenfield format and all parts of the packet following and including the HT-STF field in an HT-mixed format packet. This operation is transparent to the receiver.

When a beamforming steering matrix is applied, the Smoothing bit should be set to 0.

The CSD of Table 19-10 shall be applied at the input of the spatial mapper.

For the identity matrix direct mapping, the Smoothing bit should be set to 1.

If no spatial mapping is applied, the matrix Q_k is equal to the identity matrix and $N_{STS} = N_{TX}$.

Sounding PPDUs using spatial expansion shall use an orthonormal column matrix Q_k. When the number of rows and columns is equal, the orthonormal column matrix becomes a unitary matrix.

19.3.11.11.3 Transmission in 20 MHz HT format

For 20 MHz HT transmissions, the signal from transmit chain i_{TX}, $1 \le i_{TX} \le N_{TX}$ shall be as shown in Equation (19-58).

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$$r_{HT-DATA}^{i_{TX}}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-DATA}^{Tone}}} \sum_{n=0}^{N_{SYM}-1} w_{\mathrm{T}_{SYM}}(t - nT_{SYM}) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} \left([Q_k]_{i_{TX}, i_{STS}} \left(\tilde{D}_{k, i_{STS}, n} + p_{n+z} P_{(i_{STS}, n)}^{k}\right)\right) \cdot \exp\left(j2\pi k\Delta_F\left(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{STS}}\right)\right) \tag{19-58}$$

where

z is 3 in an HT-mixed format packet and 2 in an HT-greenfield format packet

p_n is defined in 17.3.5.10

$$\tilde{D}_{k, i_{STS}, n} = \begin{cases} 0, k = 0, \pm 7, \pm 21 \\ \tilde{d}_{M^r(k), i_{STS}, n}, \text{otherwise} \end{cases}$$

$$M^r(k) = \begin{cases} k + 28, -28 \le k \le -22 \\ k + 27, -20 \le k \le -8 \\ k + 26, -6 \le k \le -1 \\ k + 25, 1 \le k \le 6 \\ k + 24, 8 \le k \le 20 \\ k + 23, 22 \le k \le 28 \end{cases}$$

$P_{(i_{STS}, n)}^{k}$ is defined in Equation (19-54)

19.3.11.11.4 Transmission in 40 MHz HT format

For 40 MHz HT transmissions, the signal from transmit chain i_{TX} shall be as shown in Equation (19-59).

$$r_{HT-DATA}^{i_{TX}}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-DATA}^{Tone}}} \sum_{n=0}^{N_{SYM}-1} w_{\mathrm{T}_{SYM}}(t - nT_{SYM}) \cdot \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} \left([Q_k]_{i_{TX}, i_{STS}} \left(\tilde{D}_{k, i_{STS}, n} + p_{n+z} P_{(i_{STS}, n)}^{k}\right)\right) \Upsilon_k \cdot \exp\left(j2\pi k\Delta_F\left(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{STS}}\right)\right) \tag{19-59}$$

where

z is 3 in an HT-mixed format packet and 2 in an HT-greenfield format packet

p_n is defined in 17.3.5.10

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$$\tilde{D}_{k, i_{STS}, n} = \begin{cases} 0, k = 0, \pm 1, \pm 11, \pm 25, \pm 53 \\ \tilde{d}_{M^r(k), i_{STS}, n}, \text{ otherwise} \end{cases}$$

$$M^r(k) = \begin{cases} k+58, -58 \le k \le -54 \\ k+57, -52 \le k \le -26 \\ k+56, -24 \le k \le -12 \\ k+55, -10 \le k \le -2 \\ k+52, 2 \le k \le 10 \\ k+51, 12 \le k \le 24 \\ k+50, 26 \le k \le 52 \\ k+49, 54 \le k \le 58 \end{cases}$$

$P^k_{(i_{STS}, n)}$ is defined in Equation (19-55)

NOTE—The 90° rotation that is applied to the upper part of the 40 MHz channel is applied in the same way to the HT-STF, HT-LTF, and HT-SIG. The rotation applies to both pilots and the data in the upper part of the 40 MHz channel.

19.3.11.11.5 Transmission in MCS 32 format

The use of MCS 32 format is deprecated.

MCS 32 format provides the lowest transmission rate in 40 MHz. It is used only for one spatial stream and only with BPSK modulation and rate 1/2 coding.

In the MCS 32 format, the signal shall be as shown in Equation (19-60).

$$\begin{aligned} r^{i_{TX}}_{HT-DATA}(t) = {} & \frac{1}{\sqrt{N^{Tone}_{HT-Duplicate}}} \sum_{n=0}^{N_{SYM}-1} w_{T_{SYM}}(t - nT_{SYM}) \\ & \cdot \sum_{k=-N_{SR}}^{N_{SR}} (D_{k,n} + p_{n+z} P_k)([Q_{k-32}]_{i_{TX},1} \exp(j2\pi(k-32)\Delta_F(t - nT_{SYM} - T_{GI})) \\ & + j[Q_{k+32}]_{i_{TX},1} \exp(j2\pi(k+32)\Delta_F(t - nT_{SYM} - T_{GI}))) \end{aligned} \tag{19-60}$$

where

z is defined in 19.3.11.11.3
P_k and p_n are defined in 17.3.5.10
$D_{k,n}$ is defined in 19.3.9.4.3
N_{SR} has the value defined for non-HT 20 MHz transmission
$[Q_k]_{i_{TX},1}$ is an element from a vector of length N_{TX}, which may be frequency dependent
$N^{Tone}_{HT-Duplicate}$ is defined in Table 19-8

The rules of spatial expansion CSD limitation, as specified in 19.3.11.11.2, shall apply to $[Q_k]_{i_{TX},1}$.

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19.3.11.11.6 Transmission with a short GI

Short GI is used in the data field of the packet when the Short GI field in the HT-SIG is equal to 1. When it is used, the same formula for the formation of the signal shall be used as in 19.3.11.11.3, 19.3.11.11.4, and 19.3.11.11.5, with T_{GI} replaced by T_{GIS} and T_{SYM} replaced by T_{SYMS}.

NOTE—Short GI is not used in HT-greenfield format with one spatial stream, in which case the HT-SIG is immediately followed by data. It is very difficult to parse the HT-SIG in time to demodulate these data with the correct GI length if the GI length is not known in advance.

19.3.11.12 Non-HT duplicate transmission

Non-HT duplicate transmission is used to transmit to Clause 17 STAs, Clause 18 STAs, and Clause 19 STAs that may be present in either the upper or lower halves of the 40 MHz channel. The L-STF, L-LTF, and L-SIG shall be transmitted in the same way as in the HT 40 MHz transmission. The HT-SIG, HT-STF, and HT-LTF are not transmitted. Data transmission shall be as defined in Equation (19-61).

$$
\begin{aligned}
r_{LEG-DUP}^{i_{TX}}(t) = {} & \frac{1}{\sqrt{N_{Non\text{-}HT\ Duplicate}^{Tone}}} \sum_{n=0}^{N_{SYM}-1} w_{\mathrm{T}_{SYM}}(t - nT_{SYM}) \\
& \cdot \sum_{k=-26}^{26} (D_{k,n} + p_{n+1}P_k)(\exp(j2\pi(k-32)\Delta_F(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{TX}})) \\
& + j\exp(j2\pi(k+32)\Delta_F(t - nT_{SYM} - T_{GI} - T_{CS}^{i_{TX}})))
\end{aligned}
\tag{19-61}
$$

where

P_k and p_n	are defined in 17.3.5.10
$D_{k,n}$	is defined in 19.3.9.4.3
$T_{CS}^{i_{TX}}$	represents the cyclic shift of the transmit chain i_{TX} and is defined in Table 19-9
$N_{Non\text{-}HT\ Duplicate}^{Tone}$	is defined in Table 19-8

19.3.12 Beamforming

19.3.12.1 General

Beamforming is a technique in which the beamformer utilizes the knowledge of the MIMO channel to generate a steering matrix Q_k that improves reception in the beamformee.

The equivalent complex baseband MIMO channel model (3×2 example) is one in which, when a vector $\mathbf{x}_k = [x_1, x_2, \ldots x_{N_{TX}}]^T$ is transmitted in subcarrier *k*, the received vector $\mathbf{y}_k = [y_1, y_2, \ldots y_{N_{RX}}]^T$ is modeled as shown in Equation (19-62).

$$
\mathbf{y}_k = H_k \mathbf{x}_k + \mathbf{n} \tag{19-62}
$$

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where

H_k is channel matrix of dimensions $N_{RX} \times N_{TX}$

$\mathbf{n}$ is white (spatially and temporally) Gaussian noise as illustrated in Figure 19-14

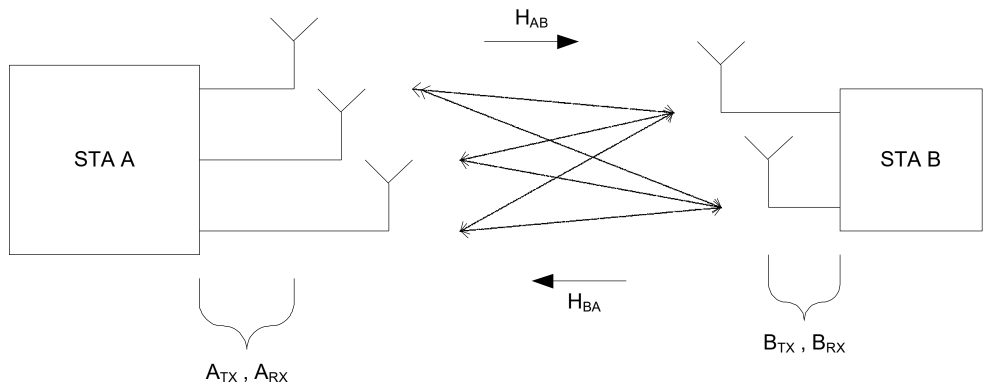

Figure 19-14—Beamforming MIMO channel model (3×2 example)

When beamforming is used, the beamformer replaces $\mathbf{x}_k$, which in this case has $N_{STS} \le N_{TX}$ elements, with $Q_k\mathbf{x}_k$, where Q_k has N_{TX} rows and N_{STS} columns, so that the received vector is as shown in Equation (19-63).

$$\mathbf{y}_k = H_k Q_k \mathbf{x}_k + \mathbf{n} \tag{19-63}$$

The beamforming steering matrix that is computed (or updated) from a new channel measurement replaces the existing Q_k for the next beamformed data transmission. There are several methods of beamforming, differing in the way the beamformer acquires the knowledge of the channel matrices H_k and on whether the beamformer generates Q_k or the beamformee provides feedback information for the beamformer to generate Q_k.

19.3.12.2 Implicit feedback beamforming

Implicit feedback beamforming is a technique that relies on reciprocity in the time division duplex channel to estimate the channel over which a device is transmitting based on the MIMO reference that is received from the device to which it plans to transmit. This technique allows the transmitting device to calculate a set of transmit steering matrices, Q_k, one for each subcarrier, which are intended to optimize the performance of the link.

Referring to Figure 19-14, beamforming transmissions from STA A to STA B using implicit techniques are enabled when STA B sends STA A a sounding PPDU, the reception of which allows STA A to form an estimate of the MIMO channel from STA B to STA A, for all subcarriers. In a TDD channel in which the forward and reverse channels are reciprocal, the channel from STA A to STA B in subcarrier k is the matrix transpose of the channel from STA B to STA A in subcarrier k to within a complex scaling factor, i.e., $H_{\mathrm{AB},k} = \rho[H_{\mathrm{BA},k}]^T$. Here $H_{\mathrm{AB},k}$ is the MIMO channel matrix from STA A to STA B at subcarrier k, and $H_{\mathrm{BA},k}$ is the channel matrix from STA B to STA A at subcarrier k. STA A uses this relationship to compute transmit steering matrices that are suitable for transmitting to STA B over $H_{\mathrm{AB},k}$.

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NOTE 1—In order for the recipient of the sounding to compute steering matrices when steered or unsteered sounding is used, the steering matrices need to have the property $(H_k Q_k)(H_k Q_k)^H = H_k H_k^H$, where X^H indicates the conjugate transpose of the matrix X.

While the over-the-air channel between the antenna(s) at one STA and the antenna(s) at a second STA is reciprocal, the observed baseband-to-baseband channel used for communication might not be, as it includes the transmit and receive chains of the STAs. Differences in the amplitude and phase characteristics of the transmit and receive chains associated with individual antennas degrade the reciprocity of the over-the-air channel and cause degradation of performance of implicit beamforming techniques. The over-the-air calibration procedure described in 10.34.2.4 may be used to restore reciprocity. The procedure provides the means for calculating a set of correction matrices that can be applied at the transmit side of a STA to correct the amplitude and phase differences between the transmit and receive chains in the STA. If this correction is done at least at the STA that serves as the beamformer, there is sufficient reciprocity for implicit feedback in the baseband-to-baseband response of the forward link and reverse channel.

Figure 19-15 illustrates the observed baseband-to-baseband channel, including reciprocity correction. Spatial mapping matrices $Q_{\mathrm{A},k}$ and $Q_{\mathrm{B},k}$ are assumed to be identity matrices here for simplicity of illustration.

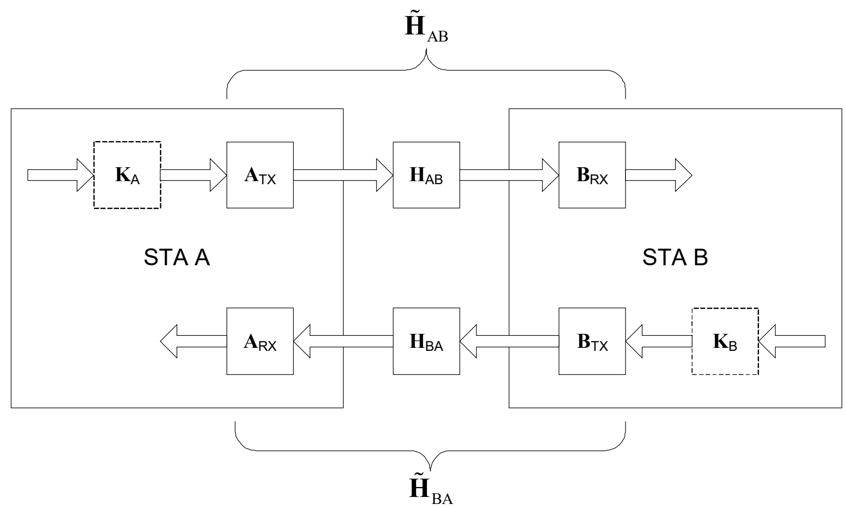

Figure 19-15—Baseband-to-baseband channel

NOTE 2—Spatial mapping matrix for sounding PPDUs are specified in 19.3.13.3.

The amplitude and phase responses of the transmit and receive chains can be expressed as diagonal matrices with complex valued diagonal entries, of the form $A_{TX,k}$ and $A_{RX,k}$ at STA A. The relationship between the baseband-to-baseband channel, $\tilde{H}_{\mathrm{AB},k}$, and the over-the-air channel, $H_{\mathrm{AB},k}$, is shown in Equation (19-64).

$$\tilde{H}_{\mathrm{AB},k} = B_{\mathrm{RX},k} H_{\mathrm{AB},k} A_{\mathrm{TX},k} \tag{19-64}$$

Similarly, the relationship between $\tilde{H}_{\mathrm{BA},k}$ and $H_{\mathrm{BA},k}$ is shown in Equation (19-65).

$$\tilde{H}_{\mathrm{BA},k} = A_{\mathrm{RX},k} H_{\mathrm{BA},k} B_{\mathrm{TX},k} \tag{19-65}$$

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As an example, consider the case where calibration is performed at both STA A and STA B. The objective is to compute correction matrices, $K_{A,k}$ and $K_{B,k}$, that restore reciprocity so that Equation (19-66) is true.

$$\tilde{H}_{AB,k}K_{A,k} = \rho[\tilde{H}_{BA,k}K_{B,k}]^T \tag{19-66}$$

The correction matrices are diagonal matrices with complex valued diagonal entries. The reciprocity condition in Equation (19-66) is enforced when Equation (19-67) and Equation (19-68) are true.

$$K_{A,k} = \alpha_{A,k}[A_{TX,k}]^{-1}A_{RX,k} \tag{19-67}$$

and

$$K_{B,k} = \alpha_{B,k}[B_{TX,k}]^{-1}B_{RX,k} \tag{19-68}$$

where $\alpha_{A,k}$ and $\alpha_{B,k}$ are complex valued scaling factors.

Using these expressions for the correction matrices, the calibrated baseband-to-baseband channel between STA A and STA B is expressed as shown in Equation (19-69).

$$\hat{H}_{AB,k} = \tilde{H}_{AB,k}K_{A,k} = \alpha_{A,k}B_{RX,k}H_{AB,k}A_{RX,k} \tag{19-69}$$

If both sides apply the correction matrices, the calibrated baseband-to-baseband channel between STA A and STA B is expressed as shown in Equation (19-70).

$$\hat{H}_{BA,k} = \alpha_{B,k}A_{RX,k}H_{BA,k}B_{RX,k} = \frac{\alpha_{B,k}}{\alpha_{A,k}}[\hat{H}_{AB,k}]^T \tag{19-70}$$

Focusing on STA A, the procedure for estimating $K_{A,k}$ is as follows:

a) STA A sends STA B a sounding PPDU, the reception of which allows STA B to estimate the channel matrices $\tilde{H}_{AB,k}$.
b) STA B sends STA A a sounding PPDU, the reception of which allows STA A to estimate the channel matrices $\tilde{H}_{BA,k}$.
c) STA B sends the quantized estimates of $\tilde{H}_{AB,k}$ to STA A.
d) STA A uses its local estimates of $\tilde{H}_{BA,k}$ and the quantized estimates of $\tilde{H}_{AB,k}$ received from STA B to compute the correction matrices $K_{A,k}$.

NOTE 3—When a nonidentity matrix is used for $Q_{A,k}$, STA A is responsible for accounting for the spatial mapping in its local channel estimate as well as in the quantized CSI fed back since the channel feedback received in step c) is actually $\tilde{H}_{AB,k}Q_{A,k}$ and not $\tilde{H}_{AB,k}$. Furthermore, since $Q_{B,k}$ is defined in 19.3.13.3, additional steps might be taken in STA A to remove the effect of $Q_{B,k}$ when computing the correction matrix $K_{A,k}$.

Steps a) and b) occur over a short time interval to so the channel changes as little as possible between measurements. A similar procedure is used to estimate $K_{B,k}$ at STA B. The details of the computation of the correction matrices is implementation specific and beyond the scope of this standard.

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19.3.12.3 Explicit feedback beamforming

19.3.12.3.1 General

In explicit beamforming, in order for STA A to transmit a beamformed packet to STA B, STA B measures the channel matrices and sends STA A either the effective channel, $H_{eff,k}$, or the beamforming feedback matrix, V_k, for STA A to determine a steering matrix, $Q_{\mathrm{steer},k} = Q_k V_k$, with V_k found from $H_k Q_k$, where Q_k is the orthonormal spatial mapping matrix that was used to transmit the sounding PPDU that elicited the V_k feedback. The effective channel, $H_{eff,k} = H_k Q_k$, is the product of the spatial mapping matrix used on transmit with the channel matrix. When new steering matrix $Q_{\mathrm{steer},k}$ is found, $Q_{\mathrm{steer},k}$ may replace Q_k for the next beamformed data transmission.

NOTE—$Q_{\mathrm{steer},k}$ is a mathematical term to update a new steering matrix for Q_k in the next beamformed data transmission.

19.3.12.3.2 CSI matrices feedback

In CSI matrices feedback, the beamformer receives the quantized MIMO channel matrix, H_{eff}, from the beamformee. The beamformer then may use this matrix to compute a set of transmit steering matrices, Q_k. The CSI matrix, H_{eff}, shall be determined from the transmitter spatial mapper input to the receiver FFT outputs. The beamformee shall remove the CSD in Table 19-10 from the measured channel matrix.

The matrices $H_{eff}(k)$, where k is the subcarrier index, are encoded so that applying the procedure in 19.3.12.3.3 optimally reconstructs the matrix.

19.3.12.3.3 CSI matrices feedback decoding procedure

The received, quantized matrix $H^q_{eff}(k)$ (of a specific subcarrier, k) shall be decoded as follows:

a) The real and imaginary parts of each element of the matrix, $H^{q(R)}_{eff(m,l)}(k)$ and $H^{q(I)}_{eff(m,l)}(k)$, are decoded as a pair of 2s complement numbers to create the complex element, where $1 \le m \le N_r$ and $1 \le l \le N_c$.

b) Each element in the matrix of subcarrier k is then scaled using the value in the carrier matrix amplitude field (3 bits), $M_H(k)$, interpreted as a positive integer, in decibels, as follows:
   1) Calculate the linear value as defined in Equation (19-71).
   2) Calculate decoded values of the real and imaginary parts of the matrix element as defined in Equation (19-72) and Equation (19-73).

$$r(k) = 10^{M_H(k)/20} \tag{19-71}$$

$$\mathrm{Re}\{\tilde{H}_{eff(m,l)}(k)\} = \frac{H^{q(R)}_{eff(m,l)}(k)}{r(k)} \tag{19-72}$$

$$\mathrm{Im}\{\tilde{H}_{eff(m,l)}(k)\} = \frac{H^{q(I)}_{eff(m,l)}(k)}{r(k)} \tag{19-73}$$

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19.3.12.3.4 Example of CSI matrices feedback encoding

The following is an example of an encoding process:

a) The maximums of the real and imaginary parts of each element of the matrix in each subcarrier are found, as defined by Equation (19-74).

$$m_H(k) = \max\left\{\max\left\{\left|\mathrm{Re}(H_{eff(m,l)}(k))\right|_{m=1,l=1}^{m=N_r,l=N_c}\right\}, \max\left\{\left|\mathrm{Im}(H_{eff(m,l)}(k))\right|_{m=1,l=1}^{m=N_r,l=N_c}\right\}\right\} \tag{19-74}$$

b) The scaling ratio is calculated and quantized to 3 bits as defined by Equation (19-75). A linear scaler is given by Equation (19-76).

$$M_H(k) = \min\left\{7, \left\lfloor 20\log_{10}\left(\frac{\max\{m_H(z)\}_{z=-N_{SR}}^{z=N_{SR}}}{m_H(k)}\right)\right\rfloor\right\} \tag{19-75}$$

where

$$M_H^{\mathrm{lin}}(k) = \frac{\max\{m_H(z)\}_{z=-N_{SR}}^{z=N_{SR}}}{10^{M_H(k)/20}} \tag{19-76}$$

c) The real and imaginary parts of each element in the matrix $H_{eff(m,l)}(k)$ are quantized to N_b bits in 2s complement encoding as defined by Equation (19-77) and Equation (19-78).

$$H_{eff(m,l)}^{q(R)}(k) = \left\lfloor \frac{\mathrm{Re}\{H_{eff(m,l)}(k)\}}{M_H^{\mathrm{lin}}(k)}(2^{N_b-1}-1)+0.5 \right\rfloor \tag{19-77}$$

$$H_{eff(m,l)}^{q(I)}(k) = \left\lfloor \frac{\mathrm{Im}\{H_{eff(m,l)}(k)\}}{M_H^{\mathrm{lin}}(k)}(2^{N_b-1}-1)+0.5 \right\rfloor \tag{19-78}$$

Each matrix is encoded using $3 + 2 \times N_b \times N_r \times N_c$ bits, where N_r and N_c are the number of rows and columns, respectively, in the channel matrix estimate computed by the receiving station and where N_b may have the value of 4, 5, 6, or 8 bits.

19.3.12.3.5 Noncompressed beamforming feedback matrix

In noncompressed beamforming feedback matrix, the beamformee shall remove the space-time stream CSD in Table 19-10 from the measured channel before computing a set of matrices for feedback to the beamformer. The beamforming feedback matrices, $V(k)$, found by the beamformee are sent to the beamformer in the order of real and imaginary components per tone as specified in 9.4.1.28. The beamformer might use these matrices to determine the steering matrices, Q_k.

The beamformee shall encode the matrices $V(k)$ so a beamformer applying the procedure below optimally reconstructs the matrix.

The received matrix $V^q(k)$ (of a specific subcarrier k) shall be decoded as follows:

a) The real and imaginary parts of each element of the matrix, $V_{m,l}^{q,R}$ and $V_{m,l}^{q,I}$, shall be decoded as a pair of 2s complement numbers to create the complex element, where $1 \le m \le N_r$ and $1 \le l \le N_c$.

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b) The dimensions of the beamforming feedback matrices are $N_r \times N_c$, where N_r and N_c are the number of rows and columns, respectively, in the beamforming feedback matrix computed by the receiving station. Each matrix is encoded using $2 \times N_b \times N_r \times N_c$ bits. N_b may have the value of 2, 4, 6, or 8 bits.

c) Columns $1 \ldots N_c$ of the beamforming feedback matrix correspond to spatial streams $1 \ldots N_c$, respectively. The mapping of spatial stream to modulation is defined in the MCS tables in 19.5. A transmitter shall not reorder the columns of the beamforming feedback matrices.

19.3.12.3.6 Compressed beamforming feedback matrix

In compressed beamforming feedback matrix, the beamformee shall remove the space-time stream CSD in Table 19-10 from the measured channel before computing a set of matrices for feedback to the beamformer. The beamforming feedback matrices, $V(k)$, found by the beamformee are compressed in the form of angles, which are sent to the beamformer. The beamformer might use these angles to decompress the matrices and determine the steering matrices Q_k.

The matrix V per tone shall be compressed as follows: The $N_r \times N_c$ beamforming feedback orthonormal column matrix V found by the beamformee shall be represented as shown in Equation (19-79). When the number of rows and columns is equal, the orthonormal column matrix becomes a unitary matrix.

$$V = \left[\prod_{i=1}^{\min(N_c, N_r - 1)} \left[D_i\left(1_{i-1} \; e^{j\phi_{i,i}} \; \ldots \; e^{j\phi_{N_r-1,i}} \; 1 \right) \prod_{l=i+1}^{N_r} G_{li}^T(\psi_{li}) \right] \right] \tilde{I}_{N_r \times N_c} \tag{19-79}$$

The matrix $D_i\left(1_{i-1} \; e^{j\phi_{i,i}} \; \ldots \; e^{j\phi_{N_r-1,i}} \; 1 \right)$ is an $N_r \times N_r$ diagonal matrix, where 1_{i-1} represents a sequence of 1s with length of i–1, as shown in Equation (19-80).

$$D\left(1_{i-1} \; e^{j\phi_{i,i}} \ldots \; e^{j\phi_{N_r-1,i}} \; 1 \right) = \begin{bmatrix} I_{i-1} & 0 & \ldots & \ldots & 0 \\ 0 & e^{j\phi_{i,i}} & 0 & \ldots & 0 \\ \ldots & 0 & \ddots & 0 & 0 \\ \ldots & \ldots & 0 & e^{j\phi_{N_r-1,i}} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{19-80}$$

The matrix $G_{li}(\psi)$ is an $N_r \times N_r$ Givens rotation matrix as shown in Equation (19-81).

$$G_{li}(\psi) = \begin{bmatrix} I_{i-1} & 0 & 0 & 0 & 0 \\ 0 & \cos(\psi) & 0 & \sin(\psi) & 0 \\ 0 & 0 & I_{l-i-1} & 0 & 0 \\ 0 & -\sin(\psi) & 0 & \cos(\psi) & 0 \\ 0 & 0 & 0 & 0 & I_{N_r-l} \end{bmatrix} \tag{19-81}$$

where each I_m is an $m \times m$ identity matrix, and $\cos(\psi)$ and $\sin(\psi)$ are located at row l and column i. $\tilde{I}_{N_r \times N_c}$ is an identity matrix padded with 0s to fill the additional rows or columns when $N_r \neq N_c$.

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For example, a 4×2 V matrix has the representation shown in Equation (19-82).

$$
\begin{aligned}
V = {} & \begin{bmatrix} e^{j\phi_{11}} & 0 & 0 & 0 \\ 0 & e^{j\phi_{21}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{31}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\psi_{21} & \sin\psi_{21} & 0 & 0 \\ -\sin\psi_{21} & \cos\psi_{21} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} \cos\psi_{31} & 0 & \sin\psi_{31} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\psi_{31} & 0 & \cos\psi_{31} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} \cos\psi_{41} & 0 & 0 & \sin\psi_{41} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\psi_{41} & 0 & 0 & \cos\psi_{41} \end{bmatrix}^T \\
& \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\phi_{22}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{32}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{32} & \sin\psi_{32} & 0 \\ 0 & -\sin\psi_{32} & \cos\psi_{32} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{42} & 0 & \sin\psi_{42} \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\psi_{42} & 0 & \cos\psi_{42} \end{bmatrix}^T \times \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}
\end{aligned}
\tag{19-82}
$$

The procedure for finding a compressed V matrix is described as follows:

A $N_r \times N_c$ beamforming feedback orthonormal column matrix V is column-wise phase invariant because the steering matrix needs a reference in phase per each column. When the number of rows and columns is equal, the orthonormal column matrix becomes a unitary matrix. In other words, V is equivalent to $\tilde{V}\tilde{D}$, where $\tilde{D}$ is a column-wise phase shift matrix such as $\tilde{D} = \mathrm{diag}\left(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_c}}\right)$. When the beamformee estimates the channel, it may find $\tilde{V}$ for the beamforming feedback matrix for the beamformer, but it should send $\tilde{V}\tilde{D}$ back to the beamformer, where $V = \tilde{V}\tilde{D}$. The angle, θ_i, in $\tilde{D}$ is found to make the last row of $\tilde{V}\tilde{D}$ to be non-negative real numbers.

The angles $\phi_{1,1} \ldots \phi_{N_r-1,1}$ in the diagonal matrix $D_1\left(e^{j\phi_{11}} \ \ldots \ e^{j\phi_{N_r-1,1}} \ 1\right)^*$ shall satisfy the constraint that all elements in the first column of $D_1^* V$ are non-negative real numbers. Now, the first column of $(G_{N_r 1} \ldots G_{31} G_{21} D_1^*) \times V$ can be $\begin{bmatrix} 1 & 0 & \ldots & 0 \end{bmatrix}^T$ by the Givens rotations G_{l1} such as shown in Equation (19-83).

$$
\begin{bmatrix} \cos\psi_{N_r 1} & 0 & 0 & \sin\psi_{N_r 1} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\psi_{N_r 1} & 0 & 0 & \cos\psi_{N_r 1} \end{bmatrix} \cdots \begin{bmatrix} \cos\psi_{31} & 0 & \sin\psi_{31} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\psi_{31} & 0 & \cos\psi_{31} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\psi_{21} & \sin\psi_{21} & 0 & 0 \\ -\sin\psi_{21} & \cos\psi_{21} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{j\phi_{11}} & 0 & 0 & 0 \\ 0 & O & 0 & 0 \\ 0 & 0 & e^{j\phi_{N_r-1,1}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^* \times V = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & V_2 & \\ 0 & & & \end{bmatrix}
\tag{19-83}
$$

For a new $(N_r - 1) \times (N_c - 1)$ submatrix V_2, this process is applied in the same way. Then, the angles $\phi_{2,2} \ldots \phi_{N_r-1,2}$ in the diagonal matrix $D_2\left(1 \ e^{j\phi_{22}} \ \ldots \ e^{j\phi_{N_r-1,2}} \ 1\right)^*$ shall satisfy the constraint that all elements in the second column of $D_2^* \times \mathrm{diag}(1, V_2)$ are non-negative real numbers. Now, the first two columns of $(G_{N_r 2} \ldots G_{32} D_2^*)(G_{N_r 1} \ldots G_{31} G_{21} D_1^*) \times V$ can be $\tilde{I}_{N_r \times 2}$ by the Givens rotations G_{l2} such as shown in Equation (19-84).

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$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{N_r2} & 0 & \sin\psi_{N_r2} \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\psi_{N_r2} & 0 & \cos\psi_{N_r2} \end{bmatrix} \cdots \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{32} & \sin\psi_{32} & 0 \\ 0 & -\sin\psi_{32} & \cos\psi_{32} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\phi_{22}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{N_r-1,2}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^* \times G_{N,1} \ldots G_{31} G_{21} D_1^* \times V = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & & \\ 0 & 0 & \multicolumn{2}{c}{V_3} \end{bmatrix} \quad (19\text{-}84)$$

This process continues until the first N_c columns of the right side matrix become $\tilde{I}_{N_r \times N_c}$. When $N_c < N_r$, this process does not need to continue because V_{N_c+1} is nulled out by $\tilde{I}_{N_r \times N_c}$. Then, by multiplying the complex conjugate transpose of the products of the D_i and G_{li} matrices on the left, V can be expressed as shown in Equation (19-85).

$$V = D_1 G_{21}^T G_{31}^T \ldots G_{N_r1}^T \times D_2 G_{32}^T G_{42}^T \ldots G_{N_r2}^T \times \ldots \times D_p G_{p+1,p}^T G_{p+2,p}^T \ldots G_{N_r p}^T \times \tilde{I}_{N_r \times N_C} \quad (19\text{-}85)$$

where $p = \min(N_c, N_r - 1)$, which can be written in short form as in Equation (19-79).

The angles found from the decomposition process above, e.g., the values of $\psi_{i,j}$ and $\phi_{k,l}$, are quantized as described in 9.6.11.7.

Columns $1 \ldots N_c$ of the beamforming feedback matrix correspond to spatial streams $1 \ldots N_c$, respectively. The mapping of spatial stream to modulation is defined in the MCS tables in 19.5. A transmitter shall not reorder the columns of the beamforming feedback matrices in determining steering matrices.

19.3.13 HT Preamble format for sounding PPDUs

19.3.13.1 General

The MIMO channel measurement takes place in every PPDU as a result of transmitting the HT-LTFs as part of the PHY preamble. The number of HT-LTFs transmitted shall be determined by the number of space-time streams transmitted unless additional dimensions are optionally sounded using HT-ELTFs and these are transmitted using the same spatial transformation that is used for the Data field of the HT PPDU. The use of the same spatial transformation enables the computation of the spatial equalization at the receiver.

When the number of space-time streams, N_{STS}, is less than the number of transmit antennas, or less than $\min(N_{TX}, N_{RX})$, sending only N_{STS} HT-LTFs does not allow the receiver to recover a full characterization of the MIMO channel, even though the resulting MIMO channel measurement is sufficient for receiving the Data field of the HT PPDU.

However, it is often desirable to obtain as full a characterization of the channel as possible. This involves the transmission of a sufficient number of HT-LTFs to sound the full dimensionality of the channel, which is in some cases N_{TX} and in other cases $\min(N_{TX}, N_{RX})$. These cases of MIMO channel measurement are referred to as *MIMO channel sounding*. A sounding PPDU may be used to sound available channel dimensions. A sounding PPDU is identified by setting the Not Sounding field in the HT-SIG to 0. A sounding PPDU may have any allowed number of HT-LTFs satisfying $N_{HT\text{-}LTF} \geq N_{STS}$. In general, if the Not Sounding field in the HT-SIG is equal to 0 and $N_{HT\text{-}LTF} > N_{STS}$, HT-ELTFs are used, except where $N_{SS} = 3$ and $N_{HT\text{-}LTF} = 4$ or in an NDP.

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19.3.13.2 Sounding with a NDP

A STA may sound the channel using a NDP (indicated by the HT Length field in the HT-SIG equal to 0) with the Not Sounding field equal to 0. The number of LTFs is the number implied by the MCS, which shall indicate two or more spatial streams. The last HT-LTF of an NDP shall not be followed by a Data field (see Figure 19-16).

It is optional for a STA to process an NDP.

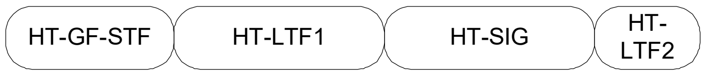

Figure 19-16—Example of an NDP used for sounding

19.3.13.3 Sounding PPDU for calibration

In the case of a bidirectional calibration exchange, two STAs exchange sounding PPDUs, the exchange of which enables the receiving STA to compute an estimate of the MIMO channel matrix H_k for each subcarrier k. In general, in an exchange of calibration messages, the number of spatial streams is less than the number of transmit antennas. In such cases, HT-ELTFs are used. In the case of sounding PPDUs for calibration, the antenna mapping matrix shall be as shown in Equation (19-86).

$$Q_k = C_{CSD}(k)P_{CAL} \tag{19-86}$$

where

$C_{CSD}(k)$ is a diagonal cyclic shift matrix in which the diagonal elements carry frequency domain representation of the cyclic shifts given in Table 19-9

P_{CAL} is one of the following unitary matrices:

For $N_{TX} = 1, P_{CAL} = 1$

For $N_{TX} = 2, P_{CAL} = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$

For $N_{TX} = 3, P_{CAL} = \frac{\sqrt{3}}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3} \\ 1 & e^{-j4\pi/3} & e^{-j2\pi/3} \end{bmatrix}$

For $N_{TX} = 4, P_{CAL} = \frac{1}{2}\begin{bmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{bmatrix}$

19.3.13.4 Sounding PPDU for channel quality assessment

In response to an MRQ, sent by STA A to STA B, the responding STA B returns to the requesting STA A an MCS selection that STA B determines to be a suitable MCS for STA A to use in subsequent transmissions to STA B. In determining the MCS, STA B performs a channel quality assessment, which entails using whatever information STA B has about the channel, such as an estimate of the MIMO channel derived from

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the sounding PPDU that carries the MRQ. To enable this calculation, the MRQ is sent in conjunction with a sounding PPDU.

The STA sending the MRQ (STA A) determines how many HT-LTFs to send, and whether to use HT-ELTFs or an NDP, based on the Transmit Beamforming Capabilities field, number of space-time streams used in the PPDU carrying the MRQ, the number of transmit chains it is using (N_{TX}), whether the transmit and receive STAs support STBC, and in some cases, the number of receive chains at the responding STA (N_{RX}).

The maximum number of available space-time streams is set by the number of transmit and receive chains and the STBC capabilities of the transmitter and receiver, as is shown in Table 19-21. While the number of receive chains is not communicated in a capabilities indicator, the maximum number of space-time streams supported may be inferred from the MCS capabilities and the STBC capabilities of the receiving STA. When the number of receive chains is known at the transmitter, the number of HT-LTFs sent to obtain a full channel quality assessment is determined according to the maximum number of space-time streams indicated in Table 19-21. The number of HT-LTFs to use in conjunction with the indicated number of space-time streams is determined according to 19.3.9.4.6.

Table 19-21—Maximum available space-time streams

N_{TX}	N_{RX}	$N_{STS,\text{max}}$ without STBC	$N_{STS,\text{max}}$ with STBC
1	1	1	N/A
2	1	1	2
3	1	1	2
3	2	2	3
4	1	1	2
4	2	2	4

If the requesting STA A sends an MRQ in a PPDU that uses fewer space-time streams in the data portion than the maximum number of space-time streams possible given the number of antennas at STA A and the responding STA B, the channel quality assessment made by STA B may be based on the HT-DLTFs alone. In this case, the MFB is limited to MCSs using the number of streams used in the Data field of the HT PPDU, or fewer. To determine whether an MCS should be chosen that uses more spatial streams than the PPDU containing the MRQ, it is necessary for the requesting STA A to either use HT-ELTFs (i.e., send the MRQ in a staggered sounding PPDU) or use an NDP (i.e., send the MRQ in conjunction with an NDP).

The sounding PPDU may have nonidentity spatial mapping matrix Q_k. For different receiving STAs, Q_k may vary.

19.3.14 Regulatory requirements

Wireless LANs (WLANs) implemented in accordance with this standard are subject to equipment certification and operating requirements established by regional and national regulatory administrations. The PHY specification establishes minimum technical requirements for interoperability, based upon established regulations at the time this standard was issued. These regulations are subject to revision or may be superseded. Requirements that are subject to local geographic regulations are annotated within the PHY

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specification. Regulatory requirements that do not affect interoperability are not addressed in this standard. Implementers are referred to the regulatory sources in Annex D for further information. Operation in countries within defined regulatory domains may be subject to additional or alternative national regulations.

19.3.15 Channel numbering and channelization

19.3.15.1 General

The STA may operate in the 5 GHz band and/or 2.4 GHz band. When using 20 MHz channels, it uses channels defined in 17.3.8.4 (5 GHz band) or 16.3.6 (2.4 GHz band). When using 40 MHz channels, it can operate in the channels defined in 19.3.15.2 and 19.3.15.3.

The set of valid operating channel numbers by regulatory domain is defined in Annex E.

19.3.15.2 Channel allocation in the 2.4 GHz band

Channel center frequencies are defined at every integer multiple of 5 MHz in the 2.4 GHz band. The relationship between center frequency and channel number is given by Equation (19-87).

$$\text{Channel center frequency} = 2407 + 5 \times n_{ch} (\text{MHz}) \tag{19-87}$$

where
$n_{ch} = 1, 2, \ldots, 13$

19.3.15.3 Channel allocation in the 5 GHz band

Channel center frequencies are defined at every integer multiple of 5 MHz above the channel starting frequency. The relationship between center frequency and channel number is given in Equation (19-88).

$$\text{Channel center frequency} = \text{Channel starting frequency} + 5 \times n_{ch} (\text{MHz}) \tag{19-88}$$

where
$n_{ch} = 1, \ldots, 200$
Channel starting frequency is defined as dot11ChannelStartingFactor × 500 kHz or is defined as 5 GHz where dot11OperatingClassesRequired is false or not defined.

A channel center frequency of 5 GHz shall be indicated by dot11ChannelStartingFactor = 8000 and n_{ch} = 200.

19.3.15.4 40 MHz channelization

The set of valid operating channel numbers by regulatory domain is defined in Annex E.

The 40 MHz channels are specified by two fields: (*Nprimary_ch*, *Secondary*). The first field represents the channel number of the primary channel, and the second field indicates whether the secondary channel is above or below the primary channel (1 indicates above, -1 indicates below). The secondary channel number shall be $Nprimary\_ch + Secondary \times 4$.

For example, a 40 MHz channel consisting of 40 MHz channel number 36 and Secondary 1 specifies the primary channel is 36 and the secondary channel is 40.

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19.3.16 Slot time

The slot time shall follow 17.3.8.6 for 5 GHz bands and 18.5.4 for 2.4 GHz bands.

The slot time for 40 MHz channel spacing shall be the same as that for 20 MHz channel spacing.

19.3.17 Transmit and receive impedance at the antenna connector

The impedance at the transmit antenna connector and receive antenna connector for each transmit and receive antenna shall follow 17.3.8.7.

19.3.18 PHY transmit specification

19.3.18.1 Transmit spectrum mask

NOTE 1—In the presence of additional regulatory restrictions, the device has to meet both the regulatory requirements and the mask defined in this subclause, i.e., its emissions can be no higher at any frequency offset than the minimum of the values specified in the regulatory and default masks.

NOTE 2—The transmit spectral mask figures in this subclause are not drawn to scale.

For rules regarding TX center frequency leakage levels by VHT STAs, see 21.3.17.4.2.

For the 2.4 GHz band, when transmitting in a 20 MHz channel, the transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 18 MHz, –20 dBr at 11 MHz frequency offset, –28 dBr at 20 MHz frequency offset, and the maximum of –45 dBr and –53 dBm/MHz at 30 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 19-17. The measurements shall be made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

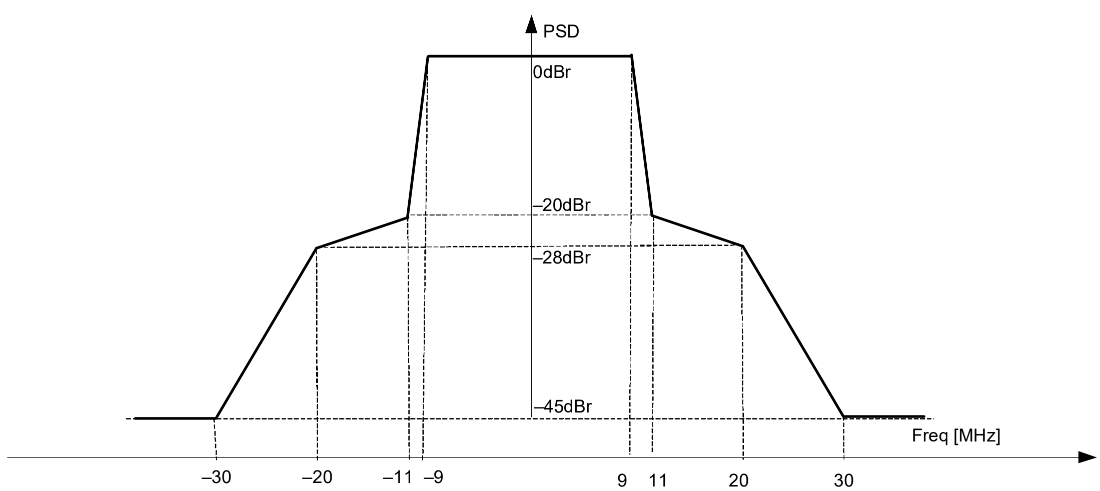

Figure 19-17—Transmit spectral mask for 20 MHz transmission in the 2.4 GHz band

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For the 2.4 GHz band, when transmitting in a 40 MHz channel, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 38 MHz, –20 dBr at 21 MHz frequency offset, –28 dBr at 40 MHz offset, and the maximum of –45 dBr and –56 dBm/MHz at 60 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 19-18.

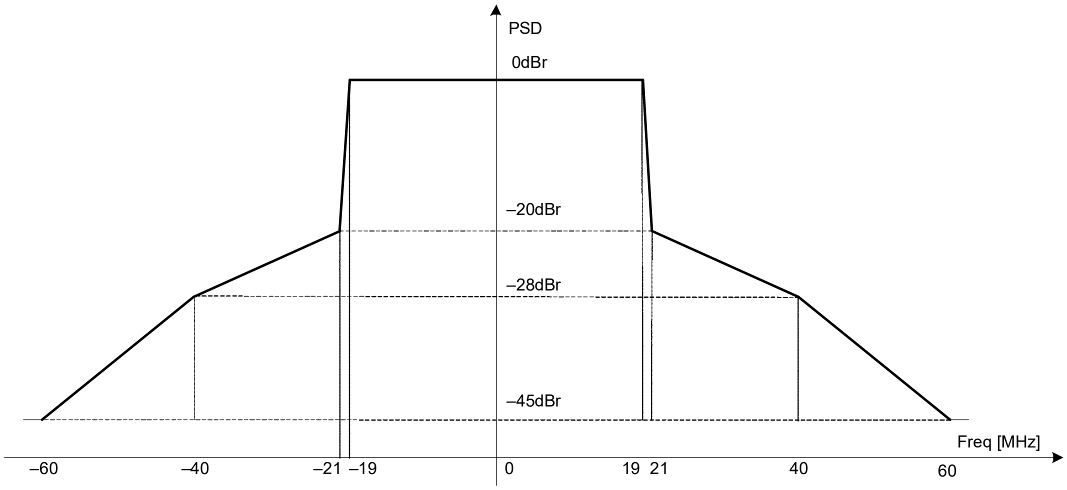

Figure 19-18—Transmit spectral mask for a 40 MHz channel in the 2.4 GHz band

For the 5 GHz band, when transmitting in a 20 MHz channel, the transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 18 MHz, –20 dBr at 11 MHz frequency offset, –28 dBr at 20 MHz frequency offset, and the maximum of –40 dBr and –53 dBm/MHz at 30 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 19-19. The measurements shall be made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

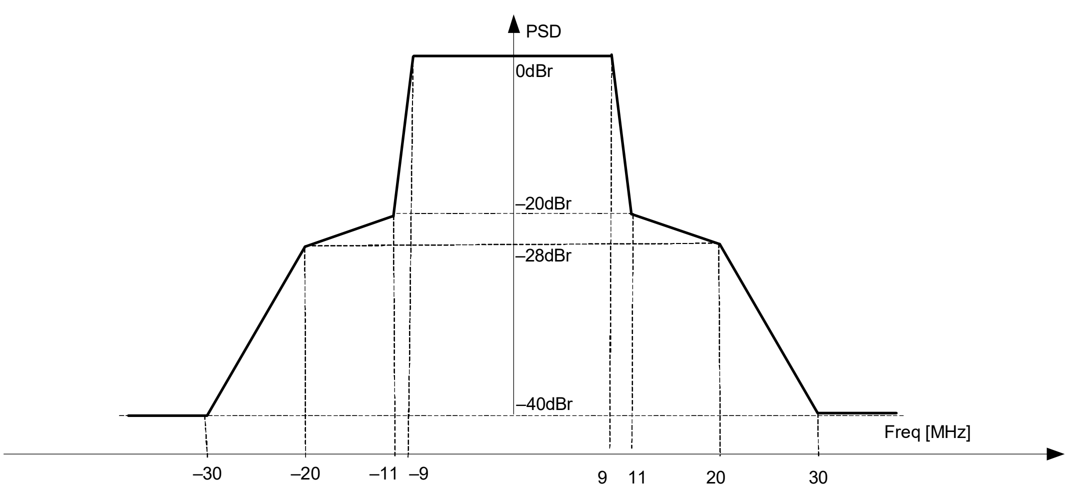

Figure 19-19—Transmit spectral mask for 20 MHz transmission in the 5 GHz band

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For the 5 GHz band, when transmitting in a 40 MHz channel, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 38 MHz, –20 dBr at 21 MHz frequency offset, –28 dBr at 40 MHz offset, and the maximum of –40 dBr and –56 dBm/MHz at 60 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 19-20.

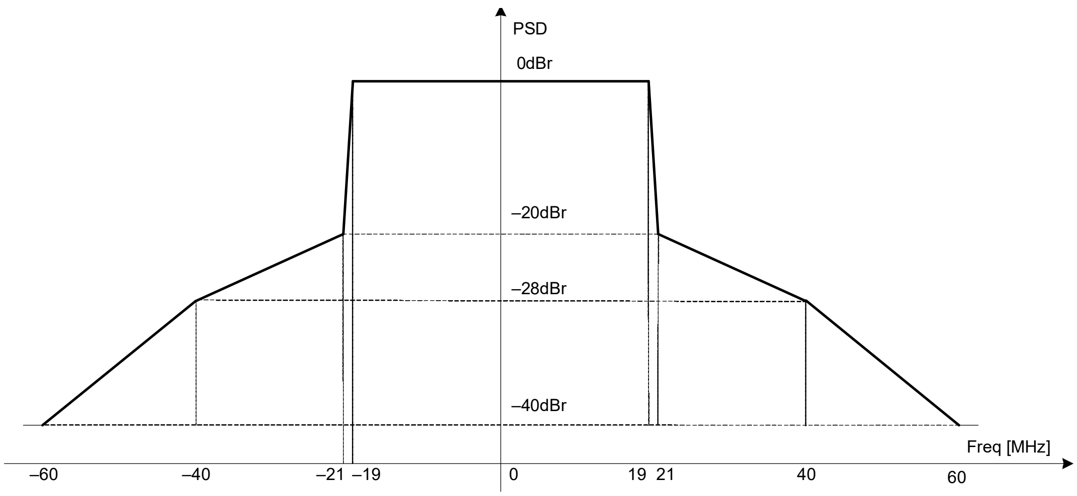

Figure 19-20—Transmit spectral mask for a 40 MHz channel in the 5 GHz band

Transmission with CH_OFF_20U, CH_OFF_20L, or CH_OFF_40 shall comply with the same mask that is used for the 40 MHz channel.

19.3.18.2 Spectral flatness

In a 20 MHz channel and in corresponding 20 MHz transmission in a 40 MHz channel, the average energy of the constellations in each of the subcarriers with indices –16 to –1 and +1 to +16 shall deviate no more than ± 4 dB from their average energy. The average energy of the constellations in each of the subcarriers with indices –28 to –17 and +17 to +28 shall deviate no more than +4/–6 dB from the average energy of subcarriers with indices –16 to –1 and +1 to +16.

In a 40 MHz transmission (excluding PPDUs in MCS 32 format and non-HT duplicate format), the average energy of the constellations in each of the subcarriers with indices –42 to –2 and +2 to +42 shall deviate no more than ± 4 dB from their average energy. The average energy of the constellations in each of the subcarriers with indices –43 to –58 and +43 to +58 shall deviate no more than +4/–6 dB from the average energy of subcarriers with indices –42 to –2 and +2 to +42.

In MCS 32 format and non-HT duplicate format, the average energy of the constellations in each of the subcarriers with indices –42 to –33, –31 to –6, +6 to +31, and +33 to +42 shall deviate no more than ± 4 dB from their average energy. The average energy of the constellations in each of the subcarriers with indices –43 to –58 and +43 to +58 shall deviate no more than +4/–6 dB from the average energy of subcarriers with indices –42 to –33, –31 to –6, +6 to +31, and +33 to +42.

The tests for the spectral flatness requirements may be performed with spatial mapping $Q_k = \mathbf{I}$ (see 19.3.11.11.2).

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19.3.18.3 Transmit power

The maximum allowable output power is measured in accordance with practices specified by the appropriate regulatory bodies.

19.3.18.4 Transmit center frequency tolerance

The transmitter center frequency tolerance shall be ± 20 ppm for the 5 GHz band and ± 25 ppm for the 2.4 GHz band. The different transmit chain center frequencies (LO) and each transmit chain symbol clock frequency shall all be derived from the same reference oscillator.

19.3.18.5 Packet alignment

If no signal extension is required (see 19.3.2), the receiver shall emit a PHY-CCA.indication(IDLE) primitive (see 8.3.5.12) at the 4 µs boundary following the reception of the last symbol of the packet. If a signal extension is required, the receiver shall emit a PHY-CCA.indication(IDLE) primitive a duration of aSignalExtension after the 4 µs boundary following the reception of the last symbol of the packet. This situation is illustrated for an HT-greenfield format packet using short GI in Figure 19-21.

If no signal extension is required, the transmitter shall emit a PHY-TXEND.confirm primitive (see 8.3.5.8) at the 4 µs boundary following the trailing boundary of the last symbol of the PPDU on the WM. If a signal extension is required, the transmitter shall emit a PHY-TXEND.confirm primitive (see 8.3.5.8) a duration of aSignalExtension after the 4 µs boundary following the trailing boundary of the last symbol of the PPDU on the WM. This situation is illustrated in Figure 19-21.

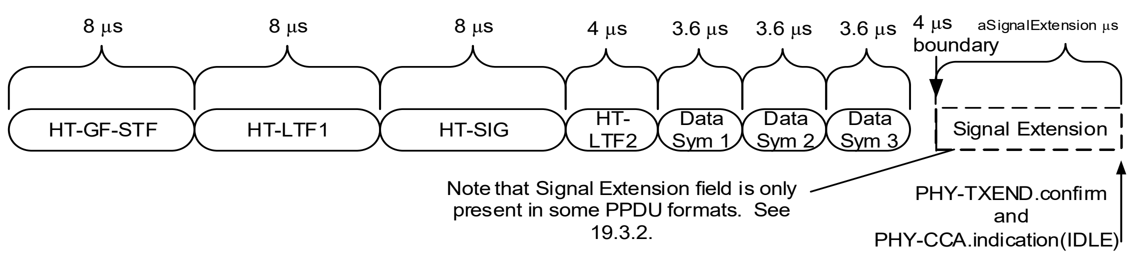

Figure 19-21—PHY-TXEND.confirm alignment (HT-greenfield format with short GI)

19.3.18.6 Symbol clock frequency tolerance

The symbol clock frequency tolerance shall be ± 20 ppm for 5 GHz bands and ± 25 ppm for 2.4 GHz bands. The transmit center frequency and the symbol clock frequency for all transmit antennas shall be derived from the same reference oscillator.

19.3.18.7 Modulation accuracy

19.3.18.7.1 Introduction to modulation accuracy tests

Transmit modulation accuracy specifications are described in 19.3.18.7.2 and 19.3.18.7.3. The test method is described in 19.3.18.7.4.

19.3.18.7.2 Transmit center frequency leakage

For VHT STAs the requirements on transmitter center frequency leakage are defined in 21.3.17.4.2; otherwise, the requirements are defined in this subclause.

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The transmitter center frequency leakage shall follow 17.3.9.7.2 for all transmissions in a 20 MHz channel width. For transmissions in a 40 MHz channel width, the center frequency leakage shall not exceed $max(P - 20, -20)$ dBm, or, equivalently, 0 dB relative to the average energy of the rest of the subcarriers. For upper or lower 20 MHz transmissions in a 40 MHz channel, the center frequency leakage (center of a 40 MHz channel) shall not exceed $max(P - 17, -20)$ dBm. The transmit center frequency leakage is specified per antenna.

19.3.18.7.3 Transmitter constellation error

The relative constellation frame-averaged RMS error, calculated first by averaging over subcarriers, OFDM frames, and spatial streams, shall not exceed a data-rate-dependent value according to Table 19-22. The number of spatial streams under test shall be equal to the number of utilized transmitting STA antenna (output) ports and also equal to the number of utilized testing instrumentation input ports. In the test, $N_{SS} = N_{STS}$ with EQM MCSs shall be used and no beamforming steering matrix shall be used. Each output port of the transmitting STA shall be connected through a cable to one input port of the testing instrumentation. The same requirement applies both to 20 MHz channels and 40 MHz channels.

Table 19-22—Allowed relative constellation error versus constellation size and coding rate

Modulation	Coding rate	Relative constellation error (dB)
BPSK	1/2	–5
QPSK	1/2	–10
QPSK	3/4	–13
16-QAM	1/2	–16
16-QAM	3/4	–19
64-QAM	2/3	–22
64-QAM	3/4	–25
64-QAM	5/6	–27

19.3.18.7.4 Transmitter modulation accuracy (EVM) test

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signals into a streams of complex samples at 40 Msample/s or more, with sufficient accuracy in terms of I/Q arm amplitude and phase balance, dc offsets, phase noise, and analog-to-digital quantization noise. Each transmit chain is connected directly through a cable to the setup input port. A possible embodiment of such a setup is converting the signals to a low intermediate frequency with a microwave synthesizer, sampling the signal with a digital oscilloscope, and decomposing it digitally into quadrature components. The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

a) Detect the start of frame.
b) Detect the transition from short sequences to channel estimation sequences, and establish fine timing (with one sample resolution).
c) Estimate the coarse and fine frequency offsets.

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d) Derotate the frame according to estimated frequency offset.

e) Estimate the complex channel response coefficients for each of the subcarriers and each of the transmit chains.

f) For each of the data OFDM symbols, transform the symbol into subcarrier received values, estimate the phase from the pilot subcarriers in all spatial streams, derotate the subcarrier values according to estimated phase, group the results from all of the receiver chains in each subcarrier to a vector, multiply the vector by a zero-forcing equalization matrix generated from the channel estimated during the channel estimation phase.

g) For each data-carrying subcarrier in each spatial stream, find the closest constellation point and compute the Euclidean distance from it.

h) Compute the average of the RMS of all errors in a frame. It is given by Equation (19-89).

$$Error_{RMS} = \frac{\displaystyle\sum_{i_f=1}^{N_f} \sqrt{\frac{\displaystyle\sum_{i_s=1}^{N_{SYM}} \left[\sum_{i_{ss}=1}^{N_{SS}} \left(\sum_{i_{sc}=1}^{N_{ST}} \left((I(i_f, i_s, i_{ss}, i_{sc}) - I_0(i_f, i_s, i_{ss}, i_{sc}))^2 + (Q(i_f, i_s, i_{ss}, i_{sc}) - Q_0(i_f, i_s, i_{ss}, i_{sc}))^2 \right) \right) \right]}{N_{SYM} \times N_{SS} \times N_{ST} \times P_0}}}{N_f} \tag{19-89}$$

where

N_f	is the number of frames for the measurement
$I_0(i_f, i_s, i_{ss}, i_{sc}), Q_0(i_f, i_s, i_{ss}, i_{sc})$	denotes the ideal symbol point in the complex plane in subcarrier i_{sc}, spatial stream i_{ss}, and OFDM symbol i_s of frame i_f
$I(i_f, i_s, i_{ss}, i_{sc}), Q(i_f, i_s, i_{ss}, i_{sc})$	denotes the observed symbol point in the complex plane in subcarrier i_{sc}, spatial stream i_{ss}, and OFDM symbol i_s of frame i_f
P_0	is the average power of the constellation

The vector error on a phase plane is shown in Figure 17-16.

The test shall be performed over at least 20 frames (N_f), and the average of the RMS shall be taken. The frames under test shall be at least 16 OFDM symbols long. Random data shall be used for the symbols.

19.3.18.8 Time of Departure accuracy

The Time of Departure accuracy test evaluates TIME_OF_DEPARTURE against aTxPHYTxStartRMS and aTxPHYTxStartRMS against TIME_OF_DEPARTURE_ACCURACY_TEST_THRESH as defined in Annex P with the following test parameters:

— MULTICHANNEL_SAMPLING_RATE is

$20 \times 10^6\left(1 + \left\lceil \frac{f_H - f_L}{20\text{ MHz}} \right\rceil\right)$ sample/s, for a CH_BANDWIDTH parameter equal to HT_CBW20

$40 \times 10^6\left(1 + \left\lceil \frac{f_H - f_L}{40\text{ MHz}} \right\rceil\right)$ sample/s, for a CH_BANDWIDTH parameter equal to HT_CBW40

where

f_H	is the nominal center frequency in Hz of the highest channel in the channel set
f_L	is the nominal center frequency in Hz of the lowest channel in the channel set, the channel set is the set of channels upon which frames providing measurements are transmitted, the channel set comprises channels uniformly spaced across $f_H - f_L \geq 50$ MHz

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— FIRST_TRANSITION_FIELD is L-STF (for HT-mixed format) or HT-GF-STF (for HT-greenfield format)
— SECOND_TRANSITION_FIELD is L-LTF (for HT-mixed format) or HT-GF-LTF1 (for HT-greenfield format)
— TRAINING_FIELD is L-LTF (for HT-mixed format) or HT-LTF1 (for HT-greenfield format) windowed in a manner which should approximate the windowing described in 17.3.2.5 with T_{TR} = 100 ns.
— TIME_OF_DEPARTURE_ACCURACY_TEST_THRESH is 80 ns (for a CH_BANDWIDTH parameter equal to HT_CBW20) or 80 ns (for a CH_BANDWIDTH parameter equal to HT_CBW40).

NOTE—The indicated windowing applies to the time of departure accuracy test equipment, and not the transmitter or receiver.

19.3.19 HT PHY receiver specification

19.3.19.1 Receiver minimum input sensitivity

The packet error ratio (PER) shall be less than 10% for a PSDU length of 4096 octets with the rate-dependent input levels listed in Table 19-23 or less. The minimum input levels are measured at the antenna connector and are referenced as the average power per receive antenna. The number of spatial streams under test shall be equal to the number of utilized transmitting STA antenna (output) ports and also equal to the number of utilized device under test input ports. Each output port of the transmitting STA shall be connected through a cable to one input port of the device under test. The test in this subclause and the minimum sensitivity levels specified in Table 19-23 apply only to non-STBC modes, MCSs 0–31, 800 ns GI, and BCC.

Table 19-23—Receiver minimum input level sensitivity

Modulation	Rate (R)	Adjacent channel rejection (dB)	Nonadjacent channel rejection (dB)	Minimum sensitivity (20 MHz channel spacing) (dBm)	Minimum sensitivity (40 MHz channel spacing) (dBm)
BPSK	1/2	16	32	–82	–79
QPSK	1/2	13	29	–79	–76
QPSK	3/4	11	27	–77	–74
16-QAM	1/2	8	24	–74	–71
16-QAM	3/4	4	20	–70	–67
64-QAM	2/3	0	16	–66	–63
64-QAM	3/4	–1	15	–65	–62
64-QAM	5/6	–2	14	–64	–61

19.3.19.2 Adjacent channel rejection

For all transmissions in a 20 MHz channel width, the adjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 19-23 and raising the power of an interfering signal of 20 MHz bandwidth until 10% PER is caused for a PSDU length

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of 4096 octets. The difference in power between the signals in the interfering channel and the desired channel is the corresponding adjacent channel rejection. The adjacent channel center frequencies shall be separated by 20 MHz when operating in the 5 GHz band, and the adjacent channel center frequencies shall be separated by 25 MHz when operating in the 2.4 GHz band.

For all transmissions in a 40 MHz channel width, the adjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 19-23 and raising the power of an interfering signal of 40 MHz bandwidth until 10% PER is caused for a PSDU length of 4096 octets. The difference in power between the signals in the interfering channel and the desired channel is the corresponding adjacent channel rejection. The adjacent channel center frequencies shall be separated by 40 MHz.

The interfering signal in the adjacent channel shall be a signal compliant with the HT PHY, unsynchronized with the signal in the channel under test. The corresponding rejection shall be no less than specified in Table 19-23. The interference signal shall have a minimum duty cycle of 50%.

The test in this subclause and the adjacent channel rejection levels specified in Table 19-23 apply only to non-STBC modes, MCSs 0–31, 800 ns GI, and BCC.

19.3.19.3 Nonadjacent channel rejection

For all transmissions in a 20 MHz channel width in the 5 GHz band, the nonadjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 19-23 and raising the power of an interfering signal of 20 MHz bandwidth until a 10% PER occurs for a PSDU length of 4096 octets. The difference in power between the signals in the interfering channel and the desired channel is the corresponding nonadjacent channel rejection. The nonadjacent channel center frequencies shall be separated by 40 MHz or more.

For all transmissions in a 40 MHz channel width in the 5 GHz band, the nonadjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 19-23 and raising the power of an interfering signal of 40 MHz bandwidth until a 10% PER occurs for a PSDU length of 4096 octets. The difference in power between the signals in the interfering channel and the desired channel is the corresponding nonadjacent channel rejection. The nonadjacent channel center frequencies shall be separated by 80 MHz or more.

The interfering signal in the nonadjacent channel shall be a signal compliant with the HT PHY, unsynchronized with the signal in the channel under test. The corresponding rejection shall be no less than specified in Table 19-23. The interference signal shall have a minimum duty cycle of 50%. The nonadjacent channel rejection for transmissions in a 20 MHz or 40 MHz channel width is applicable only to 5 GHz band.

The test in this subclause and the nonadjacent channel rejection level specified in Table 19-23 apply only to non-STBC modes, MCSs 0–31, 800 ns GI, and BCC.

19.3.19.4 Receiver maximum input level

The receiver shall provide a maximum PER of 10% at a PSDU length of 4096 octets, for a maximum input level of –30 dBm in the 5 GHz band and –20 dBm in the 2.4 GHz band, measured at each antenna for any baseband modulation.

19.3.19.5 CCA sensitivity

19.3.19.5.1 General

The thresholds in this subclause are compared with the signal level at each receiving antenna.

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19.3.19.5.2 CCA-Energy Detect (CCA-ED)

For the operating classes requiring CCA-Energy Detect (CCA-ED), the PHY shall also indicate a medium busy condition when CCA-ED detects a channel busy condition.

For improved spectrum sharing, CCA-ED is required in some bands. The behavior class indicating CCA-ED is given in Table D-2. The operating classes requiring the corresponding CCA-ED behavior class are given in E.1. The PHY of a STA that is operating within an operating class that requires CCA-ED shall operate with CCA-ED.

CCA-ED shall detect a channel busy condition when the received signal strength exceeds the CCA-ED threshold as given by dot11OFDMEDThreshold for the primary channel and dot11OFDMEDThreshold for the secondary channel (if present). The CCA-ED thresholds for the operating classes requiring CCA-ED are subject to the criteria in D.2.5.

NOTE—The requirement to detect a channel busy condition as stated in 19.3.19.5.3, 19.3.19.5.4, and 19.3.19.5.5 is a mandatory energy detection requirement on all Clause 19 receivers. Support for CCA-ED is an additional requirement that relates specifically to the sensitivities described in D.2.5.

19.3.19.5.3 CCA sensitivity for non-HT PPDUs

CCA sensitivity requirements for non-HT PPDUs in the primary channel are described in 17.3.10.6 and 18.4.6.

19.3.19.5.4 CCA sensitivity in 20 MHz

For an HT STA with the operating channel width equal to 20 MHz, the start of a 20 MHz HT signal at a receive level greater than or equal to the minimum modulation and coding rate sensitivity of –82 dBm shall cause the PHY to set PHY-CCA.indication(BUSY) with a probability > 90% within 4 μs. The receiver shall indicate a channel busy condition for any signal 20 dB or more above the minimum modulation and coding rate sensitivity (–82 + 20 = –62 dBm) in the 20 MHz channel.

An HT STA that does not support the reception of HT_GF PPDUs shall indicate a channel busy condition [PHY-CCA.indication(BUSY)] for any valid HT_GF signal in the 20 MHz channel at a receive level greater than or equal to –72 dBm.

19.3.19.5.5 CCA sensitivity in 40 MHz

This subclause describes the CCA sensitivity requirements for an HT STA with the operating channel width equal to 40 MHz.

The receiver of a 20/40 MHz STA with the operating channel width equal to 40 MHz shall provide CCA on both the primary and secondary channels.

When the secondary channel is idle, the start of a 20 MHz HT signal in the primary channel at a receive level greater than or equal to the minimum modulation and coding rate sensitivity of –82 dBm shall cause the PHY to generate a PHY-CCA.indication(BUSY, {primary}) primitive with a probability > 90% within 4 μs. The start of a 40 MHz HT signal that occupies both the primary and secondary channels at a receive level greater than or equal to the minimum modulation and coding rate sensitivity of –79 dBm shall cause the PHY to generate a PHY-CCA.indication(BUSY, {primary, secondary}) primitive for both the primary and secondary channels with a probability per channel > 90% within 4 μs.

An HT STA that does not support the reception of HT_GF PPDUs shall indicate a {primary} channel busy condition (PHY-CCA.indication(BUSY, {primary}) primitive) for any valid HT_GF signal in the primary

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channel at a receive level greater than or equal to –72 dBm when the secondary channel is idle. An HT STA that does not support the reception of HT_GF PPDUs shall indicate a {primary, secondary} channel busy condition (PHY-CCA.indication(BUSY, {primary, secondary}) primitive) for any valid 40 MHz HT_GF signal in both the primary and secondary channels at a receive level greater than or equal to –69 dBm.

The receiver shall indicate a {primary} channel busy condition for any signal at or above –62 dBm in the 20 MHz primary channel. This level is 20 dB above the minimum modulation and coding rate sensitivity for a 20 MHz PPDU. When the primary channel is idle, the receiver indicate a {secondary} channel busy condition for any signal at or above –62 dBm in the 20 MHz secondary channel. The receiver shall indicate a {primary, secondary} channel busy condition for any signal present in both the primary and secondary channels that is at or above –62 dBm in the primary channel and at or above –62 dBm in the secondary channel.

19.3.19.6 Received channel power indicator (RCPI) measurement

The RCPI is a measure of the received RF power in the selected channel for a received frame. This parameter shall be a measure by the PHY of the received RF power in the channel measured over the data portion of the received frame. The received power shall be the average of the power in all active receive chains.

The RCPI encoding is defined in 9.4.2.37.

RCPI shall equal the received RF power within an accuracy of ± 5 dB (95% confidence interval) within the specified dynamic range of the receiver. The received RF power shall be determined assuming a receiver noise equivalent bandwidth equal to the channel width multiplied by 1.1.

19.3.19.7 Reduced interframe space (RIFS)

The receiver shall be able to decode a PPDU that was transmitted with a RIFS separation from the previous PPDU.

19.3.20 PHY transmit procedure

There are three options for the transmit PHY procedure. The first two options, for which typical transmit procedures are shown in Figure 19-22 and Figure 19-23, are selected if the FORMAT field of the PHY-TXSTART.request(TXVECTOR) primitive is equal to HT_MF or HT_GF, respectively. These transmit procedures do not describe the operation of optional features, such as LDPC or STBC. The third option is to follow the transmit procedure in Clause 17 or Clause 18 if the FORMAT field is equal to NON_HT. Additionally, if the FORMAT field is equal to NON_HT, CH_BANDWIDTH indicates NON_HT_CBW20, and NON_HT_MODULATION indicates OFDM, follow the transmit procedure in Clause 17. If the FORMAT field is equal to NON_HT, CH_BANDWIDTH indicates NON_HT_CBW20, and NON_HT_MODULATION indicates other than OFDM, follow the transmit procedure in Clause 18. And furthermore, if the FORMAT field is equal to NON_HT and CH_BANDWIDTH indicates NON_HT_CBW40, follow the transmit procedure in Clause 17, except that the signal in Clause 17 is generated simultaneously on each of the upper and lower 20 MHz channels that constitute the 40 MHz channel as defined in 19.3.8 and 19.3.11.12. In all these options, in order to transmit data, the PHY-TXSTART.request primitive shall be enabled so that the PHY entity shall be in the transmit state. Further, the PHY shall be set to operate at the appropriate frequency through station management via the PLME, as specified in 19.4. Other transmit parameters, such as MCS coding types and transmit power, are set via the PHY SAP with the PHY-TXSTART.request(TXVECTOR) primitive, as described in 19.2.2.

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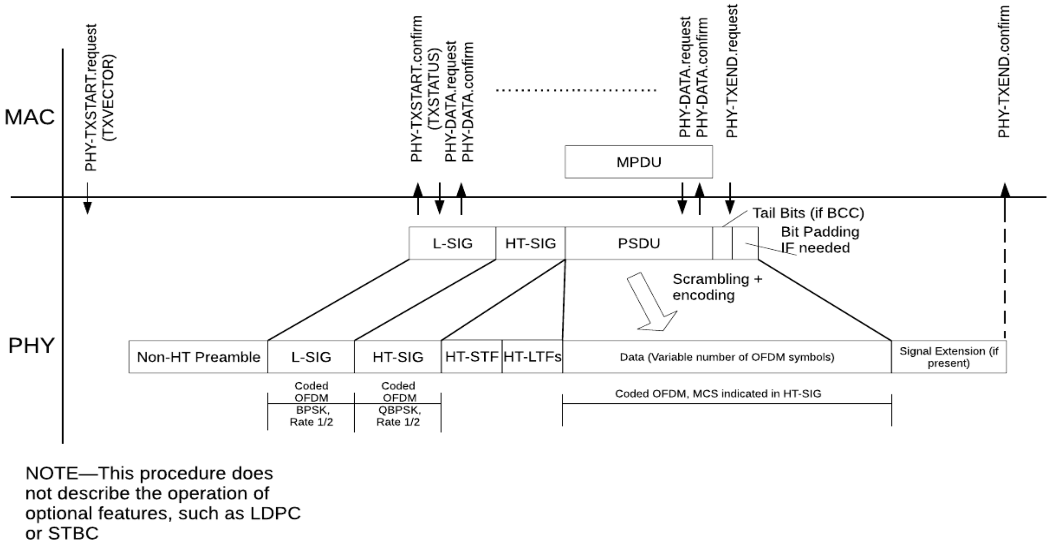

Figure 19-22—PHY transmit procedure (HT-mixed format PPDU)

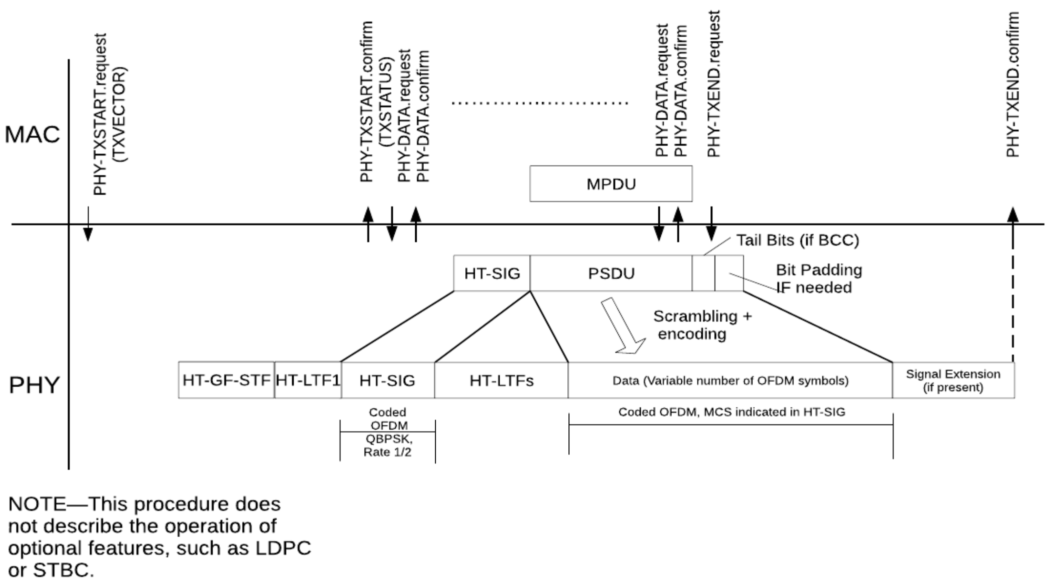

Figure 19-23—PHY transmit procedure (HT-greenfield format PPDU)

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A clear channel shall be indicated by issuing a PHY-CCA.indication(IDLE) primitive. Note that under some circumstances, the MAC uses the latest value of the PHY-CCA.indication primitive before issuing the PHY-TXSTART.request primitive. Transmission of the PPDU shall be initiated after receiving the PHY-TXSTART.request(TXVECTOR) primitive. The TXVECTOR elements for the PHY-TXSTART.request primitive are specified in Table 19-1.

Transmission of the PHY preamble may start if TIME_OF_DEPARTURE_REQUESTED is false, and shall start immediately if TIME_OF_DEPARTURE_REQUESTED is true, based on the parameters passed in the PHY-TXSTART.request primitive.

The data shall then be exchanged between the MAC and the PHY through a series of PHY-DATA.request(DATA) primitives issued by the MAC and PHY-DATA.confirm primitives issued by the PHY. Once PHY preamble transmission is started, the PHY entity shall immediately initiate data scrambling and data encoding. The encoding method shall be based on the FEC_CODING, CH_BANDWIDTH, and MCS parameter of the TXVECTOR. A modulation rate change, if any, shall be initiated starting with the SERVICE field data, as described in 19.3.2.

The PHY proceeds with PSDU transmission through a series of data octet transfers from the MAC. The SERVICE field and PSDU are encoded by the encoder selected by the FEC_CODING, CH_BANDWIDTH, and MCS parameters of the TXVECTOR as described in 19.3.3. Transmission can be prematurely terminated by the MAC through the primitive PHY-TXEND.request primitive. Normal termination occurs after the transmission of the final bit of the last PSDU octet, according to the number supplied in the LENGTH field.

The packet transmission shall be completed, and the PHY entity shall enter the receive state. Each PHY-TXEND.request primitive is acknowledged with a PHY-TXEND.confirm primitive from the PHY. If the length of the coded PSDU is not an integer multiple of the OFDM symbol length, bits shall be stuffed to make the coded PSDU length an integer multiple of the OFDM symbol length.

The GI shall be inserted in every OFDM symbol as a countermeasure against delay spread.

In some PPDU formats (as defined in 19.3.2), a signal extension is present. When no signal extension is present, the PHY-TXEND.confirm primitive is generated at the end of last symbol of the PPDU. When a signal extension is present, the PHY-TXEND.confirm primitive is generated at the end of the signal extension.

A typical state machine implementation of the transmit PHY is provided in Figure 19-24. Requests (.request) and confirmations (.confirm) are issued once per state as shown. This state machine does not describe the operation of optional features, such as LDPC or STBC. If the TXVECTOR parameter FORMAT is equal to NON_HT and NON_HT_MODULATION is equal to ERP-OFDM or OFDM, refer to the transmit procedure and state machine in 17.3.11. If the TXVECTOR parameter FORMAT is equal to NON_HT and NON_HT_MODULATION is equal to ERP-DSSS or ERP-CCK, refer to the transmit procedure in 15.3.6 or 16.2.5, respectively.

NOTE—The transmit procedure and state machine for Clause 18 when TXVECTOR parameter NON_HT_MODULATION is ERP-OFDM is described in 17.3.11, except for the signal extension (refer to 18.3.2.4).

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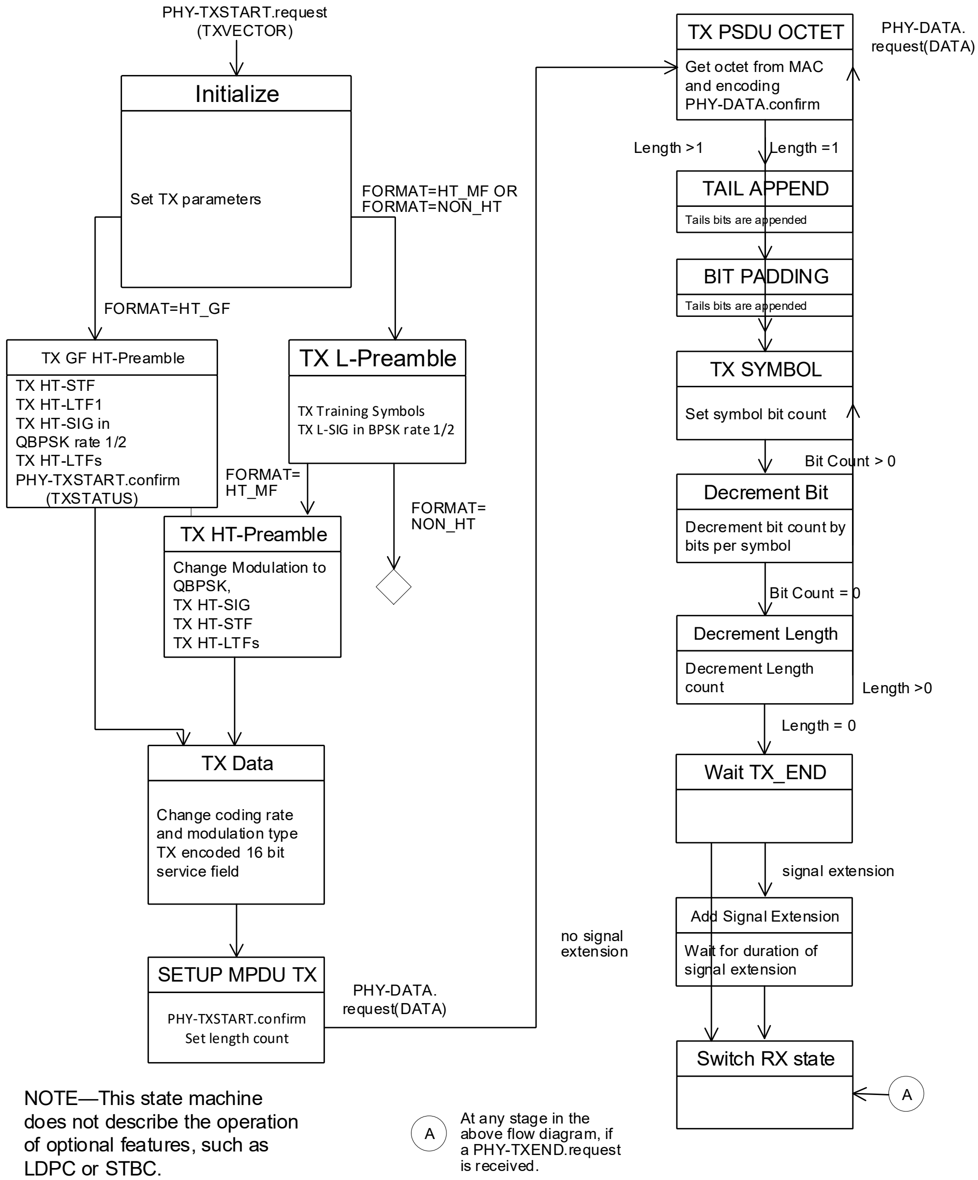

Figure 19-24—PHY transmit state machine

19.3.21 PHY receive procedure

Typical PHY receive procedures are shown in Figure 19-25 and Figure 19-26. The receive procedures correspond to HT-mixed format and HT-greenfield format, respectively. A typical state machine implementation of the receive PHY is given in Figure 19-27. These receive procedures and state machine do not describe the operation of optional features, such as LDPC or STBC. If the detected format indicates a non-HT PPDU format (denoted “Not HT-SIG” in Figure 19-27), refer to the receive procedure and state machine in 17.3.12 or 18.3.5. Further, through station management (via the PLME), the PHY is set to the appropriate frequency, as specified in 19.4. Other receive parameters, such as RSSI and indicated DATARATE, may be accessed via the PHY SAP.

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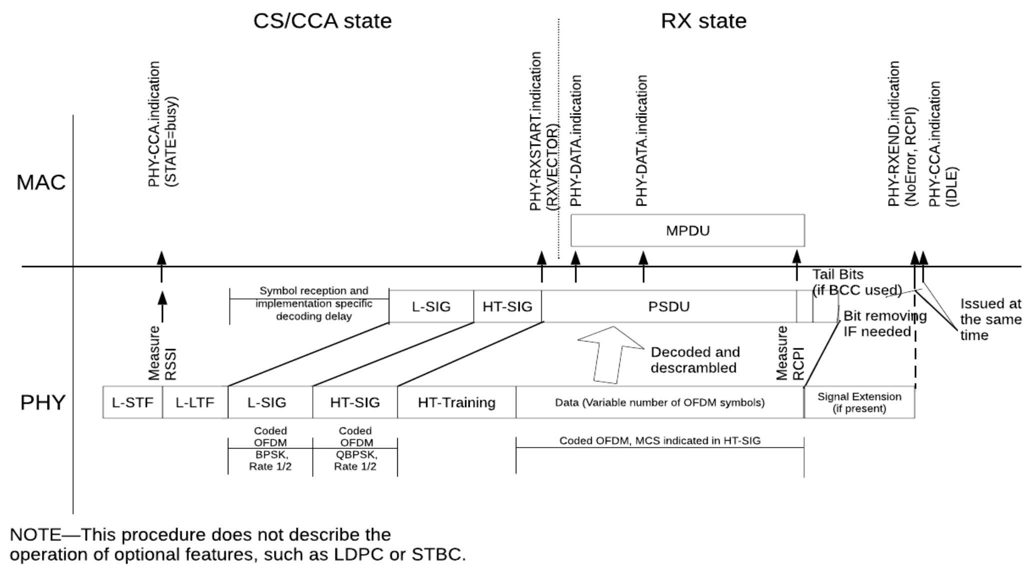

Figure 19-25—PHY receive procedure for HT-mixed format PPDU

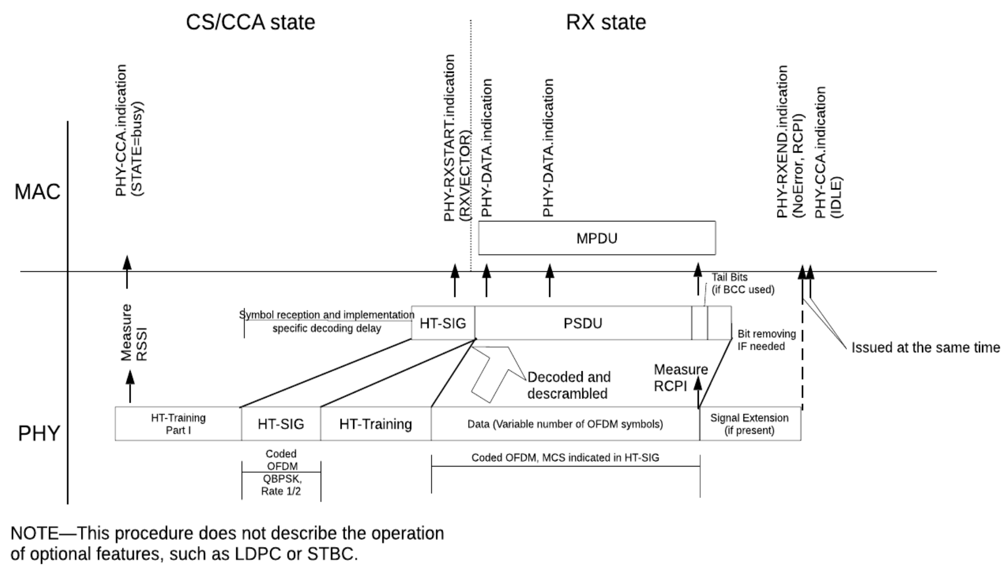

Figure 19-26—PHY receive procedure for HT-greenfield format PPDU

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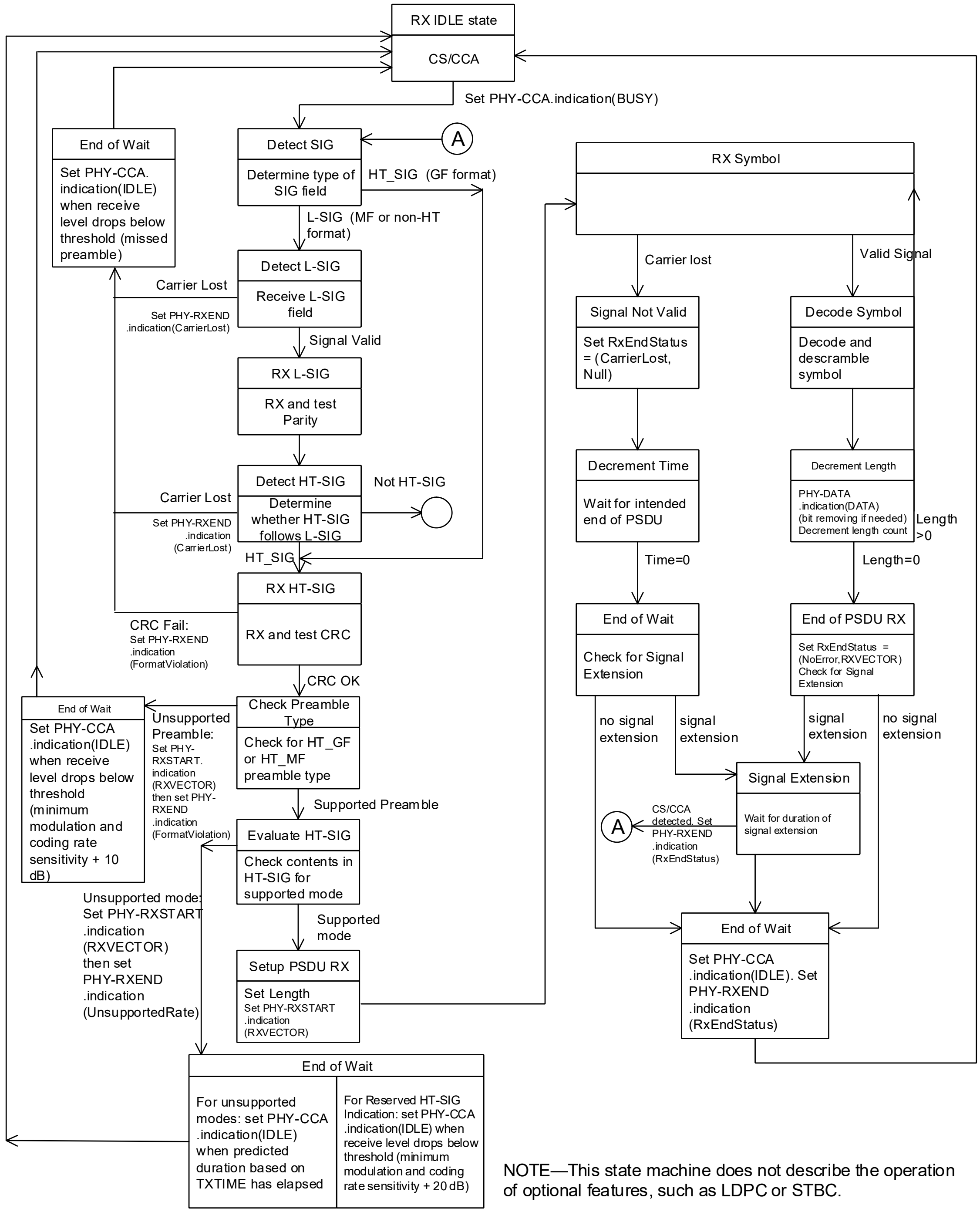

NOTE—This state machine does not describe the operation of optional features, such as LDPC or STBC.

Figure 19-27—PHY receive state machine

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Upon receiving the transmitted PHY preamble, the PHY measures a receive signal strength. This indicates activity to the MAC via the PHY-CCA.indication primitive. A PHY-CCA.indication(BUSY, channel-list) primitive shall also be issued as an initial indication of reception of a signal. The channel-list parameter of the PHY-CCA.indication primitive is set as follows:

— It is absent when the operating channel width is 20 MHz.
— It is set to {primary} when the operating channel width is 40 MHz and the signal is present only in the primary channel.
— It is set to {secondary} when the operating channel width is 40 MHz and the signal is present only in the secondary channel.
— It is set to {primary, secondary} when the operating channel width is 40 MHz and the signal is present in both the primary and secondary channels.

The RSSI parameter is reported to the MAC in the RXVECTOR.

After the PHY-CCA.indication(BUSY, channel-list) primitive is issued, the PHY entity shall begin receiving the training symbols and searching for SIGNAL and HT-SIG in order to set the length of the data stream, the demodulation type, code type, and the decoding rate. If signal loss occurs before validating L-SIG and/or HT-SIG, the HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive until the received level drops below the CCA sensitivity level (for a missed preamble) specified in 19.3.19.5. If the check of the HT-SIG CRC is not valid, a PHY-RXSTART.indication primitive is not issued. The PHY shall indicate the error condition by issuing a PHY-RXEND.indication(FormatViolation) primitive. The HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive until the received level drops below the CCA sensitivity level (for a missed preamble) specified in 19.3.19.5.

If the PHY preamble reception is successful and a valid HT-SIG CRC is indicated:

— Upon reception of an HT-mixed format preamble, the HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive for the predicted duration of the transmitted frame, as defined by TXTIME in 19.4.3, for all supported and unsupported modes except Reserved HT-SIG Indication. Reserved HT-SIG Indication is defined in the fourth item below.
— Upon reception of a GF preamble by an HT STA that does not support GF, the HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive until either the predicted duration of the packet from the contents of the HT-SIG field, as defined by TXTIME in 19.4.3, except Reserved HT-SIG Indication, elapses or until the received level drops below the receiver minimum sensitivity level of BPSK, R=1/2 in Table 19-23 + 10 dB (–72 dBm for 20 MHz, –69 dBm for 40 MHz). Reserved HT-SIG Indication is defined in the fourth item below.
— Upon reception of a GF preamble by an HT STA that supports GF, the HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive for the predicted duration of the transmitted frame, as defined by TXTIME in 19.4.3, for all supported and unsupported modes except Reserved HT-SIG Indication. Reserved HT-SIG Indication is defined in the fourth item below.
— If the HT-SIG indicates a Reserved HT-SIG Indication, the HT PHY shall not generate a PHY-CCA.indication(IDLE) primitive until the received level drops below the CCA sensitivity level (minimum modulation and coding rate sensitivity + 20 dB) specified in 19.3.19.5. Reserved HT-SIG Indication is defined as an HT-SIG with MCS field in the range 77–127 or Reserved field = 0 or STBC field = 3 and any other HT-SIG field bit combinations that do not correspond to modes of PHY operation defined in Clause 19.

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Subsequent to an indication of a valid HT-SIG CRC, a PHY-RXSTART.indication(RXVECTOR) primitive shall be issued. If dot11TimingMsmtActivated is true, the PHY shall do the following:

— Complete receiving the PHY header and verify the validity of the PHY Header.
— If the PHY header reception is successful (and the SIGNAL field is completely recognizable and supported), a PHY-RXSTART.indication(RXVECTOR) primitive shall be issued and RX_START_OF_FRAME_OFFSET parameter within the RXVECTOR shall be forwarded (see 19.2.2).

NOTE—The RX_START_OF_FRAME_OFFSET value is used as described in 6.3.55 in order to estimate when the start of the preamble for the incoming frame was detected on the medium at the receive antenna connector.

The RXVECTOR associated with this primitive includes the parameters specified in Table 19-1. Upon reception of a GF preamble by an HT STA that does not support GF, the FORMAT field of RXVECTOR is equal to HT_GF, the remaining fields may be empty, and the PHY shall indicate the error condition by issuing a PHY-RXEND.indication(FormatViolation) primitive. If the HT-SIG indicates an unsupported mode or Reserved HT-SIG Indication, the PHY shall indicate the error condition by issuing a PHY-RXEND.indication(UnsupportedRate) primitive.

Following training and SIGNAL fields, the coded PSDU (which comprises the coded PHY SERVICE field and scrambled and coded PSDU) shall be received. If signal loss occurs during reception prior to completion of the PSDU reception, the error condition shall be reported to the MAC using a PHY-RXEND.indication(CarrierLost) primitive. After waiting for the intended end of the PSDU, if no signal extension is present (as defined in 19.3.2), the PHY shall generate a PHY-CCA.indication(IDLE) primitive and return to RX IDLE state. Otherwise, the receiver waits for the duration of the signal extension before returning to the RX IDLE state.

The received PSDU bits are assembled into octets, decoded, and presented to the MAC using a series of PHY-DATA.indication(DATA) primitive exchanges. The number of PSDU octets is indicated in the HT Length field of the HT-SIG. The PHY shall proceed with PSDU reception. After the reception of the final bit of the last PSDU octet and possible tail and padding bits, the receiver shall be returned to the RX IDLE state if no signal extension is present (as defined in 19.3.2), as shown in Figure 19-27. Otherwise, the receiver waits for the duration of the signal extension before returning to the RX IDLE state. A PHY-RXEND.indication(NoError) primitive shall be issued on entry to the RX IDLE state.

While in the Signal Extension state, if the receiver detects a CS/CCA event, it issues an RXEND.indication primitive (with the RXERROR parameter set to NoError or CarrierLost, depending on whether a carrier lost event occurred during the reception of the PPDU), leaves the Signal Extension state, and enters the Detect SIG state. This sequence occurs when signal-extended PPDUs are transmitted while separated by a RIFS.

If the BCC is used, any data received after the indicated data length are considered pad bits (to fill out an OFDM symbol) and should be discarded.

19.4 HT PLME

19.4.1 PLME SAP sublayer management primitives

Table 19-24 lists the MIB attributes that may be accessed by the PHY entities and the intralayer of higher level LMEs. These attributes are accessed via the PLME-GET, PLME-SET, PLME-RESET, and PLME-CHARACTERISTICS primitives defined in 6.2 and 6.5.4.

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Table 19-24—HT PHY MIB attributes

Managed object	Default value/range	Operational semantics
dot11PHYOperationTable		
dot11PHYType	HT (X'07')	Static
dot11CurrentRegDomain	Implementation dependent	Dynamic
dot11PHYAntennaTable		
dot11CurrentTxAntenna	Implementation dependent	Dynamic
dot11DiversitySupportImplemented	Implementation dependent	Static
dot11CurrentRxAntenna	Implementation dependent	Dynamic
dot11AntennaSelectionOptionImplemented	false/Boolean	Static
dot11TransmitExplicitCSIFeedbackASOptionImplemented	false/Boolean	Static
dot11TransmitIndicesFeedbackASOptionImplemented	false/Boolean	Static
dot11ExplicitCSIFeedbackASOptionImplemented	false/Boolean	Static
dot11TransmitIndicesComputationASOptionImplemented	false/Boolean	Static
dot11ReceiveAntennaSelectionOptionImplemented	false/Boolean	Static
dot11TransmitSoundingPPDUOptionImplemented	false/Boolean	Static
dot11PHYTxPowerTable		
dot11NumberSupportedPowerLevelsImplemented	Implementation dependent	Static
dot11TxPowerLevel1	Implementation dependent	Static
dot11TxPowerLevel2	Implementation dependent	Static
dot11TxPowerLevel3	Implementation dependent	Static
dot11TxPowerLevel4	Implementation dependent	Static
dot11TxPowerLevel5	Implementation dependent	Static
dot11TxPowerLevel6	Implementation dependent	Static
dot11TxPowerLevel7	Implementation dependent	Static
dot11TxPowerLevel8	Implementation dependent	Static
dot11CurrentTxPowerLevel	Implementation dependent	Dynamic
dot11PhyDSSSTable		
dot11CurrentChannel	Implementation dependent	Dynamic
dot11RegDomainsSupportedTable		
dot11RegDomainsImplementedValue	Implementation dependent	Static
dot11FrequencyBandsSupported	Implementation dependent	Static

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Table 19-24—HT PHY MIB attributes *(continued)*

Managed object	Default value/range	Operational semantics
dot11PHYAntennasListTable		
dot11SupportedTxAntenna	Implementation dependent	Dynamic
dot11SupportedRxAntenna	Implementation dependent	Static
dot11DiversitySelectionRx	Implementation dependent	Dynamic
dot11SupportedDataRatesTxTable		
dot11SupportedDataratesTxValue	X'02' = 1 Mb/s (2.4) X'04' = 2 Mb/s (2.4) X'0B' = 5.5 Mb/s (2.4) X'16' = 11 Mb/s (2.4) X'0C' = 6 Mb/s X'12' = 9 Mb/s X'18' = 12 Mb/s X'24' = 18 Mb/s X'30' = 24 Mb/s X'48' = 36 Mb/s X'60' = 48 Mb/s X'6C' = 54 Mb/s	Static
dot11SupportedDataRatesRxTable		
dot11SupportedDataRatesRxTable	X'02' = 1 Mb/s (2.4) X'04' = 2 Mb/s (2.4) X'0B' = 5.5 Mb/s (2.4) X'16' = 11 Mb/s (2.4) X'0C' = 6 Mb/s X'12' = 9 Mb/s X'18' = 12 Mb/s X'24' = 18 Mb/s X'30' = 24 Mb/s X'48' = 36 Mb/s X'60' = 48 Mb/s X'6C' = 54 Mb/s	Static
dot11HRDSSSPHYTable		
dot11ShortPreambleOptionImplemented	true	Static
dot11PHYOFDMTable		
dot11CurrentFrequency	Implementation dependent	Dynamic
dot11TIThreshold	Implementation dependent	Dynamic
dot11ChannelStartingFactor	Implementation dependent	Dynamic
dot11PHYERPTable		
dot11ShortSlotTimeOptionImplemented	Implementation dependent	Static
dot11ShortSlotTimeOptionActivated	Implementation dependent	Dynamic

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Table 19-24—HT PHY MIB attributes *(continued)*

Managed object	Default value/range	Operational semantics
dot11PHYHTTable		
dot11FortyMHzOperationImplemented	false/Boolean	Static
dot11FortyMHzOperationActivated	false/Boolean	Dynamic
dot11CurrentPrimaryChannel	Implementation dependent	Dynamic
dot11CurrentSecondaryChannel	Implementation dependent	Dynamic
dot11NumberOfSpatialStreamsImplemented	Implementation dependent	Static
dot11NumberOfSpatialStreamsActivated	Implementation dependent	Dynamic
dot11HTGreenfieldOptionImplemented	false/Boolean	Static
dot11HTGreenfieldOptionActivated	false/Boolean	Dynamic
dot11ShortGIOptionInTwentyImplemented	false/Boolean	Static
dot11ShortGIOptionInTwentyActivated	false/Boolean	Dynamic
dot11ShortGIOptionInFortyImplemented	false/Boolean	Static
dot11ShortGIOptionInFortyActivated	false/Boolean	Dynamic
dot11LDPCCodingOptionImplemented	false/Boolean	Static
dot11LDPCCodingOptionActivated	false/Boolean	Dynamic
dot11TxSTBCOptionImplemented	false/Boolean	Static
dot11TxSTBCOptionActivated	false/Boolean	Dynamic
dot11RxSTBCOptionImplemented	false/Boolean	Static
dot11RxSTBCOptionActivated	false/Boolean	Dynamic
dot11BeamFormingOptionImplemented	false/Boolean	Static
dot11BeamFormingOptionActivated	false/Boolean	Dynamic
dot11SupportedHTMCSTxTable		
dot11SupportedHTMCSTxValue	MCS 0–76 for 20 MHz; MCS 0–76 for 40 MHz (MCS 0–7 for 20 MHz mandatory at non-AP STA and at AP that is a VHT AP; MCS 0–15 for 20 MHz mandatory at AP that is not a VHT AP)	Static

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Table 19-24—HT PHY MIB attributes *(continued)*

Managed object	Default value/range	Operational semantics
dot11SupportedHTMCSRxTable		
dot11SupportedHTMCSRxValue	MCS 0–76 for 20 MHz; MCS 0–76 for 40 MHz (MCS 0–7 for 20 MHz mandatory at non-AP STA and at AP that is a VHT AP; MCS 0–15 for 20 MHz mandatory at AP that is not a VHT AP)	Static
dot11TransmitBeamformingConfigTable		
dot11ReceiveStaggerSoundingOptionImplemented	false/Boolean	Static
dot11TransmitStaggerSoundingOptionImplemented	false/Boolean	Static
dot11ReceiveNDPOptionImplemented	false/Boolean	Static
dot11TransmitNDPOptionImplemented	false/Boolean	Static
dot11ImplicitTransmitBeamformingOptionImplemented	false/Boolean	Static
dot11CalibrationOptionImplemented	Implementation dependent	Static
dot11ExplicitCSITransmitBeamformingOptionImplemented	false/Boolean	Static
dot11ExplicitNonCompressedBeamformingMatrixOption-Implemented	false/Boolean	Static
dot11ExplicitTransmitBeamformingCSIFeedbackOption-Implemented	Implementation dependent	Static
dot11ExplicitNoncompressedBeamformingFeedbackOption-Implemented	Implementation dependent	Static
dot11ExplicitCompressedBeamformingFeedbackOption-Implemented	Implementation dependent	Static
dot11NumberBeamFormingCSISupportAntenna	Implementation dependent	Static
dot11NumberNonCompressedBeamformingMatrixSupport-Antenna	Implementation dependent	Static
dot11NumberCompressedBeamformingMatrixSupportAntenna	Implementation dependent	Static
dot11TxMCSSetDefined	false/Boolean	Static
dot11TxRxMCSSetNotEqual	false/Boolean	Static
dot11TxMaximumNumberSpatialStreamsSupported	false/Boolean	Static
dot11TxUnequalModulationSupported	false/Boolean	Static

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19.4.2 PHY MIB

HT PHY MIB attributes are defined in Annex C with specific values defined in Table 19-24. The "Operational semantics" column in Table 19-24 contains two types: static and dynamic.

- Static MIB attributes are fixed and cannot be modified for a given PHY implementation.
- Dynamic MIB attributes are interpreted according to the MAX-ACCESS field of the MIB attribute. When MAX-ACCESS is equal to read-only, the MIB attribute value may be updated by the PLME and read from the MIB attribute by management entities. When MAX-ACCESS is equal to read-write, the MIB attribute may be read and written by management entities.

19.4.3 TXTIME calculation

The value of the TXTIME parameter returned by the PLME-TXTIME.confirm primitive or calculated for the PHY receive procedure shall be calculated for HT-mixed format according to the Equation (19-90) and Equation (19-91) for short and long GI, respectively, and for HT-greenfield format according to Equation (19-92) and Equation (19-93) for short and long, respectively:

$$\begin{aligned}\text{TXTIME} = {} & T_{LEG\_PREAMBLE} + T_{L\_SIG} + T_{HT\_TRAINING} + T_{HT\_SIG} \\ & + T_{SYM} \times \left\lceil \frac{T_{SYMS} \times N_{SYM}}{T_{SYM}} \right\rceil + SignalExtension\end{aligned} \tag{19-90}$$

$$\begin{aligned}\text{TXTIME} = {} & T_{LEG\_PREAMBLE} + T_{L\_SIG} + T_{HT\_TRAINING} + T_{HT\_SIG} \\ & + T_{\text{SYM}} \times N_{SYM} + SignalExtension\end{aligned} \tag{19-91}$$

$$\text{TXTIME} = T_{GF\_HT\_TRAINING} + T_{HT\_SIG} + T_{SYMS} \times N_{SYM} + SignalExtension \tag{19-92}$$

$$\text{TXTIME} = T_{GF\_HT\_TRAINING} + T_{HT\_SIG} + T_{SYM} \times N_{SYM} + SignalExtension \tag{19-93}$$

where

$T_{LEG\_PREAMBLE} = T_{L\text{-}STF} + T_{L\text{-}LTF}$ is the duration of the non-HT preamble

$T_{HT\_TRAINING}$ is the duration of the HT-STF and HT-LTFs in HT-mixed format, given by $T_{HT-STF} + T_{HT-LTF1} + (N_{HT\text{-}LTF} - 1)T_{HT-LTFs}$

$T_{GF\_HT\_TRAINING}$ is the duration of the HT-GF-STF, HT-LTF1 and HT-LTFs in HT-greenfield format, given by $T_{HT-GF-STF} + T_{HT-LTF1} + (N_{HT\text{-}LTF} - 1)T_{HT-LTFs}$

T_{SYM}, T_{SYMS}, $T_{HT\text{-}SIG}$, $T_{L\text{-}STF}$, $T_{HT\text{-}STF}$, $T_{HT\text{-}GF\text{-}STF}$, $T_{L\text{-}LTF}$, $T_{HT\text{-}LTF1}$ and $T_{HT\text{-}LTFs}$ are defined in Table 19-6

SignalExtension is 0 µs when TXVECTOR parameter NO_SIG_EXTN is true and is aSignalExtension as defined in Table 19-25 when TXVECTOR parameter NO_SIG_EXTN is false

$N_{HT\text{-}LTF}$ is defined in Equation (19-22)

N_{SYM} is defined in Equation (19-32) for BCC and Equation (19-41) for LDPC

For non-HT modes of operation, refer to Clause 17 and Clause 18 for TXTIME calculations, except that frames transmitted with a value of NON_HT_DUP_OFDM for the TXVECTOR parameter NON_HT_MODULATION shall use Equation (18-1) for TXTIME calculation.

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19.4.4 HT PHY

The static HT PHY characteristics, provided through the PLME-CHARACTERISTICS service primitive, shall be as shown in Table 19-25. The definitions for these characteristics are given in 6.5.4

Table 19-25—HT PHY characteristics

Characteristics	Value
aRIFSTime	2 μs
aSlotTime	When operating in the 2.4 GHz band: If dot11OperatingClassesRequired is false, long slot time = 20 μs If dot11OperatingClassesRequired is true, long slot time = 20 μs plus any coverage-class-dependent aAirPropagationTime (see Table 9-95) If dot11OperatingClassesRequired is false, short slot time = 9 μs If dot11OperatingClassesRequired is true, short slot time= 9 μs plus any coverage-class-dependent aAirPropagationTime (see Table 9-95) When operating in the 5 GHz band: If dot11OperatingClassesRequired is false, 9 μs If dot11OperatingClassesRequired is true, 9 μs plus any coverage-class-dependent aAirPropagationTime (see Table 9-95)
aSIFSTime	10 μs when operating in the 2.4 GHz band 16 μs when operating in the 5 GHz bands
aSignalExtension	0 μs when operating in the 5 GHz band 6 μs when operating in the 2.4 GHz band
aCCATime	Implementation dependent, see 10.3.7.
aRxPHYStartDelay	28 μs for HT-mixed format, 24 μs for HT-greenfield format
aRxTxTurnaroundTime	Implementation dependent, see 10.3.7.
aTxPHYDelay	Implementation dependent, see 10.3.7.
aRxPHYDelay	Implementation dependent, see 10.3.7.
aRxTxSwitchTime	Implementation dependent, see 10.3.7.
aTxRampOnTime	Implementation dependent, see 10.3.7.
aAirPropagationTime	As indicated by the coverage class (see 10.22.5).
aMACProcessingDelay	Implementation dependent, see 10.3.7.
aPSDUMaxLength	65 535 octets
aPPDUMaxTime	10 ms
aIUStime	8 μs
aDTT2UTTTime	32 μs
aCWmin	15
aCWmax	1023
aMaxCSIMatricesReportDelay	250 ms

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For non-HT modes of operation, refer to Clause 17 and Clause 18 for PHY characteristics.

19.5 Parameters for HT-MCSs

Table 19-26 defines the symbols used in the rate-dependent parameter tables.

Table 19-26—Symbols used in MCS parameter tables

Symbol	Explanation
N_{SS}	Number of spatial streams
R	Coding rate
N_{BPSC}	Number of coded bits per single carrier (total across spatial streams)
$N_{BPSCS}(i_{SS})$	Number of coded bits per single carrier for each spatial stream, $i_{SS} = 1,...,N_{SS}$
N_{SD}	Number of complex data numbers per spatial stream per OFDM symbol
N_{SP}	Number of pilot values per OFDM symbol
N_{CBPS}	Number of coded bits per OFDM symbol
N_{DBPS}	Number of data bits per OFDM symbol
N_{ES}	Number of BCC encoders for the DATA field

In the MCS parameter tables that follow, data rates for a 400 ns GI are rounded to 1 decimal place.

The rate-dependent parameters for mandatory 20 MHz, $N_{SS} = 1$ MCSs with $N_{ES} = 1$ shall be as shown in Table 19-27.

Table 19-27—MCS parameters for mandatory 20 MHz, N_{SS} = 1, N_{ES} = 1

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI (see NOTE)
0	BPSK	1/2	1	52	4	52	26	6.5	7.2
1	QPSK	1/2	2	52	4	104	52	13.0	14.4
2	QPSK	3/4	2	52	4	104	78	19.5	21.7
3	16-QAM	1/2	4	52	4	208	104	26.0	28.9
4	16-QAM	3/4	4	52	4	208	156	39.0	43.3
5	64-QAM	2/3	6	52	4	312	208	52.0	57.8
6	64-QAM	3/4	6	52	4	312	234	58.5	65.0
7	64-QAM	5/6	6	52	4	312	260	65.0	72.2
NOTE—Support of 400 ns GI is optional on transmit and receive.									

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The rate-dependent parameters for optional 20 MHz, N_{SS} = 2 MCSs with N_{ES} = 1 and EQM of the spatial streams shall be as shown in Table 19-28.

Table 19-28—MCS parameters for optional 20 MHz, N_{SS} = 2, N_{ES} = 1, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
8	BPSK	1/2	1	52	4	104	52	13.0	14.4
9	QPSK	1/2	2	52	4	208	104	26.0	28.9
10	QPSK	3/4	2	52	4	208	156	39.0	43.3
11	16-QAM	1/2	4	52	4	416	208	52.0	57.8
12	16-QAM	3/4	4	52	4	416	312	78.0	86.7
13	64-QAM	2/3	6	52	4	624	416	104.0	115.6
14	64-QAM	3/4	6	52	4	624	468	117.0	130.0
15	64-QAM	5/6	6	52	4	624	520	130.0	144.4

The rate-dependent parameters for optional 20 MHz, N_{SS} = 3 MCSs with N_{ES} = 1 and EQM of the spatial streams shall be as shown in Table 19-29.

Table 19-29—MCS parameters for optional 20 MHz, N_{SS} = 3, N_{ES} = 1, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
16	BPSK	1/2	1	52	4	156	78	19.5	21.7
17	QPSK	1/2	2	52	4	312	156	39.0	43.3
18	QPSK	3/4	2	52	4	312	234	58.5	65.0
19	16-QAM	1/2	4	52	4	624	312	78.0	86.7
20	16-QAM	3/4	4	52	4	624	468	117.0	130.0
21	64-QAM	2/3	6	52	4	936	624	156.0	173.3
22	64-QAM	3/4	6	52	4	936	702	175.5	195.0
23	64-QAM	5/6	6	52	4	936	780	195.0	216.7

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The rate-dependent parameters for optional 20 MHz, N_{SS} = 4 MCSs with N_{ES} = 1 and EQM of the spatial streams shall be as shown in Table 19-30.

Table 19-30—MCS parameters for optional 20 MHz, N_{SS} = 4, N_{ES} = 1, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
24	BPSK	1/2	1	52	4	208	104	26.0	28.9
25	QPSK	1/2	2	52	4	416	208	52.0	57.8
26	QPSK	3/4	2	52	4	416	312	78.0	86.7
27	16-QAM	1/2	4	52	4	832	416	104.0	115.6
28	16-QAM	3/4	4	52	4	832	624	156.0	173.3
29	64-QAM	2/3	6	52	4	1248	832	208.0	231.1
30	64-QAM	3/4	6	52	4	1248	936	234.0	260.0
31	64-QAM	5/6	6	52	4	1248	1040	260.0	288.9

The rate-dependent parameters for optional 40 MHz, N_{SS} = 1 MCSs with N_{ES} = 1 shall be as shown in Table 19-31.

Table 19-31—MCS parameters for optional 40 MHz, N_{SS} = 1, N_{ES} = 1

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
0	BPSK	1/2	1	108	6	108	54	13.5	15.0
1	QPSK	1/2	2	108	6	216	108	27.0	30.0
2	QPSK	3/4	2	108	6	216	162	40.5	45.0
3	16-QAM	1/2	4	108	6	432	216	54.0	60.0
4	16-QAM	3/4	4	108	6	432	324	81.0	90.0
5	64-QAM	2/3	6	108	6	648	432	108.0	120.0
6	64-QAM	3/4	6	108	6	648	486	121.5	135.0
7	64-QAM	5/6	6	108	6	648	540	135.0	150.0

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The rate-dependent parameters for optional 40 MHz, N_{SS} = 2 MCSs with N_{ES} = 1 and EQM of the spatial streams shall be as shown in Table 19-32.

Table 19-32—MCS parameters for optional 40 MHz, N_{SS} = 2, N_{ES} = 1, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
8	BPSK	1/2	1	108	6	216	108	27.0	30.0
9	QPSK	1/2	2	108	6	432	216	54.0	60.0
10	QPSK	3/4	2	108	6	432	324	81.0	90.0
11	16-QAM	1/2	4	108	6	864	432	108.0	120.0
12	16-QAM	3/4	4	108	6	864	648	162.0	180.0
13	64-QAM	2/3	6	108	6	1296	864	216.0	240.0
14	64-QAM	3/4	6	108	6	1296	972	243.0	270.0
15	64-QAM	5/6	6	108	6	1296	1080	270.0	300.0

The rate-dependent parameters for optional 40 MHz, N_{SS} = 3 MCSs, with EQM of the spatial streams shall be as shown in Table 19-33.

Table 19-33—MCS parameters for optional 40 MHz, N_{SS} = 3, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mb/s)	
									800 ns GI	400 ns GI
16	BPSK	1/2	1	108	6	324	162	1	40.5	45.0
17	QPSK	1/2	2	108	6	648	324	1	81.0	90.0
18	QPSK	3/4	2	108	6	648	486	1	121.5	135.0
19	16-QAM	1/2	4	108	6	1296	648	1	162.0	180.0
20	16-QAM	3/4	4	108	6	1296	972	1	243.0	270.0
21	64-QAM	2/3	6	108	6	1944	1296	2	324.0	360.0
22	64-QAM	3/4	6	108	6	1944	1458	2	364.5	405.0
23	64-QAM	5/6	6	108	6	1944	1620	2	405.0	450.0

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The rate-dependent parameters for optional 40 MHz, N_{SS} = 4 MCSs, with EQM of the spatial streams shall be as shown in Table 19-34.

Table 19-34—MCS parameters for optional 40 MHz, N_{SS} = 4, EQM

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mb/s)	
									800 ns GI	400 ns GI
24	BPSK	1/2	1	108	6	432	216	1	54.0	60.0
25	QPSK	1/2	2	108	6	864	432	1	108.0	120.0
26	QPSK	3/4	2	108	6	864	648	1	162.0	180.0
27	16-QAM	1/2	4	108	6	1728	864	1	216.0	240.0
28	16-QAM	3/4	4	108	6	1728	1296	2	324.0	360.0
29	64-QAM	2/3	6	108	6	2592	1728	2	432.0	480.0
30	64-QAM	3/4	6	108	6	2592	1944	2	486.0	540.0
31	64-QAM	5/6	6	108	6	2592	2160	2	540.0	600.0

The rate-dependent parameters for optional 40 MHz MCS 32 format with N_{SS} = 1 and N_{ES} = 1 shall be as shown in Table 19-35.

Table 19-35—MCS parameters for optional 40 MHz MCS 32 format, N_{SS} = 1, N_{ES} = 1

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI
32	BPSK	1/2	1	48	4	48	24	6.0	6.7

The rate-dependent parameters for optional 20 MHz, N_{SS} = 2 MCSs with N_{ES} = 1 and UEQM of the spatial streams shall be as shown in Table 19-36.

Table 19-36—MCS parameters for optional 20 MHz, N_{SS} = 2, N_{ES} = 1, UEQM

MCS Index	Modulation		R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2							800 ns GI	400 ns GI
33	16-QAM	QPSK	1/2	6	52	4	312	156	39	43.3
34	64-QAM	QPSK	1/2	8	52	4	416	208	52	57.8
35	64-QAM	16-QAM	1/2	10	52	4	520	260	65	72.2
36	16-QAM	QPSK	3/4	6	52	4	312	234	58.5	65.0
37	64-QAM	QPSK	3/4	8	52	4	416	312	78	86.7
38	64-QAM	16-QAM	3/4	10	52	4	520	390	97.5	108.3

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The rate-dependent parameters for optional 20 MHz, N_{SS} = 3 MCSs with N_{ES} = 1 and UEQM of the spatial streams shall be as shown in Table 19-37.

Table 19-37—MCS parameters for optional 20 MHz, N_{SS} = 3, N_{ES} = 1, UEQM

MCS Index	Modulation			R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3							800 ns GI	400 ns GI
39	16-QAM	QPSK	QPSK	1/2	8	52	4	416	208	52	57.8
40	16-QAM	16-QAM	QPSK	1/2	10	52	4	520	260	65	72.2
41	64-QAM	QPSK	QPSK	1/2	10	52	4	520	260	65	72.2
42	64-QAM	16-QAM	QPSK	1/2	12	52	4	624	312	78	86.7
43	64-QAM	16-QAM	16-QAM	1/2	14	52	4	728	364	91	101.1
44	64-QAM	64-QAM	QPSK	1/2	14	52	4	728	364	91	101.1
45	64-QAM	64-QAM	16-QAM	1/2	16	52	4	832	416	104	115.6
46	16-QAM	QPSK	QPSK	3/4	8	52	4	416	312	78	86.7
47	16-QAM	16-QAM	QPSK	3/4	10	52	4	520	390	97.5	108.3
48	64-QAM	QPSK	QPSK	3/4	10	52	4	520	390	97.5	108.3
49	64-QAM	16-QAM	QPSK	3/4	12	52	4	624	468	117	130.0
50	64-QAM	16-QAM	16-QAM	3/4	14	52	4	728	546	136.5	151.7
51	64-QAM	64-QAM	QPSK	3/4	14	52	4	728	546	136.5	151.7
52	64-QAM	64-QAM	16-QAM	3/4	16	52	4	832	624	156	173.3

The rate-dependent parameters for optional 20 MHz, N_{SS} = 4 MCSs with N_{ES} = 1 and UEQM in the spatial streams shall be as shown in Table 19-38.

Table 19-38—MCS parameters for optional 20 MHz, N_{SS} = 4, N_{ES} = 1, UEQM

MCS Index	Modulation				R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3	Stream 4							800 ns GI	400 ns GI
53	16-QAM	QPSK	QPSK	QPSK	1/2	10	52	4	520	260	65	72.2
54	16-QAM	16-QAM	QPSK	QPSK	1/2	12	52	4	624	312	78	86.7
55	16-QAM	16-QAM	16-QAM	QPSK	1/2	14	52	4	728	364	91	101.1
56	64-QAM	QPSK	QPSK	QPSK	1/2	12	52	4	624	312	78	86.7
57	64-QAM	16-QAM	QPSK	QPSK	1/2	14	52	4	728	364	91	101.1
58	64-QAM	16-QAM	16-QAM	QPSK	1/2	16	52	4	832	416	104	115.6
59	64-QAM	16-QAM	16-QAM	16-QAM	1/2	18	52	4	936	468	117	130.0

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Table 19-38—MCS parameters for optional 20 MHz, N_{SS} = 4, N_{ES} = 1, UEQM *(continued)*

MCS Index	Modulation				R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3	Stream 4							800 ns GI	400 ns GI
60	64-QAM	64-QAM	QPSK	QPSK	1/2	16	52	4	832	416	104	115.6
61	64-QAM	64-QAM	16-QAM	QPSK	1/2	18	52	4	936	468	117	130.0
62	64-QAM	64-QAM	16-QAM	16-QAM	1/2	20	52	4	1040	520	130	144.4
63	64-QAM	64-QAM	64-QAM	QPSK	1/2	20	52	4	1040	520	130	144.4
64	64-QAM	64-QAM	64-QAM	16-QAM	1/2	22	52	4	1144	572	143	158.9
65	16-QAM	QPSK	QPSK	QPSK	3/4	10	52	4	520	390	97.5	108.3
66	16-QAM	16-QAM	QPSK	QPSK	3/4	12	52	4	624	468	117	130.0
67	16-QAM	16-QAM	16-QAM	QPSK	3/4	14	52	4	728	546	136.5	151.7
68	64-QAM	QPSK	QPSK	QPSK	3/4	12	52	4	624	468	117	130.0
69	64-QAM	16-QAM	QPSK	QPSK	3/4	14	52	4	728	546	136.5	151.7
70	64-QAM	16-QAM	16-QAM	QPSK	3/4	16	52	4	832	624	156	173.3
71	64-QAM	16-QAM	16-QAM	16-QAM	3/4	18	52	4	936	702	175.5	195.0
72	64-QAM	64-QAM	QPSK	QPSK	3/4	16	52	4	832	624	156	173.3
73	64-QAM	64-QAM	16-QAM	QPSK	3/4	18	52	4	936	702	175.5	195.0
74	64-QAM	64-QAM	16-QAM	16-QAM	3/4	20	52	4	1040	780	195	216.7
75	64-QAM	64-QAM	64-QAM	QPSK	3/4	20	52	4	1040	780	195	216.7
76	64-QAM	64-QAM	64-QAM	16-QAM	3/4	22	52	4	1144	858	214.5	238.3

The rate-dependent parameters for optional 40 MHz, N_{SS} = 2 MCSs with N_{ES} = 1 and UEQM of the spatial streams shall be as shown in Table 19-39.

Table 19-39—MCS parameters for optional 40 MHz, N_{SS} = 2, N_{ES} = 1, UEQM

MCS Index	Modulation		R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2							800 ns GI	400 ns GI
33	16-QAM	QPSK	1/2	6	108	6	648	324	81	90
34	64-QAM	QPSK	1/2	8	108	6	864	432	108	120
35	64-QAM	16-QAM	1/2	10	108	6	1080	540	135	150
36	16-QAM	QPSK	3/4	6	108	6	648	486	121.5	135
37	64-QAM	QPSK	3/4	8	108	6	864	648	162	180
38	64-QAM	16-QAM	3/4	10	108	6	1080	810	202.5	225

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The rate-dependent parameters for optional 40 MHz, N_{SS} = 3 MCSs, with UEQM of the spatial streams shall be as shown in Table 19-40.

Table 19-40—MCS parameters for optional 40 MHz, N_{SS} = 3, UEQM

MCS Index	Modulation			R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3								800 ns GI	400 ns GI
39	16-QAM	QPSK	QPSK	1/2	8	108	6	864	432	1	108	120
40	16-QAM	16-QAM	QPSK	1/2	10	108	6	1080	540	1	135	150
41	64-QAM	QPSK	QPSK	1/2	10	108	6	1080	540	1	135	150
42	64-QAM	16-QAM	QPSK	1/2	12	108	6	1296	648	1	162	180
43	64-QAM	16-QAM	16-QAM	1/2	14	108	6	1512	756	1	189	210
44	64-QAM	64-QAM	QPSK	1/2	14	108	6	1512	756	1	189	210
45	64-QAM	64-QAM	16-QAM	1/2	16	108	6	1728	864	1	216	240
46	16-QAM	QPSK	QPSK	3/4	8	108	6	864	648	1	162	180
47	16-QAM	16-QAM	QPSK	3/4	10	108	6	1080	810	1	202.5	225
48	64-QAM	QPSK	QPSK	3/4	10	108	6	1080	810	1	202.5	225
49	64-QAM	16-QAM	QPSK	3/4	12	108	6	1296	972	1	243	270
50	64-QAM	16-QAM	16-QAM	3/4	14	108	6	1512	1134	1	283.5	315
51	64-QAM	64-QAM	QPSK	3/4	14	108	6	1512	1134	1	283.5	315
52	64-QAM	64-QAM	16-QAM	3/4	16	108	6	1728	1296	2	324	360

The rate-dependent parameters for optional 40 MHz, N_{SS} = 4 MCSs, with UEQM of the spatial streams shall be as shown in Table 19-41.

Table 19-41—MCS parameters for optional 40 MHz, N_{SS} = 4, UEQM

MCS Index	Modulation				R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3	Stream 4								800 ns GI	400 ns GI
53	16-QAM	QPSK	QPSK	QPSK	1/2	10	108	6	1080	540	1	135	150
54	16-QAM	16-QAM	QPSK	QPSK	1/2	12	108	6	1296	648	1	162	180
55	16-QAM	16-QAM	16-QAM	QPSK	1/2	14	108	6	1512	756	1	189	210
56	64-QAM	QPSK	QPSK	QPSK	1/2	12	108	6	1296	648	1	162	180
57	64-QAM	16-QAM	QPSK	QPSK	1/2	14	108	6	1512	756	1	189	210

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Table 19-41—MCS parameters for optional 40 MHz, N_{SS} = 4, UEQM *(continued)*

MCS Index	Modulation				R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3	Stream 4								800 ns GI	400 ns GI
58	64-QAM	16-QAM	16-QAM	QPSK	1/2	16	108	6	1728	864	1	216	240
59	64-QAM	16-QAM	16-QAM	16-QAM	1/2	18	108	6	1944	972	1	243	270
60	64-QAM	64-QAM	QPSK	QPSK	1/2	16	108	6	1728	864	1	216	240
61	64-QAM	64-QAM	16-QAM	QPSK	1/2	18	108	6	1944	972	1	243	270
62	64-QAM	64-QAM	16-QAM	16-QAM	1/2	20	108	6	2160	1080	1	270	300
63	64-QAM	64-QAM	64-QAM	QPSK	1/2	20	108	6	2160	1080	1	270	300
64	64-QAM	64-QAM	64-QAM	16-QAM	1/2	22	108	6	2376	1188	1	297	330
65	16-QAM	QPSK	QPSK	QPSK	3/4	10	108	6	1080	810	1	202.5	225
66	16-QAM	16-QAM	QPSK	QPSK	3/4	12	108	6	1296	972	1	243	270
67	16-QAM	16-QAM	16-QAM	QPSK	3/4	14	108	6	1512	1134	1	283.5	315
68	64-QAM	QPSK	QPSK	QPSK	3/4	12	108	6	1296	972	1	243	270
69	64-QAM	16-QAM	QPSK	QPSK	3/4	14	108	6	1512	1134	1	283.5	315
70	64-QAM	16-QAM	16-QAM	QPSK	3/4	16	108	6	1728	1296	2	324	360
71	64-QAM	16-QAM	16-QAM	16-QAM	3/4	18	108	6	1944	1458	2	364.5	405
72	64-QAM	64-QAM	QPSK	QPSK	3/4	16	108	6	1728	1296	2	324	360
73	64-QAM	64-QAM	16-QAM	QPSK	3/4	18	108	6	1944	1458	2	364.5	405
74	64-QAM	64-QAM	16-QAM	16-QAM	3/4	20	108	6	2160	1620	2	405	450
75	64-QAM	64-QAM	64-QAM	QPSK	3/4	20	108	6	2160	1620	2	405	450
76	64-QAM	64-QAM	64-QAM	16-QAM	3/4	22	108	6	2376	1782	2	445.5	495

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