IEEE Standard for Information technology—
Telecommunications and information exchange between systems
Local and metropolitan area networks—
Specific requirements

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
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New York, NY 10016-5997
USA

IEEE Std 802.11™-2016
(Revision of
IEEE Std 802.11-2012)

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Prepared by the 802.11 Working Group of the

LAN/MAN Standards Committee
of the
IEEE Computer Society

Approved 7 December 2016

IEEE-SA Standards Board

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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).

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

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 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 $N_{RX} \times N_{TX}$

n is white (spatially and temporally) Gaussian noise as illustrated in Figure 19-14

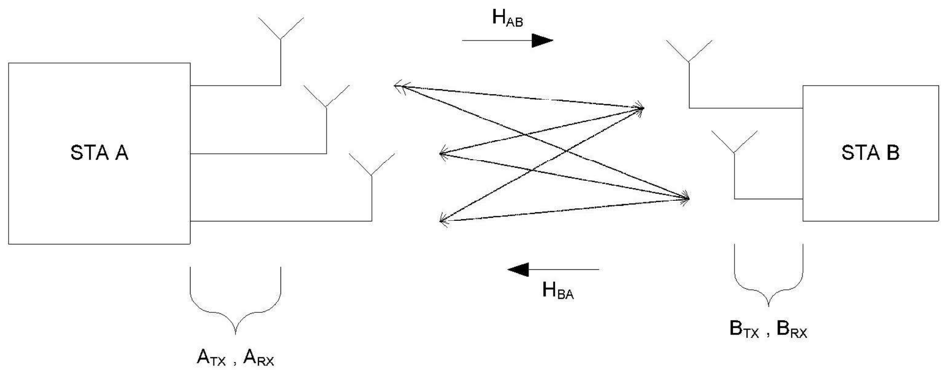

Figure 19-14—Beamforming MIMO channel model (3x2 example)

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).

$$\mathbf{y}_k = H_k Q_k \mathbf{x}_k + \mathbf{n} \quad (19\text{-}63)$$

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., $H_{AB,k} = \rho[H_{BA,k}]^T$. Here $H_{AB,k}$ is the MIMO channel matrix from STA A to STA B at subcarrier k, and

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$H_{BA,k}$ 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 $H_{AB,k}$.

NOTE—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 10.32.2.4 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 $Q_{A,k}$ and $Q_{B,k}$ are assumed to be identity matrices here for simplicity of illustration.

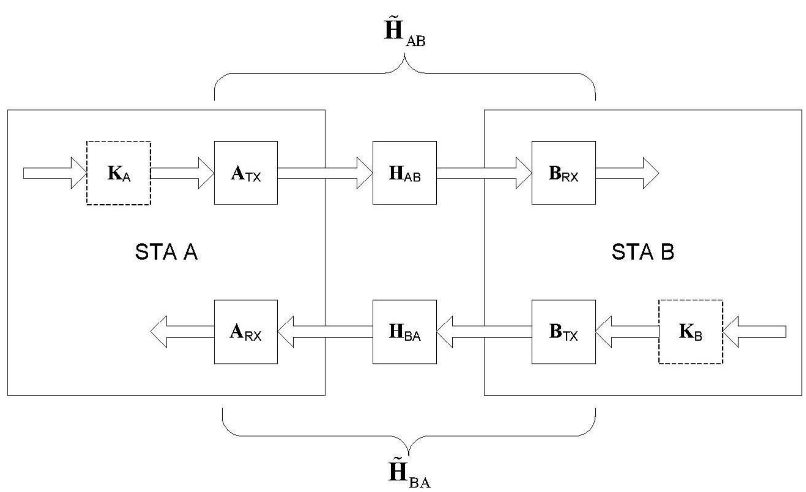

Figure 19-15—Baseband-to-baseband channel

NOTE—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, $\tilde{H}_{AB,k}$, and the over-the-air channel, $H_{AB,k}$, is shown in Equation (19-64).

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

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

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$$\tilde{H}_{BA,k} = A_{RX,k} H_{BA,k} B_{TX,k} \quad (19\text{-}65)$$

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.

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

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.

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

and

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

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).

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

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).

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

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—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, $Q_{\text{steer},k} = Q_k V_k$, 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 packet 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 $Q_{\text{steer},k}$ is found, $Q_{\text{steer},k}$ may replace Q_k for the next beamformed data transmission.

NOTE—$Q_{\text{steer},k}$ 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).

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

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

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

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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).

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

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).

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

where

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

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).

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

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

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 9.4.1.29. 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:

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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 $1 \le l \le N_c$.

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.

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

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).

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

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

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

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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 $N_r \neq N_c$.

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

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

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).

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

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

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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 $(G_{N_r2} \ldots G_{32} D_2^*)(G_{N_r1} \ldots G_{31} G_{21} D_1^*) \times V$ can be $\tilde{I}_{N_r \times 2}$ by the Givens rotations G_{l2} such as shown in Equation (19-84).

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{N_r2} & 0 & \sin\psi_{N_r2} \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\psi_{N_r2} & 0 & \cos\psi_{N_r2} \end{bmatrix} \cdots \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{32} & \sin\psi_{32} & 0 \\ 0 & -\sin\psi_{32} & \cos\psi_{32} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\phi_{22}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{N_r-1,2}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^* \times G_{N_r1} \ldots G_{31} G_{21} D_1^* \times V = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & & \\ 0 & 0 & & V_3 \end{bmatrix} \quad (19\text{-}84)$$

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 9.6.12.8.

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 packet 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

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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.

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.

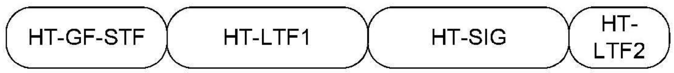

Figure 19-16—Example of an NDP used for sounding

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

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19.3.13.4 Sounding PPDU for channel quality assessment

In response to the reception of 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 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.

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Table 20-32—DMG PHY characteristics *(continued)*

PHY parameter	Value
aSCGILength	64
aSCBlockSize	512
aPPDUMaxTime	2 ms
aPSDUMaxLength	262 143 octets

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21. Very high throughput (VHT) PHY specification

21.1 Introduction

21.1.1 Introduction to the VHT PHY

Clause 21 specifies the PHY entity for a very high throughput (VHT) orthogonal frequency division multiplexing (OFDM) system.

In addition to the requirements in Clause 21, a VHT STA shall be capable of transmitting and receiving PPDUs that are compliant with the mandatory PHY specifications defined in Clause 19.

The VHT PHY is based on the HT PHY defined in Clause 19, which in turn is based on the OFDM PHY defined in Clause 17. The VHT PHY extends the maximum number of space-time streams supported to eight and provides support for downlink multi-user (MU) transmissions. A downlink MU transmission supports up to four users with up to four space-time streams per user with the total number of space-time streams not exceeding eight.

NOTE—MU transmission is different from VHT SU group addressed transmission.

The VHT PHY provides support for 20 MHz, 40 MHz, 80 MHz, and 160 MHz contiguous channel widths and support for 80+80 MHz noncontiguous channel width.

The VHT PHY data subcarriers are modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), 64-QAM, and 256-QAM. Forward error correction (FEC) coding (convolutional or LDPC coding) is used with coding rates of 1/2, 2/3, 3/4, and 5/6.

A VHT STA shall support the following features:

- Non-HT and non-HT duplicate formats (transmit and receive) for all channel widths supported by the VHT STA
- HT-mixed format (transmit and receive)
- VHT format (transmit and receive)
- 20 MHz, 40 MHz, and 80 MHz channel widths
- Single spatial stream VHT-MCSs 0 to 7 (transmit and receive) in all supported channel widths
- Binary convolutional coding

A VHT STA may support the following features:

- HT-greenfield format (transmit and receive)
- 2 or more spatial streams (transmit and receive)
- 400 ns short guard interval (transmit and receive)
- Beamforming sounding (by sending a VHT NDP)
- Responding to transmit beamforming sounding (by providing compressed beamforming feedback)
- STBC (transmit and receive)
- LDPC (transmit and receive)
- VHT MU PPDUs (transmit and receive)
- Support for 160 MHz channel width
- Support for 80+80 MHz channel width
- VHT-MCSs 8 and 9 (transmit and receive)

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21.1.2 Scope

The services provided to the MAC by the VHT 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 VHT, Clause 19 and Clause 17 PHYs.

21.1.3 VHT PHY functions

21.1.3.1 General

The VHT PHY contains two functional entities: the PHY function and the physical layer management function (i.e., the PLME). Both of these functions are described in detail in 21.3 and 21.4.

The VHT PHY service is provided to the MAC through the PHY service primitives defined in Clause 8. The VHT PHY service interface is described in 21.2.

21.1.3.2 PHY management entity (PLME)

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

21.1.3.3 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 is the set of capabilities that it offers to a user in the next higher layer. Abstract services are specified here by describing the service primitives and parameters that characterize each service. This definition is independent of any particular implementation.

21.1.4 PPDU formats

The structure of the PPDU transmitted by a VHT STA is determined by the TXVECTOR parameters as defined in Table 21-1.

In a VHT STA the FORMAT parameter determines the overall structure of the PPDU and can take one of the following values:

— Non-HT format (NON_HT), based on Clause 17 and including non-HT duplicate format.
— HT-mixed format (HT_MF) as specified in Clause 19.
— HT-greenfield format (HT_GF) as specified in Clause 19.
— VHT format (VHT). PPDUs of this format contain a preamble compatible with Clause 17 and Clause 19 STAs. The non-VHT portion of the VHT format preamble (the parts of VHT preamble preceding the VHT-SIG-A field) is defined so that it can be decoded by these STAs.

NOTE—Required support for these formats is defined in 11.40, 19.1.1, and 21.1.1.

A VHT PPDU can be further categorized as a VHT SU PPDU or a VHT MU PPDU. A VHT PPDU using a group ID value of 0 or 63 is a VHT SU PPDU and either carries only one PSDU or no PSDU. A VHT PPDU

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using a group ID value in the range 1 to 62 is a VHT MU PPDU and carries one or more PSDUs to one or more users.

21.2 VHT PHY service interface

21.2.1 Introduction

The PHY provides an interface to the MAC through an extension of the generic PHY service interface defined in 8.3.4. The interface includes TXVECTOR, RXVECTOR, and PHYCONFIG_VECTOR.

Using the TXVECTOR, the MAC supplies the PHY with per-PPDU transmit parameters. Using the RXVECTOR, the PHY informs the MAC of the received PPDU parameters. Using the PHYCONFIG_VECTOR, the MAC configures the PHY for operation, independent of frame transmission or reception.

21.2.2 TXVECTOR and RXVECTOR parameters

The parameters in Table 21-1 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 21-1—TXVECTOR and RXVECTOR parameters

Parameter	Condition	Value	TXVECTOR	RXVECTOR
FORMAT		Determines the format of the PPDU. Enumerated type: NON_HT indicates Clause 17 (Orthogonal frequency division multiplexing (OFDM) PHY specification) or non-HT duplicate 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. VHT indicates VHT format.	Y	Y
NON_HT_MODULATION	FORMAT is NON_HT	In TXVECTOR, indicates the format type of the transmitted non-HT PPDU. In RXVECTOR, indicates the estimated format type of the received non-HT PPDU. Enumerated type: OFDM indicates Clause 17 (Orthogonal frequency division multiplexing (OFDM) PHY specification) format NON_HT_DUP_OFDM indicates non-HT duplicate format	Y	Y
	Otherwise	Not present	N	N

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the unmodulated tones of L-STF and VHT-STF fields. Note that the multiplication matrices $A^k_{VHT\text{-}LTF}$ and $P_{VHT\text{-}LTF}$ are included in the calculation of $X^{(i_{Seg},m)}_{k,u}$ for the VHT-LTF and VHT-SIG-B fields, respectively.

$T_{\mathrm{GI,\,Field}}$ is the guard interval duration used for each OFDM symbol in the field. For L-STF and VHT-STF, $T_{\mathrm{GI,\,Field}} = T_{\mathrm{GI}}$ but it can be omitted from Equation (21-13) due to the periodic property of L-STF and VHT-STF over every 0.8 µs. For the L-SIG, VHT-SIG-A, VHT-LTF, and VHT-SIG-B fields, $T_{\mathrm{GI,\,Field}}$ is defined in the "Guard interval duration" column of Table 21-8.

$T_{\mathrm{CS,\,VHT}}(l)$ For pre-VHT modulated fields, $T_{\mathrm{CS,\,VHT}}(l) = 0$. For VHT modulated fields, $T_{\mathrm{CS,\,VHT}}(l)$ represents the cyclic shift per space-time stream, whose value is defined in Table 21-11.

M_u is defined in Table 21-6.

21.3.7.5 Definition of tone rotation

The function $\Upsilon_{k,\mathrm{BW}}$ is used to represent a rotation of the tones. BW in $\Upsilon_{k,\mathrm{BW}}$ is determined by the TXVECTOR parameter CH_BANDWIDTH as defined in Table 21-9.

Table 21-9—CH_BANDWIDTH and $\Upsilon_{k,\mathrm{BW}}$

CH_BANDWIDTH	$\Upsilon_{k,\mathrm{BW}}$
CBW20	$\Upsilon_{k,20}$
CBW40	$\Upsilon_{k,40}$
CBW80	$\Upsilon_{k,80}$
CBW160	$\Upsilon_{k,160}$
CBW80+80	$\Upsilon_{k,80}$ per frequency segment

For a 20 MHz PPDU transmission,

$$\Upsilon_{k,20} = 1 \quad (21\text{-}14)$$

For a 40 MHz PPDU transmission,

$$\Upsilon_{k,40} = \begin{cases} 1, & k < 0 \\ j, & k \ge 0 \end{cases} \quad (21\text{-}15)$$

For an 80 MHz PPDU transmission,

$$\Upsilon_{k,80} = \begin{cases} 1, & k < -64 \\ -1, & k \ge -64 \end{cases} \quad (21\text{-}16)$$

For an 80+80 MHz PPDU transmission, each 80 MHz frequency segment shall use the phase rotation for 80 MHz PPDU transmissions as defined in Equation (21-16).

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For a 160 MHz PPDU transmission,

$$\Upsilon_{k,\,160} = \begin{cases} 1, & k < -192 \\ -1, & -192 \le k < 0 \\ 1, & 0 \le k < 64 \\ -1, & 64 \le k \end{cases} \tag{21-17}$$

21.3.8 VHT preamble

21.3.8.1 Introduction

A VHT preamble is defined to carry the required information to operate in either single user or multi-user mode. To maintain compatibility with non-VHT STAs, specific non-VHT fields are defined that can be received by non-VHT STAs compliant with Clause 17 or Clause 19. The non-VHT fields are followed by VHT fields specific to VHT STAs.

21.3.8.2 Non-VHT portion of VHT format preamble

21.3.8.2.1 Cyclic shift for pre-VHT modulated fields

The cyclic shift value $T_{CS}^{i_{TX}}$ for the L-STF, L-LTF, L-SIG, and VHT-SIG-A fields of the PPDU for transmit chain i_{TX} out of a total of N_{TX} are defined in Table 21-10.

Table 21-10—Cyclic shift values for L-STF, L-LTF, L-SIG, and VHT-SIG-A fields of the PPDU

$T_{CS}^{i_{TX}}$ values for L-STF, L-LTF, L-SIG, and VHT-SIG-A fields of the PPDU									
Total number of transmit chains (N_{TX}) per frequency segment	Cyclic shift for transmit chain i_{TX} (in units of ns)								
	1	2	3	4	5	6	7	8	>8
1	0	–	–	–	–	–	–	–	–
2	0	–200	–	–	–	–	–	–	–
3	0	–100	–200	–	–	–	–	–	–
4	0	–50	–100	–150	–	–	–	–	–
5	0	–175	–25	–50	–75	–	–	–	–
6	0	–200	–25	–150	–175	–125	–	–	–
7	0	–200	–150	–25	–175	–75	–50	–	–
8	0	–175	–150	–125	–25	–100	–50	–200	–
>8	0	–175	–150	–125	–25	–100	–50	–200	Between –200 and 0 inclusive

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21.3.8.2.2 L-STF definition

The L-STF field for a 20 MHz or 40 MHz transmission is defined by Equation (19-8) and Equation (19-9), respectively, in 19.3.9.3.3. For 80 MHz, the L-STF field is defined by Equation (21-18). Note that these equations do not include the phase rotation per 20 MHz subchannel.

$$S_{-122,122} = \{S_{-58,58}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, S_{-58,58}\} \quad (21\text{-}18)$$

where

$S_{-58,58}$ is defined in Equation (19-9)

For 160 MHz, the L-STF is defined by Equation (21-19).

$$S_{-250,250} = \{S_{-122,122}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, S_{-122,122}\} \quad (21\text{-}19)$$

where

$S_{-122,122}$ is defined in Equation (21-18)

For an 80+80 MHz transmission, each 80 MHz frequency segment shall use the L-STF pattern for the 80 MHz ($S_{-122,122}$) defined in Equation (21-18).

The time domain representation of the signal on frequency segment i_{Seg} and transmit chain i_{TX} shall be as specified in Equation (21-20).

$$r_{\text{L-STF}}^{(i_{Seg}, i_{TX})}(t) = \frac{1}{\sqrt{N_{\text{L-STF}}^{\text{Tone}} N_{\text{TX}}}} w_{T_{\text{L-STF}}}(t) \sum_{k = -N_{SR}}^{N_{SR}} \Upsilon_{k,\text{BW}} S_k \exp(j2\pi k \Delta_F (t - T_{CS}^{i_{TX}})) \quad (21\text{-}20)$$

where

$T_{CS}^{i_{TX}}$	represents the cyclic shift for transmit chain i_{TX} with a value given in Table 21-10
$\Upsilon_{k,\text{BW}}$	is defined by Equation (21-14), Equation (21-15), Equation (21-16). and Equation (21-17)
$N_{\text{L-STF}}^{\text{Tone}}$	has the value given in Table 21-8

21.3.8.2.3 L-LTF definition

For a 20 MHz or 40 MHz transmission, the L-LTF pattern in the VHT preamble is defined by Equation (19-11) and Equation (19-12) in 19.3.9.3.4, respectively. For an 80 MHz transmission, the L-LTF pattern is defined by Equation (21-21). Note that these equations do not include the phase rotation per 20 MHz subchannel.

$$L_{-122,122} = \{L_{-58,58}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, L_{-58,58}\} \quad (21\text{-}21)$$

where

$L_{-58,58}$ is defined in Equation (19-12)

For a 160 MHz transmission, the L-LTF is defined by Equation (21-22). Note that this equation does not include the phase rotations per 20 MHz subchannel.

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$$r^{i_{TX}}_{\text{non-HT}, BW}(t) = \frac{1}{\sqrt{N^{\text{Tone}}_{\text{NON\_HT\_DUP\_OFDM-Data}}}} \sum_{n=0}^{N_{SYM}-1} w_{T_{SYM}}(t - nT_{SYM}) \cdot \sum_{i_{BW}=0}^{N_{20\text{MHz}}-1} \left(\sum_{k=-26}^{26} \Upsilon_{(k - K_{\text{Shift}}(i_{BW})), BW}(D_{k,n} + p_{n+1}P_k) \cdot \exp(j2\pi(k - K_{\text{Shift}}(i_{BW}))\Delta_F(t - nT_{SYM} - T_{GI} - T^{i_{TX}}_{\text{CS}})) \right) \quad (21\text{-}100)$$

where

$N_{20\text{MHz}}$ and $K_{\text{Shift}}(i)$ are defined in 21.3.8.2.4

P_k and p_n are defined in 17.3.5.10

$D_{k,n}$ is defined in Equation (21-26)

$\Upsilon_{k, BW}$ is defined in Equation (21-16) and Equation (21-17)

$T^{i_{TX}}_{\text{CS}}$ represents the cyclic shift for transmitter chain i_{TX} with a value given in Table 21-10

$N^{\text{Tone}}_{\text{NON\_HT\_DUP\_OFDM-Data}}$ has the value given in Table 21-8

In an 80+80 MHz non-HT duplicate transmission, data transmission in each frequency segment shall be as defined for an 80 MHz non-HT duplicate transmission in Equation (21-100).

21.3.11 SU-MIMO and DL-MU-MIMO Beamforming

21.3.11.1 General

SU-MIMO and DL-MU-MIMO beamforming are techniques used by a STA with multiple antennas (the beamformer) to steer signals using knowledge of the channel to improve throughput. With SU-MIMO beamforming all space-time streams in the transmitted signal are intended for reception at a single STA. With DL-MU-MIMO beamforming, disjoint subsets of the space-time streams are intended for reception at different STAs.

For SU-MIMO beamforming, the steering matrix Q_k can be determined from the beamforming feedback matrix V_k that is sent back to the beamformer by the beamformee using the compressed beamforming feedback matrix format as defined in 19.3.12.3.6. The feedback report format is described in 9.4.1.49.

For DL-MU-MIMO beamforming, the receive signal vector in subcarrier k at beamformee u, $\boldsymbol{y}_{k,u} = [y_{k,0}, y_{k,1}, \ldots, y_{k,N_{RX_u}-1}]^T$, is shown in Equation (21-101), where $\boldsymbol{x}_k = [\boldsymbol{x}^T_{k,0}, \boldsymbol{x}^T_{k,1}, \ldots, \boldsymbol{x}^T_{k,N_{user}-1}]^T$ denotes the transmit signal vector in subcarrier k for all N_{user} beamformees, with $\boldsymbol{x}_{k,u} = [x_{k,0}, x_{k,1}, \ldots, x_{k,N_{STS,u}-1}]^T$ being the transmit signal for beamformee u.

$$\boldsymbol{y}_{k,u} = \boldsymbol{H}_{k,u} \times [Q_{k,0}, Q_{k,1}, \ldots, Q_{k,N_{user}-1}] \times \boldsymbol{x}_k + \boldsymbol{n} \quad (21\text{-}101)$$

where

$\boldsymbol{H}_{k,u}$ is the channel matrix from the beamformer to beamformee u in subcarrier k with dimensions $N_{RX_u} \times N_{TX}$

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N_{RX_u} is the number of receive antennas at beamformee u

$Q_{k,u}$ is a steering matrix for beamformee u in subcarrier k with dimensions $N_{TX} \times N_{STS_u}$

N_{user} is the number of VHT MU PPDU recipients (see Table 21-6)

$\boldsymbol{n}$ is a vector of additive noise and may include interference

The DL-MU-MIMO steering matrix $Q_k = [Q_{k,0}, Q_{k,1}, \ldots, Q_{k,N_{user}-1}]$ can be determined by the beamformer using the beamforming feedback matrices for subcarrier k from beamformee u, $V_{k,u}$, and SNR information for subcarrier k from beamformee u, $SNR_{k,u}$, where $u = 0, 1, \ldots, N_{user} - 1$. The steering matrix that is computed (or updated) using new beamforming feedback matrices and new SNR information from some or all of participating beamformees might replace the existing steering matrix Q_k for the next DL-MU-MIMO data transmission. The beamformee group for the MU transmission is signaled using the Group ID field in VHT-SIG-A (see 21.3.8.3.3 and 21.3.11.4).

21.3.11.2 Beamforming Feedback Matrix *V*

Upon receipt of a VHT NDP sounding PPDU, the beamformee shall remove the space-time stream CSD in Table 21-11 from the measured channel before computing a set of matrices for feedback to the beamformer. The beamforming feedback matrix, $V_{k,u}$, found by the beamformee u for subcarrier k shall be compressed in the form of angles using the method described in 19.3.12.3.6. The angles, $\phi(k,u)$ and $\psi(k,u)$, are quantized according to Table 9-68. The number of bits for quantization is chosen by the beamformee, based on the indication from the beamformer as to whether the feedback is requested for SU-MIMO beamforming or DL-MU-MIMO beamforming. The compressed beamforming feedback using 19.3.12.3.6 is the only Clause 21 beamforming feedback format defined.

The beamformee shall generate the beamforming feedback matrices with the number of rows (Nr) equal to the N_{STS} of the NDP.

After receiving the angle information, $\phi(k,u)$ and $\psi(k,u)$, the beamformer reconstructs $V_{k,u}$ using Equation (19-79). For SU-MIMO beamforming, the beamformer can use this $V_{k,0}$ matrix to determine the steering matrix Q_k. For DL-MU-MIMO beamforming, the beamformer may calculate a steering matrix $Q_k = [Q_{k,0}, Q_{k,1}, \ldots, Q_{k,N_{user}-1}]$ using $V_{k,u}$ and $SNR_{k,u}$ ($0 \le u \le N_{user} - 1$) in order to suppress crosstalk between participating beamformees. The method used by the beamformer to calculate the steering matrix Q_k is implementation specific.

The beamformee decides the tone grouping value to be used in the beamforming feedback matrix V. A beamformer shall support all tone grouping values and Codebook Information values.

21.3.11.3 Maximum Number of Total Spatial Streams in VHT MU PPDUs

An MU beamformee capable STA shall support reception of VHT MU PPDUs with the total number of space-time streams across the N_user users being less than or equal to the value indicated in the Maximum $N_{STS,total}$ subfield of the Supported VHT-MCS and NSS Set field of the VHT Capabilities element.

21.3.11.4 Group ID

A value in the Group ID field in VHT-SIG-A (see 21.3.8.3.3) in the range 1 to 62 indicates a VHT MU PPDU. Prior to transmitting a VHT MU PPDU, group assignments have been established by the AP for DL-MU-MIMO capable STAs using the Group ID Management frame as defined in 9.6.23.3.

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After the PHY is configured using the PHYCONFIG_VECTOR parameter GROUP_ID_MANAGEMENT, the following lookup tables are populated:

a) Group ID to Membership Status, denoted by MembershipStatusInGroupID[g] for $1 \leq g \leq 62$
b) Group ID to User Position, denoted by UserPositionInGroupID[g] for $1 \leq g \leq 62$

When a STA receives a VHT MU PPDU where the Group ID field in VHT-SIG-A has the value k and where MembershipStatusInGroupID[k] is equal to 1, then the number of space-time streams for that STA is indicated in the MU[UserPositionInGroupID[k]] NSTS field in VHT-SIG-A. The space-time streams of different users are ordered in accordance to user position values, i.e., the space-time streams for the user in user position 0 come first, followed by the space-time streams for the user in position 1, followed by the space-time streams for the user in position 2, and followed by the space-time streams for the user in position 3.

A STA is also able to identify the space-time streams intended for other STAs that act as interference. VHT-LTF symbols in the VHT MU PPDU are used to measure the channel for the space-time streams intended for the STA and can also be used to measure the channel for the interfering space-time streams. To successfully demodulate the space-time streams intended for the STA, the STA may use the channel state information for all space-time streams to reduce the effect of interfering space-time streams.

If a STA finds that it is not a member of the group, or the STA is a member of the group but the corresponding MU NSTS field in VHT-SIG-A indicates that there are zero space-time streams for the STA in the PPDU, then the STA may elect to not process the remainder of the PPDU.

21.3.12 VHT preamble format for sounding PPDUs

NDP is the only VHT sounding format.

The format of a VHT NDP PPDU is shown in Figure 21-28.

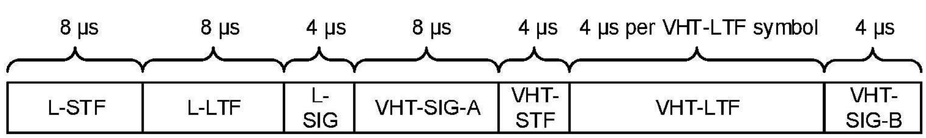

Figure 21-28—VHT NDP format

NOTE—The number of VHT-LTF symbols in the NDP is determined by the SU NSTS field in VHT-SIG-A.

The VHT NDP PPDU has the following properties:

— Uses the VHT PPDU format but without the Data field.
— Is a VHT SU PPDU as indicated by the VHT-SIG-A field.
— Has the data bits of the VHT-SIG-B field set to a fixed bit pattern (see 21.3.8.3.6).

21.3.13 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 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

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countries within defined regulatory domains might be subject to additional or alternative national regulations.

21.3.14 Channelization

A VHT channel is specified by the four PLME MIB fields specified in Table 21-22.

Table 21-22—Fields to specify VHT channels

Field	Meaning
dot11CurrentChannelWidth	Channel width. Possible values represent 20 MHz, 40 MHz, 80 MHz, 160 MHz, and 80+80 MHz channels.
dot11CurrentChannelCenterFrequencyIndex0	For a 20 MHz, 40 MHz, 80 MHz, or 160 MHz channel, denotes the channel center frequency. For an 80+80 MHz channel, denotes the center frequency of the frequency segment 0, which is the frequency segment containing the primary channel. Valid range is 1 to 200. See Equation (21-102).
dot11CurrentChannelCenterFrequencyIndex1	For an 80+80 MHz channel, denotes the center frequency of the frequency segment 1, which is the frequency segment that does not contain the primary channel. Valid range is 1 to 200. See Equation (21-102). For a 20 MHz, 40 MHz, 80 MHz, or 160 MHz channel, set to 0.
dot11CurrentPrimaryChannel	Denotes the location of the primary 20 MHz channel. Valid range is 1 to 200. See Equation (21-103).

Given dot11CurrentChannelCenterFrequencyIndex0 and dot11CurrentChannelCenterFrequencyIndex1, the respective center frequency is given by Equation (21-102).

$$\text{Channel center frequency [MHz]} = \text{Channel starting frequency} + 5 \times \text{dot11CurrentChannelCenterFrequencyIndex} \quad (21\text{-}102)$$

where

Channel starting frequency is given by the operating class (Annex E)

dot11CurrentChannelCenterFrequencyIndex is either dot11CurrentChannelCenterFrequencyIndex0 or dot11CurrentChannelCenterFrequencyIndex1

The center frequency of the primary 20 MHz channel is given by Equation (21-103).

$$\text{Primary 20 MHz channel center frequency [MHz]} = \text{Channel starting frequency} + 5 \times \text{dot11CurrentPrimaryChannel} \quad (21\text{-}103)$$

The channel starting frequency is defined as dot11ChannelStartingFactor × 500 kHz. If a channel center frequency is 5.000 GHz, it shall be indicated by dot11ChannelStartingFactor = 8000 and dot11CurrentPrimaryChannel = 200.

For an 80+80 MHz channel, any two channels that would each be allowed as 80 MHz channels and whose center frequencies are separated by greater than 80 MHz (difference between dot11CurrentChannelCenterFrequencyIndex0 and dot11CurrentChannelCenterFrequencyIndex1 corresponds to a frequency difference greater than 80 MHz) may be used.

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