802.11 WLAN: History and New Enabling MIMO Techniques for Next Generation Standards

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ABSTRACT

IEEE 802.11, which designs wireless local area networks (WLAN), is one of the most successful standards in wireless communication systems. In this article, we review the history of WLAN standards, and provide technical overviews of the recent development of WLAN systems. Especially, as the original inventor and the proposer, we focus on beamforming and compressed feedback schemes, which have been adopted in 802.11 WLAN standards, to improve the throughput for a multiple-input multiple-output (MIMO) system. These techniques are essential to maximize the downlink system throughput for multiple user transmission as well as for single user transmission. Also, we present discussions on new technologies to further enhance user throughput, which are currently considered for future WLAN systems.

INTRODUCTION

Wireless local area networks (WLANs) have been widely deployed in communication networks for decades. As portable devices become prevalent, a demand to access internet without any constraint on location has been growing. This wireless connectivity has become more important features, especially for smartphones and tablets, as internet traffic increases. While we have witnessed the explosive growth of wireless communications recently, the history of WLANs is not that long.

IEEE created a project called 802 in 1980 and many working groups have been made under the project. For WLAN, the first specification was published under 802.11 working group in 1997. Initially, the specification defined only the data rate of 1 or 2 Mb/s operated at 2.4 GHz band using either frequency hopping spread spectrum (FHSS), infrared (IR) or direct sequence spread spectrum (DSSS). Later, they decided to expand the standard under two task groups, at either 2.4 GHz band and 5 GHz band, which became 802.11b and 802.11a, respectively. The complementary code keying (CCK) mode was introduced in 802.11b to support up to 11 Mb/s, while orthogonal frequency division multiplexing (OFDM) was applied for 802.11a which supports up to 54 Mb/s. Both amendments were published in 1999.

While it was expected to use different systems depending on applications with lower or higher data rates, the WLAN market based on the 5 GHz band was not fully utilized due to its high cost of radio frequency (RF) implementation in early 2000. On the other hand, there was a demand for higher data rates than 11b systems at the 2.4 GHz band. In 2002, in order to support the data rate up to 54 Mb/s in the 2.4 GHz band, 802.11g task group (TGg) decided to adopt the same physical layer (PHY) and media access control (MAC) specification of 802.11a [1].

With growth of the usage of internet browsing and multimedia contents, a demand on higher data rates has never stopped growing in WLAN. As a result, IEEE 802.11 committee approved to create another task group, 802.11n, to work on a new amendment for high throughput (HT). The goal of 802.11n was to achieve the throughput of 100 Mb/s at the MAC layer. In order to realize such a throughput enhancement, the 802.11n employed multiple-input multiple-output (MIMO) techniques including spatial-division multiplexing (SDM) [2] with up to 4 streams, space-time block coding (STBC) and transmit beamforming (TxBF).

Utilizing multiple antennas at the transmitter and the receiver, SDM allows multiplexing of multiple data streams across spatial dimensions, and the throughput increases as much as the number of data streams [3]. In addition, TxBF improves the received signal strength by emphasizing the dominant modes of transmission for the channel. However, the consensus on the channel state information (CSI) feedback for TxBF has not been made, which ended up with four different feedback mechanisms, consisting of one implicit feedback method and three explicit feedback schemes, as all optional modes.

After the completion of 802.11n in 2009 [4], 802.11ac added more evolutionary changes on MIMO methods. This new amendment, initiated by very high throughput (VHT) study group,

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adopted more advanced MIMO techniques such as downlink multi-user (MU)-MIMO and allowed up to 160 MHz bandwidth and up to 8 streams. These techniques enable to achieve the network throughput higher than 1 Gb/s. However, the CSI feedback overhead becomes more challenging because the performance of MU-MIMO is sensitive to CSI mismatch over fading channels. Also, implicit feedback turned out to be infeasible due to its frequent calibration operation. These issues were resolved by choosing the compressed explicit feedback [5] as a sole mandatory mode. Finally, debates on the CSI feedback for TxBF over five years came to an end.

In this article, we provide a technical overview of the recent development of WLAN technologies. Also, we illustrate the future direction of the WLAN research, focusing on multiple antenna schemes currently being discussed for the next generation standards. This article starts with a basic description of the preamble of 802.11 frames, which handles control signals from a PHY perspective. Especially, we address the control signals related to MIMO features, including beamforming and MU-MIMO. We include more details on TxBF and its feedback mechanism. Also, we introduce the future WLAN techniques which further improve the performance of MIMO systems. We conclude this article with discussions.

PHY Preamble

Legacy Portion for Basic Information

The packet starts with the PHY preamble that consists of short training field (STF) followed by long training field (LTF) and a signal field (SIG). This general preamble structure is common for all 802.11 specification with variations under very important requirement: backward compatibility. If this requirement is not met, a legacy station (STA) may often get lost to access the media by non-understandable packets without any knowledge when such medium-busy status would last.

For 802.11n, this requirement led to define a mixed-mode format that starts with a legacy preamble, as 802.11a/g, followed by new preamble portion (also known as HT portion). Similarly, 802.11ac also chooses a mixed-mode format with new portion (also known as VHT portion). Both amendments enable an efficient preamble design for MIMO operation. Figure 1 illustrates the time samples of the preamble with 2 transmit antennas in 802.11ac.

The preamble starts with legacy short training field (L-STF), which consists of 10 repeated time samples. It is typically employed for detection of incoming packets, timing synchronization, gain control setting and coarse frequency offset estimation.

After the L-STF, legacy long training field (L-LTF) is located, which triggers all the tones available in operating bandwidth for channel estimation. The L-LTF is also used for fine frequency offset estimation.

After the L-STF and the L-LTF, legacy signal field (L-SIG) follows, which contains the modulation and coding set (MCS) and its length information. For 802.11n and 11ac, these information is overwritten in the V/HT-SIG, because the L-SIG does not support higher MCS and longer length for 11n/ac. The MCS setting in the L-SIG for 11n/ac packets is only to calculate the packet duration with the length field. Thus, even though legacy devices do not understand the V/HT portion, they can at least collect information on the duration of the packet.

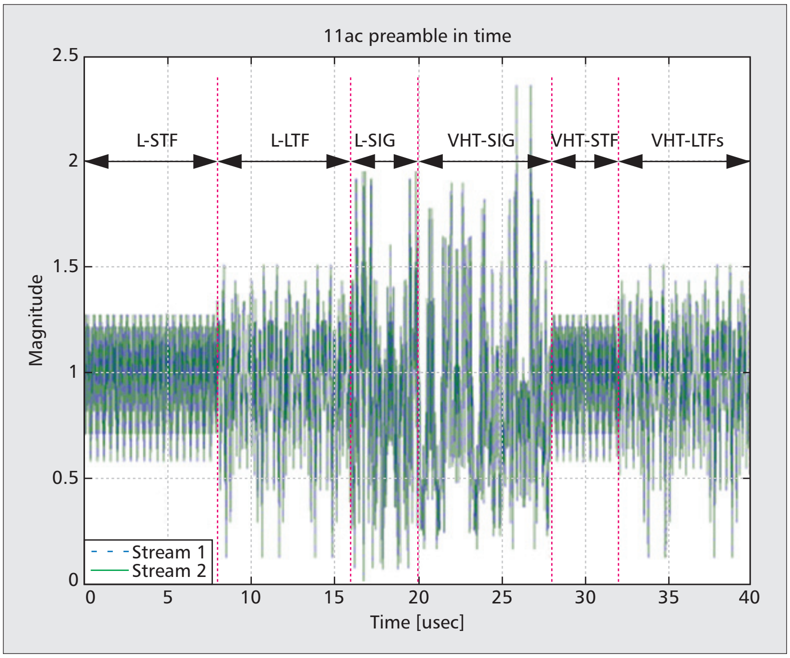

Figure 1. Time samples of the preamble for an 802.11ac system with two transmit antennas.

VHT portion for MIMO information

After 20 μsec long legacy portion of the preamble, more control signals are defined in high throughput signal field (HT-SIG) for 11n and very high throughput signal field (VHT-SIG) for 11ac. Such control signals are MCS (up to 64 QAM with 5/6 coding rate for 11n (MCS7), or up to 256 QAM with 3/4 coding rate for 11ac (MCS9)), coding schemes (convolutional or low-density parity check (LDPC)), STBC mode, short guard interval (SGI) mode, bandwidth (up to 40 MHz for 11n, or up to 160 MHz for 11ac), and so on. The V/HT-SIG is rotated 90 degree with different combination over two OFDM symbols, which enables receivers to identify whether the preamble format is non-legacy mode, 11n or 11ac.

After the V/HT-SIG, a couple of training fields exist to set up the MIMO operation, because it is the point where beamforming may be applied. As this spatial processing changes the beam pattern for certain directions, the receiver may see sudden changes in the dynamic range of the signal strength, which may end up with operating in the non-linear region of an RF amplifier. In order to adjust the gain control to find the sweet spot of the RF scaling for MIMO, there is one OFDM symbol long V/HT-STF.

The V/HT-LTFs are training sequences to estimate MIMO channels. To preserve orthog-

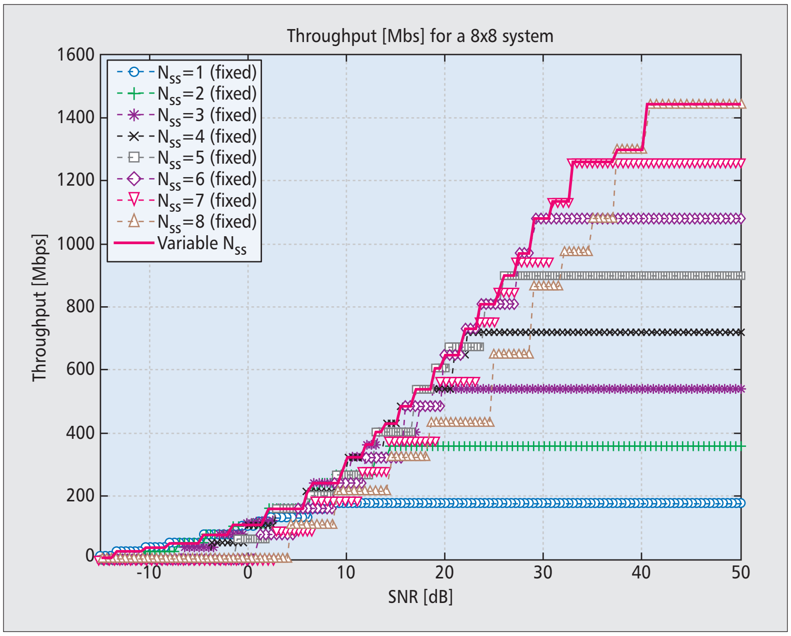

Figure 2. Throughput of 802.11ac systems with up to 8 streams with long guard interval of 0.8 µsec.

onality between antennas, the V/HT-LTF is designed as the original legacy training sequence multiplied by the Hadamard matrix. Unfortunately, the Hadamard matrix is available only for an exponent of two, such as 2, 4, or 8. For six transmit antennas in 11ac, a new orthogonal 6 × 6 matrix based on fast Fourier transform (FFT) is introduced. Since the length of V/HT-LTF in the unit of OFDM symbols should be no less than the number of transmit antennas, for the odd number of transmit antennas, we apply the Hadamard matrix with one dimension higher than the number of transmit antennas. Figure 2 shows an example of throughput performance using channel estimation with up to 8 streams. In this plot, each dashed line represents the throughput with a fixed number of streams.

For 802.11ac, VHT-SIG fields are split into two fields, VHT-SIGA and VHT-SIGB [6]. The VHT-SIGA, shown as in Fig. 3, is located at the same location as HT-SIG in 11n, and the VHT-SIGB is placed after the VHT-LTF field. While the VHT-SIGA has common information for all users, the VHT-SIGB includes user-specific information, such as MCS and the packet length per user, for MU-MIMO. The VHT-SIGB may not be correctly decoded for non-recipients, because this field is beamformed for MU-MIMO. More detailed descriptions regarding MU-MIMO operations follow later.

Contents of Signal Field for MU-MIMO Operations

With a new MU-MIMO feature introduced in 802.11ac, the VHT-SIG should indicate necessary information for recipients to process MU-MIMO packets. Especially, it should identify which stream belongs to which STA, for simultaneous transmission to up to 4 STAs. There have been a couple of proposed methods, however, most of them fail to meet the requirement of giving no impact on the packet detection.

Finally, the Group ID was proposed [7] and accepted unanimously by TGac. The Group ID, which is pre-assigned by the Group ID management frame [8], notifies the order of users over multiple streams. For example, let us assume Group ID = 1 in the VHT-SIGA, where 'Group ID = 1' was announced in advance by the management frame for a group of 4 STAs, [STA-A, STA-B, STA-C and STA-D] in the order. Then, the number of streams for the ith STA, N_{sts_i} in the VHT-SIGA indicates which streams belong to whom, where the STA number 1 to 4 corresponds to A to D. For example, if $N_{sts1} = 2$, $N_{sts2} = 1$, $N_{sts3} = 0$ and $N_{sts4} = 1$, STA-A, B and D would decode the first two, the 3rd and the 4th streams only, respectively. In this example, STA-C has no stream to decode, and thus drops the packet without further process.

One of the benefits of Group ID is to allow recipients to identify the destination of the packet earlier in the PHY preamble, which avoids processing the payload all the way to decode the MAC address in the MAC header. This enables power savings for WLAN STAs, which do not have to decode the payload to find whether the packet is intended for itself or not. However, for single user (SU) transmission, which is signaled by Group ID = 0, such mechanism is missing. In order to have the same benefits for the SU operation, partial associate identification (PAID) was also introduced [9]. By receiving the PAID which represents partial information (9 bits) out of 12 AID bits, recipients can recognize the destination of the packet similarly, and drop the packet earlier if the PAID does not match with the parts of its own AID. The first 3 bits of $N_S$ts field remain valid to signal the number of streams for a SU receiver, as shown in Fig. 3.

Also, the SU coding bit in the VHT-SIGA2 indicates either LDPC or convolutional coding for SU mode. For MU mode, this bit determines the coding scheme for user 1, while other bits in MU-coding-2 to MU-coding-4 identify a coding scheme for user 2 to user 4. In addition, the beamformed bit for SU mode is set to recommend recipients not to use a smoothing algorithm for channel estimation, because the channels may be discontinuous over tones due to beamforming. For MU mode, this bit is reserved since MU packets are always beamformed.

Beamforming

Beamforming is one of advanced MIMO techniques to enhance the throughput significantly. Antenna coordination for directional beams is enabled with an aid of CSI feedback, and thus it is essential to efficiently deliver such information from a beamformee to a beamformer. Out of 4 CSI feedback schemes for 802.11n, the compressed explicit feedback was acknowledged with its benefits [5] and finally accepted as a sole feedback format for 802.11ac, eliminating the other feedback schemes [10]. In this section, the details of the compressed explicit feedback scheme [11] is explained.

INTERPRETATION OF A BEAMFORMING MATRIX

With TxBF, the transmit signals are steered to enhance the quality of streams in terms of channel characteristics and crosstalk avoidance by applying a transmit beamforming matrix **V**. The beamforming matrix **V** can be designed in many different ways, but one popular way is to apply a singular value decomposition (SVD) technique. For $M_R \times M_T$ MIMO systems with M_T transmit antennas and M_R receive antennas, the $M_S \times 1$ transmitted signal can be beamformed by adopting a beamforming matrix **V** of size $M_T \times M_S$ which transmits M_S streams.

In order for a beamformer to properly implement beamforming, prompt and accurate CSI feedback is important. However, minimizing the feedback overhead size is often an issue while maintaining good quality of feedback information. To reduce the total number of bits in the feedback channel, we may utilize the orthonormal property of the beamforming matrix **V** to represent in angle domain.

For instance, with a 2 × 2 MIMO system with $M_S = 2$, **V** can be expressed as

$$V = \begin{bmatrix} \cos\psi_1 e^{j\phi_1} & \cos\psi_2 e^{j\phi_2} \\ \sin\psi_1 & \sin\psi_2 \end{bmatrix} = \begin{bmatrix} e^{j\phi_1} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\psi_1 & -\sin\psi_1 \\ \sin\psi_1 & \cos\psi_1 \end{bmatrix} \quad (1)$$

where ψ_1, ψ_2, ϕ_1 and ϕ_2 are the phase parameters, and the last row of **V** is chosen to be positive real as a reference phase using the column-wise phase invariant property. In order to have $\mathbf{V}^*\mathbf{V} = \mathbf{V}\mathbf{V}^* = \mathbf{I}$, where $(\cdot)^*$ denotes complex conjugate transpose, these phase values need to satisfy either $\psi_1 - \psi_2 = \pi/2$, $\phi_1 = \phi_2$ or $\psi_1 + \psi_2 = \pi/2$, $\phi_1 = \phi_2 + \pi$, where one of two conditions for angles would be sufficient. Thus we can choose one by limiting the range of angles to be $\psi \in [0, \pi/2]$ and $\phi \in [-\pi, \pi]$ such that $\psi_1 + \psi_2 = \pi/2$, $\phi_1 = \phi_2 + \pi$. These conditions lead us to decompose **V** as a multiplication of two matrices as shown in Eq. 1, with one diagonal matrix for the phase and the other with sinusoid functions for rotation.

GENERALIZED DECOMPOSITION FOR V

The idea of representing **V** in the angle domain can be generalized for higher dimension of the matrix [11]. From Eq. 1, **V** can be expressed as a special form of Givens rotation with a complex diagonal matrix. Let us define $\mathbf{I}_N$ as an identity matrix of size N, and $[\mathbf{A}]_{ii}$ as the (i, i)th element of a matrix **A**. Then, an arbitrary $M_T \times M_S$ unitary matrix **V** can be decomposed as

$$V = \prod_{i=1}^{M_{\min}} \left[D_i \prod_{l=i+1}^{M_T} G^*_{l,i}(\psi_{l,i}) \right] \times \tilde{I}, \quad (2)$$

where $M_{\min} = \min(M_S, M_T - 1)$, $\mathbf{D}_i = \mathrm{diag}\,(\mathbf{I}_{i-1}, e^{j\phi_{i,i}}, \cdots, e^{j\phi_{M_T-1,i}}, 1)$ is an $M_T \times M_T$ diagonal matrix, $\tilde{\mathbf{I}}$ denotes an $M_T \times M_S$ diagonal matrix with $[\mathbf{I}]_{i,i} = 1$ for $i = 1, \cdot s, M_S$, and $\mathbf{G}_{l,i}(\psi_{l,i})$ indicates an $M_T \times M_T$ Givens rotation matrix with rotation angle $\psi_{l,i}$ as

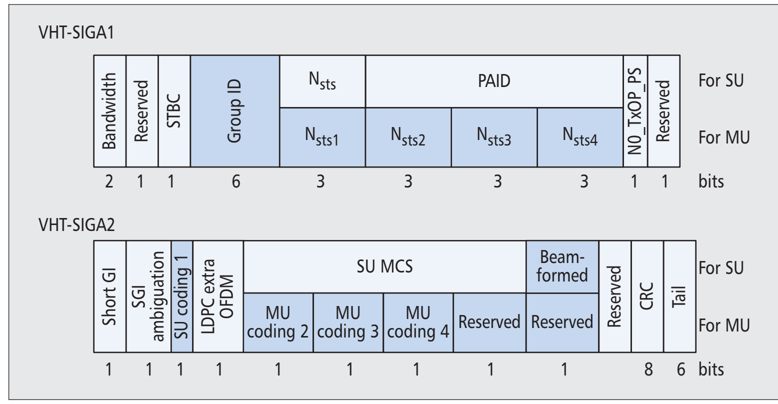

Figure 3. Bit definition in the VHT-SIGA fields for single-user and multi-user operations.

$$G_{l,i}(\psi_{l,i}) = \begin{bmatrix} I_{i-1} & 0 & 0 & \cdots & 0 \\ 0 & \cos\psi_{l,i} & 0 & \sin\psi_{l,i} & 0 \\ 0 & 0 & I_{l-i-1} & 0 & 0 \\ 0 & -\sin\psi_{l,i} & 0 & \cos\psi_{l,i} & 0 \\ 0 & 0 & 0 & \cdots & I_{M_T-l} \end{bmatrix}$$

with non-identity elements located at the lth and ith rows and columns. Note $\phi_{*,i}$ in $\mathbf{D}_i$ are found to make elements of the ith column real, before Givens rotation by $\mathbf{G}_{l,i}$ is performed .

When a beamformee finds an arbitrary beamforming matrix $\tilde{\mathbf{V}}$, which is column-wise phase-invariant, each column of $\tilde{\mathbf{V}}$ can be phase shifted by a diagonal matrix $\tilde{\mathbf{D}} = diag(e^{j\theta_1}, \cdots, e^{j\theta_{M_T}})$, where θ_i can be arbitrarily chosen to make the last row of $\mathbf{V} = \tilde{\mathbf{V}} \times \tilde{\mathbf{D}}$ real. Therefore, the minimum set of parameters to determine the beamforming matrix **V** is ψ_{li} for $i = 1, 2, \cdots, M_{\min}$ and $l = i + 1, \cdots, M_T$, and ϕ_{ji} for $i = 1, 2, \cdots, M_{\min}$ and $j = i, \cdots, M_T - 1$, where θ_i are not required to be fed back for beamforming.

QUANTIZATION AND GROUPING FOR ADJACENT TONES

When **V** is decomposed in sequence based on Eq. 2, it may rely on the previously quantized values of angles in the steps of Givens rotation for each column. Technically, these quantization errors can be accumulated with index i in Eq. 2. However crosstalk between streams is still minimized. On the other hand, if the quantization is performed after all decomposition process is done, the quantized angles found in each step do not rotate the matrix toward nullifying off-diagonal terms in each decomposed matrix.

Therefore, how to quantize the angles needs to be carefully approached. Also, angle resolution for ϕ and ψ should be properly chosen to minimize the quantization error. It was shown in [11] that the choice of $\phi_b = \psi_b + 2$ is optimal, where ϕ_b and ψ_b are the number of bits for ϕ and ψ, respectively. Considering different dynamic range as defined earlier, this implies that the same angle resolution for ϕ and ψ is required to minimize the quantization noise.

In addition, by utilizing the correlation property of the channel between tones, we can further reduce the network overhead of the feedback packet. Considering the coherent bandwidth of the channel and the tone width of an OFDM packet, we may choose one feedback value for a group of tones [12], where a beamformer may interpolate angles to recover those missing tones. For the channel with smaller delay spread, which has larger coherent bandwidth, we may be able to reduce the overhead by grouping more tones.

Performance of Beamforming

Here, we present the performance of the beamforming techniques based on compressed explicit feedback as illustrated in the previous subsections. We use channel D and channel E [13], where they have root mean square (rms) delay spread of 50 nsec and 100 nsec, respectively. Table 1 summarizes the total number of bytes required to deliver the beamforming matrix to reach within a 0.5 dB performance penalty (or 1 dB in *italic font*) with bandwidth of 20 MHz (or 40 MHz) due to a quantization loss for the worst case of channel E for grouping. For 2 × 2 systems operating with BPSK and 1/2 rate-coding, the compressed explicit feedback with 4-tone grouping can reduce the network overhead to only 5 percent, compared to a conventional Cartesian method without a significant performance degradation.

$M_T \times M_S$	2 × 2	3 × 3	4 × 2	4 × 4
Cartesian	260 (540)	468 (972)	416 (864)	832 (1728)
Givens	52 (108)	156 (324)	195 (406)	312 (648)
Group – 2	26 (54)	78 (162)	98 (203)	156 (324)
Group – 4	13 (27)	39 (81)	49 (102)	78 (162)

Table 1. The number of information bytes required to deliver the beamforming matrix V for 20 MHz (or 40 MHz) bandwidth with channel E.

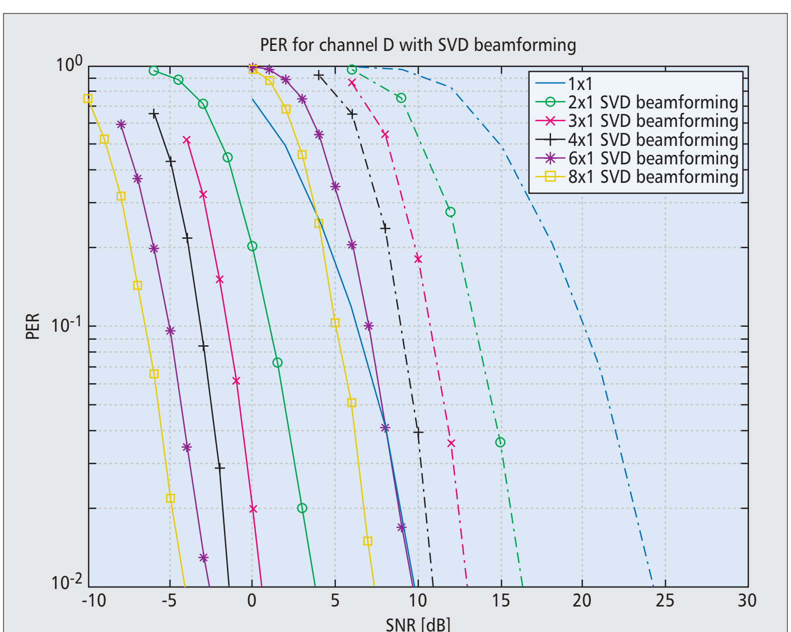

Figure 4. PERs for 802.11ac systems with MT transmit antennas and a single receive antenna using SVD beamforming.

Figure 4 illustrates a packet error rate (PER) performance gain with SVD beamforming for channel D, using compressed explicit feedback with grouping of 4 tones. In this plot, solid lines and dashed lines represent PER performances with MCS0 (BPSK with 1/2-rate) and MCS4 (16QAM with 1/2-rate), respectively. Regardless of MCS choice, beamforming with compressed explicit feedback shows significant performance gain.

Extension to Multiple Users

Beamforming can also be applied to transmit multiple streams simultaneously to multiple users, by nullifying interference between users. In MU-MIMO as shown in Fig. 5, where a beamformer collects CSI from users based on the compressed explicit feedback, a group of spatially separated users can be chosen, which is signaled with Group ID described earlier, and then a steering matrix is recalculated. Typically, the steering matrix found by the beamformer may be different from the beamforming matrix **V** fed back from a user, since it is designed to minimize interference to other users. The bit resolution for **V** in MU-MIMO is also selected higher than SU feedback, as the performance of the steering matrix is more sensitive to the channel mismatch.

This steering matrix is applied starting from the VHT-STF, where the designated user may receive its own streams with relatively much higher strength than other streams for other users. In order to suppress the interference at the receiver, the VHT-LTF contains training sequences for other streams as well. The number of the VHT-LTFs is the total number of streams for all participating users. For MU operations, MCS per user is included in the VHT-SIGB, which is user-specific information, however not decodable by other users because it is nullified by the steering matrix.

Future Techniques

In this section, we describe some promising techniques which allow to further enhance the spectrum efficiency of WLAN systems. These advanced techniques include, however are not limited to, sub-band transmission with group of tones based on orthogonal multiplexing division multiple access (OFDMA), uplink MU-MIMO and full duplex transmission.

Sub-band OFDMA

For downlink transmission, it is difficult to get a real benefit of the increased bandwidth due to commonly used secondary channels in neighboring basic service sets (BSSs) and restrictions on non-continuous channel assignments. We can employ the OFDMA technique, however with a unit of group of tones to reduce the implementation complexity, to maximize resource utilization in wider bandwidth and increase multiplexing flexibility. The sub-band OFDMA can assign subsets of subcarriers to individual users as a multi-user version of the popular OFDM scheme. Compared to the legacy operation which cannot use remaining secondary channels when interference is detected in the secondary channel, the sub-band OFDMA enables to access concurrent channels from multiple users and also utilizes non-continuous channels within a given FFT size.

The sub-band OFDMA technique can be combined with MIMO schemes [2] and then it leads to higher data rate and better reliability by utilizing SDM and spatial diversity methods in the MIMO systems. In addition, employing the resource allocation strategies including proper scheduling of sub-channels to users and transmit power control for each sub-band, the MIMO-OFDMA systems can improve channel utilization efficiency. Such systems exploit advantages of both techniques, providing simultaneously flexibility in resource allocation and increased system performance [16].

Uplink MU-MIMO

Currently, MU-MIMO technique is supported only for downlink to achieve higher aggregated throughput from an access point (AP) to STAs. However, for future WLAN services, it is expected to have more balanced bi-directional traffic between the AP and STAs. In order to achieve uplink efficiency enhancements, MU-MIMO transmission, as shown in Fig. 5, can be applied to uplink as well as downlink. As the counterpart of the downlink MU-MIMO, users simultaneously transmit their data to an AP. This allows us to reduce the number of contentions and the overhead for the back-off time and polling.

To implement the uplink MU-MIMO, the challenges are to determine how to synchronize the timing offset between users and how to compensate frequency offsets which are different between users by nature. Specifically, an AP receives uplink data from users with different arrival timing. However, if the contention period length is sufficiently greater than the sum of channel delay and time difference, then system performance is not deteriorated by uplink MU transmission. In [14], the timing offset problem was solved by expanding the guard interval. Also, the frequency offset requirements in 11ac specification need to be below 30.7 percent and 64 percent of the subcarrier spacing at 2.4 GHz and 5 GHz, respectively. Employing compensation schemes such as guard subcarriers among uplink data streams and frequency offset adjustments, the frequency offset problem can also be alleviated. Then, the implementation complexity of the uplink MU-MIMO may become reasonable for both the AP and users, and thus the uplink MU-MIMO technique may be feasible to improve the uplink spectrum efficiency.

Full Duplex

Existing 802.11 technologies only adopt separate transmission and reception at different time, which is called half duplex transmission. On the other hand, full duplex transmission allows simultaneous transmission and reception over the same time and frequency, which could significantly improve the spectrum efficiency up to two times higher. In this case, self-interference cancellation is critical to realization of the full duplex transmission.

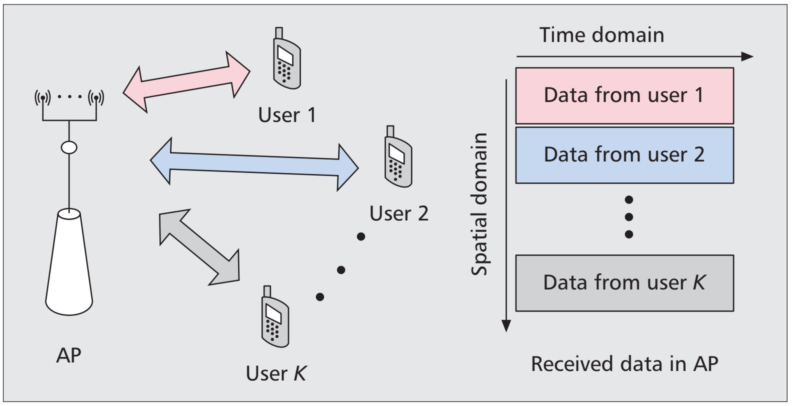

Figure 5. Schematic diagram of multi-user MIMO transmissions.

In order to solve this problem, there are three main cancellation techniques:

1 Antenna level cancellation: the antenna layout minimizes leakage from a transmit antenna into a receive antenna,

2 Analog cancellation: a noise cancellation circuit is applied to adjust the amplitude and phase of the interference reference signal to match the self-interference,

3 Digital cancellation: the scaled and rotated version of the ideal transmit signal is subtracted from the received signal.

By exploiting these techniques, the self-interference can be made to a marginal level \citeDuplex, which helps to improve the spectrum efficiency of future WLANs.

Other Future Considerations

In addition, there are still some other promising techniques that can improve the performance of future WLAN systems. These include cooperative beamforming, 3D beamforming, and relay techniques. Since many BSSs are often deployed by overlapping with each other, conventional carrier sense multiple access (CSMA) may incur performance degradations due to numerous neighboring interference signals. In this case, we can utilize the cooperative beamforming which eliminates the interference to adjacent APs by coordinating cooperative transmissions among APs. Also, the 3D beamforming which considers the three dimensional channel model enables to adjust the radiation beam pattern in both elevation and azimuth planes, and this allows us to increase the link capacity and decrease inter-node interference. Finally, relay methods which forward the signal received from the source to the destination can be adopted to improve link reliability and extend coverage.

Conclusions

In this article, we have examined the IEEE 802.11 standard which defines WLAN. First, we have reviewed the generations of WLAN, starting from 802.11a and 11b to 802.11ac which is

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being published. Then, we have provided technical overviews of the WLAN systems including the PHY preamble structure. Also we have presented the recent developments focusing on MIMO techniques and the compressed explicit feedback scheme which were adopted in 802.11n and 11ac. Finally, we have added future MIMO methods which are possibly considered for next generation WLAN.

Acknowledgements

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References

[1] IEEE Std 802.11 WG, Part 11, "IEEE standard for wireless LAN medium Access Control (MAC) and Physical Later (PHY) Specifications — Amendment 4: Further Higher-Speed Physical Layer Extension in the 2.4GHz Band," June 2003.

[2] H. Lee, B. Lee, and I. Lee, "Iterative Detection and Decoding With an Improved V-BLAST for MIMO-OFDM Systems," *IEEE JSAC*, vol. 24, Mar. 2006, pp. 504–13.

[3] G. J. Foschini and M. J. Gans, "On Limits Of Wireless Communication in A Fading Environment When Using Multiple Antennas," *Wireless Personal Commun.*, Mar. 19986, pp. 311–35.

[4] IEEE Std 802.11 WG, Part 11, "IEEE standard for wireless LAN Medium Access Control (MAC) and Physical Later (PHY) Specifications — Amendment 5: Enhancements for Higher Throughput," Oct. 2009.

[5] J. Kim, "Benefits of Compressed Explicit Feedback," IEEE 802.11-07/0666r1, May 2007.

[6] H. Zhang, R. Banerjea, V. Erceg, J. Kim *et al.*, "802.11ac preamble," IEEE 802.11-10/0070r5, Mar. 2010.

[7] J. Kim *et al.*, "Group ID concept for downlink MU-MIMO transmission," IEEE 802.11-10/0073r2, Jan. 2010.

[8] IEEE Std 802.11 WG, Part 11, "IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical later (PHY) Specifications — Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6GHz," no. D7.0, Nov. 2013.

[9] J. Kim and M. Fischer, "Preamble and Header Bit Allocation for Power Savings Within Multiple User, Multiple Access and/or MIMO Wireless Communications," US Patent 20110194475 A1, Feb. 2010.

[10] J. Kim *et al.*, "802.11ac Explicit Feedback Format," IEEE 802.11-10/1227r0, June 2010.

[11] J. Kim and C. Aldana, "Efficient Feedback of the Channel Information for Closed Loop Beamforming in WLAN," *Proc. IEEE VTC*, vol. 5, May 2006, pp. 2226–30.

[12] J. Kim, "Method and System for Utilizing Tone Grouping with Givens Rotations to Reduce Overhead Associated with Explicit Feedback Information," US Patent 7,873,016 B2, Jan. 2006.

[13] V. Erceg, L. Schumacher *et al.*, "IEEE 802.11 TGn Channel Models," IEEE Std 802.11-03/940r4, May 2004.

[14] R. V. Nee, "Uplink MU-MIMO Sensitivity to Power Differences and Synchronization Errors," IEEE 802.11-09/1036r0, Sept. 2009.

[15] A. Bourdoux *et al.*, "Full-Duplex Technology for HEW," IEEE 802.11-13/0764r1, July 2013.

[16] I. Lee, A. M. Chan, and C. W. Sundberg, "Space-Time Bit-Interleaved Coded Modulation for OFDM Systems," *IEEE Trans. Signal Processing*, vol. 52, Mar. 2004, pp. 820–25.

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