INVITED SURVEY PAPER

Survey of Transmission Methods and Efficiency Using MIMO Technologies for Wireless LAN Systems

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SUMMARY Multiple-input multiple-output (MIMO) transmission is attracting interest for increasing the transmission rates of wireless systems. This paper surveys MIMO transmission technology from the viewpoints of transmission methods, access control schemes, and total transmission efficiency. We consider wireless local area networks (WLAN) systems that use MIMO technology; moreover, we focus on multiuser MIMO (MU-MIMO) technology, which will be introduced in next-generation WLAN systems such as IEEE802.11ac. This paper explains the differences in the detailed access control procedures for MIMO and MU-MIMO transmission, including channel state information (CSI) acquisition. Furthermore, the issues related to CSI feedback and solutions are also discussed. Related works on the medium access control (MAC) protocol in MIMO/MU-MIMO transmission are introduced. In addition, the throughput performance using MIMO/MU-MIMO transmission is evaluated considering an IEEE802.11ac-based WLAN system. From the numerical evaluation, it is shown that the overhead due to CSI feedback from the user terminals to the base station causes a decrease in the throughput. We verified that implicit beamforming, which eliminates CSI feedback, is effective for solving this issue.

key words: *MIMO, MU-MIMO, transmission efficiency, overhead, access control, MAC protocol, CSI feedback, implicit beamforming, PHY*

1. Introduction

Representative wireless broadband systems such as Long-Term Evolution (LTE) [1] and wireless local area networks (WLANs) using the IEEE802.11 standard [2] have been implemented in various portable terminals such as laptops, smartphones/tablets, and game machines. Furthermore, these systems have been used as broadband access services and have rapidly spread worldwide.

Wireless communication systems have the problem of "how to improve the transmission rate with a limited frequency band [3], [4]". However, a high transmission rate has been achieved by various *new* technologies. In the past fifteen years, the most effective and most attractive technology for obtaining a high transmission rate is multiple-input multiple-output (MIMO) transmission technology [5]–[11]. MIMO technology has been incorporated into many of the latest wireless communication standards such as LTE, Wi-Fi, and Wi-MAX [12].

In MIMO transmission, both the transmitter and receiver employ multi-antenna array. Different signals are simultaneously transmitted from multiple antennas, and multiple data streams are decoded at multiple receive antennas. Many studies have been conducted on the realization of MIMO transmission, and MIMO transmission is now an essential tool for high-speed wireless communication. However, the transmission rate of the terminal stations, which have a smaller number of antennas than the base station, is generally determined by the terminal stations because the MIMO transmission rate is limited by the smaller number of antennas at the transmitter and receiver [5], [6].

In order to realize MIMO transmission with a limited number of antennas at the terminal stations, multiuser MIMO (MU-MIMO) has attracted much attention [13]–[16]. MU-MIMO transmission realizes communication with multiple terminal stations with a limited number of antennas called space division multiple access (SDMA) [17]–[19]. MU-MIMO transmission has been incorporated into the IEEE802.11ac standard [20] and LTE-Advanced standard [21], and commercial products based on these standards will appear in the near future. Moreover, the standardization of next-generation wireless LAN (WLAN) aims to achieve further high performance and high efficiency by using MU-MIMO transmission technology, and a task group for that standard called IEEE802.11ax [22] was established. From this technological background, MIMO/MU-MIMO transmission technologies are key technologies for next-generation WLAN. In order to distinguish between MIMO and MU-MIMO, MIMO is called single-user MIMO (SU-MIMO) hereafter in this paper.

Studies on SU-MIMO/MU-MIMO have mainly focused on the technologies of signal processing and the decoding methods at the receivers [23]–[28] as well as the transmit beamforming methods [29]–[31], in which the transmission performance in the physical layer (PHY) is evaluated. Current IEEE802.11 WLANs contribute to approximate 40% of overall Internet Protocol (IP) traffic [32]. However, the transmission rate achieved by SU-MIMO/MU-MIMO transmission is not currently adequately utilized because the overhead of the access control protocol in the medium access control (MAC) layer decreases the transmission efficiency, even though the physical transmission rate has been increased in the PHY layer by the adoption of SU-MIMO/MU-MIMO technology. Therefore, the MAC-service access point (MAC-SAP) throughput including the protocol in the MAC layer decreases greatly [2], even though the PHY layer improves the transmission rate via in-

Manuscript received October 13, 2014.
Manuscript revised February 12, 2015.
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DOI: 10.1587/transcom.E98.B.1250

creases in multilevel modulation and the number of subcarriers in WLAN systems. The decrease in the transmission efficiency is a significant issue because the ratio of the overhead of the MAC protocol is larger for MU-MIMO transmission. Although there are above issues, the frequency utilization and channel capacity have been evaluated in only PHY-layer.

Further, the throughput and delay characteristics in relation to the access control scheme have been evaluated in the MAC layer. Therefore, these studies have been individually evaluated. No adequate evaluation of the throughput and transmission efficiency considering both the PHY and MAC layers has not been published.

This paper surveys conventional SU-MIMO/MU-MIMO transmission technology from the viewpoints of both wireless communication systems and transmission efficiency, and the most popular WLAN systems that use SU-MIMO/MU-MIMO technology are chiefly discussed. Moreover, we survey the MU-MIMO technology used in next-generation WLAN systems. Furthermore, the latest trend of implicit-beamforming technology in enhanced MU-MIMO is introduced regarding its role in reducing channel state information (CSI) feedback [33]. CSI feedback is introduced into the current WLAN Standard (IEEE802.11n and ac). However, because the implicit beamforming without CSI feedback has not been introduced into WLAN Standard, hence, this technique will be introduced into one of main techniques in the future WLAN system.

This paper is organized as follows. Reviews of standardization to achieve high transmission rate in IEEE802.11 are described in Sect. 2. In Sect. 3, the basic principles of SU-MIMO/MU-MIMO transmission are described from the viewpoint of the PHY layer. Next, access control schemes for WLAN-based SU-MIMO/MU-MIMO systems are discussed in Sect. 4. In Sect. 5, we focus on issues related to CSI feedback and solutions. The transmission efficiency for SU-MIMO/MU-MIMO transmission is discussed in Sect. 6, and Sect. 7 summarizes the study and the plans for future work regarding SU-MIMO/MU-MIMO transmission.

2. Reviews of Standardization to Achieve High Transmission Rate in IEEE802.11

For the technology of WLAN, the standardization to meet various demands such as the high transmission rate, the relay function, the security, and the communication quality are advanced by IEEE802.11 [2]. A more strict nomenclature designates standards as documents with mandatory requirements (denoted as IEEE802.11 followed by the published year, e.g., IEEE802.11-2012), and amendments as documents that add to, remove from, or alter material in a portion of existing standards [34]. The IEEE802.11 is one of working group (WG) in IEEE802 committee of the international standardization organization. As for the trend of standardization in IEEE802.11WG, the technologies regarding "High function support" and "Speed-up of transmission" have ever been discussed. In "High function support" as for IEEE802.11e, the function of quality of service (QoS) support for the access control of the MAC layer was enhanced, although the conventional WLAN standard was the best-effort type communication [35]–[38]. Moreover, the standard of high-speed hand over (IEEE802.11r) and mesh networking (IEEE802.11s) was completed, hence "High function support" was achieved. In recently year, as video delivery that supports QoS, the discussion of aiming at the quality assurance of the multicast transmission was achieved in IEEE802.11aa [39]–[41], and this standard was completed in June 2012.

In "Speed-up of transmission", the transmission rate has been enhanced to 11 Mbit/s (IEEE802.11b) and 54 Mbit/s (IEEE802.11a/g) afterward, although the maximum transmission rate was 2 Mbit/s in legacy IEEE802.11 standard. WLAN products of IEEE802.11b/g and IEEE802.11a standard are generally widespread. As the wireless communications technology in recent years, MIMO transmission technology with two or more antennas has been developed as one of key technologies, and the MIMO technology was incorporated into IEEE802.11n standard [42]. The supported bandwidth has been expanded from 20 MHz to 40 MHz in IEEE802.11n standard. In the PHY layer, the maximum transmission rate of 600 Mbit/s is achieved by transmitting the different signals from four antennas at the same time. Because IEEE802.11n is highly required for the commercial products at the beginning of standardization, a lot of prior products by the draft version had been produced on to the market before standardization is completed. Most marketed WLAN products are now IEEE802.11n compliant.

Because a lot of attention had gathered in the standardization trend as for IEEE802.11n, the standardization of IEEE802.11ac that aimed at a further transmission rate of over 1 Gbit/s was advanced [20]. As for IEEE802.11ac, the SDMA technologies for the downlink by the MU-MIMO transmission technology was proposed in 5GHz band. Moreover, the bandwidth is expanded from 20 MHz to 80 MHz (optionally, maximum 160 MHz), and a very high transmission rate was realized. The maximum transmission rate in PHY layer is approximately 7 Gbit/s by these technologies. The supported number of antennas is increased from four to eight in IEEE802.11ac standard, in order to achieve the transmission rate with 7 Gbit/s at maximum. The standardization of IEEE802.11ac was aggressively accomplished, and the standards work was completed in February 2014. IEEE802.11ac has already been marketed with the prior product of the draft version as well as IEEE802.11n, and WLAN products of IEEE802.11ac compliant will be expected to become a main current products in the future.

In the next generation WLAN, IEEE802.11ac was enhanced, high efficiency WLAN (HEW) of new study group (SG) to improve the transmission efficiency etc. has been established since May 2013. The resources of the space and the frequency are effectively used by a method of improving the transmission efficiency. For example, bandwidth is

Table 1 Project authorization request for high transmission rate in IEEE802.11.

Task Group (TG)	Project authorization request (PAR)	Year of completion or target year (*)
11e	MAC enhancements QoS	March 2007
11n	High-speed WLAN for over 100 Mbit/s	Sept. 2009
11aa	Enhancement function for video transport streams	June 2012
11ac	Very high throughput up to 6GHz	Feb. 2014
11ad	Very high throughput up to 60GHz	Oct. 2012
11ax	High Efficiency WLAN	March 2019(*)

expanded for further speed-up. Two or more basic service set (BSS) using the same frequency will overlap, when the bandwidth is expanded. This technology is called overlap BSS (OBSS), and the transmission efficiency in the service area decreases because a frequency band is shared between cells. The MU-MIMO is enhanced to improve such a problem, BS suppresses interference in the adjacent area, and the interference between cells will be controlled. The interference control technology between cells that the communication of the same time and the same frequency is possible are proposed in HEW SG, if the BS that uses the same channel for the vicinity is set up. This HEW SG became Task Group in May 2014 and the standard started as "IEEE802.11ax" [22].

Not only downlink but also uplink is very important work in MU-MIMO transmission. However, regarding concrete access control methods in the uplink MU-MIMO have not defined in WLAN standard, because the simultaneous transmission among UTs after the CSI estimation is very severe issue. Although the synchronization methods have been proposed for MU-MIMO uplink [43], [44], these techniques have not been introduced into the standard of IEEE802.11ac.

The list of main standardization effort is shown in Table 1 [45].

3. Principle of SU-MIMO/MU-MIMO Transmission

3.1 Basic Principles of SU-MIMO/MU-MIMO

Figure 1 shows the basic principles of SU-MIMO/MU-MIMO systems in the downlink channel. The numbers of transmit antennas at the BS, receive antennas at the UE, and users are N_T, N_R, and N_U, respectively. In Fig. 1, N_U is one and two when SU-MIMO and MU-MIMO are assumed, respectively. The total channel matrix is $\boldsymbol{H} \in \mathbb{C}^{N_R \cdot N_U \times N_T}$, and $\boldsymbol{H}^{(k)} \in \mathbb{C}^{N_R \times N_T}$ $(k = 1 \sim N_U)$ denotes the channel matrix for user k. The transmit signal at the t-th symbol is $\boldsymbol{s}(t) \in \mathbb{C}^{N_R \cdot N_U \times 1}$, and $\boldsymbol{s}^{(k)}(t) \in \mathbb{C}^{N_R \times 1}$ $(k = 1 \sim N_U)$ denotes the transmit signal for user k. The weight matrix is $\boldsymbol{W} \in \mathbb{C}^{N_T \times N_R \cdot N_U}$, and $\boldsymbol{W}^{(k)} \in \mathbb{C}^{N_T \times N_R}$ $(k = 1 \sim N_U)$ denotes the weight matrix for user k. When $N_U = 2$, $\boldsymbol{s}(t)$, $\boldsymbol{H}$, and $\boldsymbol{W}$ are given by

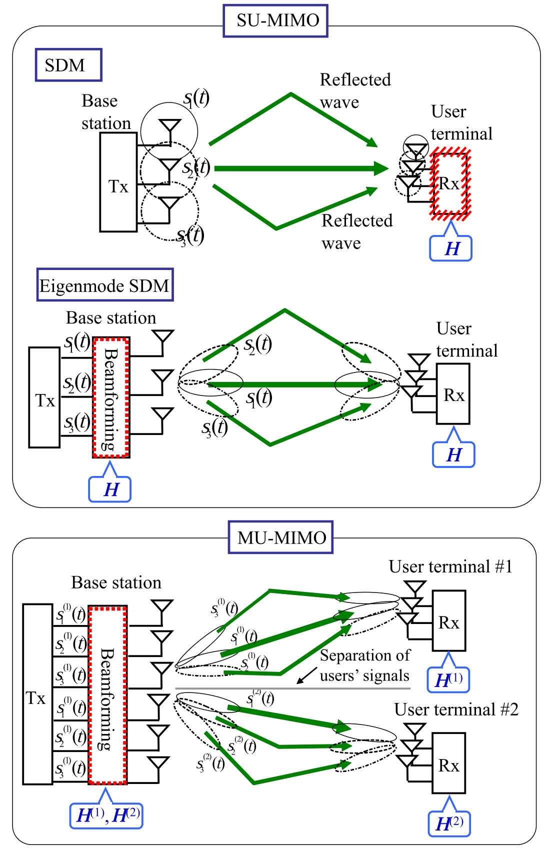


Fig. 1 Basic principles of SU-MIMO/MU-MIMO systems.

$$\boldsymbol{s}(t) = \left[\left(\boldsymbol{s}^{(1)}(t)\right)^T \ \left(\boldsymbol{s}^{(2)}(t)\right)^T\right]^T, \tag{1}$$

$$\boldsymbol{H} = \left[\left(\boldsymbol{H}^{(1)}\right)^T \ \left(\boldsymbol{H}^{(2)}\right)^T\right]^T, \tag{2}$$

$$\boldsymbol{W} = \left[\boldsymbol{W}^{(1)} \ \boldsymbol{W}^{(2)}\right], \tag{3}$$

where T represents the transpose of the matrix.

First, we explain the basic features of SU-MIMO transmission without transmit beamforming. The transmission scheme, in which multiple data streams are simultaneously transmitted by multiple antennas, is called *space division multiplexing (SDM)* [8], [9]. The received signal vector, $\boldsymbol{y}(t) \in \mathbb{C}^{N_R \times 1}$ is expressed as

$$\boldsymbol{y}(t) = \boldsymbol{H}\boldsymbol{s}(t) + \boldsymbol{n}(t), \tag{4}$$

where $\boldsymbol{n}(t) \in \mathbb{C}^{N_R \times 1}$ is the noise vector. Because each received signal is corrupted by inter-substream interference, as shown in Eq. (4), a substream detector with a function to suppress interference is required.

To solve this issue, many studies that have received considerable attention have been carried out [5]–[11]. The optimal multi-substream detection for SDM is MLD [23], [24]. The number of possible signal constellations for each substream is defined by the modulation scheme employed. Assuming that the number of modulated signal constellations is M, there are M^L possible combinations of each substream constellation, where L is the number of data streams.

Hence, the reduction in the number of calculations in MLD is a very important issue. To solve this issue, sphere decoding [28], QRM-MLD (complexity-reduced MLD with QR decomposition) [11], etc. have been proposed.

Because MLD is a very complicated signal detection scheme, spatial filtering algorithms such as the zero forcing (ZF) [8] and minimum mean square error (MMSE) [25] algorithms are used as the simplest method. Spatial filtering is well known as an adaptive array that realizes interference cancellation by using an array antenna [46], [47]. In Sect. 5, the ZF algorithm is used as the signal detection scheme. The inverted channel matrix, $\boldsymbol{H}^{-1}$ is used as the receive weight of the ZF algorithm. The receive signal vector after the ZF algorithm, $\boldsymbol{y}(t) \in \mathbb{C}^{N_R \times 1}$, is expressed as

$$\boldsymbol{y}(t) = \boldsymbol{H}^{-1}\boldsymbol{r}(t) \tag{5}$$

$$= \boldsymbol{s}(t) + \boldsymbol{H}^{-1}\boldsymbol{n}(t). \tag{6}$$

Although the ZF algorithm enables perfect interference suppression, as shown in Eq. (6), a noise power enhancement might occur if the norm of the inverted channel matrix is large. On the other hand, the MMSE algorithm avoids this problem by minimizing the interference and noise power when calculating the optimal weight. When $N_R \geq N_T$, the receive weight of the ZF algorithm is generally expressed as

$$\boldsymbol{W}_{\mathrm{ZF}}^{T} = (\boldsymbol{H}^{H}\boldsymbol{H})^{-1}\boldsymbol{H}^{H}, \tag{7}$$

where H denotes Hermitian transpose of the matrix.

There is a trade-off between the performance and the calculation complexity when using a signal detection method in SDM. In order to realize simple signal processing at the UE in the downlink channel, transmit beamforming at the BS is proposed; this method is called eigenmode SDM [29]–[31]. In addition, spatial filtering such as ZF and MMSE etc. can be applied for the algorithm of transmit beamforming. In this paper, the principle of eigenmode SDM is shown in Fig. 2. As can be seen in Fig. 2, eigenmode SDM utilizes the fact that the channel matrix, $\boldsymbol{H}$, is represented by singular value decomposition (SVD) as

$$\boldsymbol{H} = \boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^{H}, \tag{8}$$

where $\boldsymbol{U} \in \mathbb{C}^{N_R \times N_R}$ and $\boldsymbol{V} \in \mathbb{C}^{N_T \times N_T}$ are the left and right singular value matrices, respectively, and these matrices are unitary matrices. Hence, the following condition is obtained as

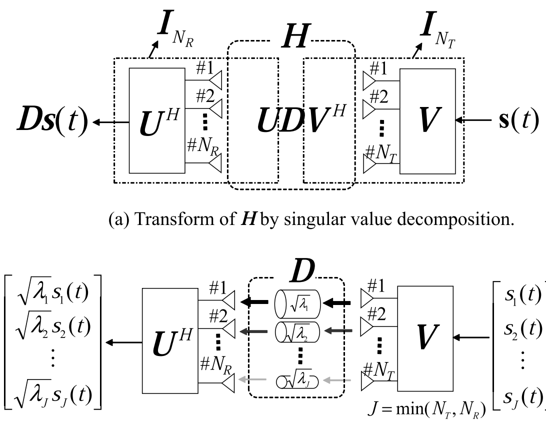
$$\boldsymbol{U}\boldsymbol{U}^{H} = \boldsymbol{I}_{N_R}, \tag{9}$$

$$\boldsymbol{V}^{H}\boldsymbol{V} = \boldsymbol{I}_{N_T}, \tag{10}$$

where $\boldsymbol{I}_{N_R} \in \mathbb{C}^{N_R \times N_R}$ and $\boldsymbol{I}_{N_T} \in \mathbb{C}^{N_T \times N_T}$ are identity matrices. Moreover, $\boldsymbol{D}$ is the diagonal matrix expressed as

$$\boldsymbol{D} = \begin{bmatrix} \sqrt{\lambda_1} & 0 & \cdots & 0 \\ 0 & \sqrt{\lambda_2} & & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sqrt{\lambda_J} \end{bmatrix}, \tag{11}$$

where $\lambda_k (k = 1 \sim J)$ is an eigenvalue, and $J = \min(N_T, N_R)$.



(a) Transform of $\boldsymbol{H}$ by singular value decomposition.

(b) Equivalent circuit of eigenmode SDM.

Fig. 2 Principle of eigenmode SDM.

In eigenmode SDM, $\boldsymbol{V}$ and $\boldsymbol{U}^H$ are used as the transmit and receive weights, and the receive signal vector $\boldsymbol{y}(t)$ is

$$\boldsymbol{y}(t) = \boldsymbol{H}\boldsymbol{V}\boldsymbol{s}(t) + \boldsymbol{n}(t). \tag{12}$$

The decoded received signal, $\tilde{\boldsymbol{s}}(t)$, is given by

$$\tilde{\boldsymbol{s}}(t) = \boldsymbol{U}^{H}(\boldsymbol{H}\boldsymbol{V}\boldsymbol{s}(t) + \boldsymbol{n}(t)) \tag{13}$$

$$= \boldsymbol{U}^{H}\left(\boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^{H}\boldsymbol{V}\boldsymbol{s}(t) + \boldsymbol{n}(t)\right) \tag{14}$$

$$= \left(\boldsymbol{U}^{H}\boldsymbol{U}\right)\boldsymbol{D}\left(\boldsymbol{V}^{H}\boldsymbol{V}\right)\boldsymbol{s}(t) + \boldsymbol{U}^{H}\boldsymbol{n}(t) \tag{15}$$

$$= \boldsymbol{D}\boldsymbol{s}(t) + \boldsymbol{U}^{H}\boldsymbol{n}(t). \tag{16}$$

As can be seen in Eq. (16), an interference-free channel can be realized thanks to the transmit and receive weights ($\boldsymbol{V}$, $\boldsymbol{U}^H$). Moreover, because $\boldsymbol{U}^H$ is a unitary matrix, a noise power enhancement cannot occur, unlike in the ZF algorithm. However, the BS must know the CSI to realize eigenmode SDM. This issue is explained in the next section in detail.

In an SU-MIMO system, transmit beamforming is not essential because multi-substream detection can be realized by the MLD, ZF, and MMSE algorithms. Hence, eigenmode SDM is introduced as an optional function in the IEEE802.11n standard. On the other hand, as shown in Fig. 1, the interference among users must be realized in MU-MIMO transmission because the UE1 (UE2) cannot cancel the signal for UE2 (UE1) due to the smaller number of antennas at UEs compared to that at BS. In Fig. 1, UE#1 (#2) cannot know the information regarding $\boldsymbol{H}^{(2)}$ ($\boldsymbol{H}^{(1)}$). Hence, transmit beamforming is an essential technique in an MU-MIMO system.

3.2 Block Diagonalization (BD) Algorithm

Here, we introduce a block diagonalization (BD) algorithm which is well known as the MU-MIMO downlink beamforming method [48], [49]. Figure 3 shows the system model for the MU-MIMO downlink channel. As shown in Fig. 3, $\boldsymbol{H}^{(1)}\boldsymbol{W}^{(1)}\boldsymbol{s}^{(1)}(t)$ and $\boldsymbol{H}^{(2)}\boldsymbol{W}^{(2)}\boldsymbol{s}^{(2)}(t)$ must be transmitted to user 1 and 2, respectively. On the other hand,

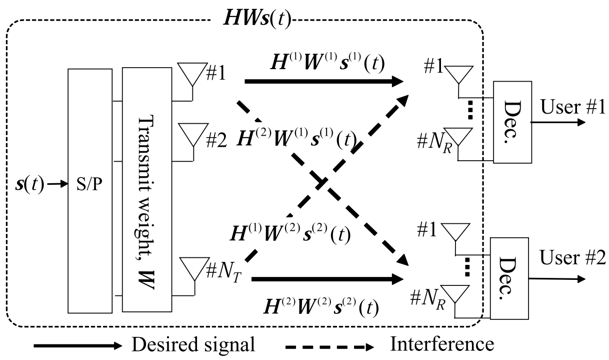


Fig. 3 System model in an MU-MIMO downlink ($N_U = 2$).

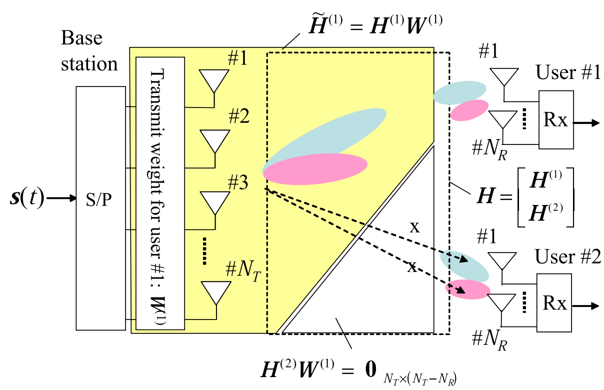


Fig. 4 Spatial channel for user 1 using the BD algorithm ($N_U = 2$).

$\boldsymbol{H}^{(1)}\boldsymbol{W}^{(2)}\boldsymbol{s}^{(2)}(t)$ and $\boldsymbol{H}^{(2)}\boldsymbol{W}^{(1)}\boldsymbol{s}^{(1)}(t)$ are the interference for users 1 and 2, respectively. Regardless of the transmit signals, the following condition must be obtained to cancel interuser interference:

$$\boldsymbol{H}^{(1)}\boldsymbol{W}^{(2)} = \boldsymbol{H}^{(2)}\boldsymbol{W}^{(1)} = \boldsymbol{0}_{N_R\times(N_T-N_R)}. \tag{17}$$

Figure 4 shows a spatial channel created by the BD algorithm considering the system model in Fig. 3. In the BD algorithm, $\boldsymbol{W}^{(1)}$ and $\boldsymbol{W}^{(2)}$ are calculated to obtain the conditions in Eq. (17). Here, we explain the BD algorithm with an arbitrary number of users. For transmitting a signal only to user k ($k = 1 \sim N_U$), we first prepare the matrix $\bar{\boldsymbol{H}}^{(k)}$ as

$$\bar{\boldsymbol{H}}^{(k)} = \left[\left(\boldsymbol{H}^{(1)}\right)^T, \cdots, \left(\boldsymbol{H}^{(k-1)}\right)^T, \left(\boldsymbol{H}^{(k+1)}\right)^T \right.$$
$$\left. \cdots, \left(\boldsymbol{H}^{(N_U)}\right)^T\right]^T, \tag{18}$$

where $\bar{\boldsymbol{H}}^{(k)} \in \mathbb{C}^{(N_U-1)\cdot N_R\times N_T}$ excludes the channel matrix $\boldsymbol{H}^{(k)}$. Next, SVD is employed for the matrix, $\bar{\boldsymbol{H}}^{(k)}$, resulting in

$$\bar{\boldsymbol{H}}^{(k)} = \bar{\boldsymbol{U}}^{(k)}\bar{\boldsymbol{D}}^{(k)}\left(\bar{\boldsymbol{V}}^{(k)}\right)^H, \tag{19}$$
$$= \bar{\boldsymbol{U}}^{(k)}\left[\bar{\boldsymbol{D}}_s^{(k)} \ \ \boldsymbol{0}_{(N_U-1)\cdot N_R\times(N_T-(N_U-1)\cdot N_R)}\right]$$
$$\cdot\left[\bar{\boldsymbol{V}}_s^{(k)} \ \ \bar{\boldsymbol{V}}_n^{(k)}\right]^H, \tag{20}$$

where $\bar{\boldsymbol{V}}_n^{(k)}$ and $\bar{\boldsymbol{V}}_s^{(k)}$ are the right singular matrices consisting of the singular vectors corresponding to nonzero singular values and zero singular values, respectively. To precancel the interference of all users except user k, we choose the matrix $\bar{\boldsymbol{V}}_n^{(k)}$. The following relationship between $\bar{\boldsymbol{V}}_n^{(k)}$ and $\bar{\boldsymbol{H}}^{(k)}$ exists:

$$\boldsymbol{H}^{(1)}\bar{\boldsymbol{V}}_n^{(k)} = \cdots = \boldsymbol{H}^{(k-1)}\bar{\boldsymbol{V}}_n^{(k)} = \boldsymbol{H}^{(k+1)}\bar{\boldsymbol{V}}_n^{(k)} = \cdots$$
$$= \boldsymbol{H}^{(N_U)}\bar{\boldsymbol{V}}_n^{(k)} = \boldsymbol{0}_{N_R\times(N_T-(N_U-1)\cdot N_R)}. \tag{21}$$

Hence, *block diagonatization* can be realized when $\boldsymbol{W}^{(k)} = \bar{\boldsymbol{V}}_n^{(k)}$.

As shown in Fig. 4, the channel matrix $\tilde{\boldsymbol{H}}^{(k)} = \boldsymbol{H}^{(k)}\bar{\boldsymbol{V}}_n^{(k)}$ is regarded as that of SU-MIMO by using $\bar{\boldsymbol{V}}_n^{(k)}$ for user k. In the BD algorithm, eigenmode SDM [29], [30] is employed for the matrix $\tilde{\boldsymbol{H}}^{(k)}$. Finally, the total transmit weight of the BD algorithm is given by

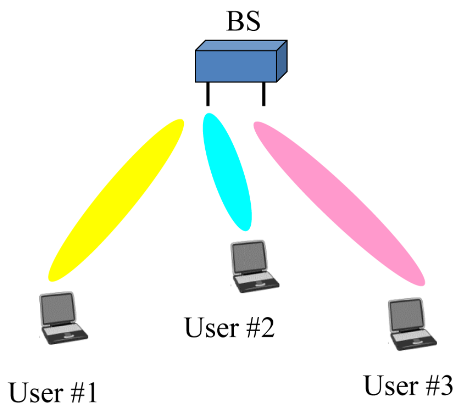
$$\boldsymbol{W}_{BD}^{(k)} = \bar{\boldsymbol{V}}_n^{(k)}\tilde{\boldsymbol{V}}_s^{(k)}, \tag{22}$$

where $\tilde{\boldsymbol{V}}_s^{(k)}$ denotes the right singular matrix consisting of the singular vectors corresponding to the nonzero singular values of $\tilde{\boldsymbol{H}}^{(k)}$.

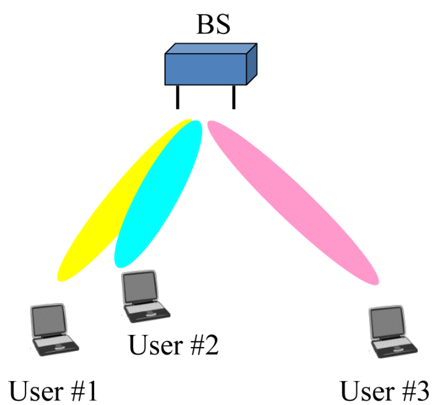
3.3 User Scheduling and Nonlinear Precoding

Transmit beamforming techniques including the ZF, MMSE, and BD algorithms are called linear precoding techniques because the weight matrix at the transmitters can be obtained in a closed form. However, when the spatial correlation between users is high, it is well known that the transmission rate using linear precoding is severely degraded. Moreover, the transmission rate using linear precoding decreases when the number of transmit antennas is equal to the total number of received antennas.

A method for improving the performance of linear precoding is a combination of linear precoding and a user selection algorithm that comes close to the sum capacity achieved by dirty paper coding (DPC) [50], [51]. Figure 5 shows an example in which the effect of user scheduling is expected. N_T, N_R, and N_U are two, one, and three, respectively, in Fig. 5. Therefore, the BS must select two users among the three users. In order to easily show the user separation characteristics, the single beam pattern for each user is illustrated. However, note that actual radiation patterns are different from the patterns Fig. 5, because the radiation pattern is very complex unlike the pattern in Fig. 5 in actual multipath environment. Figure 5(a) shows an example in which the spatial distribution is almost constant among users. In this case, user selection does not affect the transmission rate using linear precoding. On the other hand, the transmission rate is severely degraded if users 1 and 2 are selected when considering the scenario in Fig. 5(b) because the spatial correlation between users 1 and 2 is high. In the user scheduling algorithm, users are selected to avoid such a scenario in Fig. 5(b), e.g., users 1 and 3 or users 2 and 3 are selected. As specific algorithm, several methods have been



(a) Spatial distribution is constant.



(b) Spatial distribution is not constant.

Fig. 5 Example of where the effect of using user scheduling is expected.

proposed [52]–[55].

Figure 6 shows the effectiveness of user scheduling for MU-MIMO transmission. N_T, N_R, and N_U are four, two, and two, respectively, in Fig. 6. The BD algorithm is applied for MU-MIMO transmit beamforming. The bit error rate (BER) versus the signal-to-noise power ratio (SNR) is plotted in this figure. The total transmission rate is 8 bits/symbol (4 bits/symbol/user), and an error coding scheme is not employed. The modulation schemes in this evaluation is shown in Table 2. The upper bound shows the BER by eigenmode SDM with (N_T, N_R) = (4,4) [50], [51]. As can be seen in Fig. 6, the BER using the BD algorithm without user scheduling is degraded compared to that for the upper bound. On the other hand, the BER is improved thanks to user scheduling, and its degradation at BER = 10^{-3} is less than 1 dB when the number of candidates for user scheduling is 10. Although user scheduling is very effective for improving the transmission performance in MU-MIMO transmission, in general, a considerable amount of information regarding the CSI is required for the user scheduling algorithm [52], [54]. This issue and its performance are discussed in Sect. 6 in detail.

Another way to improve the performance of an MU-MIMO downlink is to use a nonlinear precoding

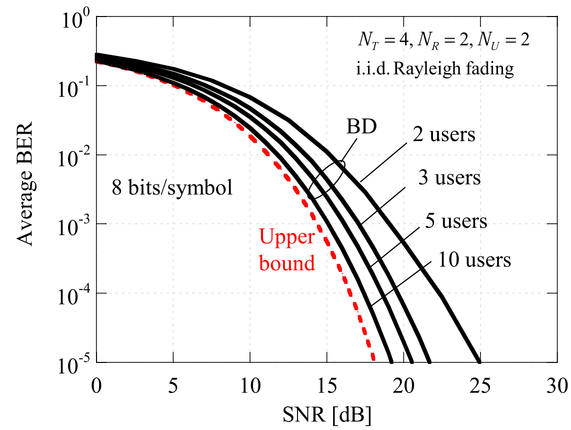


Fig. 6 BER using user scheduling.

Table 2 Modulation schemes (4 bits/symbol/user).

Modulation 1	Modulation 2	Symbol/bit
QPSK	QPSK	[2, 2]
8QAM	BPSK	[3, 1]
16QAM	–	[4]

method [56]–[58]. Vector perturbation (VP) has been proposed to enhance the performance of the BD algorithm [59]. However, the calculation complexity becomes very large owing to the use of VP because an optimal perturbation is required for each symbol in this method. Therefore, we focus on linear precoding with user scheduling, and its throughput is evaluated in Sect. 6.

4. Overview of Access Control Schemes for 802.11 WLAN-Based SU-MIMO/MU-MIMO Systems

Carrier sense multiple access with collision avoidance (CSMA/CA) is used as the access control scheme in the MAC layer on WLAN systems [60], [61]. CSMA/CA performs carrier sensing before data packets are sent from wireless terminals, in order to detect the influence of signals or data packets from other wireless terminals. Carrier sensing is achieved at a random time; then, transmission processing is interrupted immediately when the channel is busy. The transmitter changes to the transmission state when the channel changes to idle. CSMA/CA is adopted for the MAC layer in all standards up to the present, although the transmission technology of the PHY layer has been changed in the previous WLAN standard to provide an increase in the transmission rate. Naturally, CSMA/CA is adopted even by MIMO transmission. The carrier sense performs two procedures of the distributed inter-frame space (DIFS) at a fixed period and the backoff procedure occurs at random time in the range of the contention window (CW). The data packet is transmitted if channel is idle for only the period of carrier sensing of both DIFS and random backoff.

An example of the access control procedure for 2 × 2 MIMO transmission with two antennas (Antenna#1 and Antenna#2) for CSMA/CA is shown in Fig. 7. Data packets are transmitted after carrier sensing. Then, the transmission succeeds when an acknowledgment (ACK) frame is received as a reply from the receiver terminal. When ACK is not replied, the transmission is considered to be a reception failure, and retransmission control is performed. Therefore, retransmission control repeatedly performs carrier sensing of the DIFS+backoff again. The maximum packet size for Ethernet is 1500 bytes, whereas the supported data payload size in the IEEE802.11n or the IEEE802.11ac standard is 1048575 bytes. This is continuously transmitted by uniting Ethernet packets that are called an aggregation function [aggregation-MAC protocol data unit (A-MPDU)] [62]–[64]. When the A-MPDU aggregation function is used, the ratio of the overhead spent according to the procedure in the MAC layer decreases, and the transmission efficiency will improve rapidly, resulting in an increase in the throughput.

Next, access control for MU-MIMO transmission in the IEEE802.11ac standard is illustrated in Fig. 8 [65]–[68]. The BS achieves transmission beamforming that dynamically turns the beam to direction of the UTs and transmits different signals at the same time by same channel. MU-MIMO transmission is able to transmit data to two or more UTs at the same time, although conventional MIMO transmission in the IEEE802.11n standard transmits data by time division. The BS can have a maximum of eight antennas; therefore, the eight data streams are transmitted at maximum in the IEEE802.11ac standard, although the BS has maximum of four antennas in the IEEE802.11n standard.

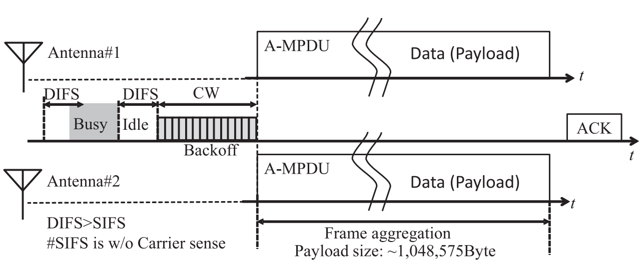


Fig. 7 Access control procedure for MIMO transmission.

As an initial procedure, carrier sensing of the DIFS+backoff is performed. If the channel is idle, the BS sends a null data packet announcement (NDPA) frame to all UTs as a start announcement. To form the beam to each UT by transmission beam forming, channel estimations are performed between the BS and all UTs. The BS sends the UTs an already-known signal [a null data packet (NDP)] according to the channel estimations, and the CSI of the channel characteristics is fed back to the BS by the beamforming report (BR). These procedures are performed for all UTs by the polling opportunity of the beamforming report poll (BRP). When the beam is formed afterwards, data packets are transmitted to the destination UTs at the same time by the space division multiple access. Therefore, the multiple data packets must be transmitted synchronously when the channel estimations by CSI feedback are completed. In SU-MIMO transmission, the BS forms a beam to only one UT. A block ACK (BA) from each UT is sent to the BS as a reply when the UTs receive a block ACK request (BAR) from the BS. The BA is an ACK corresponding to aggregation (A-MPDU, etc.) of the data packet, and this is used in both the IEEE802.11ac and IEEE802.11n standards. A maximum of eight antennas have been determined for use in IEEE802.11ac. The number of data streams is four streams when two antennas are coupled, and the beams are turned to each direction of UTs. When the number of UTs increases, the channel estimation procedure is repeatedly executed for all UTs using these eight antennas, and the BS should select four UTs such that space division multiple access is possible. This channel estimation procedure will consume a considerable amount of overhead time.

In addition, the bandwidth in the SU-MIMO/MU-MIMO are enhanced from 40 MHz (802.11n and 802.11ac) to 80 MHz (802.11ac) (maximum 160 MHz) to achieve a higher transmission rate, as shown Fig. 9. However, in this paper, the 40-MHz bandwidth is assumed to impartially evaluate the performance of various MIMO technologies when IEEE802.11n is compared with IEEE802.11ac.

The maximum transmission rate of IEEE802.11n using MIMO is 600 Mbit/s in the PHY layer because the max-

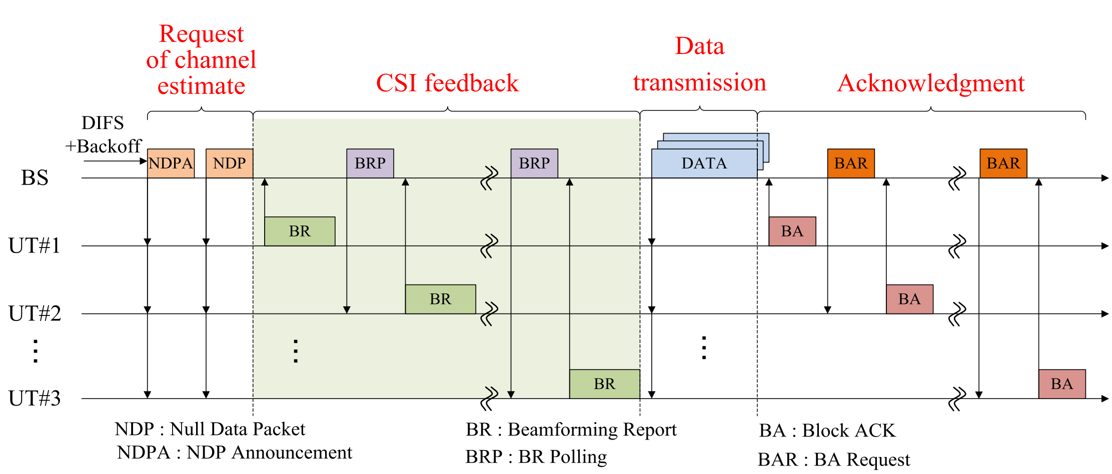


Fig. 8 Access control procedure for MU-MIMO transmission.

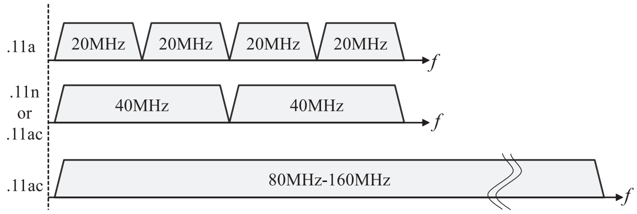


Fig. 9 Bandwidth in the IEEE802.11 standard.

imum modulation scheme is 64-QAM, and the bandwidth is 40 MHz. In addition, the number of subcarriers is 108, one subcarrier is 6 bits, and the number of antennas is four. On the other hand, in 802.11ac using the MU-MIMO transmission, the maximum transmission rate is approximately 7 Gbit/s in the PHY because the maximum modulation scheme is 256-QAM, and the bandwidth is 160 MHz. Furthermore, the number of subcarrier is 468, one subcarrier is 8 bits, and the numbers of antennas is eight. However, in MU-MIMO transmission, it will be difficult to always obtain the maximum transmission rate, because the combination of the modulation schemes is selected by the transmit distance between the BS and the UTs. Therefore, the same modulation schemes among all data streams are not used. Hence, the best modulation scheme is selected for each data stream. In addition, the number of data streams that equals to the number of transmit antennas might not be necessarily transmitted.

5. Issue Regarding CSI Feedback and its Countermeasures

5.1 Issue Regarding CSI Feedback

Figure 10 shows the frame format with CSI feedback. To initiate MU-MIMO transmission in the downlink channel, Period A is required as a negotiation time for user selection. As can be seen in Fig. 10, the CSI is estimated at the UTs by using the information in Period B, and the estimated CSI must be returned to the BS using Period C. When considering the MU-MIMO system, N_T should be greater than or equal to $N_R \times N_U$. Therefore, Period B incurs a large overhead. Although user scheduling is effective in MU-MIMO transmission, as discussed in the previous section, Period C incurs a very large overhead when considering user scheduling. The influence due to the CSI feedback overhead is discussed in the next section.

5.2 Compression of CSI Feedback

CSI feedback in a communication system enables the transmitter to exploit channel conditions and avoid interference. For an SU-MIMO/MU-MIMO channel, feedback can be used to specify a precoding matrix at the transmitter, which activates the strongest channel modes [69]. In order to reduce the overhead on the transmission efficiency due to CSI feedback, various types of CSI compression methods have

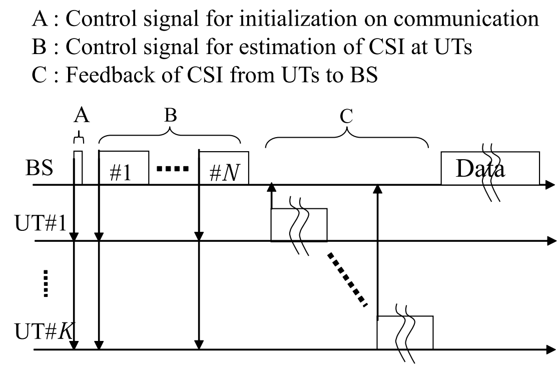


Fig. 10 Frame format for MU-MIMO transmission with CSI feedback.

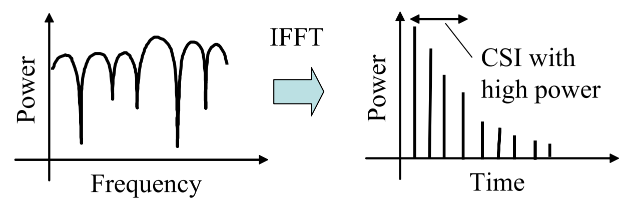


Fig. 11 Basic principle of CSI compression.

been proposed [69]–[79]. The simplest way is to prepare a preset weight in advance called a *codebook*. More precisely, this method is not CSI compression, and multiple *codebooks* are prepared between the BS and the UTs. Because the optimal codebook is selected at the receivers by using the CSI, only the index number is feedback, and CSI feedback is not required. This method is incorporated into the LTE standard.

The limitation of limited CSI feedback is described in [70]–[73], and detailed design methods for the codebook are discussed in [74]. The method for the BD algorithm has been proposed in [75], and [76] proposed a user selection method considering limited CSI feedback. The method for utilizing the characteristics of MIMO-OFDM systems, which are incorporated into the latest broadband communication systems, was proposed in [77].

In this paper, we introduce one of CSI compression methods. Fig. 11 shows an example of a CSI compression method [78], [79]. Because OFDM is generally introduced in the latest broadband wireless communication systems, the CSI must be estimated for each subcarrier in the OFDM signal. As shown in Fig. 11, the estimated CSI in the frequency domain is transformed into the CSI in the time domain by using an inverse FFT. Because the CSI in the time domain represents the delay profile itself, the power for the long delay time is very small; thus, these signals can be neglected. In this method, only the CSI with high power is used and fed back to the BS. Therefore, the total amount of CSI feedback in the time domain is reduced compared to that in the frequency domain.

5.3 Implicit Beamforming

Even if CSI compression is employed, the CSI feedback still

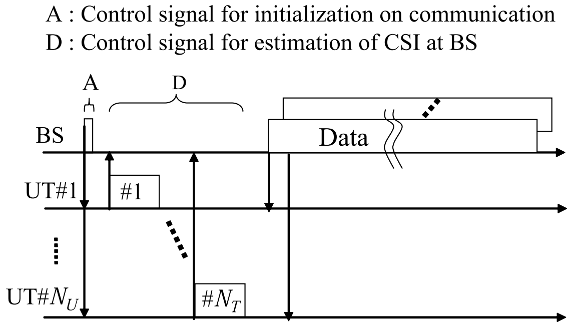


Fig. 12 Frame format of MU-MIMO without CSI feedback.

incurs a large overhead when a large number of antennas at the BS (e.g., massive MIMO [80]–[82]) and/or user scheduling are assumed. In order to overcome this issue, beamforming without CSI feedback called *implicit* beamforming [33] has been proposed. Originally, an adaptive array utilizing the channel reciprocity was proposed to realize interference avoidance using the uplink channel [83], [84]. Channel reciprocity means that the uplink and downlink share the same frequency band in time division duplex (TDD) systems, and the receive weight created by the uplink channel can be utilized for the transmit weight [85]. A calibration technique is essential among the transmitters and receivers for realizing implicit beamforming [86]–[91].

Figure 12 shows the frame format of MU-MIMO without CSI feedback. As can be seen in Fig. 12, the BS directly obtains the CSI from multiple UTs during Period D by utilizing channel reciprocity between the transmission and the reception in TDD [33]. Moreover, because K is much smaller than M, the overhead during Period B can be decreased by using the frame format in Fig. 10.

6. Efficiency of SU-MIMO/MU-MIMO Transmission for WLAN Systems

In this section, works related to SU-MIMO and MU-MIMO are introduced. These related works are evaluations that include the performance of entire systems. Therefore, the system performance that integrates the technologies of the MAC and PHY layers is evaluated. Moreover, under suitable conditions, we re-evaluated the system performance on the basis of the evaluation results of these related works. Finally, we considered the optimum applicable conditions for SU-MIMO and MU-MIMO. In addition, the effectiveness of implicit beamforming which eliminate the CSI feedback is verified.

6.1 Related Works and Motivation

We introduce works related to SU-MIMO and MU-MIMO for WLAN systems in this subsection [92]–[105]. For these technologies, the transmission schemes including the MAC protocol over the PHY layer are evaluated. In the typical evaluation of conventional MIMO technology, MAC layer technology and PHY layer technology have been evaluated individually. However, as feature of MIMO technology, if the performance of the PHY layer is high, the performance, such as throughputs, delay and transmission efficiency etc., may be not enough for the entire wireless system. On the other hand, if the performance in only MAC is evaluated in disregard of PHY layer technology, it is also not enough. Hence, the detailed operation and performance of a wireless LAN system using MIMO transmission must be confirmed by evaluating a combination of both MAC and the PHY layer.

6.1.1 Related Works of Proposed MAC Protocol on the Transmission Rate Using ZF-Based Algorithm

First, several related works are discussed. The transmission rate is selected by the ZF-based algorithm in the PHY layer in [92]. In addition, the throughput of the UTs in the MAC layer is evaluated. However, a method that decreases packet collision is proposed in [92], which is different from the conventional method or WLAN standard. However, because this related work evaluates the performance using different method with access control scheme of the standard, the method in [92] is not considered in our evaluation, because the purpose of this survey paper is to evaluate the transmission efficiency of MIMO transmission on IEEE802.11 standard.

The throughput characteristics of the MCS index of SU-MIMO and MU-MIMO in the uplink traffic models are compared in [93]. However, in [93], it is assumed that SU-MIMO uses SDM without eigenmode SDM because CSI feedback is not used. A trade-off relationship between the CSI feedback and the channel capacity in MU-MIMO was described in [94] and the channel capacity was evaluated by a theoretical analysis and an experimental evaluation by using only the PHY-layer parameters. However, the transmission efficiency in WLAN systems is not clear because it is not evaluated including the MAC protocol. Various approaches and new methods have been proposed in these related works. The evaluation conditions such as network configuration, propagation conditions and parameters are undefined in [93] and [94] even though MU-MIMO performance including the transmission rate and CSI feedback is evaluated, because the rigorous MAC protocol is not included. We performed a preliminary evaluation of these related works. For the preliminary evaluation, the throughput and transmission efficiency in each MCS index are described in Sect. 6.3.

6.1.2 Related Works of Modification on the Frame Aggregation

Second, works related to WLAN systems with a frame aggregation function are introduced to improve the MAC transmission efficiency. The performance of a WLAN with frame aggregation that considers a limited buffer is evaluated in [95]. The length/size of the aggregation is fixed, and the throughput characteristic is confirmed. In [94], the throughput characteristics of the MCS index are evaluated when the frame aggregation size is changed. The effects of space-time block coding (STBC) and MU-MIMO with a frame aggregation function are confirmed in [96]. Moreover, a new method to aggregate the data packets of two or more user addresses is proposed for the frame aggregation function in [96]. Therefore, because this method aggregates UTs with different addresses, it is a special method not provided by the IEEE802.11 standard. However, implementation of this method will be difficult because the combined control of different UTs is very complex. This special method in [92] is excluded in this survey paper. In this paper, the aggregation size provided by the IEEE802.11 standard is changed within the regulated range, and the detailed effects on the transmission efficiency of the aggregation is investigated on the basis of these related works. These evaluation results are described in Sect. 6.4.

6.1.3 Related Works of the Transmission Efficiency Including Overhead of CSI Feedback

Third, we introduce related works that evaluate the performance including the overhead due to CSI feedback using the relationship between the CSI feedback and the transmission efficiency. The authors in [97] found that the channel estimation error predominantly decreases the throughput more than the influence of the overhead due to CSI feedback for MU-MIMO transmission. However, in [97], the throughput is evaluated by using several UTs. When the WLAN service is assumed, the number of UTs connected to a BS is large. Moreover, because all connected UTs achieve CSI feedback for MU-MIMO transmission, the overhead time due to CSI feedback is not negligible. A general network must be evaluated by the network configuration with which not the evaluation of several UTs using MU-MIMO transmission but many UTs are connected. On the other hand, the performance at the system level including the CSI feedback is evaluated in [98]. These papers are not an impartial evaluation because the CSI feedback procedure is only achieved for specific UTs. The relationship between the CSI feedback to the number of UTs connected is described in Sect. 6.5 on the basis of these related works.

6.1.4 Related Works of the Evaluation by Transmission Distance

Finally, we introduce related works that evaluated the system performance of SU-MIMO and MU-MIMO as the transmission distance. In [99]–[103], the error of the data packets are taken into account for the parameter, and calculate the throughput characteristics that both MAC and PHY technologies are included. Because the evaluation in [99] and [100] uses the MAC protocol with a simple procedure, the IEEE802.11 standard is not reproduced accurately. Therefore, generation on the packet error is modeled by not the propagation characteristics but the error due to uniform distribution. For the UT selection algorithm of MU-MIMO in [100], a simplified list algorithm is used. [101]–[103] are cited by [100], but only PHY layer is evaluated in [101]–[103]. PHY and MAC are separately evaluated in [104]. In evaluation of PHY, the SNR and the channel capacity are evaluated by ZF, and in the evaluation of MAC, the collision probability is theoretically analyzed by Markov chain model on uplink traffic. Moreover, throughput, and delay on the number of UTs are evaluated. However, CSI feedback is not included. Therefore, because the overhead is not considered, these evaluations are insufficient. In addition, the reliability of these evaluations is insufficient because they are only evaluated by a theoretical analysis. The Markoff model is often utilized as for the theoretical analysis for MAC evaluation. The main parameter of the Markoff model is transmission probability and collision probability. In the wired network, the Markoff model is useful, because the transmission rate is almost constant. However, in wireless communication, the transmission link rate is different according to the transmission distance or propagation environment. In the theoretical analysis using the Markoff model, the accurate analysis might be difficult, because the transmission rates are different among each stream when considering the eignenmode transmission which is used in our evaluation as SU-MIMO transmission scheme. Moreover, the analysis model for the space division multiple transmission must improve Markoff model, and it will be very complex.

In [105], a MAC protocol for MU-MIMO is proposed. However, MAC protocol different from IEEE802.11ac is discussed. The PHY layer selects the transmission rate from a calculation of the received power, and MAC is modeled using the theoretical Markov chain model. The reliability of this evaluation is insufficient because it is evaluated only by a theoretical analysis, as in [104].

In this survey paper, the MCS index of each stream (or each antenna) is selected by using the SNR based on these related works, and the throughput characteristic is evaluated (the SNR is determined by the transmit distance between the BS and UT according the pathloss and fading conditions). The relationship between the throughput and the transmission distance is described in Sect. 6.6. Moreover, in Sect. 6.7, the applicable area and the consideration by each method when considering the MAC-SAP are discussed in relation to these evaluations.

6.2 Simulation Conditions

In next subsection, the throughput and the transmission efficiency obtained by conventional MIMO and SU-MIMO/MU-MIMO in WLAN systems are evaluated. These evaluations used the parameters listed in Table 3 in accordance with the IEEE802.11ac standard. Moreover, the BS has eight antennas, and the UTs have two antennas. Therefore, the numbers of data streams for the BS and a UT are eight and two, respectively; hence, multiple space transmissions are offered to four users (four UTs) or less for these evaluation conditions. For single-user transmission, conventional MIMO transmission is written as MIMO,

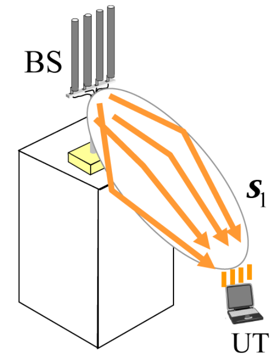
Table 3 Major simulation parameters.

Number of transmit antennas (N_T)	4, 8, 16, 64
Number of receive antennas (N_R)	1,2
Number of users (N_U)	4
Frequency (f_c)	5200 MHz
Bandwidth	40 MHz
Transmit distance (d)	1 ~ 50 m
Path loss (L)	$31\log_{10}(d) + 20\log_{10}(f_c)$ -28 [108]
Transmit power	19 dBm
Antenna gain	2 dBi
NPDA (Null Data Packet Announcement)	52 ~ 76μs
NDP (Null Data Packet)	52 ~ 292μs
NDP (for Implicit beamforming)	40 μs
BR (Beamforming Report)	62 ~ 450μs
BA (Beamforming ACK)	64μs
BAR (Beamforming ACK Request)	56μs
SIFS	16μs
DIFS	34μs
Backoff (Average time)	67.5μs
Frame aggregation	810 ~ 40000 Byte

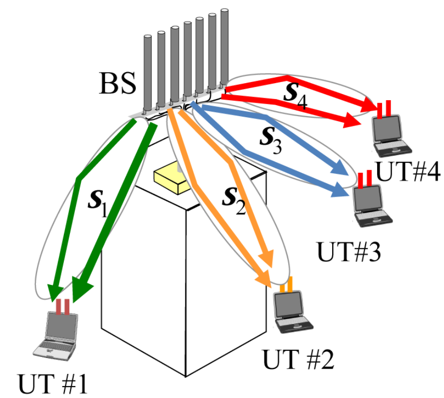
and MIMO using eigenmode transmission is written as SU-MIMO. MU-MIMO transmission for each number of users is written as MU2, MU3, and MU4. In order to evaluate the basic performance characteristics of SU-MIMO/MU-MIMO, the network configurations are simple configurations, as shown in Figs. 13(a) and (b).

Table 4 denotes the relationship between TR and SNR in IEEE802.11ac (40 MHz mode) [20]. The SNR is shown in Table 4 when the BER with IEEE802.11ac based single stream transmission is zero. Hence, error correction and bit interleave are considered for the relationship between the SNR and modulation scheme in Table 4. Next, because eigenvalues by eigenmode transmission and BD algorithm denote the received power, the modulation schemes can be selected by only $\lambda/(N_T\sigma^2)$ [107]. Here, λ and σ^2 are the eigenvalue and noise power, respectively.

Because it is reported the frequency correlation among sub-carriers is regarded to be very low [106], we assume that the independent flat fading channel is assumed for each sub-carrier in OFDM transmission: i.i.d. Rayleigh fading channel is assumed for each trial. Moreover, the correlation between antennas at the transmitters and receivers is not considered in this simulation. The CSI estimation itself is assumed to be perfect, in order to compare pure performance whether the CSI feedback is employed or not. The correlation between UTs is not considered for the evaluation of MU-MIMO. Therefore, they are assumed to be ideal environments. Moreover, the traffic direction is only the downlink (BS to UTs), and the propagation loss and packet collisions were evaluated on the condition. For simplification on the computer simulation, the transmission distance between the BS and the UEs was set to the same distance on the evaluation of MU-MIMO: the average SNRs are same among UEs.



(a) SU-MIMO configuration



(b) MU-MIMO configuration

Fig. 13 Evaluation models for the network configurations of SU-MIMO/MU-MIMO systems.

Table 4 Relationship between the modulation scheme and the transmission rate (40 MHz).

MCS index	Modulation scheme	Coding rate	Rmin [dBm]	TR [Mbps]	SNR [dB]
0	BPSK	1/2	-79	15	6
1	QPSK	1/2	-76	30	9
2	QPSK	3/4	-74	45	11
3	16-QAM	1/2	-71	60	14
4	16-QAM	3/4	-67	90	18
5	64-QAM	2/3	-63	120	22
6	64-QAM	3/4	-62	135	23
7	64-QAM	5/6	-61	150	24
8	256-QAM	3/4	-56	180	29
9	256-QAM	5/6	-54	200	31

6.3 Performance Evaluation for Each MCS Index

In this subsection, the throughput characteristics and transmission efficiency of MIMO, SU-MIMO, and MU-MIMO with MU2–MU4 are evaluated by computer simulations using the parameters in Table 4, which are the transmission rate of each modulation. Hence, these transmission rates are replaced by the MCS index number. The A-MPDU size set to 7500 bytes. In this A-MPDU size, 1500 bytes of the Ethernet packet maximum size are stored within 8191 bytes of the mandatory size of the IEEE802.11ac standard in in-

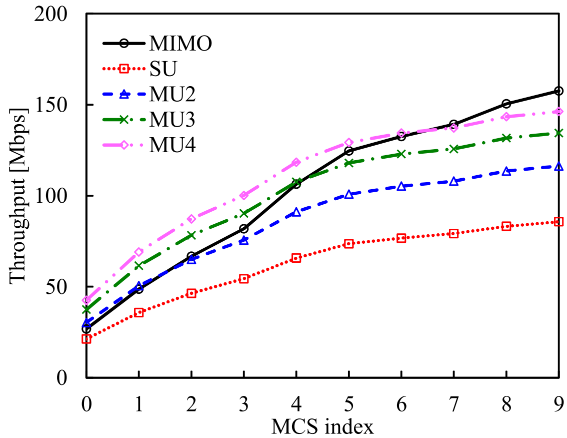


Fig. 14 Throughput characteristics of the MCS index.

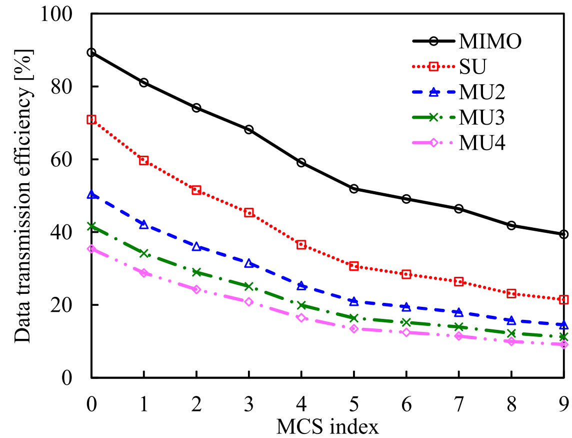


Fig. 15 Transmission efficiency characteristics of the MCS index.

teger multiples. Further, the data frame of this A-MPDU size is transmitted from the BS to the UTs in the MIMO and SU-MIMO/MU-MIMO simulations. The throughput characteristics of the MCS index were evaluated and are shown in Fig. 14. The throughput increases for all WLAN systems as the MCS index number increases. The throughput of MU-MIMO is higher than the throughput of SU-MIMO. When examined closely, if MCS index number is 7, 8, and 9, the throughput of conventional MIMO is higher than that of MU-MIMO. This is because the overhead due to CSI feedback has a major influence as the transmission rate increases. Because the transmission distance between the BS and the UTs was set to the same distance, even when MCS index number was changed, such a result was obtained. However, there is a case showing the large effect of MU-MIMO or SU-MIMO when the MCS index corresponding to the transmission distance is selected. These details will be explained in Sect. 6.6.

The transmission efficiency characteristic for the same conditions was evaluated and is shown in Fig. 15. For the transmission efficiency, the ratio of the throughput to the PHY transmission rate of each MCS is evaluated. The transmission rate of the MCS is assumed to be 100%, and the occupancy rate of the data of the MAC layer (payload length) is calculated. In Fig. 15, the transmission efficiency of conventional MIMO is the highest, followed SU, MU2, MU3, and MU4, in order. This is because the overhead due to CSI feedback increases. In any case, the transmission efficiency decreases as the MCS index number increases. Therefore, the influence of the overhead increases because the data transmission time for the same data size is shortened as the transmission rate increases.

6.4 Performance Evaluation Including the Aggregation Function

In Sect. 6.3, we used the mandatory size (7500 byte) of A-MPDU in the IEEE802.11ac standard. However, the A-MPDU size was changed to confirm the influence of the throughput. The transmission rate was set to MCS index number 9 for the maximum rate. The same parameters used in Sect. 6.3 were used, excluding the A-MPDU size.

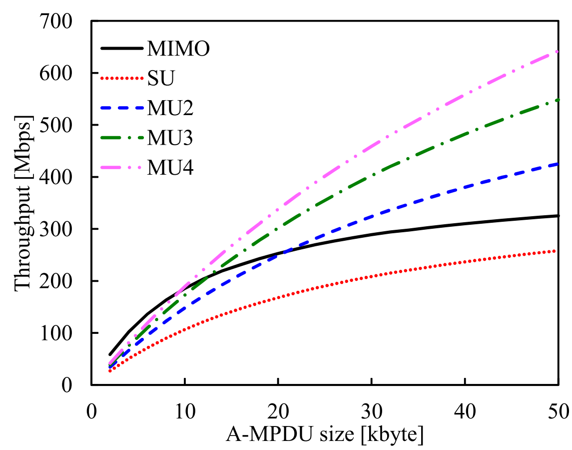


Fig. 16 Throughput characteristics for various A-MPDU sizes.

The throughput characteristics were evaluated when the A-MPDU size changed, as shown in Fig. 16. The horizontal axis is A-MPDU size per user. For example, the total A-MPDU size is four times for all UTs when four UTs using MU-MIMO (MU4) are connected to the BS. The vertical axis is total throughput. The throughput increased when the A-MPDU size increased in Fig. 16. In particular, when the A-MPDU size is small, the throughput of MU4 is lower than the throughput of MIMO. However, when the A-MPDU size was increased, a throughput that is higher than MIMO was obtained. This is because the transmission efficiency has been improved as the data transmission time increases in comparison to the overhead. Hence, it is important for the transmission efficiency to consider the A-MPDU size to efficiently operate various transmission schemes.

6.5 Investigation of the Effect of CSI Feedback

In this subsection, the effects on the throughput characteristic and transmission efficiency due to the CSI feedback overhead are investigated for SU-MIMO and MU-MIMO.

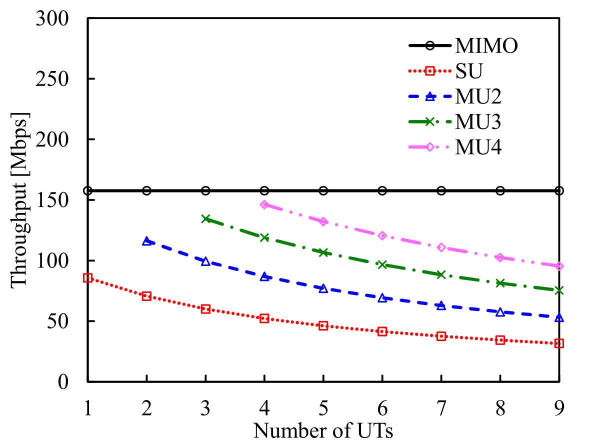


Fig. 17 Throughput characteristics as a function of the number of UTs using CSI feedback.

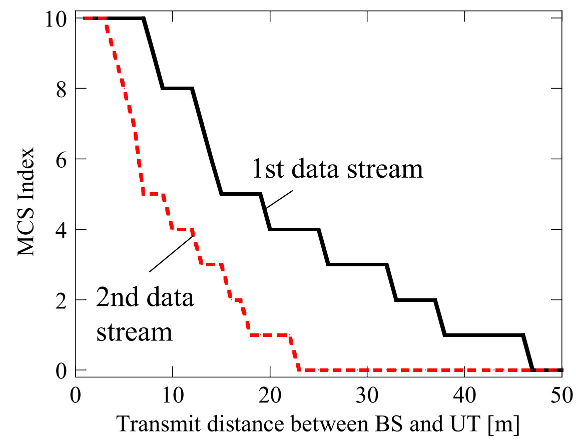


Fig. 18 MCS index of the MU4 stream as a function of the distance between the BS and the UTs.

The transmission rate was set to MCS index 9 for the maximum rate. The A-MPDU size is the mandatory size (7500 bytes) of the IEEE802.11ac standard.

The throughput characteristics as a function of the number of UTs using CSI feedback for channel estimation are presented in Fig. 17. The horizontal axis is the number of UTs using CSI feedback, and the vertical axis is total throughput in Fig. 17. MIMO transmission is not influenced by the overhead as the number of UTs increases because CSI feedback is not achieved. Therefore, a flat throughput characteristic of one UT is obtained, even if the number of UTs is increased. In Fig. 17, the throughput decreases as the number of UTs increases. This is because the effect of the CSI feedback overhead increases because CSI feedback performs the number of UTs. Moreover, the throughput is lower than MIMO without CSI feedback. The method of selecting UTs to perform CSI feedback will be important issue.

6.6 Distance Characteristics between an Access Point and the Terminals

In this subsection, the influence of the distance between the BS and the UTs is evaluated. This evaluation considers the SNR in the propagation environment and the transmission distance of the PHY layer. Further, the throughput characteristic of MAC-SAP including the overhead of the MAC layer was analyzed on the basis of these PHY conditions. This evaluation aims to confirm the communication efficiency considering a control signal such as CSI. The identically-independent-distribution (i.i.d.) Rayleigh fading of an ideal environment for MU-MIMO transmission was adopted as a propagation environment. Because the effect improves the transmission directivity control at an area edge, the propagation loss model of ITU-R recommended as an indoor model was employed [108]. The carrier frequency is set to 5.2 GHz, and the propagation loss coefficient of the transmission distance is set to 3.1. The service area (cell radius) is 1~50 m. The MU-MIMO antenna directional control used the BD method. The modulation method is determined from the eigenvalue ($\tilde{\lambda}_{BDi}$). $\tilde{\lambda}_{BDi}/(N_T\sigma^2)$ is calculated for each trial that changes the propagation channel matrix. When these values increase more than the SNR in Table 4, the corresponding modulation method was selected. σ^2 is the thermal noise power, and i is the stream number.

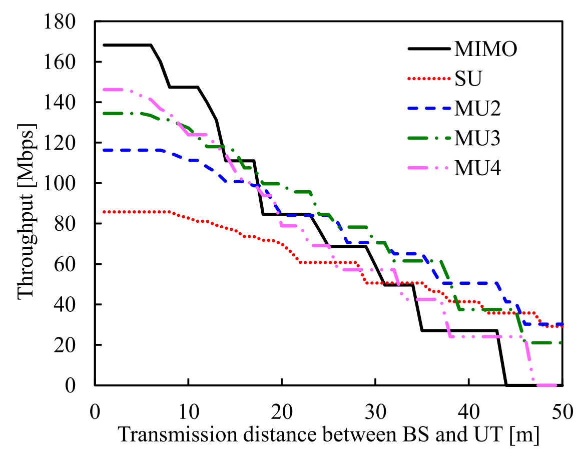


Fig. 19 Throughput as a function of the distance between the BS and the UTs.

For example, the MCS index of each stream as a function of the distance for MU4 is shown in Fig. 18. The transmission rate decreases because the MCS index becomes small when the transmission distance is large. Other basic evaluation parameters are the same values as those in Sect. 6.4.

The distance characteristics of the throughput for each transmission method are shown in Fig. 19. MU-MIMO transmission obtains a high throughput in an area edge far from the BS when the number of UTs is low. As a point of focus, SU-MIMO in the area edge is higher than the throughput of MU-MIMO. Moreover, in MIMO transmission, the throughput at a position far from the BS decreases remarkably, although the throughput is the highest in the neighborhood of the BS. From these results, the performance at the area edge is high because of the effect of beamforming. In addition, when single data stream is transmitted the transmit power per data stream is 3 dB higher than that by using two data streams. Therefore, the selection of the optimum transmission technology according to the transmission distance can achieve a throughput enhancement.

6.7 Applicability and Consideration of Each Method in MAC-SAP

In the various evaluation results, the optimum usage conditions of the applicable service domains or the various transmission technologies are considered using the throughput characteristics and transmission efficiency of MIMO, SU-MIMO, and MU-MIMO in this subsection. In Sect. 6.3, when the MCS index (the transmission rate) was changed, it was confirmed that the throughput and transmission efficiency of MU-MIMO decreased more than conventional MIMO if the transmission rate was high. As a result, it is important for MIMO or MU-MIMO transmission to select the MCS index corresponding to the transmission distance. Moreover, it is necessary to select the MCS index of each antenna combined on the basis of the propagation channel and SNR corresponding to the transmission distance, even though they were confirmed by the evaluation results in Sect. 6.6. The transmission efficiency in Fig. 15 corresponds to the condition where the transmission distance is small in Fig. 18 and Fig. 19 when the MCS index is 8 and 9 with a high transmission efficiency for MIMO. In all usage conditions, we confirmed that conventional MIMO has a higher effect than MU-MIMO when the distance between the BS and the UTs is several dozens of meters. For the throughput characteristic of SU-MIMO, the decrease in the throughput is less than that for MU-MIMO when the transmission distance is large. For example, when the transmission distance is 50 m, the throughput of SU-MIMO is higher than MU3 and MU4; however, the throughput for conventional MIMO decreases rapidly with increasing distance.

The effect of multiplexing MU-MIMO is demonstrated when the A-MPDU size is large, and a very high throughput is obtained in the results presented in Sect. 6.4. However, in actual usage scenarios, a very large A-MPDU size causes concern when the application is assumed. An application that generates burst data is necessary to achieve a high effect due to the aggregation function, and it is the operative technology only when such an application is used. Moreover, when the A-MPDU size is large, the communication band will be occupied for a long time; therefore, especially, when the MU-MIMO transmission is used, frame aggregation will achieve great effect. However, when the UTs of other transmission technologies are included, the transmission acquisition rate decreases because the WLAN is a distributed coordination function (DCF), and the network environment becomes very unfair. For example, it is effective when a special application service generates heavy traffic, such as high-resolution video, and many users use the service concurrently.

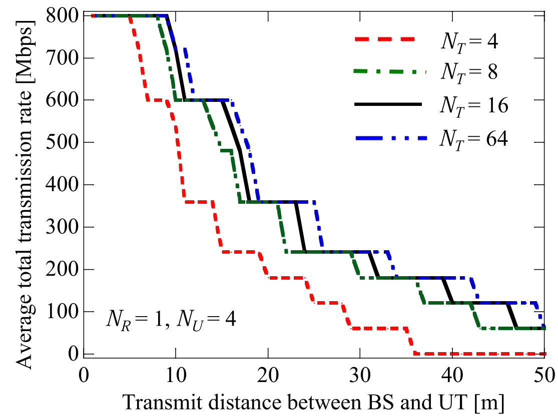


Fig. 20 Transmission rate in the PHY layer versus the transmit distance.

Applicable area and the conditions of assumed actual usage in WLAN systems were confirmed, because the evaluations successfully integrated the PHY and MAC layers in conventional SU-MIMO and MU-MIMO transmission.

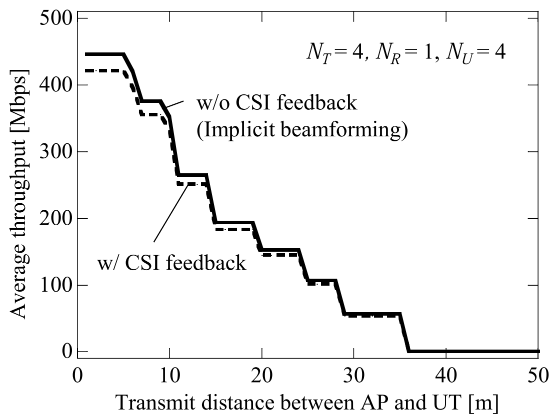
6.8 Effectiveness of Implicit Beamforming

In order to verify the effectiveness of the implicit beamforming method with the calibration technique, we carried out a simulation considering the IEEE802.11ac signal format. The main simulation parameters are listed in Table 3. The path loss according to the ITU-R model [108] and i.i.d. Rayleigh fading are assumed in this simulation. Block diagonalization is employed as the algorithm for MU-MIMO transmission [48], [49].

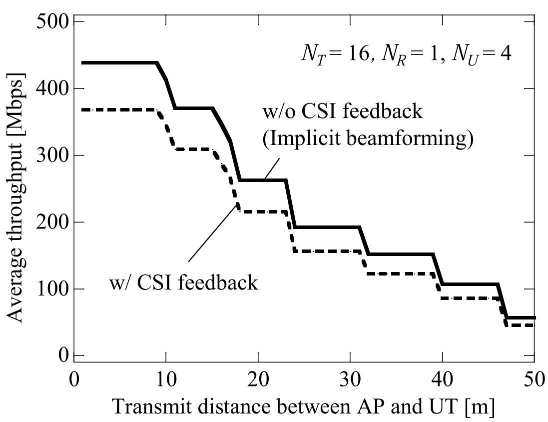
Figure 20 shows the average transmission rate versus the transmit distance between the AP and the UT. The overhead due to control signals such as CSI feedback (BR) are not considered. As can be seen in this figure, the effect of beamforming gain by massive MIMO is observed; both the transmission rate and service area for $N_T = 16$ are dramatically improved compared to that for $N_T = 4$.

Figure 21 shows the average throughput considering the control signals in Table 3. The results with and without CSI feedback are shown in this figure. When $N_T = 4$, the degradation in the throughput due to CSI feedback is small. On the other hand, the difference in the throughput with and without CSI feedback is from approximately 50 to 160 Mbps when $N_T = 64$.

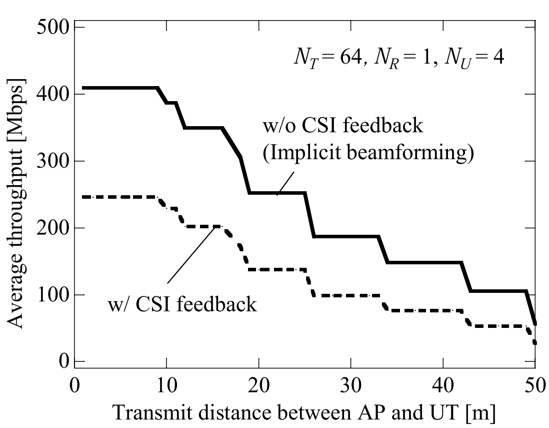
Figure 22 shows the average throughput versus the data size. The transmit distance, d, is 20 and 40 m in this figure. As can be seen in Fig. 22, when $d = 20$ m, the average throughput by the implicit beamforming is 1.2 and 1.6 times compared to that by using CSI feedback at maximum for $NT = 4$ and 16, respectively. Moreover, when $d = 40$ m and $N_T = 16$, the average throughput by the implicit beamforming is twice compared to that by using CSI feedback. Therefore, it is essential to apply implicit beamforming with a calibration technique for MU-MIMO transmission, especially, for massive MIMO transmission.



(a) $N_T = 4$



(b) $N_T = 16$



(c) $N_T = 64$

Fig. 21 Throughput including the MAC efficiency versus the transmit distance.

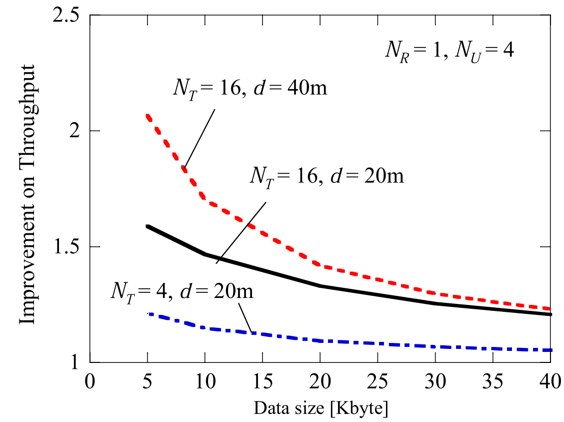


Fig. 22 Effectiveness of implicit beamforming when the data size is changed.

7. Conclusion

There are many studies related to SU-MIMO/MU-MIMO transmission because they can improve the frequency utilization within a limited frequency band. However, most works have focused on the enhancement in the transmission rate in the PHY layer. This paper focused on WLAN systems in which SU-MIMO/MU-MIMO is introduced and describes the transmission efficiency of SU-MIMO/MU-MIMO transmission considering IEEE802.11ac-based WLAN systems. First, the basic transmit beamforming and decoding methods and access control schemes for SU-MIMO/MU-MIMO were described. The issues regarding the CSI feedback from the UTs to the BS and their countermeasures were surveyed.

In this paper, related works were introduced considering the MAC protocol in SU-MIMO/MU-MIMO transmission. Furthermore, the throughput performance for SU-MIMO/MU-MIMO transmission considering IEEE802.11ac-based WLAN systems was evaluated. Our numerical evaluations showed that the overhead due to CSI feedback from the UTs to the BS (especially, when considering the large number of antennas and user scheduling) decreased the throughput. We verified that implicit beamforming, which eliminates CSI feedback, is effective for overcoming this issue.

Because the amount of data traffic is doubling every year, MIMO transmission is a key technology for 5G and future WLAN systems. However, the number of antennas will be greater than one hundred in massive MIMO [80]–[82]. Therefore, a scheduling algorithm will be essential when a very large number of users exists in a very heavy traffic area. In future wireless communication systems, the research and development of communication with very efficient CSI acquisition will be required.

Acknowledgments

Part of this work is supported by KAKENHI, a Grant-in-Aid for Scientific Research (C) (25420362 and 25330111), Telecommunication Advancement Foundation in 2014 and Hoso Bunka Foundation 2015. The authors would like to thank Dr. Toshiyuki Ogawa for the help on the evaluation.

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