Beamforming Method for Broadband MIMO-OFDM Systems

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Abstract

We propose two methods for MIMO with beamforming to overcome the inherent problems in MIMO-OFDM with beamforming: calculation complexity and low MIMO effect in line-of-site environments. The multiple-input-multiple-output (MIMO) technique is the most attractive candidate for improving spectrum efficiency in the next-generation wireless communication systems. The combination of MIMO with orthogonal frequency division multiplexing (OFDM) is a promising way to achieve a higher data rate in indoor wireless local area networks. After introducing MIMO-OFDM with multiple access points to enhance the channel capacity even in line-of-site cases, we describe a novel approximate eigenvector beam generation method for reducing the calculation complexity by using the power method and the Gram–Schmidt orthogonalization procedure. Simulation and experimental results show that the combination of these two methods has a very high potential to improve the system capacity and drastically reduce the calculation complexity.

1. Introduction

The recent popularity of wireless local area networks (LANs) has pushed the demand for even higher data rates enabling real-time multimedia applications [1]. However, frequency resources are strictly limited and most frequencies located in the microwave band, which are suitable for wireless LANs, have already been assigned to various radio systems. Thus, broadband services will be provided using limited frequency bands, so spectrum efficiency will be even more important for next-generation wireless LAN systems than it already is in current systems [2].

Multiple-input-multiple-output (MIMO) is one of the most attractive candidates for achieving spectrum efficiency [3], [4]. In identically independently distributed fading channels, it can linearly increase the channel capacity as the number of antenna branches increases. And a higher channel capacity is expected if the channel state information (CSI) is known at the receiver as well as at the transmitter [5], [6]. However, in the MIMO data transmission scheme, different signal streams are transmitted among multiple spatial channels and this creates high-interference environments. Moreover, in broadband wireless access systems, delayed waves make the interference condition worse so highly sophisticated demodulators are required at receivers, especially for single-carrier systems.

Thus, orthogonal frequency division multiplexing (OFDM) systems in time division duplexing (TDD) with MIMO techniques have been receiving much attention because OFDM can alleviate the influence of the long-delayed waves and MIMO techniques using CSI can be easily implemented for each sub-carrier [7]. This is because a perfect calibration method has been proposed [8] that enables CSI to be used in the uplink as well as in the downlink. Although the MIMO data transmission scheme increases the hardware complexity of the system, a MIMO receiver in which the MIMO demodulators for the sub-carriers work simultaneously has been tested in trials [9] and practical application is

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approaching. In general, MIMO is effective only in rich multipath environments and its effect decreases in correlated fading environments such as in a line-of-sight (LOS) condition [10]. To overcome this problem, a beamforming technique for both transmitter and receiver has been proposed [11]. This method can enhance the desired signal power and improve the signal-to-noise performance. However, it cannot utilize the spatial multiplexing effect, so the improvement in channel capacity is limited.

In this paper, we introduce a new MIMO data transmission scheme for wireless LANs that combines a single-frequency-network (SFN) with TDD-OFDM-MIMO. SFN with OFDM has been proposed for broadcasting systems to improve the transmission quality in overlapping cells [11]. In our proposal, we advocate the use of SFN for multiple access point (MAP) MIMO data transmission. Thus, the proposed scheme achieves very high channel capacity in both LOS and non-line-of-sight (NLOS) environments. Since multiple access points cooperate with each other in the proposed scheme, higher performance can be achieved as the number of access points (APs) increases, while the performance is significantly degraded by the strong interference from adjacent APs in the conventional scheme.

From the viewpoint of practical implementation, the calculation cost in the proposed method must be reduced. This is because it becomes high as the number of APs increases. To overcome this problem, this paper also introduces a suboptimal approach for spatial channel control to reduce the calculation complexity. The performance with a suboptimal approach is shown and the feasibility of the suboptimal approach is discussed.

2. Data transmission scheme in MAP-MIMO systems

The proposed configuration for wireless LANs with OFDM is shown in **Fig. 1**. Multiple APs are connected to one access controller (AC). Since OFDM can mitigate the influence of the delayed waves, this system can also compensate for the delay caused by the different distances between APs and wireless terminals (WTs). Thus, it creates a virtual large array of antennas and enhances the MIMO effect in both the uplink and downlink. The data transmission scheme in the uplink and downlink with CSI at both APs and WTs is as follows.

In the uplink, OFDM data frames consist of a training period and a data period. In the training period, known signals are transmitted from each antenna branch of the WT. After that, multiple OFDM data symbols are transmitted using multiple beams. Then, all signals received at all APs are delivered to the AC. At the AC, all channel responses are estimated at the same time in each sub-carrier in the training period and multiple beams for the virtual large antenna array can be optimized by the minimum mean squared error (MMSE) algorithm. After data has been received using the multiple beamforming network, it is demodulated. Note that this system works in TDD systems and the channel responses in the downlink can be regarded as being equal to those in the uplink. And by using the perfect calibration method at each AP, the generated beam patterns can also be employed in the downlink and the transmission power of each beam is optimized by the water pouring theory. In the downlink, multiple OFDM data frames with training symbols are conveyed to multiple beamforming networks, and transmission signals

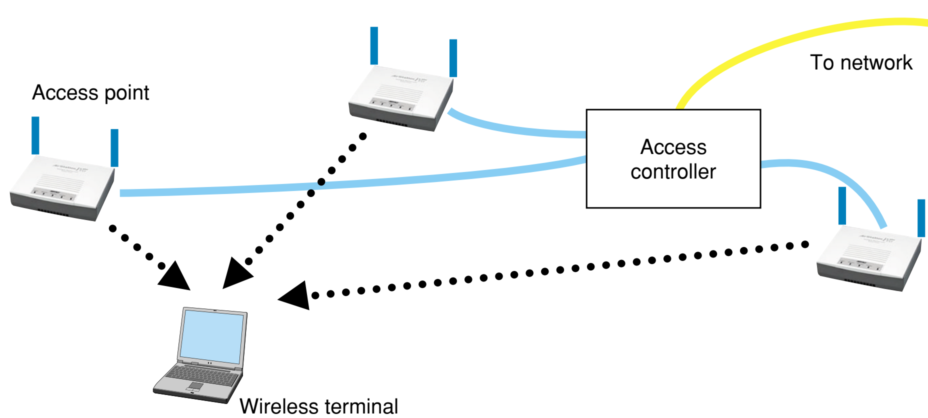

Fig. 1. System model.

for each antenna branch are generated. Then, those signals are delivered to APs and transmitted from array antennas simultaneously. At a WT, channel responses are estimated in the training period and multiple beams are optimized by MMSE criteria. After that spatially multiplexed data are separated by multiple beams and demodulated.

3. Performance evaluation of the proposed scheme

3.1 Simulation model for indoor multipath environments

The simulation model is shown in **Fig. 2**. In this model, one short-delayed cluster and two exponentially attenuated long-delayed clusters are assumed. We also assume that the average power of long-delayed clusters is set to be equal regardless of the WT location. Therefore, only the short-delayed cluster power changes as the WT moves. The *K*-factor, which represents the ratio between direct-path power and diffuse power, is set to 0 dB at the zone edge of each access point and the number of waves in each cluster is set to 20. The angular spread of short-delayed cluster equals 5° and that of the long-delayed clusters is 20°. The delay spread is set to 30 ns [12]. The number of antenna branches at each AP is four. The same number of antenna branches is assumed at the WT. The element spaces at both APs and WT are 0.7 λ and a circular array is used. Three APs are assumed; their locations are (0, 0, 3 m), (10, 0, 3 m), and (10, 10, 3 m). The height of the WT is 0.7 m. The center frequency is 5.2 GHz, the number of sub-carriers is 52, and the sub-carrier spacing is 312.5 kHz. We conducted a large number of trials and evaluated the cumulative probability of the channel capacity and the ergodic channel capacity.

For the multi-user case, we evaluated the average achievable throughput performance with the multi-access scheme. In this evaluation, all APs used the same frequency channel to enable us to evaluate the total achievable throughput in the spatial channel. In the conventional method, each AP works independently, and simultaneous transmission occurs, whereas no collision occurs in the proposed scheme as a result of employing time division multiple access (TDMA). Note that if all APs are synchronized and each AP selects a different transmission timing, it becomes the one-user case. In the evaluation of the conventional methods, an orthogonal spatial filter was assumed at the WT to decompose the interference from the APs and the channel capacity was calculated after the decomposition. The data packets were randomly generated for users and the achievable data rate was calculated from the channel capacity of each link.

An example of the data transmission scheme is shown in **Fig. 3**. In the conventional scheme, users A and B access AP-1 while users C and D access AP-2 and AP-3, respectively. In the proposed scheme, all

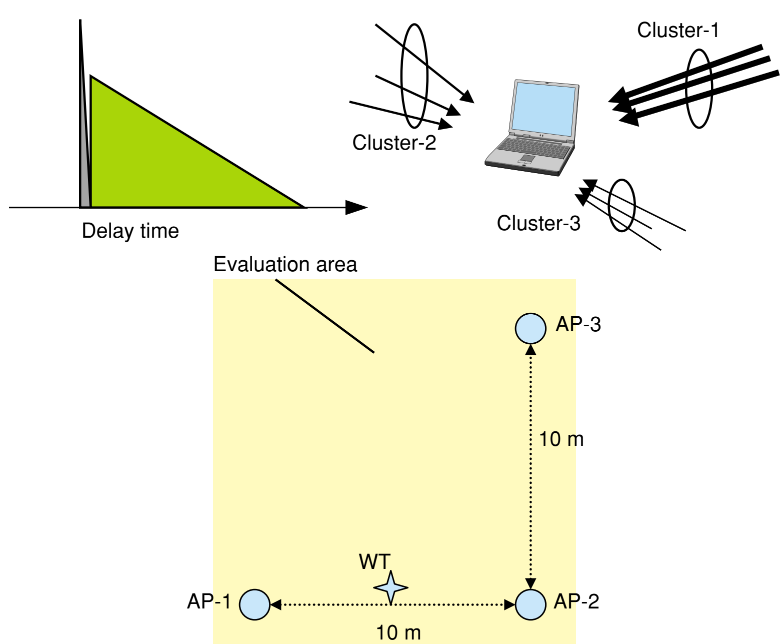

Fig. 2. Simulation model.

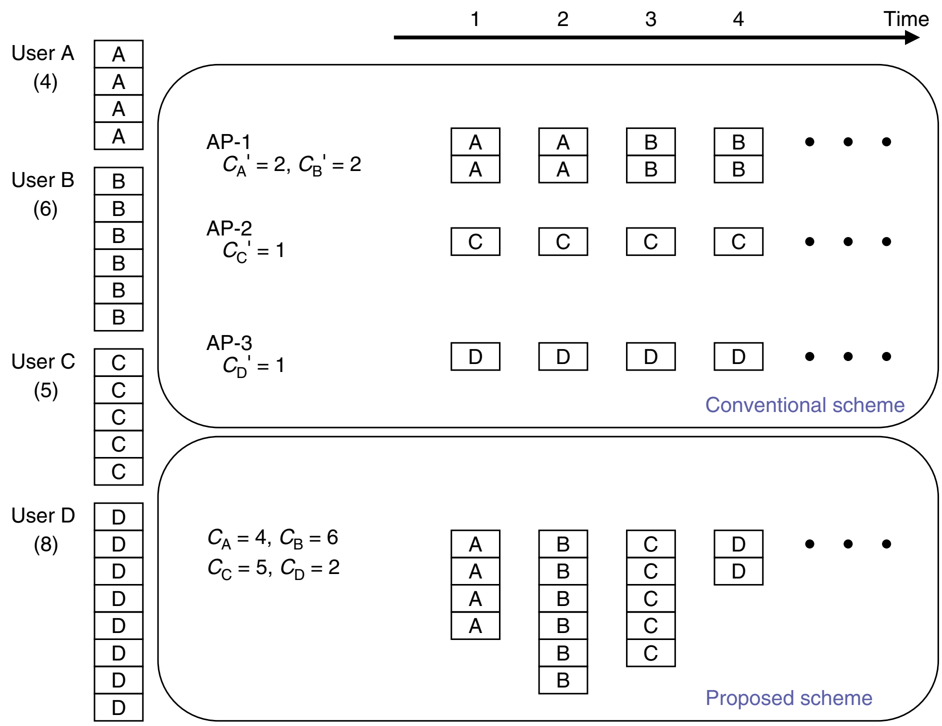

Fig. 3. An example of the schedules for conventional and proposed schemes.

users access all APs. The maximum throughputs that can be achieved for users in the conventional scheme are assumed to be, $C_A' = 2$, $C_B' = 2$, $C_C' = 1$, and $C_D' = 1$. Those for the proposed scheme are assumed to be $C_A = 4$, $C_B = 6$, $C_C = 5$, and $C_D = 2$. At t = 0, four, six, five, and eight packets are generated for users A to D, respectively. In the conventional method, the data for users A, C, and D is transmitted during the first frame, whereas in the proposed scheme, only the data for user A is transmitted then. Thus, the total number of data packets in this frame is four in both methods. However, in the next frame, the proposed scheme increases the number of packets from four to six, so the proposed scheme achieves higher throughput. After four frames, the conventional scheme has only completed data transmission to user A, while the proposed scheme has completed transmission to all users except user D. In computer simulations, we evaluated the average of the total achievable throughput for various WT locations.

3.2 Simulation results for one-user case

We evaluated the spatial channel separation performances when the WT was located at (5, 0, 0.7 m) and clarified the operation in multipath fading environments. After that, we obtained the ergodic channel capacity in the various WT position.

Figure 4 shows the cumulative probability of the eigenvalues of the channel transfer matrix H_k in the proposed scheme compared with those of the conventional MIMO systems. In MIMO systems, eigenvalues indicate the power of each spatial channel. In this figure, M is the number of antenna branches at

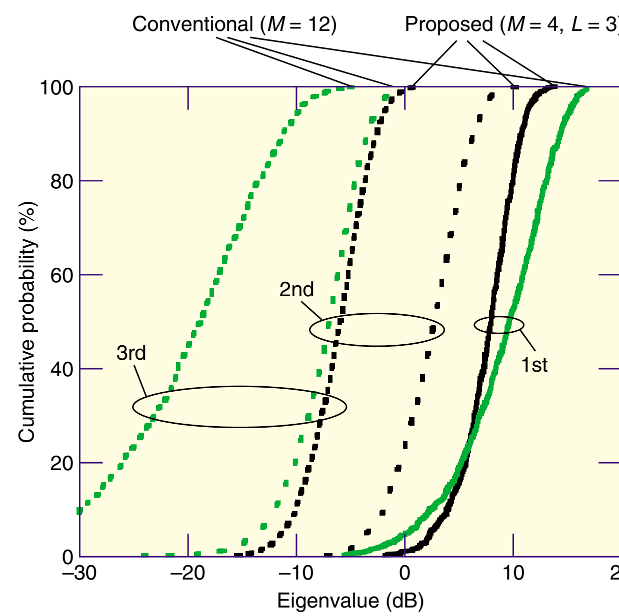

Fig. 4. Cumulative probabilities of eigenvalues.

each AP and L is the number of APs. As this figure shows, the proposed scheme improved the magnitude of the third and fourth eigenvalues (i.e., the third and fourth spatial channels), while the first eigenvalue had almost the same magnitude. It indicates that the proposed method improves the spatial separation performance and enables the use of the third and fourth eigenvalues.

The cumulative probability of the channel capacity with proposed scheme is compared with the conventional MIMO systems in **Fig. 5**. In the conventional MIMO systems, one AP is selected to achieve the maximum channel capacity. As this figure shows, the proposed scheme doubles the channel capacity of the conventional MIMO systems with the same antenna configuration. Moreover, it indicates that the proposed scheme outperforms the conventional system even if each conventional AP uses three times as many antenna branches as the proposed method.

The distribution of the ergodic channel capacity in the evaluation area is shown in **Figs. 6**, **7**, and **8**. The white and dark areas indicate high and low ergodic

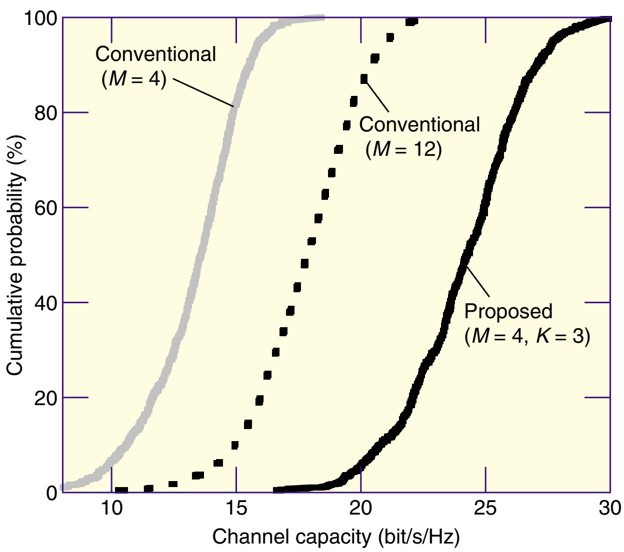

Fig. 5. Cumulative probabilities of channel capacity.

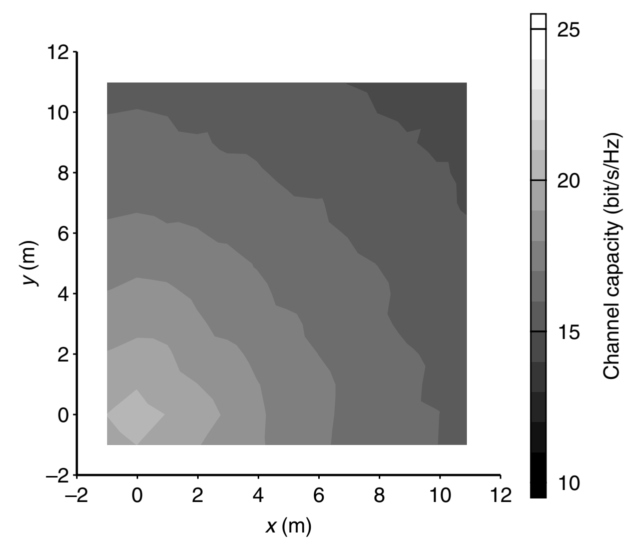

Fig. 7. Ergodic channel capacity distribution with a conventional scheme where 12 antenna branches are assumed at one AP.

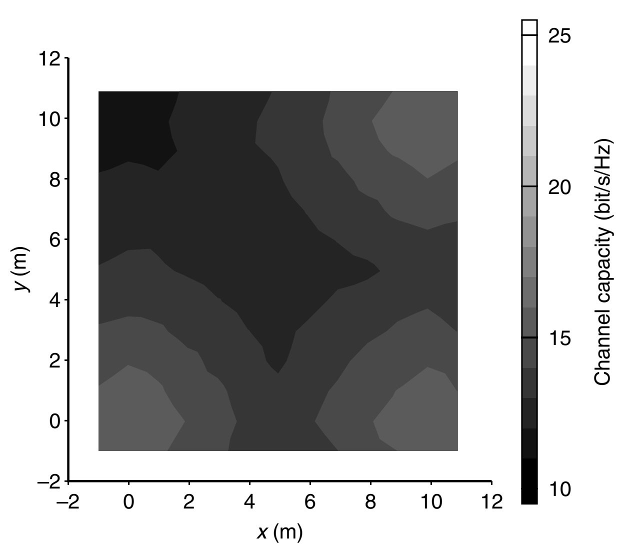

Fig. 6. Ergodic channel capacity distribution with a conventional scheme with four antenna branches at each AP.

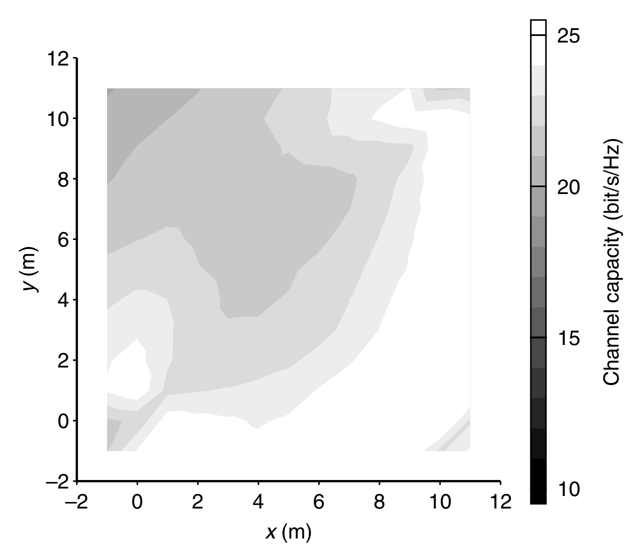

Fig. 8. Ergodic channel capacity distribution with the proposed scheme with 4 antenna branches at each AP.

channel capacity, respectively. In Fig. 6, perfect synchronization among APs was assumed in the conventional data transmission scheme and no interference was considered. The best AP was selected to achieve the highest performance. Since only four antenna branches were used at APs, high channel capacity could not be achieved. In Fig. 7, one AP with twelve antenna branches was assumed as a conventional AP while three APs were assumed in other scenarios. As Fig. 7 shows, although high channel capacity was achieved around the AP area, the performance was degraded as the distance between APs increases. On the other hand, as Fig. 8 shows, the proposed method achieved very high channel capacity and outperformed both the conventional methods at any point. And higher channel capacity was achieved around the area between two APs. This is because the distance between each AP and WT became small and APs could cooperate with each other. These results confirm the effectiveness of the proposed method.

3.3 Simulation results for multi-user case

Figure 9 shows the cumulative probability of the average total throughput achievable with the proposed scheme compared with that of the conventional MIMO systems where each AP works independently. In this figure, d indicates the distance between AP and WT. As this figure shows, higher throughput was achieved in the proposed scheme regardless of the distance between AP and WT, but the improvement decreased as the distance increased. For d = 50 m, the highest throughput with the conventional scheme was almost the same as that with the proposed scheme because high throughput could be achieved if each WT was close to the AP being accessed and the influence of interference was negligible. However, the performance of the conventional method degraded as the distance between AP and WT decreased. This is because the interference increased as the distance decreased, while the channel capacity of the proposed scheme improved as a result of cooperation among multiple APs. These results confirm that our proposed scheme is very attractive for future wireless hotspot scenarios where a high density of APs is expected.

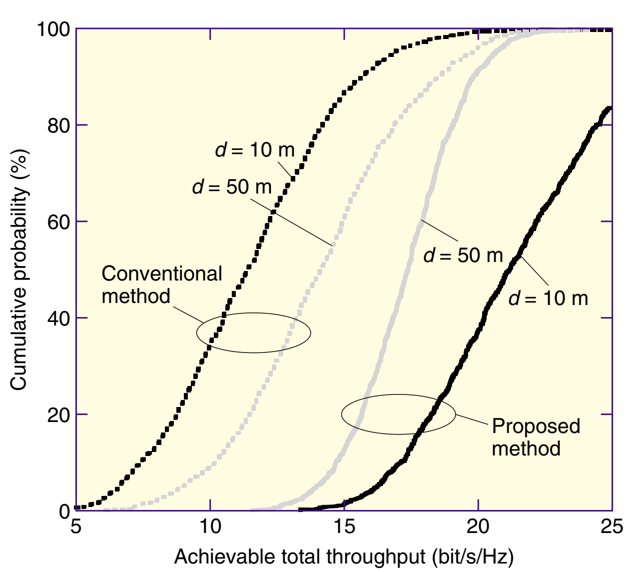

Fig. 9. Cumulative probability of the achievable throughput.

4. Reduction of calculation complexity using a suboptimal approach

Since a virtual array of antennas has a large number of antenna branches, the calculation complexity of the spatial channel decomposition with the SVD (singular value decomposition) algorithm is very high. To decrease the calculation complexity of our proposed system, we introduce a new suboptimal orthogonal beamforming method in this section. In the following, M_{WT} is the number of antenna branches at each WT, M_{AP} is the number of antenna branches at each AP, and N is the number of APs connected to the same AC. We also assume the condition $N\ M_{\mathrm{AP}} > M_{\mathrm{WT}}$ because the calculation complexity is significant for this condition.

The aim of the spatial channel decomposition is to generate multiple orthogonal beams and find the desired signal subspace. To do this, the proposed method uses the combination of the power method and Gram–Schmidt orthogonalization procedure to enhance the desired signal power while keeping orthogonality among multiple beams. In the power method, the beam pattern is updated using a linear transformation. Since this procedure does not require SVD calculation, it can greatly decrease the calculation complexity. A trial system is shown in **Fig. 10**. It can evaluate two-AP systems. The measured beam pattern of the proposed suboptimal approach at a WT is shown in **Fig. 11**. In this evaluation, two antenna branches were set at both a WT and at APs and the number of APs was two. As this figure shows, the first beam captured the signal from AP_1 while the second beam generated a null toward AP_1. It confirms that the suboptimal approach can find the signal space accurately. The output signal-to-noise-plus-interference ratio (SINR) for the location of AP_2 is

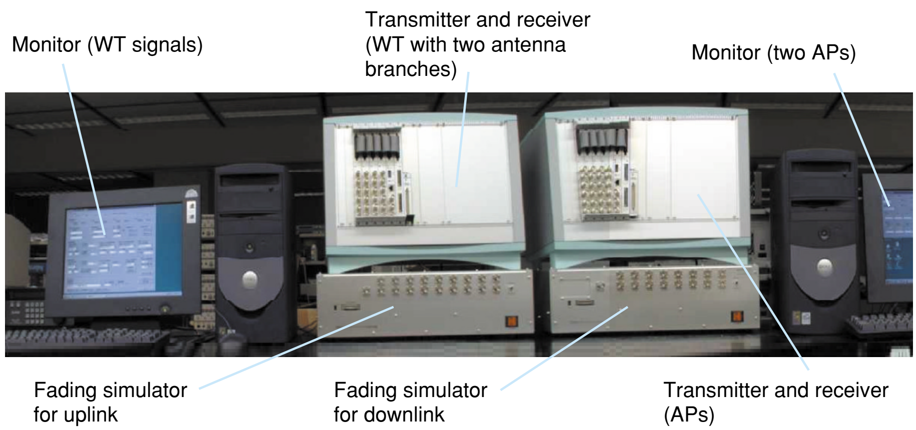

Fig. 10. Trial system.

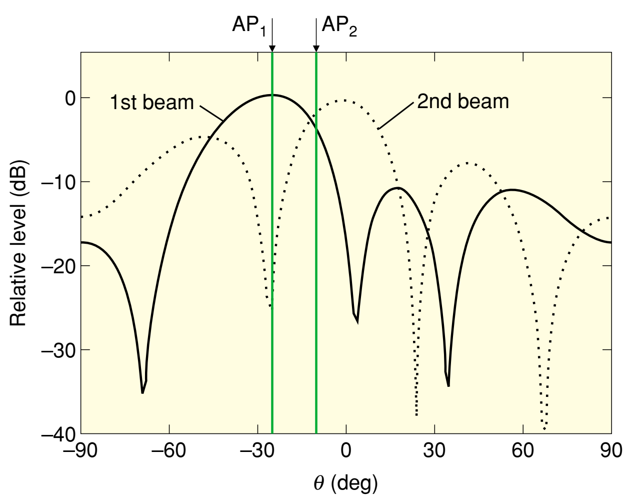

Fig. 11. Suboptimal beam patterns at a WT.

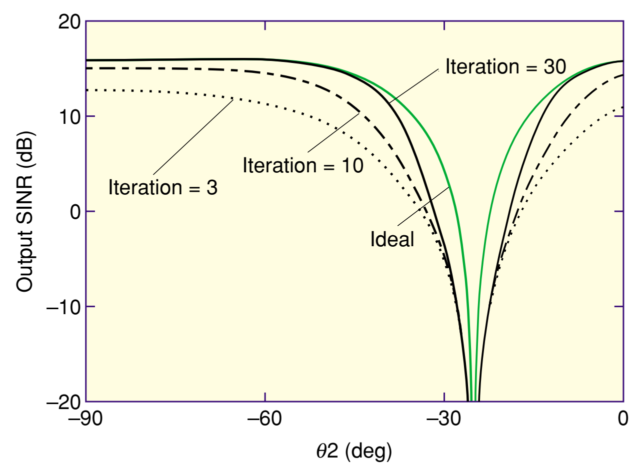

Fig. 12. SINR when a suboptimal approach is used.

shown in **Fig. 12**. In this evaluation, the direction to AP_1 was set to 25°. When the difference in directions of two APs was 20° or more, then 30 iterations produced a good approximation of the ideal performance. Moreover, the performance degradation with three iterations was less than 2 dB when the differences in directions among APs were significant. Thus, the suboptimal approach is suitable for the proposed method.

5. Conclusion

In this paper, we proposed a multiple access point MIMO data transmission scheme that combines a single-frequency-network with TDD-OFDM-MIMO using array antennas at access points (APs). We derived the channel capacity of the proposed scheme in the direct path environment. The results confirm that the proposed method outperforms the conventional MIMO system in strongly correlated environments. We evaluated the proposed scheme with conventional MIMO systems in multipath environments and showed its potential. The simulation results confirm that the proposed scheme improved the higher eigenvalues of the channel transfer matrices and enabled us to double the channel capacity for the conventional MIMO systems in the one-user case. Moreover, evaluating the total throughput performance in the multi-user case, we found that the proposed scheme improved the performance through cooperation among multiple APs as the distance between AP and wireless terminal decreased, while the performance in the conventional method was significantly deteriorated by interference from adjacent APs. These results confirm that our proposed scheme is very attractive for future wireless hotspot scenarios where a high density of APs is expected.

In the proposed method, the calculation complexity is a problem. To reduce the calculation cost, we introduced a suboptimal approach and evaluated the performance of a trial system. The results confirmed that the suboptimal beamforming approach is suitable for the proposed method.

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