On the Exploitation of Multiple Access Points in a Wireless Single–Frequency–Network Using TDD–OFDM–MIMO Techniques

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***Abstract*— The multiple–input–multiple–output (MIMO) technique is the most attractive candidate to improve the spectrum efficiency in the next generation wireless communication systems. However, the efficiency of MIMO techniques reduces in the line of sight (LOS) environments. In this paper, we propose a new MIMO data transmission scheme, which combines Single–Frequency–Network (SFN) with TDD–OFDM–MIMO applied for wireless LAN networks. In our proposal, we advocate to use SFN for multiple access points (MAP) MIMO data transmission. The goal of this approach is to achieve very high channel capacity in both LOS and non line of sight (NLOS) environments. The channel capacity of the proposed method is derived for the direct path environments and it confirms the effectiveness of the proposed scheme in the LOS scenario. Moreover, solid computer simulation results confirm the effectiveness of the proposed method in both, single user and multiuser scenarios.**

***Keywords*— MIMO, OFDM, SFN, multiple access points, beamforming**

I. INTRODUCTION

The recent popularity of wireless LANs has pushed the demand for even higher data rates enabling real–time multimedia applications. However, frequency resources are strictly limited and most frequencies located in the microwave band, which are suited for wireless LANs, have already been assigned to various radio broadcast systems. Thus, the broadband services should be provided with limited frequency band and spectrum efficiency is getting even more importance for next generation wireless LAN systems than it has already in omnipresent systems.

Multiple–Input–Multiple–Output (MIMO) is one of the most attractive candidate with respect to spectrum efficiency [1]. In identically independent distributed fading channel, it can linearly increase the channel capacity as the number of antenna branches increases. And it achieves higher channel capacity if the Channel State Information (CSI) is known at the receiver as well as the transmitter. However, in the MIMO data transmission scheme, each antenna branch transmits different signal streams and it generates high interference environments. Moreover, in broad band wireless access systems, delayed waves cause the interference condition worse and highly sophisticated demodulators are required at receivers especially for single carrier systems.

Thus, Orthogonal Frequency Division Multiplex (OFDM) systems in Time Division Duplex (TDD) with MIMO have been receiving much attention because OFDM can mitigate the influence of the frequency selective fading channel and MIMO techniques using CSI can be easily implemented to each sub–carrier [2]. This is because perfect calibration method has been proposed [3] and it enables to use the CSI in uplink as that in downlink. Although the MIMO data transmission scheme increases the hardware complexity of the system, the trial product of the MIMO receiver, where the MIMO demodulator in each subcarrier works simultaneously, has been achieved [2] and practical application is becoming reality. However, in general, MIMO is effective only in rich multi–path environments and its effect decreases in correlated fading environments such as in line–of–sight scenario (LOS) [4]. To overcome this problem, beamforming technique for both transmitter and receiver has been proposed [5]. This method can enhance the desired signal power and improves the SNR performances. However, it can not increase the spatial channel and the channel capacity improvement is limited.

In this paper, we propose a new MIMO data transmission scheme for wireless LANs, which combines Single–Frequency– Network (SFN) with TDD–OFDM–MIMO. SFN with OFDM has been proposed for broad casting systems to improve the transmission quality in over lapping cells [6]. In our proposal, we advocate to use SFN for multiple access points (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 (APs) cooperate each other in the proposed scheme, higher performances can be achieved as the number of APs increases while the performances are significantly degraded by the strong interferences from the adjacent APs in the conventional data transmission scheme.

In the following, the proposed data transmission scheme is described in Section II. In Section III, the channel capacity of the proposed scheme is derived and basic operation in the strong correlated fading environment is shown. Afterwards the simulation results for one user and multiple users scenarios are presented in Section IV. The paper is concluded in Section V.

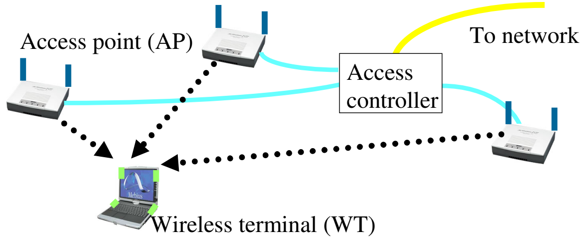

Fig. 1. Proposed system configuration.

II. DATA TRANSMISSION SCHEME IN MAP–MIMO SYSTEMS

Figure 1 shows the proposed configuration for wireless LANs with OFDM. As this figure shows, multiple APs are connected to one access controller. Since OFDM can mitigate the influence of the delayed waves, this system can compensate the delay caused by the different distance from each AP to each wireless terminal (WT). Thus, it achieves virtual large array antennas and enhances the MIMO effect in both uplink and downlink. The data transmission scheme in uplink and downlink with perfect CSI at both APs and WTs are as follows.

In uplink, OFDM data frames are consisted with training period and data period. In the training period, known signals are transmitted from each antenna element of WT. After that, multiple OFDM data symbols are transmitted with multiple beams. Then, all received signals at all APs are delivered to the access controller. At the access controller, all channel responses are estimated at the same time in each sub–carrier in the training period and multiple beams for virtual large array antennas are optimized by Minimum Mean Squared Error (MMSE) criteria. After that receiving data are separated using the multiple beam–forming network and those data are demodulated. Note that, this system works in TDD systems and the channel responses in downlink can be considered to be equal to that in uplink. And by using the perfect calibration method at each AP [3], the generated beam patterns can be also employed in downlink and the transmission power of each beam is optimized by the water pouring theory [1]. In downlink, multiple OFDM data frames with training symbols are input to multiple beam–forming network and transmission signals for each antenna element are generated. Then, those signals are delivered to APs and transmitted from array antennas simultaneously. At 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.

III. OPERATION ANALYSIS OF THE PROPOSED SCHEME

As described in the previous section, multiple signal streams are transmitted from multiple APs and it generates the artificial multipath environments. Thus, the proposed scheme improves the spatial separation performance even in the LOS scenario where the strong direct path causes highly correlated fading channels. In this section, we focus on the operation for the direct path environments in downlink to clarify the spatial separation characteristic in the highly correlated fading environments. Note that the operation can be easily translated to that in uplink scenario by exchanging the transmitter and the receiver.

A. Numerical analysis

In downlink, the received signal in sub–carrier *k* at WT can be expressed as the following equation.

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{s}_k + \mathbf{n}_k \tag{1}$$

where, $\mathbf{r}_k$ is the received signal vector, $\mathbf{H}_k$ is the channel matrix, $\mathbf{s}_k$ is the transmission signal vector and $\mathbf{n}_k$ is the noise vector. In the proposed scheme in direct path environments, the channel matrix can be rewritten as follows

$$\mathbf{H}_k = \mathbf{A}\mathbf{D}\mathbf{B}^H \tag{2}$$

where superscript ^{H} denotes the transpose conjugation of matrices, the *l*–th row vector of $\mathbf{A}$, $\mathbf{a}_l$, is the steering vector at WT for *l*–th AP, $\mathbf{D}$ is the diagonal matrix and $\mathbf{B}$ is defined by the following equation.

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{b}_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{b}_L \end{bmatrix} \tag{3}$$

where $\mathbf{b}_l$ is the steering vector at *l*–th AP and *L* is the number of APs. Steering vectors $\mathbf{a}_l$ and $\mathbf{b}_l$ satisfy the following equation.

$$\mathbf{a}_l^H \mathbf{a}_l = 1, \mathbf{b}_l^H \mathbf{b}_l = 1$$

The diagonal element of $\mathbf{D}$ is the magnitude of the channel response between each AP and WT. If identical array antennas are used at APs and all antenna branches are assumed to be omni–directional, *l*–th element of $\mathbf{D}$ can be expressed as follows.

$$d_{l,l} = \alpha_l \sqrt{MN} \tag{4}$$

where α_l is the amplitude of the direct path between the *l*–th AP and the WT, *M* is the number of antenna branches at each AP, and *N* is the number of antenna branches at WT. The correlation matrix in sub–carrier *k* can be written as follows.

$$\mathbf{R}_k = \mathbf{H}_k \mathbf{H}_k^H = \mathbf{A}\mathbf{D}^2\mathbf{A}^H \tag{5}$$

The above equation shows that the correlation matrix does not depend on the matrix $\mathbf{B}$ and it indicates that the channel capacity can be determined regardless of the array configuration at each AP.

If the CSI is completely unknown at the transmitter, the channel capacity is expressed as follows [1].

$$C_{unknown} \quad = \quad log_2[det(\mathbf{I}_N + \frac{1}{\sigma^2 ML}\mathbf{H}\mathbf{H}^H)] \tag{6}$$

where $\mathbf{I}_N$ is the $N \times N$ identity matrix. And if the propagation loss between each AP and WT is the same, α, and the thermal noise at each antenna branch is independent, the channel capacity can be simplified as follows.

$$\begin{aligned} C_{unknown} &= log_2[det(\mathbf{I}_N + \frac{N\alpha^2}{\sigma^2 L}\mathbf{A}\mathbf{A}^H)] \\ &= \sum_{l=1}^{L} log_2[1 + \frac{N\alpha^2}{L\sigma^2}\lambda_l] \end{aligned} \tag{7}$$

where λ_l is the l–th eigenvalue of $\mathbf{A}\mathbf{A}^H$, σ^2 is the power of thermal noise. Thus, the channel capacity does not depend on *M*. This is because each AP does not know the WT location and it can not generate the beam directed toward WT. If all APs are located in the same position, the rank of $\mathbf{A}\mathbf{A}^H$ becomes 1 and the channel capacity is minimized. And if each AP is located in the different position and *L* eigenvalues become equal, the channel capacity is maximized. Thus, the channel capacity satisfies the following inequality.

$$log_2[1 + \frac{N\alpha^2}{\sigma^2}] \leq C_{unknown} \leq L log_2[1 + \frac{N\alpha^2}{L\sigma^2}] \tag{8}$$

And if the perfect CSI can be assumed at the transmitter, the channel capacity can be written as follows [1].

$$C_{known} \quad = \quad \sum_{l=1}^{L} log_2[1 + \frac{N\alpha^2}{L\sigma^2}\lambda_l \gamma_l] \tag{9}$$

where γ_l indicates the transmission power and determined by the water pouring theory [1].

$$\gamma_l^{opt} = (\mu - \frac{L\sigma^2}{\lambda_l N\alpha^2})_+ \tag{10}$$

where μ is constant and determined to satisfy the following equation to constrain the transmission power.

$$\sum_{l=1}^{L} \gamma_l = ML \tag{11}$$

where $(x)_+$ implies

$$(x)_+ = \{ \begin{array}{lll} x & if & x \geq 0 \\ 0 & if & x < 0 \end{array}$$

If all APs are located in the same position, the rank of $\mathbf{AA}^H$ becomes 1 and the channel capacity is minimized. And if each AP is located in the different position and L eigenvalues become equal, the channel capacity is maximized like the unknown CSI case. Thus, the channel capacity satisfies the following inequality.

$$log_2[1+\frac{MN\alpha^2}{\sigma^2}] \leq C_{known} \leq Llog_2[1+\frac{MN\alpha^2}{L\sigma^2}] \qquad (12)$$

If all antenna branches are located in the same area, it represents conventional single AP MIMO system. Therefore, it confirms that the proposed scheme achieves the higher channel capacity than the conventional system does in any cases, although the proposed scheme requires the access controller and it increase the complexity of the system.

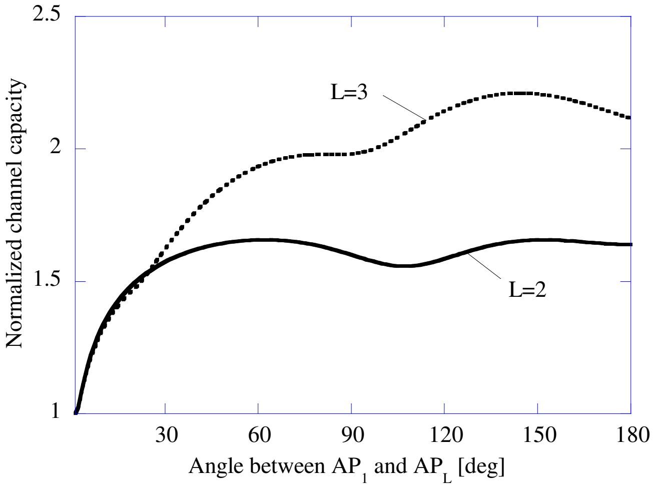

Fig. 2. Channel capacity of MAP–MIMO in the direct path environment.

B. Operation in the direct path environments

Figure 2 shows the relationship between the channel capacity and the APs's locations. In this calculation, the same circular array antenna is assumed for each AP and WT. The number of antenna branches at each AP and WT is 4, the element space is 0.5λ, and the number of APs are 2 and 3. The distance between each AP and WT is assumed to be equal. In this figure, the transverse axis indicates the angle between first AP and *l*–th AP. Each channel capacity is normalized by the channel capacity at $\theta = 0$ to clarify the spatial separation performances. And *l*–th AP is located in $(l-1)\theta/3L$ and θ is varied. The SNR for SISO channel is set to 20dB. As this figure shows, the channel capacity increases as the AP spread increases. And in case of 3 APs, the channel capacity becomes more than twice of that for $\theta = 0$. These basic operations indicate that the proposed method can achieve higher channel capacity even in the highly correlated fading environments. In the following section, the effectiveness is confirmed for the frequency selective multipath fading environments.

IV. PERFORMANCE EVALUATION OF THE PROPOSED SCHEME

A. Simulation model

Figure 3 shows the simulation model. In this model, we assume one short delayed cluster and two exponentially attenuated long delayed clusters. And we also assume that averaged power of long delayed clusters is set to equal regardless of the WT location. Therefore, only the short delayed cluster power is changed 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 degrees and that of the long delayed clusters is 20 degrees. The delay spread is 30 nsec. 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 0.5 λ and circular array is used. Three APs are assumed and each location is (0m,0m,3m), (10m, 0m, 3m), (10m, 10m, 3m). The height of WT is 0.7 m. Center frequency is 5.2 GHz, number of sub–carriers is 52 and sub–carrier space is 312.5 KHz. We conducted large number of trials and evaluate the cumulative probability of the channel capacity and the ergodic channel capacity.

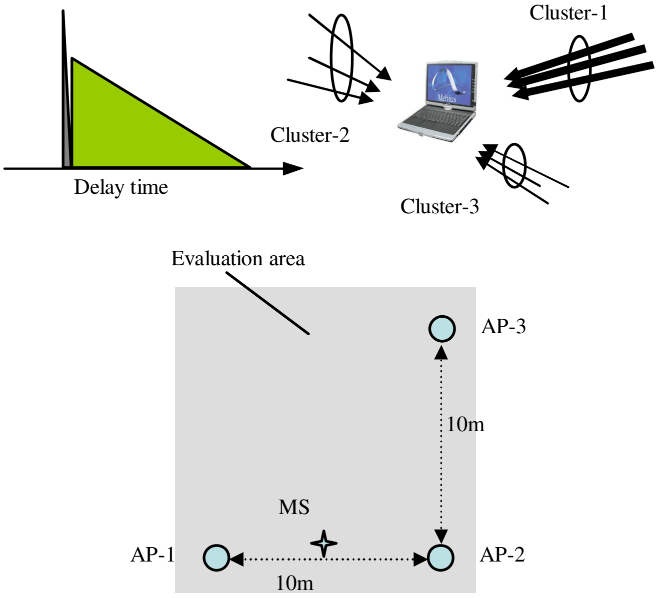

Fig. 3. Simulation model.

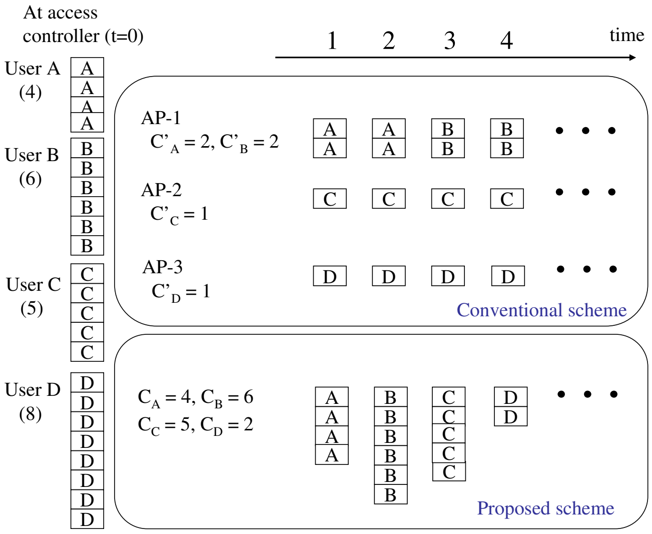

Fig. 4. Data transmission scheme in multiuser scenario.

For the multiuser case, we evaluated the average achievable

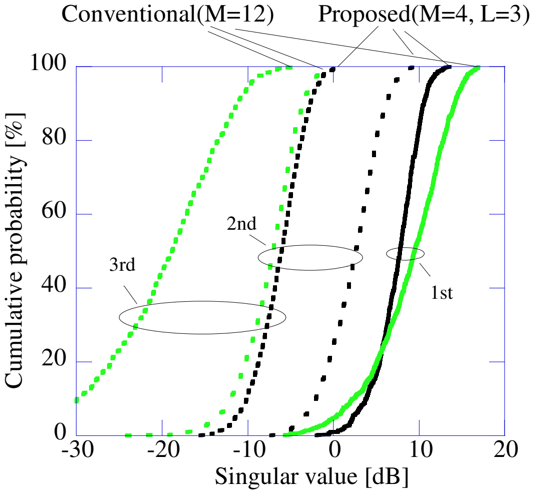

Fig. 5. Cumulative probability of the eigenvalues.

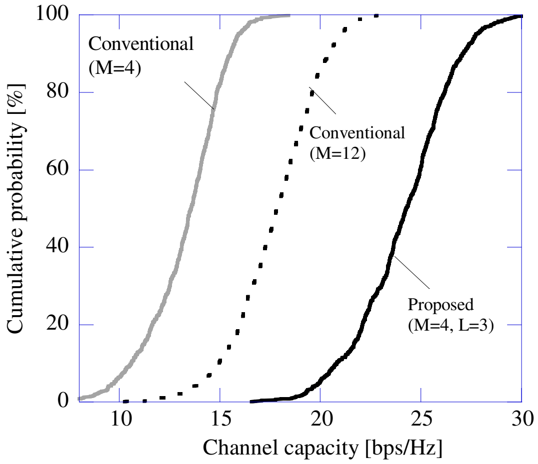

Fig. 6. Channel capacity of the one user model.

throughput performance with the multiple access scheme. In this evaluation, all APs use the same frequency channel to evaluate the total achievable throughput in the spatial channel. In the conventional method, each AP works independently and simultaneous transmission occurs, while no collision occurs in the proposed scheme by employing Time Division Multiple Access (TDMA). Note that if all APs are synchronized and each AP selects the different transmission timing, it becomes the one user case. In the evaluation of the conventional methods, an orthogonal spatial filter is assumed at WT to decompose the interferences from the APs and the channel capacity is calculated after the decomposition. The data packets were randomly generated for users and the achievable data rate is calculated from the channel capacity of each link.

Figure 4 shows the example of the data transmission scheme. User–A and user–B access for AP–1, and user–C, user–D access for AP–2, AP–3, respectively in the conventional scheme, while all users access to all APs in the proposed scheme. And the achievable maximum throughput of the conventional scheme for users are assumed to be, $C_A^{'} = 2$, $C_B^{'} = 2$, $C_C^{'} = 1$ and $C_D^{'} = 1$. The achievable throughput of the proposed scheme for users are assumed to be,$C_A = 4$, $C_B = 6$, $C_C = 5$ and $C_D = 2$. At $t = 0$, 4, 6, 5, and 8 packets are generated for user A–D respectively. In the conventional method, the data for user–A, user–C, and user–D are transmitted at the frame timing 1 while the data for user–A is only transmitted in the proposed scheme. Thus, the total number of data packets in this frame is 4 in both methods. However, in the next frame, the proposed scheme increases the number of packets from 4 to 6 and the proposed scheme achieves higher throughput. After the 4 frames, only the data transmission to the user–A has accomplished in the conventional scheme, while the only user–D has not accomplished in the proposed scheme. In the computer simulations, we evaluate the averaged total achievable throughput for various WT locations.

B. Simulation results for one user case

In the following, the cumulative probabilities of the singular values of the channel transfer matrix and the channel capacity are evaluated in case of the WT is located at $(5m, 0m, 0.7m)$ and clarifies the operation in the multipath fading environments. After that, the ergodic channel capacity in the various WT position is shown.

Figure 5 shows the cumulative probability of the singular–values of the channel transfer matrix H_k in the proposed scheme comparing with those of the conventional MIMO systems. In this figure, M is the number of antenna branches at each AP and L is the number of APs. As this figure shows, the proposed scheme improves magnitude of the third and forth singular values while the first singular value has almost the same magnitude. It indicates that the proposed method improves the spatial separation performance and enables the use of the third and forth eigenvalues.

Figure 6 shows the cumulative probability of the channel capacity with proposed scheme comparing with the conventional MIMO systems. 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 3–times as many antenna branches as the proposed method.

In Figure 7, 8, and 9 the ergodic channel capacity distribution in the evaluation area is shown. In these figures, white area and dark area indicates the high and the low ergodic channel capacity, respectively. In Figure 7, perfect synchronization among APs is assumed in the conventional data transmission scheme and no interference is considered. The best AP is selected to achieve the highest performance. Since only four antenna branches are used at APs, the high channel capacity can not be achieved. In Figure 8, one AP with twelve antenna branches is assumed as a conventional AP while three APs are assumed in other scenarios. As Figure 8 shows, although high channel capacity is achieved around the AP area, the performance is degraded as the distance between APs increases. On the other hand, as Figure 9 shows, the proposed method achieves very high channel capacity and outperforms the both conventional methods at any point. And the higher channel capacity is achieved around the area between two APs. This is because the distance of each AP and WT becomes small and APs can cooperate each other. These results confirm the effectiveness of the proposed method.

C. Simulation results for multiuser case

Figure 10 shows the cumulative probability of the average achievable total throughput of the proposed scheme comparing 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, while the improvement reduces as the distance increases. In case of $d = 50m$, the highest throughput of the conventional scheme is almost the same as that of the proposed scheme,

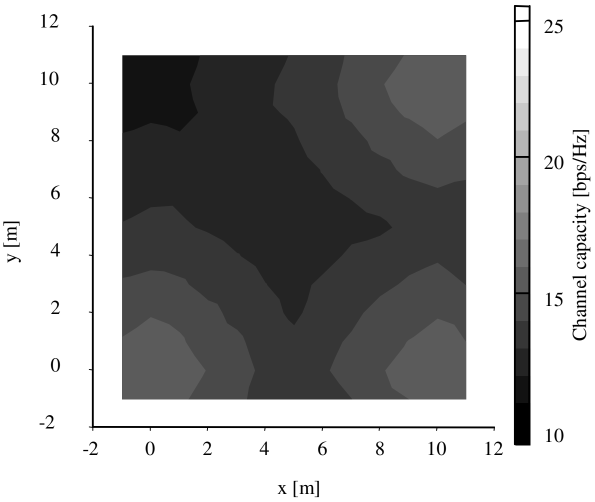

Fig. 7. Channel capacity distribution of the conventional data transmission scheme in case of L=3, M=4.

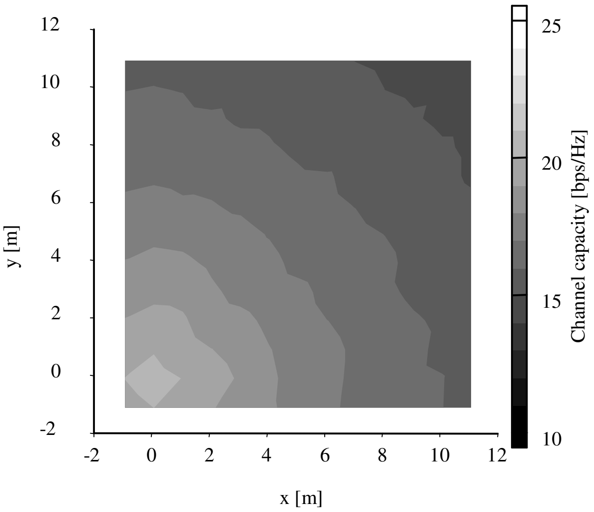

Fig. 8. Channel capacity distribution of the conventional data transmission scheme in case of L=1, M=12.

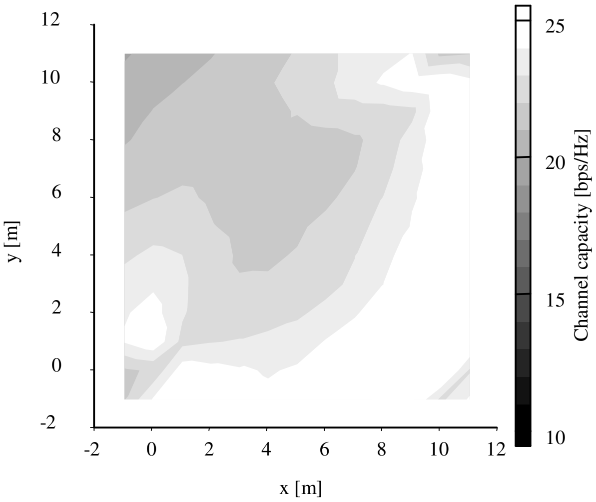

Fig. 9. Channel capacity distribution of the proposed data transmission scheme in case of L=3, M=4.

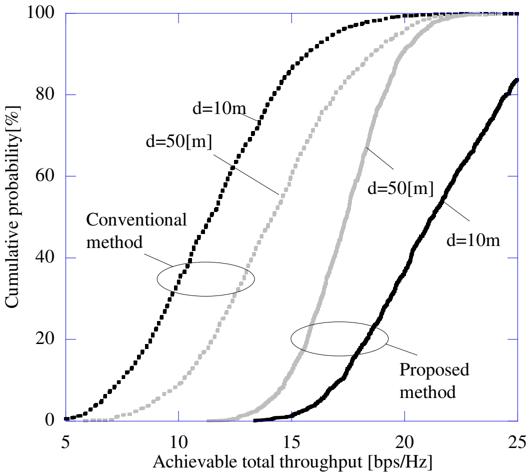

Fig. 10. Cumulative probability of the achievable total throughput.

because such high throughput can be achieved if each MP is close to accessing AP and the influence of the interference becomes negligible. However, the performance of the conventional method degrades as the distance between AP and WT decreases. This is because the interference increases as the distance decreases, while the proposed scheme improves the channel capacity by the cooperative operation with multiple APs. These results confirm the effectiveness of the proposed scheme.

V. CONCLUSION

In this paper, we proposed a MAP–MIMO data transmission scheme, which combines Single–Frequency–Network (SFN) 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 and it confirmes that the proposed method outperforms conventional MIMO system in the strong correlated environments. And we evaluated the proposed scheme with conventional MIMO systems in multi–path environments and showed the potential of the proposed scheme. The simulation results confirm that the proposed scheme improves the later singular values of the channel transfer matrices and enables to double the channel capacity for the conventional MIMO systems in one user case. Moreover, the total throughput performance was evaluated in the multiuser scenario and found that the proposed scheme improves the performance by the cooperative operation with multiple APs as the distance between AP and WT decreases, while the performance in the conventional method is significantly deteriorated by the interference from adjacent APs.

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