Performance Evaluation of Primary-Secondary Transmission in Actual Indoor Environments

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1. Introduction

By the spread of wireless LAN systems, a lot of access points (APs) are set up in various places such as residence and office etc. The increase of the number of APs causes the inter-cell interference (ICI). In WLAN systems, the ICI can be mitigated by Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) using Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). However, system capacity is not increased because of limited frequency and time resources. The issue of the ICI is being argued as the OBSS (Overlapping Basic Service Set) issue in IEEE802.11ac and 11aa [1].

To dramatically increase system capacity in the overlapping cell environment, we focused on beamforming techniques using array antenna [2]. Because spatial domain resource can increase in proportion to the number of antennas, increase of system capacity is expected As spatial domain resource sharing, either centralized [3] or decentralized [4], [5] approaches have been proposed. Although centralized approaches are able to achieve higher system capacity, all APs must be synchronized and share all of the transmission data and the channel state information (CSI). Decentralized approaches increase the system capacity by using the CSI for stations (STAs) that communicate with the other AP. While they offer less system capacity increase than centralized approach, they are more suitable for WLAN systems because the APs that different owners have are less likely to cooperate with each other.

Paper of [5] proposed the primary-secondary (PS) transmission scheme on the basis of the decentralized approach and this scheme attains the high achievable bit rate in an overlapping cell environment by virtual wall. In this paper, we show performance evaluation of the PS transmission using the CSI measured in an actual overlapping cell environment. In the PS transmission, the primary AP and secondary AP communicate with their own destination STAs, and the ICI from the secondary cell on the primary cell is mitigated by beamforming of the secondary AP while the primary AP works as it would in an isolated cell. To evaluate this scheme performance in actual overlapping cells, we measured the 8×4 channel matrices of MIMO-OFDM signals in an indoor apartment environment. The results show that this scheme can increase system capacity for horizontal and vertical cell orientations. Moreover, evaluations of this scheme in both cell orientations show that the effectiveness of this scheme can be estimated by just the interference to noise ratio (INR).

2. System model

We consider the downlink MIMO-OFDM system in the overlapping cell environment where two APs utilize the same frequency channel, see Fig.1. It is assumed that the primary AP (P-AP) and secondary AP (S-AP) communicate with their own destination STAs. The STAs that communicates with P-AP and S-AP are defined as P-STA and S-STA, respectively. The secondary AP uses beamforming to mitigate the expectation of the ICI on P-STA. Both P-AP and S-AP have N transmit antennas, and each STA has M receive antennas. $\mathbf{H}_{P,i}\in\mathbb{C}^{M\times N}$ and $\mathbf{H}_{Sj}\in\mathbb{C}^{M\times N}$ denote the channel matrices of desired signal between P-AP and i-th P-STA, and between S-AP and j-th S-STA, respectively. $\mathbf{H}_{SP,i}\in\mathbb{C}^{M\times N}$ and $\mathbf{H}_{PS,j}\in\mathbb{C}^{M\times N}$ denote the channel matrices of

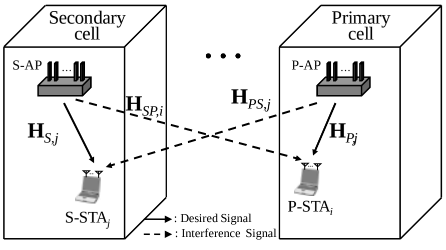

Figure 1: System model

interference signal between P-AP and j-th S-STA, and between S-AP and i-th P-STA, respectively. In this system model, the received signal vectors, $\mathbf{y}_{Pi}\in\mathbb{C}^{M\times 1}$ at i-th P-STA and $\mathbf{y}_{S,j}\in\mathbb{C}^{M\times 1}$ at j-th S-STA are expressed by transmit signal vector $\mathbf{x}_{P,i}\in\mathbb{C}^{N\times 1}$ of P-AP and $\mathbf{x}_{S,i}\in\mathbb{C}^{N\times 1}$ of S-AP as

$$\mathbf{y}_{P,i} = \mathbf{H}_{P,i}\mathbf{W}_{P,i}\mathbf{x}_{P,i} + \mathbf{H}_{SP,i}\mathbf{W}_{S,j}\mathbf{x}_{S,j} + \mathbf{n}_{P,i}, \qquad \mathbf{y}_{S,j} = \mathbf{H}_{S,j}\mathbf{W}_{S,j}\mathbf{x}_{S,j} + \mathbf{H}_{PS,j}\mathbf{W}_{P,i}\mathbf{x}_{P,i} + \mathbf{n}_{S,j}, \quad (1)$$

where $\mathbf{W}_{P,i}\in\mathbb{C}^{N\times N}$ is the transmission weight of P-AP, $\mathbf{W}_{S,j}\in\mathbb{C}^{N\times N}$ is expressed by the transmission weight of S-AP and the transmission weight of S-AP so as to mitigate the interference to i-th P-STA. $\mathbf{n}_{P,i}$ and $\mathbf{n}_{S,j}$ are additive white Gaussian noise vectors with E[$\mathbf{nn}^H$]= $\sigma^2\mathbf{I}$. $(.)^H$ denotes the conjugate transpose of the corresponding vector or matrix, and $\mathbf{I}$ is the identity matrix.

3. Primary-Secondary transmission scheme

3.1 Capacity of primary cell

In PS transmission scheme, P-AP transmits signals to i-th P-STA using eigenvector transmission (EV). We assume that equal power is allocated to each data stream. This is because the effectiveness of the water filling strategies is negligible for the high SNR environment. EV maximizes the received signal to noise ratio (SNR) corresponding to the eigenvalues. By using singular value decomposition (SVD), channel matrix $\mathbf{H}_{P,i}$ for i-th P-STA is expressed as

$$\mathbf{H}_{P,i} = \mathbf{U}_{P,i}\begin{pmatrix}\mathbf{\Sigma}_{P,i} & \mathbf{0}\end{pmatrix}\begin{pmatrix}\mathbf{V}_{P,i}^{(s)} & \mathbf{V}_{P,i}^{(n)}\end{pmatrix}^H, \quad (2)$$

where $\mathbf{U}_{P,i}\in\mathbb{C}^{M\times M}$ is the left singular vectors, ($\mathbf{V}_{P,i}^{(s)}$ $\mathbf{V}_{P,i}^{(n)}$) is the right singular vectors. $\mathbf{V}_{P,i}^{(s)}\in\mathbb{C}^{N\times M}$ and $\mathbf{V}_{P,i}^{(n)}\in\mathbb{C}^{N\times(N-M)}$ correspond to the eigenvalues and zero, respectively. The diagonal elements of $\mathbf{\Sigma}_{P,i}$ represent the square roots of the eigenvalues, $\lambda_{1,i},\lambda_{2,i},\ldots, \lambda_{M,i}$. The transmission weight at the P-AP, $\mathbf{W}_{P,i}$, is expressed as

$$\mathbf{W}_{P,i} = \frac{1}{\sqrt{M}}\mathbf{V}_{P,i}^{(s)}, \quad (3)$$

The transmission capacity from P-AP to i-th P-STA, $C_{P,i}$ is given by

$$C_{P,i} = \log_2 \det\left(\mathbf{I}_M + \frac{\frac{1}{\sigma^2}\mathbf{H}_{P,i}\mathbf{W}_{P,i}^H\mathbf{W}_{P,i}^H\mathbf{H}_{P,i}^H}{\mathbf{I}_M + \frac{1}{\sigma^2}\mathbf{H}_{SP,i}\mathbf{W}_{S,j}\mathbf{W}_{S,j}^H\mathbf{H}_{SP,i}^H}\right), \quad (4)$$

where $\mathbf{W}_{S,i}$ is transmit weight of S-AP.

3.2 Capacity of secondary cell

S-AP transmits signals to j-th S-STA to mitigate the ICI at i-th P-STA. This method achieves higher system capacity by using the CSI between S-AP and i-th P-STA. By using SVD, channel matrix $\mathbf{H}_{SP,i}$ between S-AP and i-th P-STA is expressed as

$$\mathbf{H}_{SP,i} = \mathbf{U}_{SP,i}\begin{pmatrix}\mathbf{\Sigma}_{SP,i} & \mathbf{0}\end{pmatrix}\begin{pmatrix}\mathbf{V}_{SP,i}^{(s)} & \mathbf{V}_{SP,i}^{(n)}\end{pmatrix}^H \quad (5)$$

where $\mathbf{U}_{SP,i}\in\mathbb{C}^{M\times M}$ represents the left singular vectors, ($\mathbf{V}_{SP,i}^{(s)}$ $\mathbf{V}_{SP,i}^{(n)}$) represent the right singular vectors; $\mathbf{V}_{SP,i}^{(s)}\in\mathbb{C}^{N\times M}$ and $\mathbf{V}_{SP,i}^{(n)}\in\mathbb{C}^{N\times(N-M)}$ correspond to the eigenvalues and zeros, respectively. When S-AP uses a null space weight, the desired channel matrix is expressed as

$$\mathbf{H}_{S,j}\mathbf{V}_{SP,i}^{(n)} = \mathbf{U}_{S,j}\mathbf{\Sigma}_{S,j}\mathbf{V}_{S,j}^{(s)H} \quad (6)$$

where $\mathbf{U}_{S,j}\in\mathbb{C}^{M\times M}$ represents the left singular vectors, $\mathbf{\Sigma}_{S,j}\in\mathbb{C}^{M\times M}$ represents the diagonal matrix, and the diagonal elements of are the square root of the space eigenvalues, $\lambda_{1,j},\lambda_{2,j},\ldots, \lambda_{M,j}$.; $\mathbf{V}_{S,j}^{(S)}$ represents the right singular vector. The transmission weight at S-AP, $\mathbf{W}_{P,i}$, is expressed as

$$\mathbf{W}_{S,i} = \frac{1}{\sqrt{M}}\mathbf{V}_{S,j}^{(s)}\mathbf{V}_{SP,i}^{(n)}, \quad (7)$$

The capacity from the AP to j-th S-STA, $C_{S,j}$, is given by

$$C_{S,j} = \log_2 \det \left(\mathbf{I}_M + \frac{\frac{1}{\sigma^2} \mathbf{H}_{S,j} \mathbf{W}_{S,j} \mathbf{W}_{S,j}{}^H \mathbf{H}_{S,j}^H}{\mathbf{I}_M + \frac{1}{\sigma^2} \mathbf{H}_{PS,j} \mathbf{W}_{P,i} \mathbf{W}_{P,i}^H \mathbf{H}_{PS,j}^H} \right). \tag{8}$$

4. Measurement environment

This section introduces the MIMO-OFDM measurement experiments. Fig.2 shows the configuration of the MIMO-OFDM measurement testbed. Each transmitter and receiver employed eight and four antennas, respectively. By using the testbed, 8×4 MIMO-OFDM channel matrices were obtained for 108 subcarriers. The receiver stored the captured signal and the channel matrices were obtained in offline processing. We measured the 8×4 channel matrices between AP and STAs in single room and between different rooms providing horizontal and vertical orientations. Fig.3 shows the apartment in Yokkaichi city, Japan. We measured the channel matrices using 7 rooms. Fig. 4 indicates the room layout and the locations of APs and STAs. It was assumed that four STAs communicated with the AP in each room. Room size was 4.4m × 3m × 3m (L × W × H). The MIMO channel matrices were all AP-STA combinations. We used a linear array of eight dipole antennas with element spacing of 0.5 λ and a linear array of four dipole antennas with element spacing of 0.5 λ as the transmit antennas and the receive antennas, respectively. Table I shows the measurement parameters. The center frequency and bandwidth were 4.85GHz and 40MHz, respectively.

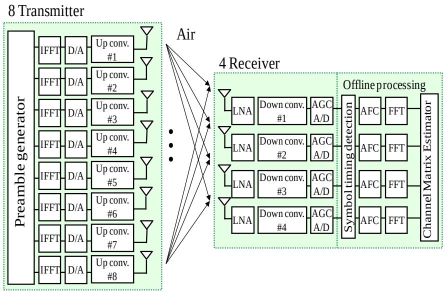

Figure 2: Configuration of MIMO-OFDM measurement testbed

5. Performance evaluation

5.1 The ICI analysis in an apartment environment

Fig. 5 plots the SNR versus distance from the AP of Room 1 to the STA of Rooms 2, 3, 4, and 5 (horizontal orientation) and the SNR versus distance from the AP of Room 6 to the STA of Rooms 1 and 7 (vertical orientation). The measured channels correspond to $\mathbf{H}_{PS,j}$ and $\mathbf{H}_{SP,i}$ in Fig. 1. This figure also shows the theoretical line according to the 802.11n propagation model [6] with wall loss values of 0 and 10 [dB]. It was found that the horizontal cell orientation is the more significant problem in this apartment environment.

Figure 3: Photograph of measurement apartment

5.2 Eigenvalue analysis

Fig.6 shows the cumulative distribution functions (CDFs) of eigenvalues for the horizontal and vertical orientations when the SNR is normalized. This figure shows that the ratio of the first eigenvalue to the other eigenvalues is large in both orientations. The ratio of the first eigenvalue to the other eigenvalues in the horizontal orientation is larger than that in the vertical cell orientation. Therefore, in the horizontal orientation, the ratio of the first eigenvalue to the other eigenvalues of $\mathbf{H}_{PSij}$ and $\mathbf{H}_{SP,i}$ are also large.

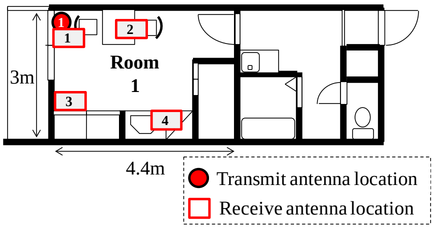

Figure 4: Room layout and measurement locations

5.2 Effectiveness of the PS transmission scheme

The system capacity for the PS transmission scheme was calculated for both horizontal and vertical orientation. For the former, we assume that the cells are Room1 and Rooms 2-5. For the latter, we assume that the cells are Room 6 and Rooms 1 and 7.

Table I: Measurement parameter

Number of antenna	8 (Tx), 4(Rx)
Radio frequency	4.85 GHz
Bandwidth	40 MHz
Average SNR	30 dB
Sampling rate	40 MHz (A/D), 80 MHz (D/A)
Number of FFT points	128
Number of subcarriers	108

Figures 7 and 8 shows the CDF of the system capacity for horizontal and vertical orientation, respectively. To compare them to the conventional methods, the CDF of the channel capacity in TDMA is also shown. In TDMA system, each AP uses EV transmission and the time resource is equally allocated for each AP. As can been seen, the PS transmission scheme has higher system capacity than TDMA in both orientations. Moreover, the system capacity increases with the separation between the primary and secondary cell because the ICI from the primary cell decreases as the distance increases. In Fig.7, the system capacity is increased by about 1.3 (pair 1-2), 1.5 (pair 1-3), 1.6 (pair 1-4), 1.7 (pair 1-5) times higher than that of TDMA. In Fig.8, the system capacity is increased by about 1.6 (pair 6-1), 1.8 (pair 6-7) times higher than that of TDMA.

Fig. 9 shows the average system capacity versus INR between Room 1 and Rooms 2 to 5 and Room 6 to Rooms 1 and 7 for horizontal and vertical orientations. The black circles and white squares denote the system capacities in the vertical and horizontal cell orientation, respectively. Since the results in both orientations show the same tendency, we can confirm that the effectiveness of the proposed scheme can be estimated by the INR.

6. Conclusion

This paper evaluated that the effectiveness of the primary-secondary (PS) transmission scheme in an actual apartment environment for WLAN systems. The PS transmission scheme mitigates the ICI from the secondary cell to the primary cell by beamforming while the primary cell works as it would in an isolated cell. The results showed that the PS transmission scheme is able to increase the system capacity compared to conventional schemes such as TDMA in both horizontal and vertical cell orientations. Moreover, it was found that the effectiveness of this scheme depends on just the INR.

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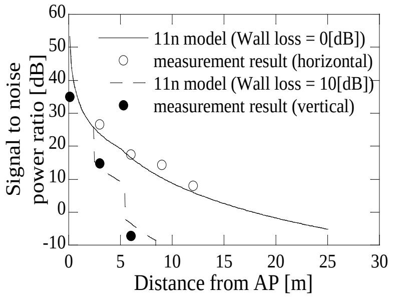

Figure 5: SNR versus distance from AP

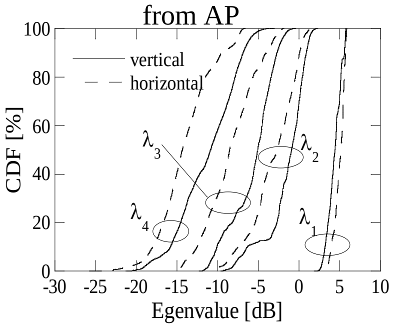

Figure 6: Eigenvalue distribution when SNR of channel is normalized.

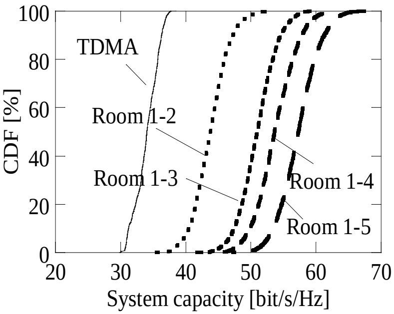

Figure 7: System capacity in horizontal orientation

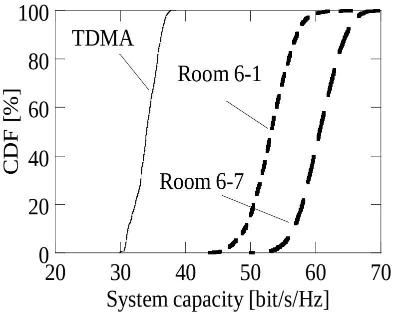

Figure 8: System capacity in vertical orientation

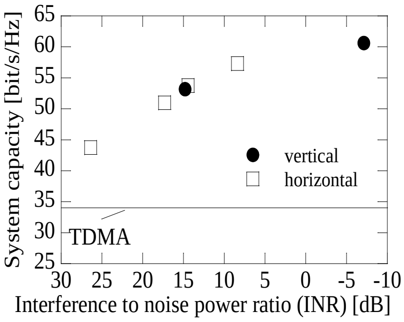

Figure 9: Average system capacity in horizontal and vertical orientation