

Investigation on Distributed Antennas Deployment Method for Indoor Line-of-Sight Multiple Input Multiple Output Wi-Fi System

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Abstract —Generally, it is difficult to increase the regular MIMO channel capacity between transmitter and receiver for indoor Line-of-sight (LoS) communication due to the channel correlation is always high. Therefore, in this paper, we proposed a distributed multiple antennas deployment method over relay to optimize the downlink multiple input multiple output (MIMO) channel capacity by simply adjusting the adjacent antenna distance of relay. The simulation result shows that using the proposed deployment method under certain circumstance, the MIMO channel capacity can be approximately 115% improved in maximum than that in the non-relay MIMO case.

I. INTRODUCTION

The Wi-Fi technology is now dominant to the indoor communication market. The Wi-Fi wireless access provides user with internet communication which is ubiquitous, high quality-of-service (QoS), secure, and low-cost for indoor spaces. The Wi-Fi network is also known as Wireless Local Area Network (WLAN) in which the coverage ranges from 10 meters to 100 meters, theoretically. However, inside the empty spaces indoor such as concert halls, arenas, and hallways the number of Wi-Fi access points (AP) at service is limited, such that the received signal strength (RSS) at user device is usually too weak to guarantee networking QoS due to the free space path loss and shadowing experienced during a long microwave propagation.

The solution to the weak Wi-Fi RSS problem in long range is the signal extension technique using relay. In the industry, this technique is called the Wi-Fi Distribution System (WDS) function which constructs a mesh network (i.e., Extended Service Set (ESS)) composed by multiple of APs. In such network infrastructure, the AP that connects to the internet modem is denoted “master” which maintains the Dynamic Host Configuration Protocol (DHCP) function that assigns IP address to users inside the entire WLAN, whereas the AP that does not connect to the internet modem is denoted “slave” in which the DHCP function is disabled. Note that both master and slave can provide radio communication to users. Therefore, the slaves are used only for signal extension, that is, the slaves are actually relays in the WDS function.

In order to increase the channel capacity of the WDS function, MIMO technique is adopted among master, slaves, and users.

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However, due to the lack of obstacles (i.e. the rise of Rician K -factor in the meanwhile [1-2]) in empty spaces, the LoS MIMO channel correlation will be high and the Channel Status Information (CSI) matrix will not be full rank [3-5], leading to both low diversity gain and multiplexing gain. In sight of the problem above, in this paper, we equipped the slave with distributed antenna system (DAS) [6], where the antenna distance between adjacent antennas are variable such that the channel correlation can be reduced, and hence the MIMO channel capacity can be increased. In LoS MIMO cases, by utilizing scattering, the multiplexing gain can be increased [7]. Moreover, we evaluated the MIMO channel capacity with variable adjacent antenna distances in different spaces enumerated.

The rest of this paper is organized as follows. In Section II the mathematical analysis of CSI matrix is performed. In section III the simulation environment is introduced. In section IV the MIMO channel capacity is simulated and analyzed for scenarios enumerated.

II. ANALYSIS FOR CSI MATRIX AND LOS MIMO CHANNEL CAPACITY DERIVATION

In this paper, assume the master, slave, and user have N_t antennas and the receiver that has N_r antennas, respectively, and omnidirectional antennas are used. Consider the CSI matrix for LoS condition between the transmitter and receiver [8]

$$\mathbf{H}_{\text{LoS}} = \begin{bmatrix} h_{11}^{\text{LoS}} & h_{12}^{\text{LoS}} & \cdots & h_{N_r N_t}^{\text{LoS}} \\ h_{21}^{\text{LoS}} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ h_{N_r 1}^{\text{LoS}} & \cdots & \cdots & h_{N_r N_t}^{\text{LoS}} \end{bmatrix} \tag{1}$$

where $1 \leq \{i, j\} \leq \min(N_t, N_r)$. Since the element h_{ij}^{LoS} of \mathbf{H}_{LoS} is affected by LoS distance, (1) can rewritten below in terms of LoS distance

$$\mathbf{H}_{\text{LoS}} = \begin{bmatrix} e^{-j\frac{2\pi}{\lambda}d_{11}} & e^{-j\frac{2\pi}{\lambda}d_{12}} & \cdots & e^{-j\frac{2\pi}{\lambda}d_{1N_r}} \\ e^{-j\frac{2\pi}{\lambda}d_{21}} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ e^{-j\frac{2\pi}{\lambda}d_{N_r 1}} & \cdots & \cdots & e^{-j\frac{2\pi}{\lambda}d_{N_r N_t}} \end{bmatrix} \tag{2}$$

where d_{ij} is the Euclidean distance between the i^{th} antenna of transmitter and the j^{th} antenna of receiver, and λ is the wave length of signal during transmission. To increase

MIMO channel capacity, Rician scatter waves are utilized, and therefore define the CSI matrix for LoS MIMO as [8]

$$\mathbf{H} = \sqrt{\frac{K}{K+1}} \mathbf{H}_{LoS} + \sqrt{\frac{1}{K+1}} \mathbf{H}_{Scat} \quad (3)$$

where K is the Rician K -factor and $\mathbf{H}_{Scat} \in C^{N_r \times N_t}$ in which the element $h_{ij}^{Scat} \sim CN(0,1)$. Therefore, the element of \mathbf{H} , say h_{ij} , is calculated by below

$$h_{ij} = \sqrt{\frac{K}{K+1}} h_{ij}^{LoS} + \sqrt{\frac{1}{K+1}} h_{ij}^{Scat} \quad (4)$$

then the MIMO channel capacity is defined as

$$C = \log_2 \left(\mathbf{I}_{N_r} + \frac{\rho}{N_t} \mathbf{H} \mathbf{H}^* \right) \quad (5)$$

where ρ is the averaged signal-to-noise ratio (SNR) along the $N_r \times N_t$ LoS paths arriving at the receiver and the superscript $*$ denotes the Hermitian transpose. Then (5) can be rewritten as

$$C = \log_2 \left(\begin{array}{cc} 1 + \frac{\rho}{N_t} (|h_{11}|^2 + |h_{12}|^2) & \frac{\rho}{N_t} (h_{11} h_{21}^* + h_{12} h_{22}^*) \\ \frac{\rho}{N_t} (h_{21} h_{11}^* + h_{22} h_{12}^*) & 1 + \frac{\rho}{N_t} (|h_{21}|^2 + |h_{22}|^2) \end{array} \right) \quad (6)$$

In this paper, 2×2 MIMO is considered (i.e., $N_r = N_t = 2$).

Given the fact that $|h_{ij}|^2 = 1 \quad \forall i, j$, then

$$C = \log_2 \left(\begin{array}{cc} 1 + \rho & \frac{\rho}{2} (h_{11} h_{21}^* + h_{12} h_{22}^*) \\ \frac{\rho}{2} (h_{21} h_{11}^* + h_{22} h_{12}^*) & 1 + \rho \end{array} \right) \quad (7)$$

By performing the complex multiplication with the characteristic of $h_{ij} h_{ij}^* = 1$, we have

$$C = \log_2 (1 + 2\rho + \frac{\rho^2}{2} [1 - \text{Re}\{h_{11} h_{22} (h_{21} h_{12})^*\}]) \quad (8)$$

Further, from (8) we observe that C is always periodical regardless of d_{ij} because the term $\text{Re}\{h_{11} h_{22} (h_{21} h_{12})^*\}$ can actually be represented by cosine function, that is,

$$C = \log_2 (1 + 2\rho + \frac{\rho^2}{2} [1 - \cos(\theta)]) \quad (9)$$

where θ is the phase of the term $h_{11} h_{22} (h_{21} h_{12})^*$.

III. SIMULATION ENVIRONMENT

In this paper, in order to prove that the use of DAS-oriented relay can outperform the regular MIMO relay in the aspect of downlink MIMO channel capacity, here we evaluated the LoS MIMO channel capacity of WDS function within an L-shaped hallway where both master and user are located at the edge and the slave locates at the corner. The simulation environment is shown in Fig. 1. The L-shaped hallway is built with 10-cm thick brick walls that block the direct path between master and user. The width of the hallway is 5 meters. In order to evaluate the MIMO channel capacity with different hallway sizes, we let the horizontal hallway length L be variable and up to 50 meters, whereas

the vertical length W is fixed to 50 meters. Denote D the fixed adjacent antenna distance of both master and user, and denote D_s the adjacent antenna distance of slave. Apart from the direct path between master and user, the use of relay (i.e., WDS slave) can improve RSS at user side. Moreover, after applying DAS to the slave by changing D_s along the diagonal line of the corner, the MIMO channel capacity can be increased. The height of master, slave, and user are 5, 3, and 1.5 meters, respectively. The plane coordinates of antennas are symmetric and shown in Table I.

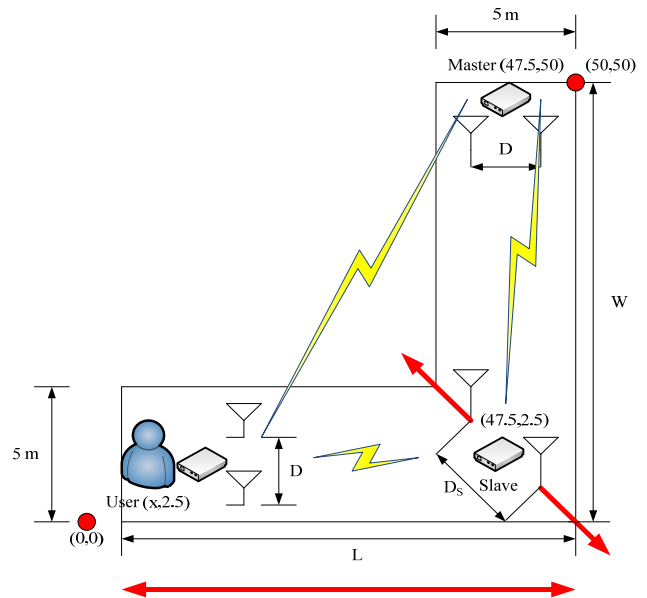


Fig. 1 Simulation environment.

TABLE I
THE PLANE COORDINATES OF ANTENNAS

Antenna	Horizontal coordinate (meters)	Vertical coordinate (meters)
Master1	$47.5 - D/2$	50
Master2	$47.5 + D/2$	50
Master (SISO)	47.5	50
Slave1	$47.5 - D_s/2\sqrt{2}$	$2.5 + D_s/2\sqrt{2}$
Slave2	$47.5 + D_s/2\sqrt{2}$	$2.5 - D_s/2\sqrt{2}$
Slave (SISO)	47.5	2.5
User1	$50 - L$	$2.5 + D/2$
User2	$50 - L$	$2.5 + D/2$
User (SISO)	$50 - L$	2.5

With the coordinates above, the Euclidean distances between transmitting antenna and receiving antenna can be calculated, and thus the downlink LoS CSI matrix \mathbf{H}_{LoS} along the master-to-user path, master-to-relay path, and relay-to-user path, can be obtained respectively. After considering the Rician scattering, the channel capacity along each path will be compared, and thus we can obtain the optimal location of slave regarding different hallway sizes.

During the downlink transmission, the free space path loss (i.e., Friis Law) is considered, and the shadowing loss made

by the brick walls is assumed 1 dB/cm. Since there are two brick walls along the master-to-user path, the total shadowing loss is 20 dB. The specification of devices is shown in Table II, in which the transmit power complies the IEEE 802.11n standard, and only IEEE 802.11n Greenfield mode is assumed. In Fig. 1, there are two phases during the downlink transmission of the WDS function. At the first phase (i.e., broadcast phase), the master broadcasts signal to both slave and user, and at the second phase (i.e., cooperative phase), the user combines signal transmitted from both master and slave. While comparing MIMO channel capacity between the master-to-slave path and slave-to-user path during simulation, the weaker one actually limits the entire master-slave-user path, thus we analyzed minimum MIMO channel capacity performance using slave, in addition, we also compared such results to the MIMO and single input single output (SISO) cases along the master-to-user path, respectively.

TABLE II
SPECIFICATION OF DEVICES

Device	Transmit power (dBm)	Gain of each antenna (dBi)	Antenna type	Antenna height (m)
Master (MIMO)	14	2	Omni	5
Master (SISO)	17	2	Omni	5
Slave (MIMO)	10	2	Omni	3
User (MIMO)	n/a	2	Omni	1.5

IV. MIMO CHANNEL CAPACITY PERFORMANCE EVALUATION

TABLE III
PHYSICAL PARAMETERS

Parameter	Value
Frequency	2.4 GHz
λ	0.125 m
Wi-Fi Bandwidth	40 MHz
Temperature	27 °C
Thermal noise	-97.9794 dBm
D	20λ
D_s	$1\lambda \sim 56\lambda$
W	50 m
L	W/5, W/2, 2W/3, W
Rician K-factor (K)	20 dB

In this paper, we evaluate the LoS MIMO channel capacity with variables D_s and L. The maximum length of D_s is 56λ , where λ is the wave length. The thermal noise is used for calculating received SNR. The physical parameters are shown in Table III. The Monte-Carlo run is conducted to

evaluate the ergodic channel capacity by randomly generating 1,000 times the scattering matrices for each path.

A. MIMO channel capacity when $L:W=1:1$

The channel capacity versus adjacent antenna distance is shown in Fig. 2. We have observations below. First, regarding the master-to-user path, the channel capacity using regular MIMO is approximately 73% improved from that using SISO. Second, in the case of $L:W=1:1$, since the transmit power of master is larger than that of slave, the channel capacity along the master-to-slave path is approximately 1.09 times larger than that along the slave-to-user path, and we say the slave-to-user path limits the overall channel capacity performance along the master-slave-user path. Third, by referring (9), the MIMO channel capacity along the master-to-slave path and slave-to-user path are periodical and being improved approximately 94% and 107% in maximum respectively than that along the master-to-user path in MIMO case.

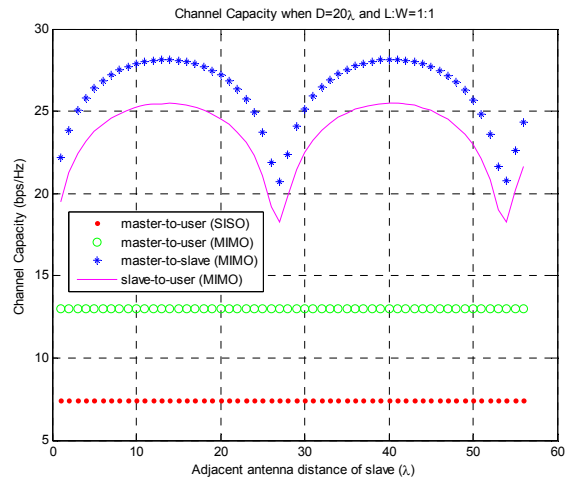


Fig. 2 Adjacent antennas distance vs. channel capacity when $L:W=1:1$

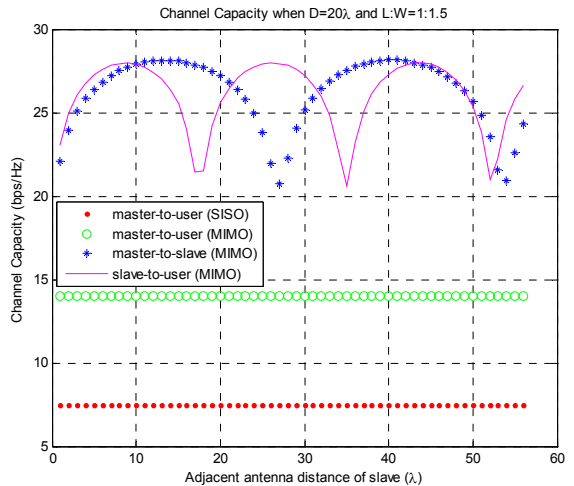


Fig. 3 Adjacent antennas distance vs. channel capacity when $L:W=1:1.5$

B. MIMO channel capacity when $L:W=1:1.5$

The channel capacity versus adjacent antenna distance is shown in Fig. 3. Since the distance between slave and user is shortened, the peak channel capacity values along the master-to-slave path and slave-to-user path are very close, and the period of the channel capacity along slave-to-user path is shortened. The MIMO channel capacity using slave is approximately 102% improved in maximum than that along the master-to-user path in MIMO case.

C. MIMO channel capacity when $L:W=1:2$

The channel capacity versus adjacent antenna distance is shown in Fig. 4. In such case the peak channel capacity along the slave-to-user path is approximately 1.05 times greater than that along the master-to-slave path, and we say the master-to-slave path limits most of the channel capacity performance along the master-slave-user path. We observe that the period of the channel capacity along slave-to-user path is further shortened.

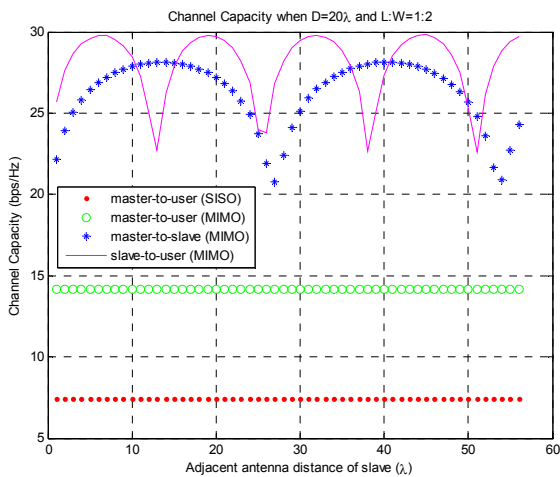


Fig. 4 Adjacent antennas distance vs. channel capacity when $L:W=1:2$

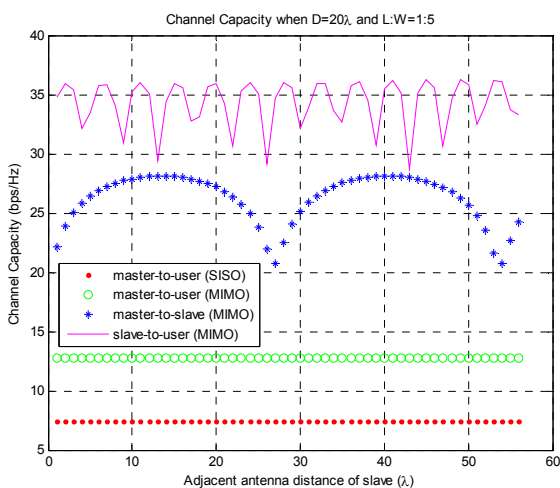


Fig. 5 Adjacent antennas distance vs. channel capacity when $L:W=1:5$

D. MIMO channel capacity when $L:W=1:5$

The channel capacity versus adjacent antenna distance is shown in Fig. 5. We observe that although the MIMO channel capacity along the master-slave-user path is absolutely limited by the master-to-slave path, the MIMO channel capacity along the master-to-slave path is still approximately 115% more in maximum than that along the master-to-user path in MIMO case. We also conclude that as the horizontal length L is shortened, the MIMO channel capacity along the slave-to-user is enlarged and meanwhile the period is shortened.

V. CONCLUSION

In this paper, we adopted DAS to the slave of the WDS function to increase the LoS MIMO channel capacity with consideration of scattering. The simulation results show that the use of slave can certainly increase MIMO channel capacity. By appropriated selecting adjacent antenna distance of slave while deploying the distributed antenna system, the optimal MIMO channel capacity can be achieved in indoor LoS environment.

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