Direct/Cooperative AF Relay Switching Using Spectrum Division/Adaptive Subcarrier Allocation For SC-FDMA Uplink

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***Abstract*— In this paper, we propose a direct/cooperative amplify-and-forward relay (D/AR) switching using a spectrum division/adaptive subcarrier allocation (SDASA) for increasing the uplink capacity of single carrier-frequency division multiple access (SC-FDMA). In the D/AR switching, switching between direct communication and cooperative AF relay is done so that the channel capacity is maximized. In the SDASA, the transmit SC signal spectrum is divided into sub-blocks, to each of which a different set of subcarriers (resource block) is adaptively allocated. We evaluate the achievable channel capacity by the Monte-Carlo numerical computation method. It is shown that the proposed D/AR switching can reduce the transmit power by about 4 (2) dB compared to the direct communication (the cooperative AF relay) for the 1% - outage capacity of 4.0bps/Hz. Also shown is that the D/AR switching using SDASA can further reduce the transmit power by about 2dB compared to the D/AR switching without SDASA.**

Keywords-component; Cooperative AF relay, SC-FDMA, Spectrum division/adaptive subcarrier allocation

I. INTRODUCTION

In the next generation mobile communication systems, broadband data services are demanded. However, very high transmit power is required due to the propagation path loss and the shadowing loss as well as frequency-selective fading. Cooperative relay has been attracting much attention to solve this transmit power problem [1]-[3].

In 2 time-slot uplink cooperative relay, a base station (BS) receives the same signal from mobile terminal (MT) in the first time-slot and relay station (RS) in the second time-slot and combines them to obtain the spatial diversity gain. Since the MT-RS distance is in most cases shorter than that the MT-BS distance, the average received signal power can be increased significantly. In the past, several cooperation protocols have been proposed [1]; among most popular relaying protocols are amplify-and-forward (AF) and decode-and-forward (DF). The achievable channel capacity of the cooperative AF relay was discussed in [2], [3].

In our previous paper [4], we proposed a spectrum division/adaptive subcarrier allocation (SDASA) for cooperative AF relay using single carrier-frequency division multiple access (SC-FDMA). In the SDASA, the SC frequency domain signal is divided into sub-blocks (each sub-blocks consists of several consecutive subcarriers), to each of which a different set of subcarriers (resource block) is adaptively allocated based on the channel state information (CSI) so that the achievable channel capacity can be maximized. It was shown [4] that the SDASA provides the higher outage capacity than a localized subcarrier allocation scheme [5]. However, the achievable channel capacity of the cooperative relay is upper limited to half the direct communication, because RS and MS need to use orthogonal channels (i.e., 2 time-slots) for their transmissions without interference.

In this paper, we propose a direct/cooperative AF relay (D/AR) switching using the SDASA. In the D/AR switching, switching from the cooperative AF relay to the direct communication is done when the direct communication can achieve larger channel capacity than the cooperative AF relay. We evaluate the uplink channel capacity of the proposed D/AR switching using SDASA by the Monte-Carlo numerical computation method.

The rest of this paper is organized as follows. Section II presents the system model. Section III derives a channel capacity expression for the D/AR switching using SDASA. Section IV describes the principle operation of SDASA and relay selection. Section V discusses the simulation results on the channel capacity of the D/AR switching using SDASA. Section VI concludes the paper.

II. SYSTEM MODEL

We consider the SC-FDMA uplink transmission using cooperative AF relay in a single-cell and a single-user environment. Figure 1 shows the system model considered in this paper. K relays are located in a cell. The AF strategy is used for the cooperative relay. The cell radius is denoted by R. The distances between MT and BS, between MT and the i-th RS (denoted by RS_i), and between the RS_i and BS are denoted by R_{MB}, R_{Mi}, and R_{iB}, respectively. The channel is assumed to be an L-path frequency-selective block Rayleigh fading channel. SC-FDMA is a block transmission. It is assumed that the channel stays constant during transmission of a symbol block and the maximum delay of the channel is shorter than the cyclic prefix (CP) length.

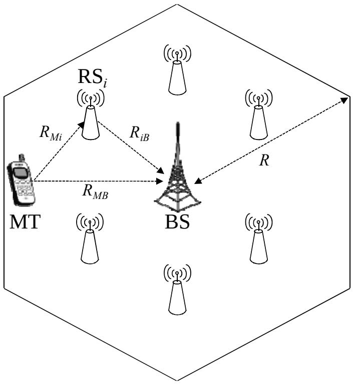


Fig. 1 System model.

III. DIRECT/COOPERATIVE AF RELAY SWITCHING

A total number of subcarriers available in the system is denoted by N_c and are divided into resource blocks of M/D consecutive subcarriers each. Therefore, the number of resource blocks is $N_c/(M/D)$. In this paper, each user is assumed to transmit an M-symbol block. Before the transmission, the symbol block to be transmitted is transformed by M-point discrete Fourier transform (DFT) into the frequency-domain signal consisting of M frequency components, which is then divided into D sub-blocks of M/D components each. D different resource blocks are allocated based on the channel condition. An example of the SDASA with (M, D, N_c)=(8, 4, 16) is illustrated in Fig. 2.

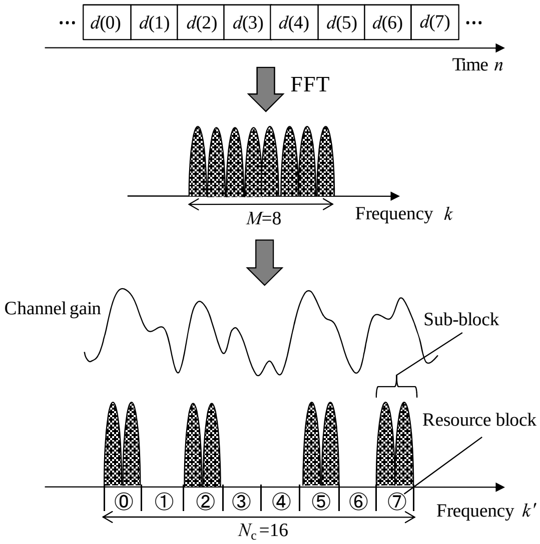


Fig. 2 An example of SDASA with $(M, D, N_c) = (8, 4, 16)$.

In D/AR switching, direct communication and cooperative AF relay are switched so that larger channel capacity is obtained. The details of SDASA and relay selection are described in Sect. IV. Below, we assume that SDASA has already been performed and the RS$_i$ is selected for cooperative AF relay. The sample-spaced discrete-time signal representation is used.

A. Direct communication

In the direct communication, the received signal power $P_{r,MB}^{DC}$ at BS is expressed as

$$P_{r,MB}^{DC} = \overline{P}_T \cdot r_{MB}^{-\alpha} \cdot 10^{-\eta/10}, \tag{1}$$

where $\overline{P}_T = P_T \cdot R^{-\alpha}$ is the MT normalized transmit power with P_T being the MT transmit power and α being the path loss exponent, $r_{MB} = R_{MB}/R$ is the normalized distance, and η is the shadowing loss in dB.

The frequency-domain received signal $Y_{MB}^{DC}(k)$ at BS can be expressed as

$$Y_{MB}^{DC}(k) = \sqrt{2P_{r,MB}^{DC}}H_{MB}(k)S(k) + N_{MB}(k), \tag{2}$$

where $S(k)$ is the k-th frequency component of the MT transmit block. $H_{MB}(k)$ and $N_{MB}(k)$ are respectively the channel gain and the zero-mean noise component having the variance $2N$ for the MT-BS link.

B. Cooperative relay

The cooperative AF relay using 2 time-slots [6]-[8] is considered. As shown in Fig. 3, in the first time-slot, MT broadcasts to both BS and RS; in the second time-slot, RS transmits an amplified version of its received signal to BS.

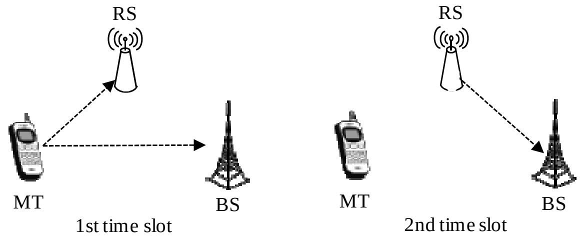


Fig. 3 Cooperative AF relay.

The received signal powers, $P_{r,MB}^{CR}$ and $P_{r,Mi}^{CR}$, at BS and RS$_i$ in the first time-slot are respectively given as

$$\begin{cases} P_{r,MB}^{CR} = \overline{P}_{t,M} \cdot r_{MB}^{-\alpha} \cdot 10^{-\eta/10} \\ P_{r,Mi}^{CR} = \overline{P}_{t,M} \cdot r_{Mi}^{-\alpha} \cdot 10^{-\eta/10} \end{cases}, \tag{3}$$

where $\overline{P}_{t,M} = P_{t,M} \cdot R^{-\alpha}$ and $r_{Mi} = R_{Mi}/R$. $\overline{P}_{t,M}$ is the normalized transmit power with $P_{t,M}$ being the MT transmit power in the cooperative AF relay and r_{Mi} is the normalized distance between MT and RS$_i$.

The frequency-domain signals, $Y_{MB}^{CR}(k)$ and $Y_{Mi}^{CR}(k)$, respectively received at BS and RS$_i$ in the first time-slot can be expressed as

$$\begin{cases} Y_{MB}^{CR}(k) = \sqrt{2P_{r,MB}^{CR}}H_{MB}(k)S(k) + N_{MB}(k) \\ Y_{Mi}^{CR}(k) = \sqrt{2P_{r,Mi}^{CR}}H_{Mi}(k)S(k) + N_{Mi}(k) \end{cases}, \tag{4}$$

where $H_{Mi}(k)$ and $N_{Mi}(k)$ are the channel gain and the zero-mean noise component having the variance $2N$ at the k-th subcarrier for the MT-RS$_i$ link, respectively.

The received signal is re-transmitted by RS$_i$ at the π_k-th subcarrier in the second time-slot. The received signal $Y_{iB}^{CR}(\pi_k)$ at BS in the second time-slot can be expressed as

$$\begin{aligned} Y_{iB}^{CR}(\pi_k) &= \sqrt{2P_{r,Mi}^{CR}\cdot 2P_{r,iB}^{CR}}\,H_{iB}(\pi_k)H_{Mi}(k)S(\pi_k) \\ &\quad + \sqrt{2P_{r,iB}^{CR}}\,H_{iB}(\pi_k)N_{Mi}(k) + N_{iB}(\pi_k) \end{aligned} \tag{5}$$

with

$$P_{r,iB}^{CR} = \beta_i \overline{P}_{t,i} r_{iB}^{-\alpha} 10^{-\eta/10}, \tag{6}$$

where $\overline{P}_{t,i} = P_{t,i}\cdot R^{-\alpha}$ is the normalized transmit power with $P_{t,i}$ being the RS$_i$ transmit power, $r_{iB} = R_{iB}/R$ is the normalized distance between RS$_i$ and BS. $H_{iB}(\pi_k)$ and $N_{iB}(\pi_k)$ are respectively the channel gain and the zero-mean noise component having the variance $2N$ at the π_k-th subcarrier for the RS$_i$-BS link.

β_i in Eq. (6) is the normalization factor for RS$_i$, given as

$$\beta_i = \frac{1}{\mathrm{E}\{|Y_{Mi}^{CR}(k)|^2\}} = \frac{1}{2P_{r,Mi}^{CR}\sum_{k=0}^{N_c-1}\tau_{i,k}^{CR}\frac{|H_{Mi}(k)|^2}{M} + 2N}, \tag{7}$$

where $\tau_{i,k}^{CR}$ takes 0 or 1 (“$\tau_{i,k}^{CR}$ =1” indicates that the k-th subcarrier is allocated in the first time slot and 0 otherwise).

For the fairness of comparison with the direct communication case (no relay), the sum of transmit powers of MT and RS$_i$ is set to

$$\overline{P}_{t,M} + \overline{P}_{t,i} = \overline{P}_T\,. \tag{8}$$

C. Channel capacity

The channel capacities, $C^{DC}(k)$ and $C_i^{CR}(k)$, at the k-th subcarrier for the direct communication and the cooperative AF relay using RS$_i$ are respectively given from [6], [9] as

$$\begin{cases} C^{DC}(k) = \log_2\left(1 + \dfrac{P_{r,MB}^{DC}}{N}\left|H_{MB}(k)\right|^2\right) \\ C_i^{CR}(k) = \dfrac{1}{2}\log_2\left(1 + \dfrac{P_{r,MB}^{CR}}{N}\left|H_{MB}(k)\right|^2 \right. \\ \qquad\qquad \left. + \dfrac{\dfrac{P_{r,Mi}^{CR}}{N}\left|H_{Mi}(k)\right|^2\cdot\dfrac{P_{r,iB}^{CR}}{N}\left|H_{iB}(\pi_k)\right|^2}{\dfrac{P_{r,Mi}^{CR}}{N}\sum_{k'=0}^{N_c-1}\tau_{i,k'}^{CR}\dfrac{\left|H_{Mi}(k')\right|^2}{M} + \dfrac{P_{r,iB}^{CR}}{N}\left|H_{iB}(\pi_k)\right|^2 + 1}\right) \end{cases}. \tag{9}$$

The channel capacities, C^{DC} and C_i^{CR}, for the direct communication and the cooperative AF relay using RS$_i$ can be respectively given as

$$\begin{cases} C^{DC} = \dfrac{1}{D}\sum_{m=0}^{\frac{N_c}{M/D}-1}\tau_m^{DC,Blk}C^{DC,Blk}(m) \\ C_i^{CR} = \dfrac{1}{D}\sum_{m=0}^{\frac{N_c}{M/D}-1}\tau_{i,m}^{CR,Blk}C_i^{CR,Blk}(m,\pi_m^{Blk}) \end{cases}, \tag{10}$$

where $\tau_m^{DC,Blk}$ and $\tau_{i,m}^{CR,Blk}$ takes 0 or 1 (“$\tau_m^{DC,Blk}$ =1” and “$\tau_{i,m}^{CR,Blk}$ =1” indicate that the m-th resource block is allocated and 0 otherwise). $C^{DC,Blk}(m)$, m=0~$N_c/(M/D)-1$, is the channel capacity of the m-th resource block consisting of consecutive M/D subcarriers for the direct communication, $C_i^{CR,Blk}(m,\pi_m^{Blk})$ is the channel capacity of the cooperative AF relay using RS$_i$ for a pair of the m-th resource block on the MT-RS$_i$ link and the π_m^{Blk}-th resource block on the RS$_i$-BS link. $C^{DC,Blk}(m)$ and $C_i^{CR,Blk}(m,\pi_m^{Blk})$ are respectively given as

$$\begin{cases} C^{DC,Blk}(m) = \dfrac{1}{M/D}\sum_{k=(M/D)m}^{(M/D)(m+1)-1}C^{DC}(k) \\ C_i^{CR,Blk}(m,\pi_m^{Blk}) = \dfrac{1}{M/D}\sum_{k=(M/D)m}^{(M/D)(m+1)-1}C_i^{CR}(k) \end{cases}, \tag{11}$$

The channel capacity of the D/AR switching C^{SW} is given by

$$C^{SW} = \max\{C^{DC}, C_i^{CR}\}, \tag{12}$$

IV. SDASA & RELAY SELECTION METHOD

A. SDASA

In this paper, the SDASA is performed by full-search to find the best combination of the resource blocks to maximize the channel capacity.

Our aim is to maximize the channel capacity C^{SW} given by Eq. (12). The maximization problem can be written as

$$\begin{aligned} &\left\{\tau_m^{DC,Blk}, \tau_{i,m}^{CR,Blk}\right\} = \underset{\tau_m^{DC,Blk},\tau_{i,m}^{CR,Blk}}{\arg}\ \max C^{SW} \\ &s.t. \begin{cases} \tau_m^{DC,Blk}, \tau_{i,m}^{CR,Blk} \in \{0,1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau_m^{DC,Blk} = \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau_{i,m}^{CR,Blk} = D \end{cases} \end{aligned}. \tag{13}$$

C^{DC} and C_i^{CR} in C^{SW} depend on $\tau_m^{DC,Blk}$ and $\tau_{i,m}^{CR,Blk}$, respectively. Therefore, Eq. (13) can be rewritten as

$$\begin{cases} \tau_m^{DC,Blk} = \arg\max_{\tau_m^{DC,Blk}} C^{DC} \\ \tau_{i,m}^{CR,Blk} = \arg\max_{\tau_{i,m}^{CR,Blk}} C_i^{CR} \end{cases} \quad . \qquad (14)$$

$$s.t. \begin{cases} \tau_m^{DC,Blk}, \tau_{i,m}^{CR,Blk} \in \{0,1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1} \tau_m^{DC,Blk} = \sum_{m=0}^{\frac{N_c}{M/D}-1} \tau_{i,m}^{CR,Blk} = D \end{cases}$$

In this paper, the values of $\tau_m^{DC,Blk}$ and $\tau_{i,m}^{CR,Blk}$ are determined independently using Eq. (14) by full-search.

B. *Relay selection*

The best relay which provides the maximum channel capacity is selected among *K* relays. The relay selection method is as follows. First, SDASA is done for each RS as

$$\tau_{i,m}^{CR,Blk} = \arg\max_{\tau_{i,m}^{CR,Blk}} C_i^{CR}$$

$$s.t. \begin{cases} \tau_{i,m}^{CR,Blk} \in \{0,1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1} \tau_{i,m}^{CR,Blk} = D \end{cases} \qquad \textit{for all } i. \qquad (15)$$

Then, the best relay is selected as

$$i = \arg\max_i C_i^{CR} \, . \qquad (16)$$

V. NUMERICAL EVALUATION

We evaluate the distribution of channel capacity by Monte-Carlo numerical computation method. The numerical evaluation conditions are summarized in Table 1. The MT is assumed to be randomly located in a cell. The channel is an *L*=16 path frequency-selective block Rayleigh fading channel. *K*=6 relays are located in a concentric pattern as shown in Fig. 1. The normalized distance between RS$_i$ and BS is set to $r_{iB} = 0.5$. $M = 64$ subcarriers out of $N_c = 128$ subcarriers are given to the user for the signal transmission. *M*=64 subcarriers are divided into *D*=4 sub-blocks. In the cooperative AF relay, the total transmit power is equally allocated to MT and RS$_i$ as

$$\overline{P}_{t,M} = \overline{P}_{t,i} = \overline{P}_T / 2 \, . \qquad (17)$$

Links of MT-BS and MT-RS are assumed to suffer from independent shadowing. Since RSs are stationary, the received SNR Γ_{iB} of the RS$_i$-BS link is kept constant and is given by

$$\Gamma_{iB} = 10\log_{10} \overline{P}_{t,i} r_{iB}^{-\alpha} / N + \Delta \ \text{(dB)}, \qquad (18)$$

where Δ is related to the shadowing loss and is a design parameter to determine the RS location. In this paper, each RS is located at a position which provides $\Delta = 0$ dB (i.e., in practice, the position which provides $\Delta = 0$ dB can be easily determined by slightly changing the position of RS).

Table 1 Numerical evaluation conditions.

Fading type	Block Rayleigh fading
Power delay profile	Uniform
No. of paths	*L*=16
No. of users	*U*=1
No. of relays	*K*=6
Normalized distance RS$_i$-BS	r_{iB}=0.5
No. of total subcarriers	N_c=128
No. of subcarriers per user	*M*=64
No. of divided SC spectra	*D*=4
Path loss exponent	α=3.5
Shadowing standard deviation	σ=7.0(dB)
Average received SNR RS$_i$-BS	$\Gamma_{iB} = 10\log_{10} \overline{P}_{t,i} r_{iB}^{-\alpha} / N$ (dB)
Power allocation (for cooperative AF relay)	Equal power allocation $(\overline{P}_{t,M} = \overline{P}_{t,i} = \overline{P}_T / 2)$

A. *Capacity improvement due to D/AR swithcing*

Figure 4 shows the 1% - and 50% - outage capacities of the D/AR switching (SDASA is not used for D/AR switching), where the *x*% - outage capacity is the one below which the channel capacity falls with probability of *x*%. One resource block, which consists of *M*=64 consecutive subcarriers, is allocated to a user randomly. For comparison, outage capacities of the direct communication and the cooperative AF relay are also plotted in Fig. 4. It can be seen from Fig. 4 that the D/AR switching can reduce the transmit power compared to the direct communication and the cooperative AF relay. For 1% - outage capacity of 4.0bps/Hz, the transmit power can be reduced by about 4dB compared to direct communication and by about 2dB compared to cooperative AF relay. It is interesting to note that D/AR switching and direct communication provide almost the same 50% - outage capacity while cooperative AF relay provides much lower capacity. Since this capacity can be achieved when the MT-BS distance is shorter (i.e., a better link quality) than the MT-RS-BS distance and hence relaying is not advantageous. In such a case, the use of cooperate relay reduces the capacity and thus, D/AR switching chooses the direct communication.

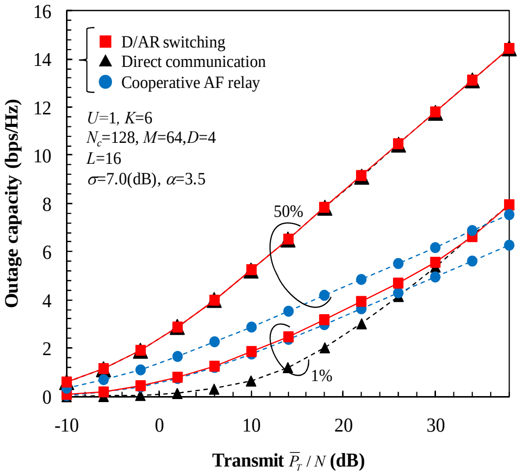
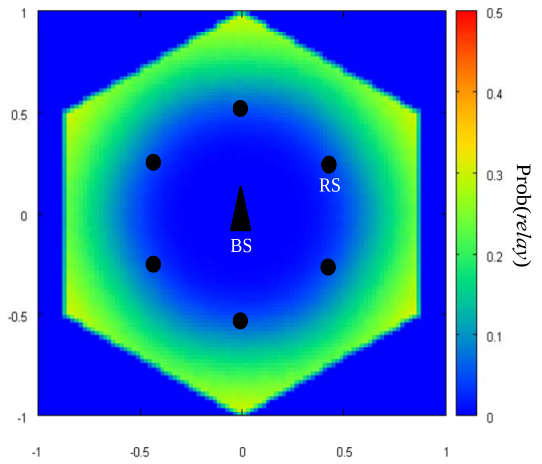


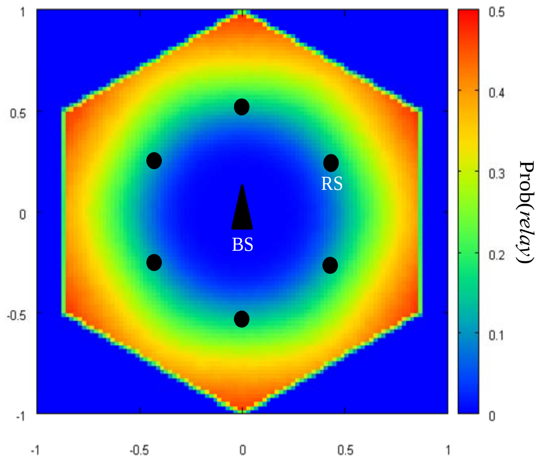
Fig. 4 Capacity improvement due to D/AR switching.

B. *Spatial distribution of relaying probability*

Figure 5 shows how the probability, Prob(*relay*), of the use of relaying is distributed within a cell. It can be seen from the figure that relaying probability increases as MT approaches the cell edge; when the transmit SNR=10dB, the relaying probability becomes 0.30 at the cell edge. It should be noted that when reducing the transmit SNR, the relaying probability increases; when the transmit SNR=0dB, the relaying probability increases to 0.46.



(a) Transmit $\overline{P}_T / N = 10$ dB



(b) Transmit $\overline{P}_T / N = 0$ dB

Fig. 5 Spatial distribution of relaying probability.

C. *Additional capacity improvement due to SDASA.*

Figure 6 shows the 1% - and 50% - outage capacities of the D/AR switching jointly used SDASA. For comparison, outage capacities of the D/AR switching without SDASA are also plotted in Fig. 6. It can be seen from Fig. 6 that the use of SDASA can further reduce the transmit power compared to the D/AR switching without SDASA. The transmit power can be reduced by about 2dB for both the 1% - and 50% - outage capacities of 4.0bps/Hz compared to the D/AR switching without SDASA. This is because the frequency diversity gain can be obtained by SDASA.

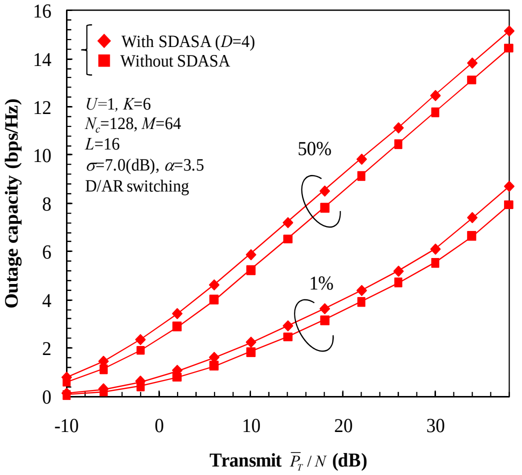


Fig. 6 Additional capacity improvement due to SDASA.

VI. CONCLUSION

In this paper, we proposed the D/AR switching using SDASA for SC-FDMA and evaluated channel capacity. We showed that the D/AR switching can reduce transmit power by about 4 (2) dB compared to the direct communication (the cooperative AF relay) for the 1% - outage capacity of 4.0bps/Hz. We also showed that the D/AR switching using SDASA can further reduce the transmit power by about 2dB compared to the D/AR switching without SDASA. The proposed SDASA in this paper assumes the full-search and therefore, requires very high computational complexity. The complexity reduction of the proposed SDASA is left as our future work.

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