PAPER

Outage Channel Capacity of Direct/Cooperative AF Relay Switched SC-FDMA Using Spectrum Division/Adaptive Subcarrier Allocation

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SUMMARY In this paper, a direct/cooperative relay switched single carrier-frequency division multiple access (SC-FDMA) using amplify-and-forward (AF) protocol and spectrum division/adaptive subcarrier allocation (SDASA) is proposed. Using 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 according to the channel conditions of mobile terminal (MT)-relay station (RS) link, RS-base station (BS) link, and MT-BS link. Cooperative relay does not always provide higher capacity than the direct communication. Switching between direct communication and cooperative relay is done depending on the channel conditions of MT-RS, RS-BS, and MT-BS links. We evaluate the achievable channel capacity by the Monte-Carlo numerical computation method. It is shown that the proposed scheme can reduce the transmit power by about 6.0 (2.0) dB compared to the direct communication (the cooperative AF relay) for a 1%-outage capacity of 3.0 bps/Hz.

key words: *cooperative AF relay, SC-FDMA, spectrum division/adaptive subcarrier allocation*

1. Introduction

In the next generation mobile communication systems, broadband data services are demanded. However, the communication quality degrades due to propagation path loss, shadowing loss as well as frequency-selective fading. Cooperative relay has been attracting much attention to solve this problem [1]–[4].

In 2 time-slot uplink cooperative relaying, 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 and RS-BS links are in most cases much shorter than the MT-BS link, the average received signal power at the BS is significantly increased. Recently, several cooperation protocols have been proposed [1]; most popular relaying protocols are amplify-and-forward (AF) and decode-and-forward (DF). AF relay is much simpler and has less processing burden on the relay compared to DF relay [3], [4]. Therefore, in this paper, cooperative AF relay using 2 time-slots [5]–[7] is considered. The achievable channel capacity of the cooperative AF relay was discussed in [8], [9].

We proposed in [10] a spectrum division/adaptive subcarrier allocation (SDASA) for cooperative AF relay using single carrier-frequency division multiple access (SC-FDMA) [11]. In SDASA, the SC frequency domain signal is divided into sub-blocks (each sub-block 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 in [10] that the cooperative AF relay using SDASA provides higher outage capacity than a localized subcarrier allocation scheme [11]. However, the achievable channel capacity of the cooperative relay cannot exceed 50% of the capacity of direct communication, because RS and MS transmissions need to be orthogonal (i.e., 2 time-slots) [12], [13].

The direct communication may provide higher capacity if an MT is close to BS and the MT-BS link has a good channel condition. Therefore, the capacity is always reduced if relaying is employed irrespective of the channel conditions of MT-RS, RS-BS, and MT-BS links. In this paper, we propose a direct/cooperative relay switched SC-FDMA using AF protocol and SDASA to avoid the capacity loss. In the direct/cooperative relay switched SC-FDMA, switching from the cooperative relay to the direct communication is done when the direct communication can achieve larger channel capacity than the cooperative relay.

The aim of this paper is to develop an optimal and a suboptimal method for direct/cooperative relay switched SC-FDMA with SDASA that can maximize the channel capacity. The optimal method employs exhaustive search. The exhaustive search can maximize the channel capacity, but its complexity is unacceptably high. The suboptimal method has much lower complexity than the optimal method. Note that the evaluation of the channel capacities for the direct communication and the cooperative relay can be done individually. Therefore, the maximization problem of the channel capacity can be separated into two independent problems for the direct communication and the cooperative relay, respectively. Based on this, SDASA is performed independently for the direct communication and the cooperative AF relay. For the cooperative relay, the best combinations of the resource blocks are found according to the channel qualities of MT-RS and RS-BS links irrespective of the channel qual-

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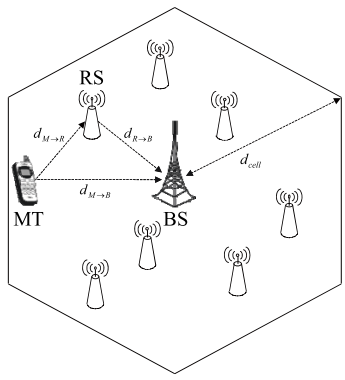


Fig. 1 System model.

ity of MT-BS link. We evaluate the uplink channel capacity of the proposed scheme by the Monte-Carlo numerical computation method.

The rest of this paper is organized as follows. Section 2 presents the system model. Section 3 derives a channel capacity expression for the direct/cooperative relay switched SC-FDMA. Section 4 describes the principle operation of SDASA. Section 5 discusses the simulation results on the channel capacity of the direct/cooperative relay switched SC-FDMA using SDASA. Section 6 concludes the paper.

2. System Model

The uplink transmission using SC-FDMA with N_c subcarriers is considered, which can accommodate up to U users (i.e., $M = N_c/U$ subcarriers are allocated to each user). For the performance evaluation, however, the single-user case is assumed.

Figure 1 shows the system model. K relays are located in a cell. The cell radius is denoted by d_{cell}. The distances between MT and BS, between MT and RS, and between RS and BS are denoted by $d_{M\to B}$, $d_{M\to R}$ and $d_{R\to B}$ ($R \in \{0, 1, \ldots, K-1\}$), 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.

3. Direct/Cooperative AF Relay Switching

N_c subcarriers of SC-FDMA are grouped into $U \times D$ resource blocks of M/D consecutive subcarriers each, where $N_c = M \times U$. In SDASA, the symbol block of M data symbols to be transmitted from a user 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 sub-blocks are mapped onto D different resource blocks based on the channel condition. As an example of U=2, SDASA with $(M, D, N_c) = (8, 4, 16)$ is illustrated in Fig. 2.

In the direct/cooperative relay switched SC-FDMA,

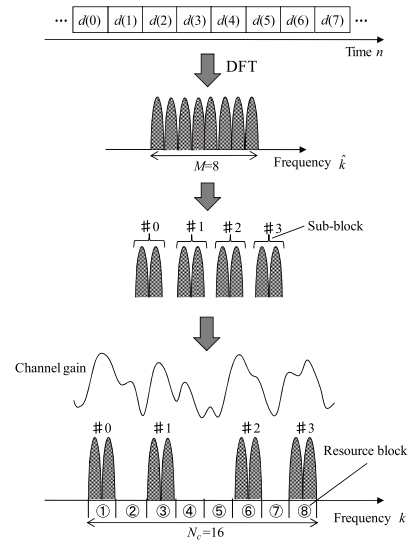


Fig. 2 SDASA with $(M, D, N_c) = (8, 4, 16)$.

either direct communication or cooperative relay, which achieves larger channel capacity, is selected. The channel capacity $C^{(SW)}$ of the direct/cooperative relay switched SC-FDMA is given as

$$C^{(SW)} = \max\{C^{(DC)}, C_R^{(CR)}\}, \tag{1}$$

where $C^{(DC)}$ and $C_R^{(CR)}$ are the channel capacities for the direct communication and the cooperative relay, respectively.

The relay selection is important for cooperative AF relay. The best relay R^* which provides the largest channel capacity is selected among K=6 relays as

$$R^* = \arg\max_R C_R^{(CR)}. \tag{2}$$

In the following, $C^{(DC)}$ and $C_R^{(CR)}$ are derived assuming that SDASA has been performed (the operation principle of SDASA is described in Sect. 4).

3.1 Direct Communication

In the direct communication, the received signal power $P_{r,M\to B}^{(DC)}$ at BS is expressed as

$$P_{r,M\to B}^{(DC)} = \bar{P}_T \cdot r_{M\to B}^{-\alpha} \cdot 10^{-\eta_{M\to B}/10}, \tag{3}$$

where $\bar{P}_T = P_T \cdot d_{cell}^{-\alpha}$ is the MT normalized transmit power with P_T being the MT transmit power and α being the path loss exponent, $r_{M\to B} = d_{M\to B}/d_{cell}$ is the normalized distance, and $\eta_{M\to B}$ is the shadowing loss between MT and BS in dB.

The frequency-domain received signal $\{Y_{M\to B}^{(DC)}(k);\ k = 0, \ldots, N_c - 1\}$ at BS can be expressed as

$$Y_{M\to B}^{(DC)}(k) = \sqrt{2P_{r,M\to B}^{(DC)}} H_{M\to B}(k) S(k) + N_{M\to B}(k), \tag{4}$$

where $S(k)$ is the k-th frequency component of the MT transmit block. $H_{M\to B}(k)$ and $N_{M\to B}(k)$ are respectively the channel gain and the zero-mean noise component having the

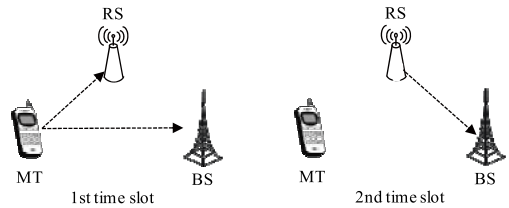


Fig. 3 Cooperative AF relay.

variance $2N$ for the MT-BS link.

3.2 Cooperative Relay

Cooperative AF relay protocol using 2 time-slots is illustrated in Fig. 3. MT broadcasts to both BS and RS in the first time-slot and RS transmits an amplified version of its received signal to BS in the second time-slot.

The received signal powers, $P^{(CR)}_{r,M\to B}$ and $P^{(CR)}_{r,M\to R}$, at BS and RS in the first time-slot are respectively given as

$$\begin{cases} P^{(CR)}_{r,M\to B} = \bar{P}_{t,M} \cdot r^{-\alpha}_{M\to B} \cdot 10^{-\eta_{M\to B}/10} \\ P^{(CR)}_{r,M\to R} = \bar{P}_{t,M} \cdot r^{-\alpha}_{M\to R} \cdot 10^{-\eta_{M\to R}/10} \end{cases}, \tag{5}$$

where $\bar{P}_{t,M} = P_{t,M} \cdot d^{-\alpha}_{cell}$ and $r_{M\to R} = d_{M\to R}/d_{cell}$. $\bar{P}_{t,M}$ is the normalized transmit power with $P_{t,M}$ being the MT transmit power in the cooperative AF relay, $r_{M\to R}$ is the normalized distance between MT and RS, and $\eta_{M\to R}$ is the shadowing loss between MT and RS in dB.

The frequency-domain signals, $\{Y^{(CR)}_{M\to B}(k);\ k = 0, \ldots, N_c - 1\}$ and $\{Y^{(CR)}_{M\to R}(k);\ k = 0, \ldots, N_c - 1\}$, respectively received at BS and RS in the first time-slot can be expressed as

$$\begin{cases} Y^{(CR)}_{M\to B}(k) = \sqrt{2P^{(CR)}_{r,M\to B}} H_{M\to B}(k) S(k) + N_{M\to B}(k) \\ Y^{(CR)}_{M\to R}(k) = \sqrt{2P^{(CR)}_{r,M\to R}} H_{M\to R}(k) S(k) + N_{M\to R}(k) \end{cases}, \tag{6}$$

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

The received signal is re-transmitted by RS at the k'-th subcarrier in the second time-slot. The received signal $\{Y^{(CR)}_{R\to B}(k, k');\ k, k' = 0, \ldots, N_c - 1\}$ at BS in the second time-slot can be expressed as

$$\begin{aligned} Y^{(CR)}_{R\to B}(k, k') = & \sqrt{2P^{(CR)}_{r,R\to B} \cdot 2P^{(CR)}_{r,M\to R}} H_{R\to B}(k') H_{M\to R}(k) S(k) \\ & + \sqrt{2P^{(CR)}_{r,R\to B}} H_{R\to B}(k') N_{M\to R}(k) + N_{R\to B}(k') \end{aligned} \tag{7}$$

with

$$P^{(CR)}_{r,R\to B} = \beta_R \bar{P}_{t,R} r^{-\alpha}_{R\to B} 10^{-\eta_{R\to B}/10}, \tag{8}$$

where $\bar{P}_{t,R} = P_{t,R} d^{-\alpha}_{cell}$ is the normalized transmit power with $P_{t,R}$ being the RS transmit power, $r_{R\to B} = d_{R\to B}/d_{cell}$ is the normalized distance between RS and BS, and $\eta_{R\to B}$ is the shadowing loss between RS and BS in dB. $H_{R\to B}(k')$ and $N_{R\to B}(k')$ are respectively the channel gain and the zero-mean noise component having the variance $2N$ at the k'-th subcarrier (for the RS-BS link).

β_R in Eq. (8) is the normalization factor for RS, given as

$$\begin{aligned} \beta_R &= \frac{1}{\mathrm{E}\{|Y^{(CR)}_{M\to R}(k)|^2\}} \\ &= \frac{1}{2P^{(CR)}_{r,M\to R} \sum_{k=0}^{N_c-1} \sum_{k'=0}^{N_c-1} \tau^{(CR)}_R(k, k') \frac{|H_{M\to R}(k)|^2}{M} + 2N}, \end{aligned} \tag{9}$$

where $\mathrm{E}\{\cdot\}$ denotes the average operation in the frequency domain. $\tau^{(CR)}_R(k, k')$ takes 0 or 1. "$\tau^{(CR)}_R(k, k') = 1$" indicates that the k-th subcarrier and k'-th subcarrier are allocated to the first time slot and the second time slot, respectively.

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

$$\bar{P}_{t,M} + \bar{P}_{t,R} = \bar{P}_T. \tag{10}$$

3.3 Channel Capacity

SDASA allocates D sub-blocks over $U \times D$ $(= N_c/(M/D))$ resource blocks of M/D consecutive subcarriers each. The channel capacities, $C^{(DC)}$ and $C^{(CR)}_R$, of Eq. (1) can be respectively expressed as

$$\begin{cases} C^{(DC)} = \frac{1}{D} \sum_{m=0}^{\frac{N_c}{M/D}-1} \tau^{(DC)}_{Blk}(m) C^{(DC)}_{Blk}(m) \\ C^{(CR)}_R = \frac{1}{2D} \sum_{m=0}^{\frac{N_c}{M/D}-1} \sum_{m'=0}^{\frac{N_c}{M/D}-1} \tau^{(CR)}_{Blk,R}(m, m') C^{(CR)}_{Blk,R}(m, m') \end{cases}, \tag{11}$$

where $\tau^{(DC)}_{Blk}(m)$ and $\tau^{(CR)}_{Blk,R}(m, m')$ takes 0 or 1. "$\tau^{(DC)}_{Blk}(m) = 1$" indicates that a sub-block is mapped onto the m-th resource block on the MT-BS link; "$\tau^{(CR)}_{Blk,R}(m, m') = 1$" indicates that a sub-block is mapped onto the m-th resource block in the first time slot and the m'-th resource block in the second time slot (an example is shown in Fig. 4, where $\tau^{(CR)}_{Blk,R}(m, m') = 0$ except for $\tau^{(CR)}_{Blk,R}(6, 5) = \tau^{(CR)}_{Blk,R}(1, 6) = \tau^{(CR)}_{Blk,R}(7, 2) = \tau^{(CR)}_{Blk,R}(4, 1) = 1$).

In Eq. (11), $C^{(DC)}_{Blk}(m)$ is the channel capacity for the m-th resource block for the direct communication and $C^{(CR)}_{Blk,R}(m, m')$ is the channel capacity for a pair of the m-th resource block in the first time slot and the m'-th resource block in the second time slot for the cooperative AF relay. Each resource block consists of consecutive M/D subcarriers. Therefore, $C^{(DC)}_{Blk}(m)$ and $C^{(CR)}_{Blk,R}(m, m')$ are respectively given as

$$\begin{cases} C^{(DC)}_{Blk}(m) = \frac{1}{M/D} \sum_{k=0}^{\frac{M}{D}-1} C^{(DC)}\left(m \cdot \frac{M}{D} + k\right) \\ C^{(CR)}_{Blk,R}(m, m') = \frac{1}{M/D} \sum_{k=0}^{\frac{M}{D}-1} C^{(CR)}_R\left(m \cdot \frac{M}{D} + k, m' \cdot \frac{M}{D} + k\right) \end{cases}, \tag{12}$$

where $C^{(DC)}(k)$ is the channel capacity of the k-th subcarrier for the direct communication and $C^{(CR)}_R(k, k')$ is the channel

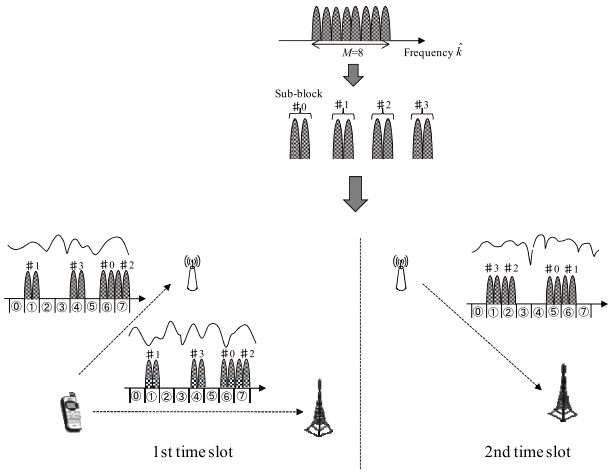


Fig. 4 An example of the SDASA for the cooperative relay assuming $(M, D, N_c) = (8, 4, 16)$.

capacity of a pair of the k-th subcarrier in the first time slot and the k'-th subcarrier in the second time slot for the cooperative AF relay. $C^{(DC)}(k)$ and $C_R^{(CR)}(k, k')$ are respectively given from [11], [14] as

$$\begin{cases} C^{(DC)}(k) = \log_2\left(1+\frac{P^{(DC)}_{r,M\to B}}{N}|H_{M\to B}(k)|^2\right) \\ C_R^{(CR)}(k,k') = \log_2\left(1+\frac{P^{(CR)}_{r,M\to B}}{N}|H_{M\to B}(k)|^2\right. \\ \left.+\frac{\frac{P^{(CR)}_{r,M\to R}}{N}|H_{M\to R}(k)|^2\cdot\frac{P^{(CR)}_{r,R\to B}}{N}|H_{R\to B}(k')|^2}{\frac{P^{(CR)}_{r,M\to R}}{N}\sum_{j=0}^{N_c-1}\sum_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}+\frac{P^{(CR)}_{r,R\to B}}{N}|H_{R\to B}(k')|^2+1}\right) \end{cases}. \quad (13)$$

4. SDASA

4.1 Optimal Method

According to the channel conditions of MT-RS-BS and MT-BS links, the best combination of the resource blocks which can maximize the channel capacity is chosen.

Our aim is to find the best combination of the resource blocks which can maximize the channel capacity $C^{(SW)}$ given by Eq. (1). The maximization problem can be written as

$$\left\{\tau^{(DC)}_{Blk}(m), \tau^{(CR)}_{Blk,R}(m,m')\right\} = \underset{\tau^{(DC)}_{Blk}(m),\tau^{(CR)}_{Blk,R}(m,m')}{\arg\max} C^{(SW)}$$
$$s.t.\begin{cases} \tau^{(DC)}_{Blk}(m),\ \tau^{(CR)}_{Blk,R}(m,m') \in \{0,\ 1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau^{(DC)}_{Blk}(m) = \sum_{m=0}^{\frac{N_c}{M/D}-1}\sum_{m'=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = D \\ \sum_{m'=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = 0\ or\ 1 \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = 0\ or\ 1 \end{cases}. \quad (14)$$

The third and fourth constraints in Eq. (14) indicate whether the m-th resource block in the first time slot and the m'-th resource block in the second time slot are allocated or not, respectively (the right hand side of the third constraint takes 1 if the m-th resource block in the first time slot is allocated and 0 otherwise; the right hand side of the fourth constraint takes 1 if the m'-th resource block in the second time slot is allocated and 0 otherwise).

To find the best combination of the resource blocks for the cooperative AF relay using optimal SDASA, the exhaustive search is required since both MT-BS and MT-RS-BS link conditions need to be taken into account (see Eqs. (11)~(13)). However, the complexity of the exhaustive search is unacceptably high. Therefore, we consider a suboptimal method which has low complexity in the next subsection.

4.2 Suboptimal Method

$C^{(DC)}$ and $C_R^{(CR)}$ depend on $\tau^{(DC)}_{Blk}(m)$ and $\tau^{(CR)}_{Blk,R}(m,m')$, respectively. Therefore, Eq. (14) can be separated into two independent problems and rewritten as

$$\begin{cases} \tau^{(DC)}_{Blk}(m) = \underset{\tau^{(DC)}_{Blk}(m)}{\arg\max} C^{(DC)} \\ s.t.\begin{cases} \tau^{(DC)}_{Blk}(m) \in \{0,\ 1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau^{(DC)}_{Blk}(m) = D \end{cases} \end{cases} \quad (15)$$

and

$$\begin{cases} \tau^{(CR)}_{Blk,R}(m,m') = \underset{\tau^{(CR)}_{Blk,R}(m,m')}{\arg\max} C_R^{(CR)} \\ s.t.\begin{cases} \tau^{(CR)}_{Blk,R}(m,m') \in \{0,\ 1\} \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\sum_{m'=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = D \\ \sum_{m'=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = 0\ or\ 1 \\ \sum_{m=0}^{\frac{N_c}{M/D}-1}\tau^{(CR)}_{Blk,R}(m,m') = 0\ or\ 1 \end{cases} \end{cases}. \quad (16)$$

The best combinations of the resource blocks for the direct communication and the cooperative relay can be found independently using Eqs. (15) and (16), respectively.

The cooperative AF relay is useful when the MT-BS link is poor. In this case, the MT-BS link contribution can be neglected for finding the best combination of the resource blocks in SDASA. This leads to the suboptimal SDASA. Below, we explain the suboptimal SDASA.

4.2.1 Determination of $\tau^{(DC)}_{Blk}(m)$

Since $C^{(DC)}(k)$ is monotonically increasing function of $|H_{M\to B}(k)|^2$, $C^{(DC)}$ can be maximized by allocating the resource blocks according to the descending order of the average channel gain over a resource block (hereafter denoted by "block averaged channel gain") on the MT-BS link. Therefore, we determine the value of $\tau^{(DC)}_{Blk}(m)$ using the following steps.

1). Evaluate the block averaged channel gains on the MT-BS link. The average channel gain $H_{Blk,M\to B}(m)$ of the m $(=0,1,\ldots,N_c/(M/D)-1)$-th resource block associated with the MT-BS link is given as

$$H_{Blk,M\to B}(m)=\frac{1}{M/D}\sum_{k=0}^{\frac{M}{D}-1}\left|H_{M\to B}\left(m\cdot\frac{M}{D}+k\right)\right|^2. \quad (17)$$

2). Sort the resource blocks according to the descending order of $H_{Blk,M\to B}(m)$. The sorted resource blocks are indexed as $\{x_{M\to B}(j);\ j=0,\ldots,N_c/(M/D)-1\}$.
3). Allocate D resource blocks according to $\{x_{M\to B}(j);\ j=0,\ldots,N_c/(M/D)-1\}$ as $\{\tau_{Blk}^{(DC)}(x_{M\to B}(j))=1;\ j=0,\ldots,D-1\}$ and $\{\tau_{Blk}^{(DC)}(x_{M\to B}(j))=0;\ j=D,\ldots,N_c/(M/D)-1\}$.

As an example, let's assume $(M,D,N_c)=(4,2,8)$. If $\{H_{Blk,M\to B}(0),H_{Blk,M\to B}(1),\ H_{Blk,M\to B}(2),\ H_{Blk,M\to B}(3)\}=\{8,12,10,9\}$, we have $\{x_{M\to B}(0),\ x_{M\to B}(1),\ x_{M\to B}(2),\ x_{M\to B}(3)\}=\{1,2,3,0\}$. As a consequence, the resource block allocation results in $\{\tau_{Blk}^{(DC)}(0),\ \tau_{Blk}^{(DC)}(1),\ \tau_{Blk}^{(DC)}(2),\ \tau_{Blk}^{(DC)}(3)\}=\{0,1,1,0\}$.

4.2.2 Determination of $\tau_{Blk,R}^{(CR)}(m,m')$

When the user's channel condition is bad, for example the user is close to the cell edge, the signal-to-noise ratio (SNR) in the MT-BS channel will be much lower than that in the MT-RS-BS channel. In that case, $C_R^{(CR)}(k,k')$ in Eq. (13) can be approximated as

$$C_R^{(CR)}(k,k') \approx \log_2\left(\frac{\frac{P_{r,M\to R}^{(CR)}}{N}|H_{M\to R}(k)|^2\cdot\frac{P_{r,R\to B}^{(CR)}}{N}|H_{R\to B}(k')|^2}{\frac{P_{r,M\to R}^{(CR)}}{N}\sum_{j=0}^{N_c-1}\sum_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}+\frac{P_{r,R\to B}^{(CR)}}{N}|H_{R\to B}(k')|^2+1}\right), \quad (18)$$

where the antilogarithm in Eq. (18) is the SNR of the MT-RS-BS link. The suboptimal method finds the best combination of the resource blocks which maximizes $C_R^{(CR)}$ obtained from Eq. (18). The best combination depends on the MT-RS and RS-BS link qualities irrespective of the MT-BS link quality. $C_R^{(CR)}(k,k')$ of Eq. (18) is a monotonically increasing function of $|H_{M\to R}(k)|^2$ and $|H_{R\to B}(k')|^2$ (see Appendix A). $C_R^{(CR)}$ obtained from Eq. (18) depends on which resource blocks on the MT-RS link and RS-BS link are allocated but does not depend on how sub-blocks of MT and RS are mapped onto each link, respectively (see Appendix B). Therefore, the value of $\tau_{Blk,R}^{(CR)}(m,m')$ is determined using the following steps.

1). Evaluate the block averaged channel gains associated with the MT-RS link and the RS-BS link. The average channel gain $H_{Blk,M\to R}(m)$ of the m $(=0,1,\ldots,N_c/(M/D)-1)$-th resource block associated with the MT-RS link and the average channel gain $H_{Blk,R\to B}(m')$ of the m' $(=0,1,\ldots,N_c/(M/D)-1)$-th resource block associated with the RS-BS link are respectively given as

$$\begin{cases} H_{Blk,M\to R}(m)=\sum_{k=0}^{\frac{M}{D}-1}\left|H_{M\to R}\left(m\cdot\frac{M}{D}+k\right)\right|^2 \\ H_{Blk,R\to B}(m')=\sum_{k=0}^{\frac{M}{D}-1}\left|H_{R\to B}\left(m'\cdot\frac{M}{D}+k\right)\right|^2 \end{cases}. \quad (19)$$

2). Sort the resource blocks associated with the MT-RS link and the RS-BS link according to the descending order of $H_{Blk,M\to R}(m)$ and $H_{Blk,R\to B}(m)$, respectively. The sorted resource blocks are indexed as $\{x_{M\to R}(j);\ j=0,\ldots,N_c/(M/D)-1\}$ for the MT-RS link and $\{x_{R\to B}(j);\ j=0,\ldots,N_c/(M/D)-1\}$ for the RS-BS link.
3). Allocate D resource blocks to the MT-RS and the RS-BS links according to $x_{M\to R}(j)$ and $x_{R\to B}(j)$ as $\{\tau_{Blk,R}^{(CR)}(x_{M\to R}(j),\ x_{R\to B}(j))=1;\ j=0,\ldots,D-1\}$ and $\{\tau_{Blk,R}^{(CR)}(x_{M\to R}(j),\ x_{R\to B}(j))=0;\ j=D,\ldots,N_c/(M/D)-1\}$.

As an example, let's assume $(M,D,N_c)=(4,2,8)$. If $\{H_{Blk,M\to R}(0),\ H_{Blk,M\to R}(1),\ H_{Blk,M\to R}(2),\ H_{Blk,M\to R}(3)\}=\{6,8,4,5\}$ and $\{H_{Blk,R\to B}(0),\ H_{Blk,R\to B}(1),\ H_{Blk,R\to B}(2),\ H_{Blk,R\to B}(3)\}=\{7,8,10,9\}$, we have $\{x_{M\to R}(0),\ x_{M\to R}(1),\ x_{M\to R}(2),\ x_{M\to R}(3)\}=\{1,0,3,2\}$ and $\{x_{R\to B}(0),\ x_{R\to B}(1),\ x_{R\to B}(2),\ x_{R\to B}(3)\}=\{2,3,1,0\}$. As a consequence, the resource block allocation results in $\tau_{Blk,R}^{(CR)}(m,m')=0$ except for $\tau_{Blk,R}^{(CR)}(1,2)=\tau_{Blk,R}^{(CR)}(0,3)=1$.

5. 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. For simplicity, K=6 relays are located in a concentric pattern as shown in Fig. 5. The normalized distance between RS and BS is set to $r_{R\to B}=0.5$. $M=64$ subcarriers out of $N_c=128$ subcarriers are given to the user for the transmission. In this paper, the following transmit power allocation

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-BS	$r_{R\to B}=0.5$
No. of total subcarriers	N_c=128
No. of subcarriers per user	M=64
Path loss exponent	α=3.5
Shadowing standard deviation	σ=7.0(dB)
Average received SNR RS-BS	$\Gamma_{R\to B}=10\log_{10}(\overline{P}_{t,R}r_{R\to B}^{-\alpha}/N)$ (dB)

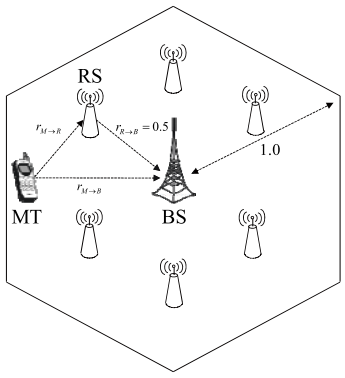


Fig. 5 System model for the computer simulation.

between MT and RS is considered for the cooperative AF relay:

$$\begin{cases} \bar{P}_{t,M} = x\bar{P}_T/2 \\ \bar{P}_{t,R} = (1-x)\bar{P}_T/2 \end{cases}, \tag{20}$$

where $\bar{P}_T$ is the total transmit power and x (=0∼1) is the power allocation factor.

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

$$\Gamma_{R\to B} = 10\log_{10}(\bar{P}_{t,R}r_{R\to B}^{-\alpha}/N) + \Delta \text{ (dB)}, \tag{21}$$

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).

5.1 Channel Capacity of the Direct/Cooperative Relay Switched SC-FDMA

Figure 6 shows the cumulative distribution function (CDF) of the channel capacity for the direct/cooperative relay switched SC-FDMA without SDASA when the transmit $\bar{P}_T/N$=10 dB. The power allocation factor is set to x=0.5 (i.e., the equal transmit power is allocated to MT and RS for the cooperative AF relay). One resource block, which consists of M=64 consecutive subcarriers, is allocated to a user randomly. For comparison, the CDFs of the channel capacities for the direct communication and the cooperative AF relay are also plotted in Fig. 6. It can be seen from Fig. 6 that the direct/cooperative relay switched SC-FDMA can achieve larger channel capacity than both the direct communication and the cooperative AF relay. The cooperative AF relay is not always effective and sometimes direct communication provides larger capacity. The direct/cooperative relay switched SC-FDMA selects either direct communication or cooperative relay which provides larger capacity.

Figure 7 shows the CDFs of the channel capacity for the direct/cooperative relay switched SC-FDMA with SDASA. In SDASA, exhaustive search is performed based

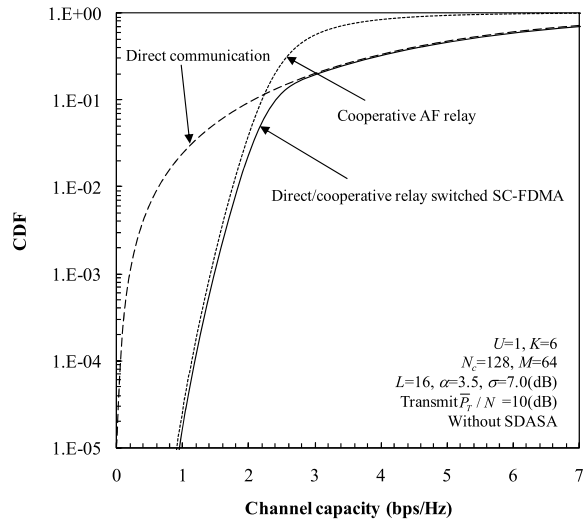


Fig. 6 CDF of the channel capacity of the direct/cooperative relay switched SC-FDMA without SDASA.

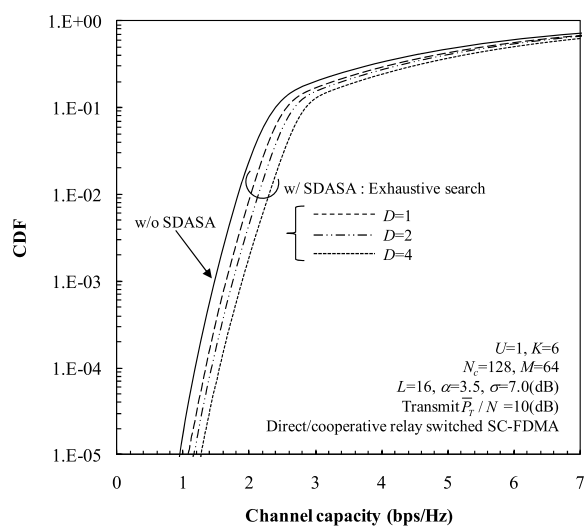


Fig. 7 CDF of the channel capacity of the direct/cooperative relay switched SC-FDMA with SDASA.

on Eq. (13). Due to its computational complexity, we plot the CDFs of $D \leq 4$ case. For comparison, CDF of the channel capacity of the direct/cooperative relay switched SC-FDMA without SDASA is also plotted in Fig. 7. It can be seen from Fig. 7 that the use of SDASA can further increase the channel capacity compared to the direct/cooperative relay switched SC-FDMA without SDASA. One of two resource blocks, consisting of subcarriers k = 0∼63 and k = 64∼127, is allocated to a user. The performance improvement of SDASA with D=1 over no SDASA is due to the frequency-diversity gain obtained by the resource block allocation. The resource block allocation is done according to the channel condition for the case of SDASA with D=1, while it is independent of the channel condition for no SDASA case. It can be also seen from Fig. 7 that the channel capacity increases as D becomes larger. This is because

the frequency diversity gain increases as D becomes larger.

5.2 Channel Capacity of the Suboptimal SDASA

5.2.1 Comparison of the Channel Capacity

Figure 8 shows the CDFs of the channel capacity of the direct/cooperative relay switched SC-FDMA using suboptimal SDASA. The power allocation factor is set to x=0.5 (i.e., the equal transmit power is allocated to MT and RS for the cooperative AF relay). For comparison, the CDFs of the channel capacity of the exhaustive search scheme are also plotted in Fig. 8. It can be seen from Fig. 8 that the suboptimal scheme can achieve the similar capacity to the exhaustive search scheme. This reason can be explained by discussing the relaying probability. Figure 9 shows how the probability, Prob(*relay*), of the use of relaying is distributed within a cell. It can be seen from Fig. 9 that relaying probability increases as MT approaches the cell edge; when the transmit SNR=10 dB, the relaying probability becomes 0.28 at the cell edge. When MT is close to the cell edge, the approximation given by Eq. (18) is valid since the MT-BS distance is much longer than the MT-RS and RS-BS distances. As MT approaches the BS, the MT-BS distance becomes shorter and hence the approximation in Eq. (18) becomes invalid. In such a case, however, relaying probability is very low, i.e. the direct communication is always selected. Therefore, the approximation in Eq. (18) is always valid when the cooperative relay is selected.

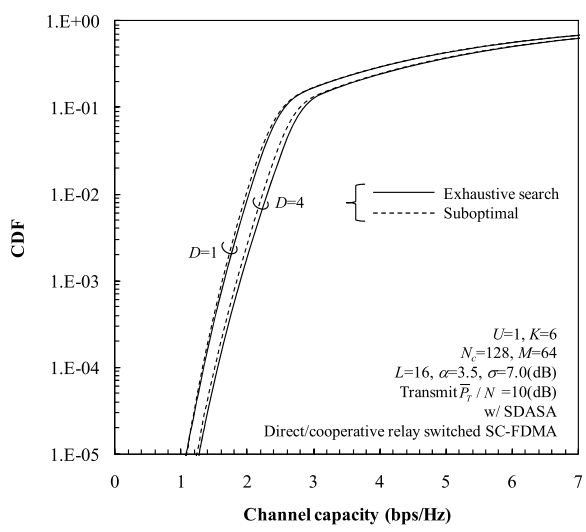


Fig. 8 CDF of the channel capacity of the suboptimal SDASA scheme.

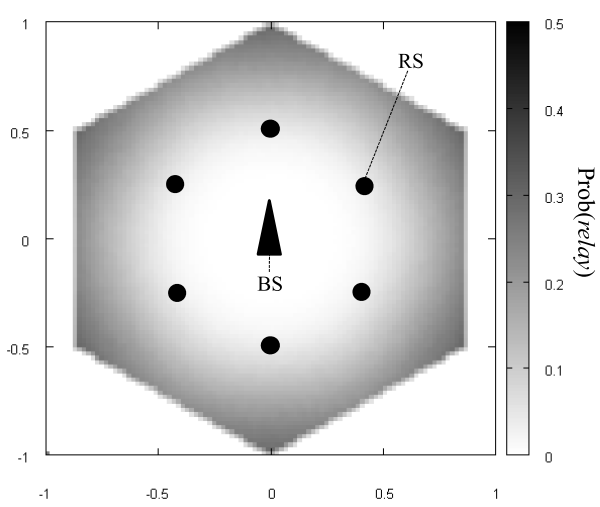


Fig. 9 Spatial distribution of relaying probability when transmit $\bar{P}_T/N$ = 10 dB.

5.2.2 Outage Capacity and PAPR Property

First, the impact of power allocation factor x is discussed. Figure 10 shows the 1%- and 50%-outage capacities of the direct/cooperative relay switched SC-FDMA using suboptimal SDASA, where the a%-outage capacity is the one below which the channel capacity falls with probability of a%. In Fig. 10, the outage capacity of the cooperative AF relay is also plotted. It can be seen from Fig. 10 that the 1%-outage capacity of the proposed scheme is maximized when x=0.5. On the other hand, the 50%-outage capacity of the proposed scheme is relatively insensitive to the power allocation factor. The reason for this is as follows. The 50%-outage capacity represents the achievable capacity when the MT-BS distance is shorter than the MT-RS distance (i.e., the MT-BS link quality is higher than the MT-RS link quality). In such a case, the direct/cooperative relay switched SC-FDMA chooses the direct communication. When the direct communication is selected, all the transmit power is allocated to MT irrespective of x. In the following, the power allocation factor x is set to x=0.5.

Figure 11 shows the impact of the spectrum division factor D on the 1%- and 50%-outage capacities of the direct/cooperative relay switched SC-FDMA using suboptimal SDASA. In Fig. 11, outage capacity of the orthogonal frequency division multiple access (OFDMA) is also

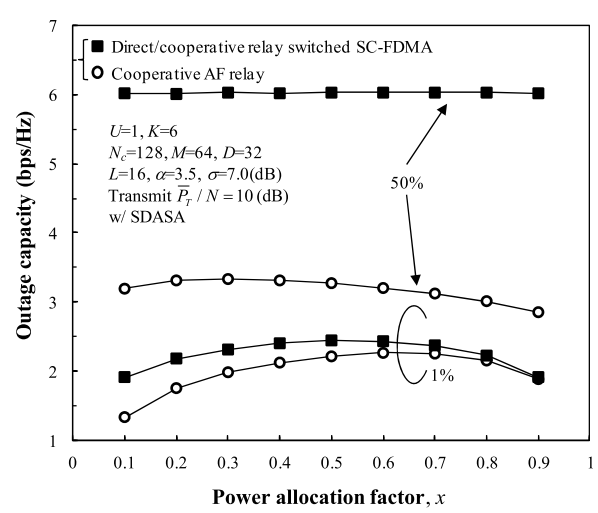
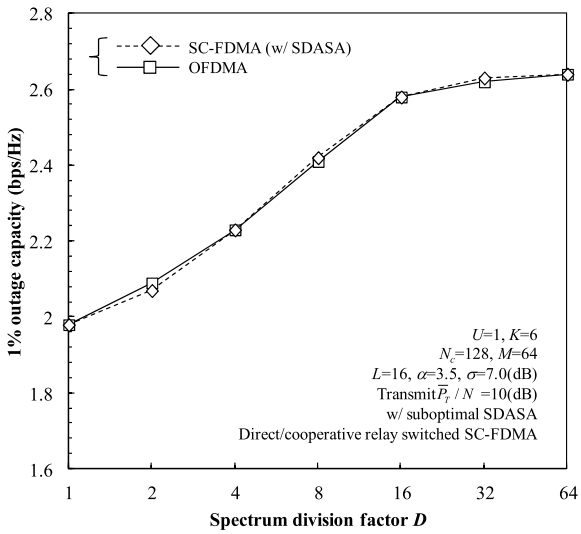
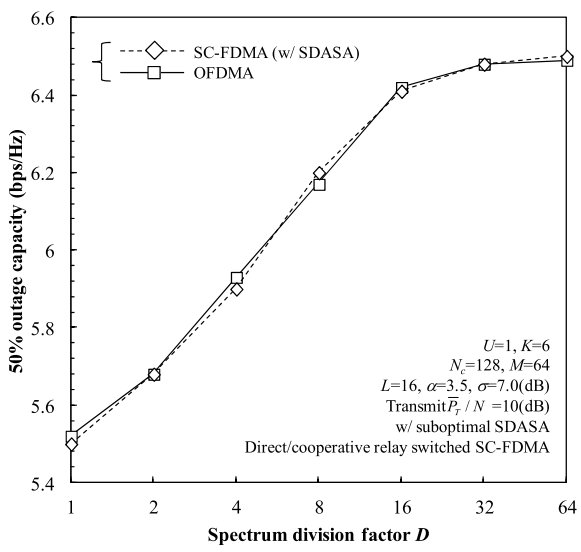


Fig. 10 Impact of power allocation factor.

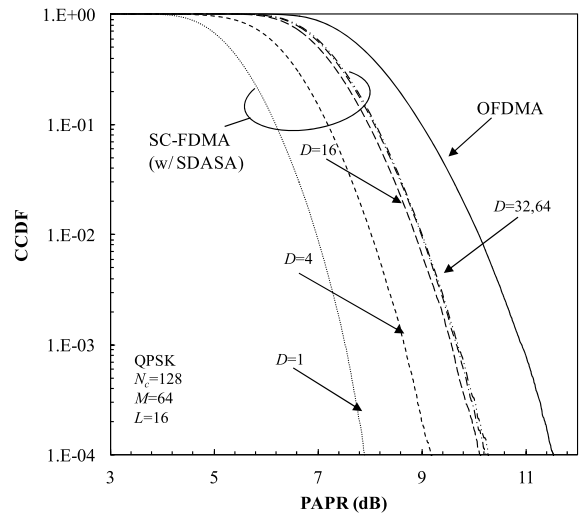


(a) 1% outage capacity.

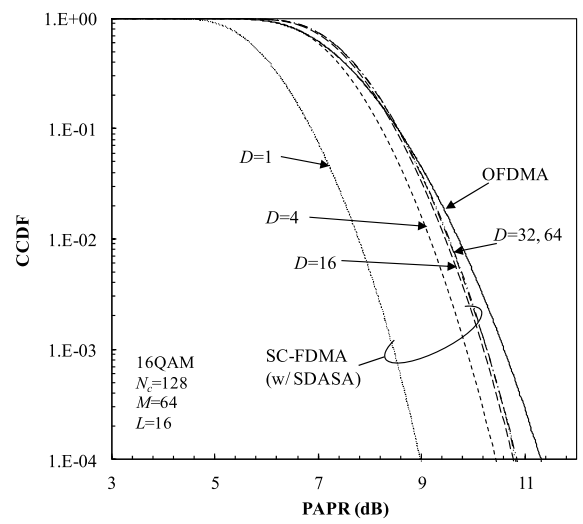


(b) 50% outage capacity.

Fig. 11 Outage capacity with D as a parameter.



(a) QPSK



(b) 16QAM

Fig. 12 PAPR with D as a parameter.

plotted. In the OFDMA, M subcarriers are divided into D clusters which consist of the consecutive M/D subcarriers as same as the SDASA, and D resource blocks which can maximize the channel capacity are allocated for signal transmission. It can be seen from Fig. 11 that the 1%- and 50%-outage capacities increase as D becomes larger, but it remains almost the same D=32. The reason for this can be explained as bellow. The fading correlation averaged over one resource block (consisting of M/D subcarriers) becomes stronger as D. Therefore, the frequency diversity gain increases as D increases; D=32 achieves the maximum channel capacity. It can be also seen from Fig. 11 that the SDASA can achieve the similar capacity to the OFDMA. This is because the mathematical expression of the channel capacity for the OFDMA is same as that for the SC-FDMA.

Figure 12 shows the complementary CDF (CCDF) of the peak-to-average power ratio (PAPR) with D as a parameter. In Fig. 12, the PAPR of OFDMA case is also plotted for comparison. For the measurement of the PAPR, QPSK and 16QAM data modulations are assumed. It can be seen from Fig. 12 that the PAPR increases as D increases. This is because the transmit signal waveform is distorted more strongly as D increases. Therefore, there exists a tradeoff relationship between the channel capacity and the PAPR. It can also be seen from Fig. 12, however, that the PAPR of SC-FDMA remains almost the same beyond D=32 and is still lower than that of OFDMA. Therefore, the SDASA achieves the channel capacity similar to the OFDMA while keeping lower PAPR. This means that SC-FDMA w/SDASA has a significant advantage over OFDMA when the available peak transmit power is limited.

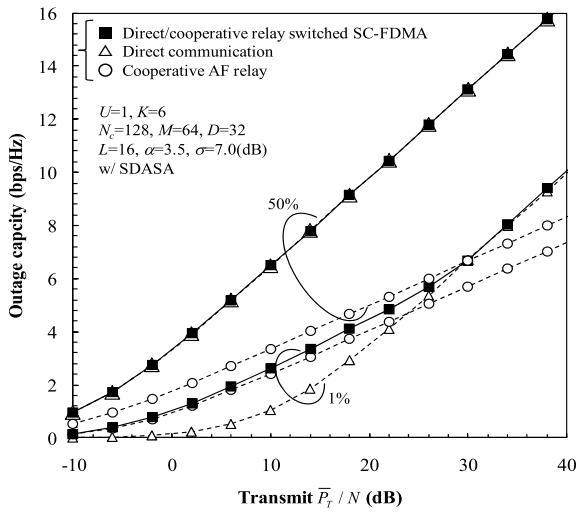


Fig. 13 Outage capacity of the direct/cooperative relay switched SC-FDMA using SDASA.

5.3 Transmit Power Reduction Effect

Figure 13 shows the 1%- and 50%-outage capacities of the direct/cooperative relay switched SC-FDMA using SDASA. In SDASA, the transmit SC spectrum is divided into D=32 sub-blocks. For comparison, outage capacities of the direct communication and the cooperative AF relay are also plotted in Fig. 13. It can be seen from Fig. 13 that the proposed scheme can reduce the transmit power compared to the direct communication and the cooperative AF relay. For 1%-outage capacity of 3.0 bps/Hz, the transmit power can be reduced by about 6.0 dB compared to direct communication and by about 2.0 dB compared to cooperative AF relay. It is interesting to note that proposed scheme and direct communication provide almost the same 50%-outage capacity while cooperative AF relaying 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 relaying reduces the capacity and thus, the direct/cooperative relay switched SC-FDMA chooses the direct communication.

6. Conclusion

In this paper, we proposed the direct/cooperative relay switched SC-FDMA using AF protocol and SDASA. It was shown that the direct/cooperative relay switched SC-FDMA can achieve larger channel capacity than either direct communication or cooperative AF relay in isolation. It was also shown that the use of SDASA can further increase the channel capacity compared to the direct/cooperative relay switched SC-FDMA without SDASA. We developed optimal and suboptimal methods for the direct/cooperative relay switched SC-FDMA using SDASA to maximize the channel capacity and evaluate the channel capacity. It was shown that the suboptimal scheme can basically match the capacity of the optimal scheme. Transmit power reduction effect of the direct/cooperative relay switched SC-FDMA using SDASA was discussed. It was shown that the proposed scheme can reduce the transmit power by about 6.0 (2.0) dB compared to the direct communication (the cooperative AF relay) for a 1%-outage capacity of 3.0 bps/Hz.

In this paper, the single-user case was assumed although SC-FDMA can accommodate up to U user. The developed suboptimal subcarrier allocation can be applied to the multi-user case. However, user scheduling or user selection algorithm needs to be developed. The performance evaluation in the multi-user case is left as an important future study.

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Appendix A: Proof that Eq. (18) Is the Monotonically Increasing Function of $|H_{M\to R}(k)|^2$ and $|H_{R\to B}(k')|^2$

The derivative of $C_R^{(CR)}(k,k')$ given by Eq. (17) with respect to $|H_{M\to R}(k)|^2$ is given as

$$\frac{\partial C_R^{(CR)}(k,k')}{\partial |H_{M\to R}(k)|^2} = \frac{1}{2\ln 2}\times \frac{\left(\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\sum\limits_{\substack{j=0\\ j\neq k}}^{N_c-1}\sum\limits_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}\\ +\frac{P_{r,R\to B}^{(CR)}}{N}|H_{R\to B}(k')|^2+1\end{array}\right)}{|H_{M\to R}(k)|^2\left(\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\sum\limits_{j=0}^{N_c-1}\sum\limits_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}\\ +\frac{P_{r,R\to B}^{(CR)}}{N}|H_{R\to B}(k')|^2+1\end{array}\right)} > 0. \tag{A·1}$$

Similarly, the derivative of $C_R^{(CR)}(k,k')$ given by Eq. (17) with respect to $|H_{R\to B}(k')|^2$ is given as

$$\frac{\partial C_R^{(CR)}(k,k')}{\partial |H_{R\to B}(k')|^2} = \frac{1}{2\ln 2} \cdot \frac{\left(\frac{P_{r,M\to R}^{(CR)}}{N}\sum\limits_{j=0}^{N_c-1}\sum\limits_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}+1\right)}{|H_{R\to B}(k')|^2\left(\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\sum\limits_{j=0}^{N_c-1}\sum\limits_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{|H_{M\to R}(j)|^2}{M}\\ +\frac{P_{r,R\to B}^{(CR)}}{N}|H_{R\to B}(k')|^2+1\end{array}\right)} > 0. \tag{A·2}$$

We can find from Eqs. (A·1) and (A·2) that $C_R^{(CR)}(k,k')$ given by Eq. (18) is monotonically increasing function of the channel gains $|H_{M\to R}(k)|^2$ and $|H_{R\to B}(k')|^2$.

Appendix B: Proof that $C_R^{(CR)}$ Does Not Depend on How Sub-Blocks of MT and RS Are Mapped onto Allocated Resource Blocks in MT-RS and RS-BS Links

Without loss of generality, we assume that the m-th resource block ($m = 0, 1, \ldots, D-1$) on the MT-RS link and the m'-th resource block ($m' = 0, 1, \ldots, D-1$) on the RS-BS link are given to MT and RS. The approximated channel capacity for the cooperative AF relay $C_R^{(CR)}$ can be written as

$$C_R^{(CR)} = \frac{1}{2D}\sum_{m=0}^{D-1}\sum_{m'=0}^{D-1}\tau_{Blk,R}^{(CR)}(m,m')C_{Blk,R}^{(CR)}(m,m')$$

$$= \frac{1}{2M}\sum_{m=0}^{D-1}\sum_{m'=0}^{D-1}\tau_{Blk,R}^{(CR)}(m,m')\times \left[\sum_{k=0}^{\frac{M}{D}-1}\log_2\left(\frac{\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\left|H_{M\to R}\left(m\cdot\frac{M}{D}+k\right)\right|^2\\ \times\frac{P_{r,R\to B}^{(CR)}}{N}\left|H_{R\to B}\left(m'\cdot\frac{M}{D}+k\right)\right|^2\end{array}}{\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\sum\limits_{j=0}^{N_c-1}\sum\limits_{j'=0}^{N_c-1}\tau_R^{(CR)}(j,j')\frac{\left|H_{M\to R}\left(m\cdot\frac{M}{D}+j\right)\right|^2}{M}\\ +\frac{P_{r,R\to B}^{(CR)}}{N}\left|H_{R\to B}\left(m'\cdot\frac{M}{D}+k\right)\right|^2+1\end{array}}\right)\right]$$

$$= \frac{1}{2M}\log_2\left(\frac{\begin{array}{c}\frac{P_{r,M\to R}^{(CR)}}{N}\prod\limits_{m=0}^{D-1}\prod\limits_{k=0}^{\frac{M}{D}-1}\left|H_{M\to R}\left(m\cdot\frac{M}{D}+k\right)\right|^2\\ \cdot\frac{P_{r,R\to B}^{(CR)}}{N}\prod\limits_{m'=0}^{D-1}\prod\limits_{k=0}^{\frac{M}{D}-1}\left|H_{R\to B}\left(m'\cdot\frac{M}{D}+k\right)\right|^2\end{array}}{\prod\limits_{m'=0}^{D-1}\prod\limits_{k=0}^{\frac{M}{D}-1}\left(\frac{P_{r,R\to B}^{(CR)}}{N}\left|H_{R\to B}\left(m'\cdot\frac{M}{D}+k\right)\right|^2+A\right)}\right), \tag{A·3}$$

with

$$A = \frac{P_{r,M\to R}^{(CR)}}{N}\sum_{m=0}^{D-1}\sum_{k=0}^{\frac{M}{D}-1}\frac{\left|H_{M\to R}\left(m\cdot\frac{M}{D}+k\right)\right|^2}{M}+1. \tag{A·4}$$

Since the initial assumption that the resource blocks on the MT-RS link has been already given, A given by Eq. (A·4) is constant value. Therefore, we can find from Eqs. (A·3) and (A·4) that $C_R^{(CR)}$ depends on which resource blocks on the MT-RS link and RS-BS link are allocated but does not depend on how sub-blocks of MT and RS are mapped onto allocated resource blocks in each link, respectively.

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