Power Allocation For Direct/Cooperative AF Relay Switched SC-FDMA

Masayuki NAKADA† Tatsunori OBARA† Tetsuya YAMAMOTO† and Fumiyuki ADACHI‡

Dept. of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

†{nakada, obara, yamamoto}@mobile.ecei.tohoku.ac.jp, ‡adachi@ecei.tohoku.ac.jp

Abstract— **In this paper, we propose a power allocation method for the direct/cooperative amplify-and-forward (AF) relay switched SC-FDMA using spectrum division/adaptive subcarrier allocation (SDASA). The cooperative relaying is used only when it can achieve higher channel capacity than the direct communication. In the proposed power allocation method, transmit power is adaptively allocated to mobile terminal (MT) and relay station (RS) according to the channel conditions of MT-RS link and RS-base station (BS) link when the use of cooperative relay is selected. We evaluate the achievable channel capacity of the proposed power allocation method by Monte-Carlo numerical computation method. It is shown that the proposed power allocation method can achieve almost the same channel capacity as the grid search method.**

Keywords-component; Cooperative AF relay, SC-FDMA, spectrum divisoin/adaptive subcarrier allocation

I. INTRODUCTION

In the next generation mobile communication systems, broadband data services of around 1Gbps 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]-[5].

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 from relay station (RS) in the second time-slot and combines them to obtain the spatial diversity gain. Since the distances of MT-RS link and RS-BS link are in most cases shorter than that of MT-BS link, the average received signal power can be increased significantly. In the past, several cooperation protocols have been proposed [1]; among them, 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].

Although cooperative relay can mitigate the influences of the propagation path loss and the shadowing loss, it has difficulty to cope with the frequency-selective fading. In addition, the achievable channel capacity of the cooperative relay is upper limited to half of the direct communication since RS and MS need to use orthogonal channels (i.e. 2 time-slots) for their transmissions without interfering each other. To avoid these problems, we proposed a direct/cooperative AF relay switched single carrier-frequency multiple access (SC-FDMA) [6] using spectrum division/adaptive subcarrier allocation (SDASA) [7]. In the 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. In the direct/cooperative relay switching, switching between the direct communication and the cooperative relay is done so that larger channel capacity can be achieved. It was shown in [7] that the direct/cooperative AF relay switched SC-FDMA using SDASA can always achieve larger channel capacity than either the direct communication or the cooperative AF relay. In [7], we assumed that total transmit power used by MT and RS is kept constant and is equally allocated between MT and RS. Under the total transmit power constraint, the channel capacity of the cooperative relay can be increased by allocating transmit power adaptively between MT and RS.

In this paper, we propose a power allocation method for the direct/cooperative AF relay switched SC-FDMA using SDASA. When the signal-to-noise power ratio (SNR) of the MT-BS link is much lower than that of the MT-RS-BS link, the use of relaying is selected with high probability [7]. In the proposed power allocation method, transmit power is adaptively allocated to MT and RS according to the channel conditions of MT-RS link and RS-BS link irrespective of the channel condition of MT-BS link when the cooperative relay is selected. We evaluate the uplink channel capacity achievable with the proposed power allocation method by Monte-Carlo numerical computation method.

The rest of this paper is organized as follows. Section II presents the system model. Section III proposes the power allocation method for the direct/cooperative AF relay switched SC-FDMA using SDASA. Section IV discusses the simulation results on the channel capacity of the proposed power allocation method. Section V concludes the paper.

II. DIRECT/COOPERATIVE AF RELAY SWITCHING SYSTEM

We consider the SC-FDMA uplink transmission using cooperative relay in a single-cell and a single-user environment. The AF strategy is used for the cooperative relay. We assume that K relays are located in a cell as shown in Fig. 1. The cell radius is denoted by R. The distances between MT and BS, between MT and i-th RS (denoted by RS_i), and between 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. The channel variation is assumed to be constant during transmission of a symbol block and the maximum delay of the channel is below the length of the cyclic prefix (CP).

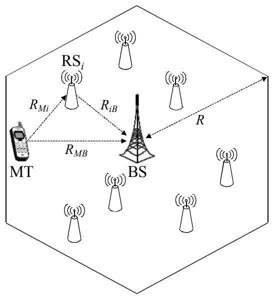

Fig. 1 System model.

A. Direct/Cooperative Relay Switching

In the direct/cooperative relay switching, switching between the direct communication and the cooperative relay is done so that larger channel capacity can be achieved [5].

We consider the cooperative AF relay using 2 time slots [8]-[10]. As shown in Fig. 2, in the first time slot, MT broadcasts the signal to both BS and RS; in the second time slot, RS transmits an amplified version of its received signal to BS.

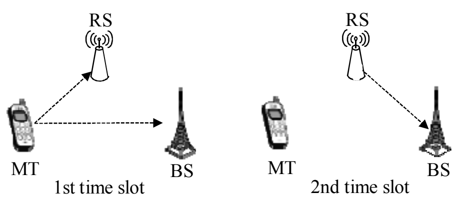

Fig. 2 Cooperative AF relay.

B. SDASA

In the SDASA, the best combinations of the resource blocks are found in the same way as [11]. SDASA is performed independently in direct communication and cooperative relay. A user is assumed to transmit an M-symbol block. The total number of subcarriers available in the system is denoted by N_c and are divided into resource blocks. Each block has M/D consecutive subcarriers. Therefore, the number of resource blocks is $N_c/(M/D)$.

In the direct communication, the average channel gain over a resource block (hereafter denoted by "block averaged channel gain") on the MT-BS link $H_{MB}^{Blk}(n)$ is calculated. Then, D resource blocks are allocated to user according to descending order of $H_{MB}^{Blk}(n)$.

In the cooperative relay, the best combinations of the resource blocks are found according to the channel conditions of the MT-RS$_i$ and RS$_i$-BS links irrespective of the MT-BS link condition. The block averaged channel gains, $H_{Mi}^{Blk}(n)$ and $H_{iB}^{Blk}(n)$, on the MT-RS$_i$ link and the RS$_i$-BS link are calculated, respectively. Then, resource blocks in the first and second time slots are paired according to the descending order of $H_{Mi}^{Blk}(n)$ and $H_{iB}^{Blk}(n)$. An example of the SDASA for the direct/cooperative AF relay switched SC-FDMA with (M, D, N_c)=(8, 4, 16) is illustrated in Fig. 3.

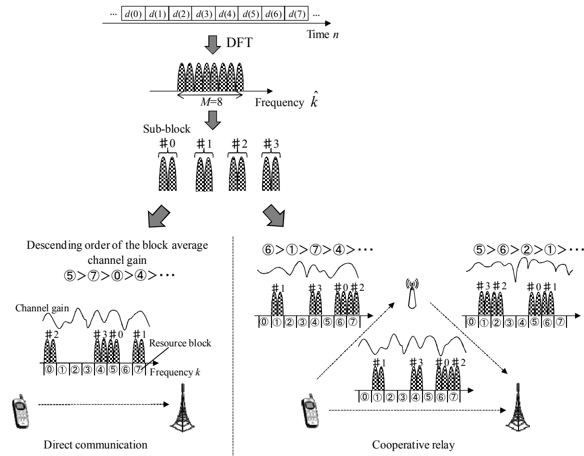

Fig. 3 SDASA for direct/cooperative AF relay switched SC-FDMA with (M, D, N_c)=(8, 4, 16).

III. Power Allocation

We propose a power allocation method for the direct/cooperative AF relay switched SC-FDMA using SDASA. When an MT is close to the cell edge, the use of relaying is selected with high probability [7]. In such a case, the SNR of MT-BS link is much lower than that of the MT-RS$_i$-BS link. Therefore, the channel capacity of the cooperative AF relay can be evaluated by removing the contribution of MT-BS link. Based on this approximation, we propose a power allocation method that maximizes the channel capacity. In the proposed power allocation method, the transmit power is adaptively allocated between MT and RS$_i$ according to the channel conditions of the MT-RS$_i$ link and the RS$_i$-BS link irrespective of the MT-BS link condition. Below, a channel capacity expression for the direct/cooperative AF relay switched SC-FDMA using SDASA will be developed and then, the power allocation method that maximizes the channel capacity will be derived.

A. Channel capacity

The channel capacity of the direct/cooperative AF relay switched SC-FDMA C^{sw} is given as

$$C^{SW} = \max\{C^{DC}, C_i^{CR}\}, \tag{1}$$

where C^{DC} and C_i^{CR} are the channel capacities of the direct communication and the cooperative AF relay using RS$_i$.

The channel capacity of the direct communication C^{DC} is given by [7]

$$C^{DC} = \frac{1}{M}\sum_{k=0}^{N_c-1}\tau_k^{DC}\log_2\left(1+\frac{P_r^{DC}}{N}|H_{MB}(k)|^2\right), \tag{2}$$

where $H_{MB}(k)$ and N are the channel gain for the MT-BS link and the noise power at BS, respectively. P_r^{DC} is the received signal power at BS and is given as

$$P_r^{DC} = \overline{P}_T \cdot r_{MB}^{-\alpha} \cdot 10^{-\eta/10}, \tag{3}$$

where $\overline{P}_T = P_T \cdot R^{-\alpha}$ is the normalized MT 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. τ_k^{DC}, $k = 0,\ldots,N_c - 1$, takes 0 or 1 ("$\tau_k^{DC} = 1$" indicates that the k-th subcarrier on the MT-BS link is allocated and 0 otherwise).

The channel capacity of the cooperative AF relay using RS$_i$ C_i^{CR} is given by [7],[12]

$$C_i^{CR} = \frac{1}{2M} \sum_{k=0}^{N_c-1} \sum_{k'=0}^{N_c-1} \tau_{i,k,k'}^{CR} \log_2 \left(1 + \frac{P_{r,MB}^{CR}}{N} \left| H_{MB}(k) \right|^2 + \frac{\frac{P_{r,Mi}^{CR}}{N} \left| H_{Mi}(k) \right|^2 \cdot \frac{P_{r,iB}^{CR}}{N} \left| H_{iB}(k') \right|^2}{\frac{P_{r,Mi}^{CR}}{N} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{\left| H_{Mi}(j) \right|^2}{M} + \frac{P_{r,iB}^{CR}}{N} \left| H_{iB}(k') \right|^2 + 1} \right), \quad (4)$$

where $H_{Mi}(k)$ and $H_{iB}(k)$ are the channel gains for the MT-RS$_i$ link and the RS$_i$-BS link, respectively. N is the noise power at RS$_i$ and BS. $P_{r,MB}^{CR}$, $P_{r,Mi}^{CR}$ and $P_{r,iB}^{CR}$ are respectively the received signal powers at BS and RS$_i$ in the first time slot and BS in the second time slot and are given as

$$\begin{cases} P_{r,MB}^{CR} = \overline{P}_{t,M} \cdot r_{MB}^{-\alpha} \cdot 10^{-\eta/10} \\ P_{r,Mi}^{CR} = \overline{P}_{t,M} \cdot r_{Mi}^{-\alpha} \cdot 10^{-\eta/10} \\ P_{r,iB}^{CR} = \overline{P}_{t,i} \cdot r_{iB}^{-\alpha} \cdot 10^{-\eta/10} \end{cases}, \quad (5)$$

where $\overline{P}_{t,M} = P_{t,M} \cdot R^{-\alpha}$ and $\overline{P}_{t,i} = P_{t,i} \cdot R^{-\alpha}$ are respectively the normalized MT transmit power with $P_{t,M}$ being the MT transmit power and the normalized RS$_i$ transmit power with $P_{t,i}$ being the RS$_i$ transmit power. $r_{Mi} = R_{Mi} / R$ and $r_{iB} = R_{iB} / R$ are the normalized distances. $\tau_{i,k,k'}^{CR}$, $k, k' = 0,\ldots,N_c - 1$, in Eq. (4) takes 0 or 1 ("$\tau_{i,k,k'}^{CR} = 1$" indicates that the k-th subcarrier in the first time slot and k'-th subcarrier in the second time slot are allocated, and 0 otherwise). For the fairness of comparison with the direct communication, the sum of transmit powers of MT and RS$_i$ is set to

$$\overline{P}_{t,M} + \overline{P}_{t,i} = \overline{P}_T . \quad (6)$$

B. Power allocation method that maximizes C_i^{CR}

The relaying is selected when the SNR of the MT-BS link is much lower than that of the MT-RS$_i$-BS link. In such a case, C_i^{CR} in Eq. (4) can be approximated as

$$C_i^{CR} \approx \frac{1}{2M} \sum_{k=0}^{N_c-1} \sum_{k'=0}^{N_c-1} \tau_{i,k,k'} \times \log_2 \left(\frac{\frac{P_{r,Mi}^{CR}}{N} \left| H_{Mi}(k) \right|^2 \cdot \frac{P_{r,iB}^{CR}}{N} \left| H_{iB}(k') \right|^2}{\frac{P_{r,Mi}^{CR}}{N} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{\left| H_{Mi}(j) \right|^2}{M} + \frac{P_{r,iB}^{CR}}{N} \left| H_{iB}(k') \right|^2 + 1} \right), \quad (7)$$

where the antilogarithm in Eq. (7) is the SNR of the MT-RS$_i$-BS link. We derive a power allocation method that maximizes C_i^{CR} given by Eq. (7). The maximization problem can be written as

$$\underset{\overline{P}_{t,M}, \overline{P}_{t,i}}{\arg} \max C_i^{CR}$$
$$s.t. \begin{cases} \overline{P}_{t,M} > 0, \ \overline{P}_{t,i} > 0 \\ \overline{P}_{t,M} + \overline{P}_{t,i} = \overline{P}_T \end{cases}. \quad (8)$$

We define the Lagrange function J as

$$J = C_i^{CR} + \mu(\overline{P}_{t,M} + \overline{P}_{t,i} - \overline{P}_T) , \quad (9)$$

where μ is the Lagrange multiplier. The solution of Eq. (8) satisfies

$$\begin{cases} \dfrac{\partial J}{\partial \overline{P}_{t,M}} = 0, \ \dfrac{\partial J}{\partial \overline{P}_{t,i}} = 0 \\ \overline{P}_{t,M} + \overline{P}_{t,i} - \overline{P}_T = 0 \end{cases}. \quad (10)$$

Solving Eq. (10), we obtain

$$\begin{cases} \overline{P}_{t,M} = \dfrac{\varepsilon}{1+\varepsilon} \overline{P}_T \\ \overline{P}_{t,i} = \dfrac{1}{1+\varepsilon} \overline{P}_T \end{cases}, \quad (11)$$

where ε is the optimum ratio of the transmit powers at MT and RS$_i$ which satisfies

$$\sum_{k=0}^{N_c-1} \sum_{k'=0}^{N_c-1} \tau_{i,k,k'}^{CR} \left(\frac{\varepsilon^2 r_{Mi}^{-\alpha} 10^{-\frac{\eta}{10}} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{|H_{Mi}(j)|^2}{M} - r_{iB}^{-\alpha} 10^{-\frac{\eta}{10}} |H_{iB}(k')|^2}{\varepsilon r_{Mi}^{-\alpha} 10^{-\frac{\eta}{10}} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{|H_{Mi}(j)|^2}{M} + r_{iB}^{-\alpha} 10^{-\frac{\eta}{10}} |H_{iB}(k')|^2} \right) = 0 , \quad (12)$$

where $\varepsilon = \overline{P}_{t,M} / \overline{P}_{t,i} > 0$. We will find ε which satisfies Eq. (12) by numerical calculation method such as the Newton-Raphson method [13]. Since Eq. (12) has a unique solution with respect to ε, the global optimum solution can be found by using the numerical calculation method. Function $f(\varepsilon)$ is defined as

$$f(\varepsilon) = \sum_{k=0}^{N_c-1} \sum_{k'=0}^{N_c-1} \tau_{i,k,k'}^{CR} \left(\frac{\varepsilon^2 r_{Mi}^{-\alpha} 10^{-\frac{\eta}{10}} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{|H_{Mi}(j)|^2}{M} - r_{iB}^{-\alpha} 10^{-\frac{\eta}{10}} |H_{iB}(k')|^2}{\varepsilon r_{Mi}^{-\alpha} 10^{-\frac{\eta}{10}} \sum_{j=0}^{N_c-1} \sum_{j'=0}^{N_c-1} \tau_{i,j,j'}^{CR} \frac{|H_{Mi}(j)|^2}{M} + r_{iB}^{-\alpha} 10^{-\frac{\eta}{10}} |H_{iB}(k')|^2} \right) . \quad (13)$$

The first order derivative of $f(\varepsilon)$ with respect to ε is given as

$$\frac{\partial f(\varepsilon)}{\partial \varepsilon}=$$

$$\sum_{k=0}^{N_c-1}\sum_{k'=0}^{N_c-1}\tau_{i,k,k'}^{CR}\left[\frac{r_{Mi}^{-\alpha}10^{-\frac{\eta}{10}}\sum_{j=0}^{N_c-1}\sum_{j'=0}^{N_c-1}\tau_{i,j,j'}^{CR}\frac{|H_{Mi}(j)|^2}{M}\times\left(\begin{array}{l}\varepsilon^2\sum_{j=0}^{N_c-1}\sum_{j'=0}^{N_c-1}\tau_{i,j,j'}^{CR}\frac{|H_{Mi}(j)|^2}{M}\\ \quad+(2\varepsilon+1)r_{iB}^{-\alpha}10^{-\frac{\eta}{10}}|H_{iB}(k')|^2\end{array}\right)}{\left(\begin{array}{l}\varepsilon r_{Mi}^{-\alpha}10^{-\frac{\eta}{10}}\sum_{j=0}^{N_c-1}\sum_{j'=0}^{N_c-1}\tau_{i,j,j'}^{CR}\frac{|H_{Mi}(j)|^2}{M}\\ \quad+r_{iB}^{-\alpha}10^{-\frac{\eta}{10}}|H_{iB}(k')|^2\end{array}\right)^2}\right]>0$$

.(14)

It can be understood from Eq. (14) that $f(\varepsilon)$ is a monotonically increasing function of ε. The extreme limits of $f(\varepsilon)$, $\varepsilon\to 0$ and $\varepsilon\to+\infty$, are given as

$$\begin{cases}\lim_{\varepsilon\to 0} f(\varepsilon)=\sum_{k=0}^{N_c-1}\sum_{k'=0}^{N_c-1}\tau_{i,k,k'}^{CR}(-1)=-M\ (<0)\\ \lim_{\varepsilon\to+\infty} f(\varepsilon)=+\infty\ (>0)\end{cases}. \quad (15)$$

Therefore, Eq. (12) has a unique solution with respect to $\varepsilon(>0)$ and the global optimum solution can be found by using numerical calculation method.

IV. NUMERICAL EVALUATION

The channel capacity distribution is evaluated by the Monte-Carlo numerical computation method. In this paper, the outage capacity is introduced; the x%-outage capacity is defined as the one which the channel capacity falls below with probability of x%. The numerical evaluation condition is summarized in Table 1. The channel is assumed to be an L=16-path frequency-selective block Rayleigh fading channel with uniform power delay profile. $M=64$ subcarriers out of $N_c=128$ subcarriers are used for the signal transmission. $M=64$ subcarriers are divided into $D=16$ sub-blocks.

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

$$\Gamma_{iB}=10\log_{10}(\overline{P}_{t,i}r_{iB}^{-\alpha}/N)+\Delta\ \text{(dB)}, \quad (16)$$

where Δ is related to the shadowing loss and is a design parameter to determine the RS location.

The best relay which maximizes the channel capacity is selected from K relays. First, the SDASA is carried out for each RS as explained in Sect. II. Then, the best relay is selected after power allocation as

$$i=\arg\max_i C_i^{CR}. \quad (17)$$

Table 1 Numerical evaluation condition.

Fading type	Block Rayleigh fading
Power delay profile	Uniform
No. of paths	L=16
No. of users	U=1
No. of total subcarriers	N_c=128
No. of subcarriers per user	M=64
No. of divided SC spectra	D=16
Path loss exponent	α=3.5
Shadowing standard deviation	σ=7.0(dB)
SNR offset from the path loss (design parameter to determine the RS location)	Δ=0, 7(dB)

A. Power allocation

In this subsection, the behavior of the proposed power allocation method is discussed. For simplicity, one dimensional model is considered as shown in Fig. 4. No shadowing loss is assumed (i.e., σ=0dB). Figure 5 shows the MT-to-RS transmit power ratio, $\varepsilon=\overline{P}_{t,M}/\overline{P}_{t,i}$ in dB, when using the proposed power allocation method with the normalized distance r_{Mi} as a parameter. It can be seen from Fig. 5 that more transmit power is allocated to MT as r_{Mi} increases and vice versa. For example, $\varepsilon=22$ dB when $r_{Mi}=$ 0.95 while $\varepsilon=-22$ dB when r_{Mi} = 0.05. With the proposed power allocation method, more transmit power is allocated to the link of lower SNR.

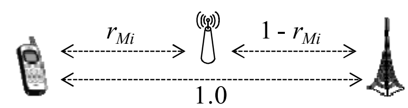

Fig.4 One dimensional model.

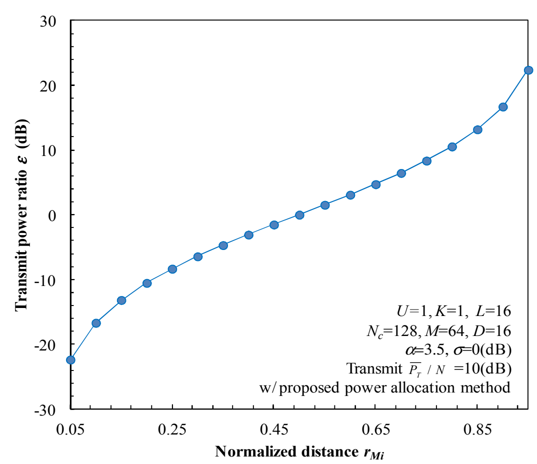

Fig. 5 MT-to-RS transmit power ratio.

B. Channel capacity

In this subsection, the two dimensional model is considered as shown in Fig. 6. The MT is assumed to be randomly located in a cell. The normalized distance between RS_i and BS is set to $r_{iB} = 0.5$. For simplicity, K=6 relays are located in a concentric pattern.

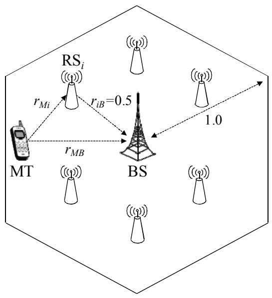

Fig. 6 Two dimensional model.

Figure 7 shows the cumulative distribution function (CDF) of the channel capacity of the proposed power allocation method when transmit $\overline{P}_T / N = 10$ dB. For comparison, CDFs of the channel capacity of the equal power allocation method and the power allocation which can maximize the channel capacity by using grid search method [14] are also plotted. In the grid search method, the transmit power ratio ε is uniformly quantized and the optimal transmit power raito is found as

$$\varepsilon = \underset{\varepsilon \in \theta}{\arg\max}\, C_i^{CR} . \qquad (18)$$

For simplicity, we set $\theta = \{0.01, 0.02, \ldots, 0.99\}$.

It can be seen from Fig. 7 that the proposed power allocation method can achieve almost the same CDF of the channel capacity as the grid search method. This is because the cooperative relaying is selected and power allocation is done only when the SNR of the MT-BS link is much lower than that of the MT-RS_i-BS link. (in this case, the approximation of Eq. (7) is always valid when the proposed power allocation method is used). Note that the proposed power allocation method increases the channel capacity compared with the equal power allocation method. For an example, when Δ =0dB, the proposed power allocation method increases the 10% outage capacity by about 0.2bps/Hz compared to the equal power allocation method. It can also be seen from Fig. 7 that the proposed power allocation method increases the capacity more significantly when $\Delta = 7$ dB than when $\Delta = 0$ dB in a low capacity region. This is because the SNR difference between the MT-RS_i and RS_i-BS links is larger when $\Delta = 7$ dB than when $\Delta = 0$ dB.

V. CONCLUSION

In this paper, a power allocation method that maximizes the uplink channel capacity for the direct/cooperative AF relay switched SC-FDMA using SDASA has been proposed. The proposed power allocation method allocates more transmit power to the lower SNR link. It can achieve almost the same channel capacity as the grid search method. It has been shown that the proposed power allocation method increases the 10% outage capacity by about 0.2bps/Hz compared to the equal power allocation method when $\Delta = 0$ dB. The evaluation of the proposed power allocation in a multi-cell and multi-user environment is left as our future work.

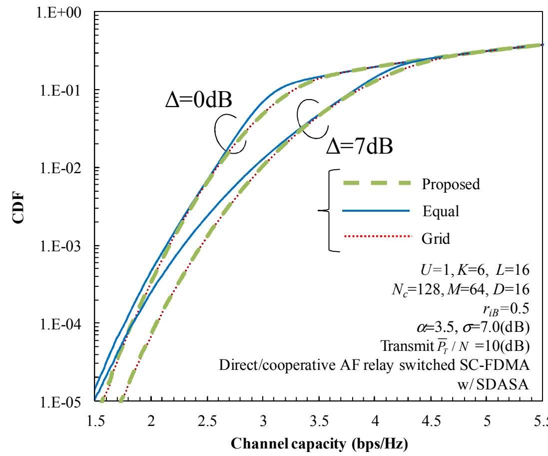

Fig. 7 CDF of channel capacity with the proposed power allocation method.

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