Single-Carrier Uplink Cooperative DF Relay Using Instantaneous CSI-Based Adaptive Modulation

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Abstract— **An introduction of the adaptive modulation improves the throughput of a 2-time slot cooperative relay. The throughput depends on conditions of mobile terminal (MT)-base station (BS) link, MT-relay station (RS) link, and RS-BS link. However, the cooperative relay is effective when the MT-BS direct link quality is worse than the others. Therefore, the best modulation combination can be chosen using instantaneous CSIs of MT-RS link and RS-BS link. In this paper, by neglecting the MT-BS direct link contribution, we introduce an adaptive modulation using instantaneous channel state information (CSI) of MT-RS link and RS-BS link. We evaluate, by computer simulation, the throughput performance of single-carrier (SC) 2-time slot cooperative decode-and-forward (DF) relay using adaptive modulation. It is shown that the introduction of adaptive modulation can reduce by about 1.8 dB the required transmit power for achieving a 1%-outage throughput of 1.4 bps/Hz compared to the conventional method.**

Keywords; cooperative DF relay, single-carrier transmission, adaptive modulation

I. INTRODUCTION

In cellular networks, the throughput performance of a user near the cell edge significantly degrades due to large propagation path loss in addition to the shadowing loss and multipath-fading [1]. The 2-time slot cooperative relay [2-4] is a well-known technique to increase the cell-edge throughput. There are two relay protocols in cooperative relay: amplify-and-forward (AF) and decode-and-forward (DF). In the first time slot, a mobile terminal (MT) transmits its signal to a relay station (RS) and a base station (BS). Then, in the second time slot, RS forwards its received signal to BS and BS combines two signals received in the first and second time slots.

The throughput depends on conditions of MT-BS link, MT-RS link, and RS-BS link. However, when an MT is close to the cell edge and the relaying is effective, the MT-BS direct link quality is worse than the others. Hence, the throughput of the cooperative relay may depend on the worse one of two links, MT-RS link and RS-BS link [3]. Remember that MT-RS link and RS-BS link may change in time according to the movement of MT. RS must forward the same amount of data in the second time slot (RS-BS link transmission) as that received in the first time slot (MT-RS link transmission). Hence, AF protocol cannot adapt to changing link condition. DF protocol has a possibility of providing higher throughput than AF protocol by adapting the data modulation (accordingly, by adapting the ratio of first and second time slot lengths) to changing link condition. The data modulation can be different for the first and second time slots. Finding the optimum modulation combination is an important issue in 2-time slot cooperative relay.

Recently, we investigated to which extent an introduction of the adaptive modulation improves the throughput of single-carrier (SC) 2-time slot cooperative DF relay [4]. In [4], the optimum modulation combination was chosen based on the combination of local average received signal-to-noise ratios (SNRs) of three links: MT-BS link, MT-RS link, and RS-BS link (called the conventional adaptive modulation in this paper). The local average received SNR based conventional adaptive modulation can achieve higher throughput than the fixed modulation. The use of instantaneous channel state information (CSI) instead of average SNR even further improves the throughput performance.

However, the adaptive modulation using instantaneous CSIs of MT-BS link, MT-RS link and RS-BS link may be quite difficult to implement. Remember that the cooperative relay is effective when MT-BS direct link is worse than both MT-RS link and RS-BS link (this often happens when an MT is close to the cell edge) [5]. In such a case, the contribution of MT-BS link is negligible because of its large path loss. Based on this observation, the best modulation combination can be chosen using instantaneous CSIs of MT-RS link and RS-BS link. In this paper, by neglecting the MT-BS direct link contribution, we introduce an adaptive modulation for SC 2-time slot cooperative DF relay. We evaluate, by computer simulation, the throughput performance of SC 2-time slot cooperative DF relay using adaptive modulation.

The rest of this paper is organized as follows. Section II presents the network model of SC 2-time slot cooperative DF relay. Section III presents the transmit/receive signal representation and signal combining. Section IV describes the adaptive modulation scheme. In Sect. V, the throughput performance of SC 2-time slot cooperative DF relay using adaptive modulation is evaluated by computer simulation. Section VI concludes this paper.

II. COOPERATIVE DF RELAY NETWORK USING ADAPTIVE MODULATION

A. Symtem model

Figure 1 illustrates the 2-time slot cooperative DF relay network model considered in this paper. The single-cell and single-user environment is assumed. X RSs are located in a cell. The cell radius is denoted by D. The distances between MT and BS, between MT and RS, and between RS and BS are denoted by $r_{M\to B}$, $r_{M\to R}$, and $r_{R\to B}$ ($R \in \{0,1,\ldots,X-1\}$), respectively.

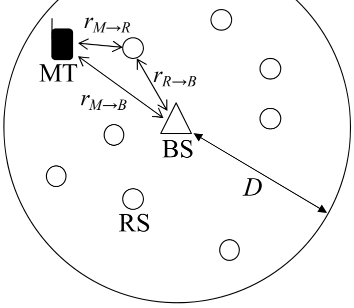

Fig. 1 System model.

B. Modulation combination

Figure 2 shows the uplink transmission in 2-time slot cooperative DF relay. During the first time slot, at the MT, the data-modulated symbol sequence is divided into a sequence of N_c-symbol blocks. The last N_g symbols of each N_c-symbol block are inserted into the guard interval (GI) as a cyclic prefix (CP). Then, the MT broadcasts the sequence of CP-inserted symbol blocks to both RS and BS. RS applies the minimum mean square error frequency-domain equalization (MMSE-FDE) [6] to each CP-removed N_c-symbol block and carries out the block data detection.

During the second time slot, RS remodulates the recovered data block and transmits to BS after CP insertion. BS combines the received signal blocks from MT in the first time slot and RS in the second time slot. The signal combining scheme depends on whether the data modulation levels in the first and second time slots are the same or not.

K blocks which consists of N_c symbols each are transmitted throughout the 2 time slots. In this paper, it is assumed that the data symbol duration T_s is the same for each time slot and the frame length is always kept constant. The number of bits per symbol m_1 (m_2) and the number of blocks K_1 (K_2) for the first (second) time slot is given as

$$\begin{cases} m_1 K_1 = m_2 K_2 \\ K_1 + K_2 = K \end{cases}. \tag{1}$$

The number of blocks allocated in each time slot depends on the modulation combination $\{m_1, m_2\}$.

The set of possible modulation combinations is shown in Table 1. An example of $K = 3$, $N_c = 256$ is illustrated by Fig. 3.

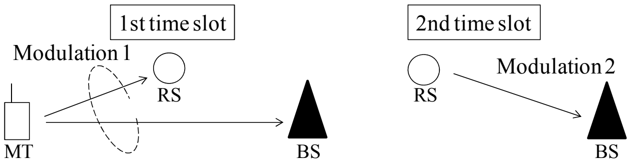

Fig. 2 Uplink transmission in 2-time slot cooperative DF relay.

Table 1 Set of possible modulation combinations.

BPSK-BPSK,	BPSK-QPSK,	BPSK-16QAM,
QPSK-BPSK,	QPSK-QPSK,	QPSK-16QAM,
16QAM-BPSK,	16QAM-QPSK,	16QAM-16QAM

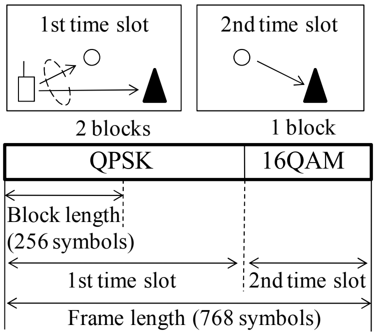

Fig. 3 An example of modulation combination.

III. SIGNAL PROCESSING OF COOPERATIVE DF RELAY

A. First time slot

In this paper, the equivalent baseband T_s-spaced discrete time signal representation is used and the maximum delay of the channel is below the length of the CP.

The CP-removed received signal blocks at RS and BS in the first time slot are respectively denoted by $\{y_{M\to R}(t);t=0,\ldots,N_c-1\}$ and $\{y_{M\to B}(t);t=0,\ldots,N_c-1\}$. $y_{M\to R}(t)$ and $y_{M\to B}(t)$ are given as

$$\begin{cases} y_{M\to R}(t) = \sqrt{2P_{M\to R}} \sum_{l=0}^{L-1} h_{M\to R}^{(l)} s_M\left((t-\tau_{M\to R}^{(l)}) \bmod N_c\right) + n_{M\to R}(t) \\ y_{M\to B}(t) = \sqrt{2P_{M\to B}} \sum_{l=0}^{L-1} h_{M\to B}^{(l)} s_M\left((t-\tau_{M\to B}^{(l)}) \bmod N_c\right) + n_{M\to B}(t) \end{cases}, \tag{2}$$

where $\{s_M(t);t=0,\ldots,N_c-1\}$ is the transmitted symbol block from MT. $h_{M\to R}^{(l)}$ and $h_{M\to B}^{(l)}$ are complex path gains and $\tau_{M\to R}^{(l)}$ and $\tau_{M\to B}^{(l)}$ are the time delays of the l-th path of MT-RS link and MT-BS link, respectively. $\{n_{M\to R}(t);t=0,\ldots,N_c-1\}$ and $\{n_{M\to B}(t);t=0,\ldots,N_c-1\}$ are zero-mean complex-valued noise samples with variance $2N_0/T_s$ at RS and BS during the first time slot, respectively, where N_0 is the single-sided power spectrum density of the additive white Gaussian noises (AWGNs). $P_{M\to R}$ and $P_{M\to B}$ are the received powers at RS and BS in the first time slot. They are expressed as

$$\begin{cases} P_{M\to R} = \overline{P}_M \cdot \overline{r}_{M\to R}^{\,-\alpha} \cdot 10^{-\eta_{M\to R}/10} \\ P_{M\to B} = \overline{P}_M \cdot \overline{r}_{M\to B}^{\,-\alpha} \cdot 10^{-\eta_{M\to B}/10} \end{cases}, \tag{3}$$

where $\overline{P}_M$ is the normalized transmit power at MT and it is expressed as $\overline{P}_M = P_M \cdot D^{-\alpha}$, where P_M is the transmit power at MT. $\bar{r}_{M\to R}$ and $\bar{r}_{M\to B}$ are the normalized distances between MT and RS and between MT and BS, respectively. They are expressed as $\bar{r}_{M\to R} = r_{M\to R}/D$ and $\bar{r}_{M\to B} = r_{M\to B}/D$, respectively. α is the path loss exponent. $\eta_{M\to R}$ and $\eta_{M\to B}$ are the log-normally distributed shadowing loss in dB of MT-RS link and MT-BS link, respectively. They are independent zero mean Gaussian random variables with standard deviation σ.

Figure 4 illustrates the RS structure. At the RS, N_c-point fast Fourier transform (FFT) is applied to the CP-removed received signal block $\{y_{M\to R}(t);t=0,\ldots,N_c-1\}$ to transform it into the frequency-domain received signal $\{Y_{M\to R}(k);k=0,\ldots,N_c-1\}$. $Y_{M\to R}(k)$ is given as

$$Y_{M\to R}(k) = H_{M\to R}(k)S_M(k) + \Pi_{M\to R}(k)\,, \tag{4}$$

where $S_M(k)$, $H_{M\to R}(k)$, and $\Pi_{M\to R}(k)$ are the k-th frequency-domain transmit signal at MT, the k-th frequency-domain channel gain and the noise of MT-RS link, respectively.

One-tap MMSE-FDE is applied as

$$\hat{Y}_{M\to R}(k) = Y_{M\to R}(k)W_{M\to R}(k)\,, \tag{5}$$

where $W_{M\to R}(k)$ is the MMSE-FDE weight (which minimizes the mean square error (MSE) between $\hat{Y}_{M\to R}(k)$ and $S_M(k)$) given as [7]

$$W_{M\to R}(k) = \frac{H^*_{M\to R}(k)}{\left|H_{M\to R}(k)\right|^2 + 2N_0/T_s}\,, \tag{6}$$

where $(.)^*$ denotes the complex conjugate operation.

The frequency-domain signal $\{\hat{Y}_{M\to R}(k); k=0,\ldots,N_c-1\}$ after MMSE-FDE is transformed by N_c-point inverse FFT (IFFT) back to the time-domain signal block $\{\hat{d}_{M\to R}(t); t=0,\ldots,N_c-1\}$. $\hat{d}_{M\to R}(t)$ is the t-th soft-decision symbol.

Finally, the data decision and remodulation is done by the RS to form the symbol block $\{s_R(t);t=0,\ldots,N_c-1\}$, to be transmitted to BS in the second time slot, as

$$s_R(t) = \arg\min_{\hat{x}(t)\in\chi}\left|\hat{d}_{M\to R}(t) - \left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}H_{M\to R}(k)W_{M\to R}(k)\right)\hat{x}(t)\right|^2, \tag{7}$$

where χ is the set of the data-modulated symbol candidate [8].

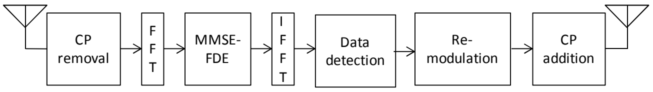

Fig. 4 RS structure.

B. Second time slot

The received signal $\{y_{R\to B}(t);t=0,\ldots,N_c-1\}$ at BS in the second time slot is given as

$$y_{R\to B}(t) = \sqrt{2P_{R\to B}}\sum_{l=0}^{L-1}h^{(l)}_{R\to B}s_R\left((t-\tau^{(l)}_{R\to B})\bmod N_c\right) + n_{R\to B}(t)\,, \tag{8}$$

where $h^{(l)}_{R\to B}$ and $\tau^{(l)}_{R\to B}$ are the complex path gain and the time delay of the RS-BS link, respectively. $n_{R\to B}(t)$ is the Gaussian noise with zero mean and variance $2N_0/T_s$ at BS during the second time slot.

The received powers $P_{R\to B}$ at BS in the second time slot can be expressed as

$$P_{R\to B} = \overline{P}_R \cdot \bar{r}_{R\to B}^{-\alpha} \cdot 10^{-\eta_{R\to B}/10}\,, \tag{9}$$

where $\overline{P}_R$ is the normalized transmit power at RS and it is expressed as $\overline{P}_R = P_R \cdot D^{-\alpha}$, where P_R is the transmit power at RS. $\bar{r}_{R\to B}$ is the normalized distance between RS and BS, and it is expressed as $\bar{r}_{R\to B} = r_{R\to B}/D$. $\eta_{R\to B}$ is the log-normally distributed shadowing loss in dB of RS-BS link. This is independent zero mean Gaussian random variables with standard deviation σ.

Figure 5 shows the BS structure. N_c-point FFT is applied to $\{y_{M\to B}(t);t=0,\ldots,N_c-1\}$ and $\{y_{R\to B}(t);t=0,\ldots,N_c-1\}$ to transform them into the frequency-domain received signals $\{Y_{M\to B}(k);k=0,\ldots,N_c-1\}$ and $\{Y_{R\to B}(k);k=0,\ldots,N_c-1\}$, respectively. $Y_{M\to B}(k)$ and $Y_{R\to B}(k)$ are given as

$$\begin{cases} Y_{M\to B}(k) = H_{M\to B}(k)S_M(k) + \Pi_{M\to B}(k) \\ Y_{R\to B}(k) = H_{R\to B}(k)S_R(k) + \Pi_{R\to B}(k) \end{cases}, \tag{10}$$

where $S_R(k)$ is the k-th frequency-domain transmit signal at RS. $H_{M\to B}(k)$ and $H_{R\to B}(k)$ are the k-th frequency-domain channel gain of MT-BS link and RS-BS link, respectively. $\Pi_{M\to B}(k)$ and $\Pi_{R\to B}(k)$ are the noise of MT-BS link and RS-BS link, respectively.

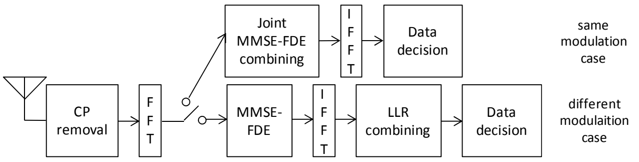

Fig. 5 BS structure.

C. Signal combining

1) Combining in case of same modulation level

When the same data modulation level is used in the first and second time slots, joint MMSE-FDE combining [7] is applied. The frequency-domain signal $\{\hat{Y}(k); k=0,\ldots,N_c-1\}$ after joint MMSE-FDE combining is expressed as

$$\hat{Y}(k) = Y_{M\to B}(k)W_{M\to B}(k) + Y_{R\to B}(k)W_{R\to B}(k)\,, \tag{11}$$

where $W_{M\to B}(k)$ and $W_{R\to B}(k)$ are the MMSE weights which jointly minimize the MSE between $\hat{Y}(k)$ and $S_M(k)$ and are given as [7]

$$\begin{cases} W_{M\to B}(k) = \dfrac{H^{*}_{M\to B}(k)}{\left|H_{M\to B}(k)\right|^{2} + \left|H_{R\to B}(k)\right|^{2} + 2N_0/T_s} \\ W_{R\to B}(k) = \dfrac{H^{*}_{R\to B}(k)}{\left|H_{M\to B}(k)\right|^{2} + \left|H_{R\to B}(k)\right|^{2} + 2N_0/T_s} \end{cases} . \qquad (12)$$

The frequency-domain signal $\{\hat{Y}(k); k = 0,\ldots,N_c - 1\}$ is transformed by N_c-point IFFT back to the time-domain signal $\{\hat{d}(t); t = 0,\ldots,N_c - 1\}$.

2) *Combining in case of different modulation level*

When the data-modulation level is different in the first and second time slots, the received signals from MT and RS are combined using log-likelihood ratio (LLR) combining [9] after MMSE-FDE.

One-tap MMSE-FDE for $\{Y_{M\to B}(k);k=0,\ldots,N_c-1\}$ and $\{Y_{R\to B}(k);k=0,\ldots,N_c-1\}$ are expressed as

$$\begin{cases} \hat{Y}_{M\to B}(k) = Y_{M\to B}(k)W_{M\to B}(k) \\ \hat{Y}_{R\to B}(k) = Y_{R\to B}(k)W_{R\to B}(k) \end{cases} , \qquad (13)$$

where $W_{M\to B}(k)$ and $W_{R\to B}(k)$ are the MMSE weights given as [7]

$$\begin{cases} W_{M\to B}(k) = \dfrac{H^{*}_{M\to B}(k)}{\left|H_{M\to B}(k)\right|^{2} + 2N_0/T_s} \\ W_{R\to B}(k) = \dfrac{H^{*}_{R\to B}(k)}{\left|H_{R\to B}(k)\right|^{2} + 2N_0/T_s} \end{cases} . \qquad (14)$$

The equalized frequency-domain signals $\{\hat{Y}_{M\to B}(k); k = 0,\ldots,N_c - 1\}$ and $\{\hat{Y}_{R\to B}(k); k = 0,\ldots,N_c - 1\}$ are transformed by N_c-point IFFT back to the time-domain signals $\{\hat{d}_{M\to B}(t); t = 0,\ldots,N_c - 1\}$ and $\{\hat{d}_{R\to B}(t); t = 0,\ldots,N_c - 1\}$ as

$$\begin{cases} \hat{d}_{M\to B}(t) = \dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{k=0}^{N_c-1} \hat{Y}_{M\to B}(k) \exp\left(j2\pi t \dfrac{k}{N_c}\right) \\ \hat{d}_{R\to B}(t) = \dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{k=0}^{N_c-1} \hat{Y}_{R\to B}(k) \exp\left(j2\pi t \dfrac{k}{N_c}\right) \end{cases} , \qquad (15)$$

from which the bit-LLRs, $\lambda_{M\to B,x}(t)$ and $\lambda_{R\to B,x}(t)$ of x-th bit within t-th symbol, are computed using [4]. The combined bit-LLR $\lambda_x(t)$ is given as

$$\lambda_x(t) = \lambda_{M\to B,x}(t) + \lambda_{R\to B,x}(t) . \qquad (16)$$

If $\lambda_x(t)$ is positive (negative), the estimated transmit bit is 1 (0).

IV. ADAPTIVE MODULATION SCHEME

In this section, instantaneous CSI based adaptive modulation for cooperative DF relay is proposed to maximize the throughput. In the proposed adaptive modulation, the modulation combination is selected according to the instantaneous channel quality of MT-RS link and RS-BS link neglecting that of MT-BS link. In the DF relay, the throughputs of MT-RS link and RS-BS link are independent because the channels of each link are independent. Therefore, the throughput of the cooperative DF relay can be maximized by selecting the modulations at MT and RS so that maximize the throughputs of MT-RS link and RS-BS link, respectively. BS selects the modulations at MT and RS, after selects one RS among X RSs using the instantaneous CSIs of MT-RS link and RS-BS link. Then, BS orders MT and selected RS to modulate using the selected modulation levels.

The modulation used at MT is selected by following steps.

Step 1) The throughput of the cooperative relay depends on the worth link between MT-RS link and RS-BS link [3]. Therefore, the RS selection is based on the throughput maximization of the worst link between MT-RS link and RS-BS link. The RS selection is expressed as

$$R = \underset{R'\in(0,1,\ldots,X-1)}{\arg\max} \left\{ \min\left(\sum_{l=0}^{L-1} \left|h^{(l)}_{M\to R'}\right|^{2} \cdot r^{-\alpha}_{M\to R'} \cdot 10^{-\eta_{M\to R'}/10}, \sum_{l=0}^{L-1} \left|h^{(l)}_{R'\to B}\right|^{2} \cdot r^{-\alpha}_{R'\to B} \cdot 10^{-\eta_{R'\to B}/10} \right) \right\} . \qquad (17)$$

Step 2) BS calculates the instantaneous signal-to-interference plus noise power ratio (SINR) at the MT-RS link after MMSE-FDE $\gamma_{M\to R}$. The instantaneous SINR $\gamma_{M\to R}$ can be computed using [7]

$$\gamma_{M\to R} = \frac{\left| \dfrac{1}{N_c} \displaystyle\sum_{k=0}^{N_c-1} H_{M\to R}(k) W_{M\to R}(k) \right|^{2}}{\left[\dfrac{1}{2} \left\{ \begin{array}{l} \dfrac{1}{N_c} \displaystyle\sum_{k=0}^{N_c-1} \left|H_{M\to R}(k) W_{M\to R}(k)\right|^{2} \\ - \left| \dfrac{1}{N_c} \displaystyle\sum_{k=0}^{N_c-1} H_{M\to R}(k) W_{M\to R}(k) \right|^{2} \end{array} \right\} + \dfrac{1}{N_c} \displaystyle\sum_{k=0}^{N_c-1} \left|W_{M\to R}(k)\right|^{2} \right]} , \qquad (18)$$

where the numerator of Eq. (18) is the desired signal power after MMSE-FDE. The denominator of Eq. (18) is the sum power of the residual inter-symbol-interference (ISI) and noise.

Step 3) BS calculates the instantaneous BERs of the all possible modulations at the MT-RS link using SINR $\gamma_{M\to R}$ calculated in step 2. The instantaneous BERs are given as

$$BER = \begin{cases} \dfrac{1}{2} erfc\left(\sqrt{\dfrac{1}{2}\gamma_{M\to R}} \right) & \text{for BPSK} \\ \dfrac{1}{2} erfc\left(\sqrt{\dfrac{1}{4}\gamma_{M\to R}} \right) & \text{for QPSK} \\ \dfrac{3}{8} erfc\left(\sqrt{\dfrac{1}{20}\gamma_{M\to R}} \right) & \text{for 16QAM} \end{cases} , \qquad (19)$$

where $erfc(.)$ is the complementary error function. BS estimates the instantaneous BERs when using BPSK, QPSK, and 16QAM and then, estimates the instantaneous packet error rates (PERs) of the MT-RS link when using BPSK, QPSK, and 16QAM. The instantaneous PER can be estimated using

$$PER = 1-(1-BER)^{N_p}, \tag{20}$$

where N_p is the number of information bits in a packet.

Step 4) BS estimates the throughputs of MT-RS link $S_{M\to R}$ using the estimated PERs when using BPSK, QPSK, and 16QAM. The throughput $S_{M\to R}$ is obtained using [11, 12]

$$S_{M\to R} = \frac{m_1(1-PER)}{1+N_g/N_c}\ \text{[bps/Hz]}. \tag{21}$$

Step 5) BS selects the modulation which throughput is maximal and orders MT to modulate using the selected modulation level.

The modulation used at RS is selected by the same way as the MT case. The instantaneous SINR $\gamma_{R\to B}$ can be computed as

$$\gamma_{R\to B} = \frac{\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1} H_{R\to B}(k)W_{R\to B}(k)\right|^2}{\left[\frac{1}{2}\left\{\begin{array}{l}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|H_{R\to B}(k)W_{R\to B}(k)\right|^2 \\ -\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1} H_{R\to B}(k)W_{R\to B}(k)\right|^2\end{array}\right\} + \frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|W_{R\to B}(k)\right|^2\right]}. \tag{22}$$

Then, BS estimates the throughputs using $\gamma_{R\to B}$ and selects the modulation according to Step 3 ~ 5.

The computational complexity of the proposed method is higher than the conventional method since BS needs to estimate the throughputs based on the instantaneous CSIs for modulation selection.

V. COMPUTER SIMULATION

We evaluate the average throughput performance of cooperative DF relay using adaptive modulation by the computer simulation. In this paper, the *x*% value of the cumulative distribution function of the throughput is defined as *x*%-outage throughput. The simulation condition is shown in Table 2. A frequency-selective block Rayleigh fading channel having a symbol-spaced L=16-path uniform power delay profile is assumed. The frame length (sum of the first and second time slots in time) is kept constant and the block size is always 512 symbols. The ideal channel estimation is assumed. Figure 6 illustrates the network model for this computer simulation model. The communication area is within the radius 1 from the BS. It is assumed that 6 RSs are located equal distantly to each other at the distance 0.5 from BS. MT is assumed to randomly move around in the cell. The normalized total transmit power $\overline{P} = P\cdot D^{-\alpha}$ is assumed to be equally allocated to MT and RS as $\overline{P}_M = \overline{P}_R = \overline{P}/2$, where P is the total transmit power.

In the adaptive modulation, the different modulation combination is chosen each time a symbol block is transmitted. Therefore, the average throughput of cooperative DF relay using adaptive modulation is given as

$$S = \frac{1}{1+N_g/N_c}\sum_{a=0}^{A-1} P_a\left\{\frac{m_{a,1}m_{a,2}}{m_{a,1}+m_{a,2}}\left(1-PER_a\right)\right\}\ \text{[bps/Hz]}, \tag{23}$$

where P_a denotes the probability that the *a*-th (a=0,…,A−1) modulation combination is selected. PER_a, $m_{a,1}$ and $m_{a,2}$ are the PER and the modulation levels in the first and second time slots when the *a*-th modulation combination is used, respectively. A is the number of possible modulation combination.

Table 2 Simulation condition.

Transmission data	Block size	N_c=512
	GI length	N_g=16
	Packet size	60 (blocks)
Channel	Fading type	Block Rayleigh fading
	Power delay profile	Uniform
	No. of paths	L=16
	Path loss exponent	α=3.5
	Shadowing loss standard deviation	σ=7.0 (dB)
RS receiver	Equalization	MMSE-FDE
	Channel estimation	Ideal
BS receiver	Equalization	MMSE-FDE
	Combining scheme	MMSE-FDE combining, LLR combining
	Channel estimation	Ideal

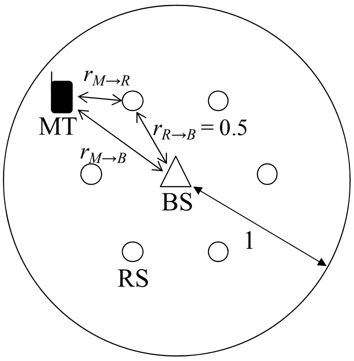

Fig. 6 System model for computer simulation

Figures 7 and 8 plot the 1% and 50%-outage throughputs of cooperative DF relay using adaptive modulation, respectively. For comparison, the 1% and 50%-outage throughputs of cooperative DF relay using conventional adaptive modulation (described as conventional method in Figs. 7 and 8), fixed modulation and full-search method are also plotted in Figs. 7 and 8. The full-search method finds the optimal modulation combination which provides the maximum throughput by measuring all possible modulation combination patterns.

It can be seen from Fig. 7 that the cooperative DF relay using adaptive modulation can reduce the required total transmit power compared to the conventional method and the fixed modulation combinations when MT is close to the cell edge. The transmit power reduction for a 1%-outage throughput of 1.4 bps/Hz is as much as about 1.8 dB compared to the conventional method. This is because the adaptive modulation can much better adapt to the channel variations than the conventional method. Also as seen from Fig. 7, the use of adaptive modulation can achieve a throughput close to the full-search method. The difference in the required transmit power for a 1%-outage throughput of 1.4 bps/Hz between the adaptive modulation and the full-search method is only about 0.3 dB. This small difference is because the MT-BS link condition is much worse than MT-RS link and RS-BS link and hence, the contribution of MT-BS link is negligible.

It can be seen from comparing Fig. 8 that the adaptive modulation increases the required transmit power compared to the full-search method and the conventional method. This is because MT is close to the BS and thus, the contribution of MT-BS link is strong. Therefore, neglecting the contribution of MT-BS link degrades the throughput performance. To avoid this situation, the adaptive modulation is applied only when MT is close to the cell edge. On the other hand, when MT is close to the cell center (i.e., the contribution of MT-BS link is large), the direct transmission is used instead of relaying.

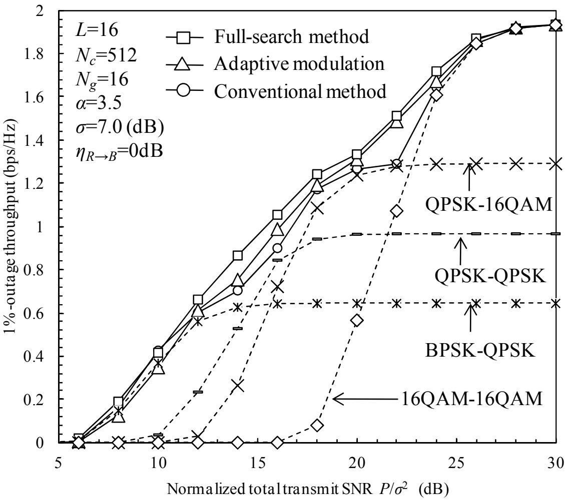

Fig. 7 1%-outage throughput performance.

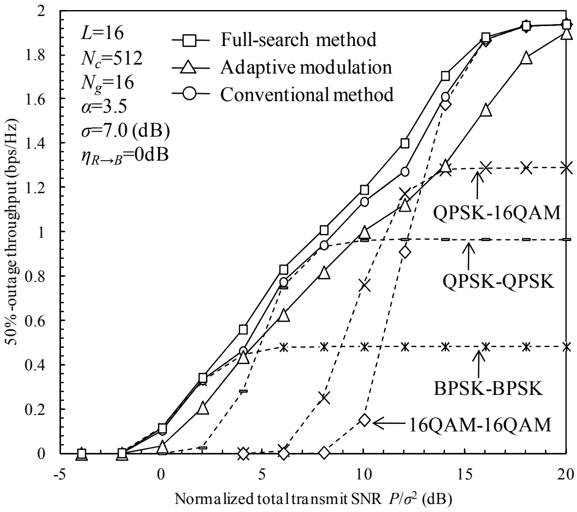

Fig. 8 50%-outage throughput performance.

VI. CONCLUSION

In this paper, we introduced adaptive modulation to SC 2-time slot cooperative DF relay. The best modulation combination is chosen according to MT-RS link and RS-BS link by neglecting the MT-BS direct link contribution. The throughput performance using adaptive modulation was evaluated by computer simulation. It was shown that neglecting the direct link contribution degrades the throughput performance only slightly and that the use of adaptive modulation can reduce by about 1.8 dB the required transmit power for achieving a 1%-outage throughput of 1.4 bps/Hz compared to the conventional adaptive modulation.

In this paper, we assumed that the cooperative relay is always used irrespective of MT location. When an MT is close to BS, the MT-BS direct link is in a fairly good condition and hence, relaying is not necessary. An introduction of switching between the direct transmission and cooperative relay transmission can further improve the throughput performance. This is left as our future study.

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