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Cooperation Method for Cellular Communication Systems

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ABSTRACT

A scheme for selecting the mode with the maximum system capacity is proposed for cooperative relaying. Three possible modes are presented based on decode-and-forward relaying, and the time required by each mode is evaluated. Based on these results, a method is then developed for selecting the optimal mode with the minimum time duration (or maximum channel capacity). Computer simulations confirm that the optimal mode outperforms the other modes.

Key Words : Cooperation relaying, Mode selection, Spectral efficiency, Channel capacity

Ⅰ. Introduction

Cooperative relaying appears to be a promising technique that allows spatially dispersed nodes in wireless networks to relay signals for each other, thereby exploiting the spatial diversity in fading channels [1]-[4]. Specifically, the use of repetition and space-time algorithms has been shown to result in spatial diversity [5], while a second-order spatial diversity has been achieved when analyzing a network using a single relay with different protocols [6]. When the channel state information is known at the transmitters, adaptive resource allocations can be performed to increase the performance as follows. For a more efficient use of power resources, the problem of optimally distributing the power among nodes has been considered in [7]-[9]. Also, using the outage probability enables the time/bandwidth and power to be optimally allocated [10]. Recently, joint optimization problem of power, bandwidth, and rate including selection of relay node and strategy has been investigated [11].

In this letter, an alternative approach to performance enhancement is considered based on the relaying protocol proposed in [6]. The relaying is operated based on a decode-and-forward mode. The three possible modes are considered in this letter. The first one is direct transmission mode that does not use any relay station (RS) for transmission between the base station (BS) and the mobile station (MS). The second one is diversity mode where the BS and RS transmit space-time coded data based on shared common data to the MS simultaneously and accordingly, diversity gain can be achieved. The last one is newly proposed mode in this letter in which the BS and RS transmit the independent data stream, respectively, to the MS and then, spatial multiplexing gain is obtained. After presenting the modes above mentioned, the time required by each mode is evaluated, as defined by their respective channel capacities. (According to the channel statistics between three links related with the BS, RS, and MS, the obtained values can be mutually different). Based on these results, a method is then developed to select the optimal mode with the minimum time duration (or maximum overall channel capacity). Computer simulations demonstrate that the optimal mode outperforms the other modes.

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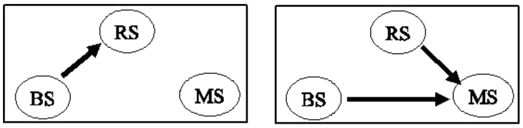
Ⅱ. Proposed optimal mode selection scheme

Fig. 1 shows the cooperation protocol considered in this paper, where the BS only communicates with the RS during the first time slot. Whereas, in the second time slot, the BS and RS both communicate with the MS. Before proceeding further, the time duration T is given by

$$T_1 = \frac{B}{\beta} \qquad (1)$$

where B is the total information data to be transmitted and β is the spectral efficiency. When the instantaneous channel gains of all links, i.e., BS-RS, BS-MS, and RS-MS, are known at the MS, the channel capacity of all links can be obtained, and intuitively replacing the spectral efficiency β with the capacity yields the time duration of (1). In the following, three different modes of relaying are examined and the corresponding time duration evaluated. The proposed selection procedure then chooses the mode with the minimum time duration.



First time slot

Second time slot

Fig. 1 Cooperation protocol

2.1 Direct transmission (no cooperation)

This is the baseline mode that does not involve any relaying, and is referred to as mode 1. In this mode, the time duration is given by

$$T_1 = \frac{B}{C_{bm}} \qquad (2)$$

where C_{bm} is the open-loop capacity of the BS-MS link. The term open-loop indicates that the channel gains of the link are not available at the transmitter.

2.2 Diversity transmission with cooperation

In this case, the BS transmits all the data to the RS, and the time required is $\frac{B}{C_{br}}$, where C_{br} is the closed-loop capacity of the BS-RS link. The term closed-loop indicates that the channel gains of the link are known at the transmitter, thus power controls can be performed at the BS. Next, using the B data, the BS and RS both consider (distributed) the space-time signal design to achieve a spatial diversity gain. Here, the time required is $\frac{B}{C_{div}}$, while the overall time duration is written by

$$T_2 = B\left(\frac{1}{C_{br}} + \frac{1}{C_{div}}\right) \qquad (3)$$

where C_{div} denotes the open-loop capacity of the diversity transmission by both the BS and the RS. Hereafter, this mode is referred to as mode 2.

2.3 Spatial multiplexing (SM) based transmission with cooperation

The newly proposed mode, called mode 3, is as follows. During the first time slot, the BS only transmits part of the data, i.e. αB for $0 \le \alpha \le 1$, to the RS, where α depends on the channel capacity of both the BS-MS and RS-MS links. The time duration of the first slot is given by $\alpha B / C_{br}$, where C_{br} is defined by (3). During the next time slot, the BS and RS transmit $(1-\alpha)B$ and αB, respectively, to the MS. If C_{sm} denotes the open-loop capacity with interferences, then the time required by each BS-MS and RS-MS link can be written as $(1-\alpha)B/C_{sm1}$ and $\alpha B/C_{sm2}$, respectively. The interesting result is that the equality $(1-\alpha)B/C_{sm1} = \alpha B/C_{sm2}$ gives $\alpha = \frac{C_{sm2}}{C_{sm1} + C_{sm2}}$, and finally the whole time duration for this mode is given by

$$T_3 = B\frac{C_{sm2}}{C_{sm1} + C_{sm2}}\left(\frac{1}{C_{br}} + \frac{1}{C_{sm2}}\right) \qquad (4)$$

If $C_{sm1} \gg C_{sm2}$, α converges to zero and the corresponding time duration is reduced to $\frac{B}{C_{sm1}}$, which is approximately equivalent to (2), thereby indicating direct transmission when the channel quality of the BS-MS link is better than that of the RS-MS link. Conversely, in the case of $C_{sm2} \gg C_{sm1}$, α converges to one and the corresponding time duration can be written as $B/\left(\frac{1}{C_{br}} + \frac{1}{C_{sm2}}\right)$, thereby indicating transmission through relaying.

2.4 Optimal mode selection algorithm

The optimal mode selection algorithm is summarized below.

Receiver (MS): optimal mode selection

- Given the instantaneous channel gains of all three links at the MS, the time duration of each mode can be obtained using (2), (3), and (4) and select the mode with the minimum value.
- The information about the selected mode and α in the case of an SM-based mode is transferred to the BS and RS.

Transmitter (BS and RS): transmission

- The data is transmitted according to the selected mode.

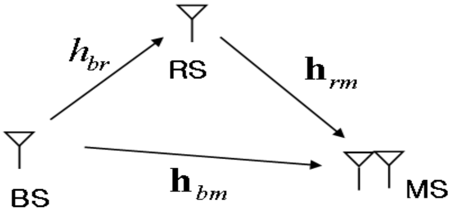


Fig. 2 Communication system mode for case 1

Ⅲ. Optimal mode selection for multiple antenna case

This section expands the optimal mode selection proposed in Section Ⅱ for multiple antenna environment. Two cases are considered: 1) BS with one transmit antenna, RS with one transmit and receive antenna, and MS with two receive antennas, 2) BS with four transmit antennas, RS with four transmit and receive antennas, and MS with two receive antennas.

3.1 Case 1

The communication system model considered in this subsection is shown in Fig. 2. The scheme for mode 1 employs maximum ratio combining (MRC) only at the receiver side and the capacity of the BS-MS link can be easily obtained by

$$C_{bm} = \log_2\left(1 + \frac{|\boldsymbol{h}_{bm}|^2 P_b}{N_0}\right). \tag{5}$$

In (5), $\boldsymbol{h}_{bm}$ is 2x1 flat-fading channel vector for the BS-MS link, N_0 is the variance of zero-mean Gaussian noise for each MS receive antennas, which is assumed to be equal to that for the RS, and P_b represents the transmission power at BS.

For mode 2, BS-RS link has the relation of single transmit and receive antenna and therefore, the capacity of BS-RS link is given by

$$C_{br} = \log_2\left(1 + \frac{|h_{br}|^2 P_b}{N_0}\right) \tag{6}$$

where h_{br} is the channel for BS-RS link. When employing STBC at both BS and RS and MRC in the MS to obtain the diversity gain, C_{div} can be written as

$$C_{div} = \log_2\left(1 + \frac{|\boldsymbol{h}_{bm}|^2 P_b + |\boldsymbol{h}_{rm}|^2 P_r}{N_0}\right) \tag{7}$$

In (7), $\boldsymbol{h}_{rm}$ is 2x1 flat-fading channel for RS-MS link and P_r denotes the transmission power at RS. The BS-RS link of the mode 3 is the same as that of mode 2. The scheme for mode 3 uses an ordered successive interference cancellation (OSIC)-based minimum mean square error (MMSE) detector at the receiver, while the

BS and RS transmit the independent data stream, respectively. Then, C_{sm1} and C_{sm2} corresponding to the BS-MS and RS-MS links, respectively, given by

$$\begin{aligned} C_{sm1} &= \log_2(1+SINR_1) \\ C_{sm2} &= \log_2(1+SINR_2) \end{aligned} \tag{8}$$

where

$$SINR_1 = \boldsymbol{h}_{bm}^H \left(\boldsymbol{H}_{bm} \boldsymbol{H}_{bm}^H + \frac{N_0}{P_b} \boldsymbol{I}_2 \right)^{-1} \boldsymbol{h}_{bm},$$

$$SINR_2 = \frac{\|\boldsymbol{h}_{rm}\|^2 P_r}{N_0},$$

$$\boldsymbol{H}_{bm} = [\boldsymbol{h}_{bm} \ \mathbf{0}].$$

In (8), $SINR$ denotes the signal-to-interference- plus-noise ratio (SINR). Using (6), (7) and (8), the time duration for mode 2 and 3 can be obtained from (3) and (4). respectively.

3.2 Case 2

In Fig. 3, the considered communication system in this subsection is shown. The scheme for mode 1 employs the double space-time transmit diversity (DSTTD) scheme in [12], involving two Alamouti STBC [13] encoders at the transmitter and an OSIC-based MMSE detector at the receiver. Based on the received signal vector given by [12], the capacity of the BS-MS link is expressed as [14, Section 8.3]

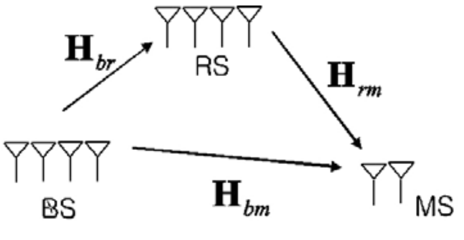


Fig. 3 Communication system mode for case 2

$$C_{bm} = \frac{1}{2} \sum_{k=1}^{4} \log_2(1+SINR_k) \tag{9}$$

where

$$SINR_k = \boldsymbol{h}_k^H \left(\sum_{j=k+1}^{4} \boldsymbol{h}_j \boldsymbol{h}_j^H + 4\frac{N_0}{P_b} \boldsymbol{I}_4 \right)^{-1} \boldsymbol{h}_k.$$

In (9), $\boldsymbol{h}_k$ is the k-th column vector of the effective channel matrix for DSTTD in BS-MS link, $SINR_k$ represents the SINR value for the k-th element of transmitted signal vector, and 1/2 is due to the reception of the two received signals. Using (9), the time duration for mode 1 can be obtained from (2).

For simplicity, mode 3 is considered first. The closed capacity of C_{br} for the BS-RS link is calculated as follows. Assuming that the channels between the BS and the RS are quasi-static due to fixed relaying, a singular value decomposition (SVD)-based modulation and detection scheme is employed for the BS-RS link and its capacity is written as [14, Section 7.1]

$$C_{br} = \sum_{i=1}^{4} \log_2\left(1 + \frac{P*_{b,i}}{N_0} \lambda_i^2\right) \tag{10}$$

where λ_is are the singular values of $\boldsymbol{H}_{br}$, $\boldsymbol{H}_{br}$ is a 4x4 channel matrix of the BS-RS link representing flat fading channels, and $\{P*_{b,i}\}$ is the power allocated to the i-th transmitting antenna at the BS:

$$P*_{b,i} = \left(\mu - \frac{N_0}{\lambda_i^2}\right)^+ \tag{11}$$

In (11), $x+ := max(x, 0)$ and μ is chosen to satisfy the power constraint $\sum_{i=1}^{4} P*_{b,i} = P_b$. For the next time slot, the STBC in [15] is used at both the BS and the RS, and OSIC-based MMSE detection used at the MS. Suppose that $\{s_{1,0}, s_{1,1}, s_{1,2}, s_{1,3}\}$ and $\{s_{2,0}, s_{2,1}, s_{2,2}, s_{2,3}\}$ are inputted to the ST encoder of the BS and RS, respectively. For the BS, the encoder then produces,

$$\begin{bmatrix} \tilde{s}_{1,0} & \tilde{s}_{1,1} & 0 & 0 \\ -\tilde{s}^*_{1,1} & \tilde{s}^*_{1,0} & 0 & 0 \\ 0 & 0 & \tilde{s}_{1,2} & \tilde{s}_{1,3} \\ 0 & 0 & -\tilde{s}^*_{1,3} & \tilde{s}^*_{1,2} \end{bmatrix}$$

where $\tilde{s}_{1,j} = Re[s_{1,j}] + jIm[s_{1,j+2(\mathrm{mod}4)}]$ for $0 \le j \le 3$. Continuing in this manner, the encoder output for the RS can also be obtained. Using the received signal model in [15], the received signal vector for the q-th receive antenna, $\boldsymbol{y}_q$, can be expressed as follows.

$$\begin{aligned} \boldsymbol{y}_1 &= \boldsymbol{H}_{c1}\tilde{\boldsymbol{s}}_1 + \boldsymbol{w}_1 \\ \boldsymbol{y}_2 &= \boldsymbol{H}_{c2}\tilde{\boldsymbol{s}}_2 + \boldsymbol{w}_2 \end{aligned} \tag{12}$$

where

$$\boldsymbol{H}_{c1} = \begin{bmatrix} h_{1,1} & h_{1,2} & h_{3,1} & h_{3,2} \\ h^*_{1,2} & -h^*_{1,1} & h^*_{3,2} & -h^*_{3,1} \\ h_{2,1} & h_{2,2} & h_{4,1} & h_{4,2} \\ h^*_{2,2} & -h^*_{2,1} & h^*_{4,2} & -h^*_{4,1} \end{bmatrix},$$

$$\boldsymbol{H}_{c2} = \begin{bmatrix} h_{1,3} & h_{1,4} & h_{3,3} & h_{3,4} \\ h^*_{1,4} & -h^*_{1,3} & h^*_{3,4} & -h^*_{3,3} \\ h_{2,3} & h_{2,4} & h_{4,3} & h_{4,4} \\ h^*_{2,4} & -h^*_{2,3} & h^*_{4,4} & -h^*_{4,3} \end{bmatrix},$$

$\tilde{\boldsymbol{s}}_1 = [\tilde{s}_{1,0}, \tilde{s}_{1,1}, \tilde{s}_{2,0}, \tilde{s}_{2,1}]^T$,
$\tilde{\boldsymbol{s}}_2 = [\tilde{s}_{1,2}, \tilde{s}_{1,3}, \tilde{s}_{2,2}, \tilde{s}_{2,3}]^T$,
$\boldsymbol{w}_1 = [w_1(0), w^*_1(1), w_2(0), w^*_2(1)]^T$, and
$\boldsymbol{w}_2 = [w_1(1), w^*_1(2), w_2(1), w^*_2(2)]^T$.
Assume that $\boldsymbol{H}_{c,1} = [\boldsymbol{c}_1, \boldsymbol{c}_2, \boldsymbol{c}_3, \boldsymbol{c}_4]$ and $H_{c,2} = [\boldsymbol{g}_1, \boldsymbol{g}_2, \boldsymbol{g}_3, \boldsymbol{g}_4]$. Based on (12), the SINR values for demodulating $\tilde{\boldsymbol{s}}_1$ can be evaluated as follows:

$$SINR_{s1,k} = \boldsymbol{c}_k^H \left(\sum_{j=k+1}^{4} \boldsymbol{c}_j \boldsymbol{c}_j^H + 2\frac{N_0}{P_b}\boldsymbol{I}_4 \right)^{-1} \boldsymbol{c}_k$$

for k=1,2. (13)

In (13), the SINR values associated with k=3,4 are obtained by replacing P_b with the transmission power of RS, P_r . Also, replacing $\boldsymbol{c}$ in (13) with $\boldsymbol{g}$ yields $SINR_{s2,k}$s, representing the SINR values for demodulating $\tilde{\boldsymbol{s}}_2$. Similarly to mode 1, (13) produces C_{sm1} and C_{sm2} corresponding to the BS-MS and RS-MS links, respectively, given by

$$C_{smi} = \frac{1}{4}\sum_{k=2i-1}^{2i} log_2(1 + SINR_{s1,k})(1 + SINR_{s2,k}) \tag{14}$$

where i=1,2 and 1/4 is due to the reception during the four-symbol duration for demodulating $\tilde{\boldsymbol{s}}_1$ and $\tilde{\boldsymbol{s}}_2$. Based on (10), (11), and (14), the time duration for mode 3 can be obtained from (4). The difference between mode 2 and 3 is that, in the former, the BS and RS share the same information data through the BS-RS link. Suppose that $\{s_{1,0}, s_{1,1}, s_{1,2}, s_{1,3}, s_{2,0}, s_{2,1}, s_{2,2}, s_{2,3}\}$ is transmitted from both the BS and the RS. Based on the STBC in [15], an ST code is also assumed where at any time the symbols transmitted by any pair of antennas must carry a component (in- or quadrature) of all eight entries $s_{1,0}, s_{1,1}, s_{1,2}, s_{1,3}, s_{2,0}, s_{2,1}, s_{2,2}, s_{2,3}$. The encoder output of BS is then given by

$$\begin{bmatrix} \tilde{s}_{1,0} & \tilde{s}_{1,1} & 0 & 0 \\ -\tilde{s}^*_{1,1} & \tilde{s}^*_{1,0} & 0 & 0 \\ 0 & 0 & \tilde{s}_{2,0} & \tilde{s}_{2,1} \\ 0 & 0 & -\tilde{s}^*_{2,1} & \tilde{s}^*_{2,0} \end{bmatrix}$$

while the RS encoder yields

$$\begin{bmatrix} \tilde{s}_{1,2} & \tilde{s}_{1,3} & 0 & 0 \\ -\tilde{s}^*_{1,3} & \tilde{s}^*_{1,2} & 0 & 0 \\ 0 & 0 & \tilde{s}_{2,2} & \tilde{s}_{2,3} \\ 0 & 0 & -\tilde{s}^*_{2,3} & \tilde{s}^*_{2,2} \end{bmatrix},$$

where, $\tilde{s}_{i,j} = Re[s_{i,j}] + jIm[s_{i(\mathrm{mod}2)+1,i}]$ for i=1,2 and $0 \le j \le 3$. Collecting all the received signals gives the equivalent vectors for (12) with the exception that $\tilde{\boldsymbol{s}}_1=[\tilde{s}_{1,0},\tilde{s}_{1,1},\tilde{s}_{1,2},\tilde{s}_{1,3}]^T$ and $\tilde{\boldsymbol{s}}_2=[\tilde{s}_{2,0},\tilde{s}_{2,1},\tilde{s}_{2,2},\tilde{s}_{2,3}]^T$. Therefore, the SINR values for $\tilde{\boldsymbol{s}}_1$ and $\tilde{\boldsymbol{s}}_2$ are redefined as

$$\overline{SINR}_{s1,k}=\boldsymbol{c}_k^H\left(\sum_{j=1}^{4}\boldsymbol{c}_j\boldsymbol{c}_j^H+2\frac{N_0}{P_b}\boldsymbol{I}_4\right)^{-1}\boldsymbol{c}_k,$$

$$\overline{SINR}_{s2,k}=\boldsymbol{g}_k^H\left(\sum_{j=1}^{4}\boldsymbol{g}_j\boldsymbol{g}_j^H+2\frac{N_0}{P_r}I_4\right)^{-1}\boldsymbol{g}_k \quad \text{for}$$

$1\le k\le 4$ respectively. When employing the OSIC-based MMSE detection, C_{div} can be obtained using (14) as follows:

$$C_{div}=\frac{1}{4}\sum_{k=1}^{4}\log_2\left(1+\overline{SINR}_{s1,k}\right)\left(1+\overline{SINR}_{s2,k}\right) \tag{15}$$

Using (10) and (11), and (15), the time duration for mode 2 can be evaluated.

Ⅳ. Simulation Results and Discussion

Computer simulations were conducted to examine the performance of the proposed scheme described in Section III. The signal-to-thermal noise ratio S was expressed, in simplest form, as follows:

$$S=\frac{P_t\sigma_h G_t G_r}{LWF} \tag{16}$$

where P_t is the transmission power, σ_h is the gain of flat-fading channel with zero-mean complex standard normal distribution, L is the path loss from transmitter output to receiver input, G_t and G_r are the antenna gains in transmitter and receiver, respectively, W is the noise bandwidth of receiver, and F is the effective noise figure. In the simulation, the following parameters were assumed: P_b=43dBm and P_r=40dBm, G_r was set at 8dB for the RS receive antenna gain, noise bandwidth was given by W=10MHz, and noise figure F was -174dBm/Hz. The path loss L as a function of the distance in meters was assumed to obey the IEEE 802.16d model in [16] given by $L=A+10\gamma\log_{10}\left(\frac{d}{d_0}\right)+s$, for $d\ge d_0$ where s was the shadow fading component set at zero and A and γ were characterized as follows. A was a fixed quantity and defined as $A=20\log_{10}\left(\frac{4\pi d_0}{\gamma}\right)$ where d_0=100m and the wavelength λ was 0.15m (evaluated at 2GHz). The path loss exponent γ was fixed at 3.28, 3.76, and 4.0 for the BS-RS, BS-MS, and RS-MS links, respectively. The location of the RS was fixed at a distance of 620m from the BS. The distance between the BS and the MS was varied from 200m to 1600m and the MS was assumed to be located on the line between the BS and the RS.

Figs. 4 and 5 show the spectral efficiency of the possible presented modes and proposed optimal mode for case 1 and case 2, respectively. Here, the spectral efficiency was the average of 1/(required time duration) of 100 independent channel realizations, where B was set at one. It was shown that the proposed scheme outperformed the other modes in both cases. Statistically, it was observed that mode 1 (direct transmission) was preferred to mode 2 (diversity transmission) and 3 (SM-based transmission) when the location of the MS was up to 900m and 450m from the BS for case 1 and case 2, respectively, while beyond this distance, the relay systems produced a better performance. As seen by Figs. 4 and 5, the spectral efficiency of the mode 1 is larger than that of the other modes using the RS by a factor of 3 and 1.5, when the MS was located 200m from the BS. When the MS was located 1000m from the BS, the spectral efficiency of the proposed optimal mode increased by a factor of 1.14 and 1.3 compared to that for

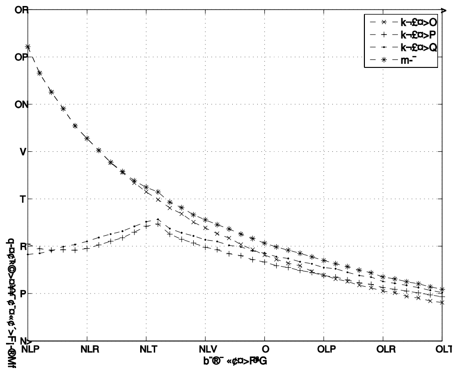


Fig. 4 Spectral efficiency of modes 1, 2, and 3 plus optimal mode for case 1

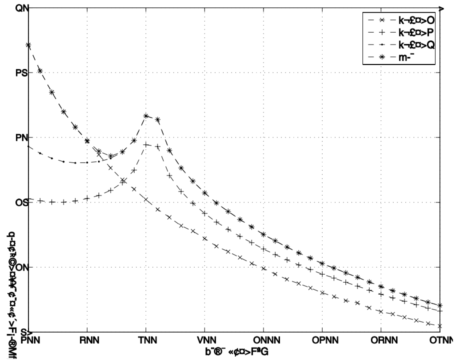


Fig. 5 Spectral efficiency of modes 1, 2, and 3 plus optimal mode for case 2

direct transmission, in case 1 and case 2, respectively. Furthermore, in both cases, mode 3 resulted in a spectral efficiency that was higher than that for mode 2, indicating that mode 3 using the SM concept was preferable to enhancing the capacity.

V. Conclusions

Three possible communication modes, which are direct transmission, diversity transmission with cooperation, and spatial-multiplexing (SM) based transmission with cooperation, were presented for wireless relay systems, along with a process for selecting the mode with the maximum spectral efficiency. In particular, a new SM-based transmission mode was proposed based on the channel capacity of the links. The channel information required by the proposed approach should be available at the mobile station. The advantage of the proposed optimal mode over the presented possible modes was demonstrated through computer simulation. Expanding the proposed mode selection algorithm to consider Doppler-induced dispersion remains as a further research topic.

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