A Full-Rate Cooperative Communication Strategy in Wireless Relay Networks

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Abstract. In this paper, we propose a new full-rate cooperative communication strategy in wireless relay networks without direct path between source and destination. This strategy coined full-rate amplify-and-forward (FRAF) utilizes multiple relay nodes to take turns to amplify and forward data package for the transmitter at different time slot. Thus the source node could continue sending without cessation. On the other hand, prevailing linear constellation precoding process is adopted at the source node to solve the problem caused by the imbalance of the error performance of the data sent at odd and even time slots. Furthermore, we analyze the outage probability and certificate that FRAF strategy can achieve the full diversity gain. The simulation results indicate that FRAF could improve the performance of the system effectively compared to the conventional amplify-and-forward (AF) and decode-and-forward (DF) strategy.

Keywords: Wireless relay networks, full-rate cooperative communication, precoding, wireless communication.

1 Introduction

In the wireless communication environment, the transmitting performance is impacted by the fading characteristic of the wireless channel seriously. By utilizing the independence of the different channels and broadcast trait of the wireless channel, cooperative communication makes the mobile nodes in the network help each other to transmit information and yield cooperative diversity gain. It is one of the most effective ways to mitigate the fading of the wireless channels in the networks. Among the cooperative schemes which have been proposed, amplify-and-forward and decode-and-forward are the most famous [1][2].

Because of the lack of the wireless frequency resource, wireless communication in high frequency band attracts considerable attention. Considering the characteristic of fast fading of the high-frequency transmission, the source node at the

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edge of the scenario can communicate with the destination node only with the help of the relays for guaranteeing the enough coverage of networks. That means there is no direct path between the source and destination. The performance of traditional AF strategy with best relay selection in this kind scene is analyzed, with the diversity gain order provided as well [3]. But the conventional cooperative communication strategies make the source transmit one data package in two time slot for obtaining the diversity gain, which means the data transmission rate between source and destination is halved. Some schemes have been proposed to solve this problem. Non-orthogonal AF (NAF) transmission strategy makes the source node send data continuously and the relay node only forwards the data sent by source node at the odd time slot [4]. It is proved that NAF strategy can obtain the optimal diversity-multiplex tradeoff [5], but it causes the imbalance of the error performance of the data sent at odd time slots and even time slots. Furthermore, a strategy which utilizes precoding and space-time coding to achieve full-rate transmission shows better performance [6]. However, all schemes mentioned above are applied in the scene where the direct path between source and destination exists, which is essential for full-rate transmission of them. So these full-rate transmission strategies are not applicable in the scenario without the direct path.

In this paper, a new cooperative communication strategy called FRAF which can achieve full-rate transmission in the scenario without direct path between source and destination is proposed. This strategy utilizes multiple relay nodes to take turns to help source node forward data at the odd and even time slots, which can guarantee the source node to send out continuously without cessation. Furthermore, precoding process avoids the imbalance of error performance of information transmitted at odd and even time slots. We analyze the performance of FRAF strategy and verify that it can achieve full diversity gain.

2 System Model

The system model is illustrated in Fig.1 where one source node S sends information to destination node D with the help of L relay nodes $R_i (i = 1, 2, \cdots, L)$. All of the nodes are equipped with only one antenna and work in the half-duplex mode. There is no direct path between source and destination which makes the help of relay nodes essential. All wireless channels are slow-fading and independent. Furthermore, the channel fading coefficient is modelled as zero-mean, independent, circularly symmetric complex Gaussian random variable. Considering slow fading, the fading coefficient remains constant over the transmission of one source data block and independent in different transmission. The additive channel noise is modelled as a complex Gaussian random variable with mean zero and variance N_0. To guarantee the full-rate transmission, we suppose the source node and relay node operating at different frequency band which causes no interference between them.

Fig.1 presents the process of FRAF strategy in which we set the i-th and $(i + 1)$-th time slots as a time slot pair. The data which will be sent in the time slot pair is precoded in the source node. At the i-th time slot, the source node S sends data to relay nodes, and then all of relay nodes receive the data except the one which is chosen to be the forward node at the $(i-1)$-th time slot (This node is sending data to destination at this time). Among the relay nodes receiving the data, the one with best channel condition is selected to be the forward node of the next time slot. At the $(i+1)$-th time slot, the relay node selected at i-th time slot forwards the data to the destination node and the others receive the data transmitted by source node. Duplicating this process, the full-rate transmission can be achieved.

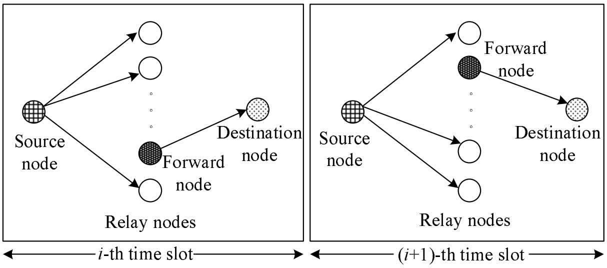

Fig. 1. System model of FRAF strategy

3 Mathematic Description and Performance Analysis

3.1 Precoding

At a time slot, the data transmitted by the source node is forwarded by the forward node selected from $(L-1)$ relay nodes according to the channel condition. If one relay node's channel situation is very good continuously, this relay node would be always selected as the forward node at the odd or even time slot which causes the imbalance of error performance of the data transmitted at odd and even time slot. To solve this problem and improve the stability of the whole system, precoding is adopted to process the data transmitted at a pair of time slots at the source node. The length of single data package is denoted as N and $\mathbf{s} = (s_1, s_2, \cdots, s_{2N})^T$ represents the source data which will be transmitted at a pair of time slots. Furthermore, $\mathbf{x} = (x_1, x_2, \cdots, x_{2N})^T$ denotes the data that have been precoded and $\mathbf{K}$ denotes the precoding matrix. Thus we obtain:

$$\mathbf{x} = \mathbf{K}_{2N \times 2N}\mathbf{s} \tag{1}$$

The source data is overlapped through precoding and can be decoded with maximum likelihood (ML) decoding algorithm. Linear constellation precoding (LCP) matrix is a common precoding matrix, which is a kind of unitary orthonormal matrix with excellent ability to overlap the source information effectively. Therefore, we select a LCP matrix mentioned in [10] to be the precoding matrix of FRAF strategy, as follow:

$$\mathbf{K} = \frac{1}{\sqrt{2N}} \begin{pmatrix} 1 & \beta_0 & \cdots & \beta_0^{2N-1} \\ 1 & \beta_1 & \cdots & \beta_1^{2N-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \beta_{2N-1} & \cdots & \beta_{2N-1}^{2N-1} \end{pmatrix} \quad (2)$$

where $\beta_k = e^{j\frac{k+1/4}{N}\pi}$ and $N = 2^{q-1}$, and q is an integer which is greater than one.

3.2 Mathematic Description and Performance of FRAF

The performance of FRAF strategy is analyzed with a pair of time slots as one unit. Assuming R_1, R_2 denote the relay nodes selected as the forward nodes at the first and the second time slot separately, P_S, P_{R_1}, P_{R_2} denote the sending power of the source node and relay nodes. The data received by the relay nodes can be described as follow:

$$y_{R_i} = \sqrt{P_S} h_{SR}^i x_i + n_i', i = \{1, 2, \cdots, 2N\} \quad (3)$$

$$h_{SR}^i = \begin{cases} h_{SR_1}, & 1 \leq i \leq N; \\ h_{SR_2}, & N < i \leq 2N. \end{cases}$$

where h_{SR}^i is the channel fading coefficient of the channel between the source node and the relay node. Also we can get the mathematics description of the data received by the destination node:

$$y_i = \sqrt{P_R^i} h_{RD}^i s_{Ri} + n_i, i = \{1, 2, \cdots, 2N\} \quad (4)$$

where h_{RD}^i is the channel fading coefficient of the channel between the relay node and the destination node. On the other hand, $s_{Ri} = y_{Ri}/\theta_i$ is the data which is normalized at the relay node. We have:

$$h_{RD}^i = \begin{cases} h_{R_1D}, & 1 \leq i \leq N; \\ h_{R_2D}, & N < i \leq 2N. \end{cases}$$

$$P_R^i = \begin{cases} \sqrt{P_S|h_{SR_1}|^2 + 1}, & 1 \leq i \leq N; \\ \sqrt{P_S|h_{SR_1}|^2 + 1}, & N < i \leq 2N. \end{cases}$$

$$\theta_i = \begin{cases} h_{R_1D}, & 1 \leq i \leq N; \\ h_{R_2D}, & N < i \leq 2N. \end{cases}$$

Considering the whole transmission procedure at a pair of time slots, the description with matrix form can be obtained as follow:

$$\mathbf{y} = \mathbf{HKs} + \mathbf{n} \tag{5}$$

where $\mathbf{s} = [s_1, s_2, \cdots, s_{2N}]^T$ and $\mathbf{y} = [y_1, y_2, \cdots, y_{2N}]^T$ denote the data sent by source and received by destination separately, and

$$\mathbf{H}_{2N\times 2N} = diag\{\sqrt{P_S P_R^1} h_{SR}^1 h_{RD}^1/\theta_1, \cdots, \sqrt{P_S P_R^{2N}} h_{SR}^{2N} h_{RD}^{2N}/\theta_{2N}\}$$

$$\mathbf{n} = [n_1 + \sqrt{P_R^1} h_{RD}^1 n_1'/\theta_1, \cdots, n_{2N} + \sqrt{P_R^{2N}} h_{RD}^{2N} n_{2N}'/\theta_{2N}]^T$$

The sum-rate achieved by the proposed strategy can be written as:

$$I = \frac{1}{2N} \log_2 \det\{\mathbf{I}_{2N} + \mathbf{HKK}^H\mathbf{H}^H\mathbf{N}^{-1}\} \tag{6}$$

where

$$\mathbf{N} = diag\{1 + P_R^1 |h_{RD}^1|^2/\theta_1^2, \cdots, 1 + P_R^{2N}|h_{RD}^{2N}|^2/\theta_{2N}^2\}$$

For the simplicity to analyze the performance of FRAF strategy, we suppose all nodes have the same transmitting power as $P = P_S = P_{R_1} = P_{R_2}$ and the high signal-to-noise ratio (SNR) assumption is applied. Also, the SNR is denoted as ρ. Considering the matrix $\mathbf{K}$ is unitary orthonormal, the following result can be obtained:

$$\begin{aligned} I &= \frac{1}{2N} \log_2 \left[\prod_{i=1}^{2N} \left(1 + \frac{\rho |h_{SR}^i|^2 |h_{RD}^i|^2}{1/\rho + |h_{SR}^i|^2 + |h_{RD}^i|^2} \right) \right] \\ &\approx \frac{1}{2} \log_2 \left[\left(1 + \frac{\rho |h_{SR_1}|^2 |h_{R_1D}|^2}{|h_{SR_1}|^2 + |h_{R_1D}|^2} \right) \times \right. \\ &\qquad \left. \left(1 + \frac{\rho |h_{SR_2}|^2 |h_{R_2D}|^2}{|h_{SR_2}|^2 + |h_{R_2D}|^2} \right) \right] \end{aligned} \tag{7}$$

Define $\lambda = |h_{SR}^i|^2 |h_{RD}^i|^2/(|h_{SR}^i|^2 + |h_{RD}^i|^2)$. As shown in (7), the performance of the whole system can be maximized if the relay node with maximal λ value is selected as the forward node. So λ is set as the criterion to select the forward node.

The desired data transmitting rate of the source node is denoted as R. The outage probability is selected as the indicator of the performance of the communication system. When the maximal transmitting rate provided by the system cannot satisfy the requirement of source node, the outage occurs. The outage probability denoted as P_{outage} can be written as:

$$P_{\text{outage}} = \Pr(I < R) \tag{8}$$

Utilizing formula (7), we obtain:

$$\begin{aligned} I &= \frac{1}{2}\log_2\left(1+\frac{\rho|h_{SR_1}|^2|h_{R_1D}|^2}{|h_{SR_1}|^2+|h_{R_1D}|^2}\right.\\ &\quad+\frac{\rho|h_{SR_2}|^2|h_{R_2D}|^2}{|h_{SR_2}|^2+|h_{R_2D}|^2}\\ &\quad\left.+\frac{\rho|h_{SR_1}|^2|h_{R_1D}|^2}{|h_{SR_1}|^2+|h_{R_1D}|^2}\times\frac{\rho|h_{SR_2}|^2|h_{R_2D}|^2}{|h_{SR_2}|^2+|h_{R_2D}|^2}\right)\\ &> \frac{1}{2}\log_2\left(1+\frac{\rho|h_{SR_1}|^2|h_{R_1D}|^2}{|h_{SR_1}|^2+|h_{R_1D}|^2}\right.\\ &\quad\left.+\frac{\rho|h_{SR_2}|^2|h_{R_2D}|^2}{|h_{SR_2}|^2+|h_{R_2D}|^2}\right) \end{aligned} \tag{9}$$

Taking it into (8), the outage probability can be shown as:

$$P_{\text{outage}} = \Pr(I < R) < \Pr\left(y_1 + y_2 < \frac{2^{2R}-1}{\rho}\right) \tag{10}$$

where $y_1 = \rho|h_{SR_1}|^2|h_{R_1D}|^2/(|h_{SR_1}|^2+|h_{R_1D}|^2)$, $y_2 = \rho|h_{SR_2}|^2|h_{R_2D}|^2/(|h_{SR_2}|^2+|h_{R_2D}|^2)$. Because the modulus square of channel fading coefficient is an exponentially distributed variable,we can get the probability distribution function of y_1, y_2 as follow [7]:

$$\begin{aligned} P(y) &= \int_y^{+\infty} e^{-z}\left(1-e^{-\frac{yz}{z-y}}\right)dz + \int_0^y e^{-z}dz\\ &= 1 - 2ye^{-2y}K_1(2y) \end{aligned} \tag{11}$$

where $K_1(x)$ is the modified Bessel function of the second kind with first order. Defining $\alpha = (2^{2R}-1)/\rho$, it is obvious that $\alpha \to 0$ for large SNR. The Bessel function can be approximated as $K_1(x) \approx 1/x$ with small value of x. Furthermore, considering the relay selection of FRAF strategy, the relay node with the largest value of selection criterion will be chosen as forward node. Therefore, the probability distribution function of y_1, y_2 changes. With (10) and (11), the following approximation can be obtained as:

$$\begin{aligned} \Pr(I < R) &< \int_0^\alpha P'(y)P(\alpha-y)^{L-1}dy\\ &\approx \int_0^\alpha 2^L(\alpha-y)^{L-1}dy\\ &\sim \alpha^L \end{aligned} \tag{12}$$

The diversity gain order of FRAF strategy is denoted as d, we can have:

$$d = \lim_{\rho\to+\infty}\left(-\frac{\log P_{\text{outage}}}{\log\rho}\right) = L \tag{13}$$

Considering that L is the number of the relay nodes, it is demonstrated that FRAF strategy achieves the full diversity gain with (13) which is also achieved by many existing cooperative communication strategy. But FRAF is a full-rate transmission strategy with full diversity gain at the scenario without direct path between source node and destination node.

4 Simulation Results

In this section, we give some simulation result to validate our theoretical analysis and the performance of FRAF strategy. Assuming $R = 2.5$bits/s/Hz and the channels between the transmitters and receivers have the identical SNR ρ. The conventional AF and DF cooperative communication strategies which select the relay node with best channel condition as the forward node are chosen as the comparison scheme.

Fig.2 shows the outage probability of three strategies when $L = 2$. Considering there are only two relay nodes, no selection of relay nodes is required and two relay nodes serve as the forward node at the odd and even time slot separately for FRAF strategy. Because the FRAF strategy achieves the full-rate transmission and the source node can send out data continuously without cessation, it is not necessary to guarantee transmission at each sending time slot to achieve the transmission rate of $2R$. Therefore, it is definite to see that FRAF strategy manifests better performance and the outage probability of it is much less compared to the other two cooperative communication strategies. On the other hand, three strategies' curves show the similar decreasing slope as the SNR goes down, which indicates that the three strategies have the same diversity gain and verifies the accuracy of our theory analysis. Furthermore, the transmission rates of three strategies are illustrated in Fig.3. It is obvious that the transmission rate achieved by FRAF strategy is much higher than the other two strategies and the advantage of full-rate transmission is manifested clearly.

The outage probabilities of three strategies are compared in Fig.4 when $L = 4$. It is obvious that the performance of each strategy is improved effectively and the slope of the curve of outage probability is much higher compared to the one in Fig.2. The reason is that the diversity gain order increases as the growth of the number of the relay nodes. Furthermore, FRAF strategy still displays much better performance than the conventional AF and DF cooperative transmission strategies.

The effect of precoding is measured by BER (the bit error ratio) of data sent at odd and even time slot separately. Assuming $L = 2$ and QPSK is adopted as the modulation mode. The SNR of the channel between relay node which is selected to forward the data sent by source node at even time slot and destination node is $(\rho - 5)$dB as the others are ρdB. It means this relay node has worse channel condition to communication with destination node than the other one. The simulation results are shown in Fig.5 and Fig.6. It is obvious that the BER of the data sent by source node at even time slot is much higher than the one sent at odd time slot when the precoding is not adopted as illustrated in Fig.5. On the

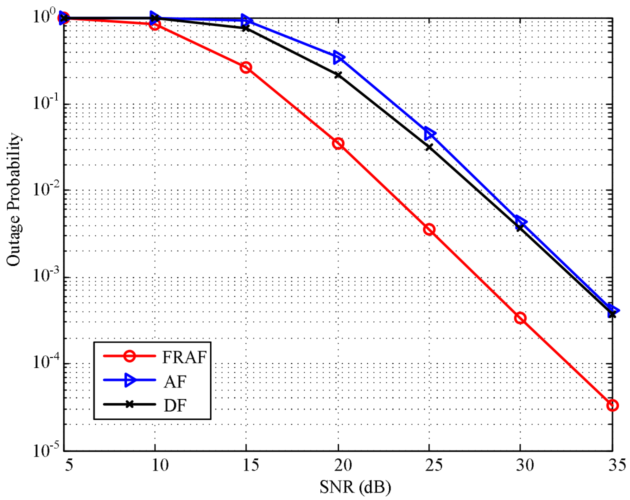

Fig. 2. Outage probability of different strategies, $L = 2$

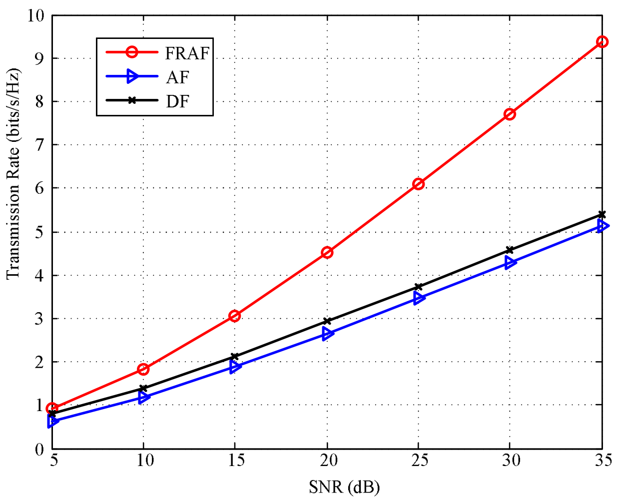

Fig. 3. Transmission rate of different strategies, $L = 2$

other hand, the imbalance of BER at odd and even time slot does not exist after the source data is operated with the precodingin the Fig.6. So the precoding is effective enough to solve the imbalance problem. Furthermore, we can find out that the total average BER of FRAF strategy decreases as the precoding is adopted through comparing the curves in Fig.5 and Fig.6. The reason is that the data is overlapped effectively by precoding and some errors can be rectified through ML decoding. It makes the ability of system to consist fading improved.

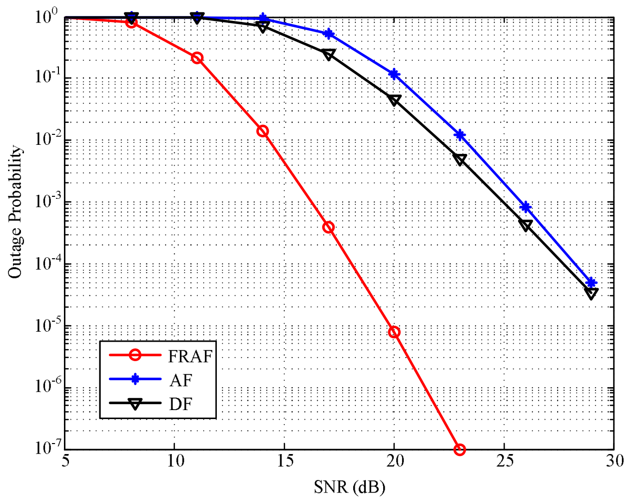

Fig. 4. Outage probability of different strategy, $L = 4$

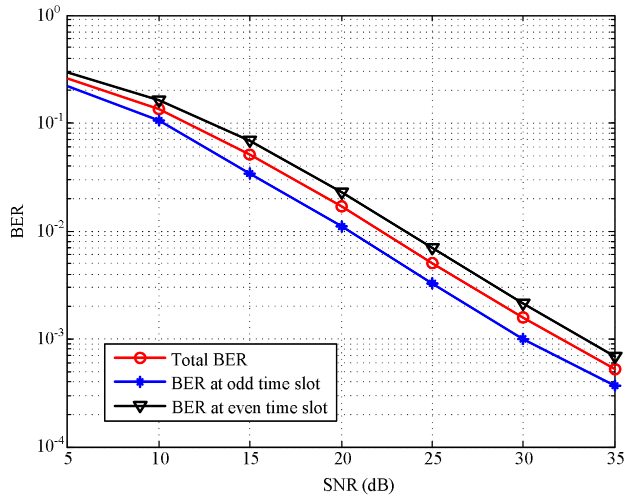

Fig. 5. The BER of FRAF without precoding

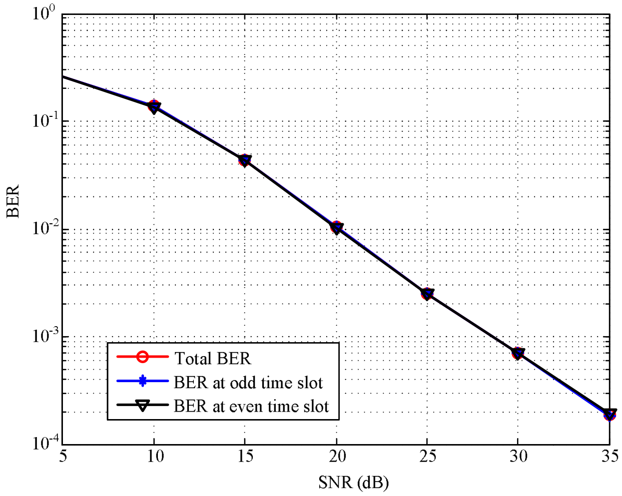

Fig. 6. The BER of FRAF with precoding

5 Conclusion

A new full-rate cooperative communication strategy called FRAF in wireless relay networks scenario without direct path between source and destination is proposed in this paper. This strategy utilizes multiple relay nodes to cooperate with one source node. At the odd and even time slot, the forward node is acted by the different relay node. Hence the source node can transmit data continuously without cessation and full-rate transmission is achieved. In addition, the precoding process at the source node avoids the imbalance of error performance of data sent at odd and even time slot. The theoretical analysis and computer simulation indicate that FRAF strategy can achieve both full-rate transmission and full diversity gain, which can improve the performance of system effectively. Furthermore, designing a specific protocol and measuring the additional expense of FRAF strategy are the next work of us.

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References

1. Sendonaris, A., Erkip, E., Aazhang, B.: User Cooperation Diversity-part I: System Description. IEEE Trans.on Commu. 51(11), 1927–1938 (2003)
2. Laneman, J.N., Tse, D.N.C., Wornell, G.W.: Cooperative diversity in wireless networks: efficient protocols and outage behavior. IEEE Trans. on Information Theory 50, 3062–3080 (2004)

3. Jing, Y., Jafarkhani, H.: Single and Multiple Relay Selection Schemes and their Achievable Diversity Orders. IEEE Trans. on Wireless Commu. 8(3), 1414–1423 (2009)
4. Nabar, R.U., Bolcskei, H., Kneubuhler, F.W.: Fading Relays Channels: Performance Limitsand Space-Time Signal Design. IEEE Journalon Selected Areas in Commu. 22(6), 1099–1109 (2004)
5. Azarian, K., Gamal, H.E., Schniter, P.: On the Achievable Diversity-Muplexing Tradeoff in Half-Duplex Cooperative Channels. IEEE Trans. on Inform. Theory 51(12), 4152–4172 (2005)
6. Zhang, W., Letaief, K.B.: Full-Rate Distributed Space-Time Codesfor Cooperative Communications. IEEE Trans. onWireless Commu. 7(7), 2446–2451 (2008)
7. Ding, Z., Ratnarajah, T., Leung, K.K.: On the study of network coded AF transmission protocol for wireless multiple access channels. IEEE Trans. on Wireless Commu. 8(1), 118–123 (2009)
8. Ding, Z., Leung, K.K., Goeckel, D.L.: On the study of network coding with diversity. IEEE Trans. on Wireless Commu. 8(3), 1247–1259 (2009)
9. Yang, S., Belfiore, J.C.: On Slotted Amplify-and-Forward Cooperative Diversity Schemes. In: IEEE ISIT, pp. 2446–2450 (July 2006)
10. Kwon, U.K., Choi, C.H., Im, G.H.: Full-Rate Cooperative Communications with Spatial Diversity for Half-Duplex Uplink Relay Channels. IEEE Trans. on Wireless Commu. 8(11), 5449–5454 (2009)