Opportunistic nonorthogonal amplify-and-forward cooperative communications

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The first opportunistic cooperative communications scheme based upon nonorthogonal transmission, namely the opportunistic nonorthogonal amplify-and-forward scheme, is proposed. It is proved that the proposed scheme can achieve a superior diversity- multiplexing trade-off performance bound than the existing opportunistic relaying schemes. Simulation results validate the proof.

Introduction: Cooperative communications [1] create diversity gains for network users with a single antenna. The classical cooperative scheme consists of two orthogonal time slots (TS): a broadcasting TS for a source (S) to transmit its signal to the intended destination *(D)*, and a relaying TS for a relay (R) to retransmit S's signal to D. There are amplify-and-forward (AF) and decode-and-forward (DF) cooperative strategies. To enhance system performance, nonorthogonal cooperative transmission that allows S to continue to transmit during the relaying TS [2], and distributed cooperation that introduces multiple relays for signal retransmissions [3] were introduced. Integrating the two approaches, the distributed nonorthogonal AF (DNAF) scheme [4] was proposed. It has a better diversity-multiplexing trade-off (DMT) [5] performance than the orthogonal distributed cooperation schemes [3]. However, distributed cooperation brings technical challenges such as user interference and power consumption owing to the retransmissions of multiple relays. Opportunistic relaying cooperation [6] alleviates those challenges by always selecting the best relay for signal retransmission. It was shown that provided the same number of relays are available, opportunistic relaying can achieve the same DMT performance as distributed cooperation. However, most of the current research on opportunistic relaying [6, 7] is restricted to orthogonal transmission, limiting the ultimate potential of system performance. Results concerning the theoretical and simulation performance of nonorthogonal opportunistic relaying are unknown. Addressing this issue, this Letter proposes an opportunistic nonorthogonal AF (ONAF) scheme. The DMT analysis and simulation results of the scheme are presented.

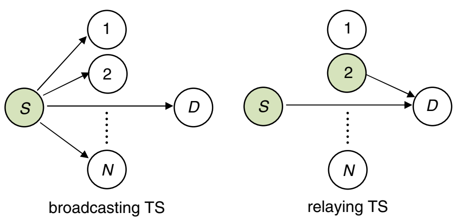

Fig. 1 *ONAF cooperative scheme*

System model: Let $S_r = \{1, 2, \ldots, N\}$ denote the set of relays willing to offer signal retransmission. All users operate with the half-duplex constraint and transmit with a normalised energy $\varepsilon = 1$. Using σ^2 to denote the variance of noise observed at the receiver, the channel signal-to-noise ratio (SNR) can be therefore defined as: $p = \sigma^{-2}$. It is assumed that all channels exhibit a similar value of ρ. The ONAF relaying cooperation is indicated in Fig. 1. In the broadcasting TS, S transmits its signal to D and it is also overheard by all relays, i.e.

$$y_D[i] = \alpha_{SD}x_S[i] + n_D[i], i = 1, 2, \ldots, l/2 \quad (1)$$

$$y_k[i] = \alpha_{Sk}x_S[i] + n_k[i], i = 1, 2, \ldots, l/2 \quad (2)$$

where $k \in S_r$, l denotes the length of S's signal over two TSs, and α_{AB} denotes the complex Rayleigh fading coefficients of the channel between nodes A and B. All channels are assumed to be quasi-static fading and statistically independent. n_A denotes the zero mean additive white Gaussian noise (AWGN) observed at node A, with variance σ_A^2. With feedback from S and D, the relays obtain instantaneous channel measurements of α_{Sk} and α_{kD}. The best relay b is chosen according to [6, 7]:

$$b = \arg\max_{k \in S_r}\{\min\{|\alpha_{Sk}|^2, |\alpha_{kD}|^2\}\} \quad (3)$$

In the relaying TS, the selected relay b will send out pilot symbols to notify others to keep silent. Then, both S and b transmit to D, and so the received signal at D is:

$$y_D[i] = \alpha_{SD}x_S[i] + \alpha_{bD}x_b[i] + n_D[i], i = l/2+1, l/2+2\ldots, l \quad (4)$$

where x_b is an amplified version of y_b, i.e. $x_b[i] = \beta_b y_b[i - l/2]$ and $\beta_b \leq (|\alpha_{Sb}|^2 + \sigma_b^2)^{-1/2}$.

Definition I: Let δ_{AB} denote the exponential order of $|\alpha_{AB}|^2$ such that:

$$\delta_{AB} = -\lim_{p\to\infty}\frac{\log|\alpha_{AB}|^2,}{\log\rho} \quad (5)$$

$|\alpha_{AB}|^2$ can be alternatively expressed as: $|\alpha_{AB}|^2 \doteq p^{-\delta_{AB}}$ [4]. Note that $\dot{\leq}$ is defined similarly and the base of the logarithm is 2.

Definition II: Consider a coded system that can achieve an outage probability of $P_o(\rho)$ and an averaged transmission rate of $R(\rho)$ bits/s/Hz, the diversity gain d and multiplexing gain r are defined as [5]:

$$d = -\lim_{p\to\infty}\frac{\log P_o(\rho)}{\log\rho}, r = \lim_{p\to\infty}\frac{R(\rho)}{\log\rho} \quad (6)$$

The balance between d and r is called the diversity-multiplexing trade-off, denoted by $d(r)$. The system outage probability can be expressed as: $P_o(p)\dot{\leq}p^{-d(r)}$. Therefore, a scheme with better DMT characteristics should yield a better outage performance.

Diversity-multiplexing trade-off analysis: The transmission model presented above can be written in a matrix form as:

$$\begin{bmatrix} y_D[i] \\ y_D[i+l/2] \end{bmatrix} = \underbrace{\begin{bmatrix} \alpha_{SD} & 0 \\ \alpha_{bD}\beta_b\alpha_{Sb} & \alpha_{SD} \end{bmatrix}}_{\Sigma} \times \begin{bmatrix} x_S[i] \\ x_S[i+l/2] \end{bmatrix}$$
$$+ \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \beta_b\alpha_{bD} & 1 \end{bmatrix}}_{\Omega} + \underbrace{\begin{bmatrix} n_D[i] \\ n_b[i] \\ n_D[i+l/2] \end{bmatrix}}_{\Gamma} \quad (7)$$

where $i = 1, 2, \ldots, l/2$. The mutual information ($\Im$) of the ONAF scheme can therefore be determined by $\Im = \frac{1}{2}\log\det\{I_2 + \Sigma\Sigma^\dagger[\Omega E(\Gamma\Gamma^\dagger)\Omega^\dagger]^{-1}\}$, where I_2 denotes the 2×2 identity matrix, $M^\dagger$ and M^{-1} denote the Hermitian conjugate and inverse of matrix M, and E is the expectation operation. Hence,

$$\Im = \frac{1}{2}\log[1 + |\alpha_{SD}|^2\rho + \frac{|\alpha_{SD}|^4\rho^2}{1+|\alpha_{bD}|^2\beta_b^2} + \frac{(|\alpha_{SD}|^2 + |\alpha_{Sb}|^2|\alpha_{bD}|^2\beta_b^2)\rho}{1+|\alpha_{bD}|^2\beta_b^2} \quad (8)$$

The scheme's outage probability is determined by $P_o = \Pr[\Im \leq R(\rho)]$. Based on Definition II, it is known $R(\rho)\doteq r\log\rho$. Therefore,

$$P_o = \Pr[1 + |\alpha_{SD}|^2\rho + \frac{|\alpha_{SD}|^4\rho^2}{1+|\alpha_{bD}|^2\beta_b^2} + \frac{(|\alpha_{SD}|^2 + |\alpha_{Sb}|^2|\alpha_{bD}|^2\beta_b^2)\rho}{1+|\alpha_{bD}|^2\beta_b^2} \leq \rho^{2r}] \quad (9)$$

Since β_b is a function of $|\alpha_{sb}|^2$, it is also associated with an exponential order δ_{β_b} such that $\beta_b^2 \doteq \rho^{-\delta_{\beta_b}}$. Assuming that δ_{bD} and δ_{β_b} are positive real values, we can have $1 + |\alpha_{bD}|^2\beta_b^2 \doteq 1 + \rho^{-(\delta_{bD}+\delta_{\beta_b}^{\beta_b})} \doteq 1$. With $\beta_b = (|\alpha_{Sb}|^2 + \sigma_b^2)^{-1/2}$, we can derive that

$$\frac{|\alpha_{Sb}|^2|\alpha_{bD}|^2\beta_b^2\rho}{1+|\alpha_{bD}|^2\beta_b^2} = f(|\alpha_{Sb}|^2\rho, |\alpha_{bD}|^2\rho) \quad (10)$$

where $f(\omega, \mu) = \dfrac{\omega\mu}{\omega+\mu+1}$, ω and μ are random variables. Equation (9) can be simplified as:

$$\begin{aligned} P_o &\doteq \Pr[1 + 2|\alpha_{SD}|^2\rho + |\alpha_{SD}|^4\rho^2 + f(|\alpha_{Sb}|^2\rho, |\alpha_{bD}|^2\rho) \leq \rho^{2r}] \\ &= \Pr[(1+\alpha_{SD}|^2\rho)^2 + f(|\alpha_{Sb}|^2\rho, |\alpha_{bD}|^2\rho) \leq \rho^{2r} \\ &\leq \Pr[(1+|\alpha_{SD}|^2\rho)^2 \leq \rho^{2r}] \times \Pr[f(|\alpha_{Sb}|^2\rho, |\alpha_{bD}|^2\rho) \leq \rho^{2r}] \end{aligned} \quad (11)$$

Since $|\alpha_{AB}|^2$ follows a chi-square distribution, yielding $\Pr[|\alpha_{AB}|^2 \le p^{-v}] = p^{-v}$, where v is a nonnegative real value [6], we have

$$\begin{aligned}\Pr[(1+|\alpha_{SD}|^2\rho)^2 \le \rho^{2r}] &= \Pr[(1+|\alpha_{SD}|^2\rho \le \rho^{r}] \\ &\dot{\le}\Pr[|\alpha_{SD}|^2 \le \rho^{r-1}] \doteq \rho^{-(1-r)}\end{aligned} \tag{12}$$

Applying lemma 4 of [6], we can determine:

$$\begin{aligned}\Pr[f(|\alpha_{Sb}|^2\rho,\ |\alpha_{bD}|^2\rho) \le \rho^{2r}] &\le \Pr[\min\{|\alpha_{Sb}|^2,\ |\alpha_{bD}|^2\} \\ &\le \rho^{2r-1} + \rho^{r-1}\sqrt{1+p^{2r}}] \\ &\doteq \Pr[\min\{|\alpha_{Sb}|^2,\ |\alpha_{bD}|^2\} \\ &\le \rho^{-(1-2r)^+}]\end{aligned} \tag{13}$$

Note that $(\omega)^+ + = \max\{0,\ \omega\}$. According to the relay selection criterion (3), it is known

$$\begin{aligned}&\Pr[\min\{|\alpha_{Sb}|^2,\ |\alpha_{bD}|^2\} \le \rho^{-(1-2r)^+}] \\ &= \prod_{k=1}^{N} \Pr[\min\{|\alpha_{Sk}|^2,\ |\alpha_{kD}|^2\} \le \rho^{-(1-2r)^+}]\end{aligned} \tag{14}$$

With

$$\Pr[\min\{|\alpha_{Sk}|^2,\ |\alpha_{kD}|^2\} \le \rho^{-(1-2r)^+}] \doteq \rho^{-(1-2r)^+} \tag{15}$$

and assisted by (13) and (14), we can determine

$$\Pr[f(|\alpha_{Sb}|^2\rho,\ |\alpha_{bD}|^2\rho) \le \rho^{2r}] \dot{\le} \rho^{-N(1-2r)^+} \tag{16}$$

By substituting (12) and (16) into (11), it can be concluded that:

$$P_o \dot{\le} \rho^{-[(1-r)+N(1-2r)^+}] \tag{17}$$

Recalling Definition II, the ONAF scheme's DMT performance can be characterised by $d(r) = (1-r) + N(1-2r)^+$, delivering a maximal diversity gain of $N+1$ and a maximal multiplexing gain of 1. It is superior to the existing opportunistic relaying schemes [6, 7] with $d(r) = (N+1)(1-2r)^+$, which limits the achievable multiplexing gain to be 0.5.

Simulation results: Outage probability performance of the ONAF scheme is evaluated using (9). It is compared with other AF-type cooperative schemes that have the same number of relays, including the distributed AF (DAF) scheme of [3], the opportunistic AF (OAF) scheme of [6, 7] and the DNAF scheme of [4]. Fig. 2 shows the performance of the ONAF scheme with two relays for different transmission rates. It can be seen that the ONAF scheme outperforms all the reference schemes. Specifically for a system with $R = 4$ bits/s/Hz, at an outage probability of 10^{-5}, its performance gain is a minimum of 2 dB over all the reference schemes. Compared to the DNAF scheme and the OAF scheme, the ONAF scheme's performance advantage is due to its features of opportunistic relay selection and nonorthogonal transmission, respectively. These two features together enable the ONAF scheme to significantly outperform the DAF scheme. Fig. 3 compares the ONAF scheme and the DNAF scheme for different numbers of relays. It can be seen that by increasing the numbers of relays, the ONAF scheme can achieve a more significant performance gain than the DNAF scheme. It underlines the importance of opportunistic relay selection in a large nonorthogonal cooperative network. The presented results also validate our DMT analysis.

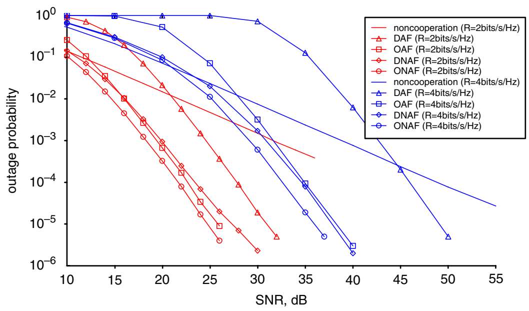

Fig. 2 *Outage probability performance of ONAF scheme with two relays, $R = 2$ or 4 bits/s/Hz*

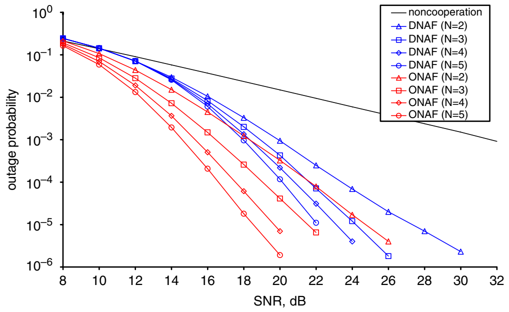

Fig. 3 *Outage probability performance of ONAF scheme with two to five relays, $R = 2$ bits/s/Hz*

Conclusion: An advanced cooperative scheme that embraces both opportunistic relay selection and nonorthogonal transmission is proposed. Its theoretical DMT characteristics have been analysed, showing it is capable of achieving a high diversity gain and yet achieving a maximum multiplexing gain of 1. Its outage performance is superior to the existing AF-type cooperative schemes.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Lanaman, J.N., Tse, D.N.C., and Wornell, G.W.: 'Cooperative diversity in wireless networks: efficient protocols and outage behavior', *IEEE Trans. Inf. Theory*, 2004, **50**, (12), pp. 3062–3080
2 Nabar, R.U., Kneubuhler, F.W., and Bolcskei, H.: 'Fading relay channels: performance limits and space-time signal design', *IEEE J. Sel. Areas Commun.*, 2004, **22**, (6), pp. 1099– 1109
3 Lanaman, J.N., and Wornell, G.W.: 'Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks', *IEEE Trans. Inf. Theory*, 2003, **49**, (10), pp. 2415–2425
4 Azarian, K., El Gamal, H., and Schniter, P.: 'On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels', *IEEE Trans. Inf. Theory*, 2005, **51**, (12), pp. 4152–4172
5 Zheng, L., and Tse, D.N.C.: 'Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels', *IEEE Trans. Inf. Theory*, 2003, **49**, (5), pp. 1073–1096
6 Bletsas, A., Khisti, A., Reed, D., and Lippman, A.: 'A simple cooperative diversity method based on network path selection', *IEEE J. Sel. Areas Commun.*, 2006, **24**, (3), pp. 659–672
7 Krikidis, I., Thompson, J., Mclaughlin, S., and Goertz, N.: 'Max-min relay selection for legacy amplify-and-forward system with interference', *IEEE Trans. Wirel. Commun.*, 2009, **8**, (6), pp. 3016–3027