Chinese Journal of Aeronautics, 2013,**26**(3): 661–667

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Relay selection based on MAP estimation for cooperative communication with outdated channel state information

Ding Wenrui [a,*], **Fei Li** [b], **Gao Qiang** [b], **Liu Shuo** [b]

[a] *Institute of Unmanned Air Vehicle, Beihang University, Beijing 100191, China*
[b] *School of Electronic and Information Engineering, Beihang University, Beijing 100191, China*

Received 29 September 2012; revised 19 February 2013; accepted 2 April 2013
Available online 15 May 2013

KEYWORDS

Cooperative communication;
MAP estimation;
Outdated CSI;
Relay selection;
Wireless networks

Abstract In this paper, we consider an amplify-and-forward (AF) cooperative communication system when the channel state information (CSI) used in relay selection differs from that during data transmission, i.e., the CSI used in relay selection is outdated. The selected relay may not be actually the best for data transmission and the outage performance of the cooperative system will deteriorate. To improve its performance, we propose a relay selection strategy based on maximum *a posteriori* (MAP) estimation, where relay is selected based on predicted signal-to-noise ratio (SNR). To reduce the computation complexity, we approximate the *a posteriori* probability density of SNR and obtain a closed-form predicted SNR, and a relay selection strategy based on the approximate MAP estimation (RS-AMAP) is proposed. The simulation results show that this approximation leads to trivial performance loss from the perspective of outage probability. Compared with relay selection strategies given in the literature, the outage probability is reduced largely through RS-AMAP for medium-to-large transmitting powers and medium-to-high channel correlation coefficients.

1. Introduction

Air traffic is increasing significantly due to the increase of unmanned aerial vehicles (UAVs) and small general aviation aircraft. The expected growth in air traffic will lead to the increment in data transmission of aeronautical communication. High-rate and high-reliability data transmission in wireless channels is needed for future aeronautical communication. Fading in wireless channels tremendously affects the performance of wireless communications. In aeronautical communication, wireless fading is severe since channel coefficients of aeronautical link change frequently. Thus it is imperative to mitigate the impact of wireless impairments to improve the performance of aeronautical communication.

In recent years, cooperative communication has been shown to be a promising approach to combat wireless impairments by exploiting spatial diversity without the need of multiple antennas at each node.[1–3] In cooperative systems, multiple single-antenna-equipped nodes are utilized as relays to assist the source in data transmission over independent wireless

* Corresponding author. Tel.: +86 10 82339906.
E-mail address: ding@buaa.edu.cn (W. Ding).

Peer review under responsibility of Editorial Committe of CJA.

ELSEVIER Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2013.05.002

channels. To improve the performance of cooperative communication, relay selection has been investigated recently and demonstrated as an effective method.[4–7]

Most relay selection strategies are based on the instantaneous channel state information (CSI) during relay selection. However, in highly mobile environments such as aeronautical communication, channel fluctuates over time due to the Doppler frequency shift and a time interval exists between relay selection and data transmission. Thus the CSI used in the relay selection can differ from that during the actual data transmission, i.e., the CSI used in the relay selection is outdated. The selected relay may not be actually the best for data transmission, yielding a degradation of the performance of cooperative systems. It is found that the outdated CSI results in a large degradation of outage probability, diversity order, and channel capacity.[8–11]

To improve the performance of cooperative communication under outdated CSI, some relay selection strategies have been proposed.[12–15] A relay selection strategy based on localization information (i.e., statistic CSI) is investigated and compared with the relay selection using instantaneous CSI.[12] In some specific scenarios, the localization-based selection achieves better performance than the strategy using instantaneous CSI during relay selection. Li et al.[13] propose a relay selection strategy where the relay is selected based on predicted outage probability in a decode-and-forward (DF) cooperative communication system. This selection strategy is simplified to the strategy using instantaneous CSI during relay selection when all the channels are independent and identically distributed and the channel correlation at each relay is the same. A minimum mean squared error (MMSE) estimator is used to predict the actual signal-to-noise ratio (SNR) during data transmission based on the CSI available during relay selection, and the relay is selected based on the predicted SNR.[14,15] Under the scenarios presented in these studies, the relay selection strategy based on MMSE estimation can achieve better performance than the strategies based on localization information and instantaneous CSI during relay selection.

The MMSE estimation adopted to predict SNR chooses the squared-error cost function. However, from the perspective of outage performance, this cost function is not appropriate. To guarantee the outage performance, we only need to select the relay that can make the transmission successful. Suppose that there are some relays satisfying the SNR requirement for successful transmission. If an estimation error is less than a value, the selected relay, which is obtained based on the predicted SNR, can still satisfy the SNR requirement at receiver and make transmission successful, thus the cost should be set to zero. On the other hand, for an estimation error larger than a value, the selected relay cannot ensure successful transmission, and hence the cost tends to be assigned a uniform value no matter what the estimation error is.

In this paper, aiming to improve the outage performance in an amplify-and-forward (AF) cooperative communication system with outdated CSI, we adopt maximum *a posteriori* (MAP) estimation to predict the actual SNR of each relay during data transmission, and propose a relay selection strategy based on the MAP estimation (RS-MAP). Unlike MMSE estimation, MAP estimation chooses a uniform cost function, i.e., zero cost is assigned for an estimation error less than a value and for an estimation error more than this value the cost is set to be uniform.[16] To reduce computation complexity, we approximate the *a posteriori* probability density of SNR and obtain a closed-form predicted SNR. The region of parameters where our proposed strategy outperforms other strategies is obtained through simulations.

2. System model

Consider an AF cooperative communication system consisting of one source (S), one destination (D), and K half-duplex relays, where each node is equipped with only one antenna, as shown in Fig. 1. Single relay is selected to cooperate. The cooperation is divided into three phases: relay selection phase, data phase 1, and data phase 2. In the relay selection phase, a relay is selected according to the CSIs of the source–relay and relay–destination links. In data phase 1, the source transmits a signal to the destination and the selected relay receives the data as well. In data phase 2, the selected relay amplifies and forwards the signal from the source to the destination. We assume a quasi-static Rayleigh fading channel where the channel response remains constant during one data phase and changes from one data phase to another.[8,14,15] Since the time duration of the relay selection phase is negligible compared with that of data transmission, the CSI of the source–relay link used in the relay selection can be considered the same as that during data phase 1, while the CSI of the relay–destination link used in the relay selection differs from that during data phase 2, i.e., the CSI of the relay–destination link used in the relay selection is outdated. This leads to that the selected relay may not be actually the best for data transmission. Since this paper focuses on the relay selection under outdated CSI, the destination is assumed to know the precise CSIs of source–destination link, source–relay link, and relay–destination link for signal combining and detection.[4–15] The destination can acquire the CSIs using pilot symbols inserted in the data packet sent by the source and forwarded by the relay.

For simplicity, we assume the same transmitting power P for all nodes and the additive white Gaussian noise (AWGN) with zero mean and the same variance σ_n^2 at each receiver. Suppose that relay k is selected, the signals received at the destination and relay k in data phase 1 are given by

$$y_D^{(1)} = \sqrt{P} h_{SD} x_S + n_{SD} \tag{1}$$

$$y_k = \sqrt{P} h_{Sk} x_S + n_{Sk} \tag{2}$$

where x_S is the symbol transmitted from the source with unit power. n_{SD} and n_{Sk} are the AWGNs at the destination and relay k, respectively. h_{SD} and h_{Sk} are the channel responses of the source–destination link S–D and the source–relay link S–k,

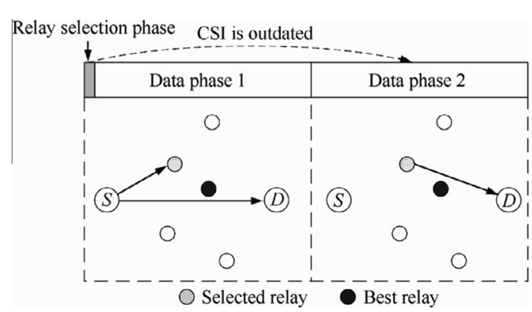


Fig. 1 AF cooperative communication with outdated CSI.

respectively. They are modeled as zero-mean circularly symmetric complex Gaussian random variables with variance σ_{SD}^2 and σ_{Sk}^2, i.e., $h_{SD} \sim CN(0, \sigma_{SD}^2)$ and $h_{Sk} \sim CN(0, \sigma_{Sk}^2)$. Based on the simplified path-loss model,[17] we model σ_{SD}^2 or σ_{Sk}^2 as

$$\sigma_{AB}^2 = \left(\frac{\lambda}{4\pi d_0}\right)^2 \left(\frac{d_0}{d_{AB}}\right)^\alpha \tag{3}$$

with $A = S$ and $B = D$, k. d_{AB} is the distance of link A–B, λ the carrier wavelength, d_0 a reference distance, and α the path-loss exponent.

In data phase 2, relay k amplifies the received signal and retransmits it. The received signal at the destination in this phase is given by

$$y_D^{(2)} = \sqrt{\frac{P}{P|h_{Sk}|^2 + \sigma_n^2}} h_{kD} y_k + n_{kD} \tag{4}$$

where n_{kD} is the AWGN of the relay–destination link k–D, and $h_{kD} \sim CN(0, \sigma_{kD}^2)$ is the channel response of the relay-destination link k–D. σ_{kD}^2 can be modeled as Eq. (3) with $A = k$ and $B = D$.

The destination jointly combines the signal received from the source in data phase 1, $y_D^{(1)}$, and that from relay k in data phase 2, $y_D^{(2)}$, by using a maximal ratio combiner (MRC), and detects the transmitted symbol according to the combiner's output. The SNR of the combined signal is given by

$$\gamma_k = \gamma_{SD} + \frac{\gamma_{Sk}\gamma_{kD}}{\gamma_{Sk} + \gamma_{kD} + 1} \tag{5}$$

where $\gamma_{SD} = P|h_{SD}|^2/\sigma_n^2$, $\gamma_{Sk} = P|h_{Sk}|^2/\sigma_n^2$, and $\gamma_{kD} = P|h_{kD}|^2/\sigma_n^2$ are the SNRs of link S–D, S–k, and k–D, respectively. The term $\gamma_{Sk}\gamma_{kD}/(\gamma_{Sk} + \gamma_{kD} + 1)$ represents the SNR of the source-to-destination-via-relay-k link S–k–D. When the SNR of the combined signal is less than a predetermined threshold, the transmission is outage.[18] The outage probability is given by

$$P_{\text{out}} = \Pr(\gamma_k < \gamma_{\text{th}}) \tag{6}$$

where $\gamma_{\text{th}} = 2^{2R} - 1$ with the required spectral efficiency R.[8,15,18]

To minimize the outage probability given in Eq. (6), the relay with the maximal SNR of the S–k–D link, i.e., the best relay, should be selected. However, as described in Section 3, the CSIs of relay–destination links used in the relay selection differ from that during data phase 2. The channel response of link k–D used in the relay selection is denoted as $\tilde{h}_{kD}$, which is an outdated version of the actual one h_{kD} during data phase 2. h_{kD} conditioned on $\tilde{h}_{kD}$ follows a Gaussian distribution, which is given by[8,10,14,15]

$$h_{kD}|\tilde{h}_{kD} \sim CN\left(\rho_k \tilde{h}_{kD}, (1-\rho_k^2)\sigma_{kD}^2\right) \tag{7}$$

where ρ_k is the correlation coefficient between $\tilde{h}_{kD}$ and h_{kD}. Correspondingly the SNR of link k–D during the relay selection $\tilde{\gamma}_{kD}$ is an outdated version of the actual one γ_{kD} during data phase 2 and is given by

$$\tilde{\gamma}_{kD} = P|\tilde{h}_{kD}|^2/\sigma_n^2 \tag{8}$$

Therefore, the *a posteriori* probability density of γ_{kD} conditioned on $\tilde{\gamma}_{kD}$ is given by

$$f(\gamma_{kD}|\tilde{\gamma}_{kD}) = \frac{1}{\bar{\gamma}_{kD}(1-\rho_k^2)} \times \exp\left(-\frac{\gamma_{kD} + \rho_k^2\tilde{\gamma}_{kD}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right) I_0\left(\frac{2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right) \tag{9}$$

where $I_0(\cdot)$ denotes the zero-order modified Bessel function of the first kind. $\bar{\gamma}_{kD}$ is the average SNR of link k–D and is given by

$$\bar{\gamma}_{kD} = \frac{P}{\sigma_n^2} E(|h_{kD}|^2) = \frac{P}{\sigma_n^2}\sigma_{kD}^2 \tag{10}$$

3. Relay selection strategy

In this section, we propose the relay selection strategy based on MAP estimation (RS-MAP), and its revised version RS-AMAP. We adopt the MAP estimation, whose cost function is appropriate for outage performance, to predict the actual SNR of link k–D during data transmission. The predicted SNR $\hat{\gamma}_{kD}^{\text{MAP}}$ is the SNR that can achieve the maximum of $f(\gamma_{kD}|\tilde{\gamma}_{kD})$, i.e.,

$$\hat{\gamma}_{kD}^{\text{MAP}} = \arg \max_{\gamma_{kD}} f(\gamma_{kD}|\tilde{\gamma}_{kD}) \tag{11}$$

If the maximum is within the allowable arrange of γ_{kD} and $\ln f(\gamma_{kD}|\tilde{\gamma}_{kD})$ has a continuous first-order derivative, a necessary condition for the maximum of $f(\gamma_{kD}|\tilde{\gamma}_{kD})$ can be obtained by differentiating $\ln f(\gamma_{kD}|\tilde{\gamma}_{kD})$ with respect to γ_{kD} and setting the result equal to zero[16]

$$\frac{\mathrm{d}\ln f(\gamma_{kD}|\tilde{\gamma}_{kD})}{\mathrm{d}\gamma_{kD}} = 0 \tag{12}$$

Based on Eq. (9), we can find that $\ln f(\gamma_{kD}|\tilde{\gamma}_{kD})$ has a continuous first-order derivative. Substituting $f(\gamma_{kD}|\tilde{\gamma}_{kD})$ given in Eqs. (9)–(12), we have

$$\sqrt{\rho_k^2\tilde{\gamma}_{kD}} I_1\left(\frac{2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right) - \sqrt{\gamma_{kD}} I_0\left(\frac{2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right) = 0 \tag{13}$$

where $I_1(\cdot)$ denotes the first-order modified Bessel function of the first kind. We solve this equation through a numerical method and choose the solution that can achieve the absolute maximum within the allowable range of γ_{kD}, i.e., $[0, \infty)$, as the estimator $\hat{\gamma}_{kD}^{\text{MAP}}$. If the *a posteriori* probability density of γ_{kD} monotonously decreases, there is no solution to achieve the absolute maximum in the range $[0, \infty)$ and we let the predicted SNR be the boundary value $\hat{\gamma}_{kD}^{\text{MAP}} = 0$.

Then the strategy RS-MAP is obtained, and the relay is selected as

$$k_{\text{MAP}}^* = \arg \max_{k \in \{1,2,\cdots,K\}} \frac{\gamma_{Sk}\hat{\gamma}_{kD}^{\text{MAP}}}{\gamma_{Sk} + \hat{\gamma}_{kD}^{\text{MAP}} + 1} \tag{14}$$

Using a numerical method to obtain the estimated SNR can make the computation highly complex. To reduce the computation complexity, we approximate the function $I_0(z)$ in the *a posteriori* probability density of SNR by $I_0(z) \approx \mathrm{e}^z/\sqrt{2\pi z}$ for $z > 1$.[19] Consequently, we have the approximate *a posteriori* probability density of SNR $f_A(\gamma_{kD}|\tilde{\gamma}_{kD})$ as

$$f_A(\gamma_{kD}|\tilde{\gamma}_{kD}) = \frac{1}{\bar{\gamma}_{kD}(1-\rho_k^2)} \times \exp\left(-\frac{\gamma_{kD}+\rho_k^2\tilde{\gamma}_{kD}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right)\frac{\exp\left(\frac{2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}}{\bar{\gamma}_{kD}(1-\rho_k^2)}\right)}{\sqrt{\frac{4\pi\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}}{\bar{\gamma}_{kD}(1-\rho_k^2)}}} \quad (15)$$

for $2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}/[\bar{\gamma}_{kD}(1-\rho_k^2)] > 1$. Substituting $f(\gamma_{kD}|\tilde{\gamma}_{kD}) \approx f_A(\gamma_{kD}|\tilde{\gamma}_{kD})$ to Eq. (12), we have

$$4\gamma_{kD} - 4\sqrt{\rho_k^2\tilde{\gamma}_{kD}\gamma_{kD}} + \bar{\gamma}_{kD}(1-\rho_k^2) = 0 \quad (16)$$

Solving this equation and noting the condition $2\sqrt{\rho_k^2\gamma_{kD}\tilde{\gamma}_{kD}}/[\bar{\gamma}_{kD}(1-\rho_k^2)] > 1$, we have the approximate MAP estimator $\hat{\gamma}_{kD}^{\text{MAP}}$ in a closed form as

$$\hat{\gamma}_{kD}^{\text{AMAP}} = \left(\frac{\sqrt{\rho_k^2\tilde{\gamma}_{kD}} + \sqrt{\rho_k^2\tilde{\gamma}_{kD} - \bar{\gamma}_{kD}(1-\rho_k^2)}}{2}\right)^2 \quad (17)$$

for $\rho_k^2\tilde{\gamma}_{kD} - \bar{\gamma}_{kD}(1-\rho_k^2) \geqslant 0$. If $\rho_k^2\tilde{\gamma}_{kD} - \bar{\gamma}_{kD}(1-\rho_k^2) < 0$, we let $\hat{\gamma}_{kD}^{\text{MAP}}$ equal to 0.

Then we have the strategy RS-AMAP, in which the relay is selected as

$$k_{\text{AMAP}}^* = \arg\max_{k\in\{1,2,\cdots,K\}} \frac{\gamma_{Sk}\hat{\gamma}_{kD}^{\text{AMAP}}}{\gamma_{Sk} + \hat{\gamma}_{kD}^{\text{AMAP}} + 1} \quad (18)$$

4. Simulation results

In this section, we simulate the proposed relay selection strategies and compare the simulation results with the following three strategies.

Opportunistic relay selection (ORS): the relay maximizing the SNR of the *S*–*k*–*D* link, which is obtained based on the outdated CSI of the *k*–*D* link, is selected as

$$k_{\text{ORS}}^* = \arg\max_{k\in\{1,2,\cdots,K\}} \frac{\gamma_{Sk}\tilde{\gamma}_{kD}}{\gamma_{Sk} + \tilde{\gamma}_{kD} + 1} \quad (19)$$

Relay selection strategy based on average SNR (RS-Ave): the relay is selected using the average SNR of the *k*–*D* link as

$$k_{\text{Ave}}^* = \arg\max_{k\in\{1,2,\cdots,K\}} \frac{\gamma_{Sk}\bar{\gamma}_{kD}}{\gamma_{Sk} + \bar{\gamma}_{kD} + 1} \quad (20)$$

Relay selection strategy based on MMSE estimation (RS-MMSE): the relay is selected based on the predicted SNR using MMSE estimation as

$$k_{\text{MMSE}}^* = \arg\max_{k\in\{1,2,\cdots,K\}} \frac{\gamma_{Sk}\hat{\gamma}_{kD}^{\text{MMSE}}}{\gamma_{Sk} + \hat{\gamma}_{kD}^{\text{MMSE}} + 1} \quad (21)$$

where $\hat{\gamma}_{kD}^{\text{MMSE}} = \rho_k^2\tilde{\gamma}_{kD} + (1-\rho_k^2)\bar{\gamma}_{kD}$ is the MMSE estimation of the actual SNR of the R_k–D link.[14]

Considering K unmanned aircraft distributed randomly in a $d \times d$ square area as relays of an aeronautical communication network. The source aircraft is located in the middle of one side of the square, and the destination aircraft is located in the middle of the opposite side from the source. The correlation coefficients for all relay–destination links are assumed to be equal, i.e., $\rho_k = \rho$ for $k = 1, 2, \ldots, K$. As IEEE L-band is widely used for aeronautical communication, the system parameters of the unmanned aircraft communication network studied are summarized in Table 1 except the correlation coefficient ρ and the transmitting power P.

We start with the comparisons of outage probabilities between RS-MAP and RS-AMAP as shown in Fig. 2. It can be found that the outage probability of RS-AMAP is perfectly in accordance with that of RS-MAP in large ranges of transmitting power and correlation coefficient for practical circumstances of wireless communication, which indicates that the approximation of the Bessel function is reasonable in practice. In other words, the approximate MAP estimation just introduces trivial outage performance loss. The computation complexity of estimation is reduced by the approximate estimator since it is given in a closed form as shown in Eq. (17). Thus, it is straightforward to adopt the strategy RS-AMAP instead of RS-MAP to select a relay.

Fig. 3 shows the outage probabilities of different relay selection strategies over transmitting power when the correlation coefficient ρ is 0.9. It can be seen that the proposed strategy RS-AMAP can reduce the outage probability except for low transmitting powers. For example, when the transmitting power is 20 dBm (i.e., 100 mW), the outage probability of RS-AMAP is about 30% less than that of ORS, 50% less than that of RS-MMSE, and one order of magnitude less than that of RS-Ave. The decrement of the outage probability will increase as the transmitting power increases. For low transmitting powers, RS-AMAP suffers from a little performance degradation compared with ORS and RS-MMSE (Fig. 3 inset). The strategy RS-MMSE performs better than ORS and RS-Ave for low transmitting powers, which is the same as that given by Lim and Cimini.[14]

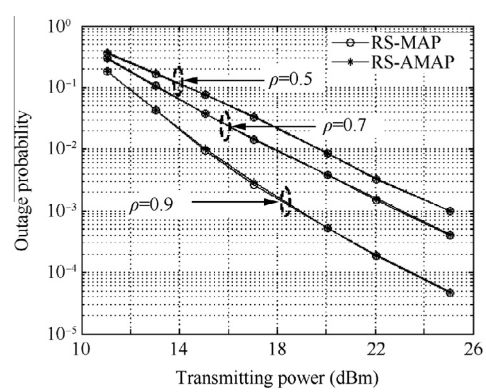


Fig. 2 Outage probability comparisons between RS-MAP and RS-AMAP under different transmitting powers and correlation coefficients.

Table 1 System parameters.

Parameter	K	D (m)	R (bit/s/Hz)	α	λ (m)	d_0 (m)	σ_n^2 (dBm)
Value	10	1000	1	3	0.2	1	−90

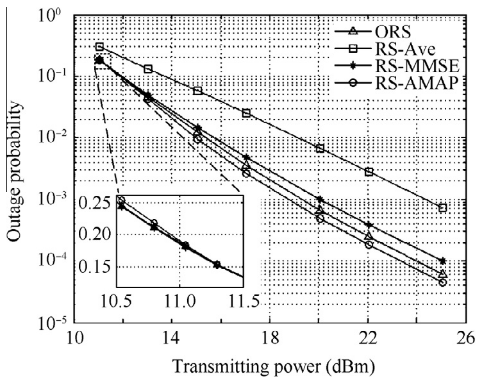


Fig. 3 Outage probabilities of different relay selection strategies over transmitting power for $\rho = 0.9$.

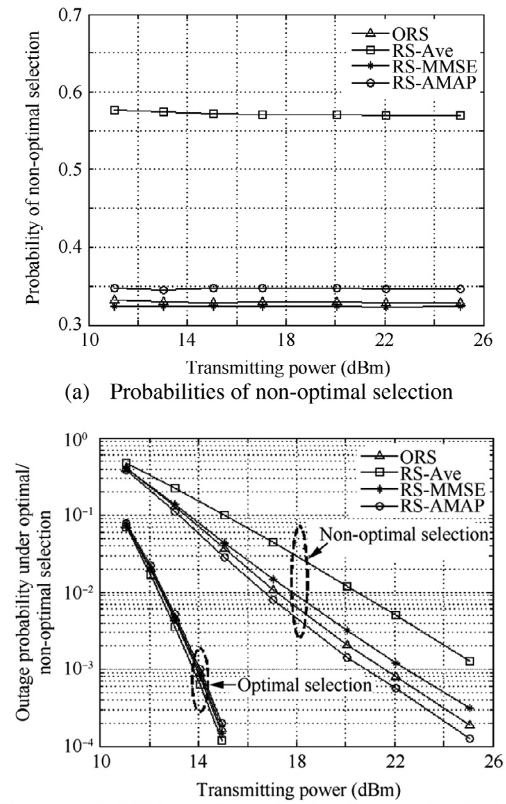
To explain the results given in Fig. 3, we divide the outage probability according to the law of total probability as

$$p_{\text{out}} = \Pr(\text{Out}|\text{Opt})\Pr(\text{Opt}) + \Pr(\text{Out}|\text{Non-opt})\Pr(\text{Non-opt}) \tag{22}$$

where Pr(Opt) and Pr(Non-opt) denote the probabilities of optimal and non-optimal selections, respectively. Pr(Out|Opt) and Pr(Out|Non-opt) denote the outage probabilities under the conditions of optimal and non-optimal selections, respectively. The term optimal selection means that the actually best relay is selected, and non-optimal selection means that the selected relay is not actually the best for data transmission. Thus we have Pr(Opt) = 1 − Pr(Non-opt).

These probabilities are plotted over transmitting power in Fig. 4. Compared with ORS and RS-MMSE, RS-AMAP has the close non-optimal selection probability Pr(Non-opt) (see Fig. 4(a)), and hence the close optimal selection probability Pr(Opt). The outage probabilities under the optimal selection Pr(Out|Opt) of RS-MAP, ORS, and RS-MMSE are close and much lower than the corresponding outage probabilities under the non-optimal selection Pr(Out|Non-opt) (see Fig. 4(b) where the y-axis is shown in a logarithmic scale). Therefore, the outage performances of these three strategies are mainly determined by Pr(Out|Non-opt). As shown in Fig. 4(b), RS-AMAP has lower Pr(Out|Non-opt) than ORS and RS-MMSE, and the gaps increase over the total transmitting power. Hence RS-AMAP performs better than ORS and RS-MMSE especially for high total transmitting powers. RS-Ave has not only the largest Pr(Non-opt) but also the largest Pr(Out|Non-opt), thus it has the worst outage performance. RS-AMAP has lower Pr(Out|Non-opt) than other strategies since it more likely selects the relay that can make data transmission successful based on the uniform cost function of the MAP estimation.

Fig. 5 shows the outage probabilities of different relay selection strategies over correlation coefficient for 20 dBm transmitting power. It can be seen that RS-AMAP achieves the lowest outage probability for correlation coefficients larger than about 0.65. Analogously, the outage performances of these strategies are mainly determined by the outage probabilities under the non-optimal selection Pr(Out|Non-opt). As RS-AMAP has lower Pr(Out|Non-opt) than other strategies for large correlation coefficients, it achieves the best outage performance. When the correlation coefficient ρ approaches to 1,



(a) Probabilities of non-optimal selection

(b) Outage probabilities under optimal and non-optimal selections

Fig. 4 Probabilities of non-optimal selection and outage probabilities under optimal and non-optimal selections over total transmitting power for different SRS strategies ($\rho = 0.9$).

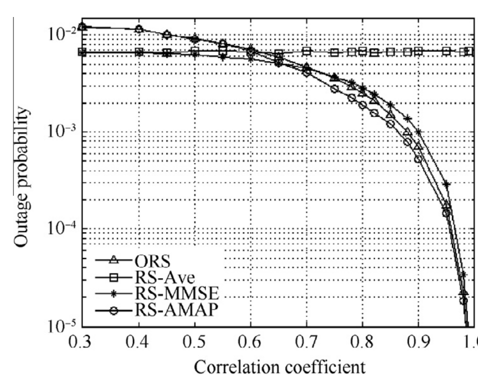


Fig. 5 Outage probabilities of different relay selection strategies over correlation coefficient for $P = 20$ dBm.

RS-AMAP, RS-Out, and RS-MMSE will perform close to each other since the values of the predicted SNR for relay selection by these strategies get closer. Specifically, when $\rho = 1$, they are the same, i.e., $\hat{\gamma}_{kD}^{\text{AMAP}} = \hat{\gamma}_{kD}^{\text{MMSE}} = \tilde{\gamma}_{kD}$. We can also find that for RS-Ave the outage probability keeps constant over correlation coefficient since a relay is selected based on the average SNR, which is not related to the correlation coefficient.

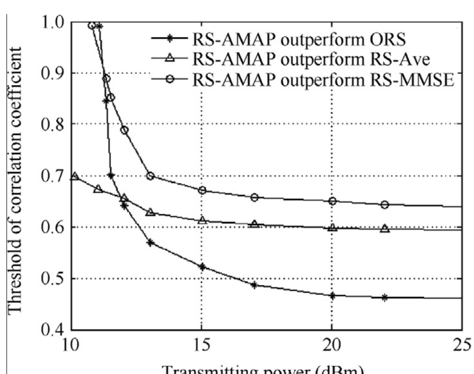
From the discussion above, we can find that our proposed strategy RS-AMAP outperforms other strategies in certain settings of transmitting power and correlation coefficient. In

Fig. 6(a), the thresholds of correlation coefficient that RS-AMAP outperforms other strategies are plotted over transmitting power. Choosing the largest one of these thresholds for each given transmitting power, we can obtain the region of parameters where RS-AMAP outperforms other strategies as shown in Fig. 6(b). It can be seen that for transmitting powers higher than about 12 dBm and correlation coefficients higher than about 0.65, our proposed strategy RS-AMAP outperforms other strategies.

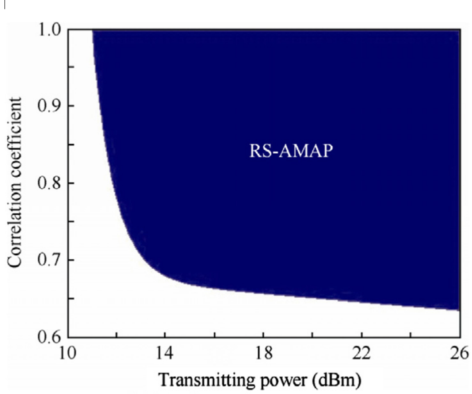
According to Jakes' channel model,[17] the correlation coefficient ρ is given by

$$\rho = J_0(2\pi f_D T) \quad (23)$$

where f_D is the maximum Doppler frequency shift, T the length of the time interval between two samples of channel response, and $J_0(\cdot)$ the zero-order Bessel function of the first kind. If we set the speed of a mobile station v equal to 140 km/h and the carrier frequency f_c equal to 1.5 GHz (IEEE L-band), we have $f_D \approx 200$ Hz. If we set the length of data packet equal to 1 Kb and the data rate equal to 1 Mbps, we have the time duration of packet transmission $T = 1$ ms. Under these settings we have $\rho \approx 0.65$. For a lower speed v, the correlation coefficient ρ becomes larger. These parameters are typical for wireless communication in an unmanned aircraft system (UAS), where wireless impairment is severe. Therefore, our proposed strategy SRS-AMAP is more applicable for the cooperative communication system in a UAS to improve its outage performance than other strategies.



(a) Thresholds of correlation coefficient



(b) Region of parameters

Fig. 6 Regions of transmitting power and correlation coefficient where RS-AMAP outperforms other strategies.

Finally, we discuss the complexity of our proposed strategy RS-AMAP. In RS-AMAP, the average SNR $\bar{\gamma}_{kD}$ and the channel correlation coefficient ρ_k, which are the statistic channel information, are needed. The statistic channel information can be obtained through calculations over several time slots, and the overhead introduced by the calculations is slight since the statistic information does not change frequently. For other strategies, the statistic channel information is also needed. RS-MMSE needs the average SNR and the channel correlation coefficient, which is the same as our strategy. RS-Ave needs the average SNR. Based on the statistic channel information and the outdated CSI, the predicted SNR can be calculated by using Eq. (17) as a closed form, which can be afforded easily by wireless nodes.

5. Conclusions

In this paper, we propose a relay selection strategy, RS-MAP, where a relay is selected based on predicted SNR, for an AF cooperative communication system with outdated CSI. To reduce the computation complexity, we approximate the *a posteriori* probability density of SNR and obtain a closed-form predicted SNR, and propose a revised strategy, RS-AMAP. The simulation results show that this approximation leads to trivial performance loss from the perspective of outage probability. In comparison with ORS, RS-Ave, and RS-MMSE, the outage performance can be improved noticeably by RS-AMAP particularly for medium-to-large transmitting powers and medium-to-high channel correlation coefficients. For example, when the transmitting power is 20 dBm and the channel correlation coefficient is 0.9, through RS-AMAP the outage probability can be reduced by about 30% compared with ORS, 50% compared with RS-MMSE, and one order of magnitude compared with RS-Ave. Our results can be used as a guideline to the design of relay selection strategy for cooperative communication in unmanned aircraft communication networks and other highly mobile environments.

Acknowledgement

This study was supported by National Basic Research Program of China (No. 2010CB731803).

References

1. Hong YW, Huang WJ, Chiu FH, Kuo CCJ. Cooperative communications in resource-constrained wireless networks. *IEEE Signal Process Mag* 2007;**24**(3):47–57.
2. Laneman JN, Wornell GW. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Trans Inf Theory* 2003;**49**(10):2415–25.
3. Ochiai H, Mitran P, Poor HV, Tarokh V. Collaborative beamforming for distributed wireless ad hoc sensor networks. *IEEE Trans Signal Process* 2005;**53**(11):4110–24.
4. Bletsas A, Shin H, Win MZ. Cooperative communications with outage-optimal opportunistic relaying. *IEEE Trans Wireless Commun* 2007;**6**(9):3450–60.
5. Bletsas A, Khisti A, Reed DP, Lippman A. A simple cooperative diversity method based on network path selection. *IEEE J Sel Areas Commun* 2006;**24**(3):659–72.

6. Zhou Z, Zhou S, Cui JH, Cui S. Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks. *IEEE Trans Wireless Commun* 2008;**7**(8):3066–78.
7. Chen X, Zhou QF, Siu TW, Lau FCM. Asymptotic analysis of opportunistic relaying based on the max-generalized-mean selection criterion. *IEEE Trans Wireless Commun* 2011;**10**(4):1050–7.
8. Vicario J, Bel A, Lopez-Salcedo JA, Seco G. Opportunistic relay selection with outdated CSI: outage probability and diversity analysis. *IEEE Trans Wireless Commun* 2009;**8**(6):2872–6.
9. Torabi M, Haccoun D. Capacity analysis of opportunistic relaying in cooperative systems with outdated channel information. *IEEE Commun Lett* 2010;**14**(12):1137–9.
10. Wu NE, Yeh PL, Li HJ. Error performance of opportunistic relaying with outdated channel state information. In: *Proceedings of the 75th IEEE vehicular technology conference*. 2012 May 6–9; Yokohama, Japan. 2012. p. 1–5.
11. Torabi M, Haccoun D. Capacity of amplify-and-forward selective relaying with adaptive transmission under outdated channel information. *IEEE Trans Vehicular Technol* 2011;**60**(5):2416–22.
12. Zhao B, Valenti MC. Practical relay networks: a generalization of hybrid-ARQ. *IEEE J Sel Areas Commun* 2005;**23**(1):7–18.
13. Li Y, Yin Q, Xu W, Wang HM. On the design of relay selection strategies in regenerative cooperative networks with outdated CSI. *IEEE Trans Wireless Commun* 2011;**10**(9):3086–97.
14. Lim G, Cimini LJ, Jr. Robust cooperative relaying in an amplify-and-forward network. In: *Proceedings of the 73th IEEE vehicular technology conference*. 2011 May 15–18; Budapest, Hungary. 2011. p. 1–6.
15. Vicario JL, Bel A, Morell A, Seco-Granados G. A robust relay selection strategy for cooperative systems with outdated CSI. In: *Proceedings of the 69th IEEE vehicular technology conference*. 2009 Apr 26–29; Barcelona, Spain. 2009. p. 1–5.
16. Van Trees HL. *Detection, estimation, and modulation theory, Part I*. New York: John Wiley & Sons; 2001.
17. Goldsmith AJ. *Wireless communications*. Cambridge: Cambridge University Press; 2005.
18. Laneman JN, Tse DNC, Wornell GW. Cooperative diversity in wireless networks: efficient protocols and outage behavior. *IEEE Trans Inf Theory* 2004;**50**(12):3062–80.
19. Proakis JG, Salehi M. *Digital communications*. 5th ed. New York: McGraw-Hill Companies; 2007.

Ding Wenrui received her B.S. degree in Computer in 1994, Ph.D. degree and the title of Senior Engineer in Communication & Information in 2007 from Beihang University, Beijing, China. She is currently the Deputy Chief Designer of National Key Model and in charge of commanding the subsystems of control, data link, and combat command in the Research Institute of Unmanned Aerial Vehicle at Beihang University. She chaired projects of the Aeronautical Science Foundation of China, the GAD Pre-Research Foundation, etc. She published more than 40 papers in domestic and international academic journals and conferences, applied for 13 patents with 5 granted, and served as the first editor establishing the national military standard "the universal criterion of telemetry and remote control systems for UAVs". Her current research areas include command and control of UAVs, image processing and pattern recognition. Dr. Ding has been named as the Deputy Chief Designer of National Key Model, Outstanding Young Engineer in Beijing, and New Century Talent by the Ministry of Education.