

Threshold-based hybrid relay selection and power allocation scheme

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Abstract—To minimize total transmit power in a system while guaranteeing the outage probability at the same time in a cooperative system, we propose and analyse two threshold-based hybrid relay selection and power allocation schemes for a three-node cooperative relaying system. They are designated as: the hybrid amplify-direct-forward relaying (HADF) and incremental hybrid decode-direct-forward relaying (IHDDF) schemes. In the HADF scheme, a specific outage probability threshold is derived to determine that the system chooses to optimize power allocation of its source and relay in amplify-and-forward (AF) mode or optimize the power of its source in direct-transmit (DT) mode without a relay. In IHDDF, according to the outage probability threshold, the system chooses to optimize its power in turn with incremental decode-and-forward opportunistic relaying (IDFO) mode or DT mode. Closed-form expressions of the total transmit power of the proposed HADF and IHDDF schemes are derived. The proposed schemes have low computational complexity and system cost. Theoretical analysis and simulation results show that the HADF scheme outperforms the AF and DT schemes, and the total transmission power of the IHDDF scheme is reduced significantly compared with the IDFO and DT schemes. Compared with the HADF scheme, the IHDDF scheme has a better total transmit power in special channel condition.

Keywords— *power allocation; three-node cooperative relaying system; amplify-and-forward; incremental decode-and-forward opportunistic relaying*

I. INTRODUCTION

As an efficient wireless transmission technique, cooperative relaying technology has been proposed to obtain spatial diversity by forming virtual antenna arrays without the need to employ multiple antennae at transmitters or receivers [1-2]. It is particularly attractive for small-size and antenna-limited wireless devices. There are two main advantages in such cooperative relaying technology: the low transmission radio frequency (RF) power requirement and the spatial diversity gain [3-4]. Among the earliest work on cooperative networks [5-6], a cooperative diversity model is proposed [5], in which two users act as partners and cooperatively communicate with a common destination, each transmitting its own bit in the first time interval and the estimated bit of its partner in the second time interval. In [6], several low-complexity cooperative protocols are proposed and studied, including fixed relaying,

selection relaying and incremental relaying, in which the relay node can either amplify and forward, or decode and forward the signal it receives. In [7], we investigate the incremental decode-and-forward opportunistic (IDFO) relay protocol, where the selected relay chooses to cooperate only if the source-destination channel is of an unacceptable quality. In [8], networks consisting of more than two users that use space-time coding to achieve the cooperative diversity are considered. Coded cooperation schemes are discussed in [9], where a user transmits part of its partner's codeword as well. The reference [10] investigates the capacity of relay networks of arbitrary size. The SNR-based selection relaying scheme in multi-relay cooperative networks with distributed space-time coding was studied in [11], which demonstrates that the error propagation could be effectively mitigated by employing the appropriate thresholds at the relays.

Power efficiency is a critical design consideration for wireless networks such as ad hoc and sensor networks, due to the limited transmission power of the (relay and the source) nodes. To that end, choosing appropriate relays to forward the source data, as well as the transmit power levels of all the nodes, become important design issues. Optimum power allocation strategies for relay networks are studied for several structures and relay transmission schemes. Three-node models are discussed in [12-13], while multi-hop relay networks are studied in [14-16]. Relay forwarding strategies for both AF and DF parallel relay channels in a wide-band regime are proposed in [17]. Recent works also discuss relay selection algorithms for networks with multiple relays. Optimum relay selection strategies for several models are identified in [18].

In the paper, we propose and analyse two threshold-based hybrid relay selection and power allocation schemes for the three-node cooperative relaying system. They are designated as: the hybrid amplify-direct-forward relaying (HADF) and incremental hybrid decode-direct-forward relaying (IHDDF) schemes, to minimize total transmission power of the system while guaranteeing the outage probability at the same time for cooperative systems. In the HADF scheme, we derive a specific outage probability threshold to determine whether the system chooses to optimize power allocation of source and relay in amplify-and-forward (AF) mode, or optimize power of source in direct-transmit (DT) mode without the relay. In

IHDDF, the system chooses to optimize power in turn with IDFO or DT modes separately, by considering the outage probability threshold. The rest of this paper is organised as follows: in Section II, the system model for the three-node cooperative relaying system is described; then, closed-form expressions of the outage probability of the proposed IHDDF and HADF schemes are derived in Section III; in Section IV, simulation results are presented, which validate the theoretical analysis, and finally, Section V summarises the key conclusions.

II. SYSTEM MODEL

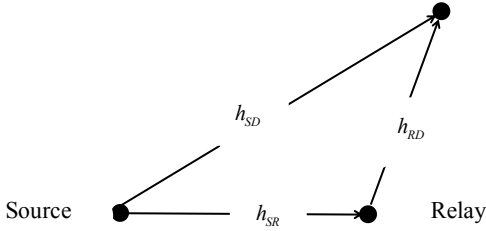


Fig. 1. Three-node cooperative relaying system.

Here, we consider a three-node cooperative relaying system (Fig. 1), which consists of one source, one relay and one destination. The link between any two nodes is modelled as a block Rayleigh fading channel with additive white Gaussian noise (AWGN), which implies that the fading coefficients of the channels are fixed within one frame transmission. It is assumed that all the receiving nodes have the exact channel state information (CSI) needed for demodulation, so the relay has the CSI of the link from the source to itself and the destination has the CSI of all links.

We assume that $h_{SD} \sim CN(0, \sigma_{SD}^2)$ is the fading coefficient of the channel from the source to the destination, $h_{SR} \sim CN(0, \sigma_{SR}^2)$ is the fading coefficient of the channel from the source to the relay, and $h_{RD} \sim CN(0, \sigma_{RD}^2)$ is the fading coefficient of the channel from the relay to the destination. And similarly, we assume $n_{SD} \sim CN(0, N_0)$, $n_{SR} \sim CN(0, N_0)$, and $n_{RD} \sim CN(0, N_0)$, correspond to each additive Gaussian noise term. Without loss of generality, we assume that the source node has transmit power p_1 and that the relay node has transmit power p_2 . In the first time-slot, the source broadcasts symbol $s(t)$ to both the destination and relay, and we can obtain

$$y_{SD} = \sqrt{p_1} h_{SD} s(t) + n_{SD} \quad (1)$$

and

$$y_{SR} = \sqrt{p_1} h_{SR} s(t) + n_{SR} \quad (2)$$

where y_{SD} and y_{SR} are the received signals at the destination and relay, respectively.

In the second time-slot, the relay sends the processed signal $x(t)$ to the destination. The corresponding received

signal y_{RD} at the destination can be written as

$$y_{RD} = \sqrt{p_2} h_{RD} x(t) + n_{RD} \quad (3)$$

In the Rayleigh fading channel, the instantaneous SNRs of the S-D, S-R, and R-D links can be expressed as

$$\gamma_{SD} = |h_{SD}|^2 p_1 / N_0 \quad (4)$$

$$\gamma_{SR} = |h_{SR}|^2 p_1 / N_0 \quad (5)$$

$$\gamma_{RD} = |h_{RD}|^2 p_2 / N_0 \quad (6)$$

respectively. Therefore, the average SNRs can be obtained as

$$\overline{\gamma_{SD}} = E(|h_{SD}|^2) p_1 / N_0 = \sigma_{SD}^2 p_1 / N_0 \quad (7)$$

$$\overline{\gamma_{SR}} = E(|h_{SR}|^2) p_1 / N_0 = \sigma_{SR}^2 p_1 / N_0 \quad (8)$$

$$\overline{\gamma_{RD}} = E(|h_{RD}|^2) p_2 / N_0 = \sigma_{RD}^2 p_2 / N_0 \quad (9)$$

where $E(\cdot)$ denotes the statistical average.

1. For the AF scheme, in the first time-slot, the source broadcasts symbol $s(t)$ to both the destination and relay. In the second time-slot, the relay sends the processed signal $x(t)$ to the destination,

$$x(t) = \sqrt{\frac{p_1}{p_1 |h_{SR}|^2 + N_0}} y_{SR} \quad (10)$$

Then we can get the SNR of the S-R-D link,

$$\gamma = \frac{\gamma_{SR} \gamma_{RD}}{1 + \gamma_{SR} + \gamma_{RD}} \quad (11)$$

By using maximum ratio combining (MRC), the destination combines the received signals at the first and second phases, then the SNR of the signal after combining can be expressed as

$$\gamma_{AF} = \gamma_{SD} + \gamma = \gamma_{SD} + \frac{\gamma_{SR} \gamma_{RD}}{1 + \gamma_{SR} + \gamma_{RD}} \quad (12)$$

Then we can obtain the channel capacity

$$I_{AF} = \frac{1}{2} \log_2(1 + \gamma_{AF}) \quad (13)$$

The system outage probability can be expressed as

$$P_{AF} = P_r(I_{AF} < R) \quad (14)$$

where R is the system information rate.

At high SNR, the outage probability can be approximately expressed as

$$P_{AF} \simeq \left(\frac{p_1 \sigma_{SR}^2 + p_2 \sigma_{RD}^2}{2 p_1^2 p_2 \sigma_{SR}^2 \sigma_{RD}^2 \sigma_{SD}^2} \right) [(2^{2R} - 1) N_0]^2 \quad (15)$$

The proof of Eq. (15) is given in the Appendix.

2. For the DF scheme, the source broadcasts symbol $s(t)$ to both the destination and relay, then we use a cyclic redundancy check (CRC) to decide the decoding accuracy at the relay node. If the decoding is wrong, we discard it. Otherwise, the relay sends the processed signal $x(t)$ to the destination,

$$x(t) = s(t) \quad (16)$$

Then we can get the SNR of the S-R-D link,

$$\gamma = \gamma_{RD} \quad (17)$$

By using MRC, the SNR of the signal after combining

the first and second phases is obtained as

$$\gamma_{DF} = \gamma_{SD} + \gamma = \gamma_{SD} + \gamma_{RD} \quad (18)$$

We get the channel capacity,

$$I_{DF} = \frac{1}{2} \min\{\log_2(1 + \gamma_{DF}), \log_2(1 + \gamma_{SR})\} \quad (19)$$

3. For the DT scheme, the source directly transmits symbol $s(t)$ without relay to the destination, then we can get the instantaneous SNR of the S-D link,

$$\gamma_{DT} = \gamma_{SD} \quad (20)$$

The channel capacity I_{DT} can be written as

$$I_{DT} = \log_2(1 + \gamma_{SD}) \quad (21)$$

According to Eq.(21), the system outage probability can be expressed as

$$P_{DT} = P_r(I_{DT} < R) \quad (22)$$

At high SNR, the outage probability can be approximately expressed as

$$P_{DT} = P_r(I_{DT} < R) \simeq \frac{(2^R - 1)N_0}{\sigma_{SD}^2 p_1} \quad (23)$$

The proof of Eq. (23) is given in the Appendix.

4. For the IDFO scheme, when the destination can directly detect and decode the data from the source node, the source transmits symbol in DT mode, otherwise, the relay transmits symbol in DF mode. At high SNR, we can get the outage probability in [8]

$$P_{IDFO} = \left[\frac{(2^{2R} - 1)^2 - (2^{2R} - 2^R)^2}{2\sigma_{RD}^2 p_2} + \frac{(2^{2R} - 1)(2^R - 1)}{\sigma_{SR}^2 p_1} \right] \frac{N_0^2}{p_1 \sigma_{SD}^2} \quad (24)$$

III. PREPARE ANALYSIS OF THE HADF AND HDAF RELAYING SCHEMES

A.HADF scheme analysis

To minimize the total transmit power of the system while guaranteeing the outage probability at the same time for cooperative systems, we propose HADF and IHDDF schemes. Firstly, we introduce the power optimization algorithms of AF and DT schemes.

1. The power optimization algorithm in the AF scheme

By simple transformation of Eq. (15), we can obtain the outage probability

$$P_{AF} = u \left(\frac{1}{p_1^2} + \frac{v}{p_1 p_2} \right) \quad (25)$$

$$\text{where } u = \frac{1}{2\sigma_{SR}^2 \sigma_{SD}^2} [(2^{2R} - 1)N_0]^2, v = \frac{\sigma_{SD}^2}{\sigma_{RD}^2}.$$

Given this system model, the power allocation problem for the AF scheme can be proposed as

$$\begin{cases} \min & (p_1 + p_2) \\ \text{s.t.} & P_{AF} \leq \delta \end{cases} \quad (26)$$

where δ is the maximum outage probability to satisfy the system requirement. From Eq. (25), we can obtain

$$p_2 = \frac{uvp_1}{P_{AF} p_1^2 - u} \quad (27)$$

Then, the optimization problem can be expressed as

$$\begin{aligned} p_3 &= \min(p_1 + p_2) \\ &= \min\left(p_1 + \frac{uvp_1}{\delta p_1^2 - u}\right) \end{aligned} \quad (28)$$

where p_3 is the minimum total transmit power of the system which guarantees the estimated outage probability. In Eq. (28), by differentiating, we can get the form

$$\frac{\partial p_3}{\partial p_1} = \frac{(\delta p_1^2)^2 - (2u + uv)\delta p_1^2 + u^2(1 - v)}{(\delta p_1^2 - u)^2} \quad (29)$$

Let $\frac{\partial p_3}{\partial p_1} = 0$, we find the optimal transmission power p_1

$$p_1 = \sqrt{\frac{u(2 + v) + u\sqrt{v^2 + 8v}}{2\delta}} \quad (30)$$

Then we can get the minimum total transmit power of the system

$$p_3 = \sqrt{\frac{u(2 + v) + u\sqrt{v^2 + 8v}}{2\delta}} \left(1 + \frac{2v}{v + \sqrt{v^2 + 8v}}\right) \quad (31)$$

2. The power optimization algorithm in the DT scheme

The outage probability P_{DT} can be expressed as

$$P_{DT} = \frac{mn}{p_1} \quad (32)$$

where $m = (2^R - 1)N_0$, $n = \frac{1}{\sigma_{SD}^2}$.

The power allocation problem for the DT scheme can be proposed thus

$$\begin{cases} \min & p_1 \\ \text{s.t.} & P_{DT} \leq \delta \end{cases} \quad (33)$$

From Eq. (33), we can obtain

$$p_4 = \min p_1 \geq \frac{mn}{\delta} \quad (34)$$

where p_4 is the minimum total transmit power of the system which guarantees the outage probability. Then we can obtain the minimum total transmit power in the system as

$$p_4 = \frac{mn}{\delta} \quad (35)$$

By analyzing the AF and DT schemes, we can set the threshold of the HADF scheme

$$\delta_0 = \frac{2(mn)^2}{[u(2 + v) + u\sqrt{v^2 + 8v}]\left(1 + \frac{2v}{v + \sqrt{v^2 + 8v}}\right)^2}$$

Then the total transmit power for the HADF scheme is derived as

$$p_6 = \begin{cases} \sqrt{\frac{u(2+v) + u\sqrt{v^2+8v}}{2\delta}} \left(1 + \frac{2v}{v + \sqrt{v^2+8v}}\right) & \delta < \delta_0 \\ \frac{mn}{\delta} & \delta \geq \delta_0 \end{cases} \quad (36)$$

when $\delta < \delta_0$, the system chooses to optimize the power allocation of the source and relay in AF mode; when $\delta \geq \delta_0$, the system optimizes the power of the source in DT mode. By comparison, we find that: when $\delta < \delta_0$, $p_6 = p_3 < p_4$; when $\delta \geq \delta_0$, $p_6 = p_4 < p_3$.

Therefore, the HADF scheme has a better total transmit power than AF and DT schemes.

B. IHDDF scheme analysis

We propose an IHDDF scheme to minimize total transmit power in the system while the outage probability meets the requirement of the system at the same time. Firstly, we introduce the power optimization algorithm used in the IDFO scheme.

1. The power optimization algorithm of the IDFO scheme

We can obtain the outage probability from Eq. (24)

$$P_{IDFO} = a \left(\frac{1}{p_1^2} + \frac{b}{p_1 p_2} \right) \quad (37)$$

where

$$a = \frac{(2^{2R} - 1)(2^R - 1)}{2\sigma_{SR}^2 \sigma_{SD}^2} N_0^2 \quad (38)$$

$$b = \frac{\sigma_{SR}^2 [(2^{2R} - 1)^2 - (2^{2R} - 2^R)^2]}{2\sigma_{RD}^2 (2^{2R} - 1)(2^R - 1)}$$

Then the power allocation can be optimized as

$$\begin{cases} \min & (p_1 + p_2) \\ s.t. & P_{IDFO} \leq \delta \end{cases} \quad (39)$$

From Eq. (37), we can get the following form

$$p_2 = \frac{abp_1}{P_{IDFO} p_1^2 - a} \quad (40)$$

Then the optimization problem can be expressed as

$$\begin{aligned} p_5 &= \min(p_1 + p_2) \\ &= \min\left(p_1 + \frac{uvp_1}{\delta p_1^2 - u}\right) \end{aligned} \quad (41)$$

where p_5 is the minimum total transmit power in the system which guarantees the outage probability. Using Eq. (41), we can obtain:

$$\frac{\partial p_5}{\partial p_1} = \frac{(\delta p_1^2)^2 - (2a + ab)\delta p_1^2 + a^2(1-b)}{(\delta p_1^2 - a)^2} \quad (42)$$

Let $\frac{\partial p_5}{\partial p_1} = 0$, the optimal transmit power p_1 is solved as

$$p_1 = \sqrt{\frac{a(2+b) + a\sqrt{b^2+8b}}{2\delta}} \quad (43)$$

Then the minimum total transmit power in the system can be expressed as

$$p_5 = \sqrt{\frac{a(2+b) + a\sqrt{b^2+8b}}{2\delta}} \left(1 + \frac{2b}{b + \sqrt{b^2+8b}}\right) \quad (44)$$

Based on both the IDFO and DT schemes, we can set the threshold of the IHDDF scheme as

$$\delta_0 = \frac{2(mn)^2}{[u(2+v) + u\sqrt{v^2+8v}]\left(1 + \frac{2v}{v + \sqrt{v^2+8v}}\right)^2}$$

Then we can get the total transmit power for the IHDDF scheme

$$p_7 = \begin{cases} \sqrt{\frac{a(2+b) + a\sqrt{b^2+8b}}{2\delta}} \left(1 + \frac{2b}{b + \sqrt{b^2+8b}}\right) & \delta < \delta_0 \\ \frac{mn}{\delta} & \delta \geq \delta_0 \end{cases} \quad (45)$$

From the above analysis, it may be seen that the system optimizes the power allocation of both source and relay in IDFO mode in the region $\delta < \delta_0$; the system optimizes the power of the source in DT mode in the region $\delta \geq \delta_0$. By comparison, we can obtain the following conclusion that: when $\delta < \delta_0$, $p_7 = p_5 < p_4$; when $\delta \geq \delta_0$, $p_7 = p_4 < p_5$.

Therefore, the IHDDF scheme outperforms both the IDFO and DT schemes.

C. Performance comparison: IHDDF and HADF schemes

We set the two parameters as follows

$$\begin{cases} h = \frac{\sqrt{u(2+v) + u\sqrt{v^2+8v}}}{\sqrt{a(2+b) + a\sqrt{b^2+8b}}} \\ g = \frac{(1 + \frac{2b}{b + \sqrt{b^2+8b}})}{(1 + \frac{2v}{v + \sqrt{v^2+8v}})} \end{cases} \quad (46)$$

By comparing the total transmit power of the HADF and IHDDF schemes, it is found that when

$$h > g \quad (47)$$

$p_6 \geq p_7$; otherwise, $p_6 \leq p_7$.

We note that if the Eq.(46) is satisfied, the IHDDF scheme has a better total transmit power than the HADF scheme.

IV. SIMULATION RESULTS

Some simulation results are presented to demonstrate the performance of both the IHDDF and HADF schemes. It is assumed that all the simulations are performed on the Rayleigh fading channels. We assume that the Eq.(46) is satisfied, and in the simulation, we set the parameters $\sigma_{SR}^2=7$, $\sigma_{RD}^2=1$, $\sigma_{SD}^2=7$, and $R = 1\text{bps} / \text{HZ}$.

The performance of three schemes including AF, DT and IDFO schemes with regards to their outage probabilities are shown in Fig. 2. For equal power allocation schemes, the source and relay nodes have equal power. As illustrated in Fig. 2, the total transmit power of the AF and IDFO schemes for

optimal power allocation are less than the corresponding total transmit power for equal power allocation. The total transmit power of the DT schemes for optimal power allocation equals to the corresponding total transmit power for equal power allocation, which verifies that the optimal power allocation scheme has a better total transmit power than the equal power allocation scheme.

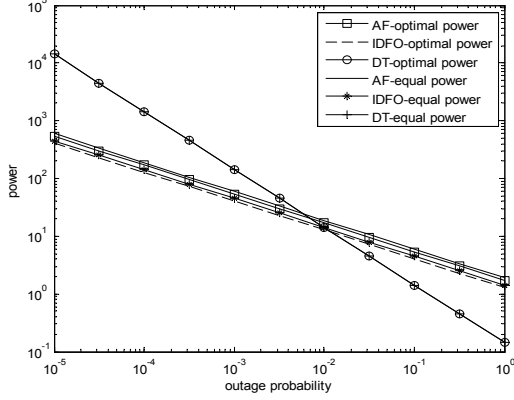


Fig.2. The total transmit power of three schemes

Fig. 3 shows the performance of four schemes including the AF, DT, IDFO, and IHDDF schemes. From Fig. 3, we note that at $\delta > 10^{-2}$, the total transmit power of the IHDDF scheme is less than those of the AF and IDFO schemes and equals to that of the DT scheme. At $\delta \leq 10^{-2}$, the total transmit power of the IHDDF scheme is less than those of the AF and DT schemes and equal to that of the IDFO scheme. So the IHDDF scheme outperforms the AF, IDFO and DT schemes.

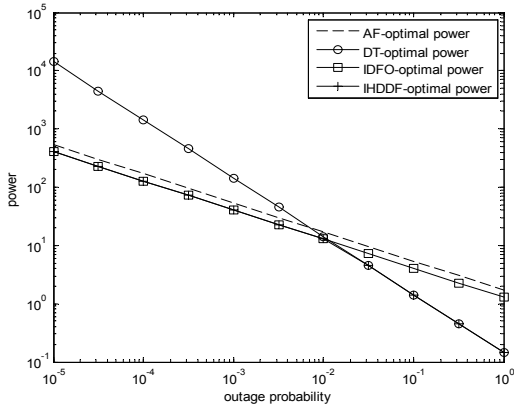


Fig.3. The total transmit power of four schemes

Fig. 4 shows the performance of three schemes including the HADF, AF and DT schemes. From Fig. 4, it can be seen that the HADF scheme is the best in the three schemes. When $\delta > 1.2 \times 10^{-2}$, the total transmit power of the HADF scheme is less than that of the AF scheme and equal to that of the DT scheme. When $\delta \leq 1.2 \times 10^{-2}$, the total transmit power of the HADF scheme is less than that of the DT scheme and equal to

that of the AF scheme. Therefore, the HADF scheme outperforms the AF and DT schemes.

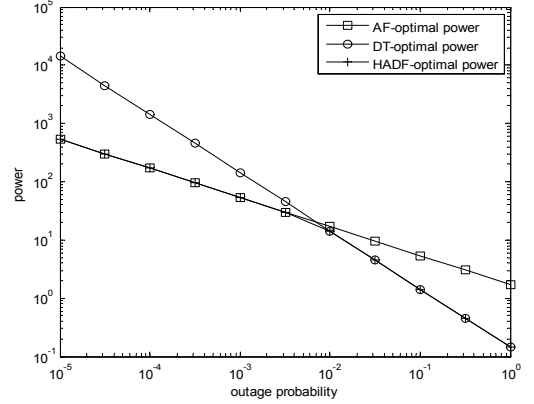


Fig.4. The total transmit power of three schemes

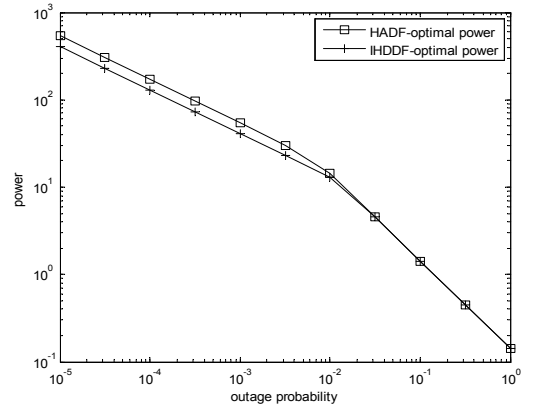


Fig.5. The total transmit power of IHDDF and HADF schemes

Fig. 5 shows the performance of the IHDDF and HADF schemes. In Fig. 5, the total transmit power performance of the IHDDF scheme is better than that of the HADF scheme. In the region of $\delta > 10^{-2}$, the total transmit power of the HADF scheme is equal to that of the IHDDF scheme; in the region where $\delta \leq 10^{-2}$, the total transmit power of the IHDDF scheme is less than that of the HADF scheme.

V. CONCLUSIONS

Based on the power optimization algorithm used in the AF, IDFO and DT schemes, IHDDF and HADF schemes have been proposed. In HADF, we set the specific outage probability threshold to determine whether the system chooses to optimize the power allocation of the source and relay in AF mode, or to optimize the power of the source in DT mode without the relay. Similarly, in IHDDF, by comparing the instantaneous outage probability and the outage probability threshold, the system chooses to optimize power in turn with incremental IDFO mode or DT mode. We obtained closed-form expressions for the total transmit power of the proposed whether or not your

simulation results show that the IHDDF relaying scheme outperforms the DT and IDFO schemes, and the HADF relaying scheme outperforms the DT and AF schemes. In a particular channel state, the IHDDF has a lower total transmit power than the HADF and AF schemes.

Some future research directions are the following. In the paper, firstly, we assume there is only one relay in the cooperative system. However, there may be several relays in the actual application environment. Therefore, how to choose the appropriate relays from all the nodes to forward the source data, as well as the transmit power levels of all the nodes become important design issues. Secondly, unmeasured channel state is an import factor to affect the system performance [19-20]. Therefore, the emphasis will be on the two aspects in the future research.

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A:PROOF OF EQ. (15)

1. Let $w = u + v$, where u and v are independent exponential random variables with parameters λ_u and λ_v , respectively. f_u and f_v are the the probability density functions of u and v . Then the cumulative distribution function (CDF) can be written as

$$\begin{aligned} P_w(w) &= \int_0^w \int_0^{w-u} f_u f_v dv du \\ &= \int_0^w f_u \int_0^{w-u} \lambda_v e^{-\lambda_v v} dv du \\ &= \int_0^w \lambda_u e^{-\lambda_u u} [1 - e^{-\lambda_v (w-u)}] du \\ &= 1 - e^{-\lambda_u w} - \int_0^w \lambda_u e^{-\lambda_u u} e^{u(\lambda_v - \lambda_u)} du \end{aligned}$$

when $\lambda_v = \lambda_u = \lambda$, the CDF is written as

$$\begin{aligned} P_w(w) &= 1 - e^{-\lambda w} - \int_0^w \lambda e^{-\lambda u} du \\ &= 1 - (1 + \lambda w)e^{-\lambda w} \end{aligned} \quad (48)$$

when $\lambda_v \neq \lambda_u$, we can obtain the CDF

$$\begin{aligned} P_w(w) &= 1 - e^{-\lambda_u w} - [\lambda_u e^{-\lambda_u w} \frac{e^{(\lambda_v - \lambda_u)w}}{\lambda_v - \lambda_u} - \frac{\lambda_u e^{-\lambda_v w}}{\lambda_v - \lambda_u}] \\ &= 1 - [\frac{\lambda_v e^{-\lambda_u w}}{\lambda_v - \lambda_u} + \frac{\lambda_u e^{-\lambda_v w}}{\lambda_u - \lambda_v}] \end{aligned} \quad (49)$$

Combining (48) with (49), the CDF is derived as

$$P_w(w) = \begin{cases} 1 - [\frac{\lambda_v e^{-\lambda_u w}}{\lambda_v - \lambda_u} + \frac{\lambda_u e^{-\lambda_v w}}{\lambda_u - \lambda_v}] & \lambda_u \neq \lambda_v \\ 1 - (1 + \lambda w)e^{-\lambda w} & \lambda_v = \lambda_u = \lambda \end{cases} \quad (50)$$

when $\lambda_v = \lambda_u = \lambda$, we make a limit of $\frac{P_w(w)}{w}$ at $w \rightarrow 0$,

$$\lim_{w \rightarrow 0} \frac{P_w(w)}{w} = \lim_{w \rightarrow 0} \frac{1 - (1 + \lambda w)e^{-\lambda w}}{w} = \frac{\lambda^2}{2} = \frac{\lambda_v \lambda_u}{2} \quad (51)$$

when $\lambda_v \neq \lambda_u$, Eq.(51) can be rewritten as

$$\lim_{w \rightarrow 0} \frac{P_w(w)}{w} = \lim_{w \rightarrow 0} \frac{1 - [\frac{\lambda_v e^{-\lambda_u w}}{\lambda_v - \lambda_u} + \frac{\lambda_u e^{-\lambda_v w}}{\lambda_u - \lambda_v}]}{w} = \frac{\lambda_v \lambda_u}{2} \quad (52)$$

Then we can obtain

$$\lim_{w \rightarrow 0} \frac{P_w(w)}{w} = \frac{\lambda_v \lambda_u}{2} \quad (53)$$

We set $\varepsilon = w$, Eq.(53) can be obtained as

$$\lim_{\varepsilon \rightarrow 0} \frac{P_w(\varepsilon)}{\varepsilon^2} = \frac{\lambda_v \lambda_u}{2} \quad (54)$$

Moreover, if function $h(\varepsilon)$ is continuous at $\varepsilon = \varepsilon_0$ and satisfies $h(\varepsilon) \rightarrow 0$ as $\varepsilon_0 = 0$, then

$$\lim_{\varepsilon \rightarrow \varepsilon_0} \frac{P_w(h(\varepsilon))}{h(\varepsilon)^2} = \frac{\lambda_v \lambda_u}{2} \quad (55)$$

2. Let $f_{(m,n)} = \frac{mn}{1+m+n}$, we assume that

$$r_\eta = \eta f\left(\frac{x}{\eta}, \frac{y}{\eta}\right), \lim_{\eta \rightarrow 0} \frac{\eta}{h(\eta)} = d < \infty \quad (56)$$

so the CDF is written as

$$\begin{aligned} P_{r_\eta}(r_\eta < h(\eta)) &= P_{r_\eta}\left[\frac{1}{x} + \frac{1}{y} + \frac{\eta}{xy} > \frac{1}{h(\eta)}\right] \\ &> P_{r_\eta}\left[\frac{1}{x} + \frac{1}{y} > \frac{1}{h(\eta)}\right] \\ &\geq P_{r_\eta}\left[\max\left(\frac{1}{x}, \frac{1}{y}\right) > \frac{1}{h(\eta)}\right] \\ &= 1 - P_{r_\eta}[x > h(\eta)]P_{r_\eta}[y > h(\eta)] \\ &= 1 - \exp[-(\lambda_x + \lambda_y)h(\eta)] \end{aligned}$$

where x and y are independent exponential random variables with parameters λ_x and λ_y . Then the probability density function is obtained: $f_{r_\eta} = (\lambda_x + \lambda_y)e^{-(\lambda_x + \lambda_y)r_\eta}$

From the above analysis, we can conclude that r_η are exponential random variables with parameters $\lambda_x + \lambda_y$. Substituting $v = r_\eta$ into Eq. (55), we can get the following form

$$\lim_{h(\varepsilon) \rightarrow 0} \frac{P_w(u + r_\eta < h(\varepsilon))}{h(\varepsilon)^2} = \frac{\lambda_u(\lambda_x + \lambda_y)}{2} \quad (57)$$

Inserting $\eta = \varepsilon$ into Eq. (57), we can obtain

$$\lim_{h(\varepsilon) \rightarrow 0} \frac{P_w(u + r_\varepsilon < h(\varepsilon))}{h(\varepsilon)^2} = \frac{\lambda_u(\lambda_x + \lambda_y)}{2} \quad (58)$$

Inserting $\eta = \varepsilon$ into Eq. (56), r_ε can be written as

$$\begin{aligned} r_\varepsilon &= \varepsilon f\left(\frac{x}{\varepsilon}, \frac{y}{\varepsilon}\right) \\ &= \varepsilon \frac{mn}{1+m+n} \\ &= \frac{xy}{\varepsilon + x + y} \end{aligned} \quad (59)$$

We know that $|h_{SD}|^2$, $|h_{SR}|^2$ and $|h_{RD}|^2$ are independent exponential random variables with parameters $1/\sigma_{SD}^2$, $1/\sigma_{SR}^2$ and $1/\sigma_{RD}^2$, respectively, so we set

$$\begin{aligned} p_1|h_{SD}|^2 &= u, p_1|h_{SR}|^2 = x, p_2|h_{RD}|^2 = y, \\ p_1/\sigma_{SD}^2 &= \lambda_u, p_1/\sigma_{SR}^2 = \lambda_x, p_2/\sigma_{RD}^2 = \lambda_y, \\ \varepsilon &= N_0, h(\varepsilon) = (2^{2R} - 1)N_0 \end{aligned} \quad (60)$$

Substituting (59) and (60) into Eq. (58), the outage probability is obtained as

$$P_{AF} \simeq \left(\frac{p_1\sigma_{SR}^2 + p_2\sigma_{RD}^2}{2p_1^2 p_2 \sigma_{SR}^2 \sigma_{RD}^2 \sigma_{SD}^2}\right) [(2^{2R} - 1)N_0]^2$$

Therefore, Eq. (15) is proved.

B: PROOF OF EQ. (23)

$$\begin{aligned} P_{DT} &= P_r(I_{DT} < R) = P_r[\log_2(1 + \gamma_{SD}) < R] \\ &= P_r[|h_{SD}|^2 < \frac{2^R - 1}{\sigma_{SD}^2} N_0] \\ &\simeq \frac{2^R - 1}{\sigma_{SD}^2 p_1} N_0 \end{aligned}$$

Therefore, Eq. (23) is proved.

