Finite Length Buffer Relaying Based Incremental Hybrid Decode-Amplify-Forward Cooperative System

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***Abstract*—In this paper, we present a finite length buffer relaying based incremental hybrid decode-amplify-forward (FLBR-IHDAF) cooperative scheme considering the high data validity instead of instantaneity in cooperative communication. The FLBR-IHDAF scheme originates from the opportunistic relaying based incremental hybrid decode-amplify-forward (OR-IHDAF) scheme and infinite length buffer relaying (ILBR) scheme, which obtains their advantages and utilizes the state of the buffer in each relay to select the suitable cooperative scheme. The proposed scheme can improve the system outage probability at the cost of a certain instantaneity and hardware complexity, which plays an important role in the non time-sensitive systems. Numerical results show the significant performance improvement of the FLBR-IHDAF scheme compared with OR-IHDAF and hybrid relay selection (HRS) cooperative schemes.**

***Keywords*—cooperative communication; buffer relaying; opportunistic relaying; IHDAF; outage probability**

I. INTRODUCTION

By sharing each antenna among the single antenna terminals, cooperative communication can enhance the transmission reliability significantly [1]-[5] and achieve significant advantages in terms of QoS equilibrium, system capacity improvement, and cost saving. Currently, cooperative technology has been widely used in cellular networks, WLAN, vehicle to vehicle communication, WSN and so on. In the real cooperative communication scenario, there are always multiple potential relays. The relay selection is very crucial to significantly improve the spectrum efficiency and system performance. The opportunistic relaying (OR) scheme was proposed by A. Bletsas et al in [6], where only the best relay will be chosen from N available candidate relays. OR scheme can achieve full diversity gain in high signal-to-noise ratio (SNR) and utilize the spectrum efficiently with the simple implementation. Based on the decode-and-forward (DF) protocol, the authors in [7] and [8] studied the OR selection cooperative scheme and OR incremental cooperative scheme and provided the corresponding outage analysis, respectively. The incremental hybrid decode-amplify-forward (IHDAF) scheme [9] and also the OR based incremental hybrid decode-amplify-forward (OR-IHDAF) scheme [10] have been presented, which can select the cooperative scheme and also the relay node based on different channel conditions.

Compared with OR, buffer relaying (BR) can utilize the best source-to-relay link and the best relay-to-destination link simultaneously and further improve the system outage performance at the acceptable degradation of instantaneity and hardware complexity. For systems that provide the data communication service, this compromise is favorable and practical. A. Ikhlef et al. in [11] proposed a hybrid relay selection (HRS) scheme based on the DF protocol, which combines the BR and OR together, and analyzed the outage and bit-error rate (BER) performance.

It has been observed that the OR-IHDAF scheme cannot further improve the system performance effectively due to the limit of OR, though it employs the outperforming IHDAF protocol. The HRS scheme in [11] took the advantage of BR, but it cannot achieve the maximum performance with the simple DF protocol. It is known that the demand for the high-speed data communications keeps growing. For the data communication service, instead of the instantaneity, the accurate transmission is more important and necessary. To our best knowledge, there exists no much research about BR based IHDAF scheme. Therefore, in this paper, we combine BR, OR, and IHDAF protocol effectively and propose a finite length buffer relaying based incremental hybrid decode-amplify-forward (FLBR-IHDAF) scheme, where the system can choose the suitable relay selection scheme based on the state of the buffer in each relay. The theoretical and simulation results show that the FLBR-IHDAF scheme outperforms the other typical excellent cooperative schemes significantly in terms of outage probability with acceptable instantaneity loss and hardware complexity increase.

II. SYSTEM MODEL FOR FLBR-IHDAF SCHEME

In this section, we present a half-duplex cooperative relaying system with the application of FLBR-IHDAF scheme, which consists of one source node (S), one destination node (D) and N possible candidate relay nodes (R_i, i=1, 2,…,

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N) as shown in Figure 1. It is assumed that perfect channel state information (CSI) can be obtained with training sequence and each node is equipped with a single antenna. A buffer with a certain length is placed in each relay. Considering the available direct transmission (DT) link, a buffer with a certain length is also needed in the destination. The coefficients of the channel, from the source to the destination(S-D), from the source to the ith relay (S-R_i), and from the ith relay to the destination (R_i-D), are expressed as h_{sd}, h_{sr_i}, and $h_{r_i d}$, respectively. Considering the main contributions of this work, we do not employ the complex channel models [4][5] and all the channels here are Rayleigh fading channels and independent with each other. The corresponding channel instantaneous SNRs are written as γ_{sd}, γ_{sr_i}, and $\gamma_{r_i d}$, and denoted as $\gamma_{sd} = |h_{sd}|^2 P_s/N_0$, $\gamma_{sr_i} = |h_{sr_i}|^2 P_S/N_0$, and $\gamma_{r_i d} = |h_{r_i d}|^2 P_R/N_0$, respectively, where $P_S=\delta P$ and $P_R=(1-\delta)P$ are the transmission power for the source and the selected best relay, respectively, and P is the total system power with $\delta \in (0,1]$ denoting the fraction of the total system power assigned for the source node. N_0 is the variance of the complex additive white Gaussian noise (AWGN) with mean zero. The average SNRs of the S-D, S-R_i and R_i-D links can be calculated respectively as $\overline{\gamma}_{sd} = E\left(|h_{sd}|^2\right) P_S/N_0$, $\overline{\gamma}_{sr_i} = E\left(|h_{sr_i}|^2\right) P_S/N_0$ and $\overline{\gamma}_{r_i d} = E\left(|h_{r_i d}|^2\right) P_R/N_0$, where $E(.)$ denotes the expectation. The instantaneous SNR γ_j, $j\in(sd, sr_i, r_i d)$, is exponentially distributed with the probability density function (PDF) written as

$$f_{\gamma_j}(\gamma) = 1/\overline{\gamma}_j \exp\left(-\gamma/\overline{\gamma}_j\right), \quad \gamma \geq 0 . \tag{1}$$

Moreover, we set $E\left(|h_{sd}|^2\right) = d_{sd}^{-\alpha}$, $E\left(|h_{sr_i}|^2\right) = d_{sr_i}^{-\alpha}$, and $E\left(|h_{r_i d}|^2\right) = d_{r_i d}^{-\alpha}$, where d_{ij} denotes the distance from node i to node j and α is the path loss factor.

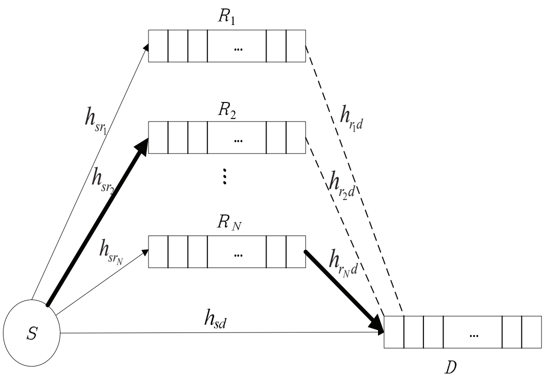

Fig. 1. System model of the FLBR-IHDAF cooperative scheme.

The communication process of OR-IHDAF scheme has been presented in [10]. In the following, we will introduce the communication process of infinite length buffer relaying based IHDAF (ILBR-IHDAF) scheme. At the first time slot, the source S will broadcast the information to all the relay nodes R_i (i=1, 2,…, N) and the destination D at the same time. D will judge whether it can recover the message from S correctly or not by comparing the instantaneous received SNR (γ_{sd}) of the S-D link with a predefined SNR threshold (SNR_{sd}). If γ_{sd} is larger than SNR_{sd}, the direct transmission will be taken and S will begin to transmit a new message at the following time slot. Otherwise, the destination will store the received message in its buffer and the system will work in cooperative mode. For BR scheme, there exist a best reception relay and a best transmission relay, and they can be different relays. The selection criterion for the best reception relay can be denoted as

$$b_r = \arg \max_{i\in\{1,2,\ldots N\}} \left\{\gamma_{sr_i}\right\} . \tag{2}$$

For the selection of the best reception relay R_{b_r}, if the instantaneous SNR $\gamma_{sr_{b_r}}$ of S- R_{b_r} link is larger than another predefined SNR threshold SNR_{sr}, R_{b_r} will decode the received signal, encode it again, and then store the encoded signal in its buffer. Otherwise, R_{b_r} will amplify the received signal and store the processed signal in its buffer. Hence, the best transmission relay is chosen as the follows

$$b_t = \arg \max_{i\in\{1,2,\ldots N\}} \left\{\gamma_{r_i d}\right\} . \tag{3}$$

We only choose one relay to receive or transmit the signal in order to avoid the reduction of the spectrum efficiency. At the second time slot, the best transmission relay R_{b_t} will forward the headmost signal in its buffer to D. D will combine the signal stored in its buffer and the one forwarded by R_{b_t}, and make the final decision. The error-free data representing the transmission order are assumed that they can help D combine the two copies of the same signal and sort the decided information.

Note that ILBR-IHDAF scheme will work normally when the buffer in R_{b_r} is not full and the buffer in R_{b_t} is not empty. Considering the real situation, the buffer in each relay should be infinitely long, which is the origin of the ILBR-IHDAF scheme. The infinite length buffer is unpractical, but the outage analysis of ILBR-IHDAF scheme is necessary since it helps to the analysis of the outage probability and the performance limit of the practical FLBR-IHDAF scheme.

With reference to the HRS scheme in [11], the communication process of the proposed FLBR-IHDAF scheme can be presented. When the buffer in R_{b_r} is full or the buffer in R_{b_t} is empty, FLBR-IHDAF scheme will become OR-IHDAF scheme. Otherwise, the finite length buffer has the same effect with the infinite one and FLBR-IHDAF scheme can work as ILBR-IHDAF scheme. The communication process of FLBR-IHDAF can be summarized as $\text{FLBR-IHDAF} \Rightarrow \begin{cases} \text{OR-IHDAF, if } N_{u,b_r} = L_R - 1 \text{ or } N_{u,b_t} = 0 \\ \text{ILBR-IHDAF, otherwise} \end{cases}$,

where $N_{u,i}$ denotes the number of the full buffer elements in relay R_i, L_R denotes the buffer element length for each relay, and each element in the buffer can store one message. We assume that the buffer in a relay is full if the number of its full elements is L_R-1, which guarantees that this relay is available in next time interval if it is selected as the best relay for OR-IHDAF scheme and avoids the degeneration of diversity order.

III. OUTAGE ANALYSIS OF FLBR-IHDAF SCHEME

According to the communication process of FLBR-IHDAF scheme in section II, its outage probability can be denoted as

$$P_{outage}^{FLBR}=P_{ILBR}P_{outage}^{ILBR}+P_{OR}P_{outage}^{OR}, \quad (4)$$

where P_{ILBR} and P_{OR} denote the probabilities of FLBR-IHDAF scheme becoming ILBR-IHDAF scheme and OR-IHDAF scheme, respectively, and $P_{ILBR}=1-P_{OR}$. P_{outage}^{ILBR} and P_{outage}^{OR} denote the outage probability of ILBR-IHDAF scheme and OR-IHDAF scheme, respectively. In the following, we present the derivation of P_{outage}^{ILBR}, P_{outage}^{OR} and P_{OR}.

A. Outage Probability of OR-IHDAF Scheme

According to the communication process of OR-IHDAF scheme introduced in [10], the outage probability can be denoted as

$$\begin{aligned} P_{outage}^{OR} &= P(\gamma_{sd}>SNR_{sd})P_{direct\,out}+P(\gamma_{sd}<SNR_{sd})P(\gamma_{sr_b}>SNR_{sr})P_{DF\,out} \\ &\quad +P(\gamma_{sd}<SNR_{sd})P(\gamma_{sr_b}<SNR_{sr})P_{AF\,out}, \end{aligned} \quad (5)$$

where $P_{directout}$, P_{DFout}, and P_{AFout} denote the outage probability in the condition of DT, DF and AF mode, respectively, and will be derived below.

$P_{direct\,out}$ can be expressed as

$$P_{direct\,out}=P(C_{direct}<R\mid\gamma_{sd}>SNR_{sd}), \quad (6)$$

where $C_{direct}=\log_2(1+\gamma_{sd})$ denotes the channel capacity in DT mode. $P_{direct\,out}$ can be further rewritten as

$$\begin{aligned} P_{direct\,out} &= P\left(\gamma_{sd}<2^R-1\mid\gamma_{sd}>SNR_{sd}\right) \\ &= \begin{cases} e^{-SNR_{sd}/\bar{\gamma}_{sd}}-e^{-\left(2^R-1\right)/\bar{\gamma}_{sd}} & SNR_{sd}<2^R-1 \\ 0 & SNR_{sd}\geq 2^R-1 \end{cases}. \end{aligned} \quad (7)$$

For the derivation of P_{DFout} and P_{AFout}, the probability distribution of the instantaneous SNR of the S-R_b link γ_{sr_b} and the R_b-D link γ_{r_bd} is very crucial. Considering the huge complexity to calculate the exact outage probability, we present an approximate method instead. The approximate cumulative distribution functions (CDFs) and probability density functions (PDFs) of γ_{sr_b} and γ_{r_bd} can be derived in the following.

For $\gamma_i=\min(\gamma_{sr_i},\gamma_{r_id})$, we can get the CDF of γ_i as

$$F_{\gamma_i}(x)=\begin{cases} 1-e^{-\left(1/\bar{\gamma}_{sr_i}+1/\bar{\gamma}_{r_id}\right)x}, & x>0 \\ 0, & \text{Otherwise} \end{cases}. \quad (8)$$

It is obvious that $\gamma_b\geq\gamma_i$ (i=1,…,N), where b is the index of the best relay node, and all the channel coefficients are independent of each other. Then, the CDF of γ_b for the best relay can be expressed as

$$F_{\gamma_b}(x)=\begin{cases} \prod_{i=1}^{N}\left[1-e^{-\left(1/\bar{\gamma}_{sr_i}+1/\bar{\gamma}_{r_id}\right)x}\right], & x>0 \\ 0, & \text{Otherwise} \end{cases}. \quad (9)$$

Following (14) in [12], we have

$$\begin{aligned} P(\gamma_b<x) &= 1-P\left(\min\left(\gamma_{sr_b},\gamma_{r_bd}\right)>x\right) \\ &= 1-P\left(\gamma_{sr_b}>x,\gamma_{r_bd}>x\right)=1-P\left(\gamma_{sr_b}>x\right)P\left(\gamma_{r_bd}>x\right) \end{aligned}, \quad (10)$$

under the assumption that γ_{sr_b} and γ_{r_bd} are independent. For simplicity, we also assume $P(\gamma_{sr_b}>x)\approx P(\gamma_{r_bd}>x)$, which always holds in the real case. Hence, (10) can be further rewritten as

$$P(\gamma_b<x)\approx 1-\left[P\left(\gamma_{sr_b}>x\right)\right]^2\approx 1-\left[P\left(\gamma_{r_bd}>x\right)\right]^2. \quad (11)$$

Considering (9) and (11), the CDF of γ_{sr_b} and γ_{r_bd} can be obtained as

$$F_{\gamma_{sr_b}}(x)\approx F_{\gamma_{r_bd}}(x)\approx 1-\sqrt{1-\prod_{i=1}^{N}\left[1-e^{-\left(1/\bar{\gamma}_{sr_i}+1/\bar{\gamma}_{r_id}\right)x}\right]} \quad (12)$$

Based on the above analysis, $P_{DF\,out}$ can be calculated as

$$\begin{aligned} P_{DF\,out} &= P\left(\gamma_{DF}^{OR}<2^{2R}-1\mid\gamma_{sd}<SNR_{sd}\right) \\ &= \int_0^c\int_0^{2^{2R}-1-x} f_{\gamma_{sd}}\left(x\mid\gamma_{sd}<SNR_{sd}\right)f_{\gamma_{r_bd}}(y)\,dxdy, \\ &= \int_0^c f_{\gamma_{sd}}\left(x\mid\gamma_{sd}<SNR_{sd}\right)F_{\gamma_{r_bd}}\left(2^{2R}-1-x\right)dx \end{aligned} \quad (13)$$

where $\gamma_{DF}^{OR}=\gamma_{sd}+\gamma_{r_bd}$, $c=\min(2^{2R}-1,SNR_{sd})$, and $f_{\gamma_{sd}}\left(x\mid\gamma_{sd}<SNR_{sd}\right)=e^{-x/\bar{\gamma}_{sd}}\Big/\left[\bar{\gamma}_{sd}\left(1-e^{-SNR_{sd}/\bar{\gamma}_{sd}}\right)\right]$. Substituting the above equations and (12) into (13), we can obtain $P_{DF\,out}$.

The expression of $P_{AF\,out}$ is given below

$$\begin{aligned} P_{AF\,out} &= P\left(\gamma_{sd}+\frac{\gamma_{sr_b}\gamma_{r_bd}}{\gamma_{sr_b}+\gamma_{r_bd}+1}<2^{2R}-1\mid\gamma_{sd}<SNR_{sd},\gamma_{sr_b}<SNR_{sr}\right) \\ &> P\left(\gamma_{sd}+\min\left(\gamma_{sr_b},\gamma_{r_bd}\right)<2^{2R}-1\mid\gamma_{sd}<SNR_{sd},\gamma_{sr_b}<SNR_{sr}\right) \\ &= P\left(\gamma_{sd}+\gamma_b<2^{2R}-1\mid\gamma_{sd}<SNR_{sd},\gamma_{sr_b}<SNR_{sr}\right) \\ &= \int_0^c\int_0^{2^{2R}-1-x} f_{\gamma_{sd}}(x\mid\gamma_{sd}<SNR_{sd})f_{\gamma_b}(y\mid\gamma_{sr_b}<SNR_{sr})\,dxdy \\ &= \int_0^c f_{\gamma_{sd}}(x\mid\gamma_{sd}<SNR_{sd})F_{\gamma_b}(2^{2R}-1-x\mid\gamma_{sr_b}<SNR_{sr})\,dx \end{aligned}, \quad (14)$$

where

$$\begin{aligned} F_{\gamma_b}(x\mid\gamma_{sr_b}<SNR_{sr}) &= \frac{P(\gamma_b\leq x,\gamma_{sr_b}\leq SNR_{sr})}{P(\gamma_{sr_b}\leq SNR_{sr})} \\ &= \frac{F_{\gamma_{sr_b}}(x)+\left[F_{\gamma_{sr_b}}(SNR_{sr})-F_{\gamma_{sr_b}}(x)\right]F_{\gamma_{r_bd}}(x)}{F_{\gamma_{sr_b}}(SNR_{sr})} \end{aligned} \quad (15)$$

Substituting (15) into (14), we can get P_{AFout}. In addition, we have $P(\gamma_{sd}<SNR_{sd})=1-\exp(-\frac{SNR_{sd}}{\bar{\gamma}_{sd}})$. Substituting (7),

(12), (13), and (14) into (5), the outage probability P_{outage}^{OR} of the OR-IHDAF scheme can be obtained.

B. Outage Probability of ILBR-IHDAF Scheme

According to the communication process of ILBR-IHDAF scheme introduced in section II, the outage probability can be denoted as

$$P_{outage}^{ILBR} = P(\gamma_{sd} > SNR_{sd})P_{direct\,out}^{ILBR} + P(\gamma_{sd} < SNR_{sd})P(\gamma_{sr_{b_r}} > SNR_{sr})P_{DF\,out}^{ILBR} + P(\gamma_{sd} < SNR_{sd})P(\gamma_{sr_{b_r}} < SNR_{sr})P_{AF\,out}^{ILBR}, \quad (16)$$

where the outage probability in the condition of DT mode $P_{direct\,out}^{ILBR}$ is same as $P_{direct\,out}$ in (7).

Based on (2) and (3), the CDF of the instantaneous SNR of S-R_{b_r} link $\gamma_{sr_{b_r}}$ and R_{b_r}-D link $\gamma_{r_{b_t}d}$ can respectively denoted as

$$F_{\gamma_{sr_{b_r}}}(x) = \prod_{i=1}^{N}\left(1 - e^{-x/\bar{\gamma}_{sr_i}}\right), \quad (17)$$

$$F_{\gamma_{r_{b_t}d}}(x) = \prod_{i=1}^{N}\left(1 - e^{-x/\bar{\gamma}_{r_id}}\right). \quad (18)$$

Therefore, $P_{DF\,out}^{ILBR}$ can be obtained as

$$\begin{aligned} P_{DF\,out}^{ILBR} &= P\left(\gamma_{DF}^{ILBR} < 2^{2R}-1 \mid \gamma_{sd} < SNR_{sd}\right) \\ &= \int_0^c\int_0^{2^{2R}-1-x} f_{\gamma_{sd}}\left(x \mid \gamma_{sd} < SNR_{sd}\right) f_{\gamma_{r_{b_t}d}}(y)\,dxdy, \quad (19) \\ &= \int_0^c f_{\gamma_{sd}}\left(x \mid \gamma_{sd} < SNR_{sd}\right) F_{\gamma_{r_{b_t}d}}\left(2^{2R}-1-x\right)dx \end{aligned}$$

where $\gamma_{DF}^{ILBR} = \gamma_{sd} + \gamma_{r_{b_t}d}$ and c=min(2^{2R}–1, SNR_{sd}).

Similarly, $P_{AF\,out}^{ILBR}$ can be given as

$$\begin{aligned} P_{AF\,out}^{ILBR} &= P\left(\gamma_{sd} + \frac{\gamma_{sr_{b_r}}\gamma_{r_{b_t}d}}{\gamma_{sr_{b_r}} + \gamma_{r_{b_t}d} + 1} < 2^{2R}-1 \mid \gamma_{sd} < SNR_{sd}, \gamma_{sr_{b_r}} < SNR_{sr}\right) \\ &> P\left(\gamma_{sd} + \min\left(\gamma_{sr_{b_r}}, \gamma_{r_{b_t}d}\right) < 2^{2R}-1 \mid \gamma_{sd} < SNR_{sd}, \gamma_{sr_{b_r}} < SNR_{sr}\right), \\ &= P\left(\gamma_{sd} + \gamma_{b_{ILBR}} < 2^{2R}-1 \mid \gamma_{sd} < SNR_{sd}, \gamma_{sr_{b_r}} < SNR_{sr}\right) \\ &= \int_0^c f_{\gamma_{sd}}(x \mid \gamma_{sd} < SNR_{sd}) F_{\gamma_{b_{ILBR}}}(2^{2R}-1-x \mid \gamma_{sr_{b_r}} < SNR_{sr})dx \end{aligned} \quad (20)$$

where

$$\begin{aligned} F_{\gamma_{b_{ILBR}}}(x \mid \gamma_{sr_{b_r}} < SNR_{sr}) &= \frac{P(\gamma_{b_{ILBR}} \le x, \gamma_{sr_{b_r}} \le SNR_{sr})}{P(\gamma_{sr_{b_r}} \le SNR_{sr})} \\ &= \frac{F_{\gamma_{sr_{b_r}}}(x) + \left[F_{\gamma_{sr_{b_r}}}(SNR_{sr}) - F_{\gamma_{sr_{b_r}}}(x)\right]F_{\gamma_{r_{b_t}d}}(x)}{F_{\gamma_{sr_{b_r}}}(SNR_{sr})} \end{aligned}. \quad (21)$$

Substitute (7), (19) and (20) into (16) and we can obtain the outage probability of ILBR-IHDAF scheme P_{outage}^{ILBR}.

Derivation of The Probability P_{OR}

For the buffer in each relay, the number of the full elements may change in each time interval. Therefore, referring to [11], we describe the state change of the buffer in each relay through Markov chain (MC). We describe the ith state of the MC as ($N_{u,1}$, $N_{u,2}$, ..., $N_{u,N}$), where $N_{u,j}$ denotes the number of full buffer elements in relay R_j and satisfies the two constraints as follows

$$\sum_{j=1}^{N} N_{u,j} = N_{u,total}, \quad (22)$$

$$0 \le N_{u,j} \le L_R - 1, \quad (23)$$

where $N_{u,total}$ denotes the sum of the full buffer elements in all the relays.

P_{OR} can be expressed as

$$P_{OR} = \sum_{i=1}^{N_S} P_{S_i} P_{OR}^{S_i}, \quad (24)$$

where N_S denotes the number of all the possible states for the MC, and P_{S_i} denotes the probability that the MC stay at state S_i, and $P_{OR}^{S_i}$ denotes the probability that FLBR-IHDAF scheme becomes OR-IHDAF scheme at state S_i.

The state transition matrix of the MC is doubly stochastic. According to [13], we have $P_{S_i} = 1/N_S$ and P_{OR} in (24) can be simplified as

$$P_{OR} = \frac{1}{N_S}\sum_{i=1}^{N_S} P_{OR}^{S_i}. \quad (25)$$

If N, L_R, and $N_{u,total}$ are given, according to (22) and (23), we can obtain N_S and the specific expression ($N_{u,1}$, $N_{u,2}$, ..., $N_{u,N}$) of each possible state through Matlab tools.

At state S_i, as the best reception relay and the best transmission relay may be different, the number of the possible relay selection cases are N*N=N^2, where we should find out $N_{OR,i}$, the number of the cases that FLBR-IHDAF scheme becomes OR-IHDAF scheme. If the buffer in a relay is full and this relay is selected as the best reception relay by (2), FLBR-IHDAF scheme will become OR-IHDAF scheme no matter which one is selected as the best transmission relay. We assume that the number of the relays with full buffer at state S_i is $N_{f,i}$, and then there are $N_{f,i}$*N cases that FLBR-IHDAF scheme becomes OR-IHDAF scheme. Similarly, if the buffer in a relay is empty and this relay is selected as the best transmission relay by (3), FLBR-IHDAF scheme will become OR-IHDAF scheme no matter how the best reception relay is selected. We assume that the relay number with empty buffer at state S_i is $N_{e,i}$, and then there are N*$N_{e,i}$ cases that FLBR-IHDAF scheme becomes OR-IHDAF scheme. Removing the repeated cases $N_{f,i}$*$N_{e,i}$, we can obtain $N_{OR,i}$ as

$$N_{OR,i} = N_{f,i} * N + N * N_{e,i} - N_{f,i} * N_{e,i} \quad (26)$$

According to the specific expression ($N_{u,1}$, $N_{u,2}$, ..., $N_{u,N}$) of each possible state obtained by Matlab simulation platform, $N_{f,i}$ and $N_{e,i}$ for each state can be easily obtained. Then, $P_{OR}^{S_i}$ can be obtained as

$$P_{OR}^{S_i} = \frac{N_{OR,i}}{N^2} \quad (27)$$

Based on (27), P_{OR} can be calculated by substituting N_S and $P_{OR}^{S_i}$ into (25). Hence, the final outage probability of FLBR-

IHDAF scheme can be achieved by substituting the above probabilities, P_{outage}^{ILBR}, P_{outage}^{OR} and P_{OR}, into (4).

IV. Numerical Results

In this section, we investigate the influence of L_R on the outage probability and the average delay of FLBR-IHDAF scheme via computer simulation, and provide the comparison with the other typical schemes. The distance of *S-D* link is normalized to be 1. The pass loss factor in the system is set as α=3 and the power allocator is set as δ=0.5. The two thresholds at the destination and the relay are set as SNR_{sd}=1.0 and SNR_{sr}=3.0, respectively. The distance of S-R_i link and the distance of R_i-D link for each relay are set as 0.6. $N_{u,total}$ is set as the maximum integer no larger than $N*L_R/2$.

Fig. 2 shows the simulation and theoretical outage probability of FLBR-IHDAF scheme considering L_R=3, 6, 25 with 3 relay nodes. The simulation results match the theoretical results well especially in high SNR region, which verifies the correctness of the theoretical analysis in section III. Moreover, the outage probability can be improved as L_R increases.

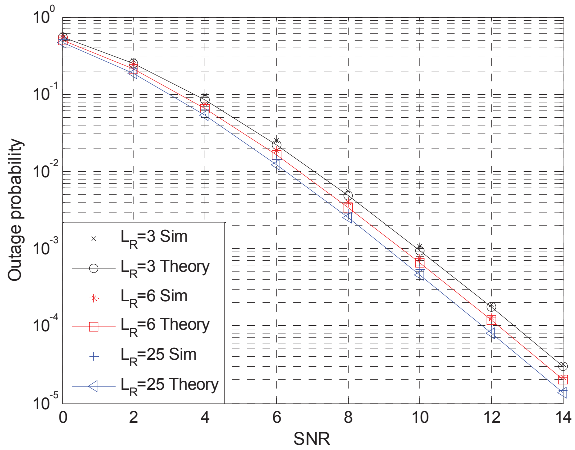

Fig. 2. Simulation and theoretical outage probability of FLBR-IHDAF scheme considering L_R=3, 6, 25 with 3 relay nodes.

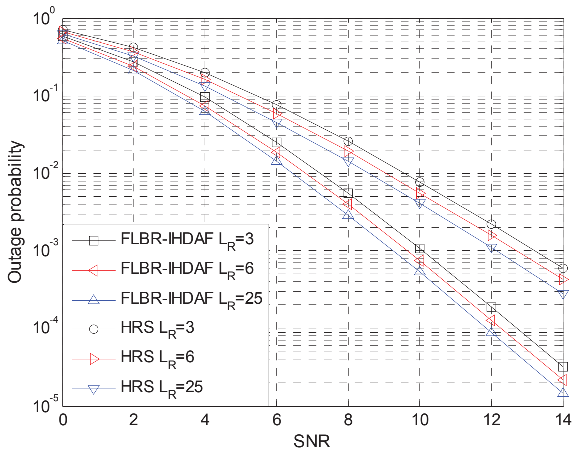

Fig. 3. Comparison of the outage performance of FLBR-IHDAF scheme and the HRS scheme considering L_R=3, 6, 25 with 3 relay nodes.

The outage performance comparison of the FLBR-IHDAF scheme with the HRS scheme proposed in [11] is shown in Fig. 3 considering L_R=3, 6, 25 with 3 relay nodes. In each L_R, FLBR-IHDAF scheme outperforms HRS scheme significantly especially in high SNR case, which demonstrates the outstanding performance advantage of FLBR-IHDAF scheme. The reason for this is that only the DF protocol is used in the HRS scheme. The performance improvement of the FLBR-IHDAF scheme profits from the advantages of the IHDAF protocol compared with the DF protocol.

Fig. 4 presents the outage probability of OR-IHDAF scheme, ILBR-IHDAF scheme, and FLBR-IHDAF scheme in L_R=3, 6, 25, 40 with 3 relay nodes. Although the outage probability decreases with the increase of L_R, the decreasing extent diminishes. Moreover, when L_R=25 and 40, the outage performance of the FLBR-IHDAF scheme is very close to that of the ILBR-IHDAF scheme and achieves about 1.4dB gains compared with that of the OR-IHDAF scheme .

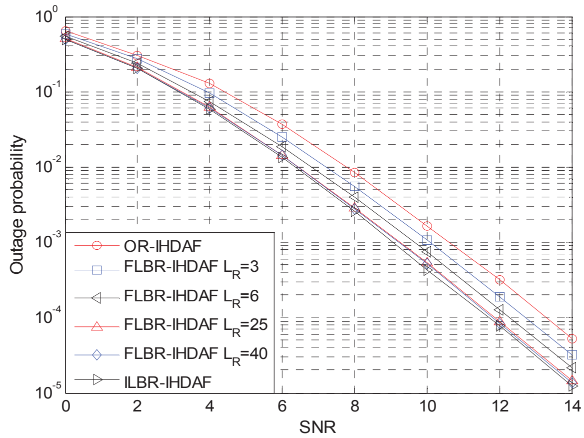

Fig. 4. Outage probability of OR-IHDAF scheme, ILBR-IHDAF scheme, and FLBR-IHDAF scheme in L_R=3, 6, 25, 40 with 3 relay nodes.

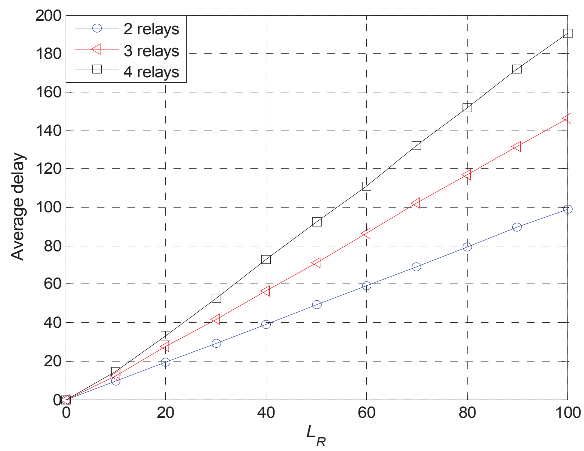

Fig. 5. Average delay of FLBR-IHDAF scheme with 2, 3, and 4 relay nodes.

Fig. 5 gives the average delay of FLBR-IHDAF scheme with 2, 3, and 4 relay nodes and the unit of the average delay is a time interval. With the increase of the number of relay nodes, the average delay increases. On the other hand, as L_R

increases, the average delay increases linearly. In the case of 3 relay nodes, when L_R =25 and 40, the average delays are 35 and 58, respectively. Therefore, when the outage performance of FLBR-IHDAF scheme is close to that of ILBR-IHDAF scheme, the average delay cost is acceptable.

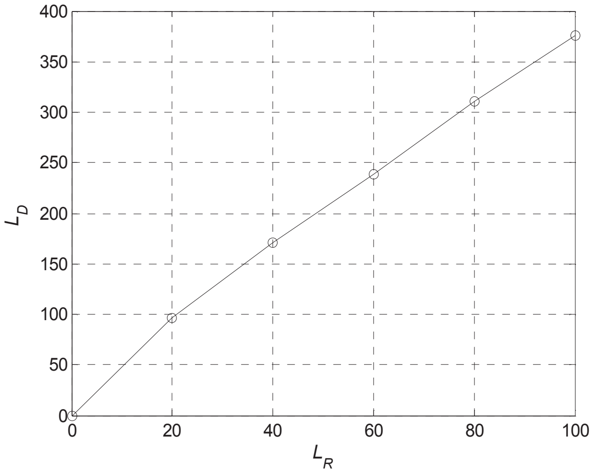

Fig. 6. Influence of L_R to L_D with 3 relays when the loss rate of copy 1 is 10^{-5}.

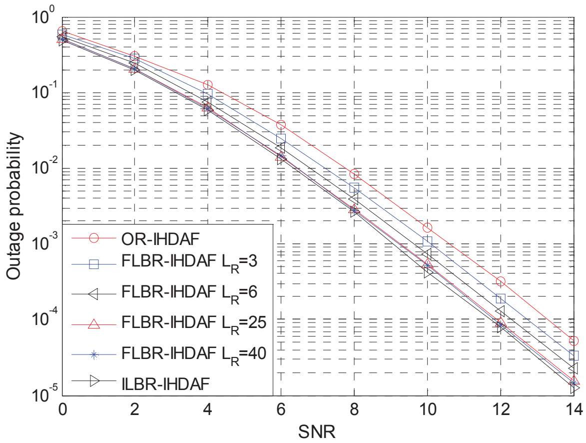

Fig. 7. Outage probability of FLBR-IHDAF scheme when the loss rate of copy 1 is 10^{-5}.

In the following, the message transmitted by *S-D* link and stored in *D* is named as copy 1 and the message forwarded by the relay to *D* is denoted as copy 2. Copy 2 will reach *D* after a certain delay. If the delay is no less than the buffer element length in *D* L_D, copy 1 will be removed from the buffer in *D* and cannot be combined with copy 2. *D* will make final decision according to copy 2. Fig. 6 shows the influence of L_R to L_D with 3 relays when the loss rate of copy 1 is 10^{-5}. L_D increases linearly with the increase of L_R and L_D is about four times of L_R. When L_R =25 and 40, L_D are 115 and 171, respectively. The order of magnitudes of L_D is practical and will not bring high complexity and cost. Fig. 7 shows the outage probability of FLBR-IHDAF scheme when the loss rate of copy 1 is 10^{-5}. Comparing it with Fig. 4, we can hardly find the slight increase of outage probability except by specific calculation.

V. Conclusion

In this paper, we have combined OR-IHDAF scheme and ILBR-IHDAF scheme to propose FLBR-IHDAF scheme and provide the theoretical outage analysis. Simulation results have verified the correctness of theoretical analysis and shown that the FLBR-IHDAF scheme outperforms the HRS scheme and OR-IHDAF scheme in terms of outage performance with the acceptable instantaneity loss and hardware complexity increase and it is more suitable for the time-insensitive systems.

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