

Buffer-Aided Relay Selection With Reduced Packet Delay in Cooperative Networks

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Abstract—Applying data buffers at relay nodes significantly improves the outage performance in relay networks, but the performance gain is often at the price of long packet delays. In this paper, a novel relay selection scheme with significantly reduced packet delay is proposed. The outage probability and average packet delay of the proposed scheme under different channel scenarios are analyzed. Simulation results are also given to verify the analysis. The analytical and simulation results show that, compared with non-buffer-aided relay selection schemes, the proposed scheme has not only significant gain in outage performance but also similar average packet delay when the channel signal-to-noise ratio (SNR) is high enough, making it an attractive scheme in practice.

Index Terms—Average delay, buffer-aided relay, relay selection.

I. INTRODUCTION

RELAY selection provides an attractive way to harvest the diversity gain in multiple relay cooperative networks [1], [2]. A typical relay selection system is shown in Fig. 1, which includes one source node (S), one destination node (D), and N relay nodes (R_k , $1 \leq k \leq N$). Analysis shows that full diversity order can be achieved with the best selected relay [3]–[5]. In the traditional max–min relay selection scheme, the best relay is selected with the highest gain among all of the minima of the source-to-relay and relay-to-destination channel gain pairs [6]. While the max–min scheme achieves a diversity order of N , its performance is practically limited by the constraint that the best source-to-relay and relay-to-destination links for a packet transmission must be determined concurrently. Recent research has, on the other hand, found that introducing data buffers at the relays yields significant performance advantage in practical systems [7]–[10]. Buffer-aided relays have also been used in ap-

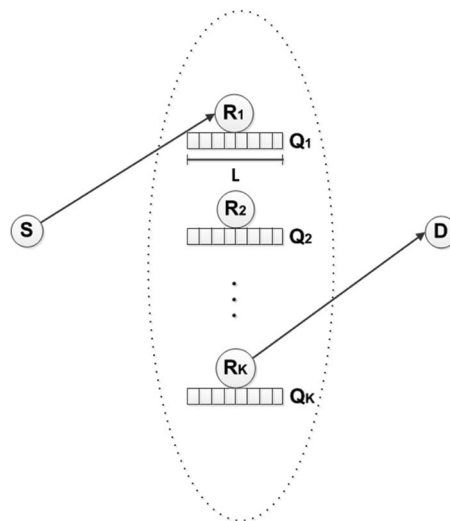


Fig. 1. System model of the relay selection system.

plications including adaptive link selection [11], [12], cognitive radio networks [13], and physical layer network security [14].

Typical buffer-aided relay selection schemes include the max–max [7] and *max-link* [8] schemes. In max–max relay selection, at one time slot t , the best link among all source-to-relay channels is selected, and a data packet is sent to the selected relay and stored in the buffer. At the next time slot ($t + 1$), the best link among all relay-to-destination channels is selected, and the selected relay (which is often not the same relay selected at time t) forwards one data packet from its buffer to the destination. The max–max scheme has significant coding gain over the traditional max–min scheme. In the max-link scheme [8], the best link is selected among all available source-to-relay and relay-to-destination links. Depending on whether a source-to-relay or a relay-to-destination link is selected, either the source transmits a packet to the selected relay or the selected relay forwards a stored packet to the destination. As a result, the max-link relay selection not only has coding gain over the max–min scheme but also has higher diversity order than both the max–min and max–max schemes, making it more attractive than its max–max counterpart.

The performance gain of either the buffer-aided max–max or max-link schemes is, however, at the price of much increased packet delay. In the non-buffer-aided relay selection scheme (e.g., the max–min scheme), it always takes two time slots for every packet passing through the network, corresponding to the source-to-relay and relay-to-destination transmission, respectively. In the buffer-aided approach, in contrast, when a packet is transmitted to a relay node, it is stored in the

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buffer and will not be forwarded to the destination until the corresponding relay-to-destination link is selected. As a result, different packets in the buffer-aided relay network may endure different delays. To be specific, in either the max-max or max-link scheme, the average packet delay increases linearly with relay number and buffer size. On the other hand, to achieve high performance gain, the relay number and the buffer size in the max-max or max-min scheme are often set as high as possible. This makes the existing buffer-aided relay selection schemes unsuitable in most applications, particularly in 5G mobile systems which require ultralow latency.

While packet delay reduction has been investigated in adaptive link selection with infinite buffer size (e.g., [11]), little has been done for buffer-aided relay selection with finite buffer size. In this paper, we propose a novel buffer-aided relay selection scheme with significantly reduced packet delay. This is achieved by giving higher priority to select the relay-to-destination than the source-to-relay links, so that the data queues at relay buffers are as short as possible. The main contributions of this paper are listed as follows.

- *Proposing a novel relay selection scheme.* The proposed scheme provides a simple yet effective way to reduce the packet delay in the buffer-aided relay selection.
- *Deriving the closed-form expression for outage probability.* The analysis is based on the general asymmetric channel assumption that the source-to-relay and relay-to-destination links may have different average gains.
- *Obtaining the closed-form expression for the average packet delay.* Using Little's law, the average packet delay of the proposed scheme is analytically obtained.
- *Analyzing the asymptotic performance that the channel SNR goes to infinity.* The asymptotic performances, including diversity order, coding gain, and average packet delay for infinite channel SNR, are analyzed.

The remainder of this paper is organized as follows: Section II proposes the new relay selection scheme; Section III analyzes the outage probability; Section IV analyzes the average packet delay; Section V analyzes the asymptotic performance; Section VI shows simulation results; and Section VII concludes this paper.

II. BUFFER-AIDED RELAY SELECTION WITH REDUCED DELAY

The system model of buffer-aided relay selection is similar to that shown in Fig. 1, except that every relay is equipped with a data buffer Q_k ($1 \leq k \leq N$) of finite size L . We assume that relays apply the decode-and-forward (DF) protocol. The channel coefficients for $S \rightarrow R_k$ and $R_k \rightarrow D$ links at time slot t are denoted by $h_{sr_k}(t)$ and $h_{r_kd}(t)$, respectively. All channels are Rayleigh fading, and the average channel gains for $S \rightarrow R_k$ and $R_k \rightarrow D$ links are given by

$$\bar{\gamma}_{sr} = E[|h_{sr_k}(t)|^2], \quad \bar{\gamma}_{rd} = E[|h_{r_kd}(t)|^2], \quad \text{for all } k \quad (1)$$

respectively. We assume without losing generality that all transmission power and noise variances are normalized to unity. We also assume that channel gains in either the source-to-relay

or relay-to-destination links are independent and identically distributed (i.i.d.), but in general $\bar{\gamma}_{sr} \neq \bar{\gamma}_{rd}$.

In the existing buffer-aided max-max and max-min relay selection schemes, the average packet delay increases linearly with relay number and buffer size. The large delay is due to the packets queuing at the buffers. This can be seen, for example, in the max-link scheme with relay number N and buffer size $L > 2$. Specifically, we assume that all buffers are initially empty and a packet s_1 is sent to relay R_1 at time $t = 1$. Then, at the next time $t = 2$, except for R_1 which contains s_1 , all other buffers are still empty. Thus, there are $(N + 1)$ available links for selection in total: N from source-to-relay ($S \rightarrow R_k$ for all k) links and one from relay-to-destination ($R_1 \rightarrow D$) link. Because the max-link scheme always selects the strongest link among all available links, the probability that $R_1 \rightarrow D$ is selected and s_1 is forwarded to the destination is $1/(N + 1)$. In other words, it is more likely [with the probability of $N/(N + 1)$] that s_1 remains in R_1 at $t = 2$, leading to one extra time slot in packet delay. It is clear that this extra delay may be avoided by forwarding s_1 to the destination immediately at $t = 2$, once the corresponding $R_1 \rightarrow D$ link is not in outage, even if it is not the strongest link.

This leads to a new principle of buffer-aided relay selection, i.e., to transmit the packets already in the buffers as fast as possible. This translates into giving higher priority to select the relay-to-destination links: only when no relay-to-destination link can be selected are the source-to-relay links considered. As a result, the packet queuing lengths at the relay buffers are minimized, as well as the average packet delay.

To be specific, at time slot t , the link selection rule is described as follows.

- 1) Choose the link with the highest channel SNR among all available relay-to-destination links ($|h_{r_kd}(t)|^2$). If the chosen link is not in outage, the corresponding relay forwards a packet from its buffer to the destination.
- 2) Otherwise, if the selected link in step 1) is in outage or there are no available relay-to-destination links at time t , choose the link with the highest channel SNR among all available source-to-relay links ($|h_{sr_k}(t)|^2$). If the selected link is not in outage, the source transmits one packet to the corresponding relay and the packet is stored in the buffer. Otherwise, outage occurs.

The aforementioned proposed scheme is easy to implement because it requires the same knowledge as that in the existing buffer-aided max-max or max-min scheme. In the following two sections, the outage and delay performance of the proposed scheme will be analyzed, respectively.

III. OUTAGE PROBABILITY

The numbers of data packets in all of the relay buffers form a "state." With N relays and buffer size L , there are $(L + 1)^N$ states in total. The l th state vector is defined as

$$s_l = [\Psi_l(Q_1), \dots, \Psi_l(Q_N)], \quad l = 1, \dots, (L + 1)^N \quad (2)$$

where $\Psi_l(Q_k)$ gives the number of data packets in buffer Q_k at state s_l . It is clear that $0 \leq \Psi_l(Q_k) \leq L$.

Every state corresponds to one pair of $(K_{s_l}^{S \rightarrow R}, K_{s_l}^{R \rightarrow D})$, corresponding to the numbers of available source-to-relay and relay-to-destination links, respectively. A source-to-relay link is considered available when the buffer of the corresponding relay node is not full, and a relay-to-destination link is available when the corresponding relay buffer is not empty. At state s_l , the total numbers of available source-to-relay and relay-to-destination links are denoted by $K_{s_l}^{S \rightarrow R}$ and $K_{s_l}^{R \rightarrow D}$, respectively. It is clear that $0 \leq K_{s_l}^{S \rightarrow R} \leq N$ and $0 \leq K_{s_l}^{R \rightarrow D} \leq N$. Specifically, if none of the buffers are full or empty, all links are available, such that $K_{s_l}^{S \rightarrow R} = K_{s_l}^{R \rightarrow D} = N$.

Considering all possible states, the outage probability of the proposed buffer-aided scheme can be obtained as

$$P_{\text{out}} = \sum_{l=1}^{(L+1)^N} \pi_l \cdot p_{\text{out}}^{s_l} \quad (3)$$

where π_l is the stationary probability for state s_l , and $p_{\text{out}}^{s_l}$ is the outage probability at state s_l . In the following two subsections, we derive $p_{\text{out}}^{s_l}$ and π_l , respectively.

A. $p_{\text{out}}^{s_l}$: Outage Probability at State s_l

For independent Rayleigh fading channels, the instantaneous SNR for every channel, i.e., $\gamma_w (w \in \{sr_k, r_kd\})$, is independently exponentially distributed. In the proposed scheme, outage occurs if all available source-to-relay links and relay-to-destination links are in outage. Thus, the outage probability at state s_l is given by

$$p_{\text{out}}^{s_l} = p_{\text{out}}^{S \rightarrow R} \cdot p_{\text{out}}^{R \rightarrow D} \quad (4)$$

where

$$\begin{aligned} p_{\text{out}}^{S \rightarrow R} &= \left(1 - e^{-\frac{\Delta}{\gamma_{sr}}}\right)^{K_{s_l}^{S \rightarrow R}} \\ p_{\text{out}}^{R \rightarrow D} &= \left(1 - e^{-\frac{\Delta}{\gamma_{rd}}}\right)^{K_{s_l}^{R \rightarrow D}} \end{aligned} \quad (5)$$

where $p_{\text{out}}^{S \rightarrow R}$ and $p_{\text{out}}^{R \rightarrow D}$ are the probabilities that all available source-to-relay links and relay-to-destination links are in outage, respectively; r_t is the target data rate; and $\Delta = 2^{r_t} - 1$.

B. π_l : Stationary Probability of the State s_l

We denote \mathbf{A} as the $(L+1)^N \times (L+1)^N$ state transition matrix, where the entry $\mathbf{A}_{n,l} = P(X_{t+1} = s_n | X_t = s_l)$ is the transition probability that the state moves from s_l at time t to s_n at time $(t+1)$.

We assume that, at time slot t , the state is at s_l . The probability to select one relay-to-destination link when not all of the available relay-to-destination links are in outage is given by

$$\begin{aligned} p_{s_l}^{R \rightarrow D} &= \frac{1}{K_{s_l}^{R \rightarrow D}} \cdot (1 - p_{\text{out}}^{R \rightarrow D}) \\ &= \frac{1}{K_{s_l}^{R \rightarrow D}} \cdot \left(1 - \left(1 - e^{-\frac{\Delta}{\gamma_{rd}}}\right)^{K_{s_l}^{R \rightarrow D}}\right). \end{aligned} \quad (6)$$

On the other hand, because a source-to-relay link is selected only when all relay-to-destination links are in outage and not all source-to-relay links are in outage, the probability to select one source-to-relay link at state s_l is given by

$$\begin{aligned} p_{s_l}^{S \rightarrow R} &= \frac{1}{K_{s_l}^{S \rightarrow R}} \cdot p_{\text{out}}^{R \rightarrow D} \cdot (1 - p_{\text{out}}^{S \rightarrow R}) \\ &= \frac{1}{K_{s_l}^{S \rightarrow R}} \cdot \left(1 - e^{-\frac{\Delta}{\gamma_{rd}}}\right)^{K_{s_l}^{R \rightarrow D}} \cdot \left(1 - \left(1 - e^{-\frac{\Delta}{\gamma_{sr}}}\right)^{K_{s_l}^{S \rightarrow R}}\right). \end{aligned} \quad (7)$$

With these observations, the (n, l) th entry of the state transition matrix \mathbf{A} is expressed as

$$\mathbf{A}_{n,l} = \begin{cases} p_{\text{out}}^{s_l}, & \text{if } s_n = s_l \\ p_{s_l}^{R \rightarrow D}, & \text{if } s_n \in U_{s_l}^{R \rightarrow D} \\ p_{s_l}^{S \rightarrow R}, & \text{if } s_n \in U_{s_l}^{S \rightarrow R} \\ 0, & \text{elsewhere} \end{cases} \quad (8)$$

where $p_{\text{out}}^{s_l}$, $p_{s_l}^{R \rightarrow D}$, and $p_{s_l}^{S \rightarrow R}$ are given by (4), (6), and (7), respectively; $U_{s_l}^{R \rightarrow D}$ and $U_{s_l}^{S \rightarrow R}$ are the sets containing all states to which s_l can move when a relay-to-destination link or a source-to-relay link is selected, respectively.

Because the transition matrix \mathbf{A} in (8) is column stochastic, irreducible, and aperiodic,¹ the stationary state probability vector is obtained as (see [15])

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1} \mathbf{b} \quad (9)$$

where $\boldsymbol{\pi} = [\pi_1, \dots, \pi_{(L+1)^N}]^T$, $\mathbf{b} = (1, 1, \dots, 1)^T$, \mathbf{I} is the identity matrix, and $\mathbf{B}_{n,l}$ is an $n \times l$ all-one matrix.

Finally, substituting (8) and (9) into (3) gives the outage probability as

$$\begin{aligned} P_{\text{out}} &= \sum_{l=1}^{(L+1)^N} \pi_l \cdot p_{\text{out}}^{s_l} = \text{diag}(\mathbf{A}) \cdot \boldsymbol{\pi} \\ &= \text{diag}(\mathbf{A}) \cdot (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1} \mathbf{b} \end{aligned} \quad (10)$$

where $\text{diag}(\mathbf{A})$ is a vector consisting of all diagonal elements of \mathbf{A} .

IV. AVERAGE PACKET DELAY

The delay of a packet in the system is the duration between the time when the packet leaves the source node and the time when it arrives the destination. Because it takes one time slot to transmit a packet from the source to a relay node, the average packet delay in the system is given by

$$\bar{D} = 1 + \bar{D}_r \quad (11)$$

where \bar{D}_r is the average delay at the relay nodes.

Because the average delay through every relay node is the same, only the average delay through relay R_k is analyzed in

¹Column stochastic means that all entries in any column sum up to one, irreducible means that it is possible to move from any state to any state, and aperiodic means that it is possible to return to the same state at any steps [15].

the following. Based on Little's law [16], the average packet delay at relay R_k is given by

$$\bar{D}_r = \bar{D}_k = \frac{\bar{L}_k}{\bar{\eta}_k} \quad (12)$$

where \bar{L}_k and $\bar{\eta}_l$ are the average queuing length and average throughput at R_k , respectively.

The average queuing length at R_k is obtained by averaging the queuing lengths at buffer Q_k over all states, or

$$\bar{L}_k = \sum_{l=1}^{(L+1)^N} \pi_l \Psi_l(Q_k) \quad (13)$$

where $\Psi_l(Q_k)$ gives the number of packets (or the buffer length) of buffer Q_k at state s_l , and π_l is given by (9).

On the other hand, because the probabilities to select any of the relays are the same, the average throughput at relay R_k is given by

$$\bar{\eta}_k = \frac{\bar{\eta}}{N} \quad (14)$$

where $\bar{\eta}$ is the average throughput of the overall system network. For delay-limited transmission, the average throughput $\bar{\eta}$ is obtained as (see [17] and [18])

$$\bar{\eta} = R \cdot (1 - P_{\text{out}}) \quad (15)$$

where R is the average data rate of the system (without considering the outage probability). In the proposed scheme, every packet requires two time slots (not necessarily consecutively) to reach the destination, we have $R = 1/2$, and thus

$$\bar{\eta}_k = \frac{1 - P_{\text{out}}}{2N}. \quad (16)$$

Substituting (13) and (16) into (12), and further into (11), gives

$$\bar{D} = 1 + \frac{2 \cdot N \cdot \sum_{l=1}^{(L+1)^N} \pi_l \Psi_l(Q_k)}{1 - P_{\text{out}}}. \quad (17)$$

V. ASYMPTOTIC PERFORMANCE

This section analyzes the asymptotic performance of the proposed scheme when the average channel SNR goes to infinity. The average channel SNRs for source-to-relay and relay-to-destination link can be respectively expressed as

$$\bar{\gamma}_{sr} = \alpha \bar{\gamma} \quad \text{and} \quad \bar{\gamma}_{rd} = \beta \bar{\gamma} \quad (18)$$

where α and β are positive real constants, and $\bar{\gamma}$ is the normalized average channel SNR. In the following, we first derive the asymptotic outage probability for $\bar{\gamma} \rightarrow \infty$, from which the diversity order, coding gain, and average packet delay are obtained.

A. Asymptotic Outage Probability

When $\bar{\gamma} \rightarrow \infty$, it is clear from (6) that

$$\lim_{\bar{\gamma} \rightarrow \infty} p_{s_l}^{R \rightarrow D} = 1, \quad \text{if } K_{s_l}^{R \rightarrow D} \neq 0. \quad (19)$$

This implies that any packets in the relay buffers will be forwarded to the destination and a new packet is transmitted to one of the relays only after all buffers are empty. Thus, when $\bar{\gamma} \rightarrow \infty$, the buffers can only be in two possible states, namely, $S^{(0)}$ and $S^{(1)}$, corresponding to the cases that all buffers are

empty and only one of the buffers has one packet, respectively. It is then from (3) that

$$\lim_{\bar{\gamma} \rightarrow \infty} P_{\text{out}} = P(S^{(0)}) \cdot p_{\text{out}}^{S^{(0)}} + P(S^{(1)}) \cdot p_{\text{out}}^{S^{(1)}} \quad (20)$$

where $P(S^{(0)})$ and $P(S^{(1)})$ are the probabilities that buffers are in states $S^{(0)}$ and $S^{(1)}$, respectively, and $p_{\text{out}}^{S^{(0)}}$ and $p_{\text{out}}^{S^{(1)}}$ are the corresponding outage probabilities.

Suppose that, at time t , all buffers are empty, so that the state is in $S^{(0)}$. Then, one packet will be transmitted to a relay at time $(t + 1)$, and the state moves to $S^{(1)}$. From (19), the packet in the buffer must be forwarded to the destination at $(t + 2)$, and the state returns to $S^{(0)}$. This process continues until all packets are transmitted. Thus, we have

$$P(S^{(0)}) = P(S^{(1)}) = \frac{1}{2}. \quad (21)$$

When the buffers are in state $S^{(0)}$, there are N available source-to-relay links and no available relay-to-destination links, or we have

$$p_{\text{out}}^{S^{(0)}} = \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{sr}}}\right)^N. \quad (22)$$

When the buffers are in state $S^{(1)}$, there is one available relay-to-destination link. In addition, the number of available source-to-relay links is denoted by K_{∞} , where $K_{\infty} = N - 1$ or N , for buffer size $L = 1$ or larger, respectively. Then, we have

$$p_{\text{out}}^{S^{(1)}} = \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{sr}}}\right)^{K_{\infty}} \cdot \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{rd}}}\right). \quad (23)$$

Substituting (21), (22), and (23) into (20) gives

$$\lim_{\bar{\gamma} \rightarrow \infty} P_{\text{out}} = \frac{1}{2} \cdot \left(1 - e^{-\frac{\Delta}{\alpha \bar{\gamma}}}\right)^N + \frac{1}{2} \cdot \left(1 - e^{-\frac{\Delta}{\alpha \bar{\gamma}}}\right)^{K_{\infty}} \times \left(1 - e^{-\frac{\Delta}{\beta \bar{\gamma}}}\right). \quad (24)$$

B. Diversity Order

The diversity order can be defined as

$$d = - \lim_{\bar{\gamma} \rightarrow \infty} \frac{\log P_{\text{out}}}{\log \bar{\gamma}}. \quad (25)$$

If the buffer size $L = 1$, substituting (24) into (25), and further noting that $e^x \approx 1 + x$ for very small x , we have the diversity order for $L = 1$ as

$$d^{(L=1)} = - \lim_{\bar{\gamma} \rightarrow \infty} \frac{\log \left[\frac{1}{2} \cdot \left(\frac{\Delta}{\alpha \bar{\gamma}}\right)^{N-1} \cdot \left(\frac{\Delta}{\alpha \bar{\gamma}} + \frac{\Delta}{\beta \bar{\gamma}}\right) \right]}{\log \bar{\gamma}} = N. \quad (26)$$

If the buffer size $L \geq 2$, from (24), the asymptotic outage probability is given by

$$\lim_{\bar{\gamma} \rightarrow \infty} P_{\text{out}}^{(L \geq 2)} = \lim_{\bar{\gamma} \rightarrow \infty} \left[\frac{1}{2} \cdot \left(\frac{\Delta}{\alpha \bar{\gamma}}\right)^N \cdot \left(\frac{\beta \bar{\gamma} + \Delta}{\beta \bar{\gamma}}\right) \right]. \quad (27)$$

Because

$$\lim_{\bar{\gamma} \rightarrow \infty} (\beta \bar{\gamma}) < \lim_{\bar{\gamma} \rightarrow \infty} (\beta \bar{\gamma} + \Delta) < \lim_{\bar{\gamma} \rightarrow \infty} (2 \cdot \beta \bar{\gamma}) \quad (28)$$

the diversity order for $L \geq 2$ can be obtained as

$$N < d^{(L \geq 2)} < N + 1. \quad (29)$$

C. Coding Gain

The coding gain is defined as the SNR difference (in decibels) between the traditional max-min and proposed schemes to achieve the same outage probability, or

$$C(\text{dB}) = -\frac{\lim_{\bar{\gamma} \rightarrow \infty} \Delta P(\bar{\gamma})}{d} \quad (30)$$

where $d = N$, which is the diversity order, and

$$\Delta P(\bar{\gamma}) = 10 \log P_{\text{out}}^{(\text{max-min})}(\bar{\gamma}) - 10 \log P_{\text{out}}^{(L=1)}(\bar{\gamma}) \quad (31)$$

where $P_{\text{out}}^{(\text{max-min})}(\bar{\gamma})$ and $P_{\text{out}}^{(L=1)}(\bar{\gamma})$ are the outage probabilities at $\bar{\gamma}$ for the max-min and proposed schemes, respectively. For fair comparison, the buffer size is set as $L = 1$, so that the diversity order for the max-min and proposed schemes are the same as $d = N$.

From (24), we have

$$\begin{aligned} \lim_{\bar{\gamma} \rightarrow \infty} 10 \log P_{\text{out}}^{(L=1)} &= 10 \cdot \log \left[\frac{1}{2} \cdot \left(\frac{1}{\alpha} \right)^{N-1} \left(\frac{1}{\alpha} + \frac{1}{\beta} \right) \right] \\ &+ \lim_{\bar{\gamma} \rightarrow \infty} 10 \cdot \log \left(\frac{\Delta}{\bar{\gamma}} \right)^N. \end{aligned} \quad (32)$$

For the traditional max-min scheme, we have

$$\begin{aligned} \lim_{\bar{\gamma} \rightarrow \infty} 10 \log P_{\text{out}}^{(\text{max-min})} &= \lim_{\bar{\gamma} \rightarrow \infty} 10 \cdot \log \left(\frac{\Delta}{\alpha \bar{\gamma}} + \frac{\Delta}{\beta \bar{\gamma}} \right)^N \\ &= 10 \cdot \log \left(\frac{1}{\alpha} + \frac{1}{\beta} \right)^N + \lim_{\bar{\gamma} \rightarrow \infty} 10 \cdot \log \left(\frac{\Delta}{\bar{\gamma}} \right)^N. \end{aligned} \quad (33)$$

Substituting (32) and (33) into (31) gives

$$\lim_{\bar{\gamma} \rightarrow \infty} \Delta P(\bar{\gamma}) = -10 \cdot \log \left[\frac{1}{2} \left(\frac{\beta}{\alpha + \beta} \right)^{N-1} \right]. \quad (34)$$

Finally, substituting (34) into (30) gives the coding gain of the proposed scheme as

$$C(\text{dB}) = \frac{-10 \cdot \log \left[\frac{1}{2} \left(\frac{\beta}{\alpha + \beta} \right)^{N-1} \right]}{N}. \quad (35)$$

It is interesting to observe that, for symmetric channel configuration with $\alpha = \beta$, the coding gain is 3 dB.

D. Average Packet Delay

We have shown that, when $\bar{\gamma} \rightarrow \infty$, the buffer states can only be in either $S^{(0)}$ or $S^{(1)}$, or a buffer can only be empty or contains one packet. When all buffers are empty, a new packet is transmitted to a relay with probability of $1/N$. Further from (21) that $P(S^{(1)}) = 1/2$, the probability that Q_k contains one packet is given by

$$P(Q_k = 1) = P(S^{(1)}) \cdot \frac{1}{N} = \frac{1}{2N}. \quad (36)$$

Thus, when $\bar{\gamma} \rightarrow \infty$, the average buffer length at relay R_k is given by

$$\lim_{\bar{\gamma} \rightarrow \infty} \bar{L}_k = 1 \cdot P(Q_k = 1) = P(S^{(1)}) \cdot \frac{1}{N} = \frac{1}{2N}. \quad (37)$$

TABLE I
ASYMPTOTIC PERFORMANCE COMPARISON AMONG
DIFFERENT SCHEMES FOR SYMMETRIC CHANNELS

| | max-min | max-max | max-link | proposed |
|-----------------|---------|--------------------|-----------|------------|
| diversity order | N | N | $[N, 2N]$ | $(N, N+1)$ |
| coding gain | 0 dB | 3 dB | 3 dB | 3 dB |
| average delay | 2 | $\frac{NL}{2} + 1$ | $NL + 1$ | 2 |

From (16), and noticing that $\lim_{\bar{\gamma} \rightarrow \infty} P_{\text{out}} = 0$, the average throughput at relay Q_k is given by

$$\lim_{\bar{\gamma} \rightarrow \infty} \eta_k = \frac{\lim_{\bar{\gamma} \rightarrow \infty} (1 - P_{\text{out}})}{2N} = \frac{1}{2N}. \quad (38)$$

Finally, substituting (37) and (38) into (12), and further into (11), gives the average packet delay for $\bar{\gamma} \rightarrow \infty$ as

$$\lim_{\bar{\gamma} \rightarrow \infty} \bar{D} = 1 + \frac{\frac{1}{(2N)}}{\frac{1}{(2N)}} = 2. \quad (39)$$

It is clearly shown in (39) that, when SNR is high enough, the average packet delay of the proposed scheme is the same as that for the non-buffer-aided schemes.

E. Comparison Between Different Schemes in Symmetric Channel Configuration

For the symmetric channel configuration, Table I compares the diversity order, coding gain, and average delay for the non-buffer-aided max-min, the traditional buffer-aided max-max and max-link, and the proposed schemes.

Table I shows that all buffer-aided schemes have the 3-dB coding gain over the max-min scheme. The proposed link has slightly higher diversity order than the max-max scheme but lower diversity order than the max-link scheme. In either the max-max or max-link scheme, the average packet delay increases linearly with relay number N and buffer size L . In the proposed scheme, when $\bar{\gamma} \rightarrow \infty$, the average delay is fixed at 2, which is the same as that for the non-buffer-aided max-min scheme.

For asymmetric channels, the comparison between schemes is not the same as that shown in Table I, and this will be discussed in the following section.

VI. SIMULATIONS AND DISCUSSIONS

This section verifies the proposed scheme with numerical simulations, where the results for previously described max-link and non-buffer-aided max-min schemes are also shown for comparison. In the following simulation, the transmission rates in all schemes are set as $r_t = 2$ b/s/Hz, and simulation results are obtained with 1 000 000 Monte Carlo runs. Particularly in the proposed scheme, the simulation results always well match the theoretical analysis.

A. Symmetric Channel Configuration: $\bar{\gamma}_{sr} = \bar{\gamma}_{rd}$

In the first simulation, we consider a symmetric channel scenario that the source-to-relay and relay-to-destination links have the same average channel SNRs.

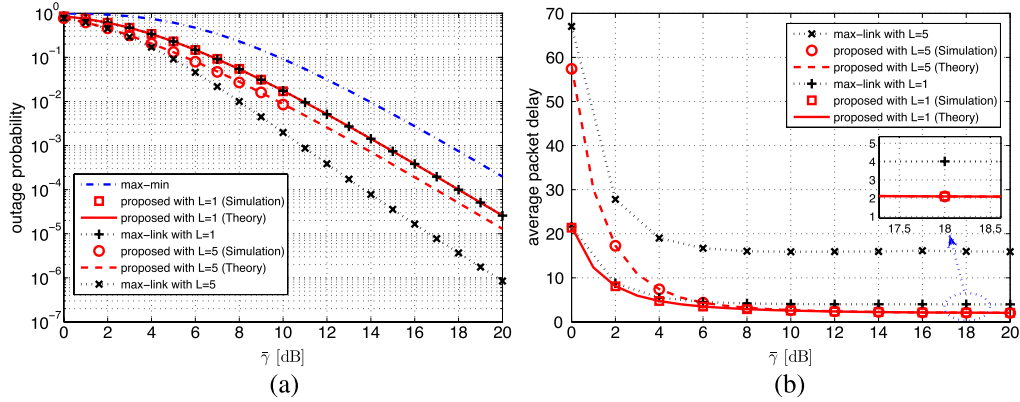


Fig. 2. (a) Outage probabilities and (b) average delay among different schemes, where $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = 10$ dB.

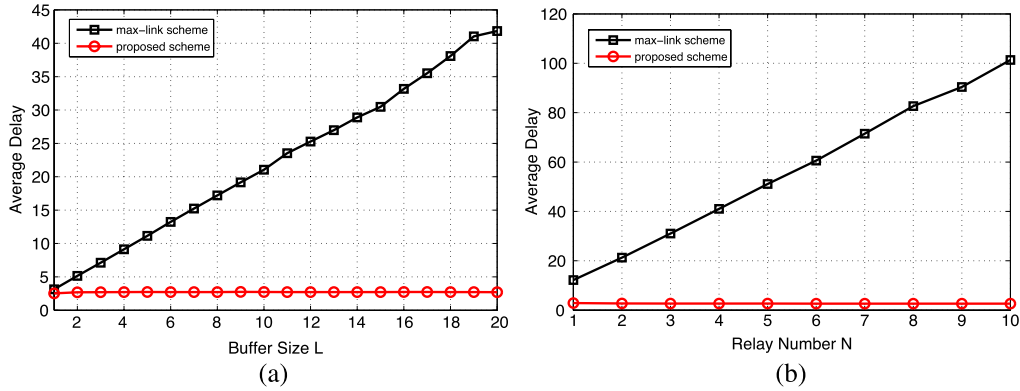


Fig. 3. Average packet delay comparison between the max-link and proposed schemes. (a) Delay versus buffer size, where $N = 2$. (b) Delay versus relay number, where $L = 10$.

Fig. 2(a) and (b) compares the outage probabilities and average packet delays for the non-buffered max-min, traditional max-link, and proposed schemes, respectively, where the relay number is fixed at $N = 3$, and we let $\alpha = \beta = 1.5$ and $\bar{\gamma} = 10$ dB in (18), so that $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = 15$ dB. Fig. 2(a) shows that, when the buffer size $L = 1$, the proposed and max-link schemes have the same outage probabilities, where both have significantly better outage performance than the traditional non-buffer-aided max-min scheme because of the 3-dB coding gain. When the buffer size increases to $L = 5$, the proposed scheme has slightly better outage performance than that for $L = 1$. This well matches the asymptotic analysis that, when $L \geq 2$, the diversity order is larger than N but smaller than $(N + 1)$ for the proposed scheme. On the other hand, for the max-link scheme, the outage performance improves more significantly with larger buffer size. This is because the diversity order of the max-link scheme goes up with the buffer size, until it reaches $2N$ when $L \rightarrow \infty$. Fig. 2(b) shows that, even for $L = 1$, the average delay of the max-link scheme is at least twice as much as that for the proposed scheme. When the buffer size increases to $L = 5$, the average packet delay of the proposed scheme still maintains at 2 in high-SNR ranges, which is the same as that for $L = 1$. On the other hand, when $L = 5$, the average packet delay of the max-link scheme increases to 18 at high SNRs, which is nine times larger than that of the proposed scheme.

To further compare the delay performance of the max-link and proposed schemes in symmetric channels, Fig. 3(a) and (b) shows the average packet delay versus the buffer size and relay

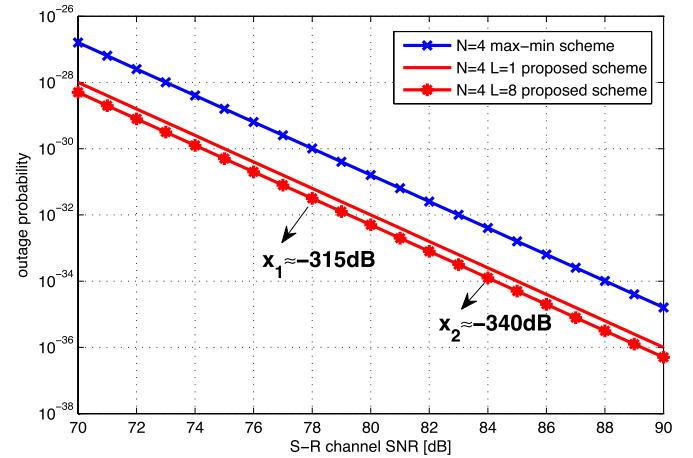


Fig. 4. Diversity order and coding gain of the proposed scheme.

number, respectively, where the average channel SNRs in both schemes are set as 10 dB. In Fig. 3(a), the relay number is fixed at $N = 2$, and the buffer size varies from 1 to 20. In Fig. 3(b), the buffer size is fixed at $L = 10$, but the relay number varies from 1 to 10. It is clearly shown in both Fig. 3(a) and (b) that the average packet delay for the proposed scheme remains at a constant value of 2. On the other hand, the packet delay in the max-link scheme goes up linearly with either N or L .

To reveal the diversity order and coding gain of the proposed scheme, Fig. 4 compares the outage probabilities of the proposed and non-buffer-aided max-min schemes at very high

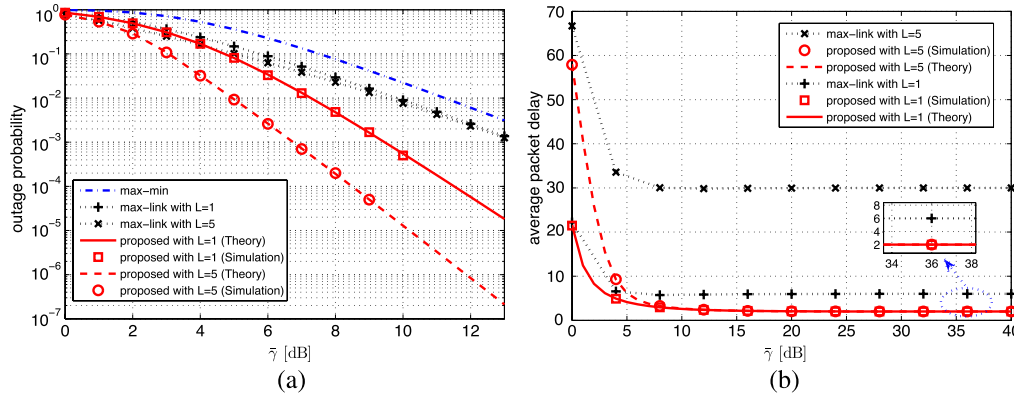


Fig. 5. (a) Outage probabilities and (b) average delay among different schemes, where $\bar{\gamma}_{sr} = 20$ dB and $\bar{\gamma}_{rd} = 10$ dB.

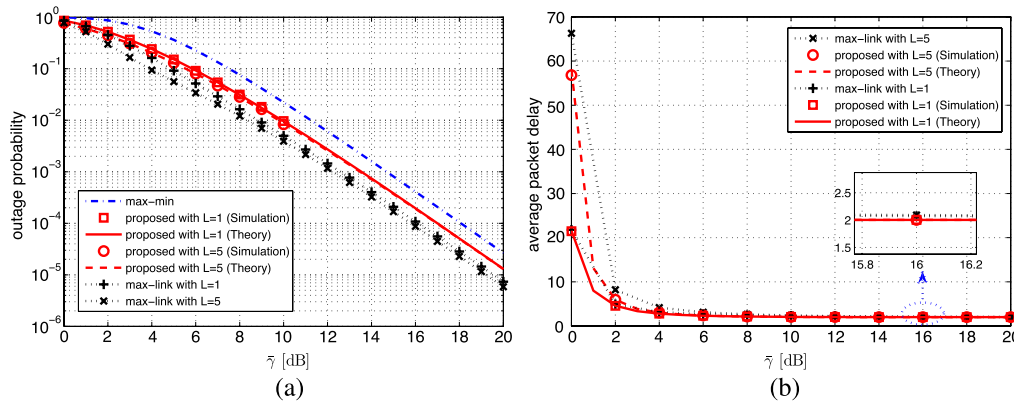


Fig. 6. (a) Outage probabilities and (b) average delay among different schemes, where $\bar{\gamma}_{sr} = 10$ dB and $\bar{\gamma}_{rd} = 20$ dB.

SNRs, where the relay number is set as $N = 4$ and all results are from theoretical analysis. First, the coding gain is clearly 3 dB, by comparing the max-min and proposed schemes with $L = 1$. For example, to achieve the outage probability of 10^{-34} , the SNRs for the max-min and proposed schemes with $L = 1$ are about 85 and 88 dB, respectively. The diversity order of the proposed scheme is also clearly shown to be $(N, N + 1)$ for $L \geq 2$. For example, as illustrated in the figure, for the proposed scheme with $L = 8$, the SNRs to achieve the outage probabilities of -315 and -340 dB are about 78 and 84 dB, respectively. Then, according to the diversity order definition in (25), the diversity order is obtained as $(340 - 315)/(84 - 78) = 4.17$, which is clearly between $N = 4$ and $N + 1 = 5$.

B. Asymmetric Channel Configuration: $\bar{\gamma}_{sr} > \bar{\gamma}_{rd}$

In Fig. 5, we consider the asymmetric channel assumption that source-to-relay links are stronger than relay-to-destination links in average, where we let $\alpha = 2$, $\beta = 1$, and $\bar{\gamma} = 10$ dB in (18), so that $\bar{\gamma}_{sr} = 20$ dB and $\bar{\gamma}_{rd} = 10$ dB, and relay number is fixed at $N = 3$.

It is very interesting to observe in Fig. 5(a) that, for both $L = 1$ and $L = 5$, the outage performance of the proposed scheme is significantly better than the max-link scheme. This is because, when the source-to-relay links are stronger than

the relay-to-destination links, the max-link scheme is more likely to select the source-to-relay links, so that the buffers are more likely full. This effectively decreases the number of available source-to-relay links, leading to lower diversity order. On the other hand, in the proposed scheme, while the channel condition gives higher priority to the source-to-relay selection, the selection rule gives higher priority to the relay-to-destination link selection. This leads to a more “balanced” buffers at the relays, or fewer full or empty buffers, which again increases the diversity order.

Fig. 5(b) shows the average delay of the max-link even worse than that in symmetric channels. This is because the buffers are more likely to be full, or because of higher queuing length at buffers. On the contrary, the average delay for the proposed scheme is still as low as about 2 at high SNR.

Therefore, when $\bar{\gamma}_{sr} > \bar{\gamma}_{rd}$, the proposed scheme has better performance in both outage probability and average delay than the max-link scheme.

C. Asymmetric Channel Configuration: $\bar{\gamma}_{sr} < \bar{\gamma}_{rd}$

Fig. 6 assumes that the source-to-relay link is weaker than the relay-to-destination link in average, where we let $\alpha = 1$, $\beta = 2$, and $\bar{\gamma} = 10$ dB in (18), so that $\bar{\gamma}_{sr} = 10$ dB and $\bar{\gamma}_{rd} = 20$ dB, and relay number is set as $N = 3$.

It is interesting to observe in Fig. 6 that, the max-link and proposed schemes have similar performance in both outage and average delay. This is because stronger relay-to-destination links “naturally” give higher priority to select the relay-to-destination links. However, even under this channel assumption, the average packet delay is still better constrained in the proposed scheme than in the max-link scheme, particularly in low-SNR ranges.

VII. CONCLUSION

This paper has proposed a novel buffer-aided relay selection scheme with significantly reduced packet delays. We have shown the outage and average delay performance under different channel configurations. To be specific, for symmetric $S \rightarrow R$ and $R \rightarrow D$ channels, the max-link scheme has better outage performance than the proposed. However, when $S \rightarrow R$ links are stronger, the proposed scheme performs better in outage than the max-link. On the other hand, when $R \rightarrow D$ links are stronger, the max-link and proposed schemes have similar outage performance. Therefore, if the relay nodes are evenly spread within an area as in many practical systems, it is reasonable to expect that the outage performances of the proposed and max-link schemes are similar. This will be left for future study. We also highlight that, in all cases, the proposed scheme has significantly better outage performance than the non-buffer-aided schemes, making it an attractive scheme in practical applications.

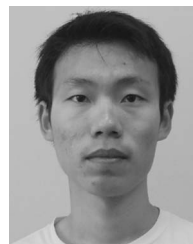
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