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 SNR is high enough, making it an attractive scheme in practice.**

***Index Terms*—Relay selection, buffer-aided relay, average delay**

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

This work was supported in part by the Engineering and Physical Sciences Research Council under Grant EP/K014307/2 and in part by the MOD University Defence Research Collaboration in Signal Processing.

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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 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 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, in order to achieve high performance gain, relay number and 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 requires ultra-low 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 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 the paper is organised 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 the 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 relays apply 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 as $h_{sr_k}(t)$ and $h_{r_k d}(t)$ 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

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

respectively. We assume without losing generality that all transmission powers 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 of N and buffer size of $L > 2$. Specifically, we assume that all buffers are empty initially 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 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 though it is not the strongest link.

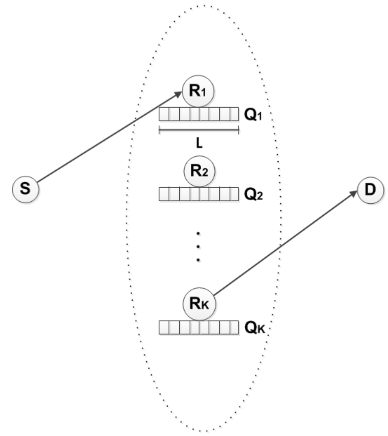


Fig. 1. The system model of the relay selection system.

This leads to a new principle of buffer-aided relay selection: that is 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, and so is the average packet delay.

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

1) Choose the link with the highest channel SNR among all available relay-to-destination links ($|h_{r_k d}(t)|^2$). 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 above proposed scheme is easy to implement as it requires the same knowledge as that in the existing buffer-aided max-max or max-min scheme. In the following 2 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 of L, there are $(L+1)^N$ states in total. The l-th state vector is defined as

$$\mathbf{s}_l = [\Psi_l(Q_1), \cdots, \Psi_l(Q_K)], \qquad l = 1, \cdots, (L+1)^N, \tag{2}$$

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 number of available source-to-relay and relay-to-destination links are denoted as $K_{s_l}^{S\to R}$ and $K_{s_l}^{R\to D}$ respectively. It is clear that $0 \le K_{s_l}^{S\to R} \le N$ and $0 \le K_{s_l}^{R\to D} \le N$. Specifically, if none of the buffers is full or empty, all links are available such that $K_{s_l}^{S\to R} = K_{s_l}^{R\to D} = N$.

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

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

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

A. $p_{out}^{s_l}$: outage probability at state $\mathbf{s}_l$

For independent Rayleigh fading channels, the instantaneous SNR for every channel, $\gamma_w (w \in \{sr_k, r_k d\})$, 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 $\mathbf{s}_l$ is given by

$$p_{out}^{s_l} = p_{out}^{S\to R} \cdot p_{out}^{R\to D} \tag{4}$$

where

$$\begin{aligned} p_{out}^{S\to R} &= \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{sr}}}\right)^{K_{s_l}^{S\to R}}, \\ p_{out}^{R\to D} &= \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{rd}}}\right)^{K_{s_l}^{R\to D}} \end{aligned} \tag{5}$$

where $p_{out}^{S\to R}$ and $p_{out}^{R\to D}$ are 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 is when not all of the available relay-to-destination links are in outage, or

$$\begin{aligned} p_{s_l}^{R\to D} &= \frac{1}{K_{s_l}^{R\to D}} \cdot \left(1 - p_{out}^{R\to D}\right) \\ &= \frac{1}{K_{s_l}^{R\to D}} \cdot \left(1 - \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{rd}}}\right)^{K_{s_l}^{R\to D}}\right). \end{aligned} \tag{6}$$

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

$$\begin{aligned} p_{s_l}^{S\to R} &= \frac{1}{K_{s_l}^{S\to R}} \cdot p_{out}^{R\to D} \cdot \left(1 - p_{out}^{S\to R}\right) \\ &= \frac{1}{K_{s_l}^{S\to R}} \cdot \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{rd}}}\right)^{K_{s_l}^{R\to D}} \cdot \left(1 - \left(1 - e^{-\frac{\Delta}{\bar{\gamma}_{sr}}}\right)^{K_{s_l}^{S\to R}}\right). \end{aligned} \tag{7}$$

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

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

where $p_{out}^{s_l}$, $p_{s_l}^{R\to D}$ and $p_{s_l}^{S\to R}$ are given by (4), (6) and (7) respectively, $U_{s_l}^{R\to D}$ and $U_{s_l}^{S\to R}$ 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])

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

where $\boldsymbol{\pi} = [\pi_1, \cdots, \pi_{(L+1)^N}]^{\mathrm{T}}$, $\mathbf{b} = (1, 1, ..., 1)^T$, $\mathbf{I}$ 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

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

where $\mathrm{diag}(\mathbf{A})$ 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

$$\bar{D} = 1 + \bar{D}_r, \tag{11}$$

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

$$\bar{D}_r = \bar{D}_k = \frac{\bar{L}_k}{\bar{\eta}_k}, \tag{12}$$

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

[1] *Column stochastic* means 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 average queuing length at R_k is obtained by averaging the queueing lengths at buffer Q_k over all states, or

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

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

$$\bar{\eta}_k = \frac{\bar{\eta}}{N} \tag{14}$$

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], [18])

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

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

$$\bar{\eta}_k = \frac{1 - P_{out}}{2N}. \tag{16}$$

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

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

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

$$\bar{\gamma}_{sr} = \alpha\bar{\gamma} \qquad \text{and} \qquad \bar{\gamma}_{rd} = \beta\bar{\gamma}, \tag{18}$$

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

A. Asymptotic outage probability

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

$$\lim_{\bar{\gamma}\to\infty} p_{s_l}^{R\to D} = 1, \qquad \text{if } K_{s_l}^{R\to D} \neq 0. \tag{19}$$

This implies that, any packets in the relay buffers will be forwarded to the destination, and only after all buffers are empty, is a new packet transmitted to one of the relays. Thus when $\bar{\gamma} \to \infty$, the buffers can only be in two possible states: $S^{(0)}$ and $S^{(1)}$, corresponding to the cases that all buffers are empty and only one of the buffers has on packet, respectively. It is then from (3) that

$$\lim_{\bar{\gamma}\to\infty} P_{out} = P(S^{(0)}) \cdot p_{out}^{S^{(0)}} + P(S^{(1)}) \cdot p_{out}^{S^{(1)}}, \tag{20}$$

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

Suppose 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

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

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

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

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

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

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

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

B. Diversity order

The diversity order can be defined as

$$d = -\lim_{\bar{\gamma}\to\infty} \frac{\log P_{out}}{\log \bar{\gamma}}. \tag{25}$$

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

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

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

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

Because

$$\lim_{\bar{\gamma}\to\infty} (\beta\bar{\gamma}) < \lim_{\bar{\gamma}\to\infty} (\beta\bar{\gamma} + \Delta) < \lim_{\bar{\gamma}\to\infty} (2 \cdot \beta\bar{\gamma}), \tag{28}$$

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

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

C. Coding gain

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

$$C(\mathrm{dB}) = -\frac{\lim_{\bar{\gamma}\to\infty} \Delta_P(\bar{\gamma})}{d}, \tag{30}$$

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

$$\Delta_P(\bar{\gamma}) = 10\log P_{out}^{(max-min)}(\bar{\gamma}) - 10\log P_{out}^{(L=1)}(\bar{\gamma}), \tag{31}$$

where $P_{out}^{(max-min)}(\bar{\gamma})$ and $P_{out}^{(L=1)}(\bar{\gamma})$ 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

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

For the tradition *max-min* scheme, we have

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

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

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

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

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

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

D. Average packet delay

We have shown that, when $\bar{\gamma} \to \infty$, 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

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

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

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

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

$$\lim_{\bar{\gamma}\to\infty} \eta_k = \frac{\lim_{\bar{\gamma}\to\infty}(1-P_{out})}{2N} = \frac{1}{2N} \tag{38}$$

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

$$\lim_{\bar{\gamma}\to\infty} \bar{D} = 1 + \frac{1/(2N)}{1/(2N)} = 2. \tag{39}$$

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, traditional buffer-aided max-max and max-link, and the proposed schemes.

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

Table I shows that all buffer-aided schemes have 3dB coding gain over the max-min scheme. While 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 $\bar{\gamma} \to \infty$, 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 as same as that shown in Table I and will be discussed in the following section.

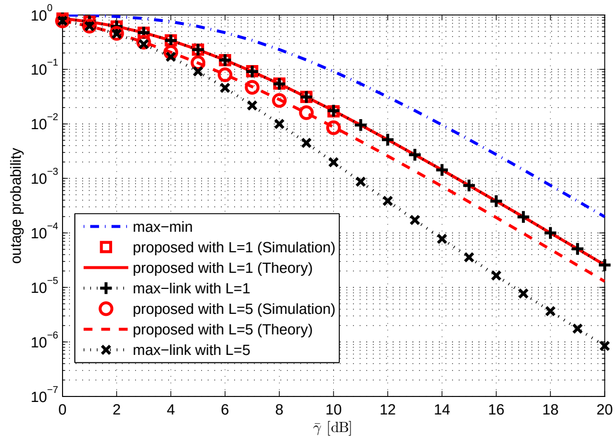
VI. SIMULATIONS AND DISCUSSIONS

This section verifies the proposed scheme with numerical simulations, where the results for previous described max-link and non-buffer-aided max-min schemes are also shown for comparison. In the simulation below, the transmission rates in all schemes are set as $r_t = 2$ bps/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.

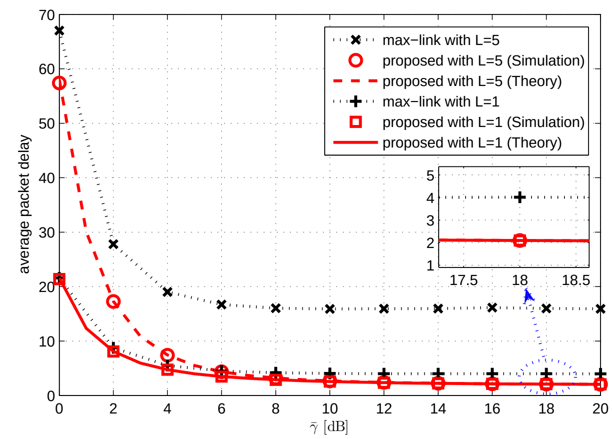
A. Symmetric channel configuration: $\bar{\gamma}_{sr} = \bar{\gamma}_{rd}$

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

Fig. 2 (a) and (b) compare 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 have

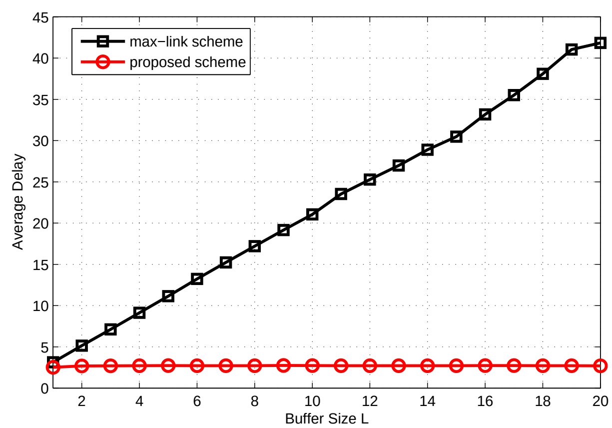


(a) Outage probability

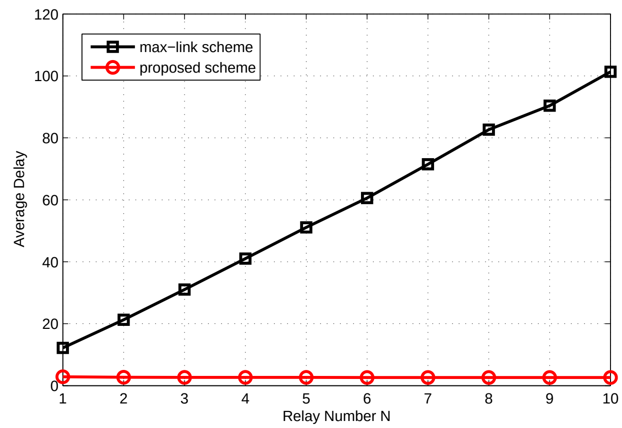


(b) Average delay

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



(a) Delay *vs* buffer size, where $N = 2$



(b) Delay *vs* relay number, where $L = 10$

Fig. 3. Average packet delay comparison between the max-link and proposed schemes

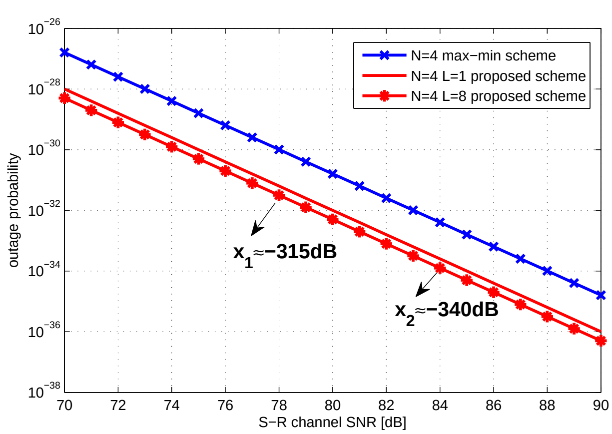
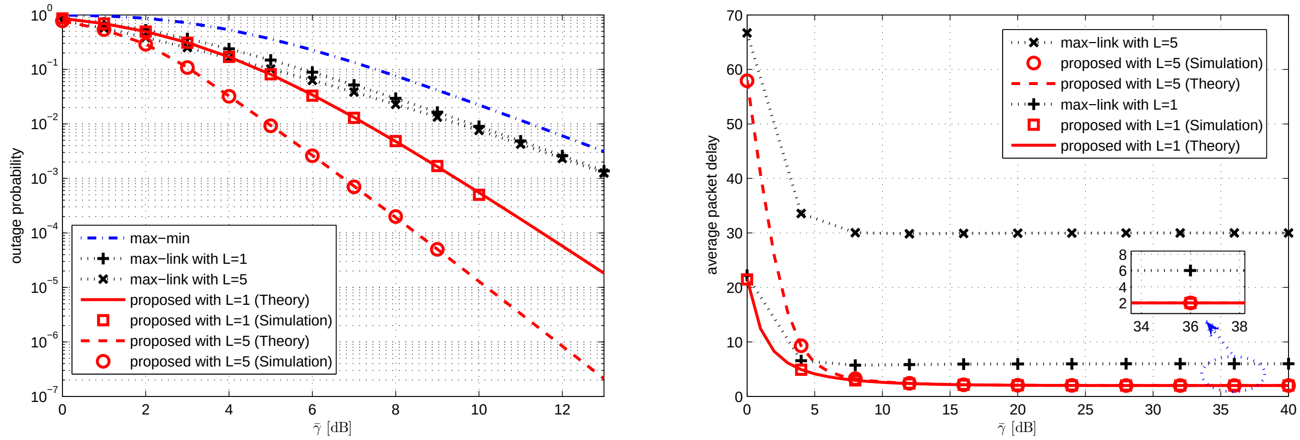


Fig. 4. Diversity order and Coding gain of the proposed scheme.

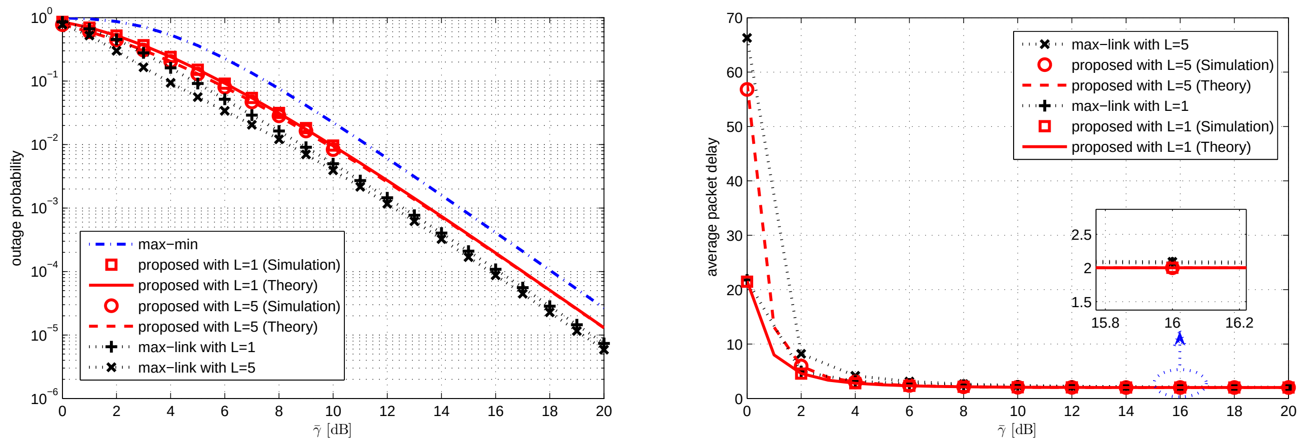
the same outage probabilities, where both have significantly better outage performance than the traditional non-buffer-aided max-min scheme because of the 3dB coding gain. When the buffer size increases to $L = 5$, the proposed scheme has slightly better outage performance than that for $L = 1$. This 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 that diversity order of the max-link scheme goes up with the buffer size, until it reaches $2N$ when $L \to \infty$. Fig. 2 (b) shows that, even for $L = 1$, the average delay of the max-link scheme is at least twice as much 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 range, 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 SNR-s, which is 9 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) show the average packet delay *vs* the buffer size and relay number respectively, where the average channel SNR-s in both schemes are set as 10 dB. In Fig. 3 (a), the relay number is



(a) Outage probability (b) Average delay

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



(a) Outage probability (b) Average delay

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

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.

In order 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 scheme at very high SNR-s, 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 scheme with $L = 1$. For example, to achieve the outage probability of 10^{-34}, the SNR-s for the max-min and proposed scheme with $L = 1$ are about 85 and 88dB respectively. The diversity order of the proposed scheme is also clearly shown to be $(N, N+1)$ for $L \geq 2$. For example, as is illustrated in the figure, for the proposes 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 asymmetric channels 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 that, when the source-to-relay links are stronger than 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 the available source-to-relay links, leading to fewer 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 that, 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 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 range.

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 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 similarly performance both in outage and average delay. This is because that, stronger relay-to-destination links 'naturally' give higher priority to select the relay-to-destination links. But 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 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 $S \to R$ and $R \to D$ channels, the max-link scheme has better outage performance than the proposed. But when $S \to R$ links are stronger, the proposed scheme performs better in outage than the max-link. On the other hand, when $R \to D$ links are stronger, the max-link and proposed scheme 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 performance 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.

Acknowledgement

The authors wish to thank associate editor and anonymous reviewers for significantly improving out the manuscript, particularly one of the reviewers for pointing out the parallel work in the Master's dissertation [19], in which Algorithms 2 and 3 were proposed with similar ideas to that in this paper. Algorithm 2 (which is based on giving higher priority to relays with longer queuing length) has similar performance to our proposed scheme, but it is more complicated to implement. Algorithm 3 trades off between outage and delay performance, and in some cases may have longer delay than the 'standard' buffer-aided *max-link* scheme. Our work was done independently from the work in the Master's dissertation.

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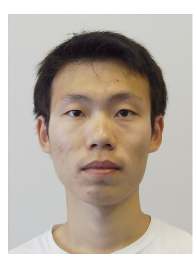

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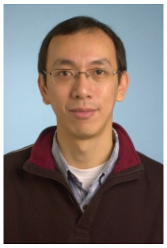

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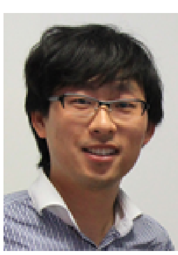

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