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Energy-efficient Buffer-aided Optimal Relay Selection Scheme with Power Adaptation and Inter-relay Interference Cancellation

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Abstract

Considering the tradeoff between energy consumption and outage behavior in buffer-aided relay selection, a novel energy-efficient buffer-aided optimal relay selection scheme with power adaptation and Inter-Relay Interference (IRI) cancellation is proposed. In the proposed scheme, energy consumption minimization is the objective with the consideration of relay buffer state, outage probability and relay power control, in order to eliminate IRI. The proposed scheme selects a pair of optimal relays from multiple candidate relays, denoted as optimal receive relay and optimal transmit relay respectively. Source-relay and relay-destination communications can be performed within a time-slot, which performs as Full-Duplex (FD) relaying. Markov chain model is applied to analyze the evolution of relay buffer states. System steady state outage probability and achievable diversity order are derived respectively. In addition, packet transmission delay and power reduction performance are investigated with a specific analysis. Numerical results show that the proposed scheme outperforms other relay selection schemes in terms of outage behavior with power adaptation and IRI cancellation in the same relay number and buffer size scenario. Compared with Buffer State relay selection method, the proposed scheme reduces transmission delay significantly with the same amount of relays. Average transmit power reduction can be implemented to relays with the increasing of relay number and buffer size, which realizes the tradeoff between energy-efficiency, outage behavior and delay performance in green cooperative communications.

Keywords: Buffer-aided relay selection, power adaptation and Inter-Relay Interference (IRI) cancellation, energy-efficiency, buffer state, outage probability

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1. Introduction

With the rapid and radical evolution of information and communication technology, corresponding energy consumption is also growing at a staggering rate. Furthermore, it has been reported that mobile operators are already among the top energy consumers [1]. Reducing energy consumption in wireless communications has attracted increasing attention and green communications has become a major research topic [1]. Recently, a lot of interests have been drawn by the cooperative relaying technique, which enhances the reliability of data transmission and expands the capacity of wireless communication system. The cooperative relaying technique has been proven to be an effective method of enhancing network capacity, reducing users' energy consumption, extending network lifetime and improving system throughput. In [2], the author introduced a new approach using Mobile Edge Computing (MEC) as ad-hoc relay nodes for overload or broken of MEC system, and find out the capacity of ad-hoc relay nodes affects the MEC recovery system throught significantly. These advantages have great significance to the energy-constrained wireless sensor networks. Therefore, energy efficiency has become a hot research topic in cooperative communications [1].

Relay selection and power control are two key technologies in cooperative communications. Communication system performance mainly depends on the selection of relay nodes, while power control is implemented to adjust relay power based on power adaptation criterion in the energy-constrained wireless network, in order to optimize system quality of service, such as throughput, outage probability, *etc* [3-4]. The earlier works in cooperative communications mainly focus on non-buffer relays, *i.e.*, relays forward data packets immediately when they receive from source node [3-4]. With the implementation of buffer-aided relays, they could decide whether it should transmit or receive data packets based on channel gain in the current time slot, thus system degrees of freedom can be improved and outage probability can be correspondingly reduced [4]. In traditional decode-and-forward based cooperative relaying system, max-min relay selection scheme is proposed in [5], where the best relay selection criterion is based on the maximum signal-to-noise ratio (SNR) criterion. The scheme achieves the optimal performance and ensures a full diversity that equals to the number of relays. In order to improve system performance, each relay equipped with a buffer. Max-max relay selection scheme is proposed in [6], which selects optimal receive and forward relays based on the criterion of best channel qualities between Source-Relay (S-R) and Relay-Destination (R-D) respectively. However, the scheme assumes that the buffer size is neither full nor empty at the relay. Since this assumption is not practical for finite buffers, max-link relay selection policy for cooperative system with finite buffers is investigated [7]. In each time slot, optimal relay can be selected dynamically in accordance with available instantaneous channel quality and buffer state. A buffer state based relay selection scheme for a finite buffer-aided cooperative relaying system is proposed in [8], which selects an optimal relay based on channel quality and buffer state in different time slots.

In the above relay selection schemes, relays are equipped with a buffer. The result show that buffering is a promising solution to cooperative networks that enhances degree of freedom and reduces outage probability. However, energy consumption at relays are rarely considered in these schemes, which may cause dramatically increasing of relay energy with the guarantee of outage behavior and link quality requirement. Traditional cooperative relays are operated at the Half-Duplex (HD) mode in which relays cannot receive or transmit data simultaneously. Hence, it results in half spectral efficiency loss [9]. To eliminate inter-relay interference and minimize system energy consumption per time slot, a Successive Opportunistic Relaying

(SOR) selection scheme is proposed in [10]. However, the authors overlooked the relationship between buffer states and channel qualities in the scheme. N. Zlatanov [11] proposed a new relaying protocol employing adaptive link selection. Both delay tolerant and delay-constrained transmission cases are taken into consideration, and the corresponding throughput performances are analyzed respectively. It is also pointed out that buffer-aided half-duplex relaying can outperform ideal full-duplex relaying in terms of throughput performance [12-13]. That is, HD relays with buffers can mimic FD relaying. Outage probability and system latency can be effectively decreased [12]. HD relays with buffers that imitates space FD max-max relay selection (SFD-MMRS) exceeds twice the capacity of the best relay selection (BRS) with HD relays and provides full diversity and large SNR gains [13]. Recent literature [14] proposes opportunistic FD based relay selection and the corresponding optimal power allocation scheme.

This work proposes an energy-efficient buffer-aided optimal relay selection scheme with power adaptation and IRI cancellation in order to solve the tradeoff problem between energy consumption and outage behavior. The main contributions of this paper are summarized as follows:

1) Selecting a pair of optimal relays based on the energy consumption, buffer state and outage probability of the relays, which is denoted as optimal receive relay and optimal transmit relay respectively in the proposed relay selection scheme. The source-relay and relay-destination communications can be performed within a time-slot, which mimics FD relaying.
2) Proposing a theoretical framework for the analysis of the evolution of relay buffer states based on a Markov chain model. Then, the system steady state outage probability and achievable diversity order are derived respectively.
3) Analyzing the average packet transmission delay at source and optimal relays and power reduction. Average transmit power reduction can be realized with the increasing of relay number and buffer size.

Numerical results show that the proposed optimal relay selection scheme outperforms other relay selection schemes mentioned in [8,10]. The outage behavior, average transmit power reduction and average delay performance metrics are uniformly improved.

The rest of this paper is organized as follows. System model is introduced in Section II. Section III provides the specific energy-efficient buffer-aided optimal relay selection scheme. The analysis of energy consumption, outage behavior and system latency are presented in Section IV respectively. Numerical results and performance analysis are shown and discussed in Section V. Finally, conclusions are drawn in Section VI.

2. System Model

System model of energy-efficient buffer-aided relay selection is shown in **Fig. 1**. We assume that a simple cooperative network consisting of one source S, one destination D and a cluster C with K relays $R_k \in \mathrm{C}$ $(1 \le k \le K)$. The cluster C has a cluster head (CH) which is in charge of handling the broadcasting information in the cluster and selects appropriate relay to participate in cooperative communications. All relays operate in the HD mode and Decode-and-Forward protocol is implemented to forward information [9]. A direct link between the source and the destination does not exist and communication can be established only via relays [11]. Each relay is equipped with a data buffer of size L, where the source information can be stored and decoded at the relay. We use $L_k (0 \le L_k \le L)$ to denote the number of packets stored in the buffer of the k-th relay R_k. l_{ij}, $(i \in \{S, R_1, \ldots, R_K\}$, $j \in \{R_1, \ldots, R_K, D\})$ are denoted the channel link between node *i* and node *j*. We use h_{ij} to denote the channel coefficients between node *i* and node *j*, and the channel coefficients is assumed to be a circularly symmetric complex Gaussian distributed random variable with zero mean and variance Ω_{ij}.

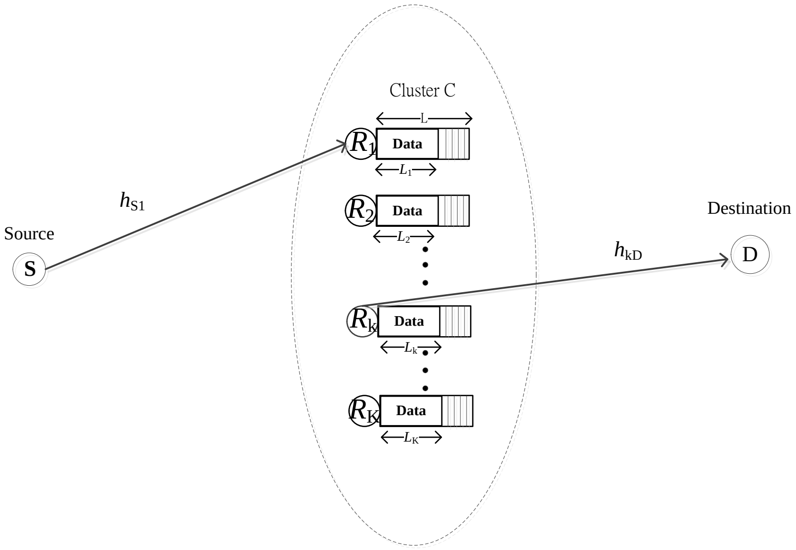

Fig. 1. System model of energy-efficient buffer-aided relay selection

In this system model, time is assumed to be divided into slots with equal length. At each time slot, the CH selects a pair of relays that have the highest channel gain and the lowest energy consumption in accordance with optimal relay selection strategy, namely, the best receive relay R_r^* and the best transmit relay R_t^*. In one time slot, CH chooses the optimal receive relay (R_r^*) from the candidate relays. Source sends data packets to this best receive relay R_r^* and stores these packets into its buffer. At the same time slot, CH selects the optimal transmit relay (R_t^*) from the candidate relays. The best transmit relay R_t^* forwards data packets form its buffer to destination in accordance with "first-in–first-out" rule.

In traditional cooperative systems, relays directly forward data packets from source node [3-4]. In the proposed scheme, each relay has its own buffer that can store data packets, *i.e.*, the buffer-aided relaying [6-8,10]. Therefore, in the proposed cooperative relay selection scheme, CH determines the best receive relay and transmit relay in accordance with channel quality and buffer state in the current time slot. It selects a pair of optimal relays based on energy-efficient buffer-aided optimal relay selection scheme. For example, CH chooses a relay as optimal receive relay R_r^* and stores packets from source into its buffer during the first time slot. These data packets will not be forwarded promptly in second time slot. CH will recollect channel quality and relays' buffer state and choose a pair of optimal relays (denoted as the best receive relay R_r^* and the best transmit relay R_t^*) to complete cooperative transmission. It implements FD relaying and enhances the system spectral efficiency. The retransmission process is based on an Acknowledgement/Negative-Acknowledgement (ACK/NACK) mechanism. If the receivers (either a relay R_r^* or the destination D) do not receive a packet successfully, it will send a NACK to the transmitter. Then, the transmitter will retransmit the packets. If the receivers receive a packet successfully, it will send a ACK to the transmitter.

Without loss of generality, before the description of specific relay selection scheme, we make the following assumptions:

1) Each relay equips with a omni-directional antenna whose maximum transmit power is $P_{\max}$. The transmit power level can be adaptively adjusted in the range of $[0, P_{\max}]$. Relay transmits a packet in each time slot, therefore, the maximum energy consumption is denoted as $E_{\max} = P_{\max} T_s$ for a packet transmission.
2) All the channel links are assumed to be Rayleigh flat fading and Additive White Gaussian Noise (AWGN). The channel is assumed to be stationary in one time slot.
3) Channel coefficients (h_{S,R_k}, $h_{R_k,D}$) are independent identical distribution (i.i.d) from one time slot to another.
4) One relay can only receive or forward a packet in one time slot. Namely, the relay R_k receives a data packet, the buffer state can be denoted as $L_k + 1$.
5) Noise variance is identical for relay and destination.

3. Energy-efficient buffer-aided optimal relay selection scheme

In this section, we investigate optimal relay selection policy called energy-efficient buffer-aided optimal relay selection. Considering that the buffer-aided HD relaying can achieve ideal FD relaying in terms of throughput performance [12-13] and opportunistic FD based relay selection [14], we proposed an optimal relay selection scheme to select the optimal receive relay and the optimal transmit relay simultaneously in one time slot. It mimics FD relaying. Relay power adaptation and IRI cancellation can be achieved. Hence, system spectral efficiency can be enhanced. The scheme can be divided into the following two steps:

Step 1: At the beginning of each slot, the source broadcasts a pilot sequence and the K relays estimate the $(S-R_k)$ channel state information (CSI). We assume the channel gain between source and destination is in deep fading, the D cannot get the $(S-D)$ CSI. Then, the destination sends pilot signals to the relays, which extract the (R_k-D) CSI. Relays attains channel gains denoted by $H_{SR_k} = |h_{SR_k}|^2$, $H_{R_kD} = |h_{R_kD}|^2$, as well as $(S-R_k)$ and (R_k-D) channel link states denoted by l_{SR_k} and l_{R_kD} in the current time slot.

Step 2: In this step, the CH is used to collect the channel gains attained in the step 1 of all the links. Any relay that can communicate with the others is selected as the CH. Without loss of generality, we assume that R_1 is the CH. Thus, CH collects channel qualities and buffer states of each relay at the current time slot. For different values of buffer size L_k, relay R_k has different cases of available links:

1) $L_k = 0$, relay buffer is empty. It can only be used for packet reception.
2) $L_k = L$, relay buffer is full. It can only be used to forward a packet.
3) $0 < L_k < L$, relay buffer is neither full nor empty. It can be used to receive or forward a packet.

CH collects CSI and divides relay cluster into two sets (Q_t, Q_r) in accordance with adaptive link selection rules (**Table 1**). Suppose Q_t is relay set that is composed of relays forwarding data packets to D while Q_r is relay set that is made up of relays receiving data packets from S. In **Table 1**, we assume that $L \geq 2$.This assumption is based on the fact: For the relay with buffer size $L = 1$, if a relay receive a packet, the relay will transmit the packet immediately in order to increase the number of available links of the system in the following time slot. As a result, the benefits of relays equiped with buffer will be reduced.

Table 1. Adaptive link selection rules

Cases	**Link state** l_{SR_k}	**Link state** l_{R_kD}	**Buffer state** L_k	**Decision**
Case1	outage	outage	\	Silence
Case 2	outage	successful	$L_k>0$	Transmit
Case 3	successful	outage	$L_k<L$	Receive
Case 4	successful	successful	$2\le L_k$	Transmit
Case 5	successful	successful	$L_k<2$	Receive

In **Table 1**, the term “outage” denotes that the corresponding link is in outage. “successful” means that the link is not in outage. “Silence” denotes that the relay keeps in silence (neither transmits nor receives). “Receive” means that the relay chooses to receive a packet. “Transmit” denotes that the relay chooses to transmit a packet.

In case 4, the link states l_{SR_k} , l_{R_kD} are all stay in the “successful” state and the buffer state $L_k \ge 2$, relay R_k will decide to transmit a data packet to D. In this case, it is easier for relay to forward the data packets in its buffer to destination, which effectively reduces the packet transmission delay. For case 5 ($L_k < 2$), relay R_k will decide to receive a data packet from S. It makes that more links are available to relay. According to the above different cases, there are 4 different scenarios:

(1) $Q_r \ne \varnothing, Q_t = \varnothing$ ($\varnothing$ denotes the empty set), in this scenario, no relay will be selected to transmit a packet and the CH can only choose a relay to receive a packet from source. Denote $L_{\min} = \min(L_k \mid R_k \in Q_r)$, CH first finds out the receive relay set Q_{r1} from the set Q_r, $Q_{r1} = \{L_k = L_{\min} \mid R_k \in Q_r\}$. The Q_{r1} denote the set of the relays whose buffer has minimum number of packets. Then, CH choose R_r^* that satisfies $l_{SR_r^*}$ ’s channel gain maximization and source power minimization from Q_{r1}, $R_r^* = \arg\min\{P_s \big/ \left|h_{SR_k}\right|^2 \mid R_k \in Q_{r1}\}$. If the R_r^* receive the packet successfully, and stores a received data packet into this relay’s buffer.

(2) $Q_r = \varnothing$, $Q_t \ne \varnothing$, in this scenario, no relay will be selected to receive a packet. Denote $L_{\max} = \max(L_k \mid R_k \in Q_t)$, CH first finds out the transmit relay set Q_{t1} from the set Q_t, $Q_{t1} = \{L_k = L_{\max} \mid R_k \in Q_t\}$. The Q_{t1} denote the set of the relays whose buffer has maximum number of packets. Then, the CH choose R_t^* that satisfies $l_{R_t^*D}$ ’s channel gain maximization and R_t^* ’s power minimization from Q_{t1}, $R_t^* = \arg\min\{P_{R_k} \big/ \left|h_{R_kD}\right|^2 \mid R_k \in Q_{t1}\}$, and transmits one data packet that stored in its buffer to the destinatio

(3) $Q_r \ne \varnothing, Q_t \ne \varnothing$, in this scenario, CH select a pair of optimal relays simultaneously. CH first finds out R_r^* that satisfies $l_{SR_r^*}$ ’s channel gain maximization and source power minimization from Q_{r1}. At the same time, it finds out R_t^* that satisfies $l_{R_t^*D}$ ’s channel gain maximization and R_t^* ’s power minimization from Q_{t1}.

(4) $Q_r = \varnothing$, $Q_t = \varnothing$, in this scenario, all the available links are in outage, and there is no need to select best relays.

By implementing the energy-efficient buffer-aided optimal relay selection scheme, spatial degree of freedom is increased and system outage probability is reduced. Meanwhile, cooperative relay energy efficiency is guaranteed. In addition, this scheme selects a pair of best relays with energy consumption minimization in accordance with channel quality and relays' buffer state. The proposed scheme reduces the average latency in buffer-aided relaying system, further improves the reliability and reduces transmission energy consumption.

4. Performance analysis of energy-efficient relay selection

4.1 Energy Consumption Analysis

CH selects a pair of optimal relays in accordance with channel quality and each relay's buffer state. The proposed scheme not only guarantees energy efficiency of relays in the current time slot, but also considers buffer states and channel qualities to realize relay power adaptation and IRI cancellation.

Without loss of generality, we make specific analysis of scenario (3) ($Q_r \neq \varnothing, Q_t \neq \varnothing$), since scenario (1) (2) (4) are the special cases of scenario (3). In scenario (3), source sends a data packet x_t in the time-slot t. CH selects the best receive relay via optimal relay selection scheme. At the same time, it also chooses the best transmit relay, which forwards the packets x_p $(p < t)$ that are stored in its buffer in the previous time slots p to destination. Therefore, the optimal receive relay R_r^* received data packets in the time-slot t can be expressed as

$$y_{R_r^*} = \sqrt{P_s} h_{SR_r^*} x_t + \sqrt{P_{R_t^*}} h_{R_t^* R_r^*} x_p + N \tag{1}$$

Destination receives data packets from the best transmit relay R_t^*, which can be written as

$$y_D = \sqrt{P_{R_t^*}} h_{R_t^* D} x_p + N \tag{2}$$

where P_s is the source power level and $P_{R_t^*}$ is the selected optimal transmit relay power level. $h_{R_r^* R_t^*}$ denotes channel coefficient between the pair of selected optimal relays. Noise N denotes the additive white Gaussian noise with zero mean and variance δ^2. For simplicity, the noise is assumed to be equal at each receiver. Therefore, $S \to R_r^*$ link capacity ($I_{SR_r^*}$) and $R_t^* \to D$ link capacity ($I_{R_t^* D}$) are expressed as follows respectively

$$\begin{aligned} I_{SR_r^*} &= \log_2\left(1 + \frac{P_s \left|h_{SR_r^*}\right|^2}{P_{R_t^*}\left|h_{R_t^* R_r^*}\right|^2 + \delta^2}\right) \\ I_{R_t^* D} &= \log_2\left(1 + \frac{P_{R_t^*}\left|h_{R_t^* D}\right|^2}{\delta^2}\right) \end{aligned} \tag{3}$$

It is obvious that the reception signal of optimal receive relay R_r^* contains the interference from the optimal transmit relay R_t^* which forwards previous packets x_p to the destination. Hence, the optimal receive relay that correctly decodes its signal sent from source should satisfy two requirements: (1) The IRI cancellation should be satisfied, that is, interference between the selected optimal relay pairs must be eliminated. (2) Transmission rate at the optimal receive relay is greater than or equal to a fixed target rate r_0. For simplicity, we assume that the noise power is identical and has unit variance. Thus, R_r^* that separates the interference from R_t^* is said to be satisfied the following conditions.

$$I_{R_t^* R_r^*} = \log_2\left(1+\frac{P_{R_t^*}\left|h_{R_t^* R_r^*}\right|^2}{P_s\left|h_{SR_r^*}\right|^2+\delta^2}\right) \geq r_0 \;\Rightarrow\; \frac{(2^{r_0}-1)\left(P_s\left|h_{SR_r^*}\right|^2+\delta^2\right)}{\left|h_{R_t^* R_r^*}\right|^2} \leq P_{R_t^*} \leq P_{\max} \tag{4}$$

When the optimal receive relay R_r^* separates the interference from the optimal transmit relay R_t^*, it is said to be met the following requirements.

$$I_{SR_r^*} = \log_2\left(1+\frac{P_s\left|h_{SR_r^*}\right|^2}{\delta^2}\right) \geq r_0 \;\Rightarrow\; \frac{(2^{r_0}-1)\delta^2}{\left|h_{SR_r^*}\right|^2} \leq P_s \leq P_{\max} \tag{5}$$

Substitute (5) into (4), the range of the optimal transmit relay power $P_{R_t^*}$ can be rewritten as $\frac{(2^{r_0}-1)2^{r_0}\delta^2}{\left|h_{R_t^* R_r^*}\right|^2} \leq P_{R_t^*} \leq P_{\max}$.

Let $\Pr_{SR_k}$ represent the outage probability between source and the k-th relay, and the $\Pr_{out}^{th}$ denote the outage probability that the HD relaying system aims to deliver packet at a fixed target rate r_0 with the fixed power (*P*). Hence, the optimal receive relay R_r^* can be determined by the following optimization problem shown as below. The energy-efficient buffer-aided optimal receive relay selection scheme is considered as the source power control problem, in which source energy consumption minimization is served as objective with the constraints of source-relay outage probability, source-relay link capacity and inter-relay link capacities to eliminate IRI.

$$\begin{aligned} &R_r^* = \arg\min_{R_k\in Q_{r1}}\{P_s \big/ \left|h_{SR_k}\right|^2\} \\ &\text{s.t.}\begin{cases} \Pr_{SR_k}\left\{\log_2\left(1+\frac{P_s\left|h_{SR_k}\right|^2}{\delta^2}\right) < r_0\right\} \leq \Pr_{out}^{th} \\ I_{R_t^* R_k} \geq r_0 \\ I_{SR_k} \geq r_0 \end{cases} \end{aligned} \tag{6}$$

If data rate at the destination is greater or equal to a fixed target rate r_0, the destination can correctly decode the message sent from the optimal transmit relay. Therefore, for the destination correctly decodes the forwarded message, the range of the optimal transmit relay power level $P_{R_t^*}$ can be expressed as below.

$$I_{R_t^* D} = \log_2\left(1+\frac{P_{R_t^*}\left|h_{R_t^* D}\right|^2}{\delta^2}\right) \ge r_0 \;\Rightarrow\; \frac{\left(2^{r_0}-1\right)\delta^2}{\left|h_{R_t^* D}\right|^2} \le P_{R_t^*} \le P_{\max} \tag{7}$$

Similarly, the optimal transmit relay R_t^* selection strategy can be defined by the following optimization problem shown as below. Just as (6), the energy-efficient buffer-aided optimal transmit relay selection scheme is regarded as the relay power control problem, in which relay energy consumption minimization is served as its objective with the constraints of relay-destination outage probability, relay-destination link capacity and inter-relay link capacities to eliminate IRI.

$$\begin{aligned} &R_t^* = \arg\min_{R_k \in Q_{t1}} \{P_{R_k} \big/ \left|h_{R_k D}\right|^2\} \\ &\text{s.t.}\begin{cases} \Pr_{R_k D}\left\{\log_2\left(1+\dfrac{P_{R_k}\left|h_{R_k D}\right|^2}{\delta^2}\right) < r_0\right\} \le \Pr_{out}^{th} \\ I_{R_k R_r^*} \ge r_0 \\ I_{R_k D} \ge r_0 \end{cases} \end{aligned} \tag{8}$$

Based on the above problem formulation, we can draw conclusions that the best relay pair selection algorithm chooses an optimal receive relay as well as an optimal transmit relay simultaneously. The best receive relay R_r^* is the one that has smaller buffer size L_k, larger channel gain and lower source power level in the receive relay set Q_{r1}. The best transmit relay R_t^* is the one that has larger buffer size L_k, larger channel gain and lower relay power level in the transmit relay set Q_{t1}.

We substitute (5) into (4), and let the variance of AWGN (noise power) has unit value $\delta^2 = 1$. Then, we can deduce the minimum power level of source and the optimal transmit relay from (4), (5) and (7), which can be written as follows respectively

$$P_s = \frac{2^{r_0}-1}{\left|h_{SR_r^*}\right|^2},\; P_{R_t^*} = \max\left\{\frac{(2^{r_0}-1)2^{r_0}}{\left|h_{R_t^* R_r^*}\right|^2}, \frac{2^{r_0}-1}{\left|h_{R_t^* D}\right|^2}\right\} \tag{9}$$

4.2 Outage Behavior Analysis

A. Construction of Markov Chain State Transition Matrix

In this section, we investigate the outage behavior of the proposed energy-efficient buffer-aided optimal relay selection scheme via Markov Chain (MC) model. We use MC states to describe the states of relay buffers, which is the number of data packets L_k stored in the buffer of the k-th relay R_k. MC state transition matrix indicates the connectivity between relays' buffer states. Assuming the k-th relay buffer stores L_k $(0 \le L_k \le L)$ data packets that has total $L+1$ different state values. As a result, the cluster which consists of K buffer-aided relays have $(L+1)^K$ buffer states in total. The n-th buffer state can be written as

$$s_n \overset{\Delta}{=} (L_1, L_2, \ldots, L_K), 1 \le n \le (L+1)^K \tag{10}$$

Let $\boldsymbol{A}$ denote the $(L+1)^K \times (L+1)^K$ state transition matrix of MC. More specifically, the entry $\boldsymbol{A}_{mn} = \Pr(X_{t+1} = s_m \mid X_t = s_n)$ indicates the transition probability that the state moves from s_n at time t to s_m at time $t+1$. The transition probability $\boldsymbol{A}_{mn}$ depends on the relay buffer status and the set of available links that can successfully transmit one packet. State transition matrix $\boldsymbol{A}$ can be constructed in accordance with the connectivity between different buffer states. A relay can only receive or transmit one data packet in a time slot. Namely, when the relay R_k receives a packet, the relay buffer state can be expressed as $L_k + 1$.

If the system chooses the available link l_{ij} to complete cooperative transmission in one time slot, however, the buffer state is not changed, which means the outage behavior is occurred in the selected channel link in this time slot. Thus, the outage probability of link l_{ij} [12] can be expressed as

$$\Pr\left\{I_{ij} < r_0\right\} = \Pr\left\{\log_2\left(1+\frac{P_i\left|h_{ij}\right|^2}{\delta^2}\right) < r_0\right\} = \Pr\left\{\left|h_{ij}\right|^2 < \frac{\left(2^{r_0}-1\right)\delta^2}{P_i}\right\} = 1-\exp\left(-\frac{2^{r_0}-1}{P_i}\right) \tag{11}$$

where h_{ij} is the channel coefficients of link l_{ij}, and modeled as a circularly symmetric complex Gaussian distributed random variable with zero mean. $\left|h_{ij}\right|^2$ is a Chi-Square random variable with two degrees of freedom and the probability density function conforms to exponential distribution [15]. The variance of AWGN (noise power) has unit value $\delta^2 = 1$. Thus, the HD relaying system's link outage probability $\Pr_{out}^{th} = 1-\exp\left(-\frac{2^{2r_0}-1}{P}\right)$.

Based on relay buffer states, the channel gains, and the adaptive link selection rules (shown in **Table 1**), we can obtain the available links Ψ_n that connects to buffer state s_n (*i.e.*, buffer state moves from s_n at time t to s_m at time $t+1$). Let Ψ_n^s denote the selected channel link via optimal relay selection scheme. Due to the fact that channel gains between source and relays are different from channel gains between relays and destination, the transition probability from buffer state s_n to s_m is also different in each time slot. Hence, the entry of MC state transition matrix $\boldsymbol{A}_{mn}$ can be expressed as

$$\boldsymbol{A}_{mn} = \Big(\prod_{l_{ij}\in\Psi_n^s}(1-\Pr_{ij})\prod\nolimits_{\substack{l_{ij}\in\Psi_n \\ l_{ij}\notin\Psi_n^s}}\Pr_{ij}\Big)\Pr(s_n \to s_m \mid \Psi_n) \tag{12}$$

where the conditional probability notation $\Pr(s_n \to s_m \mid \Psi_n^s)$ depends on the proposed energy-efficient buffer-aided optimal relay selection scheme. For those states that are not connected to buffer state s_n cannot be arrived from state s_n through one step transition, the entry is denoted as $\boldsymbol{A}_{mn} = 0$. When all the available links are unable to deliver packets, the buffer state remains unchanged. Therefore, we have

$$\boldsymbol{A}_{nn} = \prod_{l_{ij}\in\Psi_n}\Pr_{ij} \tag{13}$$

B. Steady State Distribution of the MC

In the above subsection, we define the MC state transition matrix $\boldsymbol{A}$ with finite buffer size. In this subsection, we analyze the steady state distribution of the MC. The stationary distribution of buffer state which is denoted by MC column vector $\boldsymbol{\pi}$ is investigated, and the corresponding system stationary performance is explored.

In our system model, due to the fact that all the possible states of the MC may transit from one state to other states and the link outage behavior may occur with outage probability $\Pr_{ij} > 0$. Hence, the MC is irreducible. Based on the fact that the buffer state remains the same when system is in outage, the probability is greater than zero at any buffer state after N transitions. Hence, the constructed MC is non-periodic.

According to [7], as the MC state transition matrix $\boldsymbol{A}$ is irreducible and non-periodic, the steady state distribution of the MC can be obtained as

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b} \tag{14}$$

where $\boldsymbol{\pi} = [\pi_1, \cdots, \pi_{(L+1)^K}]^{\mathrm{T}}$, $\mathbf{b} = [1, \cdots, 1]^{\mathrm{T}}$, $\mathbf{I}$ denotes the identity matrix and $\mathbf{B}$ is a $(L+1)^K \times (L+1)^K$ matrix with all elements equal to one.

Just as the definition of outage probability in max-link relay selection scheme in [7], system outage behavior is assumed to be the link outage occurred in the $S \to R_k$ link and $R_k \to D$ link. In this case, no packet is transmitted and buffer state is unchanged. It is said that the outage behavior is occurred. The diagonal elements of the MC state transition matrix $\boldsymbol{A}$ represent there is no changes happened in buffer states, hence, we can calculate the outage probability in accordance with the corresponding steady state probability. Therefore, the system outage probability can be written as

$$\Pr_{out} = \sum_{n=1}^{(L+1)^K} \pi_n \boldsymbol{A}_{nn} = diag(\boldsymbol{A})\boldsymbol{\pi} \tag{15}$$

The K buffer-aided relays with L buffer size have totally $(L+1)^K$ buffer states. In these $(L+1)^K$ states, $(L-1)^K$ states are neither full nor empty. We can divide the $(L+1)^K$ buffer states into two independent categories. The first category F_1 denotes the states in which all the relay buffers are neither full nor empty. The second category F_2 contains the $(L+1)^K - (L-1)^K$ buffer states in which at least one relay buffer state is either full or empty. Assume each relay has infinite buffer size $(L \to \infty)$, the limitation of system outage probability can be expressed as

$$\Pr_{out}^{\infty} = \lim_{L\to\infty} \sum_{n\in F_1} \pi_n \boldsymbol{A}_{nn} + \lim_{L\to\infty} \sum_{n\in F_2} \pi_n \boldsymbol{A}_{nn} \tag{16}$$

Based on the proposed optimal relay selection scheme, we define $\boldsymbol{A}_{F_1F_2} = \Pr(X_{t+1} = F_1 \mid X_t = F_2)$ and $\boldsymbol{A}_{F_2F_1} = \Pr(X_{t+1} = F_2 \mid X_t = F_1)$ as the transition probability matrices from buffer state category F_2 to F_1 and buffer state category F_1 to F_2 respectively. Refer to the max-link relay selection scheme [7], the transition probability matrices $\overline{\boldsymbol{A}}_{F_1F_2}$ and $\overline{\boldsymbol{A}}_{F_2F_1}$ are also defined in this scheme. In the energy-efficient buffer-aided optimal relay selection scheme, relays with empty buffers have the highest priority to be selected as the candidate receive relays while relays with full buffers have the highest priority to be selected as the candidate transmit relays. For the Max-link relay selection scheme, it chooses the optimal relay in accordance with the best channel quality. Therefore, when the buffer size $(L \to \infty)$, we have $\boldsymbol{A}_{F_1F_2} > \overline{\boldsymbol{A}}_{F_1F_2}$. If the relay buffer size $L < 2$, it has higher priority to receive a packet, which avoids the relay buffer staying in empty. Therefore, when buffer size $(L \to \infty)$, we have $\boldsymbol{A}_{F_2F_1} < \overline{\boldsymbol{A}}_{F_2F_1}$. Let π_{F_1}, π_{F_2} represent the stationary probabilities for buffer state categories F_1 and F_2 respectively. Similarly, we can define the stationary probabilities $\overline{\pi}_{F_1}$ and $\overline{\pi}_{F_2}$ for buffer state categories F_1 and F_2 in the Max-link relay selection scheme. Hence, we have

$$\pi_{F_1} = \sum_{s_n \in F_1} \pi_n, \quad \pi_{F_2} = \sum_{s_n \in F_2} \pi_n \tag{17}$$

Since the MC state transition matrix $\boldsymbol{A}$ is reversible, it is easily to find that the transition probability matrices $\boldsymbol{A}_{F_1F_2}$ and $\boldsymbol{A}_{F_2F_1}$ are also reversible. We can obtain the relationship between transition probability matrices and the stationary probabilities for buffer state categories F_1 and F_2 shown as below.

$$\boldsymbol{A}_{F_2F_1}\pi_{F_1} = \boldsymbol{A}_{F_1F_2}\pi_{F_2}, \quad \overline{\boldsymbol{A}}_{F_2F_1}\overline{\pi}_{F_1} = \overline{\boldsymbol{A}}_{F_1F_2}\overline{\pi}_{F_2} \tag{18}$$

For the MC stationary probabilities, they satisfy $\pi_{F_1} + \pi_{F_2} = 1$ and $\overline{\pi}_{F_1} + \overline{\pi}_{F_2} = 1$, we apply (18) to find the stationary probabilities for buffer state category F_1 expressed as

$$\pi_{F_1} = \frac{\mathbf{A}_{F_1F_2}}{\mathbf{A}_{F_1F_2} + \mathbf{A}_{F_2F_1}}, \quad \overline{\pi}_{F_1} = \frac{\overline{\mathbf{A}}_{F_1F_2}}{\overline{\mathbf{A}}_{F_1F_2} + \overline{\mathbf{A}}_{F_2F_1}} \tag{19}$$

Based on the above analysis, we have $\mathbf{A}_{F_1F_2} > \overline{\mathbf{A}}_{F_1F_2}$, $\mathbf{A}_{F_2F_1} < \overline{\mathbf{A}}_{F_2F_1}$ when the buffer size $(L \to \infty)$. Substitute the conditions into (19), we can obtain $\pi_{F_1} > \overline{\pi}_{F_1}$ and $\pi_{F_2} < \overline{\pi}_{F_2}$. According to [7], it is pointed out that $\lim_{L\to\infty} \overline{\pi}_{F_2} = 0$. Due to $\pi_{F_2} < \overline{\pi}_{F_2}$, then $\lim_{L\to\infty} \pi_{F_2} = 0$. The second part in (16) equals to zero for the transition probability $\boldsymbol{A}_{nn} < 1$. Hence, for the extreme case with infinite buffer size $L \to \infty$, the outage probability of the proposed optimal relay selection scheme can be simplified as

$$\Pr_{out}^{\infty} = \lim_{L\to\infty} \sum_{n \in F_1} \pi_n \boldsymbol{A}_{nn} \tag{20}$$

According to the previous analysis, it is shown that if buffer size $L \to \infty$ and transmission power $P \to \infty$, for $S_n \in F_1$, there are $2K$ available links, the stationary outage probability can be further simplified as

$$\Pr_{out}^{\infty} = \left(1 - \exp\left(-\frac{2^{ro} - 1}{P}\right)\right)^{2K} \tag{21}$$

The achievable system diversity order is

$$d_\infty = -\lim_{P\to\infty}\frac{\log(\Pr_{out}^{\infty})}{\log P} = 2K \tag{22}$$

l

Proof of (22):

We apply (21) into the definition of system diversity order, thus

$$d_\infty = -\lim_{P\to\infty}\frac{\log(\Pr_{out}^{\infty})}{\log P} = -\lim_{P\to\infty}\frac{\log\left(1-\exp\left\{-\frac{2^{r_0}-1}{P}\right\}\right)^{2K}}{\log P}$$

The approximation of limitation formula $\lim_{x\to 0}(1-e^{-x}) = x$ is adopted, and we can obtain

$$d_\infty = -\lim_{P\to\infty}\frac{\log\left(\frac{2^{r_0}-1}{P}\right)^{2K}}{\log P} = -\lim_{P\to\infty}\frac{2K\log\left(\frac{2^{r_0}-1}{P}\right)}{\log P} = -\left(\lim_{P\to\infty}\frac{2K\log\left(2^{r_0}-1\right)}{\log P} - \lim_{P\to\infty}\frac{2K\log P}{\log P}\right) = 2K$$

4.3. Packet Latency Analysis

In general, the traditional cooperative relays are operated in the half-duplex mode. Hence, the packet latency (delay) includes two parts: (1) the transmission delay between $S \to R_k$; (2) the transmission delay between $R_k \to D$.

Suppose that the source has M packets to be sent to the destination, each packet requires two time-slots to be forwarded to the destination. According to the proposed energy-efficient buffer-aided optimal relay selection scheme, we choose a pair of optimal relays (the optimal receive relay R_r^* and the optimal transmit relay R_t^*) within a time-slot to mimic FD relaying. In the proposed scheme, packets can be delivered and forwarded to destination in one time-slot, hence the packet transmission latency can be reduced effectively [13]. If M is large enough, the overall transmission time slot to deliver M packets is approximately M. Therefore, system average throughput is denoted as $\eta = (M/M) = 1$.

According to Little's law [16], the average transmission delay D_S between source and the k-th relay $S \to R_k$ can be written as

$$D_S = \frac{E[q_S]}{\eta_S} \tag{23}$$

where $E[q_S]$ and η_S represent the average queuing length and throughput at the source respectively. We assume that the source always has packets to transmit, thus the queuing length at the source depends on the probability that a $S \to R_k$ link is selected. Thus, the average queuing length and throughput at the source can be expressed as follows respectively.

$$\begin{aligned} E[q_S] &= 1 - \Pr_{S-R} \\ \eta_S &= \Pr_{S-R} \end{aligned} \tag{24}$$

where $\Pr_{S-R}$ denotes the probability that CH selects a appropriate relay to deliver a data packet.

Based on the fact that the number of packets received by the relay R_k must be equal to these leave the relay. Let $\Pr_{R-D}$ denote the probability that CH chooses $R_k \to D$ link to transmit a packet that stored in relay's buffer. Thus, we have $\Pr_{S-R} = \Pr_{R-D}$.

Different from [8], we assume that $\Pr_{S-R-D}$ denotes the probability that CH selects the optimal receive relay R_r^* and forward relay R_t^* simultaneously, hence, we have

$$\Pr_{out} + \Pr_{S-R} + \Pr_{R-D} - \Pr_{S-R-D} = 1 \tag{25}$$

where $\Pr_{S-R-D} = \sum_{n=1}^{(L+1)^K} \pi_n \cdot \Pr_{S-R-D}^{(s_n)}$. $\Pr_{S-R-D}^{(s_n)}$ represents the probability that the optimal receive and forward relay pairs are selected at buffer state s_n with the proposed relay selection scheme.

$$\Pr_{S-R-D}^{(s_n)} = \sum \boldsymbol{A}_{mn}, \quad if\,(L_k^{S_n} = L_k^{S_m}, n \neq m) \tag{26}$$

where $L_k^{S_n}$ denotes the selected k-th relay buffer size at buffer state s_n. Hence, (24) can be written as

$$\begin{aligned} E[q_S] &= \frac{1 + \Pr_{out} - \Pr_{S-R-D}}{2} \\ \eta_S &= \frac{1 - \Pr_{out} + \Pr_{S-R-D}}{2} \end{aligned} \tag{27}$$

Based on the above analysis, the average packet delay D_S at source can be expressed as

$$D_S = \frac{1 + P_{out} - \Pr_{S-R-D}}{1 - P_{out} + \Pr_{S-R-D}} \tag{28}$$

Similarly, we analyze the average packet delay at relays. Let $\sum_{k=1}^{K} L_k^{S_n}$ denote the queuing length of the equivalent buffer size at buffer state S_n. The average queuing length at relay buffers can be written as

$$E[q_R] = \sum_{n=1}^{(L+1)^K} \sum_{k=1}^{K} \pi_n L_k^{S_n} \tag{29}$$

According to Little's law [16], the average packet delay D_R between the k-th relay and destination $R_k \to D$ can be obtained as

$$D_R = \frac{E[q_R]}{\eta_{RD}} = \frac{2}{1 - \Pr_{out} + \Pr_{S-R-D}} \sum_{n=1}^{(L+1)^K} \sum_{k=1}^{K} \pi_n L_k^{S_n} \tag{30}$$

Different from [8], due to the fact that the proposed scheme selects an optimal receive relay as well as an optimal transmit relay within the same time slot, which operates in FD relaying mode. Therefore, the overall average packet delay is the maximum value of (28) and (30) shown as below.

$$D = \max(D_S, D_R) \tag{31}$$

5. Numerical Results and Discussions

In the above section, we theoretically analyzed the energy consumption, outage probability and average packet latency of the energy-efficient buffer-aided optimal relay selection scheme. In this section, we perform numerical results for the proposed scheme in a simple buffer-aided relaying system scenario with $K = 2$ relays and buffer size $L = 2$. According to (10), there are 9 buffer states in this buffer-aided relaying system, which are shown in **Table 2**. Suppose the MC state transition matrix is $\boldsymbol{A}_{9\times 9}$. We can obtain the state transition diagram [8,10] in accordance with the proposed energy-efficient buffer-aided optimal relay selection scheme.

Table 2. Buffer states of relaying system with $K = 2$ and $L = 2$

States	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**	**S_7**	**S_8**	**S_9**
L_1L_2	00	01	02	10	11	12	20	21	22

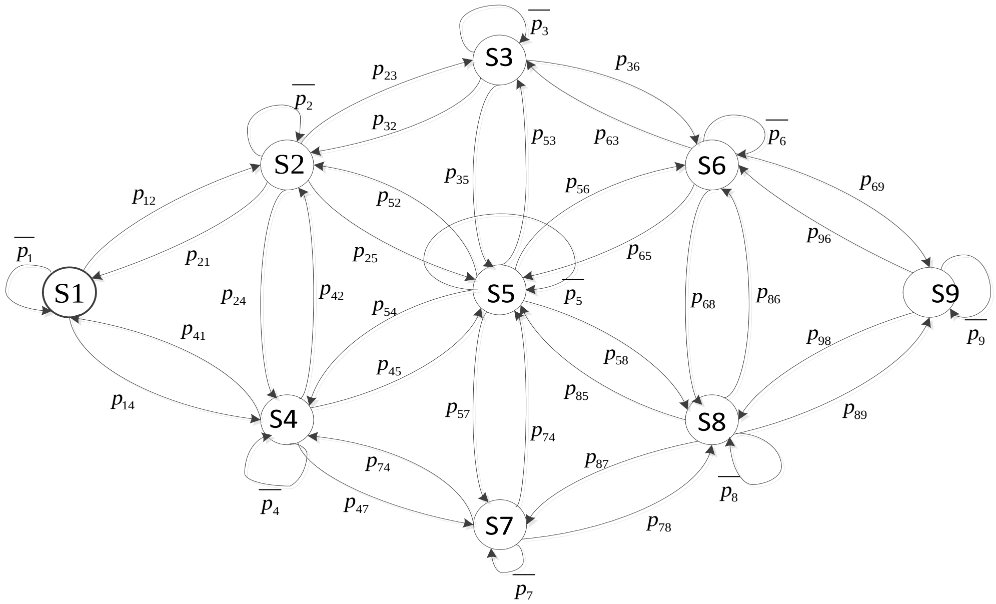

Fig. 2. The MC state transition diagram of buffer-aided relaying system with $K = 2$ and $L = 2$

Fig. 2 shows the MC state transition diagram of buffer-aided relaying system with $K = 2$ and $L = 2$. According to the proposed optimal relay selection scheme, we can get the MC state transition matrix shown as below.

$$\boldsymbol{A}=\begin{pmatrix}
\overline{p_1} & p_{12} & 0 & p_{14} & 0 & 0 & 0 & 0 & 0\\
p_{21} & \overline{p_2} & p_{23} & p_{24} & p_{25} & 0 & 0 & 0 & 0\\
0 & p_{32} & \overline{p_3} & 0 & p_{35} & p_{36} & 0 & 0 & 0\\
p_{41} & p_{42} & 0 & \overline{p_4} & p_{45} & 0 & p_{47} & 0 & 0\\
0 & p_{52} & p_{53} & p_{54} & \overline{p_5} & p_{56} & p_{57} & p_{58} & 0\\
0 & 0 & p_{63} & 0 & p_{65} & \overline{p_6} & 0 & p_{68} & p_{69}\\
0 & 0 & 0 & p_{74} & p_{75} & 0 & \overline{p_7} & p_{78} & 0\\
0 & 0 & 0 & 0 & p_{85} & p_{86} & p_{87} & \overline{p_8} & p_{89}\\
0 & 0 & 0 & 0 & 0 & p_{96} & 0 & p_{98} & \overline{p_9}
\end{pmatrix} \tag{32}$$

Based on the analysis of MC state transition matrix, we obtain system outage performance for the proposed energy-efficient buffer-aided optimal relay selection scheme with different SNR scenarios, which are compared with max-max relay selection [6], max-link relay selection [7], buffer state relay selection [8] and Successive Opportunistic Relaying (SOR) selection [10]. **Fig. 3** illustrates the outage behavior of the proposed scheme with other four relay selection schemes for $K=2$ relays with buffer size $L=2$. It is shown that the outage probability decreases as the increase of transmission SNR. The proposed energy-efficient buffer-aided optimal relay selection scheme has the best outage performance, which outperforms buffer state relay selection scheme [8] and SOR selection scheme [10]. The proposed scheme considers the relay buffer states, channel qualities and system energy consumptions simultaneously, and selects a pair of optimal relays to receive and transmit packets within a time slot. In the proposed scheme, the buffer state is neither full nor empty that provides more available links to transmit data packets, which reduces system outage probability significantly.

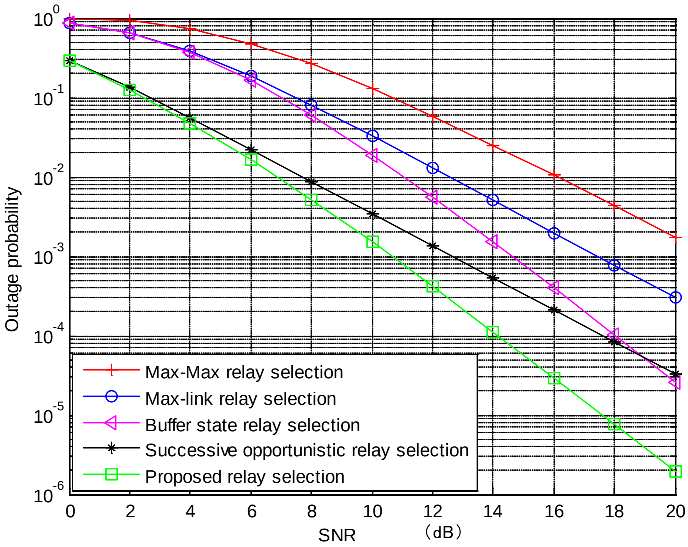

Fig. 3. Outage performance of different relay selection schemes for $K=2$ relays with buffer size $L=2$

Fig. 4 and **Fig. 5** illustrate the outage behavior of the proposed energy-efficient buffer-aided optimal relay selection scheme with different buffer size and relay numbers. In **Fig. 4**, it is obvious that the outage probability decreases with the increasing of relay buffer size L for buffer state relay selection [8] and the proposed scheme. The performance indicates that the available links increase with the length of buffer size, consequently system outage probability is reduced. Meanwhile, for the same transmission SNR and buffer size, the proposed scheme outperforms buffer state relay selection scheme. Furthermore, outage performance of the proposed scheme with buffer size $L=3$ approaches to outage performance with buffer size $L \to \infty$. The proposed scheme outperforms buffer state relay selection scheme approximately 5dB SNR in the scenario of outage probability 10^{-3}. **Fig. 5** shows the outage performance of the proposed scheme with buffer size $L=3$ and different relay numbers. It is apparent that the outage probability decreases noticeably with the increasing of relay numbers.

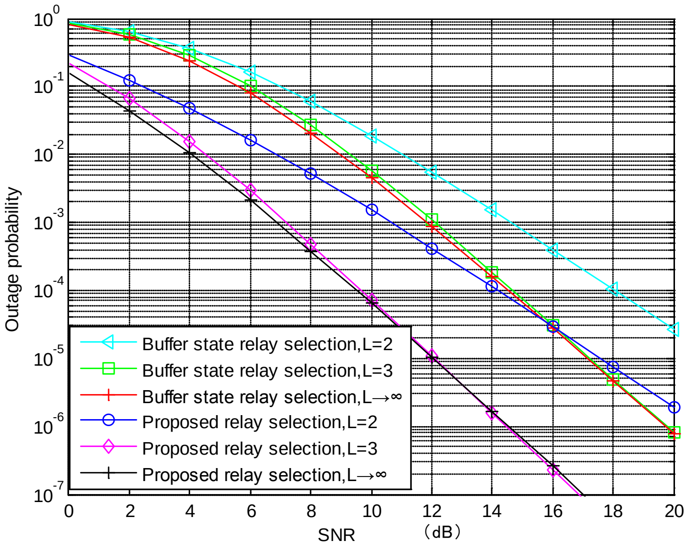

Fig. 4. Outage performance of the proposed scheme and buffer state relay selection scheme for $K=2$

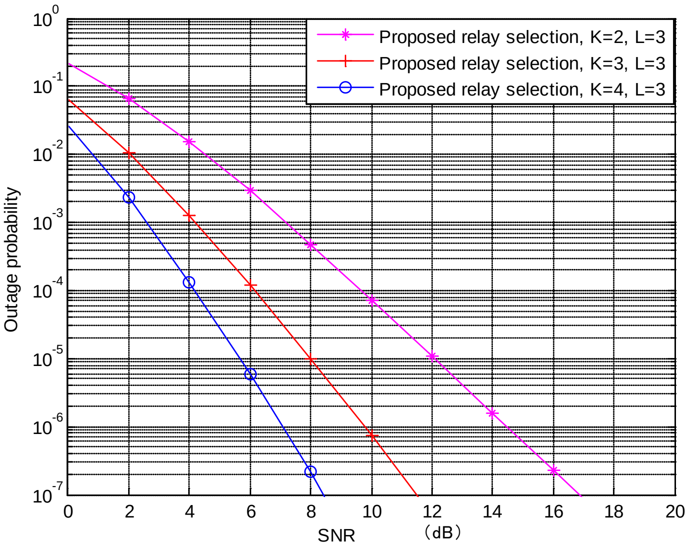

Fig. 5. Outage performance of the proposed scheme with buffer size $L=3$ and different relay numbers

Packet latency performance of different relay selection schemes are presented in **Fig. 6**. It is shown that the average packet delay decreases with the increasing of transmission SNR for each scheme. The reason is that system outage probability decreases as the transmission SNR increases, hence, in order to successfully deliver data packets, the required time slots are correspondingly reduced, so that the packet latency performance is improved. Packet latency performance of the proposed scheme and other two relay selection schemes (*i.e.*, max-link relay selection scheme [7] and buffer state relay selection scheme [8]) are provided in this figure. It is obvious that the proposed relay selection scheme has the lowest packet delay for relay number $K=2$ with buffer size $L=2$. According to (31), the proposed optimal relay selection scheme mimics the FD relaying. Packets can be received and forwarded within a time slot. Hence, the average throughput is nearly two times of the common HD relay selection schemes, and the outage performance outperforms other relay selection schemes. System packet latency performance can be improved significantly. Furthermore, it is indicated that the average packet delay increases with relay buffer size L in low SNR region, which is similar to the packet latency performance of buffer state relay selection scheme. However, in high SNR region, the average packet latency is independent of relay buffer size, which is only related with relay numbers K (the average packet latency upper bound approximates to $K+1$ if $\text{SNR} \to \infty$). Average packet delay also increases with cooperative relay numbers K.

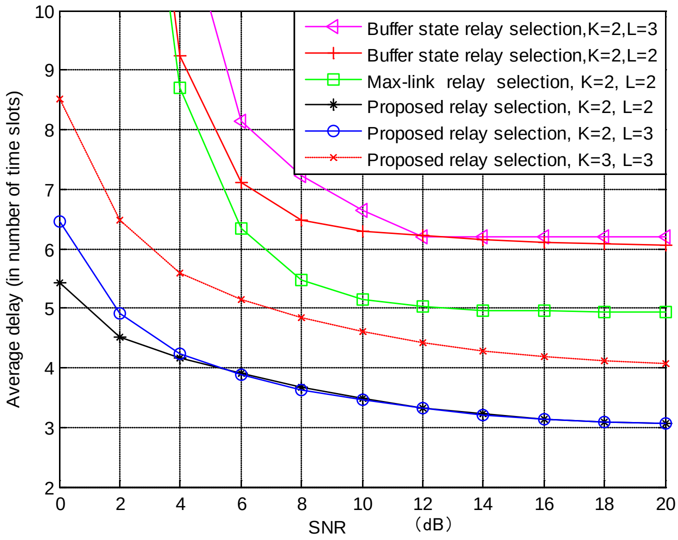

Fig. 6. Packet latency performance of different relay selection schemes

Fig. 7 shows power reduction of the proposed energy-efficient buffer-aided optimal relay selection scheme with power adaptation and IRI cancellation in different relay number and buffer size scenario. Buffer state relay selection scheme is used as a benchmark [8]. According to (9), the minimum transmit power of the optimal transmit relay is lower than buffer state relay selection scheme [8], which indicates that the proposed scheme is more energy-efficient (larger power reduction). In addition, the power reduction increases with transmission SNR. The reduced power enhances with the increasing of relay numbers for fixed relay buffer size ($L=3$), that is, the proposed scheme effectively mitigate IRI with power adaptation. For the same relay numbers ($K=2$), the differences of the reduced power are minor with the increasing of relay buffer size. The power reduction approaches to HD buffer-aided relay selection bound, which is coherent with the conclusion drawn in [10].

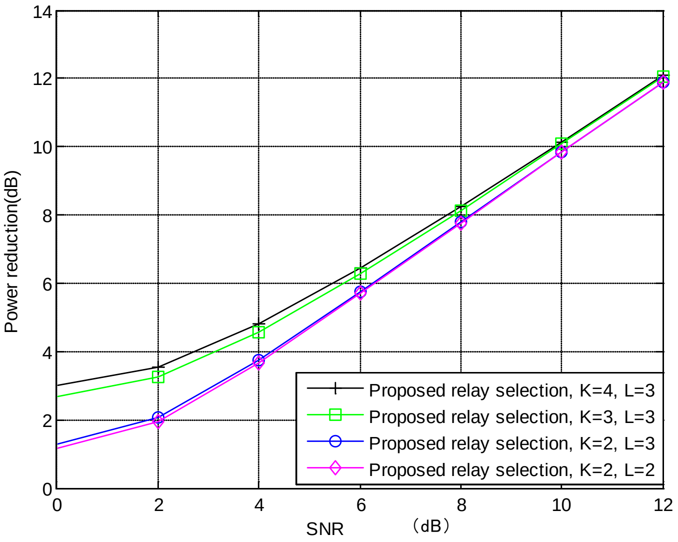

Fig. 7. Power reduction of the proposed energy-efficient buffer-aided optimal relay selection scheme with power adaptation and IRI cancellation

6. Conclusions

In this paper, an energy-efficient buffer-aided optimal relay selection scheme with power adaptation and IRI cancellation is proposed. Compared with other relay selection schemes such as max-max relay selection based on optimal channel qualities and finite buffer size max-link relay selection scheme, the proposed scheme eliminates IRI via power adaptation, and selects a pair of optimal relays with low energy consumption, high channel gain and optimal buffer state in the same time slot. The selected optimal relays can mimic FD relaying to receive and transmit data packets within a time slot. Energy consumption analysis, outage behavior analysis and packet latency analysis are provided respectively. Numerical results show that, compared with max-max relay selection scheme, max-link relay selection scheme, buffer state relay selection scheme and SOR scheme, the proposed scheme has the best outage performance in the same relay number and buffer size scenario. Compared with buffer state relay selection scheme, the proposed scheme reduces packet transmission delay and power consumption effectively in the case of the same relay numbers. Therefore, the proposed scheme enhances energy-efficiency of buffer-aided relaying in cooperative transmission, which realizes the tradeoff between energy-efficiency, outage behavior and latency performance in green cooperative communications.

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