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Max-gain relay selection scheme for wireless networks

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ABSTRACT

Next generation wireless systems are supposed to handle high amount of data with broader coverage and high quality of service (QoS). When a signal travels from a source to destination, the signal quality may suffer from the fading, which makes it difficult to receive correct messages. To handle the impact of fading, various diversity techniques are performed with Multiple Input Multiple Output (MIMO). Considering cooperative wireless networks, virtual MIMOs are being used, which also called cooperative diversity. In this paper, we propose a max-gain relay selection scheme (MGRS) for buffer-aided wireless cooperative networks. This scheme determines the best link using the maximum gain based on quality of link and available buffer size. The time slot is divided into two parts, one is used to choose the best link from the source to relay transmission (odd slot) and another time slot (even) is used based on the selection of the best link from the relay to destination. Markov chain model is use to measure buffer status and QoS parameters to evaluate the performance. The proposed scheme provides better QoS (12%) compared to the existing relay selection schemes with respect to throughput, end-to-end delay and outage probability.

1. Introduction

Wireless communication has induced a huge impact on the human society and is expected to be an important part of our future lives [1]. Wireless communication suffers from the issue of multi-path fading, which is because of the delayed copies of the same received signal. Cooperative relaying (CR) use multiple relays for communication from the source(s) to the destination(s) [1]. Specifically in a two–hop cooperative network, a single source sends signals to destination using relay(s) [2]. Cooperative communication is already included into the LTE-Advanced and expected to be an important part of the future fifth generation (5G) wireless cellular networks [3].

CR benefits from the cooperative diversity, distributed space time coding and the network coding [4], which help to improve QoS parameters such as energy efficiency and reliability [5,6]. The benefits are measures based on the increase of number of devices and minimizing the delay [7].

Traditional works regarding CR rely on single relay for data communication [8,9]. The aforementioned limitation in CR is tackled by the introduction of data buffers. It enables to exploit the best available source to relay and relay to destination links, thereby, selecting different relays for data communication [10]. When source to relay link is the strongest, data is transmitted from source to the selected relay and stored in the corresponding buffer [13]. When relay to destination link is the strongest, data is transmitted from the corresponding buffer. In this way, large diversity gain is achieved [14,15]. Buffer-aided cooperative communication finds its application in the existing 4G and the upcoming 5G enabling technologies [5]. Further, apart from the conventional cellular networks, the cooperative MIMO networks, cooperative device-to-device communication and cognitive networks also find the buffer-aided relaying paradigm as the basic functioning unit.

The buffer-aided cooperative relaying offers many advantages in terms of diversity gain, throughput, and reliability. However, it also introduces new challenges to the system design [13]. It requires channel and buffer state information to be collected by a central coordinator node. Moreover, the buffer-aided design mostly results in additional delay. Several efforts have been made

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Nomenclature

γ_{max}	maximum achievable SNR
γ_{R_kD}	instantaneous SNR of an R_kD link
γ_{SR_k}	instantaneous SNR of the SR_k link
$\psi(Q_k)$	Number of buffer packets
D	Destination
h	Rayleigh distributed
K	number of links
L	Length of in each relay
S	Source
l	Certain link
p_{max}	maximum possible transmission power
R	Set of decode and forward relays
R_r^*	used for reception
R_t^*	used for transmission
RD	Relay to Destination
SNR	Signal to Noise Ratio
SR	Source to Relay
t	time slot

in the literature to address the aforementioned challenges. The basic works in buffer-aided CR are the Max-Max and Max-Link relay selection schemes [9,10], which focus on diversity gain. In these schemes, the most suitable relay is selected either for transmission or reception only based on instantaneous quality of link which does not enable to get complete diversity gain. Therefore, the authors in [14,15] also consider the buffer status in the relay selection. Relay having the most usable buffer space is selected for reception and the relay having the most occupied buffer space is selected for transmission. This selection approach achieves the full diversity gain by achieving double number of relays using small buffer size. Similar efforts include [16,17] which incorporate the buffer status in relay selection in different ways.

Since link quality and buffer status do not ensure the reduction in packet delay, authors in [16,18] propose a scheme that prioritizes the relay to destination link over source relay link. In this way, significant reduction in packet delay is achieved. However, both schemes compromise their diversity gains. The aforementioned works either focus on link quality or on buffer status for relay selection. In this regard, authors in [19] propose a hybrid scheme that combines the effect of buffer size and link quality for a single phase relaying system.

In this work, we include the impact of both the link quality and buffer availability/occupancy in relay selection process for two phase cooperative relaying schemes. The combined effect of both the buffer occupancy and the link quality is termed as *equivalent gain*. Our purposed scheme called max-gain relay selections scheme (MGRS). In the following, we outline the contribution of this work.

1. We propose a new buffer-aided relay selection scheme termed as max-gain. In this scheme, relay communication is selected on gain which is calculated by adding the normalized values buffer status and channel quality by considering different factors which affect the link quality such as noise,interference and obstruction.
2. We model the underlying system using a Markov chain. The state transition probabilities of the Markov chain (MC) for both even and odd time-slots are calculated. These along with the outage probabilities are included into the transition matrix.
3. The steady state probability of the transition matrix is evaluated to be used for the outage probability calculation. The outage probability is further used measure the performance based on delay and diversity gain.
4. The proposed scheme evaluated as of (i) Outage probability by considering SNR and relays ratio (ii) average end-to-end delay with respect to data rate and SNR, and (iii) the average throughput with respect to data rate and relays.

The rest of the paper is organized as follows. In Section 2, we present the system model and transmission scheme of the propose scheme. In Section 3, we describe some background work relevant to the proposed scheme. The motivation and details of the proposed scheme are given in Section 4. Markov chain based outage analysis, end-to-end delay and diversity gain are given in the subsections of Section 5. In Section 6, we first give the brief details of the simulation section, then discuss the performance of the scheme on the basis of delay, throughput and outage probability. Finally, in Section 7, conclusion and future work are briefly explained.

2. System model

Before starting system modeling, it is worth to mentioned that this paper consist of different notations which are shown in List of Notations. We consider a relaying network of single source denoted by S, single destination denoted by D and a set R of K decode and forward relays, where, $R = \{R_1, R_2, \cdots, R_k, \cdots, R_K\}$ as shown in Fig. 1.

Escape special TeX symbols (Half-duplex transmission mode is used, which offers better QoS as compare to full duplex communication.Full duplex communication suffers from both self-interference and interuser interference, while in the case of half-duplex, we only need to tackle interuser interference. Recently cooperative networks using half-duplex have received high attention [23,25,24]. SATA(serial-ATA) buffer Q_k of size L (packets) is used in each relay. Buffers allow first in first out (FIFO) access to the data. $\psi(Q_k)$ denoted number of buffer packets where, $0 \leqslant \psi(Q_k) \leqslant L$. There are total K SR and RD links given as $\mathscr{L}_{SR} = \{l_{SR_1}, l_{SR_2}, \ldots, l_{SR_K}\}$ and $\mathscr{L}_{RD} = \{l_{R_1D}, l_{R_2D}, l_, \ldots, l_{R_KD}\}$, respectively.

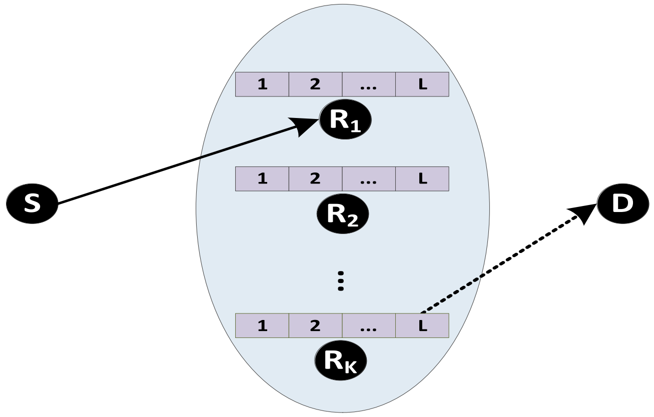

Fig. 1. System model for the proposed scheme.

2.1. Channel model

Following channel assumptions are made for the proposed scheme. The channel coefficient of l_{SR_k} is h_{SR_k} and l_{RkD} is h_{R_kD}, where these variables are Rayleigh distributed random variables. The channels having 0 mean and N_o variance due to Gaussian Noise. The source transmits with a transmission power P_S and each relay's transmission power is respectively given by P_{R_k}. Hence, the SNR of l_{SR_k} is $\gamma_{SR_k} = P_S h_{SR_k}/N_o$ and l_{R_kD} is $\gamma_{R_kD} = P_{R_k} h_{R_kD}/N_o$. As, h is Rayleigh distributed so the γ is exponentially distributed with the parameter $1/\bar{\gamma}$, where $\bar{\gamma}$ is the expected values of γ. The source and relay nodes transmit with a fixed data rate R_o (bits/s/Hz), which corresponds to an SNR threshold $\gamma_{th} = 2^{2R_o} - 1$. A certain link l is termed as qualified link if it satisfies, $\gamma_l \geqslant \gamma_{th}$. The transmission scheme is divided into odd and even time-slots. In the odd time-slot, S transmits its data to the selected relay R_k and data is stored in the respective buffer Q_k. In the even time-slot, selected relay R_k transmits from its buffer Q_k.

3. Related work and motivation

This section present some of the available literature on buffer-aided cooperative relaying networks. There are two major categories of Buffer-aided relaying schemes called single phase and dual phase schemes. In single phase schemes, at time-slot t, the best available link is selected either for the source-relay or relay-destination hop. Whereas, in dual phase schemes, time slots are divided into odd and even and selection is made based on even or odd time slots.

3.1. Single phase schemes

Existing single phase schemes proposed in the literature are discussed as follows:

3.1.1. Max-link Relay Selection (MLRS) scheme

The fundamental work in buffer-aided cooperative relaying is MLRS [10] scheme. Data transmission occur only when the source-relay link is strong with the help of buffer. Similarly on getting strong link quality, data is transmitted from relay of the selected link to the destination. The authors propose a model using Markov chain for outage probability. This enables to get diversity gain of $2K$ when buffer is able to handle large amount of data. The delay experienced by this scheme is $1 + KL$ at high SNR.The relay selection can be expressed as:

$$R^* = \arg\max_{R_k}\left\{\bigcup_{\psi(Q_k)\neq L}\{|h_{S,R_k}|^2\}\bigcup_{\psi(Q_k)\neq 0}\{|h_{R_k,D}|^2\}\right\} \tag{1}$$

3.1.2. Max-Weight Relay Selection (MWRS) scheme

In MLRS and its variants discussed previously, the relay selection was done keeping in consideration of link quality. Considering this, authors in [14] proposed a scheme that considers buffer status as a selection parameter. In time-slot t, MWRS selects the best relay on the basis of the most available buffer space or the most occupied buffer space for source-relay or relay-destination links, respectively. The scheme assigns weight to each relay depending on its buffer status. The relay with maximum available weight is selected for communication can be defined as:

$$R^* = \arg\max_{\forall R_k}\left\{\bigcup_{\psi(Q_k)\neq L}\{L - \psi(Q_k)\}\bigcup_{\psi(Q_k)\neq 0}\{\psi(Q_k)\}\right\} \tag{2}$$

In this case, the scheme is enable to get diversity gain of $2K$ with small buffer size greater than 2 and delay of the $1 + KL$ at high SNR.

3.1.3. Imax-Weight relay selection schemes

In the MWRS scheme, One link is randomly and uniformly selected for data communication at the relay. The random selection does not offer guarantee of link with good quality. In [15], the authors propose two schemes to handle the situation of equal weight links: imax-weight-quality and i-max-weight-priority. In imax-weight-quality, the link with the highest channel quality is selected in the case of equal weight links. In imax-weight-priority, the link on the relay-destination side is selected among all equal weight links.

3.2. Dual phase schemes

In MMRS [9], the rules and policies are fixed and MMRS able to consider as only metric in the selection process. selection based on even and odd time slots can be defined as:

$$R_r^* = \arg\max_{R_k}\left\{\bigcup_{\psi(Q_k)\neq L}\{|h_{S,R_k}|^2\}\right\} \tag{3a}$$

$$R_t^* = \arg\max_{R_k}\left\{\bigcup_{\psi(Q_k)\neq 0}\{|h_{R_k,D}|^2\}\right\} \tag{3b}$$

where, R_r^* is used for reception and R_t^* is used for transmission. MMRS get diversity gain of K when available links are same as number of relays in any time-slot. It achieves packet delay of $1 + \frac{KL}{2}$. MMRS scheme and Combined Relay Selection (CRS) [20] based on the concept of shortest-in longest-out (SILO) based on predefined transmission routine.

The consideration of buffer status in relay selection avoids full or empty buffers. In case of multiple relays having equal number of available or occupied buffer space, CRS selects one relay randomly and uniformly. The relay selection criteria for CRS scheme for reception and transmission can be expressed as:

$$R_r^* = \arg\max_{R_k}\left\{\bigcup_{\psi(Q_k)\neq L}\{L - \psi(Q_k)\}\right\} \tag{4a}$$

$$R_t^* = \arg\max_{R_k}\left\{\bigcup_{\psi(Q_k)\neq 0}\{\psi(Q_k)\}\right\} \tag{4b}$$

This scheme attains a diversity gain K and delay of $1 + \frac{KL}{2}$ as in MMRS. However, MMRS achieves full diversity gain at $L = \infty$ and CRS achieves full diversity gain at very small value of L. While studying the relay selection schemes in a buffer-aided relaying system, the parameters associated with relays are the most important of all. The relays are usually equipped with the limited battery and limited buffer-size. Though, the assumption of larger buffer sizes is practically feasible, we consider the buffer size in terms of its capability to store the packets and lower buffer size lead to achieve larger gains. As mentioned in the literature review, there are relaying schemes that consider the link quality in the selection process. In some schemes only buffer occupancy is taken into account relaxing the link quality. Recently a new scheme is proposed mentioned in [12], the researchers focused on the link security aspects at the physical layer along with the link quality. In [11], the researchers proposed a buffer-state-based(BSB) non-orthogonal multiple access(NOMA)-aided down link scheme for two hop cooperative network supporting multiple relay and destination nodes. Considering link quality as selection parameter doesn't guarantee an appropriate selection in term of buffer occupancy. In order to have a balanced selection scheme, the buffer capability should also be considered alongside the occupancy within the relay selection process.

4. Motivation and proposed scheme

The reasons for using multiple selection parameters is expressed here in contrast to the selection approach considering only the buffer occupancy shifts the pendulum to the other extreme side. In this situation, though the selected link is appropriate in terms of occupancy, it is not guaranteed that the quality of the selected link is at least good for the successful reception. Hence, our proposed approach includes both the buffer occupancy and the link quality into the selection process. There are some recent works in literature which pose this idea as an open question such as [12] in which they are addressing security at the physical layer, while [19] is also on this motive. The authors in this work even suggest to include the remaining energy of the relay nodes into the selection process. However, the work is lack of the validation of the proposed work with simulations. Also, the work in [19], is for single phase relay selection schemes. Based on the literature review, this is easily observed that link selections schemes mentioned in the literature focusing on the link quality as the selection parameters for link selection and there is no requirement about the buffer size. This is significant need to understand and analysis the impact of buffer size and link quality on link selection which is proposed in this paper.

4.1. Max-Gain Relay Selection (MGRS) scheme

The MGRS scheme combines the benefits of MMRS and the SILO schemes. It jointly considers both the link quality and the buffer status in the relay selection process. Based on the fixed transmission routine, in the odd time-slot, it selects the relay with the largest link gain. Let's define, two variables α_q, and α_b, which are used to control the contribution of the link quality and the buffer status, respectively, where, $\alpha_b = 1 - \alpha_q$ and $0 \leqslant \alpha_q \& \alpha_b \leq 1$. Then, we compute an equivalent gain ζ of each link which is a factor defined to combine the effects of buffer status and the link quality. Since, the buffer status and link quality are dimensionally different quantities, they cannot be added. Hence, we first normalize both of the parameters by dividing with their maximum possible values and then the normalized contribution of each part is added. The equivalent gain of an SR link ζ_k^{od} is given in the following Eq.(5):

$$\zeta_k^{od} = \alpha_b \frac{L - \psi(Q_k)}{L} + \alpha_q \frac{\gamma_{SR_k}}{\gamma_{max}} \tag{5}$$

where, γ_{SR_k} is the instantaneous SNR of the SR_k link and γ_{max} is the maximum achievable SNR which correspond to the maximum possible transmission power p_{max}. Similarly, the equivalent gain of and RD link is calculated by the following Eq.(6):

$$\zeta_k^{ev} = \alpha_b \frac{\psi(Q_k)}{L} + \alpha_q \frac{\gamma_{R_kD}}{\gamma_{max}} \tag{6}$$

where, γ_{R_kD} is the instantaneous SNR of an R_kD link. These equations work, for the MMRS scheme if $\alpha_b = 0$ and for SILO when $\alpha_q = 0$. Generally, we set $\alpha_b = \alpha_q = 0.5$, which equally combines the effects of link quality and the buffer occupancy. Using the equivalent gains of the SR links calculated in (5), The odd time-slot as given in the Eq. (7) is defining the SR link selection.

$$R_r^* = \arg\max_{R_k} \left\{ \bigcup_{R_k:\psi(Q_k)\neq L, |h_{S,R_k}|^2 \geqslant \gamma_{th}} \zeta_k^{od} \right\} \tag{7}$$

This equation ensures that a link whose corresponding relay has the best signal quality. The source node transmits with the probability $p_{S \to R_k}$ and data is stored in the selected relay buffer. In the even time-slot, similar procedure is carried out for the selection of an RD link and the transmission of the stored packet from the selected relay to the destination is carried out. The equivalent gain ζ_k^{ev} calculated in (6) is employed to find the best RD links. The corresponding selected relay is mathematically expressed as,

$$R_t^* = \arg\max_{R_k} \left\{ \bigcup_{R_k:\psi(Q_k)\neq 0, |h_{R_k,D}|^2 \geqslant \gamma} \zeta_k^{ev} \right\}. \tag{8}$$

According to this equation, a link, whose corresponding relay has the best signal quality and maximum available packets, is selected to transmit the packets to the destination. If no relay is selected i.e., $R_t^* = \phi$, then it is considered as an outage event.

Similar to the SNR threshold γ_{th} defined in previous schemes, we define an equivalent gain threshold for SR and RD sides, which is the combined effect of the buffer occupancy threshold and the link quality threshold. For SR links the gain threshold is,

$$\zeta_{th}^{od} = \alpha_b L_{th}^{od} + \alpha_q \gamma_{th} \tag{9}$$

For RD links, the equivalent gain threshold is,

$$\zeta_{th}^{ev} = \alpha_b L_{th}^{ev} + \alpha_q \gamma_{th} \tag{10}$$

These thresholds are especially used to mark the occurrence of an outage event. In the next subsection we explain more about the outage probability of a link and of a complete state depending on multiple links.

5. Outage probability analysis

In this section we explain, the proposed max-gain relay selection scheme along with Markov Modelling. Transition probabilities for the proposed Markov chain are calculated in the subsequent subsections.

5.1. Outage probability analysis

In this section, we model the proposed work using Markov chain. The details of the Markov modelling is given in the first subsection. Then, we formulate a framework to find the probabilities of states. Then, in the subsequent subsection, we compute the outage probability, end-to-end delay, the diversity gain and the throughput.

5.1.1. Markov chain

The Markov chain is used to model the Markov process; a random process whose future values depend on the most recent values [10]. The changes in buffers status of the proposed system model are also independent of the past buffer occupancy and depend on the current fullness or emptiness of the buffer. Hence, like the previous schemes, we employ the Markov chain to model the evolution of the buffers. A state of MC in the proposed system model is in-fact a K tuple describing the number of packets in each buffer. A state s_c is defined by the following equation,

$$s_c = [\psi(Q_1), \psi(Q_2), \psi(Q_3), \ldots, \psi(Q_K)] \tag{11}$$

As there are total K relays each equipped with a buffer size L, the total number of states n_S is found by considering the basic concept of the permutation with allowed repetition. In this model, $r = K$ values are chosen from $n = (L+1)$ values given in the set $\{0, 1, 2, \ldots, L\}$. Total permutations with allowed repetition are found by the formula n^r hence, there are total $n_S = (L+1)^K$ states given in the set $\mathcal{S}$. The Markov chain with specific values of $K = 2, L = 2$ is given in Fig. 2. This MC consists of $(2+1)^2 = 9$ states

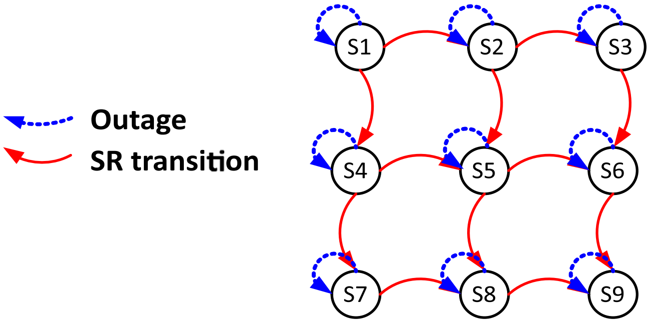

Fig. 2. Markov chain when SR links are activated.

as depicted in the figure. In the following discussion we explain the probabilities of states of MC considering the proposed MGRS as the underlying scheme (see Fig. 3).

5.1.2. Outage probabilities

Here, we explain the calculation process of the outage and transition probabilities of each state. For this purpose, we need to find the states directly accessible from a certain state. If a system is at s_r state, then the states accessible from this state are given in the set of connected states, $\mathscr{S}_{s_c}^{cs}$ [10].

$$\mathscr{S}_{s_c}^{cs} = \left\{ \bigcup_{0 \leqslant r \leqslant (L+1)^K} s_c : s_c - s_r \in \mathscr{Q} \right\} \tag{12}$$

where, $\mathscr{Q} \triangleq \{\cup_{1 \leqslant i \leqslant K} \pm \mathbf{I}_{(i,:)}\}$. Similarly, we need to find the links which are used while transiting from the state s_c to any connected state of $\mathscr{S}_{s_c}^{cs}$. The state s_c uses a unique link for each transition to the states of $\mathscr{S}_{s_c}^{cs}$. Let the set $\mathscr{L}_{s_c}^{cl}$ contains all the links used for the transition of state s_c to its connected states. Clearly, the set $\mathscr{L}_{s_c}^{cl}$ is the union of two disjoint sets, i.e., one contains all SR links and the other contains all RD link involved in the transition. These two sets are represented as $\mathscr{L}_{s_c}^{od}$, and $\mathscr{L}_{s_c}^{ev}$. Following this distinction for the set of states, the set $\mathscr{S}_{s_c}^{cs}$ is further partitioned into $\mathscr{S}_{s_c}^{od}$ and $\mathscr{S}_{s_c}^{ev}$.

If a link l_i is Rayleigh faded and achieves the average SNR $\bar{\gamma}$, its outage probability is given by the following equation,

$$p_{l_i}^{qu} = \left(1 - e^{\frac{-\gamma_{th}}{\bar{\gamma}}}\right) \tag{13}$$

$p_{l_i} \rightarrow 0$ when $\bar{\gamma}$ is sufficiently large i.e., $\rightarrow \infty$, while $p_{l_i} \rightarrow 1$ when $\bar{\gamma} \approx 0$. If $N_{s_c} = |\mathscr{L}_{s_c}^{cl}|$, are the total number of link associated with the state s_c, the outage probability is given by the following equation,

$$\varepsilon_{s_c}^{asy-qu} = \prod_{m=1}^{N_{s_c}} \left(1 - e^{\frac{-\gamma_{th}}{\bar{\gamma}_m}}\right). \tag{14}$$

where, $\bar{\gamma}_m$ is the average SNR of the m_{th} associated link which is activated when the system transit from s_c to the respective state. For symmetric channels this equation reduces to $\varepsilon_{s_c}^{sym-qu} = (p_{l_i}^{qu})^{N_{s_c}}$.

Now, we calculate the probability of each transition from the state s_c to its connected state. This is in-fact the activation probability of the corresponding link given in the set $\mathscr{L}_{s_c}^{cl}$. For this purpose we separate SR and RD links into for odd and even time-slots. We also need to find the outage probability of SR and RD links associated to s_c state. If $N_{s_c}^{od} = |\mathscr{L}_{s_c}^{od}|$ and $N_{s_c}^{ev} = |\mathscr{L}_{s_c}^{ev}|$ are the number of SR and RD links, respectively, then the outage probabilities of SR and RD links is given by the following equations,

$$\varepsilon_{s_c}^{od-asy-qu} = \prod_{mo=1}^{N_{s_c}^{od}} \left(1 - e^{\frac{-\gamma_{th}}{\bar{\gamma}_{mo}}}\right) \tag{15a}$$

where, $\bar{\gamma}_{mo}$ is the average SNR of the corresponding selected SR link while the system transits from its s_c state to any state from $\mathscr{S}_{s_c}^{od}$,

$$\varepsilon_{s_c}^{ev-asy-qu} = \prod_{me=1}^{N_{s_c}^{ev}} \left(1 - e^{\frac{-\gamma_{th}}{\bar{\gamma}_{me}}}\right) \tag{15b}$$

where, $\bar{\gamma}_{me}$ is the average SNR of the corresponding selected RD link while the system transits from its s_c state to any state from $\mathscr{S}_{s_c}^{ev}$. These equations reduce to the following equations when symmetric channel conditions are applied, i.e., $\bar{\gamma}_{mo} = \bar{\gamma}_{me} = \bar{\gamma} \forall mo and me$,

$$\varepsilon_{s_c}^{od-sym-qu} = \left(p_{l_i}^{qu}\right)^{N_{s_c}^{od}} \tag{16a}$$

$$\varepsilon_{s_c}^{ev-sym-qu} = \left(p_{l_i}^{qu}\right)^{N_{s_c}^{ev}} \tag{16b}$$

Now, we explain the process of the calculation of the outage probabilities of the proposed MGRS scheme. Since, this scheme considers the impact of buffer occupancy into relay selection process, we need to modify the Eq. (13) to include the impact of the buffer occupancy. The following equations are the generic form of Eq. (13), to include the impact of both the buffer occupancy and the link quality.

$$p_{l_i}^{od-lnk-gn} = \left(\alpha_q + \alpha_b \left[1 + \frac{(\alpha_b - 1)(L - \psi(Q_k))}{L}\right]\right) p_{l_i}^{qu} \tag{17a}$$

and for the RD links,

$$p_{l_i}^{ev-lnk-gn} = \left(\alpha_q + \alpha_b \left[1 + \frac{(\alpha_b - 1)\psi(Q_k)}{L}\right]\right) p_{l_i}^{qu} \tag{17b}$$

These equations work for MMRS and SILO when $\alpha_b = 0$ and $\alpha_q = 0$, respectively. The modified equations for the calculation of the outage probability are used in finding the outage probability of the state s_c.

$$\varepsilon_{s_c}^{od-sym-gain} = \left(p_{l_i}^{od-lnk-gn}\right)^{N_{s_c}^{od}} \tag{18a}$$

$$\varepsilon_{s_c}^{ev-sym-gain} = \left(p_{l_i}^{ev-lnk-gn}\right)^{N_{s_c}^{ev}} \tag{18b}$$

The equations for asymmetric cases would be similar and required only the products of the involved link in each state. Hence, we skip the equations of $\varepsilon_{s_c}^{od-asy-gain}$ and $\varepsilon_{s_c}^{ev-asy-gain}$ to avoid the redundancy.

After explaining the outage probabilities of each state in different conditions we move on to explain the transition probabilities of each state for both the even and odd cases. The process of finding the activation probabilities of links when the system is at s_c state is different for the symmetric and asymmetric cases. For symmetric cases, in the SNR based relay selection schemes, like [9,10], the

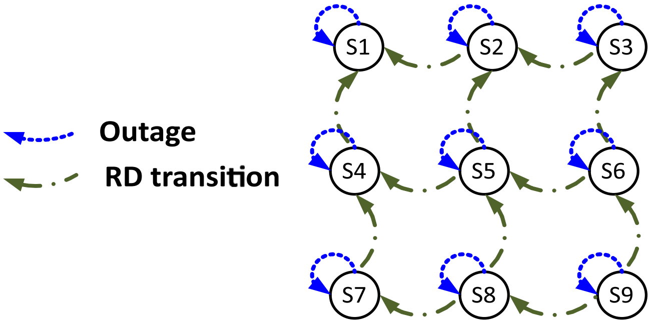

Fig. 3. Markov chain when RD links are activated.

activation probability, is actually the complement of the outage probability of each state and is equi-distributed between the competing links. This is given by the following equations for both the SR and RD links.

$$\mathcal{Q}^{sym-SNR}_{s_c} = \frac{1}{N_{s_c}}\left\{1-\left(p^{qu}_{l_i}\right)^{N_{s_c}}\right\} \tag{19a}$$

If the activation probabilities of each links are required to be found separately, following equations are employed.

$$\mathcal{Q}^{od-sym-SNR}_{s_c} = \frac{1}{N^{od}_{s_c}}\left\{1-\left(p^{qu}_{l_i}\right)^{N^{od}_{s_c}}\right\}, \tag{19b}$$

$$\mathcal{Q}^{ev-sym-SNR}_{s_c} = \frac{1}{N^{ev}_{s_c}}\left\{1-\left(p^{qu}_{l_i}\right)^{N^{ev}_{s_c}}\right\}, \tag{19c}$$

The strategy of finding the activation probabilities for the asymmetric links in link quality based schemes is quite similar with the strategy of finding the activation probabilities for the asymmetric links in the buffer occupancy or weight-based relay selection scheme. The basic idea is that activation of a link l_o with a certain weight i.e., w_o, is an event when all the other links with weight greater than w_o are in outage. However, if the weights of multiple links is equal to w_o, then the activation probability is equally divided among all links. For this purpose, we find the links whose weights are larger and equal or smaller to w_o in the the variables $N^{w_o-lrg}_{s_c}, N^{w_o-eql}_{s_c}, N^{w_o-sml}_{s_c}$, respectively. Clearly, the total number of links are the sum of all these links. The activation probability of the link l_o in the general case regardless of whether it is SR or RD link is given by the following equation;

$$\mathcal{Q}^{sym-wgt}_{s_c} = \frac{\left\{\left(1-\left(p^{qu}_{l_i}\right)^{N^{w_o-eql}_{s_c}}\right)\left(\left(p^{qu}_{l_i}\right)^{N^{w_o-lrg}_{s_c}}\right)\right\}}{N^{w_o-eql}_{s_c}} \tag{20}$$

Similar to the aforementioned procedure, the number of links for SR and RD sides are given in the following variables;

$$N^{w_o-od-lrg}_{s_c}, N^{w_o-od-eql}_{s_c}, \& N^{w_o-od-sml}_{s_c} \tag{21}$$

and

$$N^{w_o-ev-lrg}_{s_c}, N^{w_o-ev-eql}_{s_c}, \& N^{w_o-ev-sml}_{s_c} \tag{22}$$

$$\mathcal{Q}^{od-sym-wgt}_{s_c} = \frac{\left\{\left(1-\left(p^{qu}_{l_i}\right)^{N^{w_o-od-eql}_{s_c}}\right)\left(\left(p^{qu}_{l_i}\right)^{N^{w_o-od-lrg}_{s_c}}\right)\right\}}{N^{w_o-od-eql}_{s_c}} \tag{23a}$$

$$\mathcal{Q}^{ev-sym-wgt}_{s_c} = \frac{\left\{\left(1-\left(p^{qu}_{l_i}\right)^{N^{w_o-ev-eql}_{s_c}}\right)\left(\left(p^{qu}_{l_i}\right)^{N^{w_o-ev-lrg}_{s_c}}\right)\right\}}{N^{w_o-ev-eql}_{s_c}} \tag{23b}$$

After proposing the transition probabilities for link quality and weight-based schemes, now we proceed to find the transition probabilities of the proposed MGRS schemes. For this purpose we use the equivalent outage probabilities of a link and each states calculated in Eq. (17) and Eq. (8). Following the aforementioned process, here we formulate the process of finding the transition probability of a link l_o associated with the state $s-c$ and has equivalent gain ζ_o, we need to find the links, especially their total population, whose gains are, larger, equal and smaller than ζ_o. The number of these links for SR and RD sides are given in the variables;

$$N^{\zeta_o-od-lrg}_{s_c}, N^{\zeta_o-od-eql}_{s_c}, N^{\zeta_o-od-sml}_{s_c} \tag{24}$$

$$N^{\zeta_o-ev-lrg}_{s_c}, N^{\zeta_o-ev-eql}_{s_c}, N^{\zeta_o-ev-sml}_{s_c} \tag{25}$$

$$\mathcal{Q}^{od-sym-gain}_{s_c} = \frac{\left\{\left(1-\left(p^{od-lnk-gn}_{l_i}\right)^{N^{\zeta_o-od-eql}_{s_c}}\right)\left(\left(p^{od-lnk-gn}_{l_i}\right)^{N^{\zeta_o-od-lrg}_{s_c}}\right)\right\}}{N^{\zeta_o-od-eql}_{s_c}} \tag{26}$$

$$\frac{1}{N^{\zeta_o-ev-eql}_{s_c}}\mathcal{Q}^{ev-sym-gain}_{s_c} = \frac{\left\{\left(1-\left(p^{ev-lnk-gn}_{l_i}\right)^{N^{\zeta_o-ev-eql}_{s_c}}\right)\left(\left(p^{ev-lnk-gn}_{l_i}\right)^{N^{\zeta_o-ev-lrg}_{s_c}}\right)\right\}}{N^{\zeta_o-ev-eql}_{s_c}} \tag{27}$$

In the proposed scheme, the relay selection is different for odd and even time-slot, therefore, the proposed Markov chain is periodic as used in [21]. Markov state transition matrices are considered separately for odd and even time-slots in the following subsection.

5.1.3. State transition matrices

Probabilities of all states is calculated for both outage and transition probability for relaying scheme. The entries of $\mathbf{A}_{od}$ and $\mathbf{A}_{ev}$ are given in Eq. (28) and Eq. (29).

$$\mathbf{A}^{od}_{i,j} = p(s_r|s_c) = \begin{cases} \varepsilon^{od}_{s_c} & \text{if} \quad s_r = s_c, \\ p_{SR_{so}} & \text{if} \quad s_r \in \mathscr{S}^{od}_{s_c}, \\ 0 & \quad \text{otherwise.} \end{cases} \tag{28}$$

where, $p_{SR_{so}}$ is the probability of the selection of SR_{so} link where $so = [1 : N^{od}_{s_c}]$, while the system transit from s_c to a state in $\mathscr{S}^{od}_{s_c}$. It is calculated by the aforementioned process in the Eq. (26). Here, we explain the formation of the other transition matrix for the RD sides,

$$\mathbf{A}^{ev}_{i,j} = p(s_r|s_c) = \begin{cases} \varepsilon^{ev}_{s_c} & \text{if} \quad s_r = s_c, \\ p_{R_{se}D} & \text{if} \quad s_r \in \mathscr{S}^{ev}_{s_c}, \\ 0 & \quad \text{otherwise.} \end{cases} \tag{29}$$

where, $p_{SR_{se}}$ is the probability of the selection of SR_{se} link where $se = [1 : N^{ev}_{s_c}]$ is calculated in the Eq. (27) from s_c to a state in $\mathscr{S}^{ev}_{s_c}$. In the next subsection we find the steady state probability of by considering both the transition matrices.

5.1.4. Steady State Probabilities

In this section, we find the steady state probabilities of the even and odd transition matrices for further evaluation of the outage probability of the system. For this purpose, we examine Eq. (29) and Eq. (28), and conclude that the outage probability values of all states are actually the diagonal entries of the corresponding state transition matrices. Hence, we also consider the diagonal entries for the calculation of the steady state probability of each state. The steady state probability vector for odd matrix is given as,

$$\pi^{od} = \left(\mathbf{A}^{ev}\mathbf{A}^{od} - \mathbf{I} + \mathbf{B}\right)^{-1} \in \mathbb{R}^{(L+1)^K} \tag{30}$$

Similarly, probability vector of steady state for the even matrix is given by,

$$\pi^{ev} = \left(\mathbf{A}^{od}\mathbf{A}^{ev} - \mathbf{I} + \mathbf{B}\right)^{-1} \in \mathbb{R}^{(L+1)^K} \tag{31}$$

The outage probability of the buffer-aided cooperative relaying system is given by the following equation,

$$P_{out} = \frac{1}{2}\text{diag}(\mathbf{A}^{od})\pi^{od} + \frac{1}{2}\text{diag}(\mathbf{A}^{ev})\pi^{ev} \tag{32}$$

The average queuing length $E\{Q_{eq}\}$ is calculated by the following equation,

5.2. Average Diversity Gain

In this section we analyze the diversity gain achieved by the proposed MGRS scheme. It is defined as;

$$d = -\lim_{\bar{\gamma}\to\infty} \frac{\log(P_{out}(\bar{\gamma}))}{\log(\bar{\gamma})} \tag{33}$$

Few cases considered by [22] while analysing the quality of the links and buffer availability with respect to the gains. The proposed MGRS relay selection scheme achieve using different buffer sizes as shown in the equation.

$$d = \begin{cases} 1 & \text{if} \quad L = 1, \\ K-1 & \text{if} \quad L = 2, \\ K & \text{if} \quad L \geqslant 3. \end{cases} \tag{34}$$

$$\begin{bmatrix} p^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1-p^2}{2} & p^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p(1-p) & p & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1-p^2}{2} & 0 & 0 & p^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-p & 0 & p(1-p) & p^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-p & 0 & \frac{1-p^2}{2} & p & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-p & 0 & 0 & p & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-p^2}{2} & 0 & 1-p & p & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-p & 0 & 1-p & 1 \end{bmatrix} \tag{35}$$

$$\begin{bmatrix} 1 & 1-q & 0 & 1-q & 0 & 0 & 0 & 0 & 0 \\ 0 & q & 1-q & 0 & \frac{1-q^2}{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & q & 0 & 0 & 1-q & 0 & 0 & 0 \\ 0 & 0 & 0 & q & \frac{1-q^2}{2} & 0 & 1-q & 0 & 0 \\ 0 & 0 & 0 & 0 & q^2 & q(1-q) & 0 & 1-q & 0 \\ 0 & 0 & 0 & 0 & 0 & q^2 & 0 & 0 & \frac{1-q^2}{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & q & q(1-q) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & q^2 & \frac{1-q^2}{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q^2 \end{bmatrix} \tag{36}$$

Suppose that, as a specific example, $K = 2$ and $L = 2$ of the proposed relay selection scheme with 2 relay nodes each equipped with a buffer of size 2 packets. The total number of states of Markov chain is $(L+1)^K = 9$. The states representation of Markov chain is given in Table 1. For the notation-wise convenience we assume that $p = p_{l_i}^{lnk-gn-od}$ and $q = p_{l_i}^{lnk-gn-ev}$. The transition matrix is shown in Eq. (35) for odds and Eq. (36) for evens.

6. Performance evaluation

In this section, we measured the performance of proposed MGRS protocol in terms of outage probability, average end-to-end delay and average throughput. The performance of proposed scheme is compared with MMRS and CRS schemes proposed in [9,20], respectively. CRS scheme is originally presented with initially filled buffers. However, for fair comparison, we implemented CRS scheme with initially empty buffers that is also a novel contribution in this work. Fig. 4 compare the outage probabilities by considering SNR, also the outage probability of the MMRS, CRS and MGRS schemes is compared with respect to different independent parameters in Fig. 5. For this comparison, we consider *no selection* and *selection bound* as an upper and lower bounds. The no selection refers to a scheme in which a single relay is selected from all the available relays and the selected relay is employed to receive and transmit for the whole communication time. The selection bound scheme refers to an ideal situation in which there are no limitations of link quality or buffer occupancy. All the deployed relays have the buffer spaces to store the packets if an SR link is selected. Similarly, all the relays have the packets to be transmitted if an RD link is selected. Hence, all the possible $2K$ link are always available for selection. Further, in this comparison we consider two cases of the buffer size and number of relays. For, $(K, L) = (2, 2)$, the outage probability of the proposed scheme is lower that the compared MMRS and CRS schemes. Increasing the number of relays and buffer size, further reduces the outage probability of the buffer aided relaying system (see Fig. 6).

The outage probability is compared with number of relays for samples of SNR in Fig. 5.Specifically, there is a linear relationship of outage probability and relays is considered, while the underlying values of SNR is in dB. In this comparison, the proposed scheme outperforms the compared scheme for both cases of SNR as depicted in Fig. 5. This is because, the proposed work considers the buffer occupancy and channel quality into relay selection process. Hence, the selected link have the best SNR and buffer occupancy compared to the other links (see Figs. 7 and 8).

The performance of all schemes is also evaluated for the average end-to-end delay with respect to SNR as shown in Fig. 9. Increasing the SNR decreases the delay for a certain case of the number of relays and buffer size. However, the delay of all schemes converges to a single values at sufficiently larger values of SNR, i.e., $1 + KL$. For this comparison we consider two cases of buffer size and number of relays, i.e., $(K, L) = (2, 2)$and$(3, 3)$ as given in the figure. For the case $(3, 3)$ the average delay is greater than the compared case of $(2, 2)$. The proposed MGRS scheme outperforms its counterparts

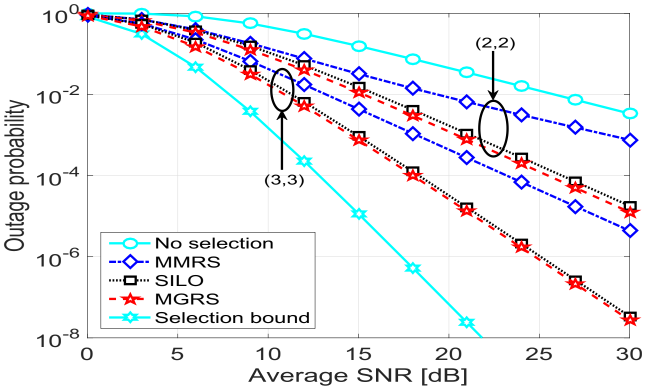

Fig. 4. Outage probability of the compared schemes with respect to SNR.

Table 1
States of Markov Chain.

States	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
Buffer	00	01	02	10	11	12	20	21	22

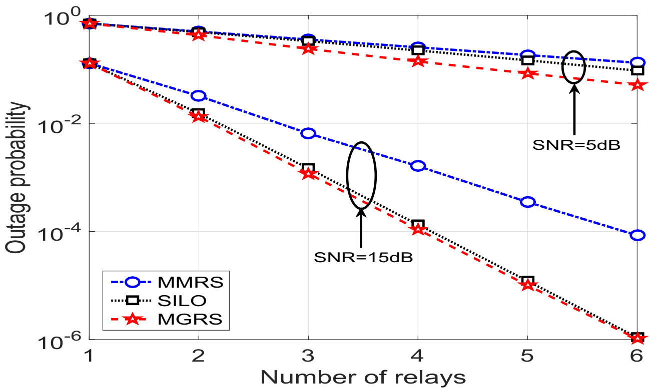

Fig. 5. Outage probability of the proposed max-gain scheme with respect to number of relays.

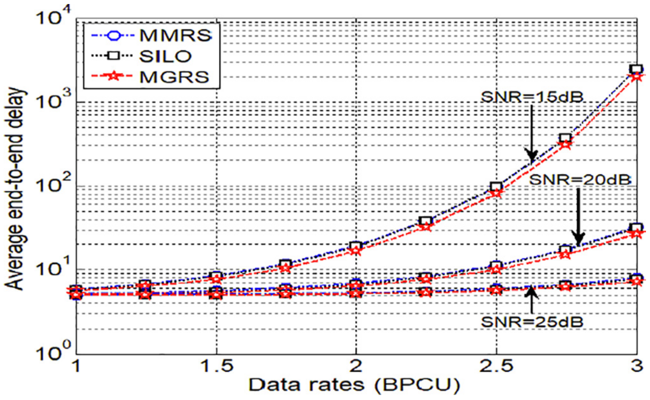

Fig. 6. Avg. delay with respect to data rate.

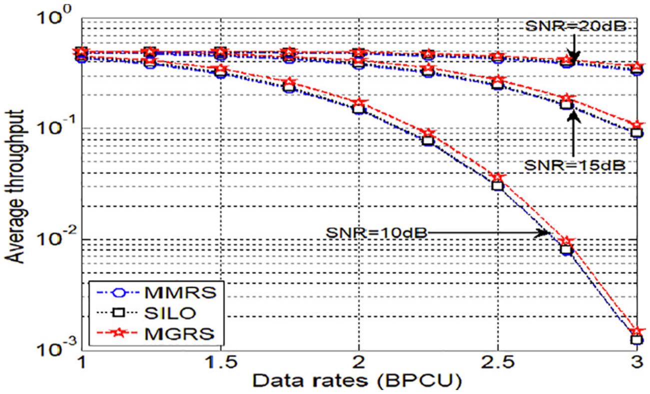

Fig. 7. Avg throughput with respect to data rate.

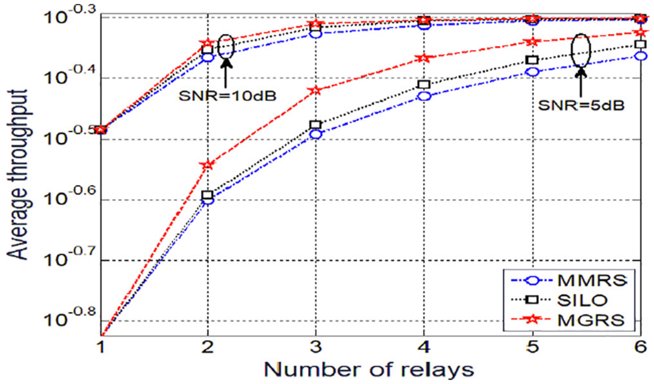

Fig. 8. Avg. throughput with respect to relays.

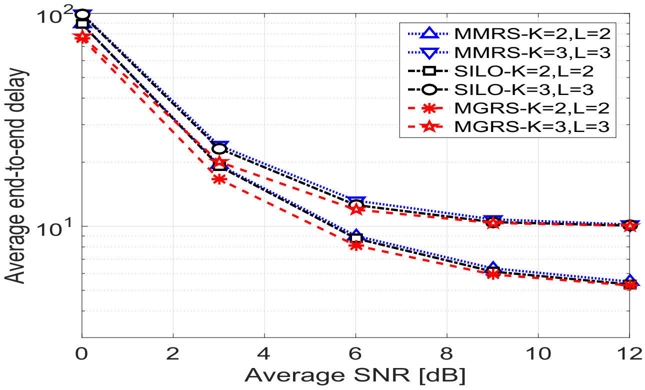

Fig. 9. Avg. delay with respect to SNR.

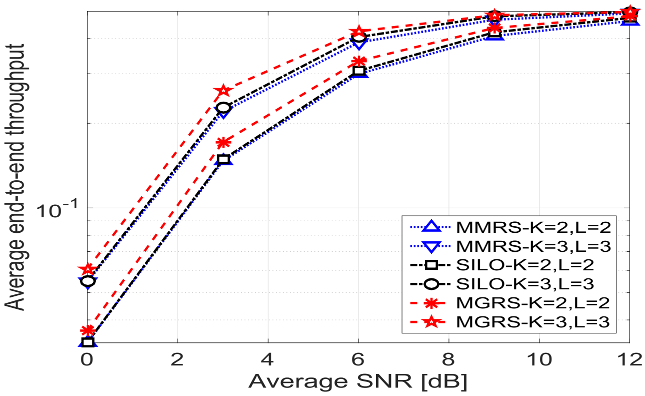

Fig. 10. Throughput with respect to SNR.

by a slight margin for this comparison. This is due to the fact that the significant decrease in the average end-to-end delay is achieved if the selection probability of RD links is increased by the underlying selection criteria. By the proposed contribution of selecting the best link which have the best SNR and buffer occupancy, the average end-to-end is not significantly improved.

We evaluate the throughput of all schemes against the increasing SNR in Fig. 10. Like the average end-to-end delay, the throughput of all schemes converges to a single value i.e., $1/2$. This is because, on average a packet takes two time-slots from the source to the destination. The comparison of the compared scheme indicates that with the increase SNR there is an increase in the average throughput of all compared schemes. For this comparison we take two cases of buffer sizes and the number of relays. The throughput of all scheme approaches to the converging limit at the lower SNR when evaluated for $(3,3)$. For both cases, the proposed scheme's throughput is sufficiently larger than the MMRS and CRS schemes. The increase in throughput in this comparison is due to decrease in the outage probability and the average end-to-end delay when evaluated against the increasing SNR.

7. Conclusion and Future Work

In this work, we proposed a relay selection scheme which jointly considers the instantaneous channel quality and the buffer occupancy in the relay selection process. The proposed work is for two-phase relaying scheme where an SR link is selected in odd time-slots and an RD link is selected in even time-slots. We employ the Markov chain for modelling the buffer status and evaluating the outage probability of the buffer-aided relaying system. The outage probability is employed to compute the average end-to-end delay, diversity gain and the average throughput of the relaying system. It is concluded that the proposed scheme outperforms the previous scheme in terms of the outage probability and the average throughput. However, there is a trade-off between these parameters and the average end-to-end delay especially when evaluated with respect to the increasing number of relays. The proposed work is evaluated in the symmetric channels with independent and identical fading. In future, we intend to implement the proposed strategy in asymmetric channels and different fading environments like the Rician and Nakagami-m. Also, We will extend our work by using NOMA and combining the link quality, buffer size and physical layer security for intelligent selection of the link. We also aim to include the remaining energy of the relays in the relay selection process to make the proposed scheme more realistic and practically appealing along with cooperative buffer pre-fetching that how a low buffer with good link quality can be chosen as other relays will cooperatively help that relay.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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