Received October 9, 2018, accepted November 1, 2018, date of publication November 13, 2018, date of current version December 27, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2881167

Virtual-Link Relay Selection Scheme for Buffer-Aided IoT Based Cooperative Relay Networks

HINA NASIR[1], NADEEM JAVAID[2], (Senior Member, IEEE), WASEEM RAZA[3], MOHSEN GUIZANI[4], (Fellow, IEEE), NABIL ALRAJEH[5], AND MOHAMAD SOUHEIL ALABED[5]

[1]Department of Computer Science and Software Engineering, International Islamic University, Islamabad 44000, Pakistan
[2]Department of Computer Science, COMSATS University Islamabad, Islamabad 44000, Pakistan
[3]Department of Technology, University of Lahore, Lahore 54000, Pakistan
[4]Department of Electrical and Computer Engineering, University of Idaho, Moscow, ID 83844, USA
[5]Department of Biomedical Technology, College of Applied Medical Sciences, King Saud University, Riyadh 11633, Saudi Arabia

Corresponding author: Nabil Alrajeh (nabil@ksu.edu.sa)

This work was supported by the Deanship of Scientific Research at King Saud University under Grant RG-1438-037.

ABSTRACT This paper investigates the performance of a buffer-aided cooperative relay network. In the proposed design, each location in a buffer is assumed to act independently called the virtual relay having a buffer of size 1. The relay selection is based on the instantaneous strength of the wireless link and status of the virtual relay buffer. The proposed scheme is analyzed for symmetric and asymmetric channel conditions and also for symmetric and asymmetric buffer sizes at the relay. Markov chain is used to model the evolution of buffer status and to derive the closed-form expressions for outage probability, diversity gain, delay, and throughput. The proposed design achieves the diversity gain of $(L_1 + L_2 + \cdots + L_K)$, where L_i is the buffer size of the i-th relay and K is the total number of relays.

INDEX TERMS Buffer-aided, virtual relaying, cooperative communication, diversity gain, relay selection.

I. INTRODUCTION

Cooperative relaying (CR) is a popular technique to enhance the performance of a wireless network. It increases the diversity gain, reduces the outage probability and increases the throughput. Normally, in a half-duplex CR network, single relay is selected which is responsible for the reception of data in the odd time slot and transmission of data in the subsequent even time slot [1]. It provides significant improvement in the system's performance, however, the selection of single relay is not often ideal because the corresponding channels undergo independent fading. This is called channel mismatch problem [2]–[4].

To ease the aforementioned problem, data buffer is incorporated at the relay. The introduction of data buffer allows the selection of different relays for reception and transmission of data. It helps to exploit the best channel for data reception at relay and the best channel for data transmission from relay. It not only decreases the outage probability, however, it also improves the diversity gain and throughput. Buffer-aided CR offers many advantages as compared to traditional schemes, however, it leads to new challenges for system design as well. In buffer-aided CR, the strongest contributive link in terms of signal to noise ratio (SNR) is selected for transmission which requires the acquisition of channel state information (CSI). Moreover, the design with finite buffers requires buffer state monitoring as well. Furthermore, storing packets in the buffers brings in the additional packet delay. There are two types of delay: block delay and packet delay. The block delay is the time required to send the block of packets from source to destination, whereas, the packet delay is the time required by an individual packet to reach from source to destination. The block delay in a buffer-aided scheme is same as in buffer-less scheme since all the packets need two time slots to reach the destination. However, the packet delay is different for different packets because a packet has to wait inside the buffer until the respective relay to destination (relay-destination) link is selected. The delay increases linearly with the increase in the number of relays or buffer size. The greater the number of relays, greater will be the packet delay because the probability of selecting relay-destination link decreases. Hence, the buffer-aided cooperative protocols generally have increased design complexity [2].

Buffer-aided relay selection schemes can be divided into two categories on the basis of their transmission scheme. They are two-slot and one-slot. In a two-slot transmission scheme, source and relay transmit in the alternate time slots like in [1], however, different relays can be selected for reception and transmission. Whereas, in one-slot transmission scheme, any relay either for reception or transmission can be selected in any time slot. The one-slot scheme provides the full diversity gain of twice the number of relays, as compared to two-slot scheme having the diversity gain equal to the number of relays, however, there coexist the increased packet delay. In this work, we focus on one-slot transmission scheme.

A. LITERATURE REVIEW

The best relay selection (BRS) scheme [1] is a traditional (buffer-less) relay selection scheme considered as a benchmark. Following the two-slot transmission regulation, it selects the best relay for reception and transmission in the odd and even time slots, respectively. The best relay is one whose minimum of both source to relay (source-relay) and relay-destination link is maximum. This scheme achieves the diversity gain of K, where K is the number of relays and a packet delay of 2 time slots.

Removing the barrier of a single relay selection for both reception and transmission purposes, a buffer-aided CR is introduced. The fundamental works in buffer-aided relay selections are max-max relay selection (MMRS) [5] scheme and max-link relay selection (MLRS) [6] scheme. MMRS scheme is based on traditional two-slot transmission routine. It considers link quality as the only metric in the relay selection process. In the odd time slot, the strongest link among all contributive source-relay links is selected and data is sent from the source to the corresponding relay and it is stored in the respective relay buffer. While in the even time slot, the strongest contributive relay-destination link is selected and data from the buffer of the selected relay is sent to the destination. In contrast to MMRS, the MLRS scheme [6] follows the one-slot transmission regulation for source and relay. Like MMRS, It also considers link quality as the only metric in the relay selection process. In any time slot, it selects the relay which has the strongest link among all contributive links between source-relay and relay-destination. When source-relay link is the strongest, source transmits the data packet to the selected relay and relay stores it in its buffer. Alternatively, when relay-destination link is the strongest, selected relay transmits the data packet from its buffer to the destination. As a result, the MLRS scheme achieves a higher diversity gain approaching to $2K$ when buffer size is very large as compared to MMRS scheme having a diversity gain of K. It has the packet delay of $1 + KL$ time slots, where L is the buffer size. Motivated by the MLRS and MMRS schemes, several other efforts have been made in buffer-aided CR with an aim to enhance performance in terms of the diversity gain, delay, throughput etc. Charalambous *et al.* [7] introduced the direct link between source and destination in the MLRS scheme and achieve a diversity gain of $2K+1$ at a very large buffer size. This scheme achieved slight reduction in the delay as compared to the delay in MLRS scheme, because some packets are transmitted directly to the destination. Tian *et al.* [8] proposed buffer-aided relay selection for amplify and forward (AF) relaying technique. It achieves same diversity and coding gain as of MLRS scheme and a delay of $1 + KL$ time slots. Recently, a buffer-aided reduced delay relay selection (RDRS) scheme is proposed in [9] that prioritizes relay-destination link over source-relay to reduce the delay. It considers link quality as the only relay selection metric and based on one-slot transmission scheme. In any time slot, it first looks for the strongest link among all contributive relay-destination links. If the strongest link is not in the outage, the selected relay transmits the data packet from its buffer to the destination. Otherwise, it selects the strongest link among all contributive source-relay links. If the strongest link is not in the outage, the source transmits the data packet to the selected relay and the selected relay stores it in its buffer. RDRS scheme is specifically designed to keep the buffer queues as short as possible. This scheme attains the delay of 2 time slots, however, it compromises its diversity gain from $2K$ to $K + 1$ at large buffer size. Another attempt to increase the diversity gain was proposed in [10]. In this scheme, the authors acquire the diversity gain equal to MLRS scheme using the two-slot MMRS transmission schedule. Furthermore, they reduced the end-to-end packet delay at high SNR.

Because the relay selection in MMRS and MLRS schemes is only based on channel quality, the relays are prone to full and empty buffers. The full buffer cannot receive data and the empty buffer cannot transmit data. Thus, reducing the number of contributive links for data transmission. To avoid full and empty buffers, a buffer status based relay selection scheme is presented in [11] that considers buffer status along with link quality in the relay selection process. In this scheme, a weight based scheme is proposed that selects the best relay for reception or transmission based on the most contributive or on the most occupied buffer space, respectively. This scheme achieves the full diversity gain of $2K$ at a small buffer of size 3. The max-weight scheme randomly selects the link for reception or transmission, when multiple links have equal weights on both sides. This problem is addressed by Raza *et al.* [12] and link priority and quality based selection parameters are proposed when multiple links have same weight to reduce the outage probability and delay. Another effort is presented in [13] in which authors propose a score based relay selection scheme based on link quality and buffer status. A buffer state based relay selection scheme is proposed in [14] that selects the best relay based on channel quality and buffer status. It prioritizes the relay-destination link when buffer has 2 or more than 2 packets to avoid empty buffers and to reduce the delay. This scheme achieves the full diversity gain at small buffer size of 3 and the less delay as compared to the delay in MLRS scheme. A similar attempt using AF relaying was proposed by Oiwa *et al.* [15]. They introduced the thresholding technique at relay and destination nodes for AF relaying and select the best relay based on the buffer status to improve the outage probability performance.

A relay selection scheme based on MMRS transmission schedule was proposed in [16]. In this scheme, the relay having a maximum available buffer space is selected for reception in the odd time slot, and a relay having maximum occupied buffer space is selected for transmission in the even time slot. This scheme achieves significant improvement in the outage probability and delay as compared to MLRS and MMRS schemes. Another attempt to reduce the overall outage probability in buffer-aided CR is made in [17] and [18]. They use the concept of inverse channel packet matching. The packets that went through bad channel conditions in the source-relay hop go through good channel conditions in the relay-destination hop to overcome channel mismatch problem and improve the overall outage probability. Few attempts in secure buffer-aided cooperative relaying are also proposed in [19] and [20] to improve the secrecy outage probability.

B. MOTIVATION

From all of the aforementioned approaches, we have the following observations:

- If the diversity gain is achieved, the delay is compromised and if the delay is reduced, the diversity gain is compromised. In other words, there exists a diversity delay trade-off. It is also observed that the diversity gain is only a function of relays. Although in some schemes, [11], [12], [14], it is claimed that the diversity gain is a function of both the number of relays and buffer size, however, their claim is for fixed value of buffer size. At buffer size greater than an optimal value, the diversity gain is only a function of the number of relays. The more the value of K, more is the diversity gain. Moreover, increasing the number of relays, increases the cost of network. This observation leads to the following questions that is our main motivation: *Can the diversity gain be a function of both the number of relays and the buffer size in case of buffer-aided CR? How can we look at buffers so that the diversity gain becomes the function of buffer size also?* There is a need to explore a way to increase the diversity without increasing the cost of relays.
- Additionally, the method to access the buffer is sequential in which data is accessed in a first in first out (FIFO) manner. Despite the fast operation of FIFO, the data placed at the head of the buffer queue is bound to be transmitted when the respective relay-destination link is selected, regardless of the fact that the other packets lying inside buffer can be better for transmission.
- Furthermore, it is observed that the buffer size is considered symmetric for all relays. In a wireless network, there are heterogeneous nodes in terms of memory, processing capability etc. Assuming the symmetric buffer size only is not a realistic assumption. Considering this, we propose a scheme that allows the diversity gain to be a function of both the number of relays and buffer size by using random access buffer method and asymmetric buffer size for a buffer-aided CR system.

C. PAPER CONTRIBUTION AND ORGANIZATION

We summarize our contributions in this work as follows:

1) We propose a novel relay selection scheme termed as virtual link relay selection (VLRS) for buffer-aided cooperative relay networks.
2) In the proposed system model, the length of buffers at each relay is variable and they allow random access to the data. We use the concept of virtual relaying in which each buffer location has its own antenna resource and is assumed to act independently known as a virtual relay. The virtual relay has a buffer of size 1. Although it behaves independently, however, it uses the resources of the relay it is attached with. In this way, we benefit from the large diversity gain using the small number of relays.
3) The advantages of virtual relaying are depicted in terms of the outage probability, diversity gain, delay and throughput. We propose a method to construct the state transition matrix of the Markov chain (MC) using random access buffers and obtain the steady state to get the outage probability, diversity gain, delay and throughput.
4) We evaluate the proposed scheme for the symmetric and asymmetric buffer size and channel conditions and provide a comprehensive set of results for four cases: 1) symmetric buffer and symmetric channel, 2) symmetric buffer and asymmetric channel, 3) asymmetric buffer and symmetric channel and 4) asymmetric buffer and asymmetric channel. Analytical results are verified by means of simulations to validate the proposed scheme.

The rest of the paper is organized as follows: Section II presents the system model of the proposed scheme. Section III presents the proposed buffer-aided virtual relay selection schemes along with the outage probability analysis, diversity gain analysis, delay analysis and a numerical example. Section IV consists of the numerical results followed by the conclusion and future research directions in Section V.

II. SYSTEM MODEL

We consider a cooperative network of a single source-destination pair represented by S and D, respectively and a set R of K decode and forward (DF) relays, where, $R = \{R_1, R_2, \cdots, R_k, \cdots, R_K\}$ as shown in Fig. 1. All nodes operate in a half-duplex transmission mode, i.e., a node cannot transmit and receive, simultaneously. A direct link between S and D does not exist due to path-loss and shadowing effects as considered in many of the existing buffer-aided relay selection schemes [5], [6], [11], [12], [14], [20]. S and D have a single antenna resource and each relay is equipped

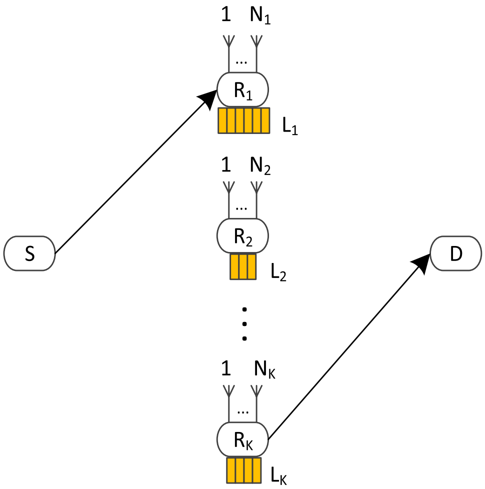

FIGURE 1. System model for buffer-aided cooperative relaying schemes.

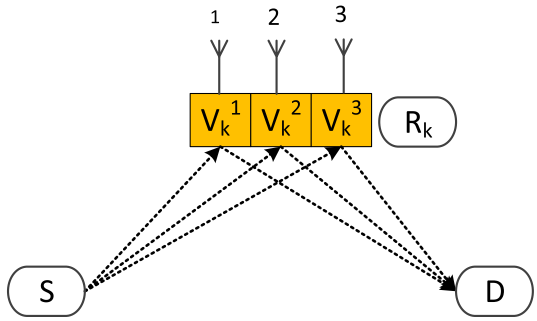

FIGURE 2. System model for proposed buffer-aided virtual relaying for the k_{th} relay and $N_k = L_k = 3$.

with N_k antennas. In addition, each relay is equipped with a data buffer of size L_k to store the received data. Unlike existing system models on buffer-aided relaying, we considered asymmetric buffer size i.e., the size of buffer at each relay is not same.

The buffers allow random access to the stored data. Data can be stored at any location and can be transmitted from any location. We assume that each location in L_k is associated with an antenna resource at the relay to receive and transmit the data. The total number of antennas at R_k is equal to the buffer size, i.e., $N_k = L_k$. Hence, each buffer location uses its corresponding antenna for data reception and transmission. Therefore, it is considered as an independent entity called the virtual relay having a buffer of size 1. The set of virtual relays is denoted by V, where, $V = \{V_1^1, \cdots, V_1^{L_1}, V_2^1, \cdots, V_2^{L_2}, \cdots, V_K^{L_K}\}$. A source to virtual relay ($S \rightarrow V_k^l$) link is considered contributive when its corresponding buffer is empty while a virtual relay to destination ($V_k^l \rightarrow D$) link is considered contributive when its corresponding buffer is full. The number of data packets stored in the buffer of each virtual relay is denoted by a binary variable $\Psi(V_k^l)$, where $\Psi(V_k^l) = \{0, 1\}$. When a packet is correctly decoded and stored at V_k^l, $\Psi(V_k^l) = 1$, and when a packet is successfully transmitted from the buffer, $\Psi(V_k^l) = 0$. In this way, instead of single link between S and R_k, L_k links exist between S and R_k, and similarly, between R_k and D as shown in Fig. 2. Thus, the total number of source-relay links are $0 \leq N_r \leq (L_1 + L_2 + \cdots + L_K)$ and relay-destination links are $0 \leq N_t \leq (L_1 + L_2 + \cdots + L_K)$.

All wireless channels exhibit independent and identically distributed block based flat Rayleigh fading. The fading envelop of a given hop remains constant during one time slot. However, it varies from one time slot to another.

A. TRANSMISSION SCHEME

The transmission of data from S to D takes place using two hops: $S \rightarrow V_k^l$ and $V_k^l \rightarrow D$. In a given time slot, a virtual relay is selected either for reception using the first hop or transmission using the second hop. In the first hop, S transmits data to the selected virtual relay. The received signal at V_k^l is given as:

$$y_{SV_k^l} = \sqrt{P} h_{SV_k^l} x_S + n_{V_k^l} \quad (1)$$

where, x_S is the transmitted signal from S with power P. $h_{SV_k^l}$ represents the channel between S and V_k^l. $h_{SV_k^l}$ is an independent and identically distributed (i.i.d) complex Gaussain random variable with zero mean and $\bar{\gamma}_{SV_k^l}$ variance. $n_{V_k^l}$ represents the additive white Gaussain noise (AWGN) at V_i having zero mean and σ_V^2 variance. The rate at first hop is expressed as $C_{SV_k^l} = \log_2(1 + \gamma_{SV_k^l})$, where, $\gamma_{SV_k^l} = P|h_{SV_k^l}|^2/\sigma_V^2$ is the received SNR at V_k^l.

Likewise, the received signal at the destination is expressed as:

$$y_{V_k^l D} = \sqrt{P} h_{V_k^l D} x_V + n_D \quad (2)$$

where, x_V is the transmitted signal from V_k^l and n_D represents the AWGN at D having zero mean and σ_D^2 average SNR. $h_{V_k^l D}$ is the channel between V_i and D. $h_{V_k^l D}$ is an i.i.d complex random variable having zero mean and $\bar{\gamma}_{SV_k^l}$ variance. The rate of $V_k^l D$ link is $C_{V_k^l D} = \log_2(1 + \gamma_{V_k^l D})$, where $\gamma_{V_i D} = P|h_{V_k^l D}|^2/\sigma_D^2$ is the received SNR at D.

In a time slot t, a virtual relay V_k^l is selected either for reception or transmission of data. If V_k^l is selected for reception, it receives data from S and stores it in its buffer. If V_k^l is selected for transmission, it transmits from its buffer. In case no relay is selected, it is considered as an outage event.

III. VIRTUAL LINK RELAY SELECTION (VLRS) SCHEME

Our proposed virtual relaying scheme combines the existing buffer-aided cooperative system model proposed in [5], [6], [8], and [10] with the virtual relaying. The proposed virtual link relay selection (VLRS) scheme is based on a two stage selection process given as follows:

1) STAGE 1: KNOWLEDGE ACQUISITION AT THE RELAYS

The proposed scheme follows a distributed method for the selection of the best link from both hops. For the link selection, the following assumptions are made for the relay reception and transmission. A relay with a full buffer cannot receive the data and a relay with an empty buffer cannot transmit the data. The $S \rightarrow V_k^l$ link is considered contributive if its corresponding buffer is not full, i.e., $\psi(V_k^l) \neq 1$. The $V_k^l \rightarrow D$ link is considered contributive if its corresponding buffer is not empty, i.e., $\psi(V_k^l) \neq 0$. Each buffer is initially empty, i.e., $\psi(V_k^l) = 0$. When a virtual relay is selected for reception, $\psi(V_k^l)$ is incremented by 1 and when it is selected for transmission, $\psi(V_k^l)$ is decremented by 1. The relays with unavailable corresponding links will not take part in the best link selection of stage 1.

At this stage, S broadcasts a reference signal to all the relays. Using this reference signal, each virtual relay individually estimates the rate $C_{SV_k^l}$ between itself and S. Then each node starts its timer whose duration is inversely proportional to its rate. The relay with the highest rate has shortest timer duration. As soon as the shortest timer expires, the corresponding relay sends a signal to all nodes declaring its rate. All other nodes, back off when they hear the signal from another relay. In this way, the relays can decide by themselves that which relay is the best for data reception.

Similarly, for the best link selection of the second hop, each virtual relay sends a reference signal to D using its associated antennas in different time slots. Using the aforementioned shortest timer approach, relays decide which one is the best for data transmission.

2) STAGE 2: BEST RELAY SELECTION

Now, the full knowledge of both hops is known at the relays and a relay can decide whether itself is the best, and if so, whether it is the best for data reception or for data transmission in a particular time slot. A flag signal is sent to all nodes in the network by the selected relay to inform them that it is chosen for reception or transmission. Mathematically, the selected relay is expressed as:

$$V_k^l * = \arg\max_{V_k^l \in V} \left\{ \bigcup_{V_k^l:\Psi(V_k^l)\neq 1} C_{SV_k^l} \bigcup_{V_k^l:\Psi(V_k^l)\neq 0} C_{V_k^l D} \right\}. \quad (3)$$

Where, V_k^l* is the selected relay. In the VLRS scheme, link quality is used as the only metric for the selection of the best relay. The best relay for reception and the best relay for transmission of data is dynamically selected among all contributive links on both sides. Specifically, in a time slot t, it selects the strongest link among all contributive $S \rightarrow V$ or $V \rightarrow D$ links for relay reception or transmission, respectively. Therefore, in terms of virtual relaying, if $S \rightarrow V_k^l$ link is the strongest, the source transmits and the data is decoded at the relay and stored in the corresponding buffer. The probability $p_{S\rightarrow V_k^l}$ of data reception from the source to the selected virtual relay is mathematically expressed as:

$$p_{S\rightarrow V_k^l} = \frac{\left[1-\left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{SV_k^l}}}\right)^{N_r}\left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{V_k^l D}}}\right)^{N_t}\right]}{N_r+N_t}. \quad (4)$$

On the other hand, when $V_k^l \rightarrow D$ link is the strongest, the corresponding virtual relay transmits from its buffer. The probability $p_{V_k^l\rightarrow D}$ of data transmission from the selected virtual relay to the destination is mathematically expressed as:

$$p_{V_k^l\rightarrow D} = \frac{\left[1-\left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{SV_k^l}}}\right)^{N_r}\left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{V_k^l D}}}\right)^{N_t}\right]}{N_r+N_t}. \quad (5)$$

The system is considered in an outage when none of the relays is selected for reception or transmission, i.e., $V_k^l* = 0$. The outage is mathematically expressed as:

$$p_{out} = \left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{SV_k^l}}}\right)^{N_r}\left(1-e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{V_k^l D}}}\right)^{N_t}. \quad (6)$$

The VLRS scheme selects among V links from $S \rightarrow V$ and V links from $V \rightarrow D$ hops. Hence, the complexity of the proposed scheme is $\mathcal{O}(2V)$.

A. OUTAGE PROBABILITY ANALYSIS

The outage is defined as the probability that the instantaneous rate falls below the predefined rate r_0 $(bits/s/Hz)$. To analyze the outage probability of the proposed schemes, we model the possible states of the buffer and the transition between the states as a Markov chain. For the asymmetric buffers with virtual relaying, the Markov chain used in [6] is applied with the following modifications. In the proposed setup, the total number of available states are 2^L, where $L = L_1 + \cdots + L_K$. A state of a MC is represented by $s_j \triangleq (\Psi_j(V_1^1) \cdots \Psi_j(V_1^{L_1}) \; \Psi_j(V_2^1) \cdots \Psi_j(V_2^{L_2}) \cdots \Psi_j(V_K^{L_K}))$, where, $j \in \mathbb{N}^+$, $1 \leq j \leq 2^L$. Let $A \in \mathbb{R}^{2^L\times 2^L}$ denote the state transition matrix of the MC. Each entry $A_{ij} = P(s_j \rightarrow s_i) = P(X_{t+1} = s_i|X_t = s_j)$ in A is a transition probability to move from state s_j at time t to state s_i at time $(t+1)$. The transition probability depends on the status of virtual relay buffer. A virtual relay with a full or empty buffer $(\Psi(V_k^l) = 1$ or $\Psi(V_k^l) = 0)$ cannot receive or transmit data, respectively. Therefore, only one link is offered in both cases for the selection process. When $\Psi(V_k^l) = 1$, $V_k^l \rightarrow D$ is contributive and $S \rightarrow V_k^l$ is non contributive. Otherwise, $S \rightarrow V_k^l$ is contributive and $V_k^l \rightarrow D$ is non contributive. Consequently, the total number of contributive links which participate in the proposed link selection process are L.

The entries of A_{ij} are represented by:

$$A_{ij} = \begin{cases} p_{out}^{s_j}, & \text{if } s_i = s_j, \\ p_{S\to V_k^l}^{s_j}, & \text{if } s_i \in U_{S\to V_k^l}^{s_j} \\ p_{V_k^l\to D}^{s_j}, & \text{if } s_i \in U_{V_k^l\to D}^{s_j}, \\ 0, & \text{elsewhere}, \end{cases} \tag{7}$$

where, $U_{S\to V_k^l}^{s_j}$ and $U_{V_k^l\to D}^{s_j}$ are the sets containing all the states to which s_j can move when $S \to V_k^l$ and $V_k^l \to D$ link is selected, respectively. $p_{S\to V_k^l}^{s_j}$ and $p_{V_k^l\to D}^{s_j}$ are taken from (4) and (5), respectively. Considering MC as column stochastic, irreducible and aperiodic, the steady state probability vector is obtained as [21]:

$$\pi = (A - I + B)^{-1} b, \tag{8}$$

where, $\pi = [\pi_1, ..., \pi_{2^L}]^T$, $b = [1, 1, ..., 1]^T$ and $B_{ij} = 1, \forall\ i, j$ and $I \in \mathbb{R}^{2^L\times 2^L}$ is the identity matrix. According to the construction of MC, an outage occurs when there is no change in the buffer status. Hence, the outage probability of the system is expressed as [6]:

$$P_{out} = \sum_{i=1}^{L} \pi_i p_{out}^{s_i} = \text{diag}(A)\pi. \tag{9}$$

B. DIVERSITY GAIN ANALYSIS

The diversity gain is defined as [23]:

$$d = -\lim_{\bar{\gamma}\to\infty} \frac{\log P_{out}}{\log \bar{\gamma}}, \tag{10}$$

where, $\bar{\gamma}$ is the average SNR. Directly substituting (9) in (10) does not explicitly show the diversity gain. Instead, we use (6) to derive the diversity gain. Since the total number of contributive links in any time slot is $L = L_1 + L_2 + \cdots + L_K$. Therefore, the probability that all contributive links are in the outage is defined as:

$$P_{out} = \left(1 - e^{-\frac{2^{2r_0}-1}{\bar{\gamma}}}\right)^L. \tag{11}$$

The diversity gain is derived as:

$$d = -\lim_{\bar{\gamma}\to\infty} \frac{\left(1 - e^{-\frac{2^{2r_0}-1}{\bar{\gamma}}}\right)^L}{\log \bar{\gamma}}. \tag{12}$$

Using the approximation: $x \to 0$, then $1 - e^x \approx x$, the diversity gain becomes:

$$d \approx -(L) \lim_{\bar{\gamma}\to\infty} \frac{\log(\frac{2^{2r_0}-1}{\bar{\gamma}})}{\log \bar{\gamma}} = L. \tag{13}$$

Here, it is to note that the proposed virtual relaying design achieves the diversity gain of L at $L \geq 1$, whereas, in the MLRS scheme, the full diversity gain is achieved at an infinite buffer size. This is because the proposed design mimics the traditional (buffer-less) relay selection scheme. In a traditional scheme, the diversity gain is equal to the number of relays. In the VLRS scheme, each buffer location is considered as a virtual relay, therefore, the diversity gain is equal to the number of virtual relays. This is because the number of contributive links do not change. The buffer size of a virtual relay is 1. When V_k^l is empty, its $V_k^l \to D$ link is unavailable. On getting a packet in its buffer, its $S \to V_k^l$ link becomes unavailable and $V_k^l \to D$ link becomes contributive. Thus, the number of contributive links stays constant all the time.

C. AVERAGE END-TO-END DELAY ANALYSIS

In this section, we analyze the average end-to-end packet delay of the proposed scheme. The packet delay is the time required by the packet to reach the destination after it leaves the source node. According to the proposed scheme, the packet delay includes the delay at the source and the delay at the virtual relay denoted by D_s and D_v, respectively. The delay at the source node is derived in [14] as:

$$D_s = \frac{1 + P_{out}}{1 - P_{out}}. \tag{14}$$

We derive the average delay at the virtual relay using Little's law [22] defined as:

$$D_v = \frac{\bar{V}_v}{\bar{\eta}_v}, \tag{15}$$

where, $\bar{V}_v$ and $\bar{\eta}_v$ are the average queuing length and the average throughput at V_k^l, respectively. To derive the average queuing length, we consider all the virtual buffers at relay R_k as one buffer. Since only one packet is transmitted per time slot, therefore, it takes $\sum_{l=1}^{L_k} V_k^l$ time slots to transmit the packets stored in the buffer. The average queuing length at R_k at a particular state s_j is obtained as:

$$L_{eq}^{s_j} = \sum_{l=1}^{L_k} V_{k^l}^{s_j}. \tag{16}$$

The average queuing length over all the states is expressed as:

$$\bar{V}_v = \sum_{j=1}^{2^L} \pi_j L_{eq}^{s_j}. \tag{17}$$

The average throughput at virtual relay V_k^l is given by [9]:

$$\bar{\eta}_v = \frac{1}{2L}(1 - P_{out}). \tag{18}$$

Substituting (17) and (18) into (15), we get:

$$D_v = \frac{2L\ \sum_{j=1}^{2^L} \pi_j L_{eq}^{s_j}}{1 - P_{out}}, \tag{19}$$

hence, the packet delay D is

$$\begin{aligned} D &= D_s + D_v \\ &= \frac{1 + P_{out}}{1 - P_{out}} + \frac{\sum_{j=1}^{2^L} \pi_j \psi_j(V_k^l = 1)}{\frac{1-P_{out}}{2L}}. \end{aligned} \tag{20}$$

TABLE 1. State representation of Markov Chain for $K = 2$, $L_1 = 2$ and $L_2 = 3$.

States	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
Buffer status	00000	00001	00010	00011	00100	00101	00110	00111	01000	01001	01010	01011	01100	01101	01110	01111
States	s_{17}	s_{18}	s_{19}	s_{20}	s_{21}	s_{22}	s_{23}	s_{24}	s_{25}	s_{26}	s_{27}	s_{28}	s_{29}	s_{30}	s_{31}	s_{32}
Buffer status	10000	10001	10010	10011	10100	10101	10110	10111	11000	11001	11010	11011	11100	11101	11110	11111

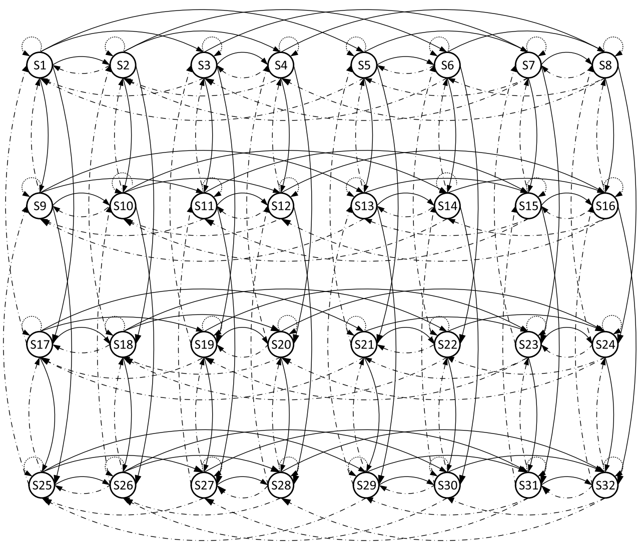

FIGURE 3. State diagram of MC for $K = 2$, $L_1 = 2$ and $L_2 = 3$.

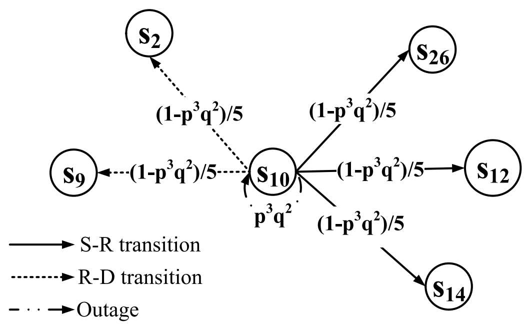

FIGURE 4. Specific example of VLRS scheme for state s_{10} when $L_1 = 2$ and $L_2 = 3$.

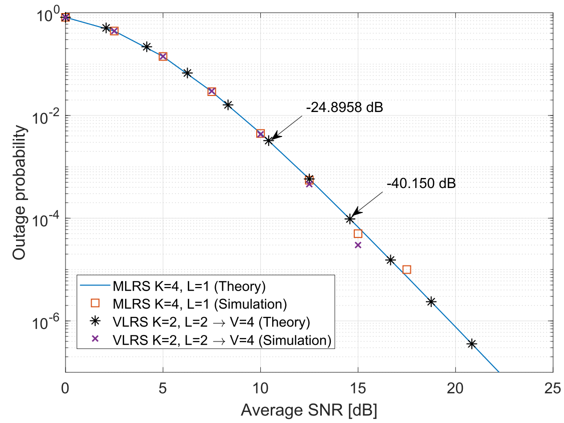

FIGURE 5. The outage probability of MLRS and VLRS schemes for $K = 2$ and $N_R = L = 2$ against SNR of the transmitted signal.

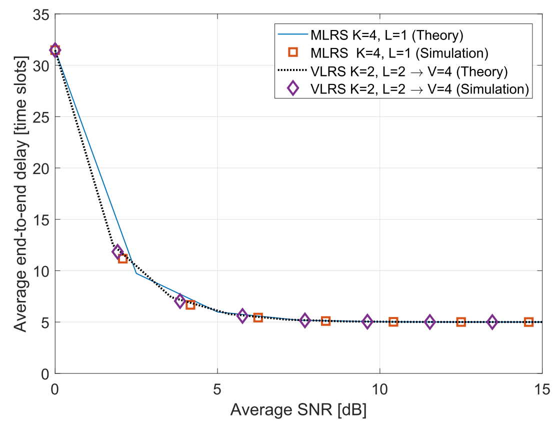

FIGURE 6. Average end-to-end delay of MLRs and VLRS schemes for $K = 2$ and $L = 2$ against average SNR of the transmitted signal.

D. NUMERICAL EXAMPLE

In this section, we present a specific example of the proposed design with a simple topology of $K = 2$ and $L_{max} = 3$. L_{max} is the maximum value of the buffer size for all relays. Let the size of L_1 and L_2 be 2 and 3, respectively. The total number of states of the Markov chain are $2^{(L_1+L_2)} = 32$. The state representation of the Markov chain is given in Table 1. Each state of the MC represents the buffer status of all the virtual relays. In Fig. 3, the black solid lines represent the transition when $S \rightarrow V$ hop is activated, while the black dashed lines represent the transition when $V \rightarrow D$ hop is activated. Both, the solid and dashed lines form a Markov state transition matrix.

To elaborate the construction of the state transition matrix, we present the example of transitions from specific state s_{10} in Fig. 4. The state s_{10} represents 01001. It shows that V_1^2 and V_2^3 have full buffers while V_1^1, V_2^1 and V_2^2 have empty buffers. Thus, there are 3 contributive links on the $S \rightarrow V$ side and 2 contributive links on the $V \rightarrow D$ side. The state s_{10} can transit to states s_2 and s_9, each with the probability $\frac{1-p^3q^2}{5}$ when $V \rightarrow D$ link is selected. Similarly, the state s_{10} can transit to states s_{12}, s_{14} and s_{26} when $S \rightarrow V_k^l$ link is selected each with the probability $\frac{1-p^3q^2}{5}$. Where, p and q are the link outages of $S \rightarrow V_k^l$ and $V_k^l \rightarrow D$, hops respectively. They are defined as; $p = (1 - e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{SV_k^l}}})$ and $q = (1 - e^{-\frac{2^{2r_0}-1}{\bar{\gamma}_{V_k^l D}}})$. A state s_{10} stays at s_{10} when no relay is selected for transmission or reception i.e., an outage event.

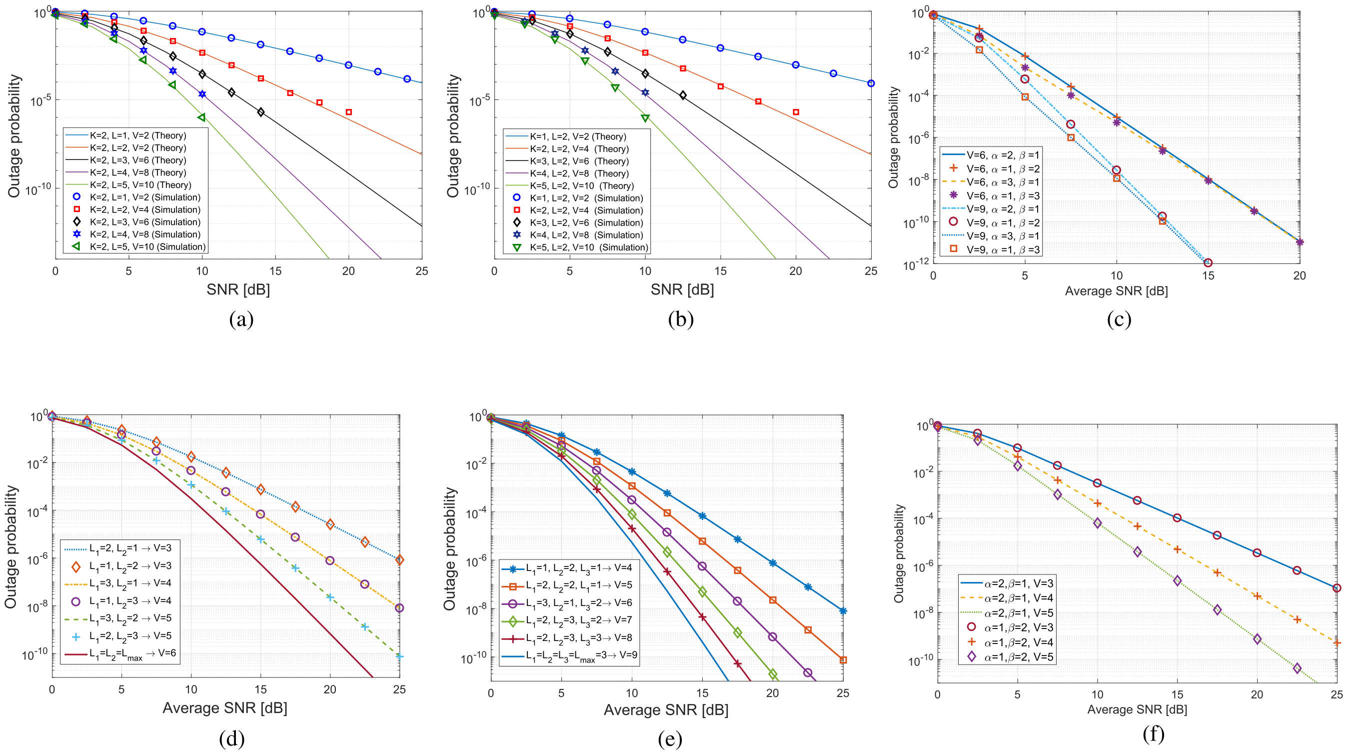

FIGURE 7. **Outage probability of the proposed scheme for symmetric and asymmetric buffer size and channel condition for variable virtual relays against SNR of the transmitted signal. (a) Symmetric buffer size and symmetric channels, $K = 2$ and variable buffer $L = 1, 2, 3, 4, 5$. (b) Symmetric buffer size and symmetric channels. Variable relays $K = 1, 2, 3, 4, 5$ and fixed buffer $L = 2$. (c) Symmetric buffer size and asymmetric channels. (d) Asymmetric buffer size and symmetric channels, $L_{max} = 3, K = 2$. (e) Asymmetric buffer size and symmetric channels, $L_{max} = 3, K = 3$. (f) Asymmetric buffer size and asymmetric channels, $L_{max} = 3, K = 3$.**

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed virtual relaying protocol for the outage probability, average end-to-end delay and average throughput. The proposed scheme is compared with the MLRS scheme presented in [6]. The results are presented for both theory and simulation. The parameter, r_0 is set to 1 bits/sec/Hz throughout. We provided comprehensive set of simulations for all the four cases of symmetric and asymmetric channel conditions and buffer sizes. For the symmetric channel conditions $\bar{\gamma}_{SV_k^l} = \bar{\gamma}_{V_k^l D} = \bar{\gamma}$ and for the asymmetric channel conditions $\bar{\gamma}_{SV_k^l} = \alpha\bar{\gamma}, \bar{\gamma}_{V_k^l D} = \beta\bar{\gamma}$, where α and β are positive real constants. For the symmetric buffer size $L_1 = L_2 = \cdots = L_K = L$ and for the asymmetric buffer size $L_1 \neq L_2 \neq \cdots \neq L_K$.

Fig. 5 shows the outage probability of the proposed VLRS scheme and the existing MLRS scheme against the average SNR. In order to have fair comparison, we set $K = 4$ and $L = 1$ for the MLRS scheme. It is seen that both schemes show identical performance. The MLRS scheme uses 4 relays while the VLRS scheme uses only 2 relays each with a buffer size of 2 to have the same outage probability performance. The virtual relaying paradigm mimics the MLRS system model, however, the same diversity gain can be achieved using less number of relays. Hence, the cost of relays is saved. Increasing the buffer size is not as costly as increasing the number of relays. Moreover, the diversity gain of the VLRS scheme is $(40.15 - 24.90)/(14.59 - 10.43) = 3.67$, that is close to 4. It concludes that the proposed virtual relaying design achieves a diversity gain of V. The theoretical results are presented using (6) and the simulation results are presented using extensive Monte Carlo simulations for 1,000,000 runs. The results of theory and simulations show good agreement with each other that confirm our analysis. Since theory and simulations are well-matched, we only plot theoretical results for rest of the analysis.

The average end-to-end delay of the proposed VLRS scheme and the MLRS scheme is presented in Fig. 6. Like the outage probability, the delay of both schemes is also the same. The delay approaches $1 + V$ for the VLRS scheme and $1 + KL$ for the MLRS scheme. The increase in the number of relays increases the delay. Thus it is concluded that, with the virtual relaying design, we can achieve the less delay using the less number of relays. The theoretical results are plotted using (20). The theory and simulations are in agreement with each other which validates the proposed scheme.

To further enhance the analysis, Fig. 7 presents the outage probability of the proposed scheme against the average SNR for all the cases of symmetric and asymmetric channel conditions and buffer sizes. The results are shown for increasing the number of virtual relays. For the symmetric buffer size and channel conditions, Fig. 7a presents the results when the

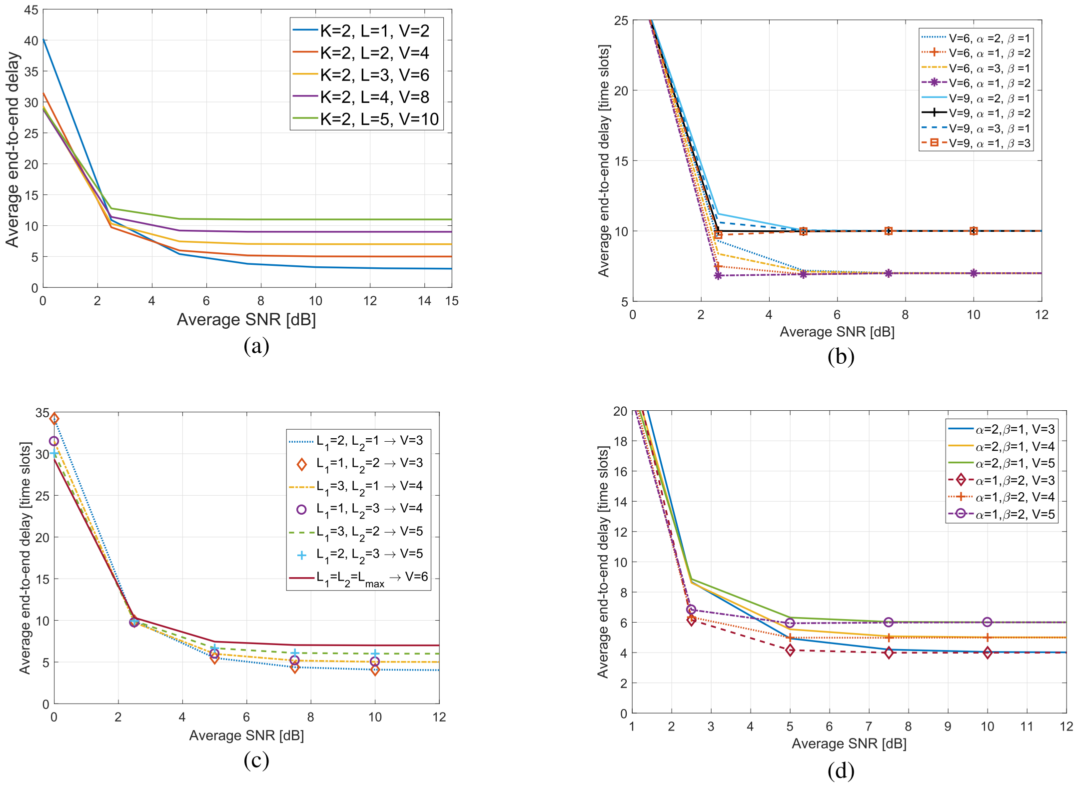

FIGURE 8. **Average end-to-end delay of the proposed scheme against SNR of the transmitted signal. (a) Symmetric buffer size and symmetric channels. (b) Symmetric buffer size and asymmetric channels. (c) Asymmetric buffer size and symmetric channels. (d) Asymmetric buffer size and asymmetric channels.**

number of relays is kept constant and the buffer size is varied from $1-5$. Similarly, Fig. 7b shows the results for variable number of relays at a fixed buffer size. For a symmetric buffer size, the number of virtual relays is $V = KL$. It is observed that when the number of virtual relays, i.e., V is same, the outage probability is the same irrespective of the variable buffer size or the number of relays. It depends on the application, whether to increase the number of relays or the buffer size. Thus, we can obtain a similar diversity gain using less number of relays. Moreover, increasing V decreases the outage probability.

In Fig. 7c, we present the results of the proposed scheme for the asymmetric channel conditions. In this plot, we present four scenarios i.e., $(\alpha, \beta) = (1, 2), (1, 3), (2, 1), (3, 1)$. When $\alpha = 2$ and $\beta = 1$, $S \rightarrow V$ is prioritized over $V \rightarrow D$ hop. Switching the values $\alpha = 2$ and $\beta = 1$ prioritizes $V \rightarrow D$ hop over $S \rightarrow V$ hop. In both cases, the outage probability is the same. This is because the relay selection is based on the channel quality only and the selection probability of both hops are equally likely. Increasing α to 3 slightly improves the outage probability, however, the results are asymptotically the same. A similar behavior is observed when virtual relays are increased from 6 to 9. Moreover, it is observed that the symmetric channel conditions have the better outage probability than the asymmetric channel conditions.

Figs. 7e, 7d and 7f show the case when the buffer size is not the same at all relays. We consider the case when $L_1 \neq L_2 \neq \cdots \neq L_K$. Let L_{max} be the maximum size of the buffer a relay can have. Now there are L_{max}^K possible combinations of the buffer size. For example, when $K = 2$ and $L_{max} = 2$, the buffer size combinations are $(L_1, L_2) = (1, 1), (1, 2), (2, 1)$ and $(2, 2)$. Next, we present the outage probability of the proposed scheme for $L_{max} = 3$ and $K = 2$ and 3 in Figs. 7d and 7e. In both Figures, it is seen that the asymmetric buffer size shows the increased outage probability as compared to the symmetric buffer size. This is because, the diversity gain is directly dependent on the number of virtual relays. The smaller the buffer size, the less will be the number of virtual relays. In the case of asymmetric buffer size, $V = L$ where, $L = L_1 + L_2 + \cdots + L_K$. Moreover, for virtual relaying system, the combinations, e.g., $(L_1, L_2) = (2, 1), (1, 2)$ produce identical results because both combinations make the same number of virtual relays. Therefore, we only consider one combination for the rest of the results. Fig. 7c shows the outage probability of the proposed scheme for $L_{max} = 3$ and $K = 3$. $(\alpha, \beta) = (2, 1), (3, 1)$ is considered to prioritize $S \rightarrow V$ hop and $(\alpha, \beta) = (1, 2), (1, 3)$ to prioritize $V \rightarrow D$ hop. It is seen that the asymmetric channel conditions and buffer size show increase in the outage probability as compared to the symmetric channel conditions and buffer size. This is because

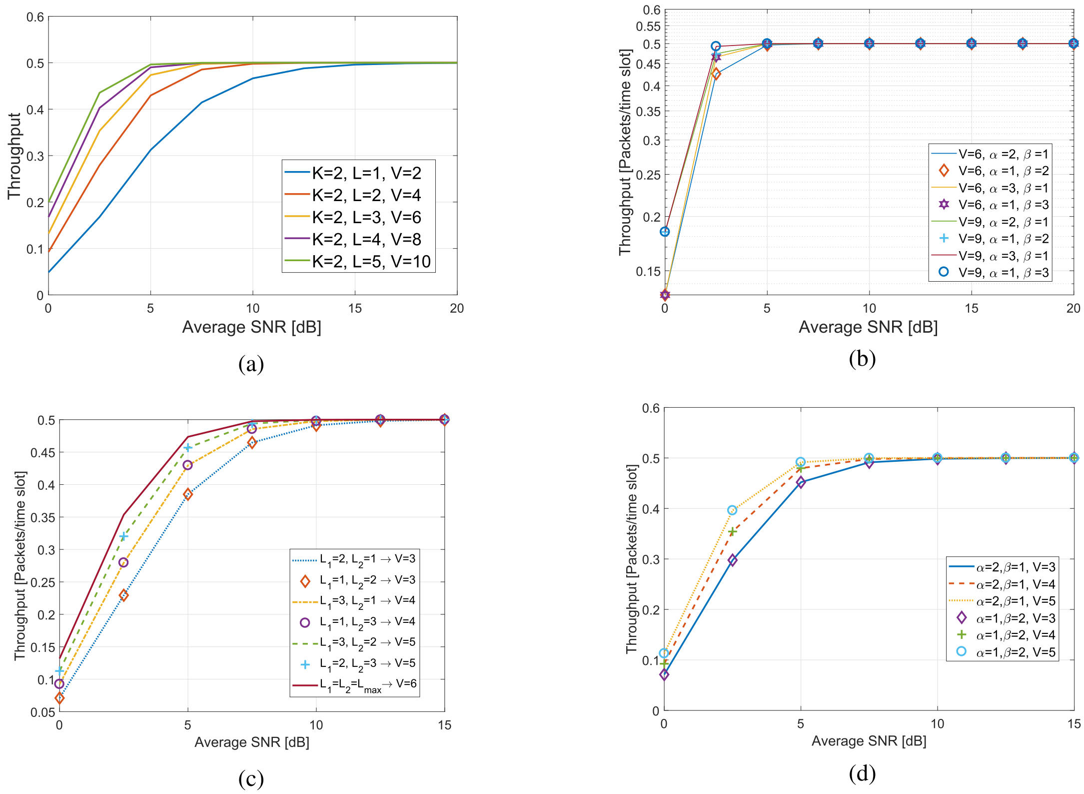

FIGURE 9. **Throughput of the proposed scheme against SNR of the transmitted signal. (a) Symmetric buffer size and symmetric channels. (b) Symmetric buffer size and asymmetric channels. (c) Asymmetric buffer size and symmetric channels. (d) Asymmetric buffer size and asymmetric channels.**

the asymmetric buffer size decreases the number of virtual relays as compared to the symmetric buffer size. And in the symmetric channel conditions, when any of the side is given priority, the selection probability of that side increases, because its SNR increases by a factor of α or β. The increased selection probability of $S \rightarrow V$ hop or $V \rightarrow D$ hop leads to the problem of full or empty buffers, respectively. It reduces the number of contributive links and therefore, the outrage probability is increased.

A. AVERAGE END-TO-END DELAY

Fig. 8 shows the average end-to-end delay of the proposed scheme against the average SNR for all the four cases of symmetric and asymmetric channel conditions and buffer sizes. The results are plotted for the different number of virtual relays.

Fig. 8a and Fig. 8c show the average end-to-end delay of the proposed scheme for the symmetric channel conditions with symmetric and asymmetric buffer sizes, respectively. It is observed that the delay approaches the theoretical bound of $1 + V$ at high SNR in both cases. The relay selection is based only on the instantaneous strength of the wireless link therefore, increasing V increases the delay as it decreases the probability of selecting particular $V \rightarrow D$ hop. There is a performance trade-off between the diversity gain and delay. A better diversity gain is achieved at the cost of increased delay. When the channel conditions are asymmetric, i.e., Fig. 8b and Fig. 8d, it is observed that prioritizing $V \rightarrow D$ hop over $S \rightarrow V$ hop reduces the average delay at low SNR because of the high selection probability of $V \rightarrow D$ hop. It allows to select $V \rightarrow D$ hop whenever its link is contributive, thus keeping the packet waiting time in the buffer as short as possible. For example, in Fig. 8b, when $V = 3$, $(\alpha, \beta) = (1, 2)$ shows the less delay as compared to $(\alpha, \beta) = (2, 1)$. At high SNR, the delay approaches to $1 + V$. The delay is asymptotically same regardless of the prioritization of both hops. Moreover, increasing the number of virtual relays, increases the delay. Furthermore, the delay of asymmetric channels is less as compared to the delay of symmetric channels at low SNR.

B. AVERAGE THROUGHPUT

Fig. 9 shows the average throughput of the proposed scheme with respect to average SNR for all the cases of symmetric and asymmetric channel conditions and buffer sizes. The results are presented for varying number of virtual relays.

It is observed in all cases that the maximum throughput achieved by the proposed scheme is not more than 0.5 BPCU. This is because the packet takes a minimum of two time slots to reach the destination. Increasing the number of relays improves the throughput. In the case of asymmetric buffer size (Fig. 9c), the combinations, e.g., $(L_1, L_2) = (1, 2)$ produces the same throughput as $(L_1, L_2) = (2, 1)$ because both combinations make the same number of independent virtual relays. In the case of asymmetric channel conditions (Figs. 9b and 9d), the combinations e.g. $(\alpha, \beta) = (1, 2)$ produces the same throughput as $(\alpha, \beta) = (2, 1)$ because the relay selection is dependent on the channel quality only.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed and investigated a buffer-aided relay selection system based on the concept of virtual relaying. It is concluded that the proposed virtual relay design considerably increases the diversity gain using a small number of relays. The diversity gain is not only dependent on the number of relays, but also on the buffer size. The same diversity gain is achieved by either increasing the number of relays keeping the buffer size constant or increasing the buffer size keeping the number of relays constant. Furthermore, the symmetric channel conditions and buffer sizes perform better as compared to the asymmetric case. As a performance trade-off, the proposed design does not achieve a full diversity gain, i.e., $2L$, where $L = L_1 + L_2 + \cdots + L_K$. Also, the design with random access buffers and virtual relaying, the overhead of processing at the relay node increases because each buffer location has to share its respective relay node resources.

In the future, we plan to explore the virtual relaying design for amplify and forward relaying.

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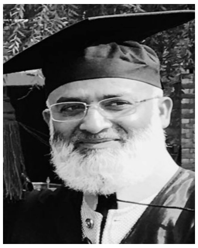
HINA NASIR received the B.S. degree in information and communication systems engineering from the School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad, in 2008, and the M.S. degree in computer science from International Islamic University, Islamabad, in 2015, under the supervision of Dr. N. Javaid, where she is currently pursuing the Ph.D. degree in computer science under the same supervision. Her research interests include cooperative communication, energy harvesting, Internet of Things, and WSNs. She was a recipient of the University Gold Medal.



NADEEM JAVAID (S'08–M'11–SM'16) received the bachelor's degree in computer science from Gomal University, Dera Ismail Khan, in 1995, the master's degree in electronics from Quid-I-Azam University, Islamabad, Pakistan, in 1999, and the Ph.D. degree from the University of Paris-Est, France, in 2010. He is currently an Associate Professor and the Founding Director of the Communications over Sensors Research Lab, Department of Computer Science, COMSATS University Islamabad, Islamabad. He has supervised 12 Ph.D. and 85 master's theses. He has authored over 650 articles in technical journals and international conferences. His research interests include energy optimization in smart grid clouds and in Internet of Things-enabled wireless sensor networks, and big data analytics in smart grids. He received the Best University Teacher Award from the Higher Education Commission of Pakistan in 2016 and the Research Productivity Award from the Pakistan Council for Science and Technology in 2017. He is also an Associate Editor of the IEEE ACCESS JOURNAL and an Editor of the *International Journal of Space Based and Situated Computing*.

WASEEM RAZA received the B.S. and M.S. degrees in telecommunication engineering from the University of Engineering and Technology, Taxila, in 2016 and 2014, respectively, under the supervision of Dr. N. Javaid. He is currently a Lecturer with the Department of Technology, The University of Lahore, Lahore. He is also a Research Associate with the ComSens Lab, Computer Science Department, COMSATS University, Islamabad, with Dr. N. Javed. His research interests include wireless communication, signal processing, communication theory, RF energy harvesting, and wireless cooperative communication.

MOHSEN GUIZANI (S'85–M'89–SM'99–F'09) received the B.S. (Hons.) and M.S. degrees in electrical engineering and the M.S. and Ph.D. degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He was an Associate Vice President of graduate studies with Qatar University; the Chair of the Computer Science Department, Western Michigan University; and the Chair of the Computer Science Department, University of West Florida. He is currently a Professor and the Electrical and Computer Engineering Department Chair with the University of Idaho, USA. He held academic positions with the University of Missouri-Kansas City, University of Colorado Boulder, Syracuse University, and Kuwait University. He has authored nine books and more than 500 publications in refereed journals and conferences. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grid. He also served as a member, the Chair, and the General Chair of a number of international conferences. He is a Senior Member of ACM. He was a recipient of the teaching award for multiple times, the Best Research Award for three times, and the Wireless Technical Committee's Recognition Award in 2017. He is currently the EiC of the *IEEE Network* and serves on the editorial boards for several international technical journals. He was the Founder and the Editor-in-Chief of the *Wireless Communications and Mobile Computing Journal* from 2000 to 2016. He guest edited a number of special issues in IEEE journals and magazines. He was the Chair of the IEEE Communications Society Wireless Technical Committee and the TAOS Technical Committee. He served as the IEEE Computer Society Distinguished Speaker from 2003 to 2005.

NABIL ALRAJEH received the Ph.D. degree in biomedical informatics engineering from Vanderbilt University, USA. He was a Senior Advisor for the Ministry of Higher Education, where his role was in implementing development programs, including educational affairs, health information systems, strategic planning, and research and innovation. He is currently a Professor of health informatics with the Biomedical Technology Department, King Saud University. His research interests include E-health applications, hospital information systems, telemedicine, intelligent tutoring systems, energy management in smart grids, and wireless sensor networks.

MOHAMAD SOUHEIL ALABED is currently an Associate Professor with the Biomedical Technology Department, College of Applied Medical Sciences, King Saud University, Riyadh, Saudi Arabia.