Virtual Full-Duplex Relaying in a Buffer-Aided Multi-Hop Cooperative Network

Ashish Kant Shukla
Bharti School of Telecommunication Technology and Management
Indian Institute of Technology Delhi
New Delhi, India
Email: ashish2015007@gmail.com

B. R. Manoj
Department of Electrical Engineering (ISY)
Linköping University
Linköping, Sweden
Email: br.manoj@gmail.com

Manav R. Bhatnagar
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India
Email: manav@ee.iitd.ac.in

***Abstract*—In this paper, we propose a virtual full-duplex (VFD) multi-hop cooperative relaying network using buffer-aided half-duplex (HD) relays. Firstly, for a given multi-hop network, the links are partitioned into three groups and then information is transmitted over a single time slot using two selected best links, which enhances the network coverage and reliability of the system. The Markov chain approach is used to analyze the state transition matrix which models the evolution of buffer states. An analytical expression of steady state probability is obtained, using which the outage probability of the system is evaluated. Numerical results validate our analytical findings and it shows that the proposed relaying scheme offers a better outage performance as compared to that of the conventional buffer-aided max-link relay selection scheme in a multi-hop communication system.**

Index Terms– Decode-and-forward (DF), Markov chain (MC), max-link relay selection, outage probability, virtual full-duplex (VFD).

I. Introduction

Buffer-aided cooperative networks improve throughput, diversity, and reliability as compared to the conventional decode-and-forward (DF) cooperative relaying networks [1]. It also gives us the flexibility of scheduling the data packets. The majority of study in a cooperative relaying network is on half-duplex (HD) relaying because of its simplicity in implementation. The HD operation occurs in two time phases, the source node transmits information to the relay node in the first phase, while the relay node forwards it to the destination in the next phase [2], [3]; as transmission occurs in two time phases the overall data rate gets reduced. To overcome this, full-duplex (FD) relaying is a possible solution which allows a relay to receive and transmit data at the same time thereby increasing the data rate. However, due to the interference between the nodes, FD is practically difficult to implement [4]. In [5], a multi-hop diversity network is studied in which the transmission takes place through the best selected link among all the available links. It improves the link performance and communication range. However, in most of the available literature [6], [7] a single link is selected to transmit the data which leads to the reduction of diversity gain. Due to the constraints of HD several FD counterparts such as virtual full-duplex (VFD) and successive relaying have been proposed in [8]–[10]. A successive relaying for a buffer-aided network is given in [9], it uses inter-relay interference (IRI) cancellation technique and increases the energy efficiency of the system. An FD max-max relay selection scheme for cooperative DF is discussed in [10], it selects two best relays to transmit and receive data at the same time thereby mimicking the FD. In [11], the transmission is based on joint opportunistic relay selection in the presence of IRI, also the beamforming technique was used by equipping multiple antennas at each relay. A VFD relaying with multiple paths and having IRI between relays is considered in [12]. Here, the source and the selected best relay is allowed to transmit a data packet simultaneusly, hence a scenario like FD is created as a new packet is served at each time slot to the relays. In [13], a relaying scheme for an HD buffer-aided dual-hop relaying network is proposed; in the given scheme at any time slot, the source transmits a data packet to the multiple relay nodes, while only a single relay node forwards the buffered data packet to the destination. It shows better outage performance compared to [10]. However, the number of buffer states increases significantly. In [14], a relaying scheme is considered that selects two independent links for data packet transmission. It enhances the performance of a buffer-aided multi-hop communication system for an odd number of relay nodes. However, the relaying scheme in [14] is not applicable for an even number of relays. Thus motivated by this we propose a novel link selection scheme for an even number of relay nodes in a multi-hop communication system to further improve the outage performance with the enhanced network coverage. Specifically, the main contributions of the paper are as follows:

- A novel link selection scheme for buffer-aided relaying with a multi-hop cooperative network with M relay nodes of buffer size of L is proposed.
- The performance of the system is analyzed in terms of outage probability; and the proposed system is compared with the conventional buffer-aided max-link scheme and the relaying scheme that is proposed for odd number of relay nodes in [14], for a multi-hop system.

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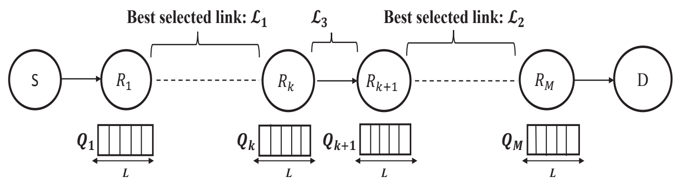

Figure 1. Multi-hop buffer-aided cooperative network with even number of relays.

- The proposed scheme outperforms the conventional max-link scheme for smaller values of buffer size. Also, it has been shown that proposed scheme can increase the range of communication for a fixed signal-to-noise ratio (SNR) in comparison to the existing scheme [14].

II. System Model

A multi-hop HD buffer-aided cooperative network is considered having a Source (S), a destination (D), and DF based M relay nodes R_m, $1 \leq m \leq M$, also the number of relay nodes are even (i.e., M is even). Each node is having a single antenna and it operates in HD mode. Also, no direct link exists between S and D because of the path loss, and the IRI between the relays is absent, the given assumption is applicable if the relays are based on some fixed infrastructure with directional antennas or if relays are separated far from each other as discussed in [10]. Furthermore, fixed relays are also of practical significance as they are low cost and low-transmit power devices. All the relay nodes are equipped with a L size data buffer which is denoted as Q_m as shown in Fig. 1. The number of packets stored at any time instant in the m-th relay buffer is denoted by the function $\psi(Q_m)$, where $0 \leq \psi(Q_m) \leq L$. It is assumed initially that all the buffers are empty and for any successful reception of data $\psi(Q_m)$ increments by one. Similarly, $\psi(Q_m)$ decrements by one for any successful transmission. The protocol to transmit data packet in the considered multi-hop communication system is given below:

1) $\psi(Q_m) = 0$, where $m \in 1 \cdots M$, the data packet can be received by the m-th relay from S or R_{m-1}.
2) $\psi(Q_m) = L$, where $m \in 1 \cdots M$, the data can be transmitted by the m-th relay to R_{m+1} or D.
3) $0 < \psi(Q_m) < L$, where $m \in 1 \cdots M$, the data packet can be received or transmitted by the m-th relay.

It is assumed that the source always have data for transmission. The fading coefficient between the i-th and the j-th nodes is denoted as h_{ij} and is modeled by independent and identically distributed (i.i.d.) circularly symmetric Gaussian random variable having zero mean and σ_{h^2} variance. We assume that the channels follow Rayleigh block fading. The signal received at any node is perturbed by additive white Gaussian noise (AWGN) with zero mean and N_0 variance. The system will work as VFD whenever data packets are transmitted through two links while it will behave as HD when a single link is getting selected for data packet transmission. The instantaneous SNR for any link is given by

$$\gamma_{ij} = |h_{ij}|^2 P_t / N_o \,, \tag{1}$$

where P_t is the transmitted power, i and j are the transmitting and the receiving nodes, respectively. The average SNR of any given link is

$$\overline{\gamma}_{ij} = \sigma_h^2 P_t / N_o \,. \tag{2}$$

Using the Shannon capacity theorem, the probability of successful transmission for a fixed rate R is given by

$$p_{_{ij}} = \Pr\left[\frac{1}{M+1}\log_2(1+\gamma_{ij}) > R\right]. \tag{3}$$

Hence, the probability for successful transmission of information can be given as

$$p_{_{ij}} = e^{-\frac{\gamma_{th}}{\overline{\gamma}_{ij}}} \,, \tag{4}$$

where, $\gamma_{th} = 2^{(M+1)R} - 1$ is the SNR threshold. Subsequently, the probability for unsuccessful transmission can be given by

$$\overline{p}_{_{ij}} = 1 - e^{-\frac{\gamma_{th}}{\overline{\gamma}_{ij}}} \,. \tag{5}$$

A. Link Selection Scheme

For the considered system model, we propose a novel link selection scheme for an even number of relays (M is even). We define R_k and R_{k+1} as the probable center relay nodes, where $k = M/2$. Relay nodes are then partitioned into three parts as:

1) Links that exist between S and R_k.
2) Links that exist between R_{k+1} and D.
3) Link that exist between R_k and R_{k+1}.

The link selection process is as follows:

- The link having highest channel gain is selected between S and R_k, which is denoted by $\mathcal{L}_1$.
- The link having highest channel gain is selected between R_{k+1} and D, which is denoted by $\mathcal{L}_2$.
- We denote the link between R_k and R_{k+1} as $\mathcal{L}_3$.
- If the channel gain of the link $\mathcal{L}_3$ is greater than either (or both) of the links $\mathcal{L}_1$ and $\mathcal{L}_2$, then we have the following cases:
  i) $\mathcal{L}_1$ is not connected to R_k and $\mathcal{L}_2$ is not connected to R_{k+1}; the selected links for data transmission are $\mathcal{L}_3$ and max$(\mathcal{L}_1, \mathcal{L}_2)$.
  ii) $\mathcal{L}_1$ is not connected to R_k and $\mathcal{L}_2$ is connected to R_{k+1}; the selected links for data transmission are $\mathcal{L}_1$ and $\mathcal{L}_3$.
  iii) $\mathcal{L}_1$ is connected to R_k and $\mathcal{L}_2$ is not connected to R_{k+1}; the selected links for data transmission are $\mathcal{L}_2$ and $\mathcal{L}_3$.
  iv) $\mathcal{L}_1$ is connected to R_k and $\mathcal{L}_2$ is connected to R_{k+1}; the selected links for data transmission are $\mathcal{L}_1$ and $\mathcal{L}_2$.
- If the channel gain of the link $\mathcal{L}_3$ is less than both the links $\mathcal{L}_1$ and $\mathcal{L}_2$, then the selected links for data transmission are $\mathcal{L}_1$ and $\mathcal{L}_2$.

In comparison to [14], we have considered an even number of relay nodes in a multi-hop network and also proposed a novel link selection scheme which is optimal for the even number of relay nodes. For a fixed relay based network, it is essential to know the performance in prior to the deployment of even or odd number of relay nodes in the network. Thus, the motivation of our work is to propose a scheme and demonstrate the performance for an even number of relay nodes in comparison to the odd number of relay nodes in a multi-hop network.

III. Outage Probability

In this section, we derive a closed-form expression of the outage probability for the considered system model. The state transition matrix that models the evolution of the relay buffer status is analyzed by an MC approach. The number of data packets in all of the relay buffers form a state of the MC at any given time. The total number of possible states for M relay nodes having a data buffer of size L will be $(L+1)^M$. For a given MC any state can be defined by

$$s_g \triangleq (\psi(Q_1)\psi(Q_2)\cdots\psi(Q_M)), \quad 1 \leq g \leq (L+1)^M. \tag{6}$$

A. State Connectivity Rule

The state transition matrix of the MC represents the connectivity between the states and is denoted by $\mathbf{A}$. The dimension of $\mathbf{A}$ is $(L+1)^M \times (L+1)^M$ and (f,g)-th entry of $\mathbf{A}$ is denoted by A_{fg}, where $f, g \in (1 \cdots (L+1)^M)$. The transition probability to move from state s_g to state s_f is given by $A_{fg} = \Pr(X_{t+1} = s_f | X_t = s_g)$. If there is no change in the state due to an outage, then the corresponding element is represented by A_{gg}. The connectivity rule for the transition from one state to another state of the buffer in the proposed relaying scheme can be given as follows:

1) For a state s_g, we define $d_g \triangleq s_f - s_g$, where $d_g(m) = 1$ and $d_g(m) = -1$ represents transmitting and receiving nodes, respectively.
2) If $d_g(1) = -1$, then transmitting node is S and it is given by $d_g(0) = 1$. Similarly, if $d_g(M) = 1$, then receiving node is D and it is denoted by $d_g(M+1) = -1$. If $d_g(1) \neq -1$ and $d_g(M) \neq 1$, then $d_g(0) = 0$ and $d_g(M+1) = 0$, respectively.
3) State transition occurs only when the condition

$$\sum_{m=0}^{M+1} d_g(m) = 0 \tag{7}$$

is satisfied. Our system is said to be in VFD mode if the pair $d_g(i) = 1$ and $d_g(j) = -1$ where $i, j \in m$ and $i \neq j$ exists on different link partitions i.e., $\{\mathcal{L}_1, \mathcal{L}_2\}$ or $\{\mathcal{L}_1, \mathcal{L}_3\}$ or $\{\mathcal{L}_2, \mathcal{L}_3\}$. It is said to be in HD if the pair exists in the same link partition, i.e., $\mathcal{L}_1$ or $\mathcal{L}_2$ or $\mathcal{L}_3$.

The available incoming link for any relay buffer Q_m is denoted by $\Psi(Q_m)$ which is mathematically expressed as:

$$\Psi(Q_m)=\begin{cases} 1, & \text{if } m=1 \text{ and } \psi(Q_m) \neq L\,, \\ 1, & \text{if } 2 \leq m \leq M-1, \psi(Q_m) \neq L, \psi(Q_{m-1}) \neq 0, \\ 0, & \text{if } 1 \leq m \leq M-1,\, \psi(Q_m) = L. \end{cases} \tag{8}$$

The incoming and the outgoing links for relay buffer Q_M is denoted as $\Upsilon(Q_M)$, which is mathematically given by

$$\Upsilon(Q_M) = \begin{cases} 1, & \text{if } \psi(Q_M) = L\,, \\ 1, & \text{if } \psi(Q_M) = 0 \text{ and } \psi(Q_{M-1}) \neq 0, \\ 2, & \text{if } 0 < \psi(Q_M) < L \text{ and } \psi(Q_{M-1}) \neq 0, \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

At any time slot, for any state s_g the number of links available between S and R_k can be given by

$$L_g = \sum_{m=1}^{k} \Psi(Q_m)\,. \tag{10}$$

Similarly the number of links available between R_{k+1} and D will be

$$R_g = \sum_{m=k+1}^{M-1} \Psi(Q_m) + \Upsilon(Q_M)\,. \tag{11}$$

Let p_a be the probability that the given link is maximum among the available N_g links, as the channels are presumed to be i.i.d., the probability p_a can be written as

$$p_a = 1/N_g\,. \tag{12}$$

Also the probability for any link to be not in outage is denoted by p_b which can be expressed as

$$p_b = 1 - \left(1 - e^{-\frac{\gamma_{th}}{\overline{\gamma}}}\right)^{N_g}, \tag{13}$$

where $\overline{\gamma}$ is the average SNR. Thus, the overall probability for successful transmission through any link can be expressed as

$$p_{N_g} = p_b / N_g\,. \tag{14}$$

B. State Transition Matrix

The successful set of transition states in VFD and HD transmission modes are denoted as F_g and H_g, respectively. Considering all the communicating states and assuming that the probability of successful transmission between S and R_k nodes is denoted by p_{L_g}; between R_k and R_{k+1} nodes is denoted by p_1 as there is only one link between R_k and R_{k+1}; and that between R_{k+1} and D nodes is denoted by p_{R_g}; where $N_g \in \{L_g, R_g\}$. The state transition matrix $\mathbf{A}$ is expressed as given below:

Case 1: When single link is selected; (f,g)-th entry is given by

$$A_{fg} = \begin{cases} p_{L_g}, \text{if } s_f \in H_g, L_g \neq 0, R_g = 0, \\ p_{R_g}, \text{if } s_f \in H_g, L_g = 0, R_g \neq 0. \end{cases} \tag{15}$$

During outage event the diagonal element A_{gg} is

$$A_{gg}=\begin{cases}\overline{p}_{L_g}, \text{if } H_g \notin \emptyset, \overline{L}_g, R_g=0,\\ \overline{p}_{R_g}, \text{if } H_g \notin \emptyset, \overline{R}_g, L_g=0,\end{cases} \tag{16}$$

where $\overline{L}_g$ denotes that the links between S and R_k are in outage, $\overline{R}_g$ denotes that the links between R_{k+1} and D are in outage, and $H_g \notin \emptyset$ denotes that the set of state transitions from s_g to s_f are in outage.

Case 2: When two links are selected; there are two ways of link selection for this case.

i) When the link between R_k and R_{k+1} is not selected: The matrix $\mathbf{A}$ for this case can be written as

$$A_{fg}=\begin{cases}p_{L_g}p_{R_g}, \text{if } s_f \in F_g, L_g \neq 0, R_g \neq 0,\\ \overline{p}_{L_g}p_{R_g}, \text{if } s_f \notin F_g, s_f \in H_g, R_g \neq 0, \overline{L}_g,\\ \overline{p}_{R_g}p_{L_g}, \text{if } s_f \notin F_g, s_f \in H_g, L_g \neq 0, \overline{R}_g\,.\end{cases} \tag{17}$$

During an outage event, $A_{gg}=\overline{p}_{L_g}\overline{p}_{R_g}$, if $F_g \notin \emptyset, H_g \notin \emptyset, \overline{L}_g, \overline{R}_g$, where $F_g \notin \emptyset$ denotes that the set of state transitions from s_g to s_f are in outage.

ii) When the link between R_k and R_{k+1} is selected: The matrix $\mathbf{A}$ can be expressed by

$$A_{fg}=\begin{cases}p_1 p_{L_g+R_g}, \text{if } s_f \in F_g, L_g \neq 0, R_g \neq 0, \mathcal{L}_3 \neq 0,\\ \overline{p}_1 p_{L_g}p_{R_g}, \text{if } s_f \in F_g, L_g \neq 0, R_g \neq 0, \overline{\mathcal{L}}_3,\\ \overline{p}_{R_g+1}P_{L_g}, \text{if } s_f \notin F_g, s_f \in H_g, L_g \neq 0, \overline{R}_g, \overline{\mathcal{L}}_3,\\ \overline{p}_{L_g+1}P_{R_g}, \text{if } s_f \notin F_g, s_f \in H_g, R_g \neq 0, \overline{L}_g, \overline{\mathcal{L}}_3,\\ \overline{p}_{L_g+R_g}p_1, \text{if } s_f \notin F_g, s_f \in H_g, \overline{L}_g, \overline{R}_g, \mathcal{L}_3 \neq 0,\end{cases} \tag{18}$$

where $\overline{\mathcal{L}}_3$ denotes that the link between R_k and R_{k+1} is in outage. If all the links are in outage, then $A_{gg}=\overline{p}_{L_g}\overline{p}_{R_g}\overline{p}_1$, if $H_g \notin \emptyset$ and $F_g \notin \emptyset$.

C. Steady State Probability

Here, we will evaluate the steady state probability of the system by using $\mathbf{A}$ of the MC. In the proposed scheme for any HD transmission unit step change occurs in only one of the partitions, while during VFD transmission change occurs in two partitions that are independent of each other. Irrespective of the state from where we have started we can transit to all the states of the MC so the MC of the proposed system is said to irreducible. Furthermore, the outage probability for any given state is non-zero so the probability to remain in any state between any time interval is also non-zero, so the MC of the system is aperiodic. Also, the sum of a column of a matrix $\mathbf{A}$ is unity hence it is column stochastic. Due to the above properties mentioned the steady state probability is given by

$$\boldsymbol{\pi}=\left(\mathbf{A}-\mathbf{I}+\mathbf{B}\right)^{-1}\mathbf{b}\,, \tag{19}$$

where $\boldsymbol{\pi}=\left[\pi_1, \pi_2, \cdots, \pi_{(L+1)^M}\right]^T$ with $\pi_g = \Pr(s_g)$, $\mathbf{b}=[\mathbf{1}, \mathbf{1}, \cdots, \mathbf{1}]^{\mathbf{T}}$, $\mathbf{I}$ is the identity matrix of dimension $(L+1)^M \times (L+1)^M$, and $\mathbf{B}$ is matrix of dimension of $(L+1)^M \times (L+1)^M$ with all elements equal to 1. For the proposed relaying model, the system is said to be in outage when it remains in the same buffer state as all the links are in outage. Considering all the buffer states and then by using (19), the outage probability expression of the considered system is given by

$$P_{out}=\sum_{g=1}^{(L+1)^M}\pi_g A_{gg}=\text{diag}(\mathbf{A})\boldsymbol{\pi}, \tag{20}$$

where diag$(\mathbf{A})$ denotes the row vector of dimension $(L+1)^M$ having all the diagonal elements of $\mathbf{A}$.

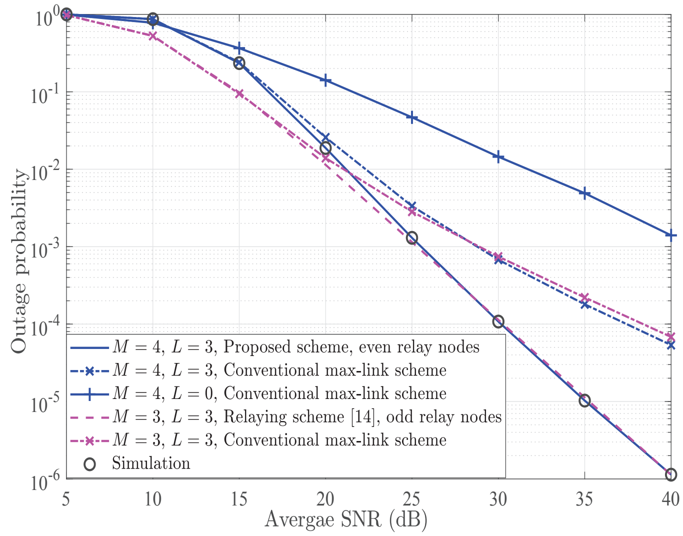

Figure 2. Outage Probability vs $\overline{\gamma}$ for $L = 3$.

IV. Results and Discussions

In this section, the performance of the proposed link selection scheme for buffer-aided multi-hop VFD networks is evaluated in terms of the outage probability and is compared with the conventional max-link scheme as well as with the link selection scheme proposed for an odd number of relay in [14]. Monte-Carlo simulations are performed of the order of 10^6 which are found to be in exact agreement with the derived numerical results. The system rate R is assumed to be unity.

In Fig. 2, the outage probability of the system is plotted against the average SNR with $L = 3$ and $M = 4$, and the obtained plots are compared with $M = 3$. It can be observed from the plot that for $L = 3$ the performance of the proposed scheme improves significantly when compared with that of the multi-hop buffer-aided DF network using conventional max-link scheme [6], [7], and with the multi-hop DF network without buffers ($L = 0$). We have compared the proposed scheme for $M = 4$ with that of the existing scheme for $M = 3$. In the figure, though γ_{th} increases with M, the proposed scheme with $M = 4$ performs similar to the existing scheme for $M = 3$ from medium to high SNR. This is advantageous in practice as with less SNR, the network coverage range can be enhanced.

Fig. 3 depicts the plot of outage probabilities versus L

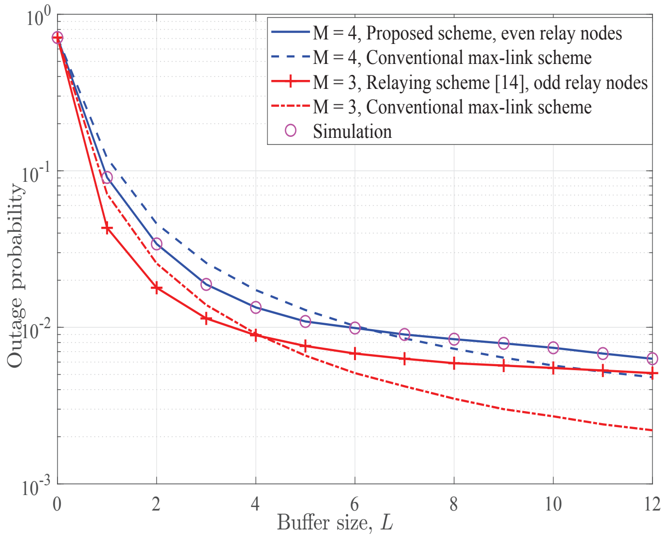

Figure 3. Outage Probability vs L for $\overline{\gamma} = 20$ dB .

for the proposed scheme with $M = 4$ and $\bar{\gamma} = 20$ dB. It can be seen from the plot that the performance of the proposed scheme improves as the buffer size increases and it is saturating for higher buffer size (i.e. L). One can also observe that at lower buffer size the outage performance of the proposed scheme is better whereas the conventional max-link scheme gives better performance at higher buffer size. This is due to the fact that for larger values of L, the probability that relay buffer is either full or empty is lower as compared to the probability of it being neither full nor empty; and for conventional max-link scheme the state transition probabilities are equiprobable whereas for the proposed scheme the failure probability of a VFD transmission is multiplied to the HD successful transmission. At low SNR, the probability of received SNR being less than γ_{th} is high, hence lower the value of M better the outage performance. However, in the medium to high SNR regime, the proposed link selection scheme for the higher value of M (i.e., M even) performs the same as that of the existing scheme for a lower value of M (i.e., M odd).

V. Conclusion

We have proposed a link selection scheme for a multi-hop HD buffer-aided cooperative network having an even number of relays. In the proposed scheme, we have partitioned links into three groups and selects two best relay links to transmit the data packet. With the help of MC approach, the expression for outage probability is obtained. The performance gain of the proposed scheme is shown with the help of analytical and simulation results and is compared with the existing HD and VFD transmission schemes. The proposed scheme performs better than current max-link scheme for smaller values of buffer size which is beneficial in practice. Also, it has been shown that our scheme can increase the range of communication for a fixed SNR in comparison to the existing scheme [14]. The proposed system setup finds application where there is a requirement of extended network coverage such as trip safety, fleet management, etc.

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