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BTRS: Buffer-Threshold Based Relay Selection Scheme for Cooperative Wireless Networks

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ABSTRACT Buffer-equipped relay selection schemes in cooperative communication offer evident performance gains in terms of the outage probability and throughput. However, it brings in the increased delay which can be reduced by increasing the selection probability of relay-to-destination links. In this paper, a controlling parameter, termed as the buffer limit, is proposed for the buffer occupancy, which modifies the selection of the corresponding (transmitting and receiving) links of the relay and also has its impact on the average delay and throughput. The probability of selecting the transmitting and receiving channels is directly controlled by reallocating the weights of links considering the buffer limit. A link having the largest weight is activated, and the corresponding relay is chosen for transmission or reception. We evaluate the outage probability, average end-to-end queuing delay, and average throughput using Markov modeling of the status of the buffers at relays. Analytical findings are studied for various values of the buffer limit and confirmed by means of the Monte Carlo simulations. The proposed scheme works as the max-weight relay selection scheme when the buffer limit is set to 1/2 of the buffer size. The suggested scheme is compared with the existing schemes. The outage probability is traded with the average end-to-end queuing delay or the average throughput by adjusting the values of the buffer limit.

INDEX TERMS Buffer-aided relay selection, outage probability, buffer-limit, Markov chain, cooperative communication, Monte-Carlo.

I. INTRODUCTION

In cooperative relaying (CR), relays help to forward the sender's signal to the receiver [1]. It improves the diversity order, throughput and network coverage [2]. It also helps to decrease the the shadowing effects by smart relay positioning and to increase the good-put [3].

The regenerative technique also called decode and forward (DF) relays process the signals like decoding, error correction and re-encoding before transmission. While, in non-regenerative technique called amplify and forward (AF), relays do not process the signal except amplifying it and forwarding to the destination. Also, relays in CR are classified on the basis of transmission modes. In full duplex mode, simultaneous transmission and reception is possible which means relays are able to simultaneously receive and send the data in time or frequency resource. In half-duplex mode, relays can not simultaneously receive and transmit signals. The count of links required in half-duplex mode is built upon the count of relays used in a cooperative system. From the perspective of the diversity order, use of more number of relays is beneficial. However, when this count is high, the more orthogonal channels is needed which reduces the multiplexing gain and spectral efficiency of CR system. Thus, a trade-off between diversity order and the spectral efficiency is observed in CR systems [6].

The loss in spectral efficiency of CR is compensated by choosing the perfect receiving or transmitting relay according to a well defined criteria. The best relay has the limitation of selecting one relay and its corresponding links [21]. While, in selection cooperation, a set containing the relays successfully decoding the packets is formed and relay with the most capable relay to destination link is selected from this set [21]. Incremental relaying is dependent on the feedback from the receiver [7]. In this approach, relays are refrained to transmit the packets that reach directly to the destination.

The traditional relaying schemes (buffer-less) choose single relay for both transmission and reception purpose. However, due to the channels impairments (fading) of the corresponding links, single relay chosen for transmission and reception does not assure the best corresponding links i.e., source-to-relay (SR) and relay-to-destination (RD). The addition of buffers at relays temporarily allows to store the received packets. It aids to select different relays, instead of a single relay, for sending or receiving purposes. When link quality is not favorable, packets remain stored in the buffers and forwarded only when they are tolerable. The losses in the multiplexing gains in traditional relaying schemes are also accommodated using buffers [8], [9].

The max-max relay selection (MMRS) scheme [10] is one of the introductory work on buffer-equipped relaying. It selects the most capable and available SR link in the odd time slot and the most capable and available RD link (not necessarily of the same relay) in the even time slot. This scheme has consecutive communication paradigm i.e., reception in the odd numbered time-slots and transmission in the even numbered time-slots and achieved the diversity gain equal to the count of relays. The consecutive paradigm puts restriction on the obtainable advantages of buffer-equipped relaying systems. Taking into account the constraints of MMRS, the max-link relay selection (MLRS) [11] scheme is proposed which chooses the most capable link among the all available links uplifting the limitation of consecutive transmission of source and relay. The MLRS attains the diversity order of twice the count of relays for large buffer size and equal to the count of relays for small buffer size. In MLRS, relay selection does not considers the current buffer status, therefore, the count of links available for selection is decreased when the corresponding buffers are either full or empty. It also limits the reduction in the outage probability and increases the queuing delay of the buffer-equipped relaying system. Thus, it allows to have another parameter, i.e., the buffer status, to be used as the link selection criteria.

Various researchers explored buffer-status based relay selection [8], [12]–[18]. The relay selection work in [8] operates in conventional two phase paradigm. In this scheme, relay with the least stored packets receives in the odd numbered time-slots and a relay with the most packets forwards in the even numbered time-slots [4]. The buffer-equipped cooperative communication for the problem of file transfer from the source to the destination is explored in [12]. The authors did not computed the outage probability and the diversity order in this contribution. Luo and Teh [13] considered both the channel quality and buffer occupancy in relay selection scheme and achieve the maximum diversity order with minimum buffer size of 2 packets. In order to overcome diversity-delay trade-off in buffer-equipped relaying, Nomikos *et al.* [14] propose a low complexity relay selection scheme with the aim to decrease the delay in asymmetric links. The buffer occupancy based relay selection scheme is proposed by Xu *et al.* [15]. If numerous links are equal to the maximum weight, i.e., equal-weight links, one link is randomly selected which is less reliable. To address this issue, the work in [16] considered the link quality and link priority as the second selection metrics. The numerous SR broadcast links activation and buffer status based relaying are exploited in [17] and [18] to attain the lower end-to-end delay and outage probability with AF relaying condition.

In this contribution, we come up with a parameter that decides on the basis of current buffer status to select either SR or RD link for buffer-equipped cooperative relay networks. The proposed design allocates the respective weights to the SR and RD links on the basis of buffer occupancy and re-allocates the weights depending on the decisive parameter. The MWRS is a particular case of the proposed scheme by the proposed weight re-assignment. Then, the Markov chain (MC) based theoretical framework is adopted to model the growth of buffer status and computation of the outage probability. Furthermore, the relations for the average throughput and end-to-end queuing delay are derived. The results of the proposed scheme are analyzed with the existing schemes for the outage probability, average throughput and end-to-end queuing delay.

The organization of the paper is as follows. The Section II discusses the system model and the basic assumptions about the buffer-equipped wireless relaying system under consideration. An overview of relevant literature is given in Section II-A. In Section II-B, the motivation for the proposed work is discussed in detail. Furthermore, the proposed scheme and Markov modeling are given in the Sections III and III-A, respectively. Analysis on the outage probability, average packet delay and the average throughput are presented in the Section III-B. The simulations and performance of the proposed schemes are discussed in Section IV, and finally, the conclusion and future work are given in Section V.

II. PROPOSED SYSTEM MODEL

A source node S, a destination node D and a set of K half-duplex DF relay nodes $\mathcal{R} = \{R_1, R_2, \ldots, R_K\}$ is considered in a dual-hop cooperative relay network as presented in Fig. 1. The data is sent from source to destination with the help of intermediate relay nodes because the direct link between S and D is considered in deep fading [16]. It is pre-assumed that the source always transmits and destination always receives. They have no constraint on buffer size. While, Each relay R_k is equipped with a finite buffer B_k of size L packets. L_k^o is the occupied buffer space (OBS) of buffer B_k and $L_k^a = L - L_k^o$ is the available buffer space (ABS). The time is considered in slots, and in each time-slot only single link is chosen either for sending or for receiving at relay. Moreover, the relays are not facilitated to exchange data packets. The total count of possible links in a CR system having one S, D and K relays is $2K$ i.e., $\mathcal{L} = \{l_1, l_2, \ldots, l_{2K}\}$. We relate the index of links i with the SR and RD links in the

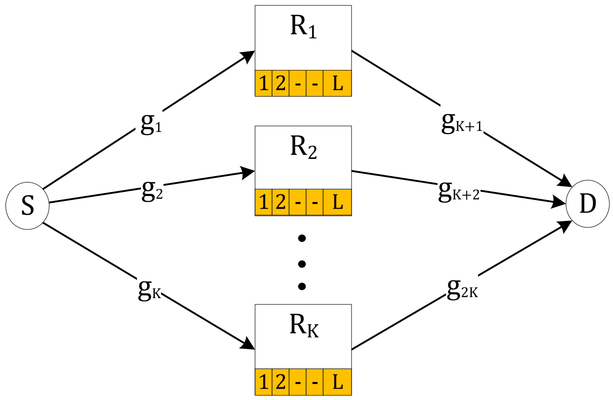


FIGURE 1. The proposed system model.

following equation as,

$$l_i = \begin{cases} R_{(i-K)}D & i > K, \\ SR_i & i \leq K. \end{cases} \quad (1)$$

For providing the channel state information to relays, S and D broadcast a reference signal in each time-slot. The channel gain g_i of each link l_i, where $i = [1 : 2K]$, has 0 mean and variance σ_i^2 [4]. The instantaneous signal-to-noise ratio (SNR) of l_i is $\gamma_i = |g_i|^2 \frac{E_x^{T_r}}{N_o}$, where $E_x^{T_r}$ is the transmission energy of the node where, $x \in \{s, R_k\}$ depending on the selection of SR or RD link and N_o is the additive white Gaussian noise (AWGN) variance. The γ_i is an exponentially distributed random variable. The block fading model is considered for signal in which the channel coefficients are same for time-slot and vary independently from one time-slot to another [6]. All the nodes sends data with a fixed information rate of r_o bits/s/Hz. A link l_i is un decode-able if $\gamma_i < \gamma_{th}$, where $\gamma_{th} = 2^{2r_o} - 1$, is the least value of SNR required for the successful decoding of signals. Hence, we call the link is a *decode-able link*, when $\gamma_i \geq \gamma_{th}$, the link is an *available link*, provided that its corresponding relay buffer is neither full nor empty and the link is a *success link*, when it is both available and decode-able [4]. Thus, $\mathcal{L} = \mathcal{L}^s U \mathcal{L}^{\bar{u}} U \mathcal{L}^{\bar{a}}$ is the universal set of links, where, $\mathcal{L}^{\bar{u}}$ is set of un-decode-able links, $\mathcal{L}^s$ is set of success links and $\mathcal{L}^{\bar{a}}$ is set of unavailable links.

A. EXISTING RELAY SELECTION SCHEMES

In this section, we describe some of the relevant relay selection policies available in literature. The traditional relay selection schemes are reliant only on the link quality and do not consider the buffering capability at relays [21]. Initially, the source and the destination broadcast the reference signals and each relay calculates the instantaneous SNR, i.e., γ_{SR}, γ_{RD}, of SR and RD links, respectively. Then, the minimum of the SNRs of SR and RD links of each relay is nominated to be used for relay selection purpose. A relay whose minimum SNR is maximum of all minima is selected for the relaying purpose as given below,

$$R^* \triangleq \underset{k=[1:K]}{\text{argmax}}\{\min\{\gamma_{SR_k}, \gamma_{R_kD}\}\}. \quad (2)$$

The MMRS [10] scheme following the traditional transmission paradigm selects the strongest RD (SR) link to transmit (receive) in the even (odd) time-slot on the basis of link/channel quality. Mathematically, the relay selection in MMRS is expressed as,

$$R_r^* \triangleq \underset{k=[1:K]}{\text{argmax}}\{\gamma_{SR_k}\}, \quad (3a)$$

$$R_t^* \triangleq \underset{k=[1:K]}{\text{argmax}}\{\gamma_{R_kD}\}. \quad (3b)$$

where, R_r^* is the chosen relay to receive and R_t^* is the chosen relay to transmit.

Krikidis *et al.* [11] of MLRS scheme lift the limitation of fixed transmission of source and relay as in MMRS and choose a link from all of the available links on both sides. The MLRS scheme selects the strongest link from the set $\mathcal{L}^s$, mathematically expressed as,

$$R^* \triangleq \underset{k=[1:K]}{\text{argmax}} \left\{ \bigcup_{L_k^a \geq 0} \gamma_{SR_k}, \bigcup_{L_k^o \geq 0} \gamma_{R_kD} \right\}. \quad (4)$$

MLRS provide significant performance enhancement, however, this scheme does not take into account the current buffer status in relay selection process. Thus, there exists a possibility that a certain relay with good link quality is chosen repeatedly. It causes the saturation of the packets in the corresponding buffer, and in turn, decreases the count of available links. Since, the diversity order of the relaying system is also reliant on the count of available links, a decrease in the count of available links decreases the diversity order of the system as well. Therefore, the MLRS scheme has the maximum diversity order of $2K$ at a large buffer size i.e., $L \to \infty$.

Like MMRS transmission paradigm, shortest in longest out (SILO) is another attempt in relay selection considering the buffer status [8]. A relay having the least count of packets in its buffer is selected for data receiving in the first phase, and a relay having the most count of packets in its buffer is selected for data forwarding in the second phase. Like SILO, the relay selection in MWRS scheme also depends on the current buffer status. A link having maximum weight is chosen from the set of successful links $\mathcal{L}_s$, either for reception or transmission. It follows the MLRS transmission paradigm as described mathematically as,

$$R^* \triangleq \underset{k=[1:K]}{\text{argmax}} \left\{ \bigcup_{L_k^a \geq 0} (L_k^a), \bigcup_{L_k^o \geq 0} (L_k^o) \right\}. \quad (5)$$

The MWRS only ensures that the selected link l_i is a decode-able link, i.e., $\gamma_i \geq \gamma_{th}$. However, it does not take into account the impact of link quality along with buffer status in the relay selection.

B. MOTIVATION

Here, we highlight the inspiration for using the decisive parameter for buffer occupancy based relay selection. Let a relay is attached with a buffer of size L and with the current number of packets (buffer occupancy) in it as L^o. Our concern is to find the probability of choosing the links on both sides (SR and RD links), which are reliant on their respective allocated weights. The weight of SR link is denoted by $\omega_{SR} = L - L^o$ and the weight of RD links is denoted by $\omega_{RD} = L^o$. The value to see here is $L/2$, which behaves as a limit to decide the respective weights of the links on both sides. If buffer is occupied with half of the total space, then the respective weights of corresponding links on both sides are same. Hence, the selection probability of both sides are equally likely. However, in the other cases, when the buffer is occupied with less (greater) than half of the total space $L/2$, left (right) side links are allocated more weight as compared to the right (left) side links. Inspired by the governing nature of half value i.e., $L/2$, we intent that in place of of $L/2$, any pre assumed value of L^o acts as this limit. To achieve this, we propose the term *buffer-limit*, L_{th} where $(1 < L_{th} < L)$, and reallocate the weights of links on both sides according to the given value of L_{th} [19].

Another important aspect to observe is the changes in performance parameters with respect to buffer occupancy. Specifically, the outage probability is inversely related to the count of available links and the count of relays. The decrease in the outage probability is desired for the improved quality of service of a wireless communication system. Hence, from the perspective of the outage probability, the maximum count of available links are obtained when we avoid full or empty buffers. The trend of the average end-to-end queuing delay against the buffer occupancy is also interesting to observe. A packet, received at a relay, experiences increased queuing delay if the buffer already contains the large number of packets (large occupancy). While, it is required to increase the selection probability of RD link to decrease the average end-to-end delay. To increase the selection probability of RD links, the weights of RD links should be increased. In general, the weights of RD links are increased by increasing the packets in the buffer which leads to the increased queuing delay. Thus, if right side links are given priority using the traditional weight allocation way, the queuing delay is increased. In this work, we propose a scheme that prioritizes right side links and avoid expanding the size of buffering delay [19]. We name the scheme as *Buffer threshold based relay selection* (BTRS). This scheme is utilized to prioritize links on both sides and decrease the average end-to-end queuing delay of buffer-equipped CR system. Considering these points as our inspirations, we computed the weights of links on both sides using the buffer occupancy L^o and BTRS-limit L_{th} as defined in the next section.

III. THE PROPOSED SCHEME

The proposed work is an extension to our previous work in [19]. In order to explain the proposed weight assignment approach, we plot the weights of the corresponding links of a particular relay with respect to the buffer occupancy L^o in Fig. 2a. Initially, when the buffer occupancy is 0, ω_{SR} is equal to L and ω_{RD} is equal to 0. When the occupancy L^o is increasing, the weight of right side link is increasing linearly (line OG) and the weight of left side link, i.e., SR link is decreasing linearly (line AB). According to the Fig. 2a, we get $\omega_{SR} = L - L^o$ and $\omega_{RD} = L^o$ resulting in $\omega_{SR} + \omega_{RD} = L$. The proposed weight assignment of SR link is explained in Fig. 2b. Generally, it is viewed, as a single line AB resolved into two lines, with different slopes and a common intersecting point i.e., $(L_{th}, L/2)$. Specifically, when $L_{th} < L/2$, the line AB is resolved into two lines AC and CB. Similarly, the lines AH and HB represent the redefined weights of SR link with respect to buffer occupancy when $L_{th} > L/2$. In both cases, the weight of SR link is equal to $L/2$ when $L^o = L_{th}$, (instead of $L^o = L/2$ which was in previous weigh assignment strategies). Following the same process, weight reassignment for RD links is also achieved. Using the equations of lines, the respective weights reassignment of SR and RD links for the buffer occupancy L^o and buffer-limit L_{th} are according to the following mathematical equation,

$$W_{SR} \triangleq \begin{cases} \dfrac{(2L_{th} - L^o)L}{2L_{th}} & L^o \leq L_{th}, \\ \dfrac{(L^o - L)L}{2(L_{th} - L)} & L^o > L_{th}. \end{cases} \tag{6a}$$

Likewise, the weight of RD link is calculated by resolving the line OG into two parts and following the similar procedure,

$$W_{RD} \triangleq \begin{cases} \dfrac{LL^o}{2L_{th}} & L^o \leq L_{th}, \\ \dfrac{(L + L^o - 2L_{th})L}{2(L - L_{th})} & L^o > L_{th}. \end{cases} \tag{6b}$$

Thus, by adjusting the value of L_{th}, the selection probability of the links on both sides can be handled depending on the requirement.

Remark 1: At $L^o = L_{th}$, i.e., the buffer occupancy is equal to the buffer-limit, the details can be found in [19].

The weight of each link on both sides is calculated by the proposed reassignment approach. Hence, we represent the reassigned weight of a k_{th} relay having the links SR_k and R_kD with W_{SR_k} and W_{S_kD}, respectively. After weight assignment, the BTRS scheme chooses a link with maximum weight as given below,

$$R^* \triangleq \underset{k=[1:K]}{\operatorname{argmax}} \left\{ \bigcup_{L_k^a \geq 0} (W_{SR_k}), \bigcup_{L_k^o \geq 0} (W_{R_kD}) \right\}. \tag{7}$$

The Markov chain based mathematics to model the buffer status progression and calculation of the outage probability of the system is discussed in the next subsection.

A. MARKOV MODELING

Each state in a Markov chain represents a sequence, i.e., the buffer occupancy L_k^o of each relay. With K buffer-equipped relays of size L, the system have a total of $(L+1)^K$ states. A general state $s_c \in \mathcal{C}$ is represented by the following equation,

$$s_c \triangleq (L_1^o, L_2^o, \ldots, L_K^o), \quad \forall 1 \leq c \leq (L+1)^K. \tag{8}$$

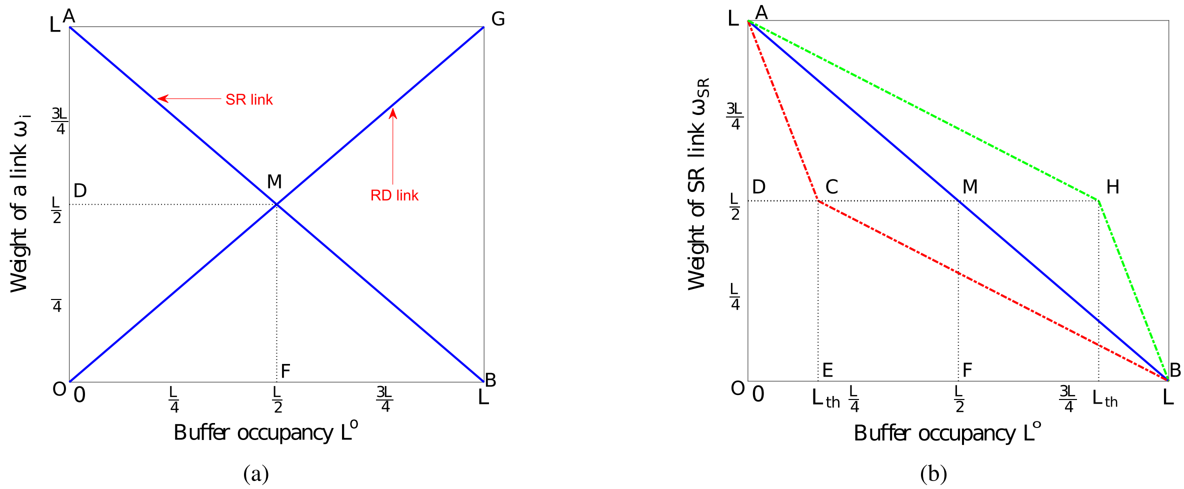


FIGURE 2. **Weight of the links against buffer occupancy. (a) Weights of SR and RD links with respect to buffer size. (b) Proposed weight assignment using L_{th}.**

If a buffer-equipped relaying system is in outage, it means no packet is added to or removed from any buffer. In Markov chain, this is the event when a state transits to itself. Activation of any link in the relaying system is in such a way that one state transit to another state in a Markov chain. A set $\mathcal{C}_c \triangleq \{s_r | s_r \in \mathcal{C} \wedge |s_r - s_c| = 1\}$, consists of all states reachable from s_c. These states are referred as the connected states. The set of all the possible $2K$ links is L, $\mathcal{L}_c^q = \{l_i | l_i \in \mathcal{L} \wedge \gamma_i > \gamma_{th}\}$ is the set of all decode-able links at s_c state. Likewise, $\mathcal{L}_c^s$ and $\mathcal{L}_c^a$ are the sets of all successful links and available links associated with this state, respectively [19].

B. OUTAGE PROBABILITY ANALYSIS

As described in system model, we assume the block based Rayleigh fading channels. In these channel conditions, the link's outage probability is calculated as,

$$p_i^o = \left(1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}_i}}\right). \tag{9}$$

$p_i^o = 0$, when $\bar{\gamma}_i \to \infty$ and $p_i^o = 1$, when $\bar{\gamma}_i \to 0$. Since, the Rayleigh distribution is the function of average received SNR $\bar{\gamma}$, it does not depend on the instantaneous received SNR γ_i. In order to find the outage probability at a certain state s_c, we need to compute the number of available links linked to the state s_c. The general expression of the outage probability at state s_c is,

$$p_c^o = \prod_{j=1}^{|\mathcal{L}_c^a|} p_j^o. \tag{10}$$

where, $\mathcal{L}_c^a$ is the set of available links linked with state s_c.

It is important to note that if $n_c^a = 0$, according to the convention, the empty product is 1, i.e., outage probability of that state is maximum i.e., 1. This relation reduces to $(p^o)^{|\mathcal{L}_c^a|}$ when $\bar{\gamma}_i$ is symmetric all links $i = [1 : 2K]$. We seek the transition matrix and its steady state probability for computing the outage probability of the system. The transfer from the state s_c to all linked states relies on the re-assigned weights of the corresponding links. A transition matrix $\mathbf{A}$ of order $(L+1)^K \times (L+1)^K$ is defined. The entries in this matrix represents $A_{rc} = p(s_r|s_c) = P(X(t+1) = s_r | X(t) = s_c)$ the transition probability from state s_c at time-slot t to state s_r in the next time-slot $t+1$. We have expressed $\mathbf{A}$ using the following piece-wise function,

$$\mathbf{A}_{rc} = p(s_r|s_c) = \begin{cases} p_c^{cr} & if s_r \in \mathcal{C}_c, \\ p_c^o & if s_c = s_r, \\ 0 & \text{otherwise}. \end{cases} \tag{11}$$

where, p_c^{cr} denotes the activation probability, from state s_c to state s_r via unique link.

In order to derive the expression for p_c^{cr} for each link, the weight $W_i \; \forall \; l_i \in \mathcal{L}_c^a$ is used. Suppose, the vector $\mathbf{v}_c$ contains the weights of all links linked to state s_c, i.e.,

$$\mathbf{v}_c = (W_1, W_2, \ldots, W_{2K}), \quad \forall s_c \in \mathcal{C}. \tag{12}$$

The transition from state s_c to s_r involves the activation of only one link, l_{cr} having weight W_{cr}, and all other links remain in-activated. Those links, whose weight is greater than W_{cr} are collected in a set $\mathcal{L}_{cr}^{bg} = \{l_i | l_i \in \mathcal{L} \wedge W_i > W_{cr}\}$, and whose weight is equal to W_{cr} are gathered in the set $\mathcal{L}_{cr}^{eq} = \{l_i | l_i \in \mathcal{L} \wedge W_i = W_{cr}\}$, and whose weights are less than W_{cr} are put together in the set $\mathcal{L}_{cr}^{ls} = \{l_i | l_i \in \mathcal{L} \wedge W_i < W_{cr}\}$.

To find the transition probability about the links coupled to state s_c, following events are determined:

$E_c \triangleq$ {A link is chosen from $\mathcal{L}_{cr}^{eq}$},

$E_{c_1} \triangleq$ {All the links are unqualified in $\mathcal{L}_{cr}^{bg}$ },

$E_{c_2} \triangleq$ {At least one link is decode-able from $\mathcal{L}_{cr}^{eq}$}.

The relay selection scheme says that the events E_{c_1} and E_{c_2} are independent of each other, and event E_c happens only, if both E_{c_1} and E_{c_2} happen. Thus, the occurrence probability of E_c is expressed as,

$$\begin{aligned} P(E_c) &= P(E_{c_1} \cap E_{c_2}) \\ &= P(E_{c_1})P(E_{c_2}) \\ &= \left(\prod_{j=1}^{|\mathcal{L}_{cr}^{bg}|} p_j^o\right)\left(1 - \prod_{j=1}^{|\mathcal{L}_{cr}^{eq}|} p_j^o\right). \end{aligned} \tag{13}$$

As there are $|\mathcal{L}_{cr}^{eq}|$ number of links having weights W_{cr}, the probability of choosing a link l_{cr} having weight W_{cr} is computed by dividing the probability of E_c with $|\mathcal{L}_{cr}^{eq}|$ according to the following mathematical equation,

$$p_c^{cr} = \frac{P(E_c)}{|\mathcal{L}_{cr}^{eq}|}. \tag{14}$$

However, when the weight of only one link is equal to W_{cr}, $\mathcal{L}_{cr}^{eq}$ is a set having single element and (13) is similar to (14). Following the same procedure, the probabilities of transition from a state to all the linked states are calculated. Furthermore, this process is used for all the states to find all the probabilities of transition linked with them, the outage probability and the probabilities of transition form $\mathbf{A}$.

The Markov matrix $\mathbf{A}$, of an aperiodic and irreducible Markov chain is aperiodic, irreducible and column stochastic [4], [11]. The steady state probability vector defined as $\boldsymbol{\pi}$ is computed using [20],

$$\boldsymbol{\pi} = (\mathbf{A} + \mathbf{Y} - \mathbf{I})^{-1}\mathbf{y}. \tag{15}$$

where, $\mathbf{Y}$ is the matrix of 1s with order $\mathbf{A}$, $\boldsymbol{y} = [1, 1, \ldots, 1]^T$ and $\mathbf{I}$ is an identity matrix. The overall outage probability is mathematically expressed using the equation,

$$P_o = \sum_{c=1}^{(L+1)^K} \pi_c p_c^o = \text{diag}(\mathbf{A})\boldsymbol{\pi}. \tag{16}$$

We use this outage probability relations to calculate the average end-to-end queuing delay and throughput.

C. AVERAGE END-TO-END QUEUING DELAY

In a buffer-equipped CR system, the average end-to-end queuing delay of a packet is composed of the sum of average delay at source as well as relay nodes. Similar to the approach adopted in [13], we used Littles law [22] to compute the queuing delay. Generally, the queuing delay is the average queuing length divided by the average throughput. Therefore, the queuing delay at S is computed as,

$$D_s = \frac{E\{Q_s\}}{\eta_s}, \tag{17}$$

where, Q_s is the queuing length and η_s is the average throughput of the source node. The queuing length of S is not proportional to the probability of selection of left side link. It is considered in [13] and [15] that the probability of choosing the links on both sides is equally likely. However, in the BTRS scheme, because of the weight re-assignment, this supposition may not be true. Therefore, we are required to compute the relationship between the respective selection probabilities of SR and RD links. Taking advantage of Fig. 2b, we first find the slopes of the line AC and CB represented by m_{AC} and m_{CB}, respectively. We define the link priority factor as β which is mathematically expressed as,

$$\beta = \frac{P_{RD}}{P_{SR}} = \frac{m_{AC}}{m_{CB}} = \frac{L - L_{th}}{L_{th}}. \tag{18}$$

In this equation, when $L_{th} = L/2$ then $\beta = 1$, it results $P_{SR} = P_{RD}$ as according to the previous schemes. When, $L_{th} < L/2$ then $\beta > 1$, it depicts $P_{RD} > P_{SR}$, i.e., the selection probability of right side links is prioritized over left side links with the factor β. Likewise, when $0 < \beta < 1$, the selection probability of SR links is prioritized over RD links. The mathematical relationship between the probabilities of choosing the links on both sides and the outage probability is expressed as,

$$P_o + P_{SR} + P_{RD} = 1. \tag{19}$$

Since, the source node is always supposed to send packets. Therefore, the queuing length is directly proportional to the probability of selection of the left side link. Using the relationship between P_{SR} and P_{RD} from (19), the average queuing length is given as,

$$E\{Q_s\} = \frac{\beta + P_o}{\beta + 1}, \tag{20}$$

Similarly, the average throughput of the source node also relies on the probability of selection of the left side links. Using the relation of P_{SR} from (19) in (20), the average throughput at the source node is expressed as,

$$\eta_s = \frac{1 - P_o}{\beta + 1}. \tag{21}$$

Thus, the average queuing delay at the source is finalized in the following equation,

$$D_s = \frac{\beta + P_o}{1 - P_o}. \tag{22}$$

For computing the average queuing delay at R, we followed [19]. The equivalent average queuing length is computed using the relation given below,

$$E\{Q_{eq}\} = \sum_{c=1}^{(L+1)^K} \sum_{i=1}^{K} \pi_c Q_c^i. \tag{23}$$

Likewise, the average throughput of relay is computed in the same way as that of source node. The throughput at relay node is expressed as,

$$\eta_{RD} = \beta \frac{1 - P_o}{\beta + 1} \tag{24}$$

Thus, the average delay at the relays is computed by the following relation,

$$D_R = \frac{\beta + 1}{\beta(1 - P_o)} \sum_{c=1}^{(L+1)^K} \sum_{i=1}^{K} \pi_c Q_c^i. \tag{25}$$

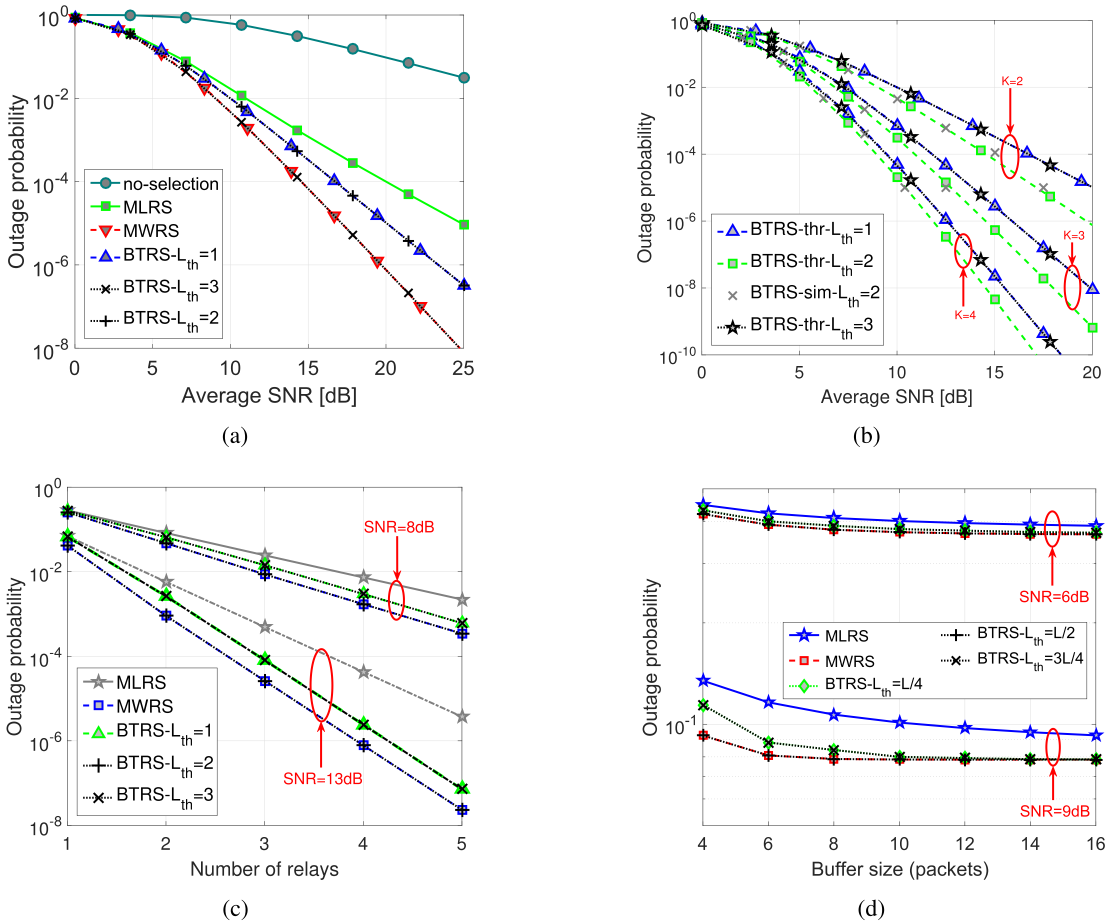


FIGURE 3. Outage probability analysis of the MWRS, MLRS and BTRS schemes. (a) Outage probability against the average SNR for $L = 4$ and $K = 2$. (b) Outage probability against the average SNR for increasing values of K at $L = 4$. (c) Outage probability against the increasing count of relays at $L = 4$ (d) Outage probability against the increasing buffer size at $K = 2$.

Hence, the total average end-to-end queuing delay $\bar{D}$ of the proposed buffer-equipped relaying system is expressed by,

$$\begin{aligned}\bar{D} &= D_s + D_R \\ &= \frac{P_o + \beta}{1 - P_o} + \frac{\beta + 1}{\beta(1 - P_o)} \sum_{c=1}^{(L+1)^K} \sum_{i=1}^{K} \pi_c Q_c^i. \end{aligned} \quad (26)$$

For $\beta = 1$, the aforementioned relationship holds true for MWRS scheme.

IV. PERFORMANCE EVALUATION

We assess the proposed BTRS scheme for three parameters i.e., the average end-to-end queuing delay, outage probability and the average throughput. For evaluation, the BTRS scheme along with its different variants is compared with the existing MLRS [11] and MWRS [16] schemes. Each performance metric is evaluated against the buffer size, average SNR and the count of relays. All schemes are implemented in MATLAB. The symmetric channel conditions (all links have same average SNR) are assumed throughout the simulations. The parameter r_o is set to 1 bits/s/Hz throughout the simulations.

Fig. 3, illustrates the outage probability of the three schemes; BTRS, MLRS and MWRS each against the average SNR, buffer size and the increasing count of relays. In Fig. 3a, the outage probability is setup against the average SNR for $K = 2$ and $L = 4$. The the minimum bound outage probability is denoted by *no selection*. In this approach, only one relay is chosen to transmit and receive the signals. When $L = 4$, $\{1, 2, 3\}$ are the feasible values of buffer-limit. In Fig. 3a, we evaluated all the three feasible cases of the BTRS scheme. The outage probability with $K = 2, 3$ *and* 4, evaluated against the average SNR, is given in Fig. 3b. The theoretical are plotted using (16). The Monte-carlo simulations for $1,000,000$ iterations are also computed. As evident that simulation results are acknowledging the theoretical results, which approves the analysis of the proposed BTRS scheme.

As discussed previously, when $L_{th} = L/2 = 2$, the MWRS scheme acts as a particular case of the BTRS scheme. The plots in the Fig. 3a confirms this analysis. As the gap in threshold/limit of the cases $L_{th} = 1$ and $L_{th} = 3$ from the case $L_{th} = 2$ are same, i.e., 1, the outage probability of the proposed scheme with the case $L_{th} = 1$ is identical to the outage probability of the case $L_{th} = 3$, as shown in Fig. 3a. Furthermore, the outage probability in these two cases is higher as compared to MWRS scheme and lower as compared to the MLRS scheme. The rise in the outage probability leads to the decline in the coding gain which is swapped for the improvement in the average end-to-end queuing delay or throughput.

In Fig. 3d the outage probability is evaluated with respect to the buffer size with SNR of 6dB and 9dB and $K = 2$ for all the compared schemes. The proposed scheme considers three different cases of the BTRS i.e., $L_{th} = [L/2\ L/4\ 3L/4]$. The MLRS and MWRS schemes exhibit the consistent behavior for the outage probability when buffer size is increased. Their outage probability is decreased with the increase in buffer size, because increasing the buffer size reduces the probability of buffers being full or empty and in turn reduces the count of unavailable links. Furthermore, the weight dependence on available or occupied buffer space in MWRS ensures that buffer should not be overloaded or under-loaded. Hence, the outage probability of the MWRS is less than the MLRS scheme for all values of buffer size. Since, the proposed BTRS scheme with $L_{th} = L/2$ works similar to the MWRS scheme, the BTRS scheme's outage probability in this case perfectly coincides with that of the MWRS scheme. Also, with the case $L_{th} = L/4$, the outage probability of the BTRS scheme matches with that of the case $L_{th} = 3L/4$, because, their differences from $L_{th} = L/2$ are same. Hence, these cases only prefer the selection of either SR or RD links.

The outage probability is also evaluated against the increasing count of relays having the same buffer size, $L = 4$ and at two different values of the average SNR, i.e., 8dB and 13dB, in Fig. 3c. As depicted in the figure, increase in the count of relays with the average SNR and the fixed buffer size, linearly decreases the outage probability, plotted on the logarithmic scale, of a buffer-equipped relaying system. However, the maximum rate of decrease is for the MWRS scheme and the proposed BTRS scheme with $L_{th} = L/2$ (which works as MWRS scheme). Whereas, the minimum rate of decrease of the outage probability is for the MLRS scheme for both values of the average SNR. When the values of L_{th} are equally spaced from $L_{th} = L/2$, their outage probability lines are superimposed on each other and these lines are in between the lines of the MWRS and MLRS relay selection schemes. The increase in the outage probability in BTRS with cases, $L_{th} = 1$ and $L_{th} = 3$ is actually traded for the decrease in the average end-to-end queuing delay discussed in the following.

The average end-to-end queuing delay of the buffer-equipped relaying system is computed using (26) and given in Fig. 4. The average end-to-end queuing delay against the average SNR is evaluated for $L = 4$ and $K = 2$, as shown in Fig. 4a. As previously mentioned, at sufficiently large value of average SNR, the average end-to-end queuing delay of the MWRS and MLRS schemes is $KL + 1$ time-slots. Similar observation holds for the BTRS scheme when $L_{th} = L/2$. However, when $L_{th} = 1$, in the BTRS scheme, the relays tend to transmit the buffered packets to the destination instead of receiving the packets from the source node. Therefore, the average end-to-end queuing delay of BTRS scheme is noticeably less than the MWRS and MLRS schemes for this scenario. In contrast, at $L_{th} = 3$, the relays are more likely to receive instead of transmitting to the destination. In this scenario, the average end-to-end queuing delay of the packets is higher as compared to the queuing delay in MWRS and MLRS schemes.

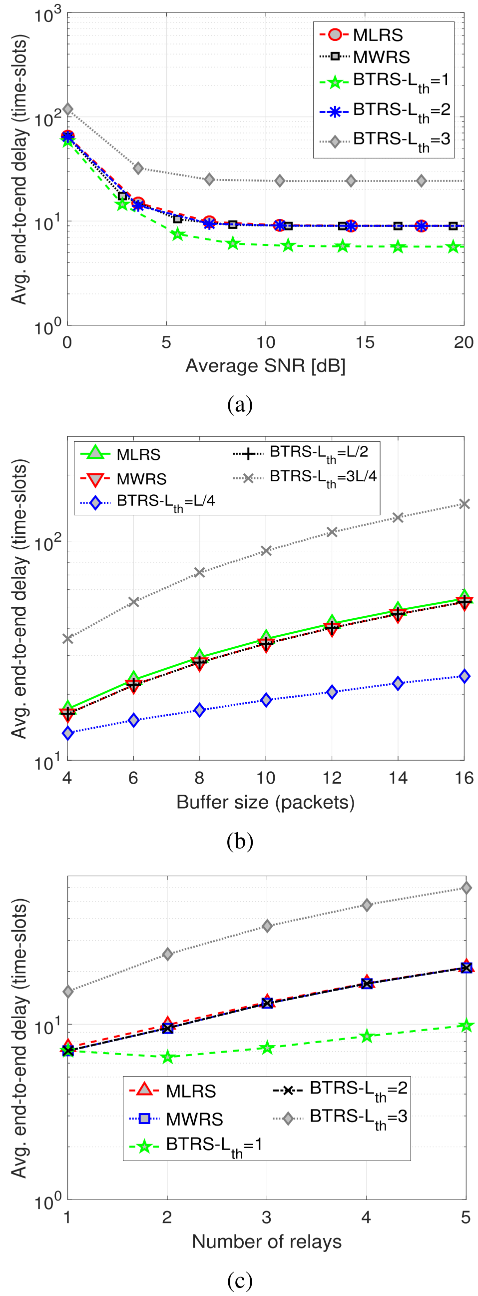


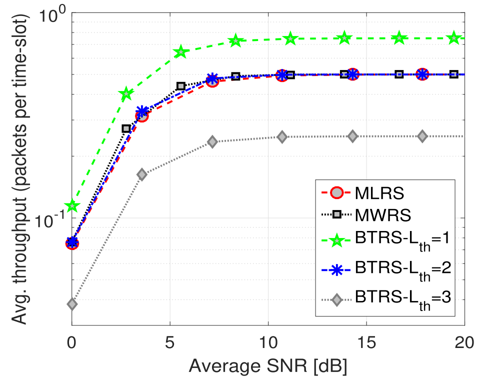
FIGURE 4. Average end-to-end queuing delay of the MWRS, MLRS and the proposed BTRS schemes. (a) The average end-to-end delay against the average SNR for $L = 4$ and $K = 2$. (b) The average end-to-end queuing delay against the increasing buffer size for $K = 2$ and the average SNR= 8dB. (c) The average end-to-end queuing delay of against the increasing count of relays for $L = 4$ and average SNR= 8dB.

In Fig. 4b, the average end-to-end queuing delay is plotted against the buffer size with SNR = 6dB and $K = 2$ for all compared schemes. Similar to the outage probability, the BTRS scheme is evaluated for different cases of L_{th}. In general, increasing the buffer size increases the average end-to-end queuing delay of the buffer-equipped system; because, the packets are stored for the increased number of time-slots. For the less values of buffer sizes, MWRS delay is slightly less than the MLRS scheme because the selection of MWRS is dependent on the buffer occupancy. The average end-to-end queuing delay of the BTRS scheme with $L_{th} < L/2$, is significantly less than that of the MWRS, MLRS schemes and the BTRS scheme with $L_{th} = L/2$. Because, the selection probability of right side links is increased in these cases of BTRS scheme.

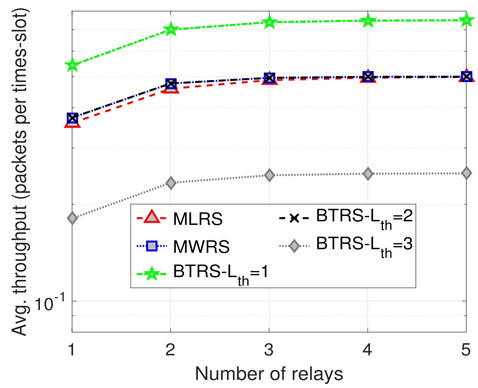
Similar to the outage probability, the average end-to-end queuing delay is also calculated against the increasing count of relays for $L = 4$ and SNR = 8dB as given in Fig. 4c. Since, increasing the count of relays increases the count of links available for selection. Hence, a single link is selected from a larger set of links, and the selection probability of each link is reduced leading to the increased queuing and average end-to-end queuing delay. The average delay of the three schemes with $L_{th} = L/2$ rises with the rise in the count of relays as clear from the figure. The delay of these schemes is comparable to one another. However, the BTRS scheme with $L_{th} = 3$ has larger delay than all of the compared schemes. The larger values of average end-to-end delay in this case are due the larger tendency of packets to reside in the buffers because of the decrease in selection probability of RD links. Finally, the average end-to-end queuing delay of the proposed BTRS scheme with $L_{th} = 1$ is minimum among all the schemes for all values of K.

The last performance evaluation metric considered in this paper is the average throughput evaluated with respect to different parameters in Fig. 5. The average throughput in single phase scheme converges to $1/2$ (packets/time-slot) at the sufficiently large SNR. In Fig. 5a, the average throughput of each compared scheme with $K = 2$ and $L = 4$ is evaluated against the average SNR. At the lower average SNR, the buffer-equipped relaying system has the increased outage probability and the decreased average throughput. However, increasing the average SNR increases the average throughput of each relaying system regardless of the underlying relay selection scheme. The average throughput of the MLRS, MWRS and the proposed BTRS with $L_{th} = L/2$ is similar to one another and approaches to the theoretically predicted value of $1/2$. However, SR prioritization in the proposed scheme with $L_{th} = 3$ decreases the average throughput of the buffer-equipped relaying system. The converse of this behavior is observed with $L_{th} = 1$, where RD prioritized link selection enhances the average throughput of the system. This is in-line with the analysis of the average end-to-end queuing delay presented earlier.

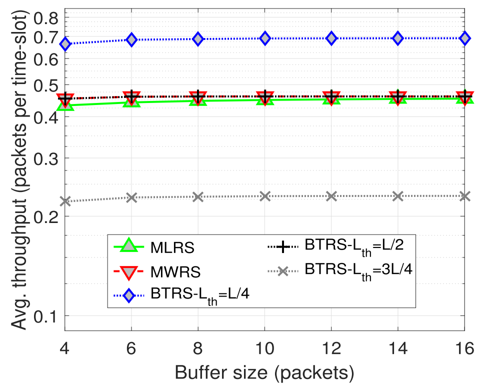
The average throughput is also evaluated with the increasing buffer size in Fig. 5c. Generally, an increment in the buffer size results in the minute increment in the average throughput of the buffer-equipped relaying system regardless of the fact that the relay selection is reliant on the link quality or the buffer occupancy. This phenomenon is observed for the MLRS, MWRS and the proposed BTRS based relay selection scheme with $L_{th} = L/2$, as their average throughput is comparable to one another. The average throughput of the proposed BTRS scheme with $L_{th} = L/4$ is more than the other compared schemes because of the prioritized selection of RD links. Contrary to this, the prioritized SR selection



(a)



(b)



(c)

FIGURE 5. Average throughput of the MWRS, MLRS and the proposed BTRS scheme. (a) Average throughput against average SNR for $L = 4$ and $K = 2$. (b) Average throughput against the increasing count of relays at average SNR=8dB. (c) Average throughput against increasing buffer size.

in $L_{th} = 3L/4$ decreases the average throughput. However, the trend of both of these cases with respect to the buffer size is similar to the other schemes.

The average throughput of the three schemes is also assesses against the increasing count of relays for a fixed buffer size $L = 4$ in 5b. In the comparison, the general trend is a rise in the average throughput with the increase in count of relays because of the decreased outage probability. The average throughput of the three schemes with $L_{th} = L/2$ converges to the maximum possible value of the average throughput, i.e., $1/2$ packets per time-slot. However, the average throughput of the BTRS with $L_{th} = 1$ is greater than the $1/2$ packets per time-slots and equal to 0.75 packets per time-slot. Conversely for $L_{th} = 3$, the average throughput of the proposed BTRS scheme is equal to 0.25 packets per time-slots.

V. CONCLUSION

The work presents the use the buffer occupancy for RD (or even SR link) prioritization in a buffer-equipped relay selection scheme. This work improved the performance of the relaying system for the average end-to-end queuing delay and the average throughput at the cost of the increased outage probability. To accomplish this, we preset a buffer-limit and reallocate the weights of links according to this limit. A link with the largest weight is chosen and the corresponding relay is accordingly chosen for reception or transmission. It is found that when the aforementioned limit is equal to the $1/2$ of the buffer size, the BTRS scheme is equivalent to MWRS scheme. However, when this limit is less than or greater than the half value by the same amount, the outage probability is increased equally for both scenarios. Also, setting the values less than the half value benefits the relaying system i.e., increase in the average throughout and decrease in the average end-to-end queuing delay.

In the future, we have an aim to explore the proposed buffer-limit for the full duplex, two-way and successive relaying. Moreover, this work can be enhanced for different channel environments. The impact of the proposed relay selection scheme with energy harvesting capability and in cognitive cooperative relaying will also be interesting horizons to explore.

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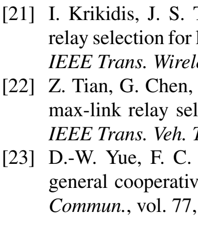

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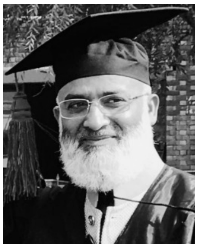

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