A Low-Delay Lyapunov-Based Relay Selection Scheme in Buffer-Aided Cooperative Networks

Ali A. Siddig, Ahmed S. Ibrahim, *Member, IEEE*, and Mahmoud H. Ismail, *Senior Member, IEEE*

***Abstract*— In this letter, we propose a hybrid half-duplex (HD)/full-duplex (FD) relay selection (RS) scheme for buffer-aided (BA) cooperative relaying networks with small buffers that enjoys the adaptability of the Lyapunov optimization framework. The proposed scheme minimizes the overall average delay by controlling the buffer lengths and optimizing the nodes' transmission rates. Due to the separable structure of the formulated problem, the imposed delay by the potential relays is assessed independently, and the relay that causes the least delay is selected. As compared to the existing HD, opportunistic, and hybrid HD/FD BA relaying schemes, simulation results show that the proposed scheme offers a lower average delay if adaptive transmission rate is used. Also, it offers a lower delay at most signal-to-ratio (SNR) regions if fixed rate is adopted.**

***Index Terms*— Relay networks, buffer-aided, Lyapunov.**

I. Introduction

AUGMENTING relays with buffers, or simply, buffer-aided (BA) relaying, can improve the coverage, throughput, and power utilization of relay-assisted communication systems [1]. However, BA relaying results in a higher queuing delay [1]. In that regards, various research works have considered reducing this queuing delay in half-duplex (HD) relaying, along with proper relay selection (RS) to compensate for the loss in spectral efficiency due to the use of HD communication [2], [3], [4], [5], [6], [7]. Considering full-duplex (FD) RS along with the HD one, i.e., hybrid HD/FD RS schemes, can reduce the delay further, as was recently shown in [8]. However, the assumption of fixed transmission rate in [8] limits its utilization in modern communication systems, which are characterized by a wide range of applications and diverse network model assumptions.

Manuscript received 14 October 2023; revised 29 November 2023; accepted 14 December 2023. Date of publication 18 December 2023; date of current version 13 February 2024. The work of Ali A. Siddig and Mahmoud H. Ismail is supported by the Smart Cities Research Institute (SCRI) at the American University of Sharjah under grant EN0281:SCRI18-07 and a Faculty Research Grant number FRG22-C-E13. The work of Ahmed S. Ibrahim is supported in part by the National Science Foundation under Award No. CNS-1816112. The associate editor coordinating the review of this letter and approving it for publication was C. Kundu. *(Corresponding author: Mahmoud H. Ismail.)*

Ali A. Siddig was with the Department of Electrical Engineering, American University of Sharjah, Sharjah, United Arab Emirates. He is now with the Electrical Engineering Department, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates (e-mail: ali.siddig@ku.ac.ae).

Ahmed S. Ibrahim is with the Electrical and Computer Engineering Department, Florida International University, Miami, FL 33174 USA (e-mail: aibrahim@fiu.edu).

Mahmoud H. Ismail is with the Department of Electrical Engineering, American University of Sharjah, Sharjah, United Arab Emirates, and also with the Department of Electronics and Electrical Communications Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt (e-mail: mhiis@cu.edu.eg; mhibrahim@aus.edu).

Digital Object Identifier 10.1109/LCOMM.2023.3343991

Therefore, in this letter, we aim to propose a novel hybrid HD/FD RS mechanism, with variable relay rates, which aims to minimize the overall average delay. The proposed RS scheme is based on the Lyapunov optimization framework [9] and is referred to as Lyapunov-based relay selection (LBRS). LBRS enjoys the *adaptability* of the Lyapunov optimization framework, and it minimizes the overall average delay by controlling the buffer lengths and optimizing the nodes' transmission rates. Furthermore, LBRS enjoys the ability to use arbitrary arriving traffic rates and channels distribution, e.g., possibly unknown distributions.

In more details, based on Lyapunov framework, the delay minimization problem is formulated as a trade-of between queue stability and delay minimization, which is referred to as drift-plus-penalty in the framework [9]. Due to the separable structure of the formulated optimization problem, the imposed delay by the potential relays is assessed independently, and the relay that causes the least delay is selected. The considered cooperative BA-aided network is widely studied in the literature such as the proposed works in [1], [2], [3], [4], [5], [6], [7], and [8]. The main contributions of this letter over related works can be summarized as follows:

1) Unlike the related works that use fixed rate for transmission, the proposed scheme can use an adaptive, fixed or set of fixed rates.
2) By virtue of Lyapunov framework's flexibility, more practical scenarios with arbitrary channels (i.e., possibly unknown distributions) can be covered as will be discussed in Sec. III. On the other hand, all the related works in [1], [2], [3], [4], [5], [6], [7], and [8] entail the knowledge of the channels statistics, e.g., Rayleigh fading.
3) The proposed scheme offers a lower average delay if adaptive transmission rate is used. Also, it offers a lower delay at most SNR regions if fixed rate is adopted.

II. System Model

Fig. 1 introduces a relay-assisted network, which consists of a source S, its destination D, and K relays, $R_1, R_2, \ldots, R_K$. Both the source and destination have a single antenna, while each of the relays has two antennas that enable each relay to have simultaneous transmission and reception, i.e., FD transmission. Each of the K relays employs the decode-and-forward (DF) mechanism. Also, the source node S and each relay R_k are equipped with a data buffer, denoted by Q_s and Q_k, respectively, to be used for storing their incoming packets. Lastly, there is no direct link between the source and its destination (i.e., direct communication is in deep fade). Indeed, the consideration of the direct link means higher

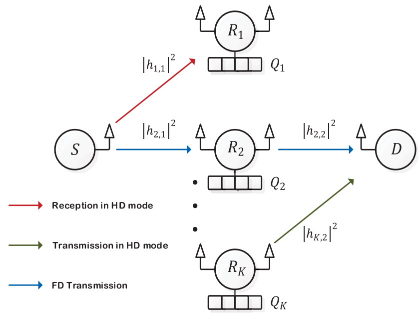

Fig. 1. A schematic of the system model.

spatial diversity (i.e., more links between the source and destination). However, to simplify the design of the proposed scheme and the comparison with the related schemes in [1], [2], [3], [4], [5], [6], [7], and [8], the direct link is assumed to be in a deep fade. Please refer to [10] for further details about the direct link impact.

Wireless links among all communication nodes of Fig. 1 are denoted by $l_{i,j}$, where $i \in \mathcal{K} = \{1, 2, \ldots, K\}$ denotes the group of K relays, and the source and destination are represented by $j = 1$ and $j = 2$, respectively. Time is split into equal slots and in each time slot, one of the relays is selected to work in either HD or FD mode. If the i-th relay, R_i, is selected for transmission, its received signal-to-interference-plus-noise-ratio (SINR) is equal to $\gamma_{i,1} = \frac{P_{i,1}|h_{i,1}|^2}{\beta P_{i,2}|h_{i,\text{SI}}|^2+\sigma_n^2}$ where $P_{i,1}$ and $P_{i,2}$ are the transmission powers by the source and i-th relay, respectively. Also, σ_n^2 is the noise power of the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2. Note that, according to the proposed scheme, the transmission information rate of the selected relay may equal to zero as will be discussed in Sec. IV. In this case, the SNR $\gamma_{i,1}$ is simplified to the HD case, i.e., $\gamma_{i,1} = P_{i,1} |h_{i,1}|^2 / \sigma_n^2$, where the term $\beta P_{i,2} |h_{i,\text{SI}}|^2$ vanishes. Moreover, $|h_{i,\text{SI}}|^2$ is the power of the self-interference (SI) channel of the i-th relay, and β, $0 < \beta \leq 1$, denotes the proportion of SI that remains after cancellation. SI cancellation usually occurs at three levels. First, passive RF isolation such as keeping separation between transmitting and receiving antennas. Second, active analog cancellation, e.g., front-end low-noise amplifier (LNA). Third, using signal processing to cancel the remaining SI. When these three techniques are combined, recent schemes achieved up to 110 dB SI cancellation [11]. The signal-to-noise-ratio (SNR) at the destination is given by $\gamma_{i,2} = \frac{P_{i,2}|h_{i,2}|^2}{\sigma_n^2}$.

It is assumed that the wireless links $l_{i,j}$, $i \in \mathcal{K}, j \in \{1, 2\}$, are subject to channel fading, where the fading coefficients $h_{i,j}$ may follow any known or unknown distribution. Also, $|h_{i,j}|^2$ and $|h_{i,\text{SI}}|^2$ are the channel power gains of the channel $h_{i,j}$ and the SI channel $h_{i,\text{SI}}$, respectively.

III. Problem Formulation

We assume an arbitrary arrival information rate to the network $a_s(t)$ that obeys a Poisson process with mean rate λ. In every time slot t, one of the relay nodes is selected for transmission. The source's and the selected relay's buffers are updated, while no change occurs at the buffers of the non-selected relays. After transmission, the queue of the source node's buffer at is equal to

$$Q_s(t+1) = \max[0, Q_s(t) - r_s(t)] + a_s(t), \tag{1}$$

where $Q_s(t)$ and $Q_s(t+1)$ are the queue states of the source node's buffer at the t-th and $(t+1)$-th slots, respectively. The function $\max[x, y]$ returns the maximum between x and y, and $r_s(t)$ is the transmission rate of the source. Similarly, the queue of the selected relay R_k buffer is given by

$$Q_k(t+1) = \max[0, Q_k(t) - r_k(t)] + r_s(t), \tag{2}$$

where $Q_k(t)$ and $Q_k(t+1)$ are the queue states of the selected relay buffer at the t-th and $(t+1)$-th slots, respectively. $r_k(t)$ is the relay's transmission information rate, respectively. Since the links between the source and the different relays may experience different channel qualities, transmission rates of these links, $r_{s,k}(t), \forall k \in \mathcal{K}$, can be different. The transmission rate of the source is equal to that of the selected relay $r_s(t) = r_{s,k}(t)$. The transmission rates $r_{s,k}(t)$ and $r_k(t)$ can be adaptive depending on the channel states (i.e., Shannon's capacity), fixed or chosen among a set of discrete transmission rates [9]. Note that, unlike the related BA works in [1], [2], [3], [4], [5], [6], [7], and [8] that assume a certain fading model, the proposed scheme can cover applications with unknown channel distribution as long as the instantaneous SNR can be measured and then the rate can be determined according to Shannon's capacity [12], which in turns reflects the *flexibility* of this selection scheme and its suitability for a wide range of applications. In this letter, we use Shannon's capacity and the current buffer states to determine these rates as follows

$$r_{s,k}(t) = \min\left[Q_s(t), \log_2(1 + \gamma_{i,1})\right], \tag{3}$$
$$r_k(t) = \min\left[Q_k(t), \log_2(1 + \gamma_{i,2})\right], \tag{4}$$

where these rates are determined in bits per channel use (BPCU), the function $\min[x, y]$ returns the minimum between x and y, and $\gamma_{i,1}$ and $\gamma_{i,2}$ are as given before.

Based on Little's law [2], the average delay is proportional to the queue length, and the latency requirement can be met by controlling the queue length [13]. To realize that, two thresholds are used to set the maximum allowed queue length Q_{max} and the tolerance probability of violating this length P_{tol} as follows [13, Eq. (10)]

$$\text{Prob}\left\{Q_k(t) \geq Q_{max}\right\} \leq P_{\text{tol}}. \tag{5}$$

According to Markov's inequality, $\text{Prob}\left\{Q_k(t) \geq Q_{max}\right\} \leq \mathbb{E}[Q_k(t)]/Q_{max}$ [13], where $\mathbb{E}[\cdot]$ is the expectation operation. Therefore, the queue length constraint in (5) can be written as

$$\mathbb{E}[Q_k(t)] \leq P_{\text{tol}} Q_{max}, \tag{6}$$

where $\mathbb{E}[Q_k(t)] = \sum_{\iota=1}^{t} r_{s,k}(\iota) - \sum_{\iota=1}^{t} r_k(\iota)$. To satisfy (6), the transmission rate of the relay R_k must be as follows

$$r_k(t) \geq \sum_{\iota=1}^{t} r_{s,k}(\iota) - \sum_{\iota=1}^{t-1} r_k(\iota) - P_{\text{tol}} Q_{max} = r_{min,k}. \tag{7}$$

Similarly, the source node must transmit according to

$$r_s(t) \geq \sum_{\iota=1}^{t} a_s(\iota) - \sum_{\iota=1}^{t-1} r_s(\iota) - P_{\text{tol}} Q_{max} = r_{min,s}. \tag{8}$$

Our goal is to minimize the time-averaged buffering delay, which is equal to the sum of the delay at the source and relay nodes. According to Little's law, the average buffering delay of a given node can be defined as the ratio between the average queue length to the average transmission rate [2, Eq. (30)]. The average queue lengths can be controlled using (7) and (8) to realize the thresholds Q_{max} and P_{tol}. Therefore, the average delay of each node can be minimized by minimizing the inverse of the average transmission rate (i.e., denominator), while the overall average delay can be minimized by minimizing the sum of the inverse of the source's average transmission rate and the inverse of the selected relay's average transmission rate. Hence, the proposed relay selection that minimizes the overall average delay can be formulated as follows

$$\min_{x_k(t),\forall k\in\mathcal{K}} \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T-1}\mathbb{E}\left[\sum_{k=1}^{K}x_k(t)\left(\frac{1}{r_{s,k}(t)}+\frac{1}{r_k(t)}\right)\right], \tag{9a}$$

subject to

$$x_k(t)\, r^o_{min,k} \le r_k(t) \le r_{max,k},\ \forall k\in\mathcal{K}, \tag{9b}$$

$$x_k(t)\, r^o_{min,s} \le r_{s,k}(t) \le r_{max,s},\ \forall k\in\mathcal{K}, \tag{9c}$$

$$x_k(t)\in\{0,1\},\ \forall k\in\mathcal{K}, \tag{9d}$$

$$\sum_{k=1}^{K}x_k(t)\le 1,\ \forall k\in\mathcal{K}, \tag{9e}$$

where T is the overall running time, $r^o_{min,k} = \max[r_{min}, r_{min,k}]$ and $r_{min,k}$ is given in (7). Similarly, $r^o_{min,s} = \max[r_{min}, r_{min,s}]$ and $r_{min,s}$ is given in (8). The constraints in (9d) and (9e) ensure that the selection variables x_k, $k\in\mathcal{K}$, are binary variables and only one relay is selected in every time slot. Also, the constraints in (9b) and (9c) ensure that the queue length constraints are fulfilled at the selected relay and the source node. Since the assumptions of the Lyapunov framework necessitate that the rates $r_k(t)$ and $r_{s,k}(t)$ must be bounded, we used the bounds $r_{max,k}$, $r_{max,s}$ and r_{min}. The values of these bounds can be set based on the application [14].

IV. Proposed Lyapunov Framework Solution

In this section, the delay minimization problem in (9) is tackled according to the Lyapunov optimization framework in [9]. For each relay R_k, we introduce the auxiliary variable $\psi_k(t)$ that satisfies

$$\overline{\psi}_k = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T-1}\mathbb{E}\left[\psi_k(t)\right]\le \overline{r}_k, \tag{10}$$

where $\overline{r}_k = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T-1}\mathbb{E}\left[r_k(t)\right]$. Henceforth, we use $\overline{x}$ to indicate to the time-averaged value of x, and the term "auxiliary variable" to denote a new variable that is defined to help transforming, and then solving the optimization problem [9]. To enforce that $\overline{\psi}_k \le \overline{r}_k$, we define the virtual queue

$$H_k(t+1) = \max\{0, H_k(t) + x_k(t)[\psi_k(t) - r_k(t)]\}, \tag{11}$$

where the virtual queue changes only if the relay R_k is selected. Similarly, for the source node we define

$$\overline{\psi}_s = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T-1}\mathbb{E}\left[\psi_s(t)\right]\le \overline{r}_s, \tag{12}$$

where $\overline{r}_s = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T-1}\mathbb{E}\left[r_s(t)\right]$, and the transmission rate of the source $r_s(t)$ is equal to that of the selected relay, i.e., $r_s(t) = \sum_{k=1}^{K}x_k(t)r_{s,k}(t)$. To enforce that $\overline{\psi}_s \le \overline{r}_s$, we define the virtual queue

$$H_s(t+1) = \max\{0, H_s(t) + \sum_{k=1}^{K}x_k(t)[\psi_{s,k}(t) - r_{s,k}(t)]\}, \tag{13}$$

where $\psi_s(t) = \sum_{k=1}^{K}x_k(t)\psi_{s,k}(t)$. The virtual queue of the source node changes based on which relay will be selected.

The Lyapunov function can now be defined as

$$F(t) = \frac{1}{2}H_s(t) + \frac{1}{2}\sum_{k=1}^{K}H_k(t), \tag{14}$$

and the Lyapunov drift-plus-penalty function is given by

$$\begin{aligned} G(t) &= \mathbb{E}\{F(t+1) - F(t)\} \\ &\quad + V\mathbb{E}\left\{\sum_{k=1}^{K}\left(\frac{1}{\psi_{s,k}(t)} + \frac{1}{\psi_k(t)}\right)\right\}, \end{aligned} \tag{15}$$

where $V \ge 0$ is a control parameter for the trade-off between network stability and minimizing the average delay. The performance-backlog trade-off obeys $[O(1/V), O(V)]$ [9]. For instance, we use $V = 0$ for delay insensitive applications, while increasing V helps the minimization of the delay. Using the fact that $(\max\{0, a-b\}+c)^2 \le a^2 + b^2 + c^2 + 2a(c-b)$ for $a,b,c \ge 0$, the upper bound of $G(t)$ can be written as $G(t) \le C + \mathbb{E}\{\theta(t)\}$ [13] where $C = \frac{1}{2}\mathbb{E}\left\{\psi_s^2(t) + r_s^2(t) + \sum_{k=1}^{K}\psi_k^2(t) + r_k^2(t)\right\}$ is a constant, while $\theta(t) = H_s(t)(\psi_s(t) - r_s(t)) + \frac{V}{\psi_s(t)} + \sum_{k=1}^{K}H_k(t)(\psi_k(t) - r_k(t)) + \frac{V}{\psi_k(t)}$. Using the fact that the virtual queue $H_s(t)$ is changed by the selected relay R_k only, i.e., $r_s(t) = \sum_{k=1}^{K}x_k(t)r_{s,k}(t)$ and $\psi_s(t) = \sum_{k=1}^{K}x_k(t)\psi_{s,k}(t)$, we can rewrite $\theta(t)$ as $\theta(t) = \sum_{k=1}^{K}x_k(t)(\theta_{s,k}(t) + \theta_k(t))$, where $\theta_k(t)$ and $\theta_{s,k}(t)$ are defined to enhance the presentation of the problem as follows

$$\theta_k(t) = H_k(t)(\psi_k(t) - r_k(t)) + \frac{V}{\psi_k(t)}, \tag{16}$$

$$\theta_{s,k}(t) = H_s(t)(\psi_{s,k}(t) - r_{s,k}(t)) + \frac{V}{\psi_{s,k}(t)}. \tag{17}$$

Now, we are ready to solve the Lyapunov- based problem in (9) by minimizing the upper bound of the Lyapunov drift-plus-penalty function as follows

$$\min_{\{x_k(t),\psi_{s,k}(t),\psi_k(t),\forall k\in\mathcal{K}\}} \sum_{k=1}^{K} x_k(t)\left(\theta_{s,k}(t)+\theta_k(t)\right) \quad \text{(18a)}$$

subject to

$$x_k(t)\,\psi^o_{min,k} \le \psi_k(t) \le r_{max,k}, \quad \forall k\in\mathcal{K}, \quad \text{(18b)}$$

$$x_k(t)\,\psi^o_{min,s} \le \psi_{s,k}(t) \le r_{max,s}, \quad \forall k\in\mathcal{K}, \quad \text{(18c)}$$

$$x_k(t)\in\{0,1\},\ \forall k\in\mathcal{K}, \quad \text{(18d)}$$

$$\sum_{k=1}^{K} x_k(t) \le 1,\ \forall k\in\mathcal{K}. \quad \text{(18e)}$$

The constraints in (18b) and (18c) ensure that the queue length constraints are fulfilled at the selected relay and the source node, respectively, where $\psi^o_{min,k} = \max[r_{min}, \sum_{\iota=1}^{t} r_{s,k}(\iota) - \sum_{\iota=1}^{t-1}\psi_k(\iota) - P_{\text{tol}}\,Q_{max}]$ and $\psi^o_{min,s} = \max[r_{min}, \sum_{\iota=1}^{t} a_s(\iota) - \sum_{\iota=1}^{t-1}\psi_s(\iota) - P_{\text{tol}}\,Q_{max}]$.

As can be seen from the problem in (18), the overall delay, which arises from the selection of a relay R_k, is independent of the information related to any other relay, e.g., their buffer states or links qualities. Due to the separability of the problem, for a known relay selection decision $x_k(t), \forall k\in\mathcal{K}$, we will first find the solution for $\psi_{s,k}(t)$ and $\psi_k(t)$. Then, we find $x_k(t)$ by selecting the relay that minimizes the overall buffering delay the most.

First, for a given decision (i.e., known $x_k(t), \forall k \in \mathcal{K}$), we solve the following problem

$$\min_{\psi_{s,k}(t),\psi_k(t)} \theta_{s,k}(t)+\theta_k(t) \quad \text{(19a)}$$

subject to

$$\psi^o_{min,k} \le \psi_k(t) \le r_{max,k}, \quad \text{(19b)}$$

$$\psi^o_{min,s} \le \psi_{s,k}(t) \le r_{max,s}. \quad \text{(19c)}$$

If $H_k(t) = 0$ or $V = 0$, $\psi^*_k(t)$ is equal to $r_{max,k}$ and $\psi^o_{min,k}$, respectively. Otherwise, since the solution region is limited to $\psi^*_k(t) \in [\psi^o_{min,k}, r_{max,k}]$ and the solution is not very sensitive (i.e., a small change in $\psi_k(t)$ leads to a small change in $\theta_k(t)$), a grid search in the range $[\psi^o_{min,k}, r_{max,k}]$ can be done to find $\psi^*_k(t)$. Similarly, $\psi^*_{s,k}(t)$ can be found. In particular, if $H_s(t) = 0$ or $V = 0$, $\psi^*_{s,k}(t)$ is equal to $r_{max,s}$ and $\psi^o_{min,s}$, respectively. Otherwise, a grid search in the range $[\psi^o_{min,s}, r_{max,s}]$ must be conducted to find $\psi^*_{s,k}(t)$.

Second, we solve for $x_k(t)$ by selecting the relay that minimizes the overall delay the most as follows

$$\arg\min_{\{x_k(t),\forall k\in\mathcal{K}\}} x_k(t)\left(\theta_{s,k}(t)+\theta_k(t)\right). \quad \text{(20)}$$

After selecting one of the relays using (20), we update the actual queues in (1) and (2) as well as the virtual queues in (10) and (12). To make the implementation of the proposed scheme straightforward, Algorithm 1 is presented. The proposed scheme works in FD mode except for the following cases where it works in HD mode: If adaptive transmission rate is adopted and the transmission rates $r_{s,k}$ and r_k, which are given by (3) and (4), respectively, are equal to zero or if fixed transmission rate r_0 is considered and the maximum possible rate according to Shannon's capacity was smaller than r_0 as stated in Step 2 in Algorithm 1.

Algorithm 1 Proposed Relay Selection Scheme

1: **Inputs**: K, λ, P_{tol}, Q_{max}, β, r_{min}, $r_{max,k}$ and $r_{max,s}$.
2: Determine the rates $r_{s,k}$ and r_k using (3) and (4), respectively. If a fixed rate r_0 is assumed, then $r_k = r_{s,k} = r_0$ as long as r_0 is not greater than the rates according to (3) and (4). Otherwise, the corresponding rate is equal to zero. For instance, if $r_k < r_0$, then we set $r_k = 0$.
3: Find $\psi^o_{min,k}$ and $\psi^o_{min,s}$ as described below (18).
4: **for** $k = 1$ to K **do**
5: Use grid search to find $\psi^*_{s,k}(t)$ and $\psi^*_k(t)$, where $\psi^*_k(t) \in [\psi^o_{min,k}, r_{max,k}]$ and $\psi^*_{s,k}(t) \in [\psi^o_{min,s}, r_{max,s}]$.
6: Compute $\theta_{s,k}(t)+\theta_k(t)$ using (16) and (17).
7: **end for**
8: Select the relay with minimum $\theta_{s,k}(t)+\theta_k(t)$.
9: Only for the selected relay R_k, update the actual queues in (1) and (2), and the virtual queues using (10) and (12).

V. Simulation Results and Discussion

The average delay performance of the proposed LBRS scheme is now assessed. In all simulations, we used $r_{max,k} = r_{max,s} = 1.2\lambda$, $r_{min} = 0$, $P_{\text{tol}} = 0.1$ and $Q_{max} = 10$, where the values of these parameters should be set based on the application [14]. To find $\psi^*_{s,k}(t)$ and $\psi^*_k(t)$, a grid search with a step size 0.1 is used. The residual SI factor β is equal to 10^{-9} unless mentioned otherwise. To compare with the hybrid scheme in [8], we assume that all the channel fading coefficients follow Rayleigh block fading, and hence are modeled as circularly symmetric complex Gaussian random variables with zero mean and variances $\sigma^2_{i,j}$, i.e., $h_{i,j} \sim \mathcal{CN}(0,\sigma^2_{i,j})$. Also, the used variances for the links are $\sigma^2_{i,1} = \{0.18, 0.81, 0.43, 0.76\}$ and $\sigma^2_{i,2} = \{0.97, 0.49, 0.79, 0.37\}$.

First, simulations with $K = 2$ relays and arrival rates per slot $\lambda \in \{1,2,3\}$ were performed. As obviously seen in Fig. 2(a), the average delay increases as the arrival rate increases. Under a limited maximum transmit power, it is difficult to meet the latency requirement at very high traffic (i.e., large λ). For instance, if the delay bound is equal to the duration of 10 slots, we have to use a transmission power $P \approx 5, 11$ and 15 dB for data arrival with means $\lambda = 1, 2$ and 3, respectively. This reveals that we need a trade-off between latency and data arrival rate for systems with power consumption constraints.

Also, Fig. 2(a) shows the impact of the control constant V on the performance of the proposed scheme. As mentioned in Sec. IV, the penalty-backlog trade-off obeys $[O(1/V), O(V)]$. Therefore, the overall average delay (i.e., the penalty) decreases as V increases [9]. Therefore, the delay, i.e., the penalty, is degraded as V decreased from $V = 100$ to $V = 0$. Moreover, when the residual SI is increased from $\beta = 10^{-9}$ to $\beta = 0.2$, the average delay increased. This is quite expected since increasing β decreases the SINR, hence, the FD utilization decreases, which in turns negatively affects

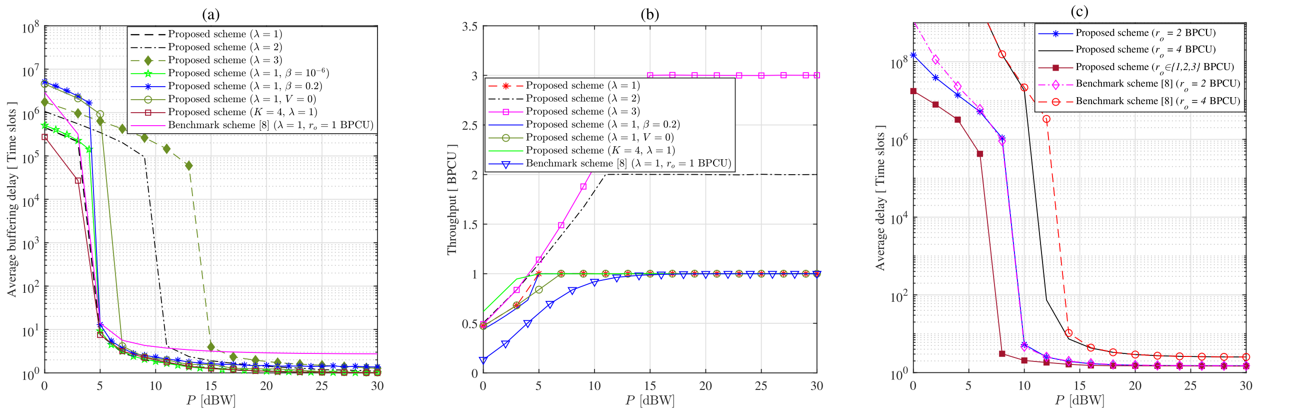

Fig. 2. a) The average delay of the LBRS scheme, b) The average throughput of the LBRS scheme, c) The impact of using fixed transmission rate r_0 on the average throughput.

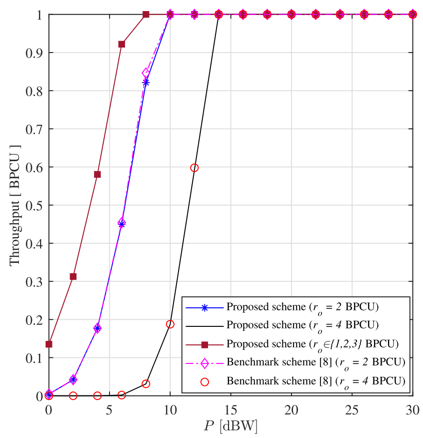

Fig. 3. The impact of using fixed transmission rate r_0 on the average throughput.

the average delay and the transmission rate as shown in Figs. 2. In addition, Fig. 2(a) shows the impact of the number of relays on the average delay. Using more relays leads to a greater spatial diversity, i.e., more potential relays for selection, and the one that minimizes the average delay the most will be selected from a larger set. Therefore, as expected, when the number of relay is increased from $K = 2$ to $K = 4$, the average delay dropped significantly.

As shown in Figs. 2(a,b), the proposed scheme offers a lower average delay and a higher throughput as compared to the scheme in [8]. However, adaptive transmission rates are adopted in the previous results of the proposed scheme while a fixed rate is used in [8]. For fair comparison, fixed transmission rate r_0 will be adopted next, which shows the flexibility of the proposed scheme.

Simulation with setting $K = 2$, $\lambda = 1$ and fixed rate $r_0 = 2$ was also performed. As discussed in Sec. III, according to Little's law, the average delay can be defined as the ratio between the average queue length to the average transmission rate. As shown in Fig 3, the two schemes offer comparable average throughput. However, by virtue of the queue length constraints in (19b) and (19c), the proposed LBRS scheme ensure low average queue length at all nodes, which in turns leads to a lower average delay at most SNR as shown in Fig. 2(c). When a set of discrete rates is considered $r_0 \in \{1, 2, 4\}$, the performance of the proposed scheme significantly improved, where at poor channel states, a low rate can be used, e.g., $r_0 = 1$, and outage events can be avoided. At high SNR, a higher rate can be adopted to improve the performance. We note that our goal is to minimize the delay, if the throughput is prioritized, the objective function in (9) should be replaced with the sum of the rates instead of their inverses.

REFERENCES

[1] N. Nomikos et al., "A survey on buffer-aided relay selection," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1073–1097, 2nd Quart., 2016.
[2] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5430–5439, Oct. 2015.
[3] B. R. Manoj, R. K. Mallik, and M. R. Bhatnagar, "Performance analysis of buffer-aided priority-based max-link relay selection in DF cooperative networks," *IEEE Trans. Commun.*, vol. 66, no. 7, pp. 2826–2839, Jul. 2018.
[4] N. Nomikos, D. Poulimeneas, T. Charalambous, I. Krikidis, D. Vouyioukas, and M. Johansson, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," *IEEE Access*, vol. 6, pp. 73531–73547, 2018.
[5] M. Oiwa and S. Sugiura, "Reduced-packet-delay generalized buffer-aided relaying protocol: Simultaneous activation of multiple source-to-relay links," *IEEE Access*, vol. 4, pp. 3632–3646, 2016.
[6] A. A. M. Siddig and M. F. M. Salleh, "Buffer-aided relay selection for cooperative relay networks with certain information rates and delay bounds," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10499–10514, Nov. 2017.
[7] A. A. M. Siddig and M. F. M. Salleh, "Balancing buffer-aided relay selection for cooperative relaying systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8276–8290, Sep. 2017.
[8] A. A. Siddig, A. S. Ibrahim, and M. H. Ismail, "A low-delay hybrid half/full-duplex link selection scheme for cooperative relaying networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 10, pp. 11174–11188, Oct. 2022.
[9] M. J. Neely, "Stochastic network optimization with application to communication and queueing systems," *Synth. Lectures Commun. Netw.*, vol. 3, no. 1, pp. 1–211, Jan. 2010.
[10] T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas, and M. Johansson, "Modeling buffer-aided relay selection in networks with direct transmission capability," *IEEE Commun. Lett.*, vol. 19, no. 4, pp. 649–652, Apr. 2015.
[11] C. Campolo, A. Molinaro, A. O. Berthet, and A. Vinel, "Full-duplex radios for vehicular communications," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 182–189, Jun. 2017.
[12] S. Supittayapornpong and M. J. Neely, "Quality of information maximization for wireless networks via a fully separable quadratic policy," *IEEE/ACM Trans. Netw.*, vol. 23, no. 2, pp. 574–586, Apr. 2015.
[13] Y. Chen, Y. Wang, M. Liu, J. Zhang, and L. Jiao, "Network slicing enabled resource management for service-oriented ultra-reliable and low-latency vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 7847–7862, Jul. 2020.
[14] T. K. Vu, C.-F. Liu, M. Bennis, M. Debbah, M. Latva-aho, and C. S. Hong, "Ultra-reliable and low latency communication in mmWave-enabled massive MIMO networks," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 2041–2044, Sep. 2017.