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Review Paper

Buffer-Aided Relaying: A Survey on Relay Selection Policies

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Abstract: Ever since the idea of buffers was incorporated in wireless communications, buffer-aided relaying has become an emerging breakthrough in the world of transmitting and receiving signals. Equipping the relays with buffers adds a new degree of freedom capable of enhancing numerous Quality-of-Service (QoS) metrics including throughput, outage probability, power efficiency and physical-layer security. The QoS enhancement is achieved by compromising the end-to-end delay that is inflicted by storing the packets in the relays' buffers until a suitable source-relay or relay-destination link is selected. In this context, the selection of a relay for transmission/reception is important since it governs the QoS-delay trade-off that can be contemplated. In this survey, we review and analyze various link selection protocols in buffer-aided relaying systems. These relaying strategies are categorized and contrasted according to their performance levels, limitations, applications, system model assumptions and complexity. Finally, we discuss current challenges, and highlight future research directions.

I Introduction

Cooperative relaying is employed to improve the performance of wireless networks where the relays assist a source in its communications with a destination. Relaying was first considered with buffer-free relays where predefined two-slot static scheduling was assumed. For this type of scheduling, a message is transmitted from the source to a relay in the first time slot while this relay retransmits a regenerated message to the destination in the second time slot. In contrast to buffer-free relaying, more recent references revolved around buffer-aided (BA) relaying where the relays are equipped with buffers [1]. This constitutes an additional degree of freedom where the relays can store the messages and retransmit them only when the channel conditions are favorable. Consequently, the static scheduling constraint can be leveraged in favor of dynamic scheduling where a relay can receive over several consecutive time slots (and store the messages in the buffer) while another relay can transmit over several consecutive time slots (by extracting messages from its buffer). This contributes to enhancing the reliability of the network at the expense of inflicting queuing delays because of data buffering.

In cooperative communication, there exist two relaying protocols. The protocols are identified according to how a relay executes its reception and transmission. These protocols might be Half-Duplex (HD) relaying or Full-Duplex (FD) relaying. In FD relaying, only one channel is utilized since a relay transmits and receives simultaneously in the same frequency band. But, FD relaying increases complexity and introduces Loop-Interference (LI), making it difficult to implement in practice [1]. The majority of the literature related to cooperative communication employs HD relaying due to its simple implementation. In HD relaying, orthogonal channels are needed, and transmission is usually prearranged in two successive time slots: during the first time slot, the relay receives a packet from the source; during the second time slot, the relay sends a packet to the destination. This type of relaying, referred to as conventional relaying, reduces spectral efficiency and performance rates, as it may prevent the relay from choosing the best channels for transmission and reception [2]. One way to recover from loss is to exploit Successive Relaying (SuR), where HD relays mimic FD relays at the cost of Inter-Relay Interference (IRI). This IRI is caused by the instantaneous transmissions [3]. Efficient IRI mitigation techniques are encouraged to reduce performance degradation.

One important performance metric is the secrecy rate, where employing the relay with the maximum secrecy rate or the relay that acts as a jammer to the eavesdropper, boosts the reliability of data exchange. Yet, the wait for preferable channel conditions introduces a delay to the system, even if it increases the system's throughput and outage probability. Consequently, a trade-off occurs between throughput and delay. Another drawback is the increased complexity compared with conventional non-buffer aided relays, since buffer-aided protocols require Channel State Information (CSI) and, sometimes, Buffer State Information (BSI) and Energy State Information (ESI), to select the best relay for transmission.

Several research efforts have been made to understand and summarize the different BA selection schemes. In [1], the authors present and classify BA relay selection policies and offer a family of hybrid BA selection algorithms. They also provide a framework for modeling BA relay selection algorithms, evaluate them, and explore applications that are related to cognitive radio and physical layer security. Our survey is motivated by the large number of papers that appeared recently in the literature and by the absence of a new survey that reviews them, to the best of our knowledge. As such, the main contributions of this manuscript are:

- Several max-link relay selection policies and buffer state-based schemes are discussed and compared; the policies offer a compromise between outage probability, average packet delay, and system throughput.
- BA relay selection schemes are introduced, taking into consideration the buffer size and energy capacity. The policies are compared based on outage probability, energy efficiency, system throughput, and delay.
- The novel BA non-orthogonal multiple-access (NOMA) schemes are evaluated and contrasted. These schemes that enhance the system throughput and decrease the packet delay were never discussed before in a survey, to the best of our knowledge.
- This survey complements the existing surveys by covering the following four new topics. (i): The enhanced security levels that can be achieved through equipping the relays with buffers. (ii): Energy harvesting (EH) where the relays can harvest *free* energy from the information-carrying signals transmitted by the source.(iii): Hybrid Radio Frequency/Free-Space Optical (RF/FSO) systems that take advantage from the broadcast nature of RF transmissions and from the high data rates that can be reaped from FSO communications. (iv): Unmanned Aerial Vehicles (UAV) with BA relays are considered to enhance the energy efficiency, network coverage and the security performance. In this context, physical layer security and EH

are attracting lots of research recently while the hybrid RF/FSO communications and UAVs constitute important emerging technologies for fifth generation (5G) networks. While security was addressed broadly in [1], the topics of EH, hybrid RF/FSO and UAVs with BA relays were never reviewed before in a survey paper.
- Finally, this survey states current challenges and future research paths that should be tackled.

In this survey, we present several buffer-aided relaying schemes as they are crucial in the fifth generation (5G) networks, as well as vehicular applications. A description is given for various types of buffer-aided protocols for HD, FD and hybrid (combining HD and FD) relays. Moreover, the motivation behind some protocols is given, as well as their goals, limitations and comparison with other protocols. The remainder of this survey is as follows. Firstly, the different system models adopted by the schemes are introduced in Section II. Secondly, the evolution of the track of research for buffer-aided relay systems is given in section III. The stated tracks are elaborated in the subsequent sections. In Section IV, a review of max-link selection policy and its comparison with different schemes are presented. Then, in Section V, a similar mechanism is performed for buffer state-based schemes. Next, Sections VI and VII analyze buffer-aided protocols, taking into consideration the energy storage and Buffer-Aided Non-Orthogonal Multiple Access (NOMA) relay policies, respectively. The security analysis for different schemes is presented in Section VIII. While in Section IX, Buffer-Aided Relay Selection Schemes for Hybrid Radio Frequency/Free-Space-optical (RF/FSO) Systems are presented. Section X introduces a relatively new concept, which is exploiting Unmanned Aerial Vehicles (UAVs) in buffer-aided wireless communications. Section XI includes some numerical results. Finally, Section XII states challenges and possible studies that must be addressed in the future, and conclusions are given in Section XIII.

II System Models

In this section, five different system models will be tackled. All models consist of one or more decode-and-forward relay(s) where the communication between the source and the destination(s) is only possible through the relay(s), and the channels suffer from Additive White Gaussian Noise. The first four models tackle half-duplex relay(s), where a new different aspect is studied in each. Starting with employing buffers in model II.1 with one destination, II.2 studies the communication between the source and two destinations where the buffers at the relays will be equally allocated to both destinations. In model II.3, an energy buffer is added at the level of each the source and relay. In this case, the received RF signal at the relay will be split according to a Power Splitting protocol between energy harvesting and information decoding. Due to the broadcasting nature of the wireless channel, eavesdroppers can potentially obstruct the transmissions in the networks. Hence, recent work paid much attention to security at the physical layer and the model in II.4 depicts this aspect where an eavesdropper has been added to the model. Another research attraction is looking for high speed wireless transmissions due to the ever-growing demands for high spectrum requirements that fulfill the fifth generation mobile applications. The model in II.5 covers this aspect as it illustrates a hybrid RF/FSO network, where the system takes advantage of both the high data rates provided by the FSO links and the RF links' reliability.

II.1 Relay Assisted Networks

We consider a wireless network where a source S communicates with a destination D through K Half-Duplex (HD) Decode-and-Forward (DF) relays as highlighted in figure 1. We assume that no direct link is available between S and D. A buffer Q_k is employed for each relay of length L (each buffer can fit L packets at most). The buffers are able to store the data, which have been sent from the source and decoded at the relay, and forward them to the destination, upon selecting the link for transmission. The source node is considered saturated, i.e. it always has data to send. But, the quality of the channels is worsened due to the Additive White Gaussian Noise (AWGN) and frequency non-selective Rayleigh block fading, according to a complex Gaussian distribution with zero-mean and variance σ_{ij}^2 for the $\{i \rightarrow j\}$ link. For simplicity, the AWGN is presumed to be normalized with zero-mean and unit variance. Time is divided into slots, during which the source or one of the relays tries to transmit a packet. In each time slot i, the channel gains of the S-R link and R-D link are symbolized by $h(i)$ and $g(i)$, respectively. All links are assumed independent and identically distributed (i.i.d) channels, where the channel gains are mutually independent complex Gaussian distributed random variables. This implies that the channel coefficients change independently from one slot to another, but remain constant within one slot. Denote by P/N_0 the unfaded SNR, where P is the constant transmit power and N_0 is the AWGN power. Both powers are assumed to be identical to all nodes. Hence, The instantaneous SNR of the $S - R_i$ and $R_i - D$ links are $\gamma_{g_i} = |g_i|^2(P/N_0)$ with mean $\bar{\gamma}_{g_i}$ and $\gamma_{h_i} = |h_i|^2(P/N_0)$ with mean $\bar{\gamma}_{h_i}$, respectively.

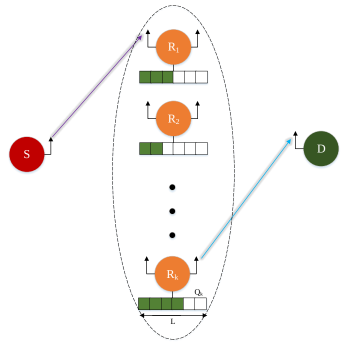

Fig. 1: Relay-Assisted Network with Buffers Model

II.2 Non-Orthogonal Multiple Access Networks

The Non-Orthogonal Multiple Access (NOMA) relay-assisted network, presented in figure 2, consists of one source S, two destinations, D_1 and D_2, and a cluster of K HD DF relays, where each relay is supplied with a buffer Q_k of size L. Each buffer is equally allocated to D_1 and D_2. The only way of communication between the source and the destinations nodes is through the relays as no direct link is available between them, due to severe fading. Similar to figure 1, the wireless channels' quality is worsened due to AWGN and frequency non-selective Rayleigh block fading, according to a complex Gaussian distribution with zero-mean and variance σ^2 for the $\{i \rightarrow j\}$ link. For simplicity, the AWGN is presumed to be normalized with zero-mean and unit variance. Time is divided into slots, during which the saturated source or one of the relays tries to transmit a packet. The channel gain, $g_{ij} \triangleq |h_{ij}|^2$, is also assumed to be exponentially non-identically distributed. The source is assumed to always have data to send and the required information rate, r_i, for successful reception at each destination, D_i where $i \in \{1, 2\}$, is fixed, but might differ from each other depending on the application. A transmission from a transmitter i to its corresponding receiver j is said to be successful if: SNR $\Gamma_{ij} \geq \gamma_j$, where the latter symbol corresponds to the capture ratio that depends on the modulation and coding characteristics of the application. The transmitter attempts to send a packet using a fixed power level $P_i, i \in \{S, R_i, ..., R_K\}$. The variance of the thermal noise at relay R_k is assumed to be AWGN, and it is represented by σ_k^2. In order to avoid starvation or overflow of the buffers, the source transmits with rate $r_1 + r_2$. Thus,

$$\Gamma_{SR_k}(P_S) \triangleq \frac{g_{SR_k} P_S}{\sigma_k^2} \geq 2^{r_1+r_2} - 1. \quad (1)$$

On the other hand, in case of transmission in the $R_k - D$ link, if NOMA transmission is performed and the information symbols of D_1 and D_2 are superimposed. Specifically, the superimposed symbol

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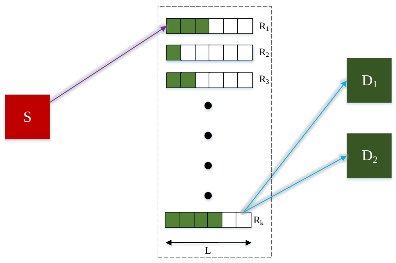

Fig. 2: NOMA System with Buffers Model

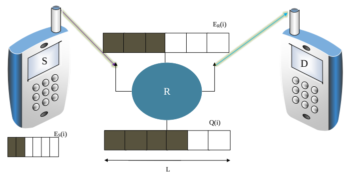

Fig. 3: Relaying System with Energy Harvesting Model

consisting of the information symbols x_1 and x_2 of each destination, is given by:

$$x = \sqrt{\alpha}x_1 + \sqrt{1-\alpha}x_2, \tag{2}$$

with $0 \leq \alpha \leq 1$. Then D_1 will receive an information symbol y_1 containing the desired symbol, as well as the symbol of D_2:

$$y_1 = h_{R_k D_1}\sqrt{\alpha P_{R_k}}x_1 + h_{R_k D_1}\sqrt{(1-\alpha)P_{R_k}}x_2 + \eta_1; \tag{3}$$

similarly, the received information symbol y_2 at D_2 is:

$$y_2 = h_{R_k D_2}\sqrt{\alpha P_{R_k}}x_1 + h_{R_k D_2}\sqrt{(1-\alpha)P_{R_k}}x_2 + \eta_2, \tag{4}$$

where η_1 and η_2 denote the AWGN at each destination.

II.3 Energy Harvesting Networks

This network consists of a source S, a HD DF buffer-aided relay R, and a destination D, with a single antenna each. The source and destination nodes communicate via the relay only. Time is equally divided into slots of length T and the two links suffer from block fading. The channel gains of the $S-R$ and $R-D$ links are denoted by $h(i)$ and $g(i)$, respectively. As observed in figure 3, the source and relay are energy harvesting nodes, i.e. the nodes are obliged to harvest ambient energy as their energy supply. The source collects energy with a constant rate H_S. In each time slot, the source harvested energy is $H_S T$. While, the relay harvests energy from the source RF signal with the Simultaneously Wireless Information and Power Transfer (SWIPT) scheme, which means that the received signal at the relay will be used for both information decoding and energy harvesting based on the Power Splitting (PS) protocol where θ fraction of the received signal will be used for energy harvesting, while the remaining $1-\theta$ fraction is used for information decoding, where $\theta \in [0,1]$ is the PS factor. Consequently, both S and R nodes are supplied with an energy buffer, to store the harvested energy during each time slot, where $E_s(i)$ and $E_r(i)$ denote the corresponding buffer states in time slot i, of each S and R, respectively. Additionally, the relay is equipped with a data buffer, which state is denoted by Q_i in time slot i.

II.4 Relay-Assisted Network with an Eavesdropper

A two-hop wireless network is considered with one source S, one destination D, K HD DF relays in addition to an eavesdropper E

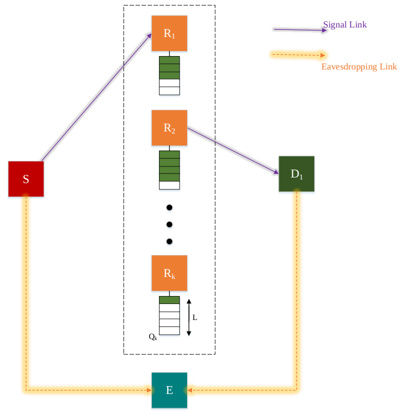

Fig. 4: Relay Assisted Network with Eavesdropper Model

who is able to seize the information from the source-relay and relay-destination links. Relay k is equipped with buffer Q_k. The S, D and E nodes are assumed to have one antenna, while the relays are equipped with N_R antennas. The relays are the only way of communication between the backlogged source, which always has packets to transmit, and the destination D. This is displayed in figure 4. The channel gains are independent and identically distributed (i.i.d.), where the channels suffer from a quasi-static Rayleigh block fading and discrete-time AWGN. The average per-antenna SNR of the $m-n$ links is denoted by $\bar{\gamma}_{mn}$:

$$\bar{\gamma}_{mn} = \begin{cases} E(P_S|h_{SR_{i,j}}(t)|^2/\sigma_R^2), & m = S, n = R; \\ E(P_S|h_{SE}(t)|^2/\sigma_E^2), & m = S, n = E; \\ E(P_R|h_{R_{i,j}D}(t)|^2/\sigma_D^2), & m = R, n = D; \\ E(P_R|h_{R_{i,j}E}(t)|^2/\sigma_E^2), & m = R, n = E, \end{cases} \tag{5}$$

where P_A is the transmit power of $A, A \in \{S, R\}$, σ_B^2 is the variance of AWGN at $B, B \in \{R, E, D\}$, $R_{i,j}$ represents the j^{th} antenna of the i^{th} relay R_i, and $h_{AB}(t)$ is the complex Gaussian channel between A and B at time t. Eventhough the channel gains are assumed to be i.i.d, any two SNRs are not necessarily identical.

II.5 Hybrid Radio Frequency/Free-Space Optical Network

Figure 5 is an illustration of a two-hop two-way hybrid Radio Frequency/Free-Space Optical (RF/FSO) network involving K mobile users, one un-coded DF relay node R, and a base station B with optical transmitter and detector. The mobile users are linked to the relay through asymmetric RF links, while R and B are connected via asymmetric FSO links. Each node has one single transmitting and receiving antenna for the RF links and one single transmitting and detecting optical aperture for the FSO links. In addition, heterodyne detection is applied as it provides a better background noise rejection and spectral efficiency as compared to intensity modulation with direct detection.

II.5.1 Radio Frequency Link: The received RF signals at the relay and the i_{th} user ($i \in \{1, ..., K\}$), U_i, are, respectively:

$$y_R^{RF} = \sqrt{P_{U_i}}h_{U_i,R}x_{U_i} + n_R, \tag{6}$$

$$y_{U_i}^{RF} = \sqrt{P_R}h_{R,U_i}x_R^{RF} + n_{U_i}, \tag{7}$$

where

- P_{U_i} and P_R represent the average transmitted electrical powers of U_i and R, respectively.
- $h_{U_i,R}$ and $h_{/R,U_i}$ denote the channel coefficients of the $U_i - R$ and $R - U_i$ links, respectively.

• x_{U_i} and x_R^{RF} are the transmitted symbols of U_i and R at the $R-U_i$ RF link, respectively, with $\mathbb{E}\left\{|x_{U_i}|^2\right\} = \mathbb{E}\left\{|x_R^{RF}|^2\right\} = 1$.
• n_R and n_{U_i} are the AWGN terms at the input of R and U_i with power spectral densities N_R^1 and N_{U_i}, respectively.

The instantaneous SNR expressions at the input of R and U_i are $\gamma_{U_i,R} = \frac{P_{U_i}}{N_R^1}|h_{U_i,R}|^2$ and $\gamma_{R,U_i} = \frac{P_R}{N_{U_i}}|h_{R,U_i}|^2$, respectively. In the RF link, $h_{U_i,R}$ and $h_{/R,U_i}$ follow Rayleigh fading model, and in accordance, the gains $|h_{U_i,R}|^2$ and $|h_{R,U_i}|^2$ are exponentially distributed random variables with mean powers $\Omega_{U_i,R}$ and Ω_{R,U_i} correspondingly. The probability density function (PDF) and cumulative distribution function (CDF) of $\gamma_{U_i,R}$ and γ_{R,U_i} are, respectively

$$f_{\gamma_{x,y}}(\gamma_{x,y}) = \lambda_{x,y} exp(-\lambda_{x,y}\gamma_{x,y}), \tag{8}$$

$$F_{\gamma_{x,y}}(\gamma_{x,y}) = 1 - exp(-\lambda_{x,y}\gamma_{x,y}), \tag{9}$$

with $\lambda_{x,y} = 1/\bar{\gamma}_{x,y}$, where $\bar{\gamma}_{x,y} = \mathbb{E}\left\{\gamma_{x,y}\right\} = \frac{P_x}{N_y}\Omega_{x,y}$ and $(x,y) \in \{(U_i,R),(R,U_i)\}$

II.5.2 Free Space Optical Link: The received optical signals at R and B, are, respectively:

$$y_R^{Opt} = g_{B,R}\left\{\sqrt{P_B^{Opt}}(1+\mathcal{M}_1 x_B)\right\} + n_R, \tag{10}$$

$$y_B^{Opt} = g_{R,B}\left\{\sqrt{P_R^{Opt}}(1+\mathcal{M}_2 y_R^{RF})\right\} + n_B, \tag{11}$$

where

• P_B^{Opt} and P_R^{Opt} are the average transmitted optical powers of B and R, respectively, which are related to the electrical powers of B and R by $P_B^{Opt} = \eta_1^B P_B$ and $P_R^{Opt} = \eta_1^R P_R$, accordingly. η_1^B and η_1^R represent the electrical-to-optical conversion efficiencies of optical transmitters of B and R, respectively.
• $g_{B,R}$ and $g_{B,R}$ denote the channel coefficients of the $B-R$ and $R-B$ links, respectively.
• $\mathcal{M}_1$ and $\mathcal{M}_2$ are the modulation indices of B and R, respectively.
• x_B is the transmitted symbol of B with $\mathbb{E}\left\{|x_B|^2\right\} = 1$.
• n_R and n_B are the AWGN terms at the input of R and B. The optical-to-electrical conversion efficiencies of R and B are represented by η_R^2 and η_B^2, respectively.

The instantaneous SNR expressions at the input of R and B are $\gamma_{B,R} = \frac{\eta_1^B\eta_2^R P_B}{N_R^2}|g_{B,R}|^2$ and $\gamma_{R,B} = \frac{\eta_1^R\eta_2^B P_R}{N_B}|g_{R,B}|^2$, respectively.
The FSO link experience a unified Gamma-Gamma fading with pointing errors. The PDFs of $\gamma_{B,R}$ and $\gamma_{R,B}$ are given by

$$f_{\gamma_{x,y}}(\gamma) = \frac{\zeta_x^2}{\gamma\Gamma(\alpha_x)\Gamma(\beta_x)} G_{1,3}^{3,0}\left[\alpha_x\beta_x\lambda_{x,y}\gamma\Big|_{\zeta_x^2,\alpha_x,\beta_x}^{\zeta_x^2+1}\right], \tag{12}$$

with

• $\lambda_{x,y} = 1/\bar{\gamma}_{x,y}$ where $\bar{\gamma}_{x,y} = \mathbb{E}\left\{\gamma_{x,y}\right\} = \frac{\eta_1^x\eta_2^y P_x}{N_y}\mu_{x,y}$, $\mu_{x,y} = \mathbb{E}\left\{|g_{x,y}|^2\right\}$ and $(x,y) \in \{(B,R),(R,B)\}$.
• ζ_x represents the ratio between the equivalent beam radius and the pointing error displacement standard deviation at the x.
• $\Gamma(.)$ is the Gamma function.
• $G(.)$ is the Meijer G-function.
• α_x and β_x are the fading parameters related to the atmospheric turbulence conditions from x to other terminal. Usually, relatively large values of α_x and β_x, that are close to each other, correspond to weak turbulence conditions. While, relatively small values of α_x and β_x, with β_x significantly greater than α_x, correspond to strong turbulence conditions.

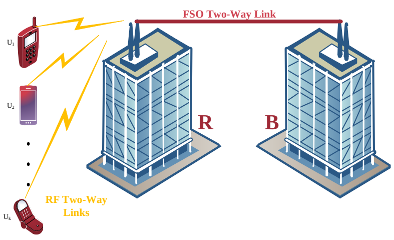

Fig. 5: Hybrid RF/FSO System Model

As for the CDF $F_{\gamma_{x,y}}(\gamma)$ for a single FSO link, it can be deducted by the integration of (12)

$$F_{\gamma_{x,y}}(\gamma) = \int_0^{\gamma} f_{\gamma_{x,y}}(\tau)d\tau = A_x G_{2,4}^{3,1}\left[\frac{B_x\gamma}{\bar{\gamma}_{x,y}}\Big|_{m_2^x,0}^{1,m_1^x}\right], \tag{13}$$

where $A_x = \frac{\zeta_x^2}{\Gamma(\alpha_x)\Gamma(\beta_x)}$, $B_x = \alpha_x\beta_x$, $m_1^x = \zeta_x^2+1$, and $m_2^x = \zeta_x^2, \alpha_x, \beta_x$.

III Evolution of the Study's Track

Since the adoption of the notion of employing buffers at the level of relays, several policies have been introduced and studied, where a drawback of one leads to the scheming of another. For instance, one of the first schemes, which is the max-link, was suggested to get over a limitation of a previous scheme, which is the max-max, as explained in the subsequent section. Moving in time, another example is the Buffer State-Based Relay Selection policy that was planned to overcome the large delay caused by the max-link. This is explained in section V. The relaying schemes of the two sections, briefly mentioned before, require Channel State Information and/or Buffer State Information. With the goal of enhancing the performance and increasing the throughput, specifically, additional schemes have been proposed, which require Energy State Information. Those energy-related schemes are investigated and studied in section VI. Encouraged by the benefits of spectral energy efficiency, relay networks have been exploited with Non-Orthogonal Multiple Access Networks (NOMA) systems, as relay networks are expected to reduce energy consumption in wireless communications. However, NOMA systems are known to serve several users on the same frequency-time resource at the same time, by non-orthogonal resource allocation in the power domain. These related schemes are studied in section VII. Apart from trying to accomplish better performance, studies have been done to analyze other aspects, such as security, where eavesdroppers are a huge threat to the reliability of information exchange. This aspect is explored in section VIII. A strategy that combines both is known as the Hybrid Radio Frequency/Free-Space Optical strategy. In section IX, the importance of this strategy is emphasized, and related schemes are explored. In the subsequent section, section X, a new aspect to wireless communications is introduced and discussed, which is the employment of Unmanned Aerial Vehicles in relaying. Some numerical results comparing the existing benchmark schemes are provided in Section XI. All reviewed studies have been classified in Table 5.

IV Review of Max-Link Relay Selection Policy and Comparison with Other Schemes

The use of buffers (or data queues) has been extensively studied at the networking and application layers for a broad variety of communications standards [4–6]. Recently, buffers were used at the physical layer for delay-insensitive application [7]. The purpose behind max-link scheme [7] is to overcome the limitation behind the max-max policy, which is having a predefined schedule for transmission. In max-link, the diversity degrees are taken advantage of, by dynamically assigning each time slot for either source or relay transmission, by opting for the strongest link, based on the buffers' states and the links' instantaneous qualities. This conventional max-link policy in [7], is adapted for the Half-Duplex (HD) relay in [8]. In [8], both HD and Full-Duplex (FD) systems with no direct link, where the system consists of a single relay, are compared in terms of outage probability (OP) and average packet delay (APD). The diversity order depends on the duplexity mode, where FD systems show better performance in terms of both OP and APD, and the impact of relay placement on the system performance is highlighted [8]. If the relay is closer to the destination, increasing the buffer size will have no effect on the OP and APD. If the relay is closer to the source, increasing the buffer size will increase the delays with no effect on the OP [8].

Duarte and de Lamare investigate relay selection protocols for two-way cooperative multi-antenna systems [9]. Two terminals can concurrently transmit to each other via relays. [9] presents a two-way relay selection protocol that depends on the selection of the best link. This scheme, Two-Way Max-Link (TW-Max-Link), takes advantage of buffers and physical-layer network coding (PLNC) [9]. With [9] as a reference to the design of multi-way cooperative multi-antenna systems, [10] presents a relay-selection scheme for such systems. The systems are supported by a central processor node, where a cluster of two users is chosen to concurrently transmit to each other via relays. [10] discusses a multi-way relay selection strategy that depends on the selection of the best link. The scheme, Multi-Way Buffer Aided Max-Link (MW-Max-Link), takes advantage of the use of buffers and PLNC. MW-Max-Link scheme outperforms TW-Max-Link and TW-maxMin schemes [10].

One drawback of the max-link scheme of [7] is needing sufficiently large buffers to achieve maximum diversity, increasing the average delay. This was the motivation behind hybrid max-link [11], max-weight [12], and Combined Relay Selection (CRS) [13]. Regarding [11], a hybrid Buffer-Aided (BA) scheme has been proposed to attain the advantage of high consistency and reduced packet delay. The scheme utilizes a pre-scheduled two-stage cooperative strategy, while utilizing all S-R and R-D links during each time slot. This strategy lowers the OP and the packet delay, while maintaining a diversity order approximately equal to the optimal diversity gain, compared with max-link scheme of [7]. Furthermore, the OP was derived from the practical assumption of finite-buffer relays [11].

Both [7] and [11] are compared with the proposed policy in [14] that combines the benefits of direct communication and BA relaying. [14] modifies the hybrid interweave-underlay spectrum access policy, limiting the interference caused by a miss-detection event. The OP and APD are derived for the secondary system assuming independent and non-identical fading channels. The policy increases the outage gain, lowers APD, increases the probability of empty buffers, and lowers the probability of full buffers, compared with max link selection (MLS) and hybrid link selection (HLS) [14]. The scheme in [12] integrates the status of the relay buffers and instantaneous strength of the links. The max-weight relay selection scheme assigns a weight related to the buffer status to each link, and selects the link with the largest weight among all qualified links. The proposed scheme attains the optimal diversity gain for L≥3, implying that the scheme exploits relay buffers without suffering from long packet delay [12]. The scheme in [13] decreases the buffer size, at the cost of increased outage. The study in [13] assumes an unlimited amount of energy at the relay nodes. Thus, in [15], a relay selection strategy for file transfer in dual-hop BA relaying system with the source and relays having limited energy, is proposed. Due to relays' limited energy, channel, energy and queue state-aware (CEQA), relay selection strategy upholds a virtual bucket of tokens, one for each relay. CEQA dynamically defines a scheduling rule at each time slot based on Channel State Information (CSI), residual energies and queue sizes. At each time slot, the scheduling rule selects the source or one of the relay nodes for packet transmission by selecting the link with the highest scheduling weight. CEQA ensures a higher number of packet transfers, and a lower file transfer time, compared with conventional energy-aware and BA energy-unaware relaying strategies [15].

Lin and Liu, in [13], ignore the links' quality and only consider the available/occupied buffer spaces. This might result in selecting the worst quality link, leading to detection concerns at the destination. In a similar manner, the work in [7] ignores the instantaneous buffer space during relay selection. This might result in having full/empty buffers, leading to a decline in diversity order. The Max-Score Relay Selection Scheme (RSS) simultaneously considers the relay's buffer size, remaining energy and link quality for relay selection [16]. The proposed idea goes as follows:

1. In each time slot, each relay determines the RSS for both its links, which is the weighted sum of the normalized values of the link quality, remaining energy and buffer space. The RSS is calculated as:
$S_i^t = \alpha_{linkquality} \dfrac{\gamma_i}{\gamma_{max}} + \alpha_{remainingenergy} \dfrac{E_k^t}{E_k} + \alpha_{buffersize} \dfrac{\beta_i^t}{B_k}$
Where S_i^t is the RSS calculating for link l_i to relay R_k at time slot t, B_k and E_k are the initial buffer size and energy respectively, γ_i is the maximum achievable received Signal-to-Noise Ratio (SNR), β_i^t and E_k^t correspond to available (occupied) buffer size. If l_i refers to S-R (R-D) link and remaining energy at t respectively, α corresponds to the assigned weight and γ_i instantaneous SNR.
2. The chosen relay for either reception or transmission is then the relay with maximum RSS value.
$R = argmax_{\forall_{l_i}} \left\{ \cup_{\forall S_i^t > S_{th}} S_i^t \right\}$
and $S_{th} = \alpha_{linkquality}\gamma_{th} + \alpha_{remainingenergy}E_{th} + \alpha_{buffersize}B_{th}$
where S_{th}, γ_{th},E_{th}, B_{th} correspond to the threshold parameters of the overall score, SNR, energy and buffer respectively.
3. For simplicity, it is assumed that the remaining energy factor is zero, i.e. there is no constraint on relays in term of energy.

RSS becomes: $S_i^t \ \frac{1}{2} \dfrac{\gamma_i}{\gamma_{max}} + \frac{1}{2} \dfrac{\beta_i^t}{B_k}$
and $S_{th} = \frac{1}{2}\gamma_{th} + \frac{1}{2}B_{th}$

Thus, relay selection equally depends on relay's buffer size and link quality. The system achieves the maximum diversity gain of $2K$ for buffer sizes ≥ 3 [16].

Going one step further from [13], [17] minimizes the delay of the max-link scheme of [13]. The first proposed protocol is the delay-aware-max-link, where R-D links are given priority, and relay selection depends on the number of packets in each buffer. Among all the available relays for transmission, the relay with the maximum number of packets in the buffer will be selected to send a packet. If relay transmission is not available, then the relay with the minimum buffer size available is selected to receive a packet from the source. Otherwise, no transmission occurs, and the system is in outage. If more than one relay have the same number of packets, one of them is chosen randomly. Although the protocol reduces the delay, this happens at the cost of increased outage and reduced diversity [17]. Thus, the second protocol is introduced. This protocol, the delay-and-diversity-aware scheme, where empty queues are given priority, ensures high diversity and reduces delay [17]. But, delay reduction is higher in the previous protocol. The time frame is divided into two time slots:

- in the first slot, an available relay with the least number of packets is selected to receive a packet.
- in the second slot, an available relay with the most number of packets is selected to send a packet.

Similar to the delay-aware-max-link, the proposed scheme in [18] gives priority to the R-D links. Nevertheless, the selection rule depends on choosing the link with the highest channel SNR, either among the available R-D links or among the available S-R links, if the chosen R-D link is in outage. Otherwise, outage ensues. [18] compares the proposed scheme with the traditional max-link of [7] in terms of outage performance in different channel scenarios. The results are shown in table 1.

Not accounting for the buffer states when selecting the strongest link for transmission in max-link [7] leads to the possibility of having buffers with empty or full states. The Balancing Relay Selection

Table 1 Comparison Between Proposed Scheme [18] and Max-Link [7] in Different Channel Scenarios

	Symmetric Channels	Stronger S-R Links	Stronger R-D Links
Better outage performance	Max-link [7]	Proposed scheme [18]	Both max-link[7] and proposed scheme [18]

(BaRS) scheme in [19] enhances the outage probability, and keeps the buffers' states balanced with equal arrival and departure rates at the buffer. This is possible by considering both CSI and Buffer State Information (BSI) for relay selection [19]. The link that is selected for transmission in each time slot is the one that aims to mend the balanced state of the most unbalanced buffer. If this link does not exist, the link that yields the slightest unbalancing effect is chosen for transmission. Compared with the max-link scheme in [7], BaRS has lower OP as it results in more balanced (stable) buffers, and consequently, more available links [19]. A single relay is considered in [20], where a slot-by-slot relaying scheme is introduced for a Decode-and-Forward (DF) BA relaying network, with a buffer size of L. Independent of the proposed scheme, if the buffer is full (respectively empty), no packets can be transmitted along the S-R (respectively R-D) link. If both links are available ($0 < l < L$, where l denotes the number of packets in the buffer), then:

1. If both are in outage, no packets can be sent nor received.
2. If the S-R (respectively R-D) link is in outage, R switches to transmission (respectively reception) mode.
3. If both links are not in outage, a threshold-based BA strategy, as a function of a buffer occupancy threshold level $l_{th} \in 0,, L$, must be implemented, where the relay decides to receive, if $l \leq l_{th}$, or transmit, if $l > l_{th}$.

OP and APD were first derived in closed-form expressions followed by an asymptotic analysis. [20] studied the impact of a threshold parameter on the diversity order, OP and queuing delay. This threshold is selected to minimize the OP or APD, or to reach suitable trade-offs between OP and APD [20].

Another limitation of [18] is that the system performance is restricted by the weaker links as the disparities of qualities between different links have not been solved yet. Thus, an optimal multi-user scheduling scheme for a multi-user FD BA relay system has been proposed to maximize the system throughput. The proposed scheme maximizes the throughput and solves the differences of the qualities between S-R and R-D links, and between different S-R (R-D) links [21]. Another two optimal multi-user scheduling schemes are presented in [22] for a FD multi-user BA relaying system, where the unbalanced channels of the links are characterized by an independent and non-identically distributed (i.ni.d.) model. [22] examines both cases of fixed and adaptive power transmission:

- In the fixed power transmission case, the proposed optimal multi-user scheduling scheme considers both instantaneous and statistical CSI. Setting the optimal weight factors assists in the user-scheduling process, where utility ratios of different links are balanced as more time slots can be allocated to the links with poor conditions, and less slots allocated to the links with strong conditions. Thus, the throughput gap between the poor and strong links is minimized, improving the system throughput.
- In the adaptive power transmission case, the system average power constraint is considered, where the transmit power of the selected user is adaptively developed. The joint multi-user scheme with power allocation is proposed, where selection functions are developed by merging the optimal weight factors and optimal power allocation. This scheme balances the different links similar to that of the fixed power transmission case, while enhancing the system throughput, compared with that of the fixed power transmission case.

The Max-Link scheme [7] and relay selection scheme with reduced packet delay [18] are special cases of the probabilistic BA relay selection scheme [23] for cooperative relay networks. The proposed scheme uses randomness in deciding the link selection outcome. This occurs when a probabilistic selection is done between the strongest available S-R link and the strongest available R-D link. By adjusting one specific parameter, different trade-offs between the OP and APD can be reached [23]. Also, the schemes in [7], [17] and [18] depend on the CSI of the S-R links hence, they require a certain level of complexity. Thus, the low-complexity (LoCo) link selection algorithm has been proposed in [24] and [25]. The LoCo - Link selects the relay with the largest buffer length and executes broadcast S-R transmissions. In other words, it prioritizes transmissions in the R-D links, even if the S-R links are better. It also reduces delay, maintains diversity and lowers complexity, compared with [7], [17] and [18] in asymmetric conditions. However, this scheme, in particular its diversity order, is significantly altered by outdated CSI. Therefore, the same study proposes a distributed version of the LoCo - Link (d - LoCo - Link) that depends on local CSI approximation. The d - LoCo - Link also exploits inter-relay channels to reduce duplicate packets in a non-error-free feedback channel [24], [25].

Motivated by max-link, a priority-based max-link relay selection scheme is proposed, aiming to improve the outage performance and to shrink the additional energy consumption [26] [27]. Another advantage drawn from this modified version of the max-link [26] [27] is reducing the computational complexity of determining the steady-state distribution, consequently, reducing the complexity of computing the OP by state-grouping, and building a reduced state transition matrix. In this scheme, qualified links (the link is said to be qualified if its channel SNR is adequate to sustain the predefined data rate) are prioritized based on BSI, and the relay selection goes in the following manner:

1. Choose the relay with the highest channel gain among the relays having full buffer states.
2. Choose the relay with the highest channel gain among the relays having empty buffer states. This applies if there does not exist any full-buffered relays or if the links connected with them are in outage.
3. Choose the relay with the highest channel gain among the relays having neither full nor empty buffer states if the preceding conditions are not met.

The work in [26] studies the network under AWGN conditions and ignores the co-channel interference (CCI) effect. In wireless networks having dense frequency reuse, it is usually the CCI that dominates AWGN. Thus, [28] analyzes the OP of a BA dual-hop DF cooperative relaying system, with CCI and AWGN at the relay and destination. A max-signal-to-interference plus noise ratio (max-SINR) relaying protocol is proposed, where transmission occurs in the link with the greatest SINR among all other S-R and R-D links. [28] assumes that the envelopes of the desired signal and the interfering signal follow asymmetric channel configuration with Rayleigh fading, and that the data buffer at the relay is of finite size. Results show that in cooperative networks with CCI and AWGN, exploiting a data buffer at the relay, and following the max-SINR relaying protocol enhance the performance of OP, compared with max-min protocol without a buffer. Furthermore, the BA relaying protocol improves the reliability of the setup, compared with buffer-free relaying protocol [28].

To take advantage of the multi-hop diversity promoted by relays, Liu *et al*. proposed an extended Proportional Fair Scheduling (PFS) for downlink scheduling of dual-hop relay access systems [29]. The extended PFS utilizes multi-hop diversity, as well as PFS spatial diversity, by planning new scheduling priority indexes and their updating rules, for base-relay stations and relay-mobile stations. The extended PFS attains a balance between effectiveness and fairness. Moreover, it does not need queue-state information, and does not comprise real-time optimization, therefore, it is simple to implement. The scheme increases the throughput and provides better fairness with the knowledge of CSI at the central controller, compared with other benchmarks [29].

Other schemes outperforming the traditional max-link [7] in terms of OP are the Buffer-Threshold-Based Relay Selection (BTRS) scheme [30] and the virtual-max-link relay selection (V-MLRS) [31]. BTRS [30] introduces a buffer-threshold that manipulates the selection probability of source-relay or relay-destination links. The link with the maximum weight is selected after reassigning the links' weights that are calculated according to the buffer occupancy (L_o), the buffer threshold (L_{th}) and L, $W_{SR} + W_{RD}$, based on table 2. Performance analysis indicates that for:

- $L_{th} = \frac{L_{th}}{2}$: BTRS acts as Max Weight Relay Selection (MWRS) scheme.
- $L_{th} < \frac{L_{th}}{2}$: BTRS performs better than MLRS and MWRS in terms of average delay as the relays prefer to transmit rather than receive packets.
- $L_{th} > \frac{L_{th}}{2}$: MLRS and MWRS perform better than BTRS in terms of average delay as the relays have a tendency to receive rather than send packets.

For the three mentioned scenarios, the outage probability of BTRS is less than MLRS and MWRS except for the third scenario, where MWRS and BTRS show similar performance [30].

Extending the work in [30], Raza *et al.* introduce a controlling parameter, named buffer-limit, for buffer occupancy deciding on link selection and impacting both average delay and throughput [32]. Initially, weight allocation of the links is done on the foundation of buffer occupancy. The probability of selecting transmitting or receiving channels is manipulated by the reallocation of the links' weights considering the buffer limit. The link with the largest weight is then activated and its respective relay is selected. The average end-to-end (E2E) queuing delay, average throughput, and OP are improved. The proposed scheme acts similarly to the max-weight scheme, when the buffer limit is half the buffer size. Other values of buffer limit, more or less than half-value, equally increase the OP. However, setting the buffer limit to less than half-value increases the average throughput and decreases the average E2E queuing delay. By altering the buffer limit value, OP can be traded with E2E queuing delay or average throughput [32]. The work in [30] also considers the buffer occupancy-based relay selection for DF relaying in Rayleigh fading channels. In contrast, [33] considers buffer occupancy-based relay selection schemes (link prioritization) for Amplify-and-Forward (AF) and DF relaying, in Nakagami-m fading channels. The load of the links is then redistributed, which is utilized for buffer load-based relay determination technique. For the AF relaying model, an updated threshold is used to choose whether the relay should store or discard the received packet. The favored link selection enhances the latency and average throughput negotiating on the OP [33].

Moving to V-MLRS, the buffers permit random access to the data, and the virtual relay is a buffer location with its individual antenna source with a buffer size of 1. The best relay in V-MLRS is selected according to the link quality. The strongest link is chosen either for relay reception (if a S-R link is selected) or transmission (if a R-D link is selected). V-MLRS attains similar diversity order to MLRS, but with fewer relays and a trivial buffer size. Diversity gains are improved while maintaining the same delay [31]. [34] tackles a different virtual FD relaying scheme for BA HD multi-hop DF cooperative network, which is the centre-partition max-link relaying. The aim is to select two distinct available links for packet transmission in the same slot, thus, the system performance increases due to a higher transmission rate. The relaying mode is decided based on the two selected relays. If both exist and are distinct, then FD transmission occurs. Else, if one of them does not exist, or both are the same, then HD transmission occurs. The novel scheme reduces both OP and APD, compared with the same network setup, BA multi-hop DF relaying network, with the conventional max-link protocol. However, for larger buffer size, the OP of the conventional max-link scheme is better, while the APD of the proposed scheme is better [34]. The V-MLRS in [31] is aspired by the proposed scheme in [35], where the authors utilize the idea of inverse channel packet matching to choose the best packet in the buffer, by allowing the packet that suffers bad channel condition in the S-R hop to go through good channel condition in the R-D hop to enhance the outage probability.

One common assumption in all the previous schemes in this section is the absence of a direct link between the source S and the destination D. However, this is not the case in the switched Multiple-Input Multiple-Output (MIMO)/max-link scheme [36] that joins the idea of switching with the max-link scheme for cooperative multi-antenna systems, where a new relay selection criterion is presented, which is the maximum-minimum-distance, based on the maximum likelihood standard. The switched MIMO/max-link scheme functions in two modes, either direct transmission or max-link, and thus, has three options:

1. Direct transmission mode, where the source directly sends a number of packets to the destination.
2. Max-link, where a number of packets is sent to the chosen relay by the source and deposited in its buffer.
3. Max-link, where a number of packets is sent to the destination by the chosen relay.

The proposed switched max-link scheme surpasses the conventional max-link scheme, when comparing the bit error rate (BER) performance [36]. Also, [37] proposes another switched max-link scheme for cooperative HD DF multi-antenna systems, where the switching and the selection of the best link are combined. This scheme, namely Switched Max-Link, incorporates a relay selection condition, Maximum Minimum Distance (MMD), based on the Maximum Likelihood principle, and the Pairwise Error Probability (PEP). The benefit of MMD algorithm lies in the maximization of the minimum value of the PEP argument, which is PEP worst case. The proposed scheme outperforms the conventional direct transmission and Quadratic Norm Max-Link scheme [37].

All the previously mentioned schemes in this section are based on selecting a relay depending on its physical link. Yet, the chosen pair may cause performance degradation as the nodes may not trust each other. Thus, [38] proposes a scheme for a relaying network with spatially random relays. This scheme associates data transmission with both trusted and strong links, and introduces a set of parameters, "the target-queuing-lengths". It attains a trade-off between the outage performance and packet delay, by establishing proper target buffer lengths at the buffers of the relays. This scheme minimizes packet delay, diversity order, and improves compromise between the diversity and delay. The scheme [38] is compared with MLRS of [7], reaching the following conclusions:

- Better performance in both outage probability and average packet delay is noticeable in the trust-aware scheme for best outage performance.
- Better performance in average packet delay is noticeable in the trust-aware scheme for minimum delay, and better outage performance is noticeable in MLRS.

With the surge of interest in mobile edge computing (MEC) and cloud offloading [39–42], BA relaying is also utilized in MEC architectures [43], where it is the fundamental system in hierarchical Multi-hop MEC. A stochastic offloading scheme is proposed, where a BA relay, equipped with a computing server, decides arbitrary to either process the source's tasks by its own server, or forward them to be handled by the server of the next node in the hierarchy. Simulations prove the efficiency of this scheme as it noticeably reduces the average response time (ART) [43].

Most of the work mentioned earlier focuses either on DF or AF relaying. In hybrid decode-amplify-forward (HDAF), instead of remaining silent on poor signal quality, the relay switches between the AF or DF mode to enhance the system performance. [44] studies the performance of SNR-based HDAF relaying policy for BA

Table 2 Equations of the SR and RD Links' Weights [30]

	W_{SR}	W_{RD}
$L_o \leq L_{th}$	$\frac{(2L_{th}-L_O)L}{2L_{th}}$	$\frac{LL_O}{2L_{th}}$
$L_o > L_{th}$	$\frac{(L_O-L)L}{2(L_{th}-L)}$	$\frac{(L+L_O-2L_{th})L}{2(L-L_{th})}$

relaying, where the relay with the best available channel, i.e. the best SNR, is used for transmission or reception.

- In case it was the S-R hop, packet is transmitted to the selected relay and its SNR is compared with a preset SNR threshold at the relay. If the SNR is greater than the threshold, the decoded data is saved in the corresponding buffer. Otherwise, the amplified data is stored.
- In case it was the R-D hop, the destination receives the data, whether decoded or amplified.

The OP of the proposed policy is superior to the existing SNR-based BA relaying schemes based on DF and AF rules by 2.43 dB and 8.6 dB, respectively [44].

V Review of Buffer State Based Relay Selection Policy and Comparison with Other Schemes

Driven by the fact that the conventional max-link scheme causes a large average delay, Luo and Teh propose a Buffer State-Based relay (BSB) selection scheme, based on both channel quality and buffer state, to reduce the average delay, and enhance the reliability of the system [45]. The policy in [45] is divided into two phases.

- Phase I: At the start of every time slot, each of the source and the destination broadcasts a short reference signal to all relays. Then, every relay node acquires its related channel gains $|h_{SRk}|^2$ and $|h_{SRk}|^2$. Next, based on the relay's buffer length, L_K, and the acquired channel coefficients, each relay node chooses to either send or receive in each slot as shown in table 3. After the relay nodes make their decision, phase II is entered.
- Phase II: All the decisions generated in phase I are accumulated by a central controlling node, i.e. any relay node that is capable of communicating with all the others, which is assumed to be R_1. R_1 chooses the best relay for transmission or reception, depending on the collected decisions. The best relay node is chosen based on the following (where Q_t and Q_r denote the sets of relay nodes that adopt to transmit and receive in phase I, respectively):

1. $Q_r = \emptyset, Q_t \neq \emptyset$ (empty set): The system only chooses a relay from Q_t to transmit a packet where the chosen relay has the maximum buffer length.
2. $Q_r \neq \emptyset, Q_t = \emptyset$: The system only chooses a relay from Q_r to receive a packet in such a way that the chosen relay has the least buffer length.
3. $Q_r = \emptyset, Q_t = \emptyset$: Outage occurs.
4. $Q_r \neq \emptyset, Q_t \neq \emptyset$: R_1 selects the relay node depending on table 4 (where $L^t_{max} = max\{L_k|R_k \in Q_t\}$ and $L^r_{min} = min\{L_k|R_k \in Q_r\}$):

The proposed scheme [45] has lower outage probability (OP) and achieves full diversity with small buffer size. Also, the buffer state-based scheme [45] lowers the average delay, for buffer size greater or equal to 3, compared with max-link [46].

Similar to [45], the study of [47] is investigated in both independent and identically distributed (i.i.d.) and independent and non-identically distributed (i.ni.d.) Rayleigh fading channels. The study considers systems with particular delay bounds and specific source information rates, i.e. the source is not packed with data and the system has specific traffic activity factor. This scheme, known as Compromising Relay Selection (CRS), minimizes the outage probability and increases throughput, by utilizing Channel State Information (CSI), Buffer State Information (BSI), and delay state information, to properly compromise between the selections of relays for transmission and reception. CRS results in higher throughput by minimizing the packet dropping probabilities of the system, i.e. successful transfer of packets and lower outage probability, by keeping the buffers away from empty state, i.e. increasing the available links for selection. It decreases packet dropping probability and increases throughput, compared with the renowned relay selection schemes for systems with high delay constraints, compared with the renowned BSB [47].

In [48], Attarkashani *et al*. study the performance of a relay selection scheme in a Buffer-Aided (BA) multi-relay network with coded transmissions. Quasi-static Rayleigh fading channels are assumed, where the links are independent and asymmetric. Two different coding schemes are considered: Turbo codes and distributed Turbo codes (DTC). For each scheme, the average throughput is measured. The system reachable diversity order is acquired in the asymptotic case of high SNR values and infinite buffer. The comparison between the Turbo code, DTC and convolutional-coded schemes illustrates the superiority of the Turbo code, while DTC outperforms the convolutional code for poor R-D channel [48].

Another relay selection in wireless packetized predictive control (PPC) systems is considered in [49] to enhance system performance. The aim is to select the relay nodes by conjointly considering communication and control sub-systems. To maintain control stability, predictive future commands are found in every PPC packet. So, when packet loss occurs, the predictive commands can be utilized. For the selection method, data freshness and availability from the control aspect, and the resource consumption from the communication aspect are conjointly considered and optimized. Results confirm the performance gain of the proposed BA relay selection scheme [49].

Similar to [47], under independent and identically distributed fading, the BSB relaying scheme in the scenario of a cooperative radio network (CRN), supporting both primary and secondary networks, was proposed in [50]. In this scheme, by presenting a flexible link selection algorithm in the secondary network, the impacts of both fading and inter-network interference were eliminated. An additional degree of freedom is achieved due to the broadcast nature of wireless communication channels between the source and relays in the secondary network, where the packet is shared among multiple secondary relays. This yields a coding gain increase and end-to-end (E2E) delay decrease. This algorithm also satisfies the requirement specific to the CRN. The selection consists of the concept of BSB relay selection, to avoid empty/full buffers, and to increase the number of available links by giving priority for the links selected. The proposed scheme attains better system performance in terms of OP and APD, compared with those of the conventional max-ratio-based scheme in BA cognitive radio network [50].

Most of the studies have been investigated only for Half-Duplex (HD) relaying systems as [45]. [51] confirms that BA relaying is an essential part of future Full-Duplex (FD) relaying. Three BA relaying schemes have been proposed for the cases of adaptive reception-transmission at the FD relay for a dual-hop relay channel with self interference (SI) for: continuous-rate transmission with adaptive-power allocation, continuous-rate transmission with fixed-power allocation, and discrete-rate transmission. These schemes enhance the system performance by ideally opting for the relay, in a particular time slot, to take, send or simultaneously take and send, depending on the conditions of the receiving, transmitting and SI channels to maximize the attainable data rate/throughput. Performance improvements are attained by employing the three proposed schemes, compared with the original FD relaying and the original BA HD relaying. In the former, the relay is permanently required to

Table 3 Phase I of BSB Scheme [45]

Cases	S-R Link	R-D Link	L_k	Decision
1	Outage	Outage	——	Silence (neither)
2	——	Outage	L	Silence
3	Outage	——	0	Silence
4	Not in Outage	Outage	$< L$	Receive
5	Outage	Not in Outage	> 0	Transmit
6	Not in Outage	Not in Outage	≥ 2	Transmit
7	Not in Outage	Not in Outage	≤ 1	Receive

Table 4 Phase II of BSB Scheme [45]

Cases	L^t_{max}	L^r_{min}	Decision
1	L	——	Transmit
2	$< L$	0	Receive
3	$2 \leq L^t_{max} < L$	> 0	Transmit
4	1	> 0	Receive

receive and transmit at the same time; in the latter, the HD relay cannot transmit and receive at the same time [51]. [51] studied discrete rate transmission with BA relay in the absence of a direct link. However, because of power constraints, the nodes in underlay networks are comparable for reasonable Quality of Service (QoS). Therefore, taking into account the direct channel is significant in underlay CRN. Any chosen rate in a signal interval is influenced by the links' instantaneous SNRs, which have significant variation in underlay CRN, as a result of peak inference constraints.

Motivated, [52] studies the performance of a BA relaying cooperative underlay CRN. In the case where two or all links can provide the same maximum rate, one of them is chosen randomly based on a "coin-toss" with a probability selected to guarantee buffer stability. A general framework for discrete-rate transmission in a 3-node relaying network, where a direct link is available, is set. Then, the joint rate and link-selection protocol are acquired, and the condition for flow-control is evaluated. In the first, joint link and rate selection is performed among the three links. In the second, the relay and source signal exploit orthogonal space-time block codes (OSTBC) whenever the R-D link is selected. The system throughput of the balanced buffer and the coin-toss probabilities, assisting in buffer balancing, are independent. From the expression of the system throughput, the buffer balancing condition is evaluated. Taking into account the direct link is significant in underlay cognitive radio, where the impact of the direct link depends on its strength with respect to the buffered path, given channel statistics and target rates [52].

The assumption that the buffer is so large in [51] is unrealistic in practice. Instead, [53] considers a FD Decode-and-Forward (DF) relay with two finite buffers in a two-way relaying system. The proposed protocol maximizes the cumulative throughput by generating a decision for either transmitting, receiving, or both simultaneously. This protocol accounts for the instantaneous links' qualities, in addition to the states of the buffers' queues to lessen the consumption of the spectrum when unused. The adaptive protocol is optimal when the buffer length is larger than a specific threshold. It enhances the transmission efficiency and avoids buffer overflow. Also, the buffering relay capabilities enhance the capacity of relay networks in slow fading environments, and this scheme increases the system throughput by queuing or de-queuing the buffers in a rapid pace, based on buffer states, lossy link, and OP. Furthermore, this protocol can fix the bottleneck of residual self-interference, and performs better than the 2-way HD network even when the FD relay undergoes huge residual self-interference [53]. [54] illustrates the benefits of BA relaying with FD relays. At a given time slot t, the relay chooses to either send, receive or do both simultaneously, based on channel qualities. The proposed scheme provides significant throughput gains compared with the conventional buffer-less FD relaying schemes [54].

Other than the residual self interference, there exists co-channel interference. [55] proposes a link selection algorithm for BA cooperative networks with multiple co-channel interferers. To lessen interferers' effects, the relay selects the better link from the first and second hops. Thus, considerable performance gains are noticed compared with the conventional DF relaying networks. Exact OP is derived for that network to calculate the transmission performance attained by the BA protocol. For the case where the buffer is either full or empty, diversity order was found to be 1. For the other case of partial occupancy in the buffer, diversity order was found to be 2 [55].

Even though the BSB scheme [45] has outperformed other schemes, it has led to imperfect conservation of the buffers' states. The aspiration behind setting a relay selection policy that conserves the states of the buffers from being empty or full, led to the Balancing Relay Selection (BaRS) scheme of [19]. For a better average packet delay, a fixed-rate generalized buffer-aided cooperative scheme is proposed, combining two notions: instantaneous S-R link activations and BSB relay selection [46]. Similar to the scheme of [45], BSB relay selections are utilized in [46], whereas the instantaneous activations of the multiple S-R links are employed simultaneously. After collecting the buffer states of the relay nodes, the central coordinator selects either a single S-R link, multiple S-R links, or a single R-D link, after giving priority to the links based on the relays' buffer states. This scheme [46] achieves a diversity gain due to the several copies of a transmitted packet (the source node transmits a packet to multiple relay nodes instantaneously). Also, delay reduction is observed as a thresholding scheme dedicates priority to link selection in a way that the number of packets stored at the relay nodes is preserved at a low rate (however, still avoiding empty buffers) [46].

A different multi-relay network was studied in [56]. A BA DF multi-relay network with finite buffers is considered, where the maximum supportable arrival rates with buffer overflow QoS guaranteed at all buffered nodes. Each of these nodes is subject to QoS constraint designated by its individual QoS exponent: θ_S and θ_{R_i} for the source and the corresponding i^{th} relay. The aim is to study the problem in a realistic condition: the inevitable data buffering delay at the relay nodes. A closed-form expression for the ergodic capacity was evaluated to decrease the computational complexity. A time slot allocation scheme was proposed based on the effective capacity (EC) function for both cases of heterogeneous (individual θ_{R_i}) and homogeneous (equal QoS constraints at the relays θ_R) queuing at the relays. For $\theta_S > \theta_R$, EC is constant with respect to θ_R and varies with respect to θ_S and vice versa. Most of the resources are allocated to the node with the most severe QoS constraint [56].

Another scheme employing the BSB policy of [57] is the generalized BSB amplify-and-forward protocol of [58] that concurrently uses multiple S-R links, while introducing buffer-state-and-thresholding-based relay selection. Taking into account the buffer states of the relay nodes, the scheme of [58] achieves full diversity order by avoiding full and empty buffer states. The thresholding technique in [58] helps to diminish noise-propagation effects since the broadcast links may contain unreliable links that diminish the SNR. Collaborative transmit beam-forming is then introduced to the scheme of [58] allowing simultaneous utilization of multiple R-D links in the relaying phase. Adding collaborative beam-forming enhances the outage probability performance in comparison with the BSB scheme of [45].

VI Buffer-Aided Relay Selection Schemes with Energy Storage

Cooperative communication gains high throughput as the source node and cooperating relay nodes spend their energy on processing and transmitting the signal to the destination node. These nodes are powered using pre-charged batteries, and when these batteries drain, the nodes will stop working. The goal is to diminish energy dissipation and/or store energy in relays.

In [59], Dong *et al.* consider a Buffer-Aided (BA) three-node network and propose the BA Opportunistic Routing (BOR) scheme. BOR merges the advantages of opportunistic routing and multi-hop diversity aided transmissions, where a Middle Access Control protocol is designed for supporting BOR as it increases the achievable throughput for multi-hop networks. There are three links: S-R, S-D and R-D; thus, three channels are established forming a 3D transmission activation probability space (TAPS). Then, TAPS is divided into four regions including the three aforementioned channels and the outage region. In a given time slot, the instantaneous fading values can be directly mapped to a particular point in the 3D TAPS. This point is employed for selecting the most suitable channel for its subsequent transmission. Performance results indicate that utilizing the BOR scheme diminishes energy dissipation. Also, by using a large enough buffer at the relay, the theoretical energy dissipation and outage probability bound are managed at the cost of larger delay [59].

[59] assumes that only one fixed transmission rate is available. This assumption is extended in [60], which considers a finite number of transmission rates at the source and the relay. In [60], a dual-hop Half-Duplex (HD) relaying system is evaluated, where the links are impaired by block fading, and the source and relay can only send data at predefined rates within finite sets. The optimal scheduling of reception and transmission at the relay is derived, namely, that of infinite buffer size, without previous knowledge of channel information. This presents unrestrained delay. Thus, the second BA protocol is proposed, with finite buffer size, aiming to limit the delay at the expense of diminishing throughput. The throughputs attained by the proposed protocols are larger than those attained by conventional relaying protocols (where HD relay shifts between reception and transmission in an alternating behavior). Moreover, the loss in throughput due to limiting the delay to a practical value in the second proposed protocol is low [60].

Moving on, the key to the second goal, storing energy, is the use of energy harvesting (EH) that accommodates the random arrivals of energy and its storage at the nodes, prolonging the lifetime of the system. A throughput optimization of an EH-assisted two-hop system by means of a buffer-aided successive relaying protocol increases the data delivered to the destination node, where a solution has been found using the interior-point method [61]. The system in [61] uses a rechargeable source and relay nodes with limited buffers for energy and data storage.

[62] proposes another scheme that considers wireless powered communication system, where an EH node harvests energy from a radio frequency (RF) signal broadcasted by an access point (AP) in the downlink (DL). The harvested energy is stored in an energy buffer used to send data to the AP in the uplink (UL). Two simple online transmission strategies for the EH node, best-effort and on-off, are studied in [62], where both do not need to know the EH profile, nor the channel. For both policies in [62], if enough energy is found in the node's energy buffer, the node transmits in each time slot, with constant preferred power. Else, the node transmits with the maximum possible power in the best-effort policy and remains silent in the on-off policy. Buffering energy enhances the outage performance, compared with directly consuming all the harvested energy without buffering [62]. For low outage probabilities, the best-effort policy has a better outage performance, compared with the on-off policy and vice versa, for high outage probabilities [62].

Moving on, [63] takes into consideration energy-efficient resource allocation in the DL of buffer-aided wireless relay networks, and maximizes the system average energy efficiency, while preserving the queue stability at both the base station (BS) and relays. As a solution, a controlling parameter of an instantaneous utility function can be regulated to trade small average queue sizes for high average energy efficiency [63].

Energy efficiency is of paramount importance for Internet of Things (IoT) networks [64, 65]. Similarly, to enhance the energy efficiency, [66] proposes a practical hybrid bit-level network coding (BNC) for BA relating 5GB-IoT network taking into consideration the unreliable transmission, limited relay-buffer size, and signaling overhead. The proposed scheme, as well as increasing the buffer size improve the system energy efficiency performance [66].

Zhan *et al.* propose two other buffer-aided relaying protocols: the harvest-then-transmit (HtT) protocol, and the joint link selection and power allocation (JLSPA) protocol [67]. Both protocols improve the throughput performance of the network. For the buffer-aided HtT protocol, both the average achievable rate and the optimal power splitting (PS) factor are analyzed by determining their closed-form expressions. For the buffer-aided JLSPA protocol, assuming known Channel State Information (CSI) and Buffer State Information (BSI), the average achievable rate of the system is maximized by choosing the link for transmission, either S-R link or R-D link, depending on the CSI and BSI in each time slot [67].

A different power allocation scheme is presented in [68]. A two-way relay system is considered, and a BA relaying protocol is analyzed. The adaptive transmission mode selection and power allocation problem are investigated. However, for a given arrival rate, the algorithm ensures the queue stability while minimal average transmit consumption happens simultaneously. A trade-off exists between the average delay and average power consumption, where at the expense of small transmission delay, a more energy efficient transmission is accomplished [68]. A different type of power allocation scheme that depends on optimal offline joint relay selection is that of [69]. In this scheme, cognitive energy harvesting two-way-relaying networks are studied, where secondary transceivers and relays are EH nodes. The aim is to maximize throughput under transmit power, in addition to primary user (PU) interference restraints. The scheme in [69] performs better than that of random relay selection scheme.

[70] and [71] are also based on two-way EH networks. The study in [70] presents a BA adaptive transmission framework, where two users are exchanging messages with the help of a relay, with very large buffer size and energy storage size, by going through the three stages: EH, multiple-access, and broadcast transmission. By fully exploiting the potential at the relay, the average achievable rate region is boosted. To fulfill the requirements for the delay sensitive systems, a delay-aware adaptive transmission (DAAT) scheme has been proposed [70], for adaptive allocation of transmit powers, and for determining the mode of transmission decided by the current BSI, the CSI and the Energy State Information (ESI). The average end-to-end (E2E) delivery delay can be guaranteed. In this DAAT scheme, a fundamental trade-off exists between the average transmission rate and the average delay, where queue stability and the maximum achievable rate region can be reached by tolerating a particular time delay [70]. In regard to [71], a throughput maximization is considered for the two-way BA and EH-enabled multi-relay network with finite buffers, and limited energy battery in the absence of a direct S-D link. Combining time switching and energy splitting for RF EH, a three time sub-slot transmission model is designed, balancing the energy storage and consumption, where the three phases in a slot are: EH, information access, and broadcast transmission. In the first two time sub-slots, the chosen relay harvests energy and receives the data sent by the source. The data is stored in the battery and data buffers. In the last sub-slot, the selected relay node transmits the stored data in the buffers to the destinations. The proposed mechanism improves the sum-throughput by assigning suitable buffer size

and battery size, in addition to better transmission energy constraints [71].

The purpose of [72] is to maximize the throughput for multiple EH set-ups for delay constrained cases comprising single user channel, two-way channel, and two-way relay channel with finite buffer sizes and finite energy storage. The delay limited throughput maximization problem for each set-up is solved by decomposing the problem into two and then solving them using alternating maximization:

• Energy scheduling problem: it is solved using a modified directional water-filling algorithm with the right penetrable taps, water pumps and overflow bins.
• Data scheduling problem: it is solved with forward induction, where optimal data amounts are identified to be transmitted on a slot-by-slot basis.

For moderate delay requirements, the reason behind the increase in throughput is having data buffers that can store the transmitted data in one time slot, on average. For severe delay requirements, even small buffer sizes are enough since transmitters can no longer handle delaying packets by employing a larger buffer [72].

Unlike the fixed resource allocation policies implemented in most relaying schemes, adaptive relaying scheme is considered in [73]. A novel time-switching based relaying (TSR) scheme is firstly adopted, in which the harvest-store-use energy management policy is implemented, and each transmission round is divided to harvest energy, receive information, and forward them at the relay, respectively. In [73], an online buffer-energy-aware adaptive (BEAA) transmission scheme is proposed to adjust the transmission based on CSI, BSI and ESI, where a trade-off has been realized between the achieved E2E throughput and the transmission delay; thus, a throughput is achieved, which is close to the optimal value with limited cost of delay. Similar to the scheme in [73], a two-phase adaptive relaying scheme is proposed, where the source sends data and the relay receives data in the first phase, and the relays collaboratively transmit the buffered data to the destination node in the second phase. Also, time slots are dynamically assigned depending on the CSI, BSI and ESI, to achieve higher temporal and spatial diversity gains [73].

BEAA scheduling has also been discussed in [74], to design a buffer-aided relaying protocol for a network with one source, one destination and multiple HD DF relays, where the scheduling of relays is the same as that adopted in the study of [73]. The proposed scheme [74] wishes to maximize the average network throughput under both buffer stability and power consumption constraints. The online BEAA scheduling scheme has been derived taking into consideration relay selection and adaptive time allocation. It shows that there exists a trade-off between transmission delay, power consumption, and the achievable throughput as the reasonable increase of occupied relay buffer size, relative to the transmission delay, results in better performance. Thus, BEAA is efficient and, achieves a throughput close to the optimal value, i.e. with limited transmission delay [74].

Similar to [73], the scheme in [75] takes into consideration CSI, BSI and ESI to determine the best link. In [75], the aim is to plan a relay selection method that enhances the device-to-device (D2D) communications performance. An Energy-Aware and Buffer-Assisted (EABA) relay selection method is proposed that selects the best link for transmission at each time slot, based on the channel state, energy and buffer size. The proposed selection method enhances the overall transmission performance [75]. Similar to [67] and [73], PS-based-relaying (PSR) and TSR protocols have also been investigated for the schemes in [76]. In these schemes, the energy constrained relay with the strongest instantaneous link is chosen either for reception or transmission. This selected relay extracts energy from the source according to one of the two predefined simultaneous wireless information and power transfer (SWIPT) protocols and consumes that energy for information relaying. Performance analysis proves that TSR performs better than PSR protocol [76].

Both aforementioned strategies have been utilized in a wireless powered cooperative Non-Orthogonal Multiple Access (NOMA) relay network [77]. This network consists of one source and two users communicating via a BA HD energy-constrained relay with an energy storage that stores harvested energy from the source. The strategies achieve the required transmission rates by both users for the initial case without any buffers. PSR outperforms TSR in terms of the realized energy efficiency [77]. For the case with buffers, depending on the current CSI, ESI and BSI, the relay is able to switch its transmission mode to either energy harvesting, relay receiving, or relay transmitting. A buffer-aided adaptive transmission scheme (BATS), able to asymptotically reach the optimal solution, was derived. BATS takes into account both the rate and power allocations, in addition to the transmission mode selection. BATS enhances energy efficiency, when compared with TSR and PSR, due to the gains of the BA transmission mechanism. In the analysis of [77], a trade-off between long-term power consumption and average queuing delay was highlighted, where less power consumption can be attained at the cost of an increase in transmission delay. Another adaptive EH-based relaying approach, the adaptive source transmission policy, has been proposed in [78], where a delay-limited transmission mode has been studied, i.e. source data will be lost if it cannot be sent within a delay time limit. Using this approach, if the harvested energy is sufficient, the source will directly send data to the destination. Otherwise, the source employs a relay with lower data rate to send data [78]. This protocol relies on system design features and the energy harvested for each packet [78].

Introducing finite battery for a system with EH relay, a dual-hop communication system with BA EH relays subject to statistical energy underflow constraint, has been considered, where the buffer is infinite, battery is limited, and CSI is assumed to be available [79]. Both optimal and ON/OF power control policies with the optimal link selection policies have been proposed. An enhancement of throughput is realized with the proposed ones in comparison with naive policies [79]. The on-off policy was also exploited [80], where the performance of a dual-hop cooperative communication network is investigated. It is assumed that the source and relay are BA energy-harvesting nodes, and the direct S-D link is available, with the presence of fixed rate signaling at both nodes. The source and the relay harvest energy from surrounding sources and store it in energy buffers. Two different energy management policies are considered:

1. Best-Effort policy (BEP), which is considered at the source.
2. On-Off policy (OOP), which is considered at both the source and the relay.

Using the former policies, two cooperative transmission schemes were proposed: Source Best-Effort and Relay On-Off (SBRO), and Source On-Off and Relay On-Off (SORO). The performance of both schemes is superior to other direct relay-less transmission schemes. At low SNR values, SBRO outperforms SORO at optimum relay location and low target rates. At high target rates, the less complex SORO shows the best performance. Even though the best-effort policy at the source results in marginally superior performance in some scenarios, the simpler policy, on-off policy, avails in most practical cases [80]. The two policies, OOP and BEP, are utilized in the studies of [81] and [82]. [81] analyzes the performance of a cooperative communication network with an energy harvesting BA relay. Fixed and adaptive rate signaling are considered; the relay harvests energy from surrounding sources, and the direct and relayed signals are optimally merged. This work uses Harvest-store-use (HSU) with best-effort or on-off policies, for finite and infinite energy buffers. Results compare the performance of the proposed scheme with that of harvest-use (HU) and direct (relay-less) transmission. For the best throughput, the relay location, the fixed rate used for signaling, and the amount of energy drawn by the relay must be optimized. When the quantum of energy used by the relay is suitably picked, small-size energy buffers achieve a performance close to that with infinite energy buffers. Also, BEP is better than OOP in terms of throughput for low and medium target rates. Otherwise, OOP is better [81].

The other work in [82] considers a dual-hop cooperative network for fixed-rate transmission with an available direct link and an energy harvesting DF relay. The relay harvests energy from the surroundings and utilizes the HSU mechanism. [82] derives the limiting (steady-state) distribution of energy for both the incremental OOP (IOFP) and incremental BEP (IBEP) and utilizes them to obtain the outage probability and throughput. Results validate the superiority of the performance of IBEP over that of non-IBEP, HU and direct transmission. The work in [82] is extended in [83], where the stable buffers using IBEP and IOFP achieve a diversity gain of two and one, respectively. Even though using IBEP is more reliable than using IOFP, their throughput is only slightly superior [83]. The study regarding SWIPT in [76] has been limited to a Rayleigh outdoor wireless channel. The difference between an outdoor and indoor wireless channel is that the latter precisely portrays shadowing from barriers and moving human figures in indoor environments, whereas using outdoor fadings, indoors might intensely diminish due to hindrances as object motion and walls. Motivated by the accuracy of log-normal channels, the study in [84] analyzes the performance of dual-hop HD and FD SWIPT systems in log-normal fading, with both DF and AF relaying along with TSR, PSR and ideal relaying receiver (IRR) EH protocols. Study analysis proves the following:

1. When disregarding the processing energy cost, DF relaying presents better probability performance compared with AF relaying. However, if that cost is considered, AF relaying might outdo DF relaying.
2. The lower the variance of the log-normal fading channel, the better the performance.
3. FD relaying enhances the system performance as the loop-back interference, because FD relaying is reasonably minimal. As that interference gets larger, HD relaying might be able to outperform FD relaying [84].

VII Buffer-Aided Non-Orthogonal Multiple Access Relay Networks

The notion of Buffer-Aided (BA) Non-Orthogonal Multiple Access (NOMA) is that the transmitter transfers the superposition of several signals to several receivers. The receivers near the transmitter have superior channel conditions and are capable of employing successive interference cancellation (SIC) to sense and eliminate the signals to receivers, which are distant from the transmitter, having inferior channel conditions. Unlike conventional orthogonal multiple-access schemes (OMA), NOMA has the ability to employ multiple-access protocols, enhancing the system performance.

Based on [17], two BA opportunistic relay selection (ORS) algorithms are proposed in [85], to reduce the average delay without reducing the diversity. The first, Delay-Aware NOMA (DANOMA), gives priority to the transmission in the R-D link from the relay with the maximum buffer length. If the links to the destination do not exist, a transmission in the S-R link is executed towards the relay with the minimum buffer length. The second, Delay and Diversity-Aware NOMA (DDA-NOMA), aims to evade having full or empty buffer states. The study demonstrates that both schemes ensure robustness, and maintain the average delay performance with the increase of relays, especially for DDA-NOMA [85].

Similar to DANOMA that prioritizes R-D links, [86] presents BA ORS for uplink NOMA, namely flex-NOMA, using multi-relay reception and dynamic decoding ordering at the S-R link, in addition to Buffer State Information (BSI) for relay selection at the R-D link. Due to the presence of multiple relays, all sources transmit packets with equal power, where the network diversity will be utilized, enhancing the probability of successful successive interference cancellation. Also, low-latency demands of 5G services are not ignored as flex-NOMA aims to reduce packet delays due to the use of BSI and R-D prioritization, accelerating concurrent transmissions from multiple sources to multiple relays. The flex-NOMA outperforms OMA, with no added complexity, by supporting 5G uplink requirements. The flex-NOMA also has the ability to fulfill the needs of coexisting users and Internet of Things (IoT) devices, achieving better robustness and less delay, without acquiring high complexity nor coordination overheads [86].

The IoT has motivated a shift in the development of different applications such as mobile health. The wireless body area network (WBAN) consists of many low-power devices that monitor physiological signals for mobile health applications. In [87], a Quality of Service (QoS)-aware BA relaying framework is studied for implant WBAN, an implanted medical device sending its measured biological parameters to a target hub with the aid of minimum one on-body device satisfying its strict requirements on size, power consumption, and QoS. The proposed study considers hierarchical modulations to fulfill QoS requirements of different sensor data from an implanted device. New transmission strategies are also proposed for BA single-relay and multi-relay implant WBANs. The proposed cooperative WBAN shows better performance in terms of system delay and bit error rate than its conventional cooperative WBAN [87].

Similar to [86], prioritization of the R-D links is exploited in [88], where a Half-Duplex (HD) BA relaying system with multiple relays is considered, where the source communicates with a fixed rate to two users. Both users might request the same rate from the source. With the exploitation of multiple BA relays, an increase in both reliability and degrees of freedom is reached. Broadcasting was also integrated in BA ORS networks, where NOMA was utilized to attain communication of one source to multiple destinations. The exploitation of broadcasting enhances the diversity of the network as more relays are able to decode and store the packets, offering more possibilities for R-D transmission. Taking advantage of NOMA's spectral efficiency and BA relaying's enhanced diversity gains, two relay selection algorithms with broadcasting are presented in [88] for power-domain NOMA and hybrid NOMA/OMA, which are the BA-NOMA and BA-NOMA/OMA, respectively. The former prioritizes R-D transmission from the relay with maximum buffer size and in case no feasible set of R-D links exist, S-R broadcasting is performed. It enhances the outage probability when the power allocation factor α is chosen to provide robustness against channel uncertainties. The selection of this factor depends on the instantaneous CSI, but an extension is set in case of outdated CSI. BA-NOMA/OMA enhances the sum-rate and avoids a complete outage due to switching to OMA transmission towards a single destination when a NOMA transmission in the R-D links is unsuccessful. Performance assessment was set for users with equal and different rate requirements, in addition to asymmetric channel conditions. Both algorithms boost the performance of the relay networks in terms of outage probability, average sum-rate and average delay due to efficient scheduling and R-D prioritization [88].

Reference [89] investigates a finite size BA relay selection for multi-relay cooperative NOMA in the IoT. NOMA in IoT is significant as NOMA develops spectrum efficiency, and IoT system involves a massive number of connections. In [89], a prioritization-based BA relay selection scheme is proposed, which is capable of easily joining NOMA and OMA transmission in the network. The prioritization-based rule is through setting a target buffer length for the buffers of each relay, resulting in a diversity order of $3K$, where K is the number of relays. This scheme develops the data throughput at both low and high values of SNRs [89].

The extent of studying BA relaying under various operation modes has not been fully studied, which has been the motivation behind [90]. In [90], a scheduling policy for full-duplex (FD) multiple BA relay networks has been investigated, where a throughput-optimal policy in closed-form has been obtained under the simultaneous FD transmission modes. Numerical simulation confirms the substantial throughput gain over all SNR regimes. To limit delays, a threshold-based flow control scheme has been proposed, attaining a finite average delay at the expense of lessened throughput. Simulation analysis proves that the proposed scheme achieves considerable throughput gains over conventional scheme, and results in better trade-offs between throughput and delay [90].

VIII Security Analysis

In addition to security at the networking and application layers [91], insecure communication can arise from un-trusted relays or eavesdroppers; thus, the aim is to attain a suitable physical layer (PHY) security performance. The studies in [92] and [93] prove that buffer-aided (BA) relay aids in improving the secrecy throughput. In [92], a novel hybrid Half-Duplex/Full-Duplex (HD/FD) relaying scheme is proposed to improve the physical-layer security in an Alice-Rooney-Bob system (S-BA FD R-D) and Eve, a potential eavesdropper, by exploiting the exact Buffer State Information (BSI) at the relay and the secrecy rates of all links. Rooney adopts two relaying strategies; in the first strategy, Rooney and Alice use different codebooks, and in the second, they use the same codebook. To enhance the system security, Rooney switches between HD and FD modes. The proposed scheme enhances the average secrecy end-to-end (E2E) throughput compared with conventional buffer-less FD relaying strategies [92]. The scheme proposed in [93], which is the joint optimal link selection and power control policy, increases the average secrecy throughput. This policy [93] enhances the secrecy throughput, in comparison with fixed scheduling schemes with time division, and link selection with constant power levels.

Unlike [92], where the transmission rate of each node is predetermined, the study in [94] has no preset transmission rates as they can be adjusted at the source and the relay. The optimal transmission rates maximize the average secrecy throughput, under a particular Secrecy Outage Probability (SOP) constraint, using statistical Channel State Information (CSI) with low overhead. In [94], the physical layer security is investigated in a BA Multiple-Input Multiple-Output (MIMO) relaying system consisting of a single source, single destination, one multi-antenna relay, and multiple eavesdroppers. Based on the CSI, the relay operates either in HD or FD mode. This scheme increases the throughput, while conserving the secrecy performance, compared with the conventional buffer-free relaying schemes [94].

A cooperative jamming scheme is proposed to pick the message relay and the jammer, depending on the quality of both legitimate link and eavesdropper link, where two relays are chosen in each hop; one acts as a message relay to send or receive packets, and another acts as a jammer relay to send jamming signals to the eavesdropper [95]. This scheme results in a better security performance than the buffer-aided relay selection schemes, without jamming or with random jamming. SOP declines as the number of relays and the buffer size increase [95] [96]. Another jamming-related scheme is in [97], where a joint relay and jammer selection (JRJS) scheme is proposed for shielding wireless communication networks with multiple intermediate nodes against eavesdroppers, under two assumptions regarding CSI, full CSI (FCSI) and partial CSI (PCSI). The scheme joins relay selection and power allocation (PA), and it goes as follows:

- Find the set of relay candidates; they are the nodes that decode the source message successfully.
- Derive the sub-optimal closed-form power allocation solution and find the secrecy rate outcome of the proposed scheme for each candidate relay.
- Select the candidate relay that attains the utmost secrecy rate as the relay that forwards the signal from the source to the destination.
- The remaining nodes operate as friendly jammers and thus, broadcast artificial noise to disturb the eavesdropper. All have been chosen in order not to increase the complexity by going through jammer selection.
- Formulate a power allocation problem for maximizing the secrecy rate of the proposed JRJS scheme under total power constraint.
- Obtain closed-form sub-optimal solutions to the created power allocation problem under FCSI and PCSI, respectively.

JRJS has higher secrecy rate than the conventional pure relay selection and pure jamming. In addition, the secrecy rate of both FCSI-PA and PSCI-PA is enhanced by adding more intermediate relays [97].

Similarly, the scheme in [98] employs friendly jamming. This study considers a broadcasting channel, such that a multi-antenna transmitter, Alice, sends K confidential message signals to K authentic users, Bobs, in the presence of L eavesdroppers, Eves.

- Alice uses MIMO pre-coding to create the information signals along with her own (Tx-based) friendly jamming (FJ).
- MIMO zero-forcing hides the information signals from unwanted receivers, and removes the interference at each Bob, thus each Bob becomes surrounded with "vulnerability region", which can be exploited by a nearby Eve.
- This problem is solved by extending Tx-based FJ (TxFJ) with Rx-based FJ (RxFJ), generated by each Bob, i.e. each Bob employs self-interference inhibition to transmit a friendly jamming signal, while simultaneously receiving an information signal over the same channel.
- The powers allocated to the information, TxFJ and RxFJ signals, are minimized under given assurances on the individual secrecy rate.
- The optimal randomization rates for wiretap coding are determined to confuse the eavesdroppers based on the given requirements.

The proposed scheme increases the system performance for multi-user Multiple Input Single Output (MISO) systems when using RxDJ with TxFJ. Moreover, under certain conditions, different scheduling approaches increase the performance [98].

Another power allocation scheme for secure communication is that of [99]. Assuming no direct link between source and users, the user selection technique is employed to improve the secure performance in a cooperative relaying network by (i): Finding the optimal instantaneous source power (maximizing the instantaneous secrecy rate), when the source obtains full CSI of all links. (ii): Evaluating the security level by obtaining the ergodic secrecy rate and secrecy outage probability with the knowledge of statistical CSIs.

Another secure communication is required for a relaying wireless system, where the Energy Harvesting (EH) BA relay is driven by radio frequency signals from a source demanding to communicate with its destination in the presence of a potential eavesdropper. To enhance the system throughput, BSI, CSI, buffering capability of relays, burstiness of source data, and the presence of direct S-D link, in addition to imposed hardware constraints are assumed. To ensure secure communication, two protocols were designed, with impressive resultant throughput gains [100]. Another secure transmission study has been accomplished, however, for a downlink two-user single-input single-output (SISO) Non-Orthogonal Multiple-Access (NOMA) system, where communications occur through trusted HD relays in the presence of an eavesdropper [101]. For each of the three relaying schemes, cooperative jamming, decode-and-forward, and amplify-and-forward, [101], secure beamforming signals have been designed at the relays to enhance the secrecy rate, either by benefiting the users, hurting the eavesdropper, or both. The analysis indicates that the best relaying scheme is influenced by the system parameters, mainly the distances between nodes [101].

Other schemes are proposed for cooperative MIMO systems in case of passive eavesdropping scenario, i.e. eavesdroppers' CSI is not available, in [102] and [103]. [102] discusses the buffer-aided joint transmit antenna and relay selection scheme. The transmit antenna selection scheme is implemented at the transmitters, and the maximal ratio combining (MRC) scheme is implemented at the receivers. The study illustrates that the absence of the eavesdropping CSI can be coped, and the system secrecy performance can be improved by utilizing multiple antennas at the cost of higher complexity [102]. The selected relay with good link conditions tends to be full or empty, resulting in a decline in available links. In [103], a pre-coded artificial noise (AN) injection scheme is proposed, for a BA MIMO relaying wireless network with finite size buffer in the presence of a potential multi-antenna eavesdropper, to heighten the security of authentic transmissions. The node selected for data transmission (relay or source) depends on CSI and BSI. The nodes transmit AN vectors to confuse Eve by exploiting the additional dimensions provided by the difference between the number of transmit and receive antennas at the transmitting and receiving nodes. This scheme improves the secure throughput, compared with the buffer-less relaying schemes [103].

AN is also used in [104]. In [104], a FD multi-user system with HD eavesdroppers (Eves) is considered, where the FD base station (BS) concurrently assists both downlink (DL) and uplink (UL) users, while it sends AN along with the sent signals to hinder Eves. The objective is to maximize the smallest (max-min) secrecy rate for all valid users. The FD-BS employs a fraction of the time slot to work for close DL user and distant UL users. The residual fraction of the time is employed to work for other users. Depending on the information known on Eves' CSI, the SR maximization (SRM) problems can be categorized as: SRM with known CSI, SRM with Eves' Statistical CSI, and SRM with worst case scenario, where Eves can employ a more advanced linear decoder. This scheme enhances the SR performance, compared with HD, conventional FD and FD-NOMA. Moreover, results show the robustness of the proposed scheme against SI and Degrees of Freedom bottleneck [104].

Wei *et al*. propose a max-weight secure link selection (MWSLS) scheme to enhance the physical layer security of a two-hop decode-and-forward (DF) BA relay network, where higher priority is given to the buffer status to avoid empty/full buffers [105]. The network consists of a source S, a destination D, M HD DF relays equipped with buffers, and an eavesdropper E with no direct S-D link. Weights are first given to the $S - R_k$ and $R_k - D$ links as $L - \phi_k$ and ϕ_k, respectively, where ϕ_k corresponds to the current number of packets in R_k's buffer ($1 \leq k \leq M$). Then, MWSLS selects the link with the largest weight among all secure available $S - R_k$ and $R_k - D$ links. Thus, the relay with the least packets is selected at the first hop, and that with the most packets is selected at the second hop. For small buffer sizes, the secrecy outage performance is improved compared with the max-link secure link selection (MLSLS) scheme. For buffers' sizes exceeding 3, the secrecy diversity gain can reach $2M$ using MWSLS, while the same can be attained using MLSLS for buffers' sizes tending to infinity. Moreover, the MWSLS scheme outperforms the MLSLS scheme in terms of average secrecy throughput and end-to-end delay for low SNR values and obtains the same performances for high SNR values [105].

Similar to [102], the scheme in [106] considers the case of having a passive eavesdropper. The problem is investigated for an Alice-Bob (Source-Destination) communication system over fading channels in the presence of a passive Eve (Eavesdropper) under two settings: fixed and adaptive power allocation. For the first setting, the solution schedules either Alice or Ray (Relay) for data transmission. For the second setting, the problem extends from adaptive link selection (ALS) to joint ALS, where Alice's and Ray's transmit powers are adaptively allocated depending on the instantaneous main channel conditions; as these conditions become more favorable, more power is allocated to increase the secrecy rate. The previously mentioned two schemes result in an unbounded queuing delay at Ray's buffer. To achieve the optimal trade-off (maximum throughput and minimum delay), buffer states are considered along with the instantaneous CSI. Simulation analysis proves the efficiency of the proposed transmission schemes over numerous benchmarks, where ALS with fixed power allocation is efficient with suitable Ray positioning (preferably midway) and resource distribution, and ALS with adaptive power allocation presents higher capacity gains at low SNR [106]. In [107], effective resource allocation algorithms are proposed for a multi-user interference system in the presence of an eavesdropper. The goal is to allocate power to boost the worst secrecy throughput among the network links or the secure energy efficiency in terms of the attained secrecy throughput. Three scenarios regarding the access of CSI are provided: perfect CSI, partial CSI with exponentially distributed transmitters channels to the eavesdropper, and not perfectly known CSI with channels between transmitters and users with exponentially distributed errors. The power allocation schemes attain superior secrecy throughput and energy effectiveness [107].

The max-link scheme is adopted in [108] that investigates the secrecy OP of a DF BA multi-relay network, with a multi-antenna destination and an eavesdropper, where the buffers can be of finite or infinite size. The use of max-link helps fully exploit the advantages of the multi-antenna at the destination and available relays. A HD secure transmission scheme, MRC, and two FD secure transmission schemes, maximal ratio combining/cooperative jamming (MRC/CJ) and zero-forcing beam-forming/cooperative jamming (ZFB/CJ) are proposed to improve secrecy. In the case of finite buffers, the secrecy diversity gains reach M, where M denotes the number of relays in the network. In the case of infinite buffers, the corresponding secrecy diversity gains of MRC, MRC/CJ and ZFB/CJ rise to $M(1 + N_D)$, MN_D and $2M$, where N_D denotes the number of antennas at the destination. The increase of M and N_D improves the secrecy coding gain. Results show that ZFB/CJ outperforms MRC and MRC/CJ for all SNR values for finite buffers. For infinite buffers, however, ZFB/CJ outperforms MRC/CJ and MRC for low SNR values only [108].

In [109], the effect of correlated fading on the secrecy performance of multiple DF relaying with outdated relay selection is analyzed, where the main and the eavesdropping channels are linked. The best relay among the N available ones is picked to support the secure transmission. The picked relay might be outdated due to the time-varying channel environment. The aim is to investigate the influence of channel correlation and outdated relay selection on the secrecy performance. This is achieved by deriving an analytical expression for the secrecy outage probability, in addition to an asymptotic one in the high main-to-eavesdropper ratio region. From the latter expression, the channel correlation does not influence the secrecy diversity order. The full secrecy diversity order of N is attained in the case of perfect CSI only [109].

A different type of schemes is proposed in [110] to secure transmission with the assistance of an energy harvesting relay. The aim is to maximize the average secrecy rate under the constraints of data and energy queues stability conditions, by allocating the relay's transmit power to securely transfer the censored messages. In each time slot, the system picks a suitable transmission link, either from the transmitter to the relay or from the relay to the receiver, and successfully allocates the relay's transmit power [110] in either the online or the offline case.

[111] takes into account the passive eavesdropper scenario. Two types of transmission mechanisms are presented: the adaptive-rate transmission and the fixed-rate transmission. For each case, link selection schemes, which exploit the flexibility offered by BA relaying, have been proposed to guarantee security. By adjusting the link selection parameters, the decision thresholds are chosen to be ideal for maximizing SOP and minimizing secrecy outage capacity (SOC). The proposed schemes enhance the performance of dual-hop eavesdropping network in terms of SOC, SOP and exact secrecy throughput [111].

All these previous schemes validate that buffer-aided relay selection is accommodating and promising for attaining a desirable PHY security performance for different scenarios. However, due to the selection and the buffer queuing processes, an additional delay may be established; thus, the issue of the security-delay trade-off. This trade-off is analyzed in [112], where the randomize-and-forward strategy is considered, i.e. the eavesdropper independently decodes the signals received in two hops. The study's findings show that a relatively higher E2E secure transmission probability can be reached if a larger E2E delay is endured. To control the security-delay trade-off, it is possible to adjust the number of relays and the buffer size [112].

The preceding work demonstrates that the activation of the advisable link enhances the transmission security. However, conducting link selection to reconcile with the quality-of-service (QoS) is still an open issue. In [113], secure communication in a dual-hop BA relaying cooperative wireless network is studied, where a passive eavesdropper tries to interrupt the data transmission from the source and the relay. Two link selection policies are designed for the cases of available/unavailable CSI at the source, adopting an adaptive-rate transmission and fixed-rate transmission mechanisms, respectively. Based on the channels' qualities, the policies exploit the flexibility of BA relaying to choose a S-R, R-D or no link transmission. Results reveal the trade-offs between the transmission security and QoS. Results also prove the efficiency of the proposed link selection policies for establishing secure communication in the network [113].

Going back to relaying with DF strategy, a new secure buffer-aided relay selection scheme is proposed that utilizes multiple SR links, instantaneously, where relay selection is based on the states of the relay buffers to avoid full and empty buffer states. This scheme incorporates cooperative beam-forming, and cooperative jamming, to improve security without depending on using the full CSI of the eavesdropper [114]. This scheme outperforms other schemes in terms of delay and secrecy outage probability [114]. The work

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in [114] is based on the ideal assumption that the packet delivery delay is unbounded. However, for delay-sensitive systems, information usually has a validity period, and once the delivery time surpasses this period, information becomes invalid. This issue is covered in [115]. A two-hop BA relaying system with eavesdropping is considered, where every packet has its own limited lifetime [115]. A security and lifetime (SELI)-aware relay selection scheme is proposed to reach a specific secrecy rate by balancing the security and lifetime constraints. This scheme satisfies a specific secrecy rate while decreasing the probability of packet discarding [115].

[101] tackles the case of an un-trusted relay for two relaying schemes, which are the compress-and-forward and amplify-and-forward schemes. In each of them, two modes of operation are taken into account: passive user mode and active user mode. In the passive user mode, the users merge the data received from both the BS and the relay to decode their messages. The active user mode confuses the relay by having the users send a jamming signal at the same time with the BS transmission. Similar to the case of external eavesdropper, the best relaying scheme depends on the physical outline of the system, mainly the distances between the nodes [101]. Another scheme with multiple un-trusted relays [116] implements multiple antennas at the transmitter relay to attain a secrecy diversity order of $(\min(N,K)-1)$, where K, the number of single antenna relays, is larger than N, the number of antennas in the transmitter. [116] utilizes pre-coding signals non-linearly with the channel gains in a way that only the destination will be capable of separating interfering signals in an efficient manner. This scheme does not exploit any type of artificial noise, leading to remarkable power savings compared with those that do [116].

IX Buffer-aided Relay Selection Schemes for Hybrid Radio Frequency/Free-Space Optical Systems

Free-Space Optical (FSO) communication has become an attractive topic for wireless back-hauling due to its large usable bandwidth, compared with Radio Frequency (RF) back-hauling. FSO communication is limited by having an available line-of-sight (LOS) and erratic connectivity due to atmospheric conditions, even though the beams utilized enhance secure communication without interference. In [117], an achievable sum rate-based relay selection strategy is proposed, for a bidirectional FSO communication system, to maximize the achievable sum rate. The considered system is a parallel relayed FSO network with two-way relays (TWRs) over an atmospheric unsettled optical channel with pointing errors and path-loss. One TWR is chosen to form an FSO communication link between two non-LOS FSO transceivers. The strategy improves the system performance, and increases the selection probability of relays, which are nearer to any of the terminal nodes [117]. As a solution to mitigate the bad connectivity (avoid end-to-end degradation) for FSO systems, a hybrid RF/FSO system is built, where the RF link is a back-up for the FSO link, and the end-to-end performance of dual-hop communication is limited by the weakest link.

The study in [118] considers two different scenarios, based on delay-limited transmission. In [118], the relay has to immediately forward the packets received from the users to the destination. Delay-tolerant transmission is favorable, where the relay is allowed to store the packets received from the users in its buffer and forward them to the destination. Depending on the Channel State Information (CSI) of the RF and FSO links, fixed and adaptive link allocation policies are proposed in [118], allocating transmission time to the RF link. A highlighted trade-off between the achievable throughput, the delay, and the required signaling overhead, are shown in figure 6:

1. Delay-Tolerant Adaptive Link Allocation (DT-AL): Adaptively switches between transmission and reception for the RF links.
2. Delay-Limited Adaptive Link Allocation (DL-AL): Allocates a fixed fraction of the transmission blocks to the relay-destination RF link to maximize the end-to-end throughput under delay constraints and signaling overhead for collecting CSI constraints.
3. Delay-Tolerant Fixed Link Allocation (DT-FL).
4. Delay-Limited Fixed Link Allocation (DL-FL).

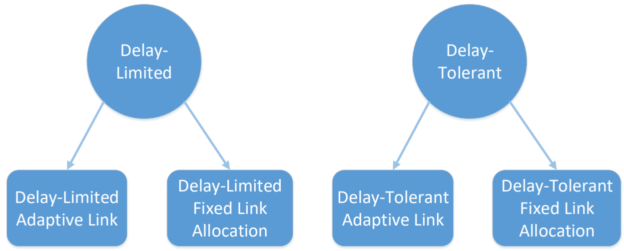

Fig. 6: Link Allocation Policies of Scheme [118]

A parallel hybrid RF/FSO relay channel is studied in [119]. [119] maximizes the throughput in the parallel hybrid RF/FSO relay channel, for both buffer-aided (BA) and non-buffer-aided relays, where a source node transmits its data to a destination node using multiple relay nodes. For both cases [119], the optimal relay selection policies for the RF and FSO links, in addition to the optimal time allocation policy for transmission and reception for the RF links are determined. Results show that the system can defeat the main weaknesses of RF systems, e.g. low data rate, and FSO systems, e.g. low reliability, at the cost of power consumption and complexity. The transmission modes for both BA and non-BA are grouped into three different modes [119] as follows. (i) Hybrid Mode: The same relay is selected for RF/FSO transmission/reception, i.e. the RF links act as support links for the FSO links. (ii) Independent Mode: The FSO and RF links are used independently, i.e. two different relays are selected for FSO reception/transmission and RF reception/transmission. (iii) Mixed Mode: One relay is used for FSO reception and RF transmission, while another relay is used for FSO transmission RF reception.

Previous studies assume symmetric channel gains on both RF and FSO links, which is not practical, especially for mobile relay links, where the coherence time is moderately low due to non-stopping mobile users' movements. Thus, multi-user mixed RF/FSO two-way relaying scheme with asymmetric channel gains is investigated in [120] and [121], with opportunistic user scheduling. The outage probability, asymptotic outage probability, and average symbol error rate are derived. The results indicate that opportunistic scheduling does not improve the network diversity. Additionally, severe pointing error may lead to total service blockage. An energy efficient power allocation scheme for the system in [120] and [121] is proposed, enhancing the outage performance. Under weak-to-moderate atmospheric turbulence conditions and small pointing error, the outage probability is dominated by the RF downlink, neglecting the user selection process at the RF uplink transmission [121]. But, for severe pointing error, the outage probability is dominated by the FSO uplink/downlink transmission [121]. Going one step further, [122] inspects the performance of the TWR-FSO network with nonzero boresight pointing errors, in terms of outage probability, where zero boresight pointing error has a better system performance. The overall speed of a cascade system depends on the speed of the slowest link. For systems where the FSO link can send one RF packet at a time, the performance of the network is limited by the RF links.

Motivated by the existing FSO back-hauling schemes, a new mixed RF and hybrid RF/FSO network, which is tolerant and effective has been designed in [123]. The network takes advantage of the extremely high FSO transmission rates for multi-user scenarios. Another hybrid system is modeled in [124], which investigates adaptive transmission (AT) schemes for a hybrid RF/FSO back-haul network. This network connects a macro cell base station with a small cell base station via multiple parallel BA relay nodes. These schemes improve the delay-throughput trade-off of the back-haul network, by utilizing the degrees of freedom over the RF and FSO links, and securing quality of service requirements. Two system configurations were investigated: the single-carrier and multi-carrier hybrid systems. The aim is to maximize the constant data arrival rate to the system, where the total queue occupancy is bounded with specific suitable queue-length bound violation probability. The proposed scheme yields better performance than the conventional switch-over hybrid transmission, particularly, in clear to moderately harsh weather conditions. The AT scheme considerably boosts the supportable data arrival for the network, compared with non-AT schemes. Accordingly, the proposed scheme maximizes the end-to-end effective capacity of the system in [124]. A transmission protocol that attains a multiplexing gain through a virtual Multiple-Input Multiple-Output system is proposed [123]. Results indicate that buffers enhance the performance, and that pointing error and severe atmospheric turbulence conditions are more bearable in the presence of a RF back-up link in the second hop [123].

X Unmanned Aerial Vehicles in Relaying Networks

Unmanned Aerial Vehicles (UAVs) are utilized as aerial base stations or mobile relays [125–127]. Of particular interest is the use of UAVs in vehicular networks [128, 129]. As UAVs models are getting stronger and their prices are decreasing, using multiple UAVs at once, as relays, increases the performance of a communication system [130–132]. [130] analyzes the UAVs' optimal positions, in two relaying options of a single multi-hop link and multiple dual-hop links, such that the average end-to-end (E2E) SNR is maximized. For each option, two relaying protocols are considered: the amplify-and-forward (AF) and the decode-and-forward (DF) protocols [130]. To determine the best settings for UAVs, the outage and bit error rate performance are compared. The setting of multiple dual-hop links is better for air-to-ground channels, whose path-loss parameters depend on UAV positions. However, when the path-loss parameters do not change with UAV positions, the multi-hop single link is better for huge distances between source and destination [130]. Aiming to provide useful design guidelines, this study analyzes the effects of various parameters on the optimum UAV positions, in addition to relaying performances [130].

[133] introduces a mobile relaying technique in wiretap channel for a mobile relaying system with UAV, to facilitate secure wireless communications in the presence of an eavesdropper. The study maximizes the secrecy rate by optimizing the transmit power of the source and relay, while taking into account information-causality constraints that guarantee that a relay cannot transmit data that has not been decoded. Substantial performance gain is achieved, in terms of secrecy augmentation, compared with conventional static relaying techniques [133].

Secrecy rate is also studied in [134]. An optimal UAV trajectory design against an eavesdropper sited arbitrary is investigated from the physical layer (PHY) security perspective of a buffer-aided (BA) UAV mobile relaying system. As the UAV relay is not fixed, the wireless channel dynamics must be considered. By optimizing the discrete trajectory anchor points based on the information causality and UAV mobility constraints, the sum secrecy rate is maximized. The proposed trajectory finding mechanism is efficient and fast converging. Also, the distribution of the eavesdropper's location has a noticeable effect on the PHY security performance as the rate improves, when the eavesdropper is located further away from the destination. Similarly, a higher maximum UAV speed is favorable to the secrecy rate and energy efficiency [134].

In terms of energy, [135] proposes an energy-efficient transmission scheme for finite BA UAV-relaying network, where adaptive link selection and adaptive power control are adopted. The source is assumed to have infinite energy and data to transmit, whereas the UAVs' energy is constrained by battery capacity. Taking into account the energy efficiency of the network, the second hop is prioritized to choose the optimal link, depending on the UAVs' remaining energy, Channel State Information, and buffer state. Based on the amount of information in the buffer, the transmit power is set. A threshold of the transmit power prevents the exponential increase of the transmission power, in case of overflowing buffer. Next, the best relay for the first hop is selected based on the SNR. The proposed scheme enhances the energy efficiency of BA UAV relaying networks, compared with conventional relaying protocols, and elongates the network lifetime by avoiding energy waste. The enhancements come at the cost of added transmission delay, making the scheme appropriate for delay-tolerant environments. The scheme results in a suitable trade-off between the network lifetime and the average throughput [135].

UAVs have been integrated in relay-assisted Free-Space Optical (FSO) systems. As proposed by [136], the integration of these flying platforms as BA moving relays improves the performance of the conventional FSO systems with stationary buffer-free relays. This study considers two potential ways to incorporate BA UAVs into the FSO systems. Results in [136] validate the promising performance gains linked to this hybrid design under small buffer sizes, where these gains are boosted through proper placement and employment of the BA UAVs in the case of parallel relaying.

[137] considers a dual-hop decode-and-forward (DF) Full-Duplex (FD) BA UAV-relaying system under a buffer constraint at the relay, due to the packet delay presented by the difference in the attainable data rate between FSO and Radio Frequency (RF) links, based on the relay's position. The buffer constraint makes the relay cycle between both terminals, back-haul and user, to avoid a buffer overflow. [137] proposes a relaying protocol exploiting hybrid RF/FSO communication, where both S-R and R-D links use FSO and RF communication under the buffer constraint. It also studies the trajectory optimization problem of this model since the relay requires a proper path to satisfy the constraint. It finds a local optimum solution for the throughput maximization problems. Specifically, the trajectory of the UAV is optimized. The proposed scheme attains 161.3% throughput gains, compared with static relaying scheme [137].

Another technique to boost the reliability of FSO network is the BA serial relaying technique of [138]. A multi-hop serial relaying FSO communication system is considered, where the relays are equipped with finite buffers. The FSO transceivers operate naturally in FD mode, where simultaneous reception and transmission can take place at the photodetector and laser placed at each relay, respectively. For dual-hop systems, exact expressions for system outage probability (OP) and average packet delay (APD) have been obtained. For systems with more than two hops, asymptotic expressions of OP and APD have been obtained. An escalation in diversity order is attained by BA relaying systems with buffer sizes not exceeding two, compared with buffer-free systems. In particular, specific conditions regarding the position of the relay must be met to reach the maximum diversity gain. The disadvantage of using BA relays lies in introducing delay, where this delay can be minimized to fall within a tolerable practical range.

The advantage of using BA UAV-based relay has been discussed in [139]. In [139], the communication system considered is a DF UAV-relay connecting mobile users (MUs) via RF links to a ground station (GS) via an FSO back-haul link. Due to the mutual orthogonality of the links, the UAV-based relay can simultaneously transmit and receive. The RF and FSO channels depend on the UAV's location and instability, respectively, where the relative position of the UAV with respect to the MUs affects the line-of-sight connection in the RF link, whereas the instability of the UAV affects the FSO channel's quality. [139] analyzes the end-to-end system performance of networks employing UAVs as BA and non-BA relays, in terms of ergodic sum rate. Results show that, when the weather conditions worsen and the atmospheric loss in the FSO channel intensifies, positioning the UAV closer to the GS improves the back-haul channel's quality. For a higher density of MUs and larger amount of data received via the RF channel, performance can be enhanced if the UAV's position becomes closer to the GS. Results reveal that the variations of the FSO channel due to the UAV's instability can be diminished by equipping the UAV relay with a buffer, resulting in larger ergodic sum rate, compared with non-BA relaying, at the expense of additional delay [139]. Depending on the network setup (position of relays), parallel relaying [136] is better in some cases, while serial relaying is better in others. Generally, if the S-D distance is extremely long, it is encouraged to employ serial-relaying as either the S-R or the R-D link will be extensive, for a particular

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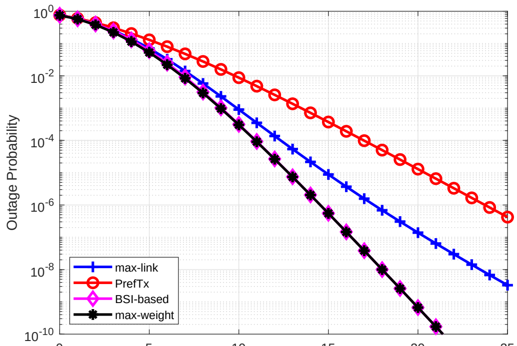

Fig. 7: OP for a 3-relay network with $L = 10$.

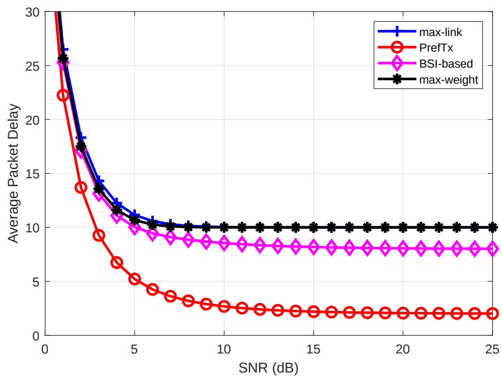

Fig. 8: APD for a 3-relay network with $L = 10$.

relay, ensuing a marginal enhancement in the diversity order [138]. For the case of serial relaying, in [140], the performance of a dual-hop BA DF relaying FSO system and the impact of activating the direct S-D link on the system performance are studied. Closed-form expressions for the OP and APD were derived. Even though activating the direct SD link decreases the APD, this activation might lead to an incline or decline in the diversity order, depending on the position of the relay [140].

XI Numerical Results

In order to further highlight on the levels of OP and APD that can be achieved, some simulation results are presented for a 3-relay symmetrical network under Rayleigh fading where a buffer size $L = 10$ is considered. In particular, we compare the max-link, preferred transmission (PrefTx), BSI-based and max-weight relaying strategies in [7], [18], [45] and [12], respectively. The OP-versus-SNR and APD-versus-SNR curves are shown in Fig. 7 and Fig. 8, respectively.

Results in Fig. 7 show that the max-link and PrefTx schemes suffer from a reduced diversity order compared to the BSI-based and max-weight schemes that achieve comparable performance levels in this simulation setup. The PrefTx scheme that privileges the APD performance metric achieves the smallest APD at the expense of suffering from the highest OP for all values of the SNR. Compared to the PrefTx scheme, the max-link protocol achieves an OP performance gain of 4.5 dB at the expense of increasing the asymptotic APD from 2 to 10. On the other hand, the BSI-based and max-weight schemes privilege the availability of the network and, hence, result in the smallest OP. This good OP performance inflicts a compromise on the APD where the APD performance is better than that of the max-link scheme but worse than that of the PrefTx scheme. In this case, the advantage of the BSI-based scheme resides in smaller APD levels especially for large values of the SNR.

XII Challenges and Opportunities for Future Research

All the mentioned schemes in the survey improve the performance of the communication system in terms of outage and throughput. However, buffer-aided relaying has faced several challenges and limitations that should be addressed in the future. As future work, it is recommended to:

- Analyze the proposed Max-Score Relay Selection policy in the case of non-identical fading environments [16].
- Combine the probabilistic scheme with BSB relay selection schemes [23].
- Improve the delay performance limited by the back-pressure theory in relay selection [141].
- Design a virtual relay scheme for packet selection [31].
- Use quantized feedback to reduce feedback overhead.
- Extend the proposed max-weight scheme to a more complicated networks, such as cognitive or multiple access relay networks [12].
- Extend to heterogeneous settings, where buffers are not identical in size [13].
- Extend to a generalized system model with multi-relays, Nakagami-m fading channel [14].
- Incorporate the proposed buffer limit in [32] for FD, two-way and successive relaying.
- Study the influence of the buffer-limit BTRS with energy harvesting [32].
- Integrate buffer load-based analysis for successive relaying [33].
- Incorporate into the system: the use of energy harvesting at the source and relay nodes, in addition to the presence of a direction like between source and destination [15].
- Extend the multi-rate framework through a delay-aware service that minimizes the system latency by efficiently using the system resources [52].
- Analyze the performance for BSB relay selection scheme in the presence of EH relays [76].
- Examine the benefits of channel space partitioning in multi-hop links [59].
- Develop the schemes of [70] to cover relays with limited energy storage and limited buffer size.
- Work on how to achieve the secrecy requirement in the two-way EH network [70].
- Develop the schemes of [70] to cover relays with limited energy storage and limited buffer size.
- Investigate the distributive implementation and adaptive transmission mode selection in BA and EH-enabled relaying networks with multiple relays [71].
- Extend the work in [74] to cover MIMO scenarios and consider buffers with finite size.
- Design a robust transmission scheme due to imperfect CSI [77].
- Consider the energy consumption required for CSI feedback, training pilots transmission for channel estimation at the source and relay as well as control decision transmission [77].
- Examine EH receivers and transmitters in the set-ups mentioned in the study and more [72].
- Consider priorities on data packets [72].
- Eradicate the assumption of fixed transmission rates in [80] by adjusting the rates based on CSI.
- Extend flex-NOMA towards advanced BSI usage by integrating the scenario of traffic with different priorities [86].
- Devise networking pairing algorithms with large numbers of coexisting users and devices to enhance the performance of NOMA communication by achieving full SIC [86].
- Tackle security issues of 5G-enabled services, such as protecting smart grids, to improve flex-NOMA. [86].
- Develop selection algorithms that aim to maximize the sum-rate of multi-source networks considering BA FD relays. [88]
- Consider jointly rate optimization and power control for BA relaying systems [94].

Table 5 Comparison and Key Points of all Studies Reviewed

Mode	HD	[2, 3, 7, 9–19, 23–28, 31, 32, 34–37, 45–48, 50, 56–58, 60–62, 67, 68, 70, 71, 73–77, 79, 80, 84–86, 88, 89, 93–96, 100–103, 105, 106, 110–115, 118, 135, 142]
	FD	[21, 22, 51, 53, 54, 84, 90, 92, 94, 98, 102, 104, 137, 140]
Direct Link	Available	[14, 35–37, 48, 49, 52, 59, 75, 78, 80, 82, 83, 90, 96, 100, 102, 103, 143]
	Unavailable	[2, 3, 7–13, 15–19, 21–28, 30–34, 43–47, 50, 51, 53–58, 60, 61, 63, 66–68, 70–74, 76, 77, 79, 84–89, 92–95, 97, 99, 102, 105, 106, 108–116, 123, 124, 134–138, 142, 144]
FSO		[8, 117, 136, 138, 140, 141]
Hybrid RF/FSO		[118–124, 137, 139]
UAV		[130, 133–140]
Data Buffer Size	Finite	[2, 3, 7–9, 11–19, 23–28, 30–34, 37, 38, 44–47, 50, 52, 53, 55, 57–59, 61, 66, 71–76, 80, 81, 85–89, 92, 95, 96, 100, 102, 103, 105, 108, 110, 112, 114, 115, 118, 123, 134–138, 140, 144]
	Infinite	[3, 7, 21, 22, 43, 48, 51, 60, 67, 68, 70, 79, 90, 93, 94, 102, 106, 108, 111, 113, 119, 124, 142, 143]
Energy Buffer Size	Finite	[62, 77, 79, 81, 100, 110]
	Infinite	[62, 81–83]
CSI	Perfect	[2, 3, 7, 9, 10, 12, 13, 15–17, 19, 21, 22, 24, 29, 35–37, 47, 48, 50–52, 56, 59, 67, 68, 70, 71, 73–77, 79, 84–89, 92–95, 98–100, 103, 104, 106–109, 111–114, 116, 118, 119, 124, 135, 141, 144]
	Imperfect	[9, 10, 13, 22, 24–26, 51, 88, 95, 98, 99, 104, 106, 107, 109, 111–113, 118]
BSI		[7, 9, 12, 13, 15, 16, 19, 24, 33, 37, 45, 47, 50, 67, 70, 71, 73–75, 77, 87, 89, 100, 103, 135, 144]
ESI		[15, 70, 71, 73–75, 77, 135]
DSI		[47]
Metric	OP	[2, 3, 7, 8, 11–13, 15–19, 21–28, 30–34, 43–47, 50, 51, 53, 55, 57–59, 62, 76, 80–86, 88, 94, 115, 120–124, 136, 138, 140, 144]
	Delay	[7, 8, 11–18, 23–25, 30–35, 38, 43, 45, 46, 48, 50–53, 57–60, 66–68, 70, 73, 74, 77, 85–90, 105, 106, 112, 114, 118, 119, 124, 135, 138–140, 142, 144]
	Throughput	[2, 16, 17, 21, 22, 29, 30, 32, 33, 47, 48, 51, 52, 54, 59–63, 66, 67, 69, 71–75, 78–83, 85, 89, 90, 92, 94, 105, 111, 113, 118, 119, 124, 135, 137, 138, 141, 143, 144]
	Diversity Gain	[2, 3, 7, 11–13, 16, 18, 19, 23, 24, 26–28, 32, 35, 38, 44–47, 50, 55, 57, 70, 74, 76, 83, 85, 88, 102, 120, 122, 138, 140, 142, 144]
	Capacity	[3, 56, 59, 84, 117–124, 141]
	BER	[2, 9, 10, 26, 37, 87, 122, 124]
	Secrecy OP	[95, 96, 98, 99, 102, 103, 105, 106, 108, 109, 111, 113, 114]
	Secrecy Rate	[95–97, 99, 101, 104–106, 110, 116, 133, 134]
	Secrecy Throughput	[93, 94, 100, 103, 106–108, 111–113, 115]
	Packet Energy Dissipation	[59]

• Develop the case of an un-trusted relay in the study of [101] to investigate multiple un-trusted relays, additional external eavesdropper or both.
• Expand the study in [101] to cover nodes with multiple antennas without having the eavesdropper's CSI at the relays.
• Extend the work in [105] to cognitive cooperative or internet-of-things scenarios.
• Study the impact of imperfect CSI on the system secrecy performance under the three transmission schemes in [108].
• Extend to beam-forming in MISO interference systems with multiple eavesdroppers [107].
• Formulate the secrecy capacity of general buffer-aided relay systems [112].
• Investigate the resulting problem of calculating the E2E ergodic capacity of serial-relaying BA FSO systems [138].

XIII Conclusion

Employing buffers in relays has significantly enriched the world of wireless communication due to the performance gains that result from their expenditure in terms of throughput and outage probability. Even though it may come at the expense of additional delay, the gains that result from their use are vast. However, for delay-limited uses, it is encouraged to propose a way to diminish the encountered delay. At this level, additional technology and knowledge should be expanded in order to progress the research behind buffer-aided relays, and resolve as many previously imposed limitations as possible.

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