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Buffer-Aided Cooperative Communications: Opportunities and Challenges

Nikola Zlatanov, Aissa Ikhlef, Toufiqul Islam, and Robert Schober

Abstract

Cooperative communication can increase the throughput and/or extend the coverage of wireless networks. However, in conventional cooperative networks, half-duplex relays transmit and receive under a prefixed schedule, which does not allow them to exploit the best receiving and transmitting channels, thus limiting performance. Recently, new protocols have been proposed that circumvent this problem by making use of the additional flexibility offered by relays with buffers. Compared to conventional relaying protocols, these buffer-aided protocols provide significant gains in terms of throughput, diversity, and signal-to-noise ratio. This article outlines several buffer-aided relaying protocols for different network topologies, including one-way single- and multi-relay networks as well as two-way single-relay networks. Moreover, some practical challenges inherent to buffer-aided relaying, such as increased delay and complexity, and topics for future research are discussed.

Introduction

The nodes of wireless communication networks are usually equipped with buffers for temporary data storage as required by many network and transportation layer protocols. For example, in the *store-carry-forward* protocol employed in delay-/disruption-tolerant networking (DTN), temporally disconnected, intermediate nodes may store data packets until they regain connection to the destination or the next forwarding node [1]. Similarly, in user-provided networks, data packets may be temporarily stored as a means for service differentiation between home users and guest users [2]. However, so far, the potential benefits of exploiting buffers for the physical layer and link layer design have received little attention in the literature.

In this article, we present the benefits of buffers for the design of relaying protocols in cooperative communication systems [3]. The basic idea of cooperative communication is that the transmitting nodes help each other to facilitate one another's communication by willingly acting as relays and sharing their resources. In particular, when a source (e.g., a mobile phone) transmits a packet to the destination (e.g., a base station), nearby relay nodes (e.g., other mobile phones) can overhear this packet, process it, and retransmit it to the destination, thus helping in the transmission process. Cooperative (or relayed) communication can improve the capacity and/or extend the coverage of wireless communications systems. Due to their benefits, simple relay schemes have been/are being included in recent/future wireless standards such as the Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE) Advanced standards [4].

In cooperative communications, two main relaying protocols are used: full-duplex (FD) relaying and half-duplex (HD) relaying. In FD relaying, the relays transmit and receive at the same time and in the same frequency band. However, given the current radio implementation limitations, FD relaying is difficult to realize in practice because of strong self-interference. As a result, the vast majority of the existing literature on cooperative communications considers HD relaying due to its implementation simplicity. In HD relaying, transmission is usually organized in two successive time slots. In the first time slot, the relay receives data transmitted by a source, and in the second time slot the relay forwards the received data to a destination. We refer to such schemes as *conventional relaying* in the following. In conventional relaying protocols, the relays employ a prefixed schedule of transmission and reception independent of the quality of the transmitting and receiving channels. This prefixed scheduling may lead to significant performance degradation in wireless systems, where the qualities of the transmitting and receiving channels significantly vary with time, since it may prevent the relays from exploiting the best transmitting and the best receiving channels. Figure 1a illustrates this limitation of conventional HD relaying. In particular, in Fig. 1a, we assume that the relay receives in odd time slots $2i - 1$ and transmits in even time slots $2i$. For the channel realizations assumed in Fig. 1a, because of the fixed schedule of transmission and reception for the relay, the system cannot exploit the link with the largest signal-to-noise ratio (SNR). More

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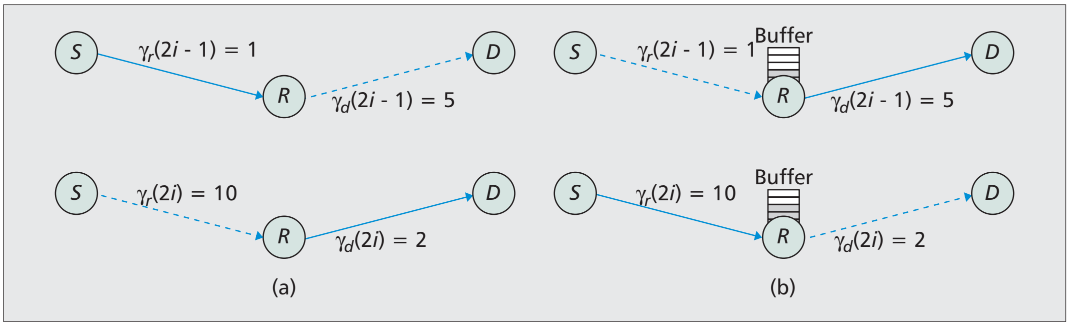

Figure 1. System model for a three-node relay network employing: a) a conventional relaying protocol; b) a buffer-aided relaying protocol where the relay is equipped with a buffer and can store the packets received from the source. Time slots $2i - 1$ and $2i$ are considered. $\gamma_r(\cdot)$ and $\gamma_d(\cdot)$ denote the SNRs of the source-relay and relay-destination links, respectively. Solid line: link selected for transmission in considered time slot; dashed line: link not selected for transmission in the considered time slot. The shaded buffer elements are full at the end of the considered time slot.

Buffer-aided relaying leads to significant performance gains in cooperative communication networks with time varying link qualities. Hence, possible applications of buffer-aided relaying include vehicular, cellular, and sensor networks.

precisely, in time slot $2i – 1$, the source-relay link with an SNR of $\gamma_r(2i – 1) = 1$ is used for transmission, although the relay-destination link has an SNR of $\gamma_d(2i – 1) = 5$. Similarly, in time slot $2i$, the relay-destination link with SNR $\gamma_d(2i) = 2$ is used although the SNR of the source-relay link is $\gamma_r(2i) = 10$. Clearly, performance could be improved if the link with the higher SNR could be used in each time slot. This can be achieved via a buffer-aided relaying protocol that does not have a prefixed schedule of reception and transmission for the relay. In particular, buffer-aided relaying can exploit the strong relay-destination link for transmission in time slot $2i – 1$ since the relay has already stored in its buffer data received from the source in previous time slots (Fig. 1b). Similarly, it can exploit the strong source-relay link in time slot $2i$ and store the received message in its buffer. Obviously, this is an idealized example, and exploiting the link with the best SNR may not always be possible as the relay first has to accumulate information in its buffer before transmitting. Furthermore, although the use of buffers improves performance and introduces new degrees of freedom for system design, it has its own practical challenges. In particular, storing packets in the relay's buffer introduces an additional delay, which has to be properly managed for delay-sensitive applications such as voice. Moreover, buffer-aided relaying protocols require the acquisition of channel state information (CSI) and may require monitoring of the state of the buffer. As a result, buffer-aided relaying protocols generally have increased complexity compared to conventional protocols. Nevertheless, buffer-aided relaying leads to significant performance gains in cooperative communication networks with time varying link qualities. Hence, possible applications of buffer-aided relaying include vehicular, cellular, and sensor networks.

The remainder of this article is organized as follows. First, we present buffer-aided relaying protocols for single-relay and multi-relay networks, respectively. We then discuss the use of buffers in multihop and two-way relaying. As a practical example, we consider a network employing the combination of bit-interleaved coded modulation (BICM) and orthogonal frequency-division multiplexing (OFDM). Next, we discuss some practical challenges related to the use of relays with buffers, such as delay, complexity, and channel estimation requirements, and highlight some interesting topics for future research. We then conclude the article.

Single-Relay Networks

To develop a basic understanding of buffer-aided relaying, we first consider a simple three-node relay network consisting of a source, S, an HD relay equipped with a buffer, R, and a destination, D. The S–D link is not available, and the source communicates with the destination only through the relay (Fig. 1b). The S–R and R–D channels are impaired by slow fading such that the channels are constant in one time slot and change from one time slot to the next. Furthermore, source and relay transmit packets, which span one time slot and are encoded by capacity-achieving codes, such as low-density parity check (LDPC) or polar codes.

For this network, we present a buffer-aided relaying protocol in which in each time slot the relay decides whether it should transmit or receive based on the instantaneous qualities of the S–R and R–D channels, and broadcasts its decision to the other nodes. This protocol is referred to as *buffer-aided relaying with adaptive link selection* and was introduced in [5–7]. Thereby, if in time slot i the relay is selected to receive, the relay receives a packet from the source, decodes it, and accumulates the information in its buffer. On the other hand, if the relay is selected to transmit, the relay extracts the stored information from its buffer, maps it into a packet, and transmits the packet to the destination. In the following, depending on the availability of CSI, we discuss transmission with adaptive rate and fixed rate [6, 7], respectively.

Adaptive Transmission Rate

For adaptive transmission rate, the source and relay adapt the data rates of their transmit packets in each time slot such that they are equal to the capacities of the S–R and R–D channels, respectively. As a result, outages are avoided, but in order to perform rate adaptation, the source and relay need full CSI of the S–R and R–D channels, respectively. Furthermore, for

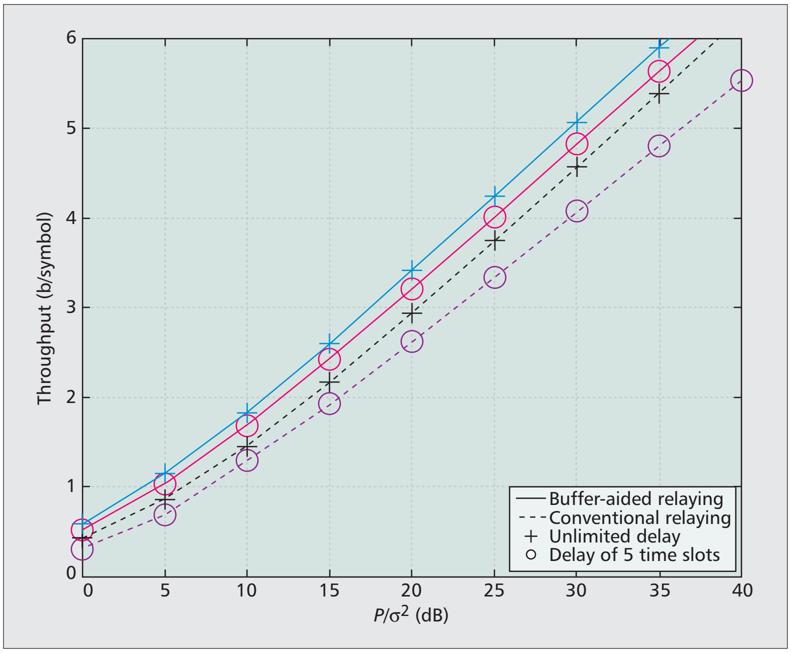

Figure 2. Throughputs of buffer-aided relaying and conventional relaying vs. transmit SNR (P/σ^2). Adaptive transmission rate without and with delay constraints.

decoding and link selection, the relay also requires full CSI of the *S-R* channel. In the following, we first present a protocol that maximizes the throughput of the considered three-node relay network. This protocol introduces unbounded delay and provides a performance upper bound for the second, more practical protocol with limited delay.

In the absence of a delay limit, based on the capacities of the *S–R* and *R–D* links in time slot i, denoted $C_{SR}(i)$ and $C_{RD}(i)$, respectively, and a suitably chosen constant $\rho > 0$, the relay selects in time slot i:

- The source for transmission and the relay for reception if $C_{SR}(i) > \rho C_{RD}(i)$
- The relay for transmission and the destination for reception otherwise

For delay-constrained transmission, the above protocol has to be slightly modified. In particular, we first limit the size of the buffer to Q_{max} bits and adopt the following modified selection scheme for time slot i:

- If the buffer is empty, the source transmits and the relay receives.
- If the buffer is full, the relay transmits and the destination receives.
- Otherwise, the transmitting/receiving nodes are selected using the protocol for the case without delay constraints.

In this protocol, the average delay can be controlled via the buffer size. The impact of limiting the delay on performance is discussed at the end of this section.

Fixed Transmission Rate

If all nodes have CSI of their respective receiving channels but not of their respective transmitting channels, the source and relay are forced to transmit with a fixed rate R_0 in all time slots, which may result in outages. Similar to the adaptive transmission rate case, for a fixed transmission rate, we first consider the case without a limit on the end-to-end delay, before imposing delay constraints. Given the outage states[1] of the *S–R* and *R–D* channels, the relay selects in time slot i:

- The relay to transmit to the destination if the *S–R* link is in outage and the *R–D* link is not in outage
- The source to transmit to the relay if the *S–R* link is not in outage and the *R–D* link is in outage
- The relay to transmit to the destination in P_C percent of the time and the source to transmit to the relay in 100 – P_C percent of the time, if the *S–R* and *R–D* links are both not in outage

For delay constrained transmission, the above protocol has to be slightly modified. In particular, if the buffer is empty or contains only one packet, and the *S–R* link is not in outage, the source always transmits to the relay. Otherwise, the transmitting link is selected based on the protocol for the case without delay constraints, and the average delay can be controlled via the percentage P_C; see [7] for details.

In the above protocols, constants ρ and P_C depend on the average SNRs of the *S–R* and *R–D* links, and are chosen such that in the long-term average, the amount of data received by the relay is identical to the amount of data transmitted by the relay; details can be found in [6, 7].

Performance of Buffer-Aided Relaying

Figures 2 and 3 depict simulation results for the performance of buffer-aided relaying in terms of throughput and outage probability, respectively, vs. transmit SNR, P/σ^2, where P is the transmit power, and σ^2 is the noise variance at the transmitting and receiving nodes, respectively. Thereby, unit power, independent, and identically distributed (i.i.d.) Rayleigh fading *S–R* and *R–D* links are assumed, and a comparison with conventional relaying is made. For conventional relaying, the source transmits to the relay in k consecutive time slots; then the relay transmits to the destination in the following n time slots. The values of k and n can be chosen to satisfy any delay requirements.

Figure 2 shows that for adaptive transmission rate, buffer-aided relaying with adaptive link selection yields significant performance gains compared to conventional decode-and-forward (DF) relaying; that is, conventional relaying requires a higher transmit SNR to achieve the same throughput as buffer-aided relaying. Furthermore, constraining the average delay to five time slots results in only a small performance degradation. In particular, for a delay of five time slots and a throughput of 3 b/symbol, the SNR gain of buffer-aided relaying over conventional relaying is around 4 dB.

Figure 3 shows the outage probability for fixed transmission rate and reveals that buffer-aided relaying with adaptive link selection achieves a diversity gain compared to conventional relaying which leads to large performance gains. In particular, for an outage probability of 10^{-2}, the achieved SNR gain of buffer-aided relaying over conventional relaying is around 10 dB. Furthermore, constraining the average delay

[1] The outage state of the R–D *channel can be acquired by the relay via one bit of feedback from the destination.*

results in a negligeable performance degradation. However, this is only true if the average delay exceeds three time slots and the fading is slot-by-slot uncorrelated[2] [7]. For slot-by-slot correlated fading, greater performance degradation is expected.

Buffer-Aided Relay Selection

Using multiple relays to establish the communication between a source and destination allows further improvement of performance in terms of throughput and/or reliability compared to using a single relay. Many different protocols have been proposed for multi-relay networks including beamforming, space-time coding, and relay selection. Relay selection has attracted much interest due to its good performance and simplicity of implementation. A well-known relay selection protocol is best relay selection (BRS) [8]. In this protocol, for each packet transmission, the relay with the best end-to-end channel is chosen for transmission out of $N \geq 2$ available relays. The packet is sent to the selected relay in the first time slot, and the relay forwards the packet to the destination in the second time slot. Assuming the channels remain constant during both time slots, BRS achieves a diversity gain of N. However, the BRS protocol is in general not able to simultaneously exploit the best available S–R and R–D channels as the selected relay does not generally experience the best S–R and R–D channels at the same time. Figure 4a illustrates this limitation of BRS. We assume that the source transmits in odd time slots and the relay in even time slots, and that the channel gains are constant during two time slots. According to BRS, relay R_1 is selected for reception and transmission since its bottleneck link SNR of $\min\{\gamma_{r1}(2i-1), \gamma_{d1}(2i)\} = 2$ is higher than that of relay R_2, leading to better end-to-end channel quality. Since in the BRS protocol R_1 has to receive and transmit in time slots $2i-1$ and $2i$, respectively, performance is limited by its bottleneck SNR, which in this case is 2. As a result, the large SNRs of the receiving channel of relay R_2 ($\gamma_{d2}(2i-1) = 10$) and the transmitting channel of relay R_1 ($\gamma_{d1}(2i) = 5$) cannot be exploited. Thus, we expect that significant performance gains can be achieved by equipping relays with buffers and exploiting the resulting additional degrees of freedom for relay selection.

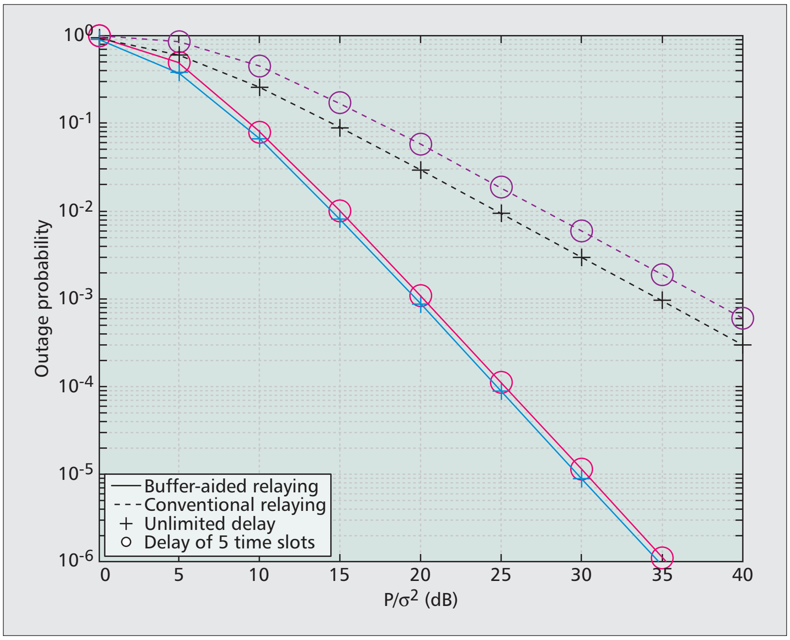

Figure 3. Outage probability of buffer-aided relaying and conventional relaying vs. transmit SNR (P/σ^2). Fixed transmission rate without and with delay constraints. $R_0 = 2$ b/symbol.

Max-Max Relay Selection

If the relays are equipped with buffers, they can store the packets received from the source and do not have to retransmit them immediately in

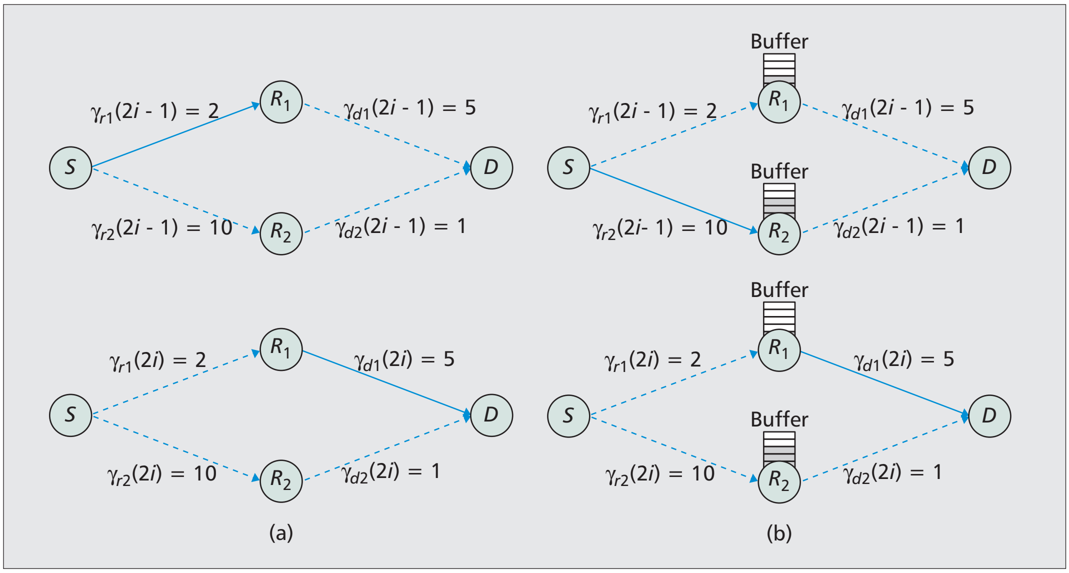

Figure 4. System model for relay networks employing: a) conventional relaying with best relay selection; b) buffer-aided relaying with max-max relay selection. Time slots $2i - 1$ and $2i$ are considered. Solid line: link selected for transmission; dashed line: link not selected for transmission. Shaded buffer elements are full at the end of the considered time slot.

[2] *Slot-by-slot uncorrelated fading can be achieved with frequency hopping.*

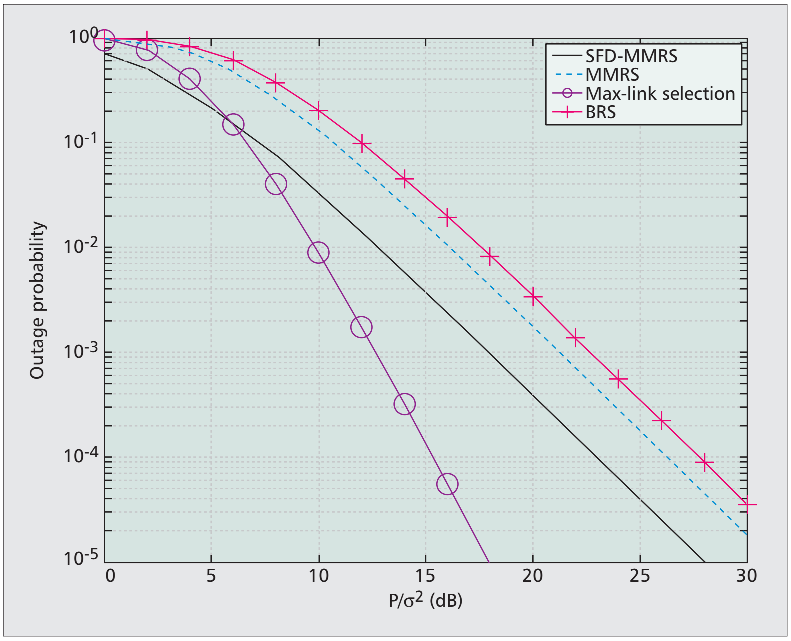

Figure 5. Outage probability of SFD-MMRS, MMRS, max-link selection, and BRS vs. transmit SNR (P/σ^2) for $N = 2$ relays. The target rate is $R_0 = 1$ bit/symbol.

the next time slot. In this way, the relay with the best *S–R* channel can be selected for reception, and the relay with the best *R–D* channel, which may be different from the relay selected for reception, can be selected for transmission. This protocol is referred to as *max-max relay selection* (MMRS) [9]. Thereby, in odd time slots the relay with the best *S–R* channel is selected for reception, and in even time slots the relay with the best *R–D* channel is selected for transmission (Fig. 4b). This protocol, for fixed transmission rate and i.i.d. Rayleigh fading, achieves a diversity gain of N and an SNR gain of $3(1 - 1/N)$ dB compared to BRS [9].

Space Full Duplex Max-Max Relay Selection

The half-duplex limitation can be bypassed by mimicking full-duplex relaying through choosing different relays for concurrent reception and transmission so that the relay selected for reception and the relay selected for transmission can receive and transmit at the same time [10]. A protocol that accomplishes this is space full-duplex max-max relay selection (SFD-MMRS). In this protocol, the relay with the best *S–R* channel and the relay with the best *R–D* channel are chosen for reception and transmission, respectively, in each time slot. If the same relay has the best *S–R* and the best *R–D* channel, a second best relay is chosen for reception or transmission. The simultaneous activation of two relays for reception and transmission may cause inter-relay interference, of course. However, in practice, this interference can be made negligible if the relays are located far enough from each other, or fixed infrastructure-based relays with directional antennas are employed. Space full-duplex max-max relay selection can avoid the HD loss, and its throughput is more than twice as large as the throughputs of BRS and MMRS [10].

Max-Link Selection

Although the buffer-aided relay selection protocols presented above improve the throughput and/or SNR gain compared to the BRS protocol, their diversity gain is limited to N. This shortcoming can be overcome by combining adaptive link selection with MMRS, which results in a new protocol to which we refer as *max-link selection protocol* [11]. The main idea of max-link selection is to select in each time slot the strongest link among all the available *S–R* and *R–D* links (i.e., among $2N$ links) for transmission. For i.i.d. links and no delay constraint, the max-link selection protocol achieves a diversity gain of $2N$, which is double the diversity gain of BRS and MMRS [11].

The three presented buffer-aided relay selection protocols were developed primarily for transmission without delay constraints and relay networks with i.i.d. links. For non-identically distributed (n.i.d.) links, the protocols may cause the buffers at the relays to be unstable. Therefore, for n.i.d. links and delay-constrained transmission, the protocols have to be appropriately modified. In general, a delay-constrained protocol can be obtained by limiting the size of the buffers in a similar manner as in the previous section for the simple three-node network. On the other hand, all three protocols require full CSI of all links at the destination. Hence, the protocols have similar complexities and applicability.

Performance of Relay Selection

Figure 5 depicts simulation results for the outage probability of the considered relay selection protocols vs. transmit SNR. We assume transmission without a delay constraint where the source and relays transmit packets with a constant rate of $R_0 = 1$ b/symbol over unit power i.i.d. Rayleigh fading channels. The channel gains remain constant during two time slots. As expected, all considered relay selection schemes achieve a diversity gain of N except for max-link selection, which achieves a diversity gain of $2N$. The coding gain of SFD-MMRS is considerably larger than those of MMRS and BRS. For example, for the considered case of $N = 2$ relays, the SNR gain of SFD-MMRS compared to BRS is around 4.5 dB. We note that the SNR gain of MMRS and SFD-MMRS over BRS increases with increasing number of relays. For more results on the above buffer-aided multi-relay protocols, we refer the reader to [9–11].

Other System and Network Architectures

Buffer-aided relaying was also extended to multihop networks, two-way relaying, and cooperative BICM-OFDM systems. In the following, we briefly review these extensions.

Multihop Relaying

In multihop relay networks, multiple relays are used to help the source communicate with the destination. By exploiting the relays' buffers, the link (hop) experiencing the best SNR can be selected for transmission [12]. This results in a diversity gain compared to conventional multihop relaying where the links are selected sequentially based on a fixed schedule. For instance, in a multihop relay network with M hops, buffer-aided relaying can achieve a diversity gain of M, whereas conventional relaying is limited to a diversity gain of one. The buffer-aided multihop relaying protocol in [12], similar to the relay selection protocols, was also developed for a network with i.i.d. links and transmission without a delay constraint.

TWO-WAY RELAYING

Up to this point, we have considered one-way relaying. However, when two nodes wish to exchange information through a relay, two-way relaying has to be employed. A popular conventional two-way relaying protocol is time-division broadcast (TDBC) comprising three successive transmission phases (source 1 to relay, source 2 to relay, and relay to both source 1 and source 2), which are repeated sequentially. Instead of the prefixed scheduling of the three phases, the authors in [13] proposed a buffer-aided protocol for two-way relaying, where in each time slot one of the three transmission phases is optimally selected such that the sum rate at both destinations is maximized, which leads to significant performance gains compared to conventional TDBC [13].

BICM-OFDM SYSTEMS

The buffer-aided relaying protocols considered so far have assumed ideal (capacity achieving) channel coding and frequency-flat channels. In practice, however, frequency-selective fading channels are often encountered, and codes may not achieve capacity. In these cases, BICM-OFDM is a popular approach to exploit the inherent diversity offered by frequency-selective fading channels. For example, BICM-OFDM forms the basis of the IEEE 802.11 and 802.16 families of standards, and LTE. In [14], the authors extended the buffer-aided adaptive link selection protocol discussed earlier to a three-node relay network employing BICM-OFDM. The new protocol selects either the source or the relay for transmission based on the quality of the associated links, and is able to exploit both the frequency diversity and the link selection diversity. Thus, assuming transmission without delay constraints, S–R and R–D links with frequency diversities L_{SR} and L_{RD}, respectively, and a convolutional code with minimum distance d_f, buffer-aided relaying achieves a diversity gain of $G_d = \min\{d_f, L_{SR}\} + \min\{d_f, L_{RD}\}$ [14], whereas the diversity gain of conventional relaying is limited to $G_d = \min\{d_f, L_{SR}, L_{RD}\}$. Figure 6 shows simulation results for the bit error rate (BER) for a rate-1/2 convolutional code with free distance $d_f = 5$, 16-ary quadrature amplitude modulation (QAM), and Rayleigh fading with uniform power delay profile. As expected, buffer-aided relaying provides a higher diversity gain compared to conventional relaying, which translates into vastly improved performance.

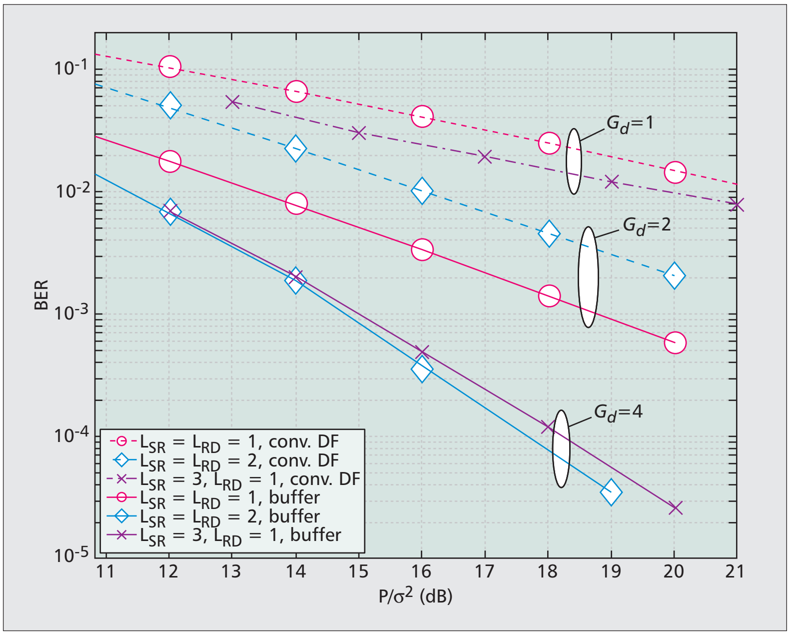

Figure 6. BER vs. transmit SNR (P/σ^2) for a BICM-OFDM system without delay constraints.

CHALLENGES AND OPPORTUNITIES FOR FUTURE RESEARCH

Although buffer-aided relaying enables significant gains in terms of throughput and/or diversity, it also introduces some new challenges that have to be addressed before successful implementation in practical systems is possible.

MORE COMPLEX NETWORKS

Throughput-optimal buffer-aided relaying protocols for delay unconstrained transmission have only been reported for very simple single-relay networks [6, 7, 13]. However, only heuristic protocols have been proposed for relay selection and multihop relaying [9–12], which are generally not optimal as far as throughput maximization and/or outage probability minimization are concerned. Consequently, these protocols do not fully exploit the degrees of freedom offered by relays with buffers. Therefore, designing optimal delay-unconstrained buffer-aided relaying protocols for relay selection, multihop relaying, and more complex cooperative networks, such as multi-source and/or multi-relay and/or multi-destination networks, is a highly relevant research topic [15]. These buffer-aided protocols can then serve as performance upper bounds for the more practical delay-constrained protocols.

DELAY

For all buffer-aided relaying protocols, delay is of paramount importance. Most of the buffer-aided relaying protocols in the literature were designed under the assumption that an infinite delay can be afforded [9–14]. However, in practice, the affordable delay is limited and depends on the application. Currently, bounding the delay is done by heuristically modifying the optimal buffer-aided relaying protocol for infinite delay [6, 7]. Moreover, the heuristic delay-limit-

Buffer-aided relaying is an emerging and promising research area in cooperative communications, and many interesting problems are still open, including the design of optimal protocols for multi-source, multi-relay, and multi-destination networks, with and/or without delay constraints.

ed buffer-aided protocols were typically developed for slot-by-slot uncorrelated fading and may have a poorer performance if the fading is correlated across time slots. Hence, developing throughput-optimal buffer-aided relaying protocols that can guarantee a prescribed finite delay in a slot-by-slot correlated and/or uncorrelated fading environment is an important research topic.

Channel State Information

In a practical system, the CSI needed for link selection in buffer-aided relaying has to be estimated first. However, due to noisy estimates, and delay between the estimation of the CSI and its use, only imperfect CSI is available at the nodes. For conventional relaying, the effect of imperfect CSI has been extensively studied in the literature. However, although CSI is of crucial importance for buffer-aided relaying, the impact of imperfect CSI on its performance has not been investigated yet.

Complexity

Another important topic is the careful evaluation of the complexity the use of buffers entails. The main factors that increase complexity are the CSI acquisition and feedback required for node/link selection.

Processing at the Relays

All existing buffer-aided relaying protocols assume that the relays perform decode-and-forward processing. The use of more advanced processing operations, such as compress-and-forward and compute-and-forward, will lead to new and interesting research problems.

Conclusion

Buffer-aided relaying protocols can significantly improve the performance of cooperative half-duplex relay networks in terms of throughput and/or outage probability compared to conventional relaying. This article has reviewed and compared buffer-aided relaying protocols for several relay network topologies and has outlined their weaknesses as well as the performance gains they achieve compared to conventional relaying protocols. Although buffer-aided relaying is very promising given the reported preliminary results, it presents several challenges. One important challenge that has to be addressed by future research is the efficient management of the delay introduced by the use of buffers. Nevertheless, buffer-aided relaying is an emerging and promising research area in cooperative communications, and many interesting problems are still open, including the design of optimal protocols for multi-source, multi-relay, and multi-destination networks, with and/or without delay constraints.

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