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On the Buffer-Aided Relaying Technique and Its Applications

Su Min Kim, Sukhyun Seo, Seung Kwan Jang, and Junsu Kim[1]

Department of Electronic Engineering, Korea Polytechnic University,
237 Sangidaehak-ro, Siheung-si, Gyeonggi-do, 15073, Korea.
[1]Corresponding author (Email: junsukim@kpu.ac.kr)

Abstract

In this paper, we investigate a buffer-aided relaying technique which is one of promising 5G mobile technologies. More specifically, we study a basic concept and recent research trends on this area. First of all, we investigate the principle of buffer-aided relaying and research results in three-node networks. Next, we study buffer-aided relay selection techniques in multi-relay networks. Finally, we investigate some applications of the buffer-aided relaying technique to cognitive radio networks and physical-layer security.

Keywords: buffer-aided relaying, full-duplex, relay selection, cognitive radio, physical-layer security.

INTRODUCTION

Beyond 4G, the main objective of relaying technique, which is one of 4G core technologies, is to extend communication coverage and to remove coverage holes. However, the relaying technique fundamentally reduces the transmission rate by a half since the relay basically forwards the received data from a source to a destination and it requires two transmissions for a single packet delivery from the source to the destination.

This limitation is caused by a half-duplex transmission which implies that transmitting and receiving cannot be performed at the same time. Therefore, there have been many studies on full-duplex transmissions [1-3]. However, the full-duplex transmission causes a very strong self-interference at the receiver from its own transmitter. To solve this problem, there have been proposed antenna separation, analog interference cancellation, digital interference cancellation, and their combinations. As a result, in [1-3], there have been shown that implementation of the full-duplex transmission is practically feasible in special environments based on specific communication protocols such as Wi-Fi and ZigBee. However, it is still premature in practice due to some limitations such as wide bandwidths required and hardware impairments.

Hence, there have been many studies in order to improve the transmission rate and reduce the error rate in half-duplex relaying by increasing a diversity gain. Recently, a buffer-aided relaying technique has been proposed exploiting a memory, which enables to store the received data at a relay [4].

Differently from the conventional simple repeater, it is natural that the relay has some memory since it has also computing and processing abilities. However, there has less attention how to exploit the buffer in half-duplex relay networks for the performance improvements. The buffer enables an opportunistic transmission that the stored data at a relay is forwarded when the wireless channel condition is good. In a three-node relay network, which consists of a single source, a single relay, and a single destination, it has been shown that exploiting buffer at relay is able to recover the half-duplex loss and various buffer-aided relaying schemes have been proposed [5-8]. In addition, buffer-aided relaying schemes based on network coding technique have been proposed to improve network efficiency for two-way three-node relay networks [9-11].

It is well-known that as the number of relays increases, an opportunistic relay selection gain gives innovative performance improvements such as increasing the transmission rate and decreasing the error rate [12]. Accordingly, there have been proposed buffer-aided relay selection schemes obtaining relay selection diversity by extending to multi-relay networks [13-14]. Their performance has been compared with conventional relay selection schemes without buffer [12].

The benefits of the buffer-aided relaying such as rate increase and error decrease has been evaluated in a wide range of different perspective. Recently, the previous studies have been applied for cognitive radio communications [15-19] and physical-layer security [20-22]. These studies will be also introduced in this paper.

The rest of this paper is organized as follows. In Section 2, the basic concept and benefits of the buffer-aided relaying technique is investigated in a three-node network. In Section 3, the buffer-aided relay selection technique is explained in multi-relay networks. Some applications of the buffer-aided relaying to cognitive radio networks and physical-layer security are provided in Section 4. Finally, conclusions are presented in Section 5.

BUFFER-AIDED RELAYING IN A THREE-NODE NETWORK

In this section, we present the basic concept of the buffer-aided relaying and the principle how to get its benefits in a three-node network. In addition, we introduce proposed buffer-aided relaying techniques.

As shown in Fig. 1, the full-duplex relay transmission yields a significant strong self-interference between the transmit antenna and the receive antenna at the relay. Since this causes some non-solvable problems in practical systems, the half-duplex relaying is still considered as a practical relaying technology.

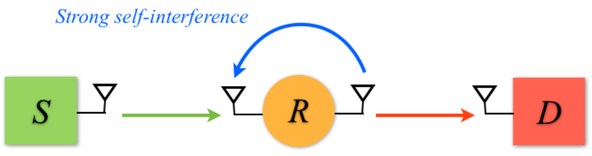

Figure 1. Full-duplex relay transmission

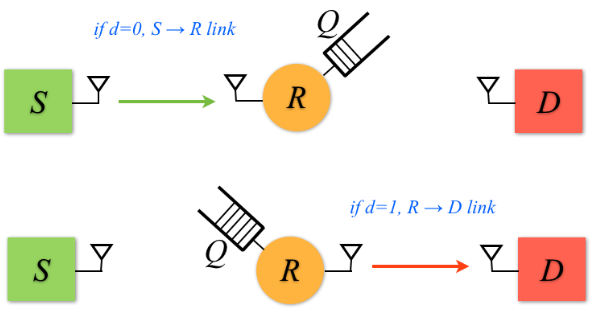

Figure 2. Half-duplex buffer-aided relaying

Fig. 2 shows the half-duplex buffer-aided relaying technique. In previous half-duplex relaying, source-relay (S-R) transmission is performed at odd time-slots and relay-destination (R-D) transmission is performed at even time-slots. This is called two-phase operation. However, if a buffer is employed at the relay, the relay does not have to forward the received data in the next time-slot and thus, it is possible the relay to wait for good channel conditions and forward the stored data when the channel condition is good. In [6-8], an adaptive link selection scheme using a link selection variable, which selects one of S-R and R-D links based on channel state information and buffer state information, has been proposed in a three-node buffer-aided relaying network. It has been shown that the proposed adaptive link selection scheme can achieve almost double transmission rate, compared to the conventional half-duplex relaying scheme with two-phase operation, when the channel conditions for {S-R} and {R-D} links are very asymmetric.

Fig. 3 shows the principle of benefit of the buffer-aided relaying when the channel conditions are asymmetric. As shown in the figure, if the channel capacity of {R-D} link is nine times better than that of {S-R} link, the conventional half-duplex relaying determines the transmission rate as the minimum of both link capacities. Assuming transmissions for ten time-slots, the amount of the transmitted data becomes $\frac{1}{2}\min(1,9)\times 10 = 5$. On the contrary, the buffer-aided relaying can store the source data at the relay for first nine time-slots and then, transmit the stored data to the destination at the last 10-th time-slot. Thus, the amount of the transmitted data for this case becomes $\min(1\times 9, 9\times 1) = 9$. As the asymmetry becomes larger, the amount of the received data approaches a double of the conventional half-duplex relaying. However, if the asymmetry becomes larger, the basic transmission rate will be reduced and thus, the absolute performance would be worse. After all, its effectiveness would be limited in practice.

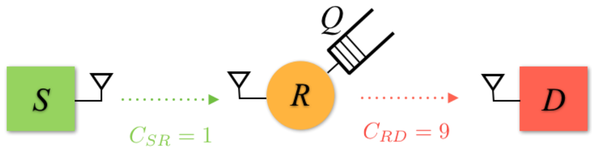

Figure 3. Principle of buffer-aided relaying benefit

BUFFER-AIDED RELAY SELECTION IN MULTI-RELAY NETWORKS

In this section, we investigate extensions to multi-relay networks. In multi-relay networks, there exist a single source node and a single destination node, but multiple relay nodes. Since the number of relays increases, if we select the best relay at transmission instance, we can obtain a selection diversity gain which provides the performance improvements in both transmission rate and error.

First of all, we investigate the best relay selection scheme without buffer [12]. Next, considering the buffer, we investigate the max-max relay selection scheme [13] and the max-link relay selection scheme [14].

Max-min Relay Selection

If there is no buffer at relays, with two-phase operation, the S-R transmissions are performed at odd time-slots and the R-D transmissions are performed at even time-slots. In this case, the transmission rate at each relay is determined by the minimum of both {S-R} and {R-D} link capacities [12]. Therefore, the best relay is selected by

$$k^* = \underset{k\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{Sk}, C_{kD}\}, \qquad (1)$$

where K denotes the number of relays, $C_{Sk} = \frac{1}{2}\log(1+SNR_{Sk})$, $C_{kD} = \frac{1}{2}\log(1+SNR_{kD})$, and SNR_{xy} denotes the signal-to-noise-ratio (SNR) of $\{x-y\}$ link.

Max-max Relay Selection

If there exist buffer at relays, the best relay can be changed according to channel conditions and buffer status. In [13], the best relay selection scheme with two-phase operation has been proposed. That is, the best relay is selected with a constraint that at odd time-slots, a relay receives the source data and at even time-slots, a relay forwards the buffered data to the destination. In this case, we do not need to select the same relay for {S-R} and {R-D} transmissions. Therefore, it is possible to select the best receiving relay for {S-R} link and the best transmitting relay for {R-D} link. In [13], the max-max relay selection scheme, which choses the best receiving relay with the maximum {S-R} channel gain and the best transmitting relay with the maximum {R-D} channel gain as follows:

$$i^* = \underset{i\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{Si}\},$$
$$j^* = \underset{j\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{jD}\}, \tag{2}$$

where i^* is the best receiving relay index for {S-R} transmission, j^* is the best transmitting relay index for {S-D} transmission, $C_{Si} = \frac{1}{2}\log(1 + SNR_{Si})$, and $C_{jD} = \frac{1}{2}\log(1 + SNR_{jD})$.

Hybrid Buffer-Aided Relay Selection

The max-max relay selection scheme assumes infinite length buffer and sufficiently large initial buffer size. Thus, it just considers channel status and not buffer status. However, since the buffer length cannot be infinite in practice, the following two cases occurs: (i) buffer full and (ii) buffer empty. In these cases, the transmission cannot be done even if the relay is selected. In order to avoid these situations, the hybrid buffer-aided relay selection scheme, which follows the max-min relay selection when the above two cases occur, has been proposed [13]. Hence, the best receiving and transmitting relays are selected as follows:

$$i^* = \begin{cases} \underset{i\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{Si}, C_{iD}\}, & if\ Q_i = Q_{max} - 1\ or\ Q_j = 0, \\ \underset{i\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{Si}\}, & Otherwise, \end{cases}$$

(3)

$$j^* = \begin{cases} \underset{j\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{Sj}, C_{jD}\}, & if\ Q_i = Q_{max} - 1\ or\ Q_j = 0, \\ \underset{j\in\{1,\cdots,K\}}{\operatorname{argmax}} \min\{C_{jD}\}, & Otherwise, \end{cases}$$

where K denotes the number of relays, Q_{max} denotes the maximum buffer length, Q_i denotes the buffer length of the i-th relay at the selection instance, and the buffer is updated after a successful transmission by the amount of data transmitted. The hybrid buffer-aided relay selection scheme always outperforms both the max-min and max-max relay selection schemes, since it is a hybrid mode of both schemes.

Max-link Buffer-Aided Relay Selection

Although the max-max relay selection and the hybrid relay selection schemes improves the transmission rate thanks to buffer benefits, they cannot achieve the full diversity gain due to the two-phase operation. That is, there exist $2K$ links in the network but at each time slot, the best relay is selected among only K relays. To achieve the full diversity gain ($2K$), the max-link relay selection scheme, which at each selection instance, either the best receiving or transmitting relay is selected among whole {S-R} and {R-D} links, has been proposed. Hence, the best relay is determined by

$$k^* = \underset{k\in\{1,\cdots,K\}}{\operatorname{argmax}} \left\{ \bigcup_{Q_k \neq Q_{max}} \{C_{Sk}\}, \bigcup_{Q_k \neq 0} \{C_{kD}\} \right\}, \tag{4}$$

where K denotes the number of relays, $C_{Sk} = \frac{1}{2}\log(1 + SNR_{Sk})$, $C_{kD} = \frac{1}{2}\log(1 + SNR_{kD})$, Q_{max} denotes the maximum buffer length, and Q_k denotes the buffer length of the k-th relay at the selection instance. According to (4), the relay with a full buffer is excepted from the best receiving relay selection and the relay with an empty buffer is excepted from the best transmitting relay selection. Assuming infinite length buffer and sufficiently large initial buffer size, the max-link relay selection scheme can achieve the full diversity gain $2K$. Therefore, it is optimal in the perspective of outage probability.

Performance Evaluation

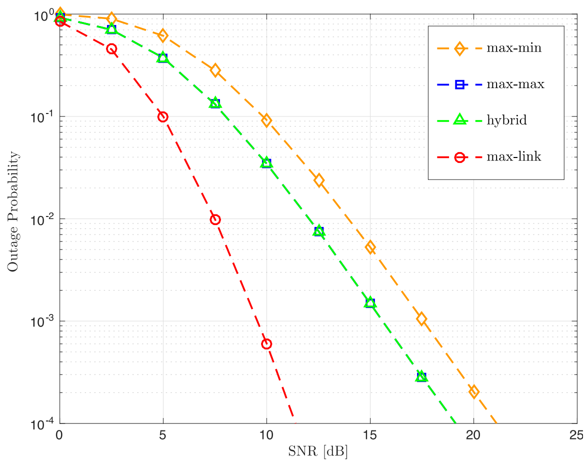

Figure 4. Outage probability of the buffer-aided relay selection schemes ($K = 3, Q_{max} \to \infty, r_0 = 1\ bps/Hz$)

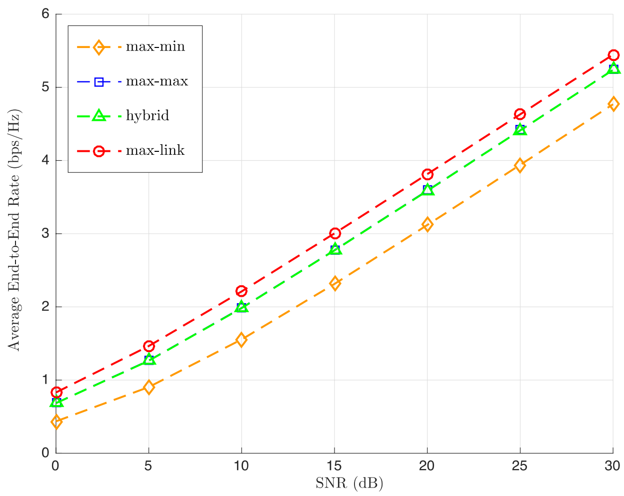

Figure 5. Achievable rate of the buffer-aided relay selection schemes ($K = 3, Q_{max} \to \infty$)

Fig. 4 shows the outage performance of the buffer-aided relay selection schemes introduced in previous sub-sections when the number of relays $K = 3$, the maximum buffer size $Q_{max} \to \infty$, the fixed target rate $r_0 = 1$ bps/Hz. The max-min relay selection achieves the worst outage probability and the max-max relay selection and hybrid relay selection schemes improves the outage performance by about 2dB, compared with the max-min relay selection scheme. Since we assume a sufficiently long buffer length, both the max-max relay selection and the hybrid relay selection schemes achieve exactly the same performance. However, the slope of the curves for both schemes are the same as that for the max-min relay selection scheme. This implies that both the max-max and hybrid relay selection schemes cannot increase the diversity order. On the contrary, the max-link relay selection not only reduce the outage probability but also increases the slope of the curve by a double. This results in that the max-link relay selection scheme achieves the full diversity $2K$.

Fig. 5 shows the achievable end-to-end rate when $K = 3$ and $Q_{max} \to \infty$. We assumed that channel state information at only receiver in outage performance so that the data is

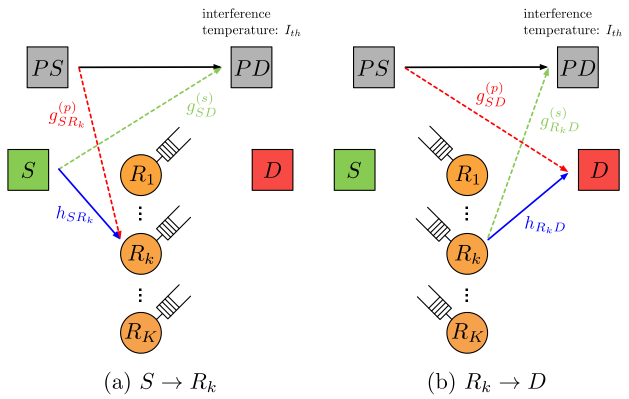

Figure 6. A system model of buffer-aided relaying in underlay cognitive radio networks

transmitted with the fixed data rate $r_0 = 1$. On the contrary, we assume the channel state information is available at transmitter so that the transmitter determines the maximum transmission rate with zero error as Shannon capacity limit and sends data with the determined data rate. As expected, the max-min relay selection scheme achieves the lowest average rate, while the max-max relay selection and the hybrid relay selection schemes achieves the same average rate assuming a sufficiently long buffer size. The max-link relay selection scheme achieves the best average end-to-end rate but it cannot achieve a double rate than the max-min relay selection scheme, while it obtained a double diversity gain in the outage performance.

APPLICATIONS OF THE BUFFER-AIDED RELAYING

Since the buffer-aided relaying employs a memory at relay and obtains a selection diversity gain, it can be applied for any research areas taking relay transmission into consideration. In this section, we consider two application areas regarded as promising next-generation communication networks: cognitive ratio networks and physical-layer security.

Applications to Cognitive Radio Networks

Cognitive radio communication is a promising technology to resolve radio resource shortage by allowing unlicensed users to share spectrum bands with licensed users. In cognitive radio networks, there exist a primary system which owns licensed bands and a secondary system which borrows the licensed bands from the primary system. According to how to share the frequency bands, it is classified as (i) overlay, (ii) interweaved, and (iii) underlay cognitive radio networks. In general, since the main focus in cognitive radio communications is how to handle cross-interference between primary and secondary systems, applications to cognitive radio networks considers to add an interference constraint. Therefore, the application of the buffer-aided relaying to cognitive radio networks is possible by adding the interference constraint into a basic formulation.

Fig. 6 show an application example of buffer-aided relaying to underlay cognitive radio networks. The secondary system has multiple relay nodes, receives the interference from the source of the primary system, and interferes to the destination of the primary

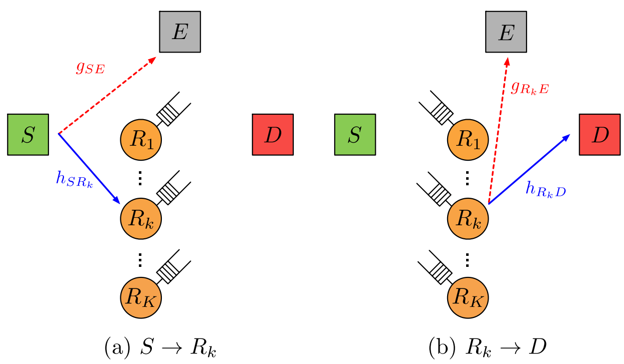

Figure 7. A system model of buffer-aided relaying in physical-layer security environments

system. In this system model, the secondary transmitter has to meet the interference temperature, allowed interference level at the primary receiver. To do this, the secondary system control the transmit power at the secondary transmitter. Therefore, the best link or relay selection considering channel state, buffer state, and power control is the main topic in the buffer-aided relaying applied to cognitive radio networks.

Among the previous work, in [15], an adaptive link selection scheme considering interference has been proposed in a three-node network. In [16], a max-ratio relay selection scheme, which is the max-link relay selection applied to a cognitive radio network but is based on signal-to-interference-ratio, has been proposed. Moreover, variations of adaptive link selection schemes have been proposed for a two-way cognitive radio relaying network [17] and for an overlay cognitive radio network [18]. Finally, in [19], a buffer-aided relay selection with sensing capability for an underlay cognitive radio network has been proposed in order to improve the performance of secondary systems.

Applications to Physical-Layer Security

Physical-layer security fundamentally prevent eavesdropping based on information theory in physical layer. Therefore, it has recently much attention and there have been many studies on this topic. The basic principle is to make the transmission rate for desired link greater than the capacity of wiretap link. In theory, if the channel condition is worse than the transmission rate, it is impossible to decode the information correctly.

In physical-layer security, the secrecy rate is defined as difference between the capacity of the desired link and the capacity of the wiretap link. Then, the previous studies try to maximize the secrecy rate. That is, the greater achieved secrecy rate is obtained, the stronger security is achieved, even if the eavesdropper can overhear some information with non-zero rate.

Fig. 7 shows a system model that the buffer-aided relaying is applied to a physical-layer security environment. While the buffer-aided relaying applied to cognitive radio networks controls transmit power to meet the interference temperature, in physical-layer security, it tried to maximize the transmission rate at the receiver and minimize information leakage to the eavesdropper. That is, the best link or relay maximizing the secrecy rate is selected. In[20], an adaptive link selection scheme has been proposed in a three-node network and in [21], the optimal relay selection scheme has been proposed in multi-relay networks. Finally, a max-ratio relay selection scheme considering amplify-and-forward relay and physical-layer security in [22].

CONCLUSION

In this paper, we investigated next-generation buffer-aided relaying techniques. The relaying technique has much attention in 4G mobile systems but its benefit is limited to coverage extension due to half-duplex transmission. After all, it could not overcome a half loss factor caused by the half-duplex transmission. However, the buffer-aided relaying technique can achieve an additional diversity gain by exploiting a memory and this enables to overcome the fundamental loss due to the half-duplex transmission. Recently, there have been many active studies on the buffer-aided relaying and its applications. Among them, we investigated applications to cognitive radio communications and physical-layer security.

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