Optimal Duplex Selection for Decode and Forward Relay Systems with Power Allocation

Taehoon Kwon[1] and Sungmook Lim[2*]
[1] Korea Institute of Science and Technology Information (KISTI),
66 Hoegi-ro, Dongdaemun-gu, Seoul, Korea 130-741
[e-mail: kth78@kisti.re.kr]
[2] Department of Electronic Engineering, Korea National University of Transportation,
50 Daehak-ro, Chungju-si, Chungbuk, Korea, 380-702
[e-mail: smlim@ut.ac.kr]
*Corresponding author: Sungmook Lim

Received November 30, 2015; revised April 29, 2016; accepted October 18, 2016; published December 31, 2016

Abstract

In decode and forward relay systems, choosing the duplex mode is an important factor to the performance. To satisfy the performance requirement, self-interference must be mitigated for the full-duplex relay (FDR), and the resource efficiency must be increased for the half-duplex ratio (HDR). Therefore, if a wise scheme to consider these two factors exists, decode and forward relay systems are used more effectively.

This study proposes a new duplex selection scheme for decode and forward relay systems. The proposed duplex selection scheme chooses the better duplex mode according to the channel statistical conditions with optimal power allocation.

The simulation results show that the proposed duplex scheme with optimal power allocation has lower outage probability than the FDR and the HDR.

Key words: duplex mode, optimal power allocation, full-duplex

A preliminary two-page version of this paper appeared in ICEIC 2015, Jan. 28–31, Singapore. This version includes a concrete analysis and an improved algorithm of the duplex mode selection.

http://dx.doi.org/10.3837/tiis.2016.12.012 **ISSN : 1976-7277**

1. Introduction

Relay systems have gained attention as a research topic of interest because of how they reduce signal attenuation by placing the relay between the transmitter and the receiver. In particular, it gives robustness to shadowing and improves power efficiency [1].

Relay systems are categorized into two types according to the duplex mode: one is the half-duplex relay (HDR) system where the relay receives and retransmits on orthogonal channels (in general, different time slots), while the other is the full-duplex relay (FDR) system where the relay receives and retransmits concurrently [2][3].

The use of the orthogonal channels in the HDR results in the loss of resource efficiency, especially time resource. For example, two time slots are required for data to be transferred from the source to the destination via the relay in a dual-hop relay system. The FDR comes into the spotlight as one of the solutions for the waste of resources as the transmissions from the source and the relay occur simultaneously at the same resource such as frequency and time slot. However, these concurrent transmissions cause self interference as the power of the interering signal from the relay's own transmit antenna is much greater than that of the desired signal from the source's transmit antenna [4][5]. As this self-interference may degrade the performance of FDR systems to a level even lower than that of HDR systems, handling self-inteference is important to completely exploit the advantage of FDR systems [4][5]. For example, in a typical Wi-Fi radio using 80 MHz bandwidth and a receiver noise floor of −90 dBm, as well as a transmission power of 20 dBm, unless FDR systems provide 60 dB of analog domain cancellation and 50 dB of digital domain cancellation, the decoding requirement may not be satisfied [5]. Apart from mitigating and canceling self-interference itself, we can consider hybrid duplex schemes, where the duplex mode is selected according to the environment and the gain of the relay can be maximized [4][6–12].

In addition, contrary to the HDR where the maximum power of relay is optimal, determining optimal power is an important factor to maximize the gain of the FDR [3]. For example, if the transmission power of the relay is too high, the connection reliability between the source and the relay is decreased because of the increased self-interference. On the contrary, if the transmission power of the relay is too low, the connection reliability between the relay and the destination is decreased because of the decreased signal power.

This study proposes a new optimal duplex selection scheme that minimizes the outage probability. The proposed method selects the duplex mode between half-duplex and full-duplex according to the channel statistical conditions. In the full-duplex mode, the optimal power is allocated to minimize the outage probability to balance between the robustness to noise and the effect of interference.

Thus, the study is organized as follows: Section 2 briefly describes previous researches about optimal power allocation for full-duplex and half-duplex schemes; Section 3 proposes a new optimal duplex selection under optimal power allocation; Section 4 discusses simulation results; and Section 5 provides the conclusion.

2. Related Work

Because of the self-interference problem, many optimal power allocation techniques are proposed to reduce the effects of the interference for full-duplex decode and forward relay systems.

Chen et al. investigated an optimal power allocation strategy for the dual-hop full-duplex decode-and-forward relay system with a joint constraint of individual and global power [13]. However, although they prove that the optimal allocation solution is located on the three boundary conditions of the constrained domain, they did not propose an accurate analytical solution for optimal allocation but merely suggested that a numerical approach can be used for the solution.

Davoodi et al. derived an optimal power allocation scheme to maximize the capacity of the full-duplex decode and forward relay channel [14]. With this, Zhu et al. proposed optimal transmission strategies for transmission signaling selection and spatial power allocation based on the outage probability of the FDR over Rayleigh fading channels [15]. Although it is important to investigate the information-theoretic aspect of the FDR, their approaches are insufficient for investigating the trade-off between the FDR and the HDR because the interference problem of the FDR, a key factor in this trade-off, is not considered.

Kim et al. proposed an optimal power allocation scheme based on minimizing the outage probability in cognitive full-duplex relay systems [16]. In addition, Zhong et al. proposed the optimal power allocation subject to individual power constraints and sum power constraints in FDR schemes [17]. However, because their solutions are derived to balance the signal-to-interference-plus-noise ratio (SINR) at the relay and the destination without considering the statistical channel condition, their performance is inferior to the performance that considers the statistical channel condition.

Riihonen et al. developed hybrid techniques that switch opportunistically between full-duplex and half-duplex relaying modes combined with the transmit power adaptation for maximizing instantaneous and average spectral efficiency [6]. Mesbah et al. simplified and recasted the full-duplex power allocation problem in a convex form and proposed the solution [18]. However, although the capacity (it is expressed as spectral efficiency in [6]) is important to investigate the information-theoretic aspect of the FDR, the outage probability is also important to investigate the reliability of the FDR. In addition, the statistical channel condition was not given consideration in [18]. Zhong et al. proposed optimal power allocation to minimize the outage probability [7]. However, Riihonen et al. and Zhong et al. proposed neither a detailed algorithm of the duplex selection scheme nor a practical method for obtaining the required parameters.

We introduced optimal power allocation for the FDR briefly in [3]. However, because of the two-page limit, a concrete analysis and proof, including an expanded idea about hybrid duplex mode selection, were not provided in [3].

Related researches about the optimal power allocation of FDR are summarized briefly in **Table 1**.

To outperform either FDR or HDR alone, a research on hybrid duplex schemes has been conducted. Miyagoshi et al. proposed the scheduling scheme for a hybrid of full-duplex and half-duplex relaying to achieve proportional fairness among users in multiuser cases [8]. Yamamoto et al. proposed an optimal transmission scheduling scheme for the hybrid duplex system to achieve a spectral efficiency higher than those of HDR or FDR [9]. Lee et al. derived the throughput of the hybrid duplex system in a heterogeneous wireless network and analyzed how to optimally determine the duplex mode to maximize this throughput [10]. Yao et al. proposed hybrid duplex systems to maximize instantaneous system capacity [11]. Khafagy et al. analyzed the queuing behavior of hybrid duplex systems [12]. However, similar to Riihonen et al. and Zhong et al., they proposed neither a detailed algorithm of the duplex selection scheme nor a practical method for obtaining the required parameters.

Related researches about the hybrid duplex system are summarized briefly in Table 2.

Table 1. Summary of Related Researches about the Optimal Power Allocation of FDR

Self-Interference Problem	Statistical Channel Condition	Author(s)
Yes	Yes	Chen et al. [13] Riihonen et al. [6] Kwon et al. [3] Zhong et al. [7]
	No	Kim et al. [16] Zhong et al. [17] Mesbah et al. [18]
No	Yes	Davoodi et al. [14] Zhu et al. [15]
	No	—

Table 2. Summary of Related Researches about the Hybrid Duplex System

Category	Author(s)
Scheduling for hybrid duplex systems	Miyagoshi et al. [8] Yamamoto et al. [9]
Opportunistic hybrid duplex systems	Yao et al. [11] Riihonen et al. [6]
Theoretical analytic framework for hybrid duplex networks	Lee et al. [10] Khafagy et al. [12]

3. An Optimal Duplex Selection for Decode and Forward Relay Systems with Power Allocation

3.1 System Model

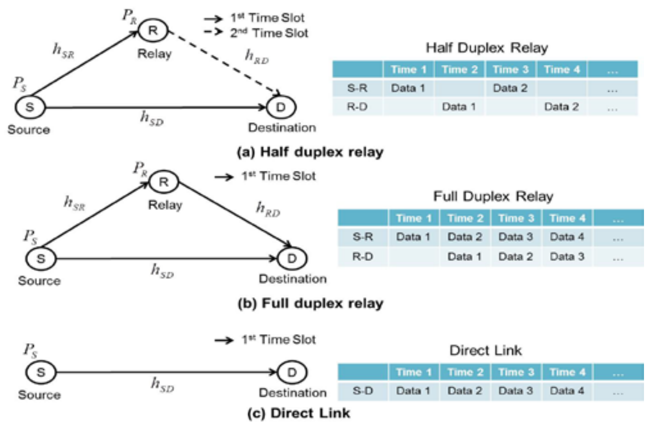

Fig. 1. System models of half-duplex relay, full-duplex relay, and direct link

As **Fig. 1** shows, h_{SR} is the channel gain of the source (S) and the relay (R) link. In the same way, h_{RD} and h_{SD} express the channel gain of the relay (R) and the destination (D) link and the S-D link, respectively. The noise variance of each link is defined as σ^2. P_S and P_R are the power of the source and the relay, respectively. In addition, this study considers the following assumption:

I. Each channel models as a complex Gaussian random variable to have Rayleigh fading gains.
II. The interference from the source to the destination can be ignored because of the path loss.

Under the same assumption, this study models the self-interfering link as a Rayleigh fading channel under the assumptions that the LOS component is reduced efficiently by the antenna isolation and that a major effect results from the scattering component [2]. If interference cancelation (IC) is used for more interference mitigations, the residual interfering link is also modeled as a Rayleigh fading channel because the residual interference comes from the channel estimation error of the self-interfering link [2].

Here, it is assumed that the relay is used for coverage extension. In this case, it is reasonable that the path loss is assumed to be large enough to ignore the interference from the source to the destination when using the FD.

1) Full-duplex relay

In the full-duplex relay, while i-th data is transmitted from the source, the i-1 th data received in the prior time slot is transmitted from the relay concurrently. Therefore, the signal from the relay to the destination acts as the interference to the signal from the source to the relay. The SINR for the S-R link of the FDR is expressed as follows:

$$\Gamma_{SR}^{FD} = \frac{P_S(|h_{SR}|^2/\sigma^2)}{P_R(|h_{RR}|^2/\sigma^2)+1} = \frac{P_S\gamma_{SR}}{P_R\gamma_{RR}+1}, \tag{1}$$

where γ_{SR} and γ_{RR} is the channel power-to-noise ratio (CNR) of the S-R link and the self-interfering link, respectively. As shown in (1), there is the loss in the SINR of the FDR similar to $P_R\gamma_{RR}$. On the contrary, as shown in **Fig. 1**, there is no loss in terms of date rate because the relay and the source transmits data concurrently on the same channel.

The signal-to-noise ratio (SNR) of the R-D link in the FDR can be expressed as follows:

$$\Gamma_{RD} = P_R\gamma_{RD}. \tag{2}$$

2) Half-duplex relay

In the half-duplex relay, the orthogonal channel is allocated to avoid the self-interference problem between the S-R link and the R-D link. For example, in the case of using different time slots to transmit data for the S-R link and the R-D link by time division, the i-th data transmission of the R-D link occurs after finishing the i-th data transmission of the S-R link completely. The SNR of the S-R link in the HDR can be expressed as follows:

$$\Gamma_{SR}^{HD} = P_S\gamma_{SR}. \tag{2}$$

As shown in (2), there is no interference problem in the SNR of the HDR. However, as shown in **Fig. 1**, there is a half loss in data rate because the relay and the source use orthogonal channels for transmission, which require double resource. The SNR of the R-D link in the HDR is the same as that of (2).

3) Direct Link

In the case of the direct link without the relay, data transmission occurs continuously via the S-D link. The SNR of the direct link can be expressed as follows:

$$\Gamma_{SD}^{DL} = P_S(|h_{SD}|^2/\sigma^2) = P_S\gamma_{SD}. \tag{3}$$

As shown in (3), the SNR of the direct link has no loss in terms of the SNR and data rate. However, there is no power gain by the relay as well.

3.2 Proposed Algorithms

The full-duplex relay has loss in the SINR and the HDR, has loss in data rates, and the direct link has no relaying gain. Therefore, if the system chooses the best duplex mode among the FDR, the HDR, and the direct link, the performance of the system can be improved.

The outage probability is one of the important indicators to show transmission reliability. This study proposes a new duplex scheme in which the best duplex mode is chosen to minimize the outage probability with optimal power allocation.

The overall outage probabilities of the FDR, the HDR, and the direct link are as follows [2][3]:

Full-duplex relay:

$$P_O^{FD}(P_R) = 1 - \frac{1}{1+\gamma_{RR}P_R(2^{R_T}-1)/\gamma_{SR}P_S} e^{-(\frac{1}{\gamma_{RD}P_R}+\frac{1}{\gamma_{SR}P_S})(2^{R_T}-1)}. \tag{4}$$

Half-duplex relay:

$$P_O^{HD}(P_R) = 1 - e^{-(\frac{1}{\gamma_{RD}P_R}+\frac{1}{\gamma_{SR}P_S})(2^{2R_T}-1)}. \tag{5}$$

Direct link:

$$P_O^{DT} = 1 - e^{-\frac{(2^{R_T}-1)}{\gamma_{SD}P_S}}. \tag{6}$$

In the HDR, the maximum transmission power of the relay is optimal because of the robustness to noise. On the contrary, in the FDR, if the transmission power of the relay is increased, the self-interfering power is also increased. If the transmission power of the relay is decreased, the noise effects are increased. Therefore, there is an optimal power to balance this trade-off and minimize the outage probability. This study derived the optimal power allocation.

To obtain the optimal power allocation of the FDR, this study formulated the optimization problem to minimize the outage probability as follows:

$$\begin{gathered} \underset{P_R^{Opt}}{Min}\, P_{Out}^{FDR}, \\ subject\ to\ 0 \le P_R^{Opt} \le P_R^{Max}, \end{gathered} \tag{7}$$

where P_{Out}^{FDR} is the overall outage probability of FDR, P_R^{Opt} is the optimal power allocation to minimize P_{Out}^{FDR}, and P_R^{Max} is the available maximum power of the relay. P_R^{Opt} can be obtained by differentiating P_{Out}^{FDR} by the power of the relay, P_R [3].

$$P_R^{Opt} = \frac{(2^R - 1) + \sqrt{\dfrac{4\gamma_{SR}\gamma_{RD}P_S}{\gamma_{RR}} + (2^R - 1)^2}}{2\gamma_{RD}}. \tag{8}$$

Unfortunately, the outage probability of FDR is not guaranteed to be convex. Therefore, the proof is required that P_R^{Opt} minimizes P_{Out}^{FDR} in the range of $0 \le P_R^{Opt} \le P_R^{Max}$.

The differential equation of the outage probability of FDR can be expressed as follows:

$$\frac{\partial P_O^{FD}(P_R)}{\partial P_R} = F_1(P_R) - F_2(P_R). \tag{9}$$

Here, the new function is defined as:

$$F_1(P_R) = \frac{\gamma_{RR}(2^{R_T} - 1)}{\gamma_{SR}P_S(1 + (2^{R_T} - 1)P_R\gamma_{RR} / P_S\gamma_{SR})^2} e^{-\left(\frac{1}{\gamma_{RD}P_R} + \frac{1}{\gamma_{SR}P_S}\right)(2^{R_T} - 1)}, \tag{10}$$

$$F_2(P_R) = \frac{(2^{R_T} - 1)}{P_R^2\gamma_{RD}(1 + (2^{R_T} - 1)P_R\gamma_{RR} / P_S\gamma_{SR})} e^{-\left(\frac{1}{\gamma_{RD}P_R} + \frac{1}{\gamma_{SR}P_S}\right)(2^{R_T} - 1)}, \tag{11}$$

$$F(P_R) = F_1(P_R) - F_2(P_R). \tag{12}$$

because $P_S, P_R, \gamma_{SR}, \gamma_{RR}, \gamma_{RD}, (2^{R_T} - 1)$ and exponential function is nonnegative, $F_1(P_R)$ and $F_2(P_R)$ are nonnegative. Therefore, if the new function $F(P_R) = \dfrac{F_1(P_R)}{F_2(P_R)} = \dfrac{P_R^2\gamma_{RD}\gamma_{RR}}{P_S\gamma_{SR}(1 + P_R\gamma_{RR}(2^{R_T} - 1) / P_S\gamma_{SR})} = \dfrac{\gamma_{RD}\gamma_{RR}}{P_S\gamma_{SR}(1/P_R^2 + \gamma_{RR}(2^{R_T} - 1) / P_R P_S \gamma_{SR})}$ is defined, $F(P_R)$ can be used to determine the sign of $\partial P_O^{FD}(P_R) / \partial P_R$. In addition, it is easily known that $F(P_R)$ is increasing with respect to P_R.

1) When $0 < P_R \le P_R^{Opt}$, it is apparent that $0 = F(0) < F(P_R) \le F(P_R^{Opt}) = 1$. Because P_R^{Opt} is the solution of $\dfrac{\partial P_O^{FD}(P_R)}{\partial P_R} = 0$, it is easily known that $F(P_R^{Opt}) = 1$. Therefore, $\dfrac{\partial P_O^{FD}(P_R)}{\partial P_R} \le 0$, and this means that $P_O^{FD}(P_R)$ is nonincreasing. Therefore, P_R^{Opt} is a local minimizer of $P_O^{FD}(P_R)$ in this range.

2) When $P_R^{Opt} \le P_R \le P_R^{Max}$, it is apparent that $1 = F(P_R^{Opt}) \le F(P_R) \le F(P_R^{Max})$. Because $F(P_R)$ is increasing with respect to P_R, it is easily known that $F(P_R^{Opt}) \le F(P_R^{Max})$.

Therefore, $\frac{\partial P_O^{FD}(P_R)}{\partial P_R} > 0$, and this means that $P_O^{FD}(P_R)$ is nondecreasing. Therefore, P_R^{Opt} is a local minimizer of $P_O^{FD}(P_R)$ in this range.

Therefore, it is apparent that P_R^{Opt} minimizes $P_O^{FD}(P_R)$ over the given range $0 < P_R \le P_R^{Max}$.

The proposed duplex algorithm is operated as follows:

1. The required parameter is estimated (each link channel gain, noise variance).
2. The optimal power is calculated by the estimated parameters in 1.
3. The overall outage probabilities of the FDR, the HDR, and the direct link are derived with the calculated optimal power and estimated parameters.
4. The duplex mode with the lowest outage probability is selected.

The required parameters include the CNR of the S-R, R-D, and S-D links and noise variance. The required parameters can be obtained as follows: first of all, all practical communication systems use a reference signal, which is known to the receiver, and has constant power for the usage of channel estimation or synchronization. For example, in 3GPP LTE, the resource block normally consists of two 0.5 ms slots and 12 subcarriers [19]. Among them, the orthogonal frequency-division multiplexing (OFDM) symbol, which is over 1 under 3, is exploited for the purpose of the control [19]. Because the modulation is fixed as quadrature phase shift keying (QPSK) in this control region symbols, at least 12 (subcarriers) * 1(OFDM symbol) samples can be used for the energy detection [19].

After performing energy detection on the reference signals, the following results can be obtained:

$$\begin{aligned}\varepsilon_x &= \frac{1}{N}\sum_{i=1}^{N}|h_x r_x + n|^2 \approx E\{|h_x|^2\}E\{|r_x|^2\} + E\{|n|^2\} \\ &= (\gamma_x P_{ref} + 1)\sigma^2,\ x \in \{SR, RR, RD\}.\end{aligned} \tag{13}$$

where $N, h_x, r_x, n, \gamma_x, P_{ref}, \sigma^2$ is the number of energy detection samples, channel, reference signal, noise, CNR, the power of reference signals of each link $x \in \{SR, RR, RD\}$, and noise variance; whereas, $E\{\cdot\}$ means an expectation operator.

In the case of noise variance, it can be obtained as follows by performing energy detection on the no-transmission region.

$$\varepsilon_n = \frac{1}{N}\sum_{i=1}^{N}|n|^2 \approx E\{|n|^2\} = \sigma^2. \tag{14}$$

The CNR of each link can be calculated as follows:

$$\gamma_x = \left(\frac{\varepsilon_x}{\varepsilon_n} - 1 \right) / P_{ref}, x \in \{SR, RR, RD\}, \tag{15}$$

where P_{ref} is the known parameters to the system.

Note that optimal duplex selection with power allocation are calculated based on average CNRs, not instantaneous CNRs. The feedback information is updated only when the channels change significantly.

4. Experimental Classification Results and Analysis

This section presents numerical results to verify the superiority of the proposed scheme. The channel is modeled as Rayleigh fading. The path loss exponent is set to 4; max power of the source and the relay is set to 1, respectively. The normalized SNR means the SNR of the S-D link and each SNR of the S-R and R-D links is used by applying the path loss effects to the normalized SNR. **Fig. 2** and **Fig. 3** show the superiority of the proposed power allocation (PA) scheme. Chen's power allocation is derived by applying the numerical approach in [13]. It shows the same performance of the proposed power allocation. However, compared to the proposed power allocation expressed as the simple closed form, Chen's power allocation is only obtained using a numerical approach and requires more computing load. Riihonen's power allocation is derived by equalizing the instantaneous SNRs of the S-R link and the R-D link [6]. Riihonen et al. derive the power allocation to maximize the capacity. However, it is also applied to maximize the outage probability. The power allocation in [16] and [17] is the same as Riihonen's power allocation. Because they consider no statistical character of the fading channel, they show worse performance than the proposed power allocation, which considers the statistical character of the fading channel. In **Fig. 2**, as the SNR of the S-D link increases, the overall SNR increases and the outage probability is reduced. In particular, as self-interference increases, the outage probability gap between the proposed power allocation and other power allocation schemes increases because the proposed power allocation reduces self-interfering effects efficiently. This trend is similar to the one in **Fig. 3**, which shows the outage probability as self-interference varies. In addition, as the relay is closer to the destination, the distance of the S-D link is longer than that of the S-R link, and the proposed power allocation gain becomes larger in **Fig. 3**. This is because the SINR is reduced by the path loss as the distance of the S-R link increases; the signal quality reduction acts as a bottleneck in the overall outage probability. Therefore, when using the proposed power allocation, the SINR of the relay increases under the reduced effects of self-interference.

Fig. 4 and **Fig. 5** show the performance comparison of the proposed duplex selection (PDS) scheme to those of the FDR and the HDR according to the position of the relay. It should be noted that the PDS chooses the optimal duplex mode with the optimal power allocation. In **Fig. 4**, the SNR of the S-D link is set to 10 dB, and in **Fig. 5**, it is set to 20 dB. As this study expected, the outage probability of the PDS is lower than that of the FDR and the HDR. In particular, if the interference can be mitigated by the optimal power allocation, such as the 0 dB or 10 dB interference case, the outage probability of PDS is lower than that of the FDR and the HDR. If the interference is too strong to be mitigated, the outage probability of the PDS shows the same performance as that of the HDR. Note that **Fig. 4** and **Fig. 5** show that the outage probabilities of FDR, HDR, and PDS are minimized at the specific ratio of the distance of the S−R link to the distance of the S−D link. As explained in **Fig. 3**, SINR is reduced by the path loss as the distance increases; the weakest signal quality between S-R link and R-D link acts as a bottleneck in the overall outage probability. Therefore, the outage probability is minimized in the relay`s position to balance the SINR at the relay and at the destination although the exact position may be varied by channel`s statistical condition. By the similar reason, as the distance of the S–R link increases compared to that of the R–D link, where the SINR of the S–R link is more reduced by the path loss compared to that of the R–D link, PDS reduces self-interference more efficiently and shows a better outage probability by the optimal power allocation compared to FDR. In addition, all results show that the analysis matches the simulation results well.

Table 3. Simulation Parameters

Parameters	Value
Channel model	Rayleigh Fading
Path loss exponent	4
Required rate	2 bps/Hz
Max power of source	1
Max power of relay	1

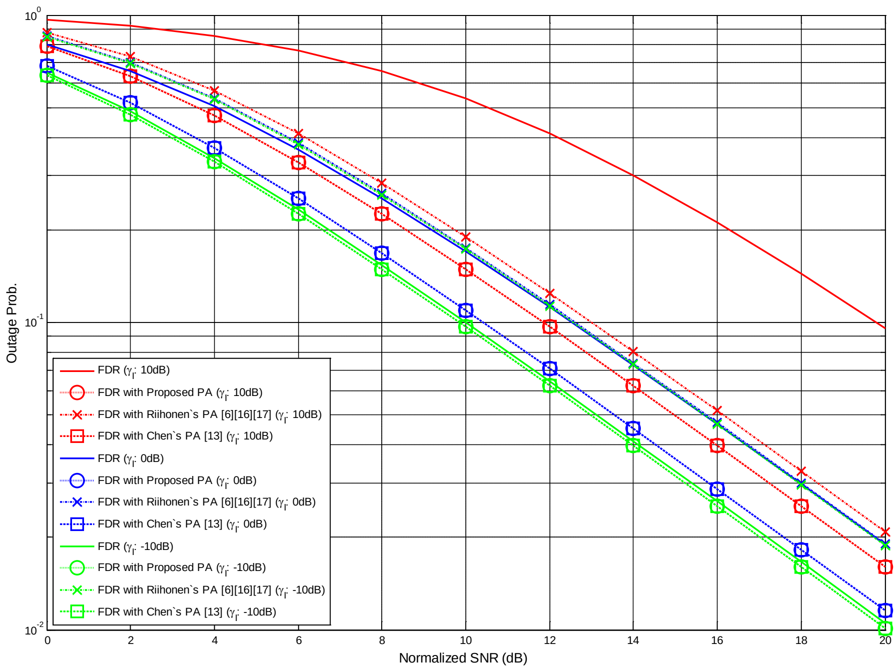

Fig. 2. Outage probability with respect to the normalized SNR (Distance of the S-R link to distance of the S-D link ratio: 3/4)

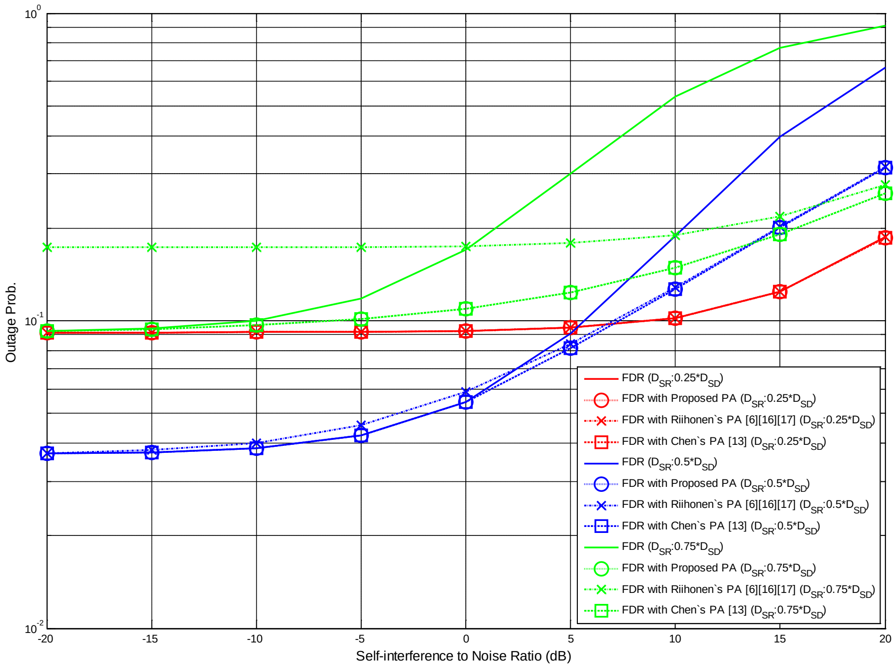

Fig. 3. Outage probability with respect to self-interference-to-noise ratio (Normalized SNR: 10 dB)

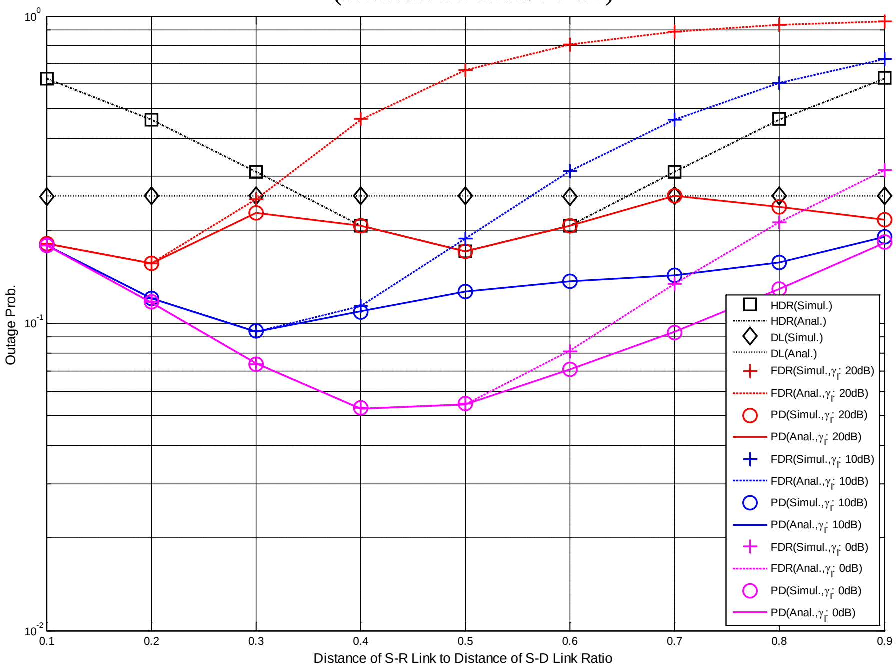

Fig. 4. Outage probability with respect to the S-R link distance to the S-D link distance ratio (SNR of S-D link: 10 dB)

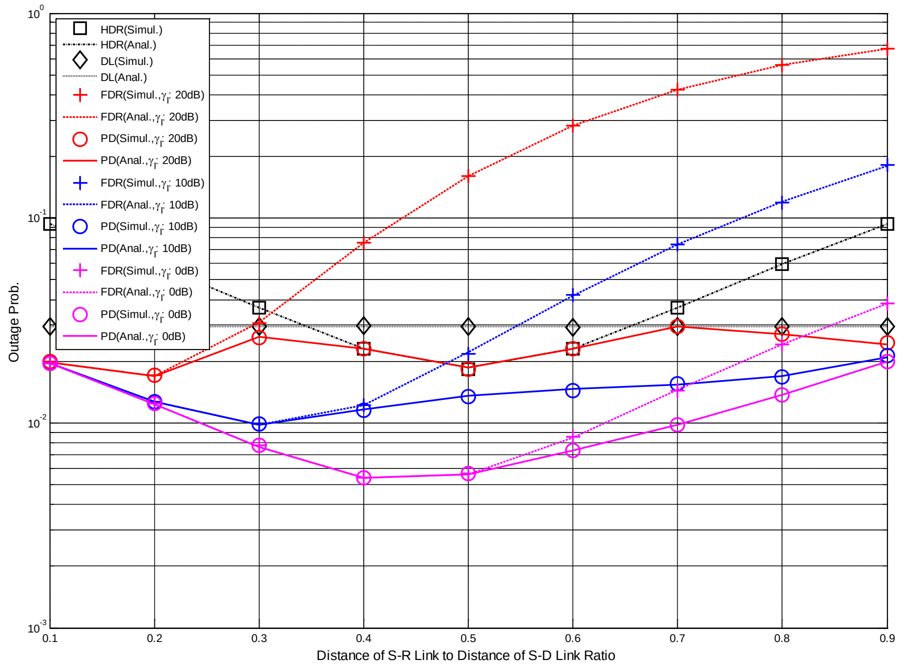

Fig. 5. Outage probability with respect to the S-R link distance to the S-D link distance ratio (SNR of S-D link: 20 dB)

5. Conclusion

This study proposes the duplex selection scheme according to environments, which include the optimal power allocation to minimize the outage probability of the FDR. In the proposed duplex selection scheme, the suitable duplex mode is selected based on the outage probability analysis of the HDR, the FDR, and the direct link. In addition, the practical method to obtain the required parameters is discussed.

Throughout the simulation, it can be verified that the proposed duplex selection scheme shows a lower outage probability compared to other schemes, such as HDR, FDR and direct link.

References

[1] J. Cho and Z. J. Haas, "On the Throughput Enhancement of the Downstream Channel in Cellular Radio Networks through Multihop Relaying," *IEEE Journal on Selected Areas in Communications*, Vol. 22, No. 7, pp. 1206–1219, September 2004. Article (CrossRef Link)

[2] T. Kwon, S. Lim, S. Choi, and D. Hong, "Optimal duplex mode for DF relay in terms of outage probability," *IEEE Trans. on Vehicular Tech.*, Vol. 59, No. 7, pp. 3628–3634, September 2010. Article (CrossRef Link)

[3] T. Kwon and J. Lee, "Optimal Power Allocation for Full Duplex Decode and Forward Relay Systems," in *Proc. of Presentation of International Conference on Electronics, Information and Communication (ICEIC)*, 29 January 2015.

[4] Z. Zhang, X. Chai, K. Long, Athanasios V. Vasilakos and L. Hanzo, “Full-Duplex Techniques for 5G Networks: Self-Interference Cancellation, Protocol Design and Relay Selection,” *IEEE Commun. Magazine*, Vol. 53, No. 5, pp. 128-137, May 2015. Article (CrossRef Link)

[5] Z. Zhang, K. Long, A. V. Vasilakos and L. Hanzo, "Full-Duplex Wireless Communications: Challenges, Solutions, and Future Research Directions," in *Proc. of the IEEE*, to be published. Article (CrossRef Link)

[6] T. Riihonen, S. Werner, and R. Wichman, “Hybrid Full-Duplex/Half-Duplex Relaying with Transmit Power Adaptation,” *IEEE Transactions on Wireless Communications*, Vol. 10, No. 9, pp. 3074–3085, September 2011. Article (CrossRef Link)

[7] B. Zhong, D. Zhang and Z. Zhang, “Power Allocation for Opportunistic Full-Duplex based Relay Selection in Cooperative Systems,” *KSII Transactions on Internet and Information Systems*, Vol. 9, No. 10, pp. 3908-3920, October 2015. Article (CrossRef Link)

[8] M. Miyagoshi, K. Yamamoto, K. Haneda, H. Murata and S. Yoshida, "Multi-user transmission scheduling for a hybrid of full- and half-duplex relaying," in *Proc. of 8th International Conference on Information, Communications and Signal Processing (ICICS)*, pp. 1-5, December 13-16, 2011. Article (CrossRef Link)

[9] K. Yamamoto, K. Haneda, H. Murata and S. Yoshida, "Optimal Transmission Scheduling for a Hybrid of Full- and Half-Duplex Relaying," *IEEE Communications Letters*, Vol. 15, No. 3, pp. 305-307, March 2011. Article (CrossRef Link)

[10] J. Lee and T. Q. S. Quek, "Hybrid Full-/Half-Duplex System Analysis in Heterogeneous Wireless Networks," *IEEE Transactions on Wireless Communications*, Vol. 14, No. 5, pp. 2883-2895, May 2015. Article (CrossRef Link)

[11] C. Yao, K. Yang, L. Song and Y. Li, "X-Duplex: Adapting of Full-Duplex and Half-Duplex," in *Proc. of 2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, pp. 55-56, April 26-May 1, 2015. Article (CrossRef Link)

[12] M. G. Khafagy, A. E. Shafie, A. Sultan and M. S. Alouini, "Throughput maximization for buffer-aided hybrid half-/full-duplex relaying with self-interference," in *Proc. of 2015 IEEE International Conference on Communications (ICC)*, pp. 1926-1931, June 8-12, 2015. Article (CrossRef Link)

[13] L. Chen, S. Han, W. Meng, and C. Li, “Optimal Power Allocation for Dual-Hop Full-Duplex Decode-and-Forward Relay,” *IEEE Communications Letters*, pp. 471–474, Vol. 19, No. 3, March 2015. Article (CrossRef Link)

[14] A. G. Davoodi, M. J. Emadi, and M. R. Aref, “Analytical power allocation for a full duplex decode-and-forward relay channel,” in *Proc. of 2013 Iran Workshop on Communication and Information Theory (IWCIT)*, pp.1–6, May 8–9, 2013. Article (CrossRef Link)

[15] Y. Zhu, Y. Xin, and P. Kam, “Outage Probability of Rician Fading Relay Channels,” *IEEE Transactions on Vehicular Tech.*, Vol. 57, No. 4, pp. 2648–2652, July 2008. Article (CrossRef Link)

[16] H. Kim, S. Lim, H. Wang, and D. Hong, “Power allocation and outage probability analysis for secondary users in cognitive full duplex relay systems,” in *Proc. of 13th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 449–453, June 17–20, 2012. Article (CrossRef Link)

[17] B. Zhong, D. Zhang, Z. Zhang, Z. Pan, K. Long, and A. V. Vasilakos,” Opportunistic full-duplex relay selection for decode-and-forward cooperative networks over Rayleigh fading channels,” in *Proc. of International Conference on Communications (ICC)*, pp. 5717–5722, June 10–14, 2014. Article (CrossRef Link)

[18] W. Mesbah and T. N. Davidson, “Optimal Power Allocation for Full-Duplex Cooperative Multiple Access,” in *Proc. of 2006 IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 689–692, May 14–19, 2006. Article (CrossRef Link)

[19] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, 3G Evolution: HSPA and LTE for Mobile Broadband, 2nd Edition, Academic Press, October 2008.

Taehoon Kwon received the B.S., M.S. and Ph.D. degrees in Electrical and Electronic Engineering at Yonsei University, Seoul, Korea in 2004, 2006 and 2010, respectively. From September 2010 to August 2013, he was a senior researcher at Samsung Electronics where his research interests were in 3GPP LTE advanced technology. Since September 2013, he joined small and medium-sized business knowledge support center at Korea Institute of Science and Technology Information. His current research interests include the field of 5G Wireless communications focusing on full duplexing, spectrum sharing, cooperative relaying and IoT.

Sungmook Lim received the B.S. and Ph.D. degrees in Electrical and Electronic Engineering at Yonsei University, Seoul, Korea in 2005 and 2012, respectively. From September 2012 to March 2014, he was a Postdoctoral Fellow at Yonsei University where his research interests were in 5G wireless communications. Since April 2014, he joined the Department of Electronics Engineering at Korea National University of Transportation as an Assistant Professor. His current research interests include the field of 5G Wireless communications focusing on multicarrier and multi-antenna systems, cooperative relaying and ITS.