# FULL-DUPLEX RELAYING UNDER I/Q IMBALANCE USING IMPROPER GAUSSIAN SIGNALING

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## ABSTRACT

In this paper, we study the benefits of employing improper Gaussian signaling (IGS) in full duplex relaying (FDR) suffering from in-phase and quadrature imbalance (IQI). Different from the traditional symmetric signaling scheme, proper Gaussian signaling (PGS), that is parametrized by its variance, IGS needs additional statistical-quantity called the pseudo-variance to be fully described. The cooperative system under consideration suffers from two types of interferences, the residual self-interference (RSI) and IQI. To evaluate the system performance gain using IGS, first we express the end-to-end achievable rate for different IQI. Then, we optimize the pseudo-variance to compensate the interferences impact and improve the end-to-end achievable rate. Interestingly, IGS-based scheme outperforms its counterpart PGS-based scheme, especially at higher interference-to-noise ratio. Our findings reveal that using single-user detection with asymmetric signaling can compensate both RSI and IQI and improve the system performance.

*Index Terms*— Full-duplex relaying, I/Q imbalance, residual self-interference, improper Gaussian signaling, achievable rate, fractional programming, DC programming.

## 1. INTRODUCTION

The ever-increasing demand of ubiquitous high data rates with low latency and high energy efficiency are the major driving forces for the upcoming 5G wireless communications. Several studies have been carried out to investigate extreme node densification and collaborative radio technologies to improve the spectral efficiency and meet the exponentially growing wireless data traffic demands [1, 2]. Full-duplex relaying (FDR) is a promising cooperative technology that extends the network coverage while improving the spectral efficiency [3]. FDR communications can be realized using two main strategies called amplify-and-forward (AF) and decode-and-forward (DF). Both relaying strategies need to compensate the effects of both residual self-interference (RSI) and different hardware imperfections that can limit the



Fig. 1. FDR system under IQI and RSI.

system performance such as non-linear power amplifier and inphase and quadrature imbalance (IQI) [4].

The effects of IQI imbalance were investigated for different communication systems in [5-13] and particularly for FDR in [11-13]. To the best of author's knowledge, the impact of asymmetric signaling scheme has not been considered on the achievable rate performance of the systems that suffers from hardware impairments.

In this paper, we study the utilization of asymmetric signaling scheme instead of the symmetric signaling scheme to combat both the RSI and IQI in FDR DF systems. Asymmetric signaling has recently proven its significance to enhance system performance under asymmetric interference [14, 15]. Symmetric signaling or proper Gaussian signaling (PGS) is the traditional signaling scheme that assumes independent signal components with equal power. Therefore, PGS can be fully described by its variance. On the other hand, Asymmetric signaling or improper Gaussian signaling (IGS) relaxes the PGS characteristics and can have dependent signal component with unequal power. Therefore, IGS needs additional statistical quantity to be accurately characterized called the pseudo-variance [16]. As such, we first express the achievable rate of the FDR with DF relaying strategy in terms of the source and relays signal variances and pseudo-variances. Then, we develop an optimization framework to optimize the source and relay statistics in order to maximize the end-to-end achievable rate.

#### 2. SYSTEM DESCRIPTION

Consider a dual hop relaying system, where a source (S) intends to communicate with a destination (D) as shown in Fig. 1. Both the high shadowing and the severe path loss effect are the responsible for the absence of the direct link between S and D. As such, a relay (R) operates with full duplex mode to facilitate the end-to-end communication by expanding the coverage area with a full transmission rate. The self interference at the relay can be partially cancelled after analog and digital stages resulting in a RSI as depicted in Fig. 1. Furthermore, various hardware impairments can drastically degrade system performance.

## 2.1. Statistical Signal Model

To characterize the difference between symmetric and asymmetric signals, we consider a complex Gaussian random variable x and introduce the following definitions:

Definition 1: [16] The variance and the pseudo-variance of x are defined, respectively, as  $\sigma_x^2 = \mathbb{E}[|x|^2]$  and  $\tilde{\sigma}_x^2 = \mathbb{E}[x^2]$ , where  $\mathbb{E}[.]$  is the expected value operator.

*Definition 2:* [16] A complex random variable is called proper if its pseudo-variance is equal to zero, otherwise it is called improper.

#### 2.2. Distortion Model

In this subsection, we describe the mathematical model of the IQI in radio frequency transceivers for single link in order to apply it for the proposed FDR system. A unity power signal x is transmitted over a flat fading channel and received as

$$y = \sqrt{ph} \left( x + \eta_{\text{tx}} \right) + \eta_{\text{rx}} + z \tag{1}$$

where p is the transmitted power, h is the fading channel, z is the additive white Gaussian noise (AWGN) with variance  $\sigma_z^2$ , and the impairment noise at the transmitter and the receiver are  $\eta_{tx}$  and  $\eta_{rx}$ , respectively, [4].

Definition 3: [17], [18] The IQI distortion noises model at the transmitter and the receiver are random variables with  $\eta_{\rm tx} \sim CN(0, \kappa_{\rm tx}^2)$  where  $\kappa_{\rm tx}^2 < \mathbb{E}[|x|^2]$  and  $\eta_{\rm rx} \sim CN(0, p|h|^2 \kappa_{\rm rx}^2)$ , where  $\kappa_{\rm rx}^2 < \mathbb{E}[|x|^2]$ .

*Lemma 1:* Equivalent aggregate effect of transceiver impairments in (1) is given by the generalized channel model

$$y = \sqrt{p}h\left(x+\eta\right) + z,\tag{2}$$

where  $\eta \sim CN(0, \kappa^2)$ ,  $\kappa^2 = \kappa_{tx}^2 + \kappa_{rx}^2$  and  $\eta$  is IGS with pseudo-variance of  $\tilde{\sigma}_{\eta}^2$  due the asymmetric characteristics of the IQI (widely linear transformation of a signal means asymmetric signal characteristics).

It is important to note that (2) reduces to the ideal hardware scenario when.  $\kappa^2 = 0$ .

#### 2.3. FDR under IQI System Model

In FDR with DF relaying strategy under IQI, the source transmits an IGS signal  $x_s$  with unity variance and pseudo-variance of  $\tilde{\sigma}_s^2$ . The received signal at the relay suffers from the RSI  $h_{rr}$  in addition to the aggregate effect of transceiver for both *S*-*R* link,  $\eta_{sr}$ , and *R*-*R* link,  $\eta_{rr}$ . Thus, the received signal is expressed as

$$y_{\rm r} = \sqrt{p_{\rm s}} h_{\rm sr} \left( x_{\rm s} + \eta_{\rm sr} \right) + \sqrt{p_{\rm r}} h_{\rm rr} \left( x_{\rm r} + \eta_{\rm rr} \right) + z_{\rm r}, \quad (3)$$

where  $p_s/p_r$  is the source/relay transmit power,  $h_{sr}$  is the fading channel of the *S*-*R* link and  $z_r$  is the AWGN at the relay node with variance  $\sigma_z^2$ . The relay node decode the transmitted signal using single user decoder, then encode it from IGS scheme as  $x_r$  with unity variance and pseudo-variance  $\tilde{\sigma}_r^2$ . The received signal the destination side is expressed as

$$y_{\rm d} = \sqrt{p_{\rm r}} h_{\rm rd} \left( x_{\rm r} + \eta_{\rm rd} \right) + z_{\rm d},\tag{4}$$

where  $h_{\rm rd}$  is the fading channel of the *R*-*D* link,  $\eta_{\rm rd}$  is the aggregate effect of transceiver for *R*-*D* link and  $z_{\rm d}$  is the AWGN at the destination node with variance  $\sigma_z^2$ .

### 3. ACHIEVABLE RATES

The overall end-to-end achievable rate of the dual-hop DF FDR system, R, is given as

$$R = \min\left\{R_{\rm sr}, R_{\rm rd}\right\},\tag{5}$$

where  $R_{\rm sr}$  and  $R_{\rm rd}$  are the achievable rates of *S*-*R* and *R*-*D* links, respectively. In our work, we deal with the RSI and the IQI as noise terms, thus  $R_{\rm sr}$  considering the IGS scheme and assymetric IQI terms can be obtained as [19]

$$R_{\rm sr} = \frac{1}{2} \log_2 \frac{\sigma_{y_{\rm r}}^4 - |\tilde{\sigma}_{y_{\rm r}}^2|^2}{\sigma_{f_{\rm r}}^4 - |\tilde{\sigma}_{f_{\rm r}}^2|^2},\tag{6}$$

where  $\sigma_{y_r}^2$  and  $\tilde{\sigma}_{y_r}^2$  are the variance and the pseudo-variance of  $y_r$ , respectively, and  $\sigma_{I_r}^2$  and  $\tilde{\sigma}_{y_r}^2$  are the variance and the pseudo-variance of the interference signals plus noise. Therefore,  $R_{\rm sr}$  reduces to

$$R_{\rm sr}\left(\tilde{\sigma}_{\rm s}^{2}, \tilde{\sigma}_{\rm r}^{2}\right) = \frac{1}{2}\log_{2}\frac{\alpha_{\rm sr} - \left|p_{\rm s}h_{\rm sr}^{2}\left(\tilde{\sigma}_{\rm s}^{2} + \tilde{\sigma}_{\eta_{\rm sr}}^{2}\right) + p_{\rm r}h_{\rm rr}^{2}\left(\tilde{\sigma}_{\rm r}^{2} + \tilde{\sigma}_{\eta_{\rm rr}}^{2}\right)\right|^{2}}{\beta_{\rm sr} - \left|p_{\rm s}h_{\rm sr}^{2}\tilde{\sigma}_{\eta_{\rm sr}}^{2} + p_{\rm r}h_{\rm rr}^{2}\left(\tilde{\sigma}_{\rm r}^{2} + \tilde{\sigma}_{\eta_{\rm rr}}^{2}\right)\right|^{2}}$$
(7)

where 
$$\beta_{\rm sr} = \left(p_{\rm s}|h_{\rm sr}|^2 \kappa_{\rm sr}^2 + p_{\rm r}|h_{\rm rr}|^2 \left(\sigma_{\rm r}^2 + \kappa_{\rm rr}^2\right) + \sigma_z^2\right)$$
, and  
 $\alpha_{\rm sr} = \left(p_{\rm s}|h_{\rm sr}|^2 \left(\sigma_{\rm s}^2 + \kappa_{\rm sr}^2\right) + p_{\rm r}|h_{\rm rr}|^2 \left(\sigma_{\rm r}^2 + \kappa_{\rm rr}^2\right) + \sigma_z^2\right)^2$ .

According to (7),  $R_{\rm sr}$  is a function of  $\tilde{\sigma}_{\rm s}^2$  and  $\tilde{\sigma}_{\rm r}^2$ , which provides additional degrees of freedom to mitigate the presented forms of the asymmetric nature of both the IQI selfinterference and the RSI. Similarly,  $R_{\rm rd}$  is expressed as

$$R_{\rm rd}\left(\tilde{\sigma}_{\rm r}^2\right) = \frac{1}{2} \log_2 \frac{\alpha_{\rm rd} - \left|P_{\rm r}h_{\rm rd}^2\left(\tilde{\sigma}_{\rm r}^2 + \tilde{\sigma}_{\eta_{\rm rd}}^2\right)\right|^2}{\beta_{\rm rd} - \left|P_{\rm r}h_{\rm rd}^2\tilde{\sigma}_{\eta_{\rm rd}}^2\right|^2} \qquad (8)$$

where  $\alpha_{\rm rd} = \left(P_{\rm r}|h_{\rm rd}|^2 \left(\sigma_{\rm r}^2 + \kappa_{\rm rd}^2\right) + \sigma_z^2\right)^2$ , and  $\beta_{\rm rd} = \left(P_{\rm r}|h_{\rm rd}|^2 \kappa_{\rm rd}^2 + \sigma_z^2\right)^2$ .

# 4. IQI- AND RSI-AWARE SIGNALING DESIGN

In this section, we design the transmitted signals, to maximize R under IQI and RSI. The main goal of the system design is to optimize the statistical asymmetric characteristics of the transmitted signals to maximize R as follows

$$\begin{aligned} \mathbf{P1}: \quad \max_{\tilde{\sigma}_{\mathrm{s}}^{2}, \tilde{\sigma}_{\mathrm{r}}^{2}} R\left(\tilde{\sigma}_{\mathrm{s}}^{2}, \tilde{\sigma}_{\mathrm{r}}^{2}\right) \\ \text{s. t.} \quad 0 \leq \left|\tilde{\sigma}_{t}^{2}\right| \leq \sigma_{t}^{2}, \ t \in \{\mathrm{s}, \mathrm{r}\}. \end{aligned}$$

To solve **P1**, we write it in a vector form. First, we define a real vector **s** that captures the real and imaginary variables as  $\mathbf{s} = \left[\Re\{\tilde{\sigma}_{s}^{2}\}\Im\{\tilde{\sigma}_{s}^{2}\}\Re\{\tilde{\sigma}_{r}^{2}\}\Im\{\tilde{\sigma}_{r}^{2}\}\right]^{T}$ . Then we express the equivalent problem as

$$\mathbf{P2}: \max_{\mathbf{s}} \min_{1 \le m \le 2} \frac{\mathcal{N}_m(\mathbf{s})}{\mathcal{D}_m(\mathbf{s})}$$
  
s. t. C1 :  $0 \le \mathbf{s}^T \Xi_1 \mathbf{s} \le \sigma_s^2$ ,  
C2 :  $0 \le \mathbf{s}^T \Xi_2 \mathbf{s} \le \sigma_r^2$ ,

where  $\Xi_1 = \text{diag}[1\ 1\ 0\ 0]$  and  $\Xi_2 = \text{diag}[0\ 0\ 1\ 1]$ . The numerator and denominator functions of the objective function of **P2** are defined based on (7) and (8) as  $\mathcal{N}_m(\mathbf{s}) =$  $a_{n,m} - \mathbf{s}^T \mathbf{B}_{n,m} \mathbf{s} - \mathbf{c}_{n,m} \mathbf{s} - e_m$  and  $\mathcal{D}_m(\mathbf{s}) = a_{d,m} \mathbf{s}^T \mathbf{B}_{d,m} \mathbf{s} - \mathbf{s}^T \mathbf{c}_{d,m} - e_m$ . The coefficients of the second order polynomials  $\mathcal{N}_m(\mathbf{s})$  and  $\mathcal{D}_m(\mathbf{s})$  are defined as  $\mathbf{B}_{n,m} = \mathbf{b}_{n,m} \mathbf{b}_{n,m}^H, \mathbf{c}_{n,m} = (d_m^* \mathbf{b}_{n,m}^T + d_m \mathbf{b}_{n,m}^H), e_m =$  $|d_m|^2, a_{n,1} = (p_{\mathbf{s}}|h_{\mathbf{sr}}|^2(1 + \kappa_{\mathbf{sr}}^2) + p_{\mathbf{r}}|h_{\mathbf{rr}}|^2(1 + \kappa_{\mathbf{rr}}^2) + \sigma_z^2)^2,$  $a_{d,1} = (p_{\mathbf{s}}|h_{\mathbf{sr}}|^2\kappa_{\mathbf{sr}}^2 + p_{\mathbf{r}}|h_{\mathbf{rr}}|^2(1 + \kappa_{\mathbf{rr}}^2) + \sigma_z^2)^2, a_{n,2} =$  $(p_{\mathbf{r}}|h_{\mathbf{rd}}|^2(1 + \kappa_{\mathbf{rd}}^2) + \sigma_z^2)^2, a_{d,2} = (p_{\mathbf{r}}|h_{\mathbf{rd}}|^2\kappa_{\mathbf{rd}}^2 + \sigma_z^2)^2,$  $d_1 = p_{\mathbf{s}}h_{\mathbf{sr}}^2\sigma_{\eta_{\mathbf{sr}}}^2 + p_{\mathbf{r}}h_{\mathbf{rr}}^2\sigma_{\eta_{\mathbf{rr}}}^2, d_2 = p_{\mathbf{r}}h_{\mathbf{rd}}^2\sigma_{\eta_{\mathbf{rd}}}^2 \mathbf{b}_{\mathbf{n1}} =$  $[p_{\mathbf{s}}h_{\mathbf{sr}}^2 \ jp_{\mathbf{s}}h_{\mathbf{sr}}^2 \ p_{\mathbf{r}}h_{\mathbf{rr}}^2]^T, \mathbf{b}_{d1} = [0\ 0\ p_{\mathbf{r}}h_{\mathbf{rr}}^2\ jp_{\mathbf{r}}h_{\mathbf{rr}}^2]^T$  $\mathbf{b}_{\mathbf{n2}} = [0\ 0\ p_{\mathbf{r}}h_{\mathbf{rd}}^2\ jp_{\mathbf{r}}h_{\mathbf{rd}}^2]^T$  and  $\mathbf{b}_{d2} = 0.$ 

The max-min fractional problem in **P2** can be efficiently solved using the generalized Dinkelbach algorithm [20]. For this purpose, we first define the following non-linear parametric subtractive function

$$F(\lambda) = \max_{\mathbf{s}} \min_{1 \le m \le 2} \left\{ \mathcal{N}_m(\mathbf{s}) - \lambda \mathcal{D}_m(\mathbf{s}) \right\}.$$
(9)

Then, we study the relationship between the objective function in P2 and (9) using the following lemma.

*Lemma 2:* Under the assumption that  $\mathcal{D}_m(\mathbf{s}) > 0$ , and by defining  $\bar{\lambda}$  as  $\bar{\lambda} = \max_{\mathbf{s}} \min_{1 \le m \le 2} \frac{\mathcal{N}_m(\mathbf{s})}{\mathcal{D}_m(\mathbf{s})}$ , we find that  $F(\lambda)$  has the following features [21]

- 1.  $F(\lambda)$  is continuous and monotonically decreasing in  $\lambda$
- 2.  $F(\bar{\lambda}) \leq 0$ , as  $F(\lambda) \geq 0$  iff  $\lambda \leq \bar{\lambda}$

3. The optimal solution of **P2**,  $\overline{\lambda}$ , gives  $F(\overline{\lambda}) = 0$ .

According to Lemma 2, **P2** can be transformed equivalently to the following optimization problem with the parametric subtractive objective function

**P3**: 
$$\max_{\mathbf{s}} \min_{1 \le m \le 2} \left\{ \mathcal{N}_m \left( \mathbf{s} \right) - \bar{\lambda} \mathcal{D}_m \left( \mathbf{s} \right) \right\}$$
  
s. t. C1, C2.

Since the non-negative parameter  $\bar{\lambda}$  is unknown, the solution of problems in the form of **P3** can be found iteratively using the generalized Dinkelbach algorithm [20].

To solve **P3**, we first introduce another variable  $\gamma$  that models the minimum part of **P3** and gives the following optimization problem

$$\begin{aligned} \mathbf{P4} : & \max_{\mathbf{s},\gamma} \gamma \\ & \text{s. t. } & \mathcal{N}_m\left(\mathbf{s}\right) - \bar{\lambda}\mathcal{D}_m\left(\mathbf{s}\right) \geq \gamma, \text{ C1, and C2.} \end{aligned}$$

Problem **P4** is a non-convex problem as its first constraint is a difference of concave (DC) function. An efficient way to find a feasible suboptimal solution for **P4** is derived using sequential convex programming [22]. First, we approximate the first constraint by using the first order of the Taylor series expansion for the  $D_1$  (**s**) as

$$\widetilde{\mathcal{D}}_1(\mathbf{s}, \mathbf{s}^{(k)}) = \mathcal{D}_1(\mathbf{s}^{(k)}) + \nabla^T \mathcal{D}_1(\mathbf{s}^{(k)})(\mathbf{s} - \mathbf{s}^{(k)}), \quad (10)$$

where the expansion is evaluated at  $\mathbf{s}^{(k)}$ , and  $\nabla \mathcal{D}_1(\mathbf{s}^{(k)}) = -\left(\mathbf{B}_{d,1} + \mathbf{B}_{d,1}^T\right) x^{(k)} - \mathbf{c}_{d,1}$  is the gradient of  $\mathcal{D}_1(\mathbf{s}^{(k)})$ . It is important to note that no trust region is required as  $\widetilde{\mathcal{D}}_1(\mathbf{s}, \mathbf{s}^{(k)}) \leq \mathcal{D}_1(\mathbf{s}^{(k)})$  [22]. Thus, the optimization problem **P4** can be convexified using the aforementioned concaveconvex procedure giving the following problem

**P5**: 
$$\max_{\mathbf{s},\gamma} \gamma$$
  
s. t.  $\mathcal{N}_1(\mathbf{s}) - \bar{\lambda} \widecheck{\mathcal{D}}_1(\mathbf{s}, \mathbf{s}^{(k)}) \ge \gamma,$   
 $\mathcal{N}_2(\mathbf{s}) - \bar{\lambda} \mathcal{D}_2(\mathbf{s}) > \gamma, \text{ C1, and C2.}$ 

Therefore, the solution of **P5** reduces to a feasible suboptimal solution, which can be found using the generalized Dinkelbach algorithm and the sequential convex programming as is discussed in the following subsection.

## 4.1. Proposed Algorithm

The proposed solution is developed based on a two-loop scheme. The outer loop computes iteratively  $\overline{\lambda}$  using the generalized Dinkelbach algorithm by updating  $\lambda$  in step 5 of Algorithm 1 base on the computed  $\mathbf{s}^*$  at step 3 for a given  $\lambda$  value using Algorithm 2. The solution is obtained once  $F(\lambda)$  is less than specific tolerance.

 Algorithm 1 : Generalized Dinkelbach algorithm

 1: Initialize  $j \leftarrow 0, \lambda_j \leftarrow 0, \mathbf{s} \leftarrow \mathbf{0}$  and Set tolerance  $\delta_1$  

 2: while  $F(\lambda_j) > \delta_1$  do

 3: Compute  $\mathbf{s}^*$  for a given  $\lambda_j$  using Algorithm II.

 4: Update  $F(\lambda_j) = \min_{\substack{1 \le m \le 2 \\ 1 \le m \le 2}} \{\mathcal{N}_m(\mathbf{s}^*) - \lambda_j \mathcal{D}_m(\mathbf{s}^*)\}$  

 5:  $\lambda_{j+1} \leftarrow \min_{\substack{1 \le m \le 2 \\ 1 \le m \le 2}} \frac{\mathcal{N}_m(\mathbf{s}^*)}{\mathcal{D}_m(\mathbf{s}^*)}$  

 6:  $j \leftarrow j+1$  

 7: end while

The inner loop computes **s** for a given  $\lambda$  through successive quadratic constraint linear programming problems as introduced in Algorithm 2. The stopping convergence criterion is when the absolute difference between two successive solutions is less than a predefined threshold  $\delta_2$ .

Algorithm 2 Sequetial Convex Programming algorithm	
1:	<b>Initialize</b> $k \leftarrow 0, \epsilon \leftarrow \infty$ and <b>Set</b> tolerance $\delta_2$
2:	<b>Choose</b> feasible starting point $s^{(k)}$
3:	while $\epsilon \geq \delta_2$ do
4:	Solve <b>P5</b> and obtain <b>s</b> using $s^{(k)}$
5:	$\mathbf{s}^{(k+1)} \leftarrow \mathbf{s}$
6:	Update $\epsilon \leftarrow  \mathbf{s}^{k+1} - \mathbf{s}^k $
7:	$k \leftarrow k+1$
8: end while	

# 5. NUMERICAL AND SIMULATION RESULTS

In this section, we use the PGS scheme as a benchmark to signify the gain reaped by the IGS scheme. Moreover, we assume  $p_{\rm s} = p_{\rm r} = 1$ ,  $\sigma_z^2 = 1$ ,  $\kappa_{\rm sr}^2 = \kappa_{\rm rr}^2 = \kappa_{\rm rd}^2 = 1$ ,  $|\tilde{\sigma}_{\eta_{\rm sr}}^2| = |\tilde{\sigma}_{\eta_{\rm rr}}^2| = |\tilde{\sigma}_{\eta_{\rm rd}}^2| = |\tilde{\sigma}_{\eta_{\rm r}}^2| = 0.9$  and  $\mathbb{E}[|h_{\rm rr}|^2] = \pi_{\rm rr} = 10$  dB, unless otherwise specified.

First, we study the IGS based scheme gain on the achievable end-to-end rate over the PGS based scheme versus different levels of IQI,  $|\tilde{\kappa}|^2$  in Fig. 2. We assume that  $\kappa^2$  varies from 0 representing the ideal hardware to 1 representing the maximally impaired hardware system model. The results shows that the end-to-end achievable rate is drastically affected by the presence of hardware impairments at very good channels gain. The Proposed IGS scheme provide significant rate compensation/improvement at different levels of impairments as compared to its counterpart PGS scheme.

In the second simulation example, we study the advantage of employing IGS in suppressing the RSI effect on the average achievable end-to-end rate versus the RSI gain  $\pi_{rr}$ for different IQI levels in Fig. 3. IGS scheme succeeds to combat the RSI effect for different IQI levels on the average rate. The best relative improvement is achieved at high RSI and low IQI levels. The RSI represents the dominant parameter on degrading the rate performance at different IQI levels



**Fig. 2**. Average achievable rate versus IQI level with equal impairment levels at different nodes  $\kappa_{sr}^2 = \kappa_{rrl}^2 = \kappa_{rd}^2$ .



**Fig. 3**. Average rate vs. RSI  $\pi_{rr}$  for PGS and IGS schemes assuming different symmetric impairment levels.

for PGS scheme. On the other hand, IGS scheme reliefs the RSI impact and reduce the rate degradation.

# 6. CONCLUSION

In this paper, we analyzed the effectiveness of using IGS scheme in two-hop DF FDR systems under IQI and RSI. To this end, we expressed the achievable rate for the underlying system. and tuned the IGS pseudo-variance to maximize the end-to-end achievable rate. IGS proved to be a promising candidate for next generation network that can significantly improve the overall achievable rate under various IQI and RSI levels, which has asymmetric signatures on the useful signal.

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