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Approximate Capacity of the Gaussian Interference Channel with Noisy Channel-Output Feedback

Victor Quintero, Samir M. Perlaza, Iñaki Esnaola and Jean-Marie Gorce

Abstract—In this paper, an achievability region and a converse region for the two-user Gaussian interference channel with noisy channel-output feedback (G-IC-NOF) are presented. The achievability region is obtained using a random coding argument and three well-known techniques: rate splitting, superposition coding and backward decoding. The converse region is obtained using some of the existing perfect-output feedback outer-bounds as well as a set of new outer-bounds that are obtained by using genie-aided models of the original G-IC-NOF. Finally, it is shown that the achievability region and the converse region approximate the capacity region of the G-IC-NOF to within a constant gap in bits per channel use.

Index Terms—Capacity, Interference Channel, Noisy Channel-Output Feedback.

I. NOTATION

Throughout this paper, $(\cdot)^+$ denotes the positive part operator, i.e., $(\cdot)^+ = \max(\cdot, 0)$ and $\mathbb{E}_X[\cdot]$ denotes the expectation with respect to the distribution of the random variable X . The logarithm function \log is assumed to be base 2.

II. SYSTEM MODEL

Consider the two-user G-IC-NOF in Figure 1. Transmitter i , with $i \in \{1, 2\}$, communicates with receiver i subject to the interference produced by transmitter j , with $j \in \{1, 2\} \setminus \{i\}$. There are two independent and uniformly distributed messages, $W_i \in \mathcal{W}_i$, with $\mathcal{W}_i = \{1, 2, \dots, 2^{NR_i}\}$, where N denotes the block-length in channel uses and R_i is the transmission rate in bits per channel use. At each block, transmitter i sends the codeword $\mathbf{X}_i = (X_{i,1}, X_{i,2}, \dots, X_{i,N})^T \in \mathcal{X}_i^N$, where \mathcal{X}_i and \mathcal{X}_i^N are respectively the channel-input alphabet and the codebook of transmitter i .

The channel coefficient from transmitter j to receiver i is denoted by h_{ij} ; the channel coefficient from transmitter i to receiver i is denoted by \vec{h}_{ii} ; and the channel coefficient from channel-output i to transmitter i is denoted by \overleftarrow{h}_{ii} . All channel coefficients are assumed to be non-negative real numbers. At a given channel use $n \in \{1, 2, \dots, N\}$, the channel output at receiver i is denoted by $\vec{Y}_{i,n}$. During channel use n , the input-output relation of the channel model is given by

$$\vec{Y}_{i,n} = \vec{h}_{ii}X_{i,n} + h_{ij}X_{j,n} + \vec{Z}_{i,n}, \quad (1)$$

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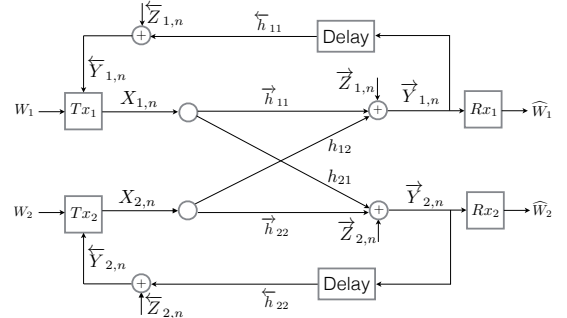


Fig. 1. Gaussian interference channel with noisy channel-output feedback at channel use n .

where $\vec{Z}_{i,n}$ is a real Gaussian random variable with zero mean and unit variance that represents the noise at the input of receiver i . Let $d > 0$ be the finite feedback delay measured in channel uses. At the end of channel use n , transmitter i observes $\vec{Y}_{i,n}$, which consists of a scaled and noisy version of $\vec{Y}_{i,n-d}$. More specifically,

$$\overleftarrow{Y}_{i,n} = \begin{cases} \vec{Z}_{i,n}, & \text{for } n \in \{1, 2, \dots, d\} \\ \overleftarrow{h}_{ii}\vec{Y}_{i,n-d} + \vec{Z}_{i,n}, & \text{for } n \in \{d+1, d+2, \dots, N\}, \end{cases} \quad (2)$$

where $\overleftarrow{Z}_{i,n}$ is a real Gaussian random variable with zero mean and unit variance that represents the noise in the feedback link of transmitter-receiver pair i . The random variables $\vec{Z}_{i,n}$ and $\overleftarrow{Z}_{i,n}$ are independent and identically distributed. In the following, without loss of generality, the feedback delay is assumed to be one channel use, i.e., $d = 1$. The encoder of transmitter i is defined by a set of deterministic functions $f_i^{(1)}, \dots, f_i^{(N)}$, with $f_i^{(1)} : \mathcal{W}_i \rightarrow \mathcal{X}_i$ and for all $n \in \{2, \dots, N\}$, $f_i^{(n)} : \mathcal{W}_i \times \mathbb{R}^{n-1} \rightarrow \mathcal{X}_i$, such that

$$X_{i,1} = f_i^{(1)}(W_i), \quad \text{and} \quad (3a)$$

$$X_{i,n} = f_i^{(n)}(W_i, \overleftarrow{Y}_{i,1}, \dots, \overleftarrow{Y}_{i,n-1}). \quad (3b)$$

The components of the input vector \mathbf{X}_i are real numbers subject to an average power constraint:

$$\frac{1}{N} \sum_{n=1}^N \mathbb{E}(X_{i,n}^2) \leq 1, \quad (4)$$

where the expectation is taken over the joint distribution of the message indexes W_1, W_2 , and the noise terms, i.e., $\vec{Z}_1, \vec{Z}_2, \overleftarrow{Z}_1$, and \overleftarrow{Z}_2 . The dependence of $X_{i,n}$ on W_1, W_2 , and the previously observed noise realizations is due to the effect of feedback as shown in (2) and (3).

Assume that during a given communication, T blocks are transmitted. Hence, the decoder of receiver i is defined by a deterministic function $\psi_i : \mathbb{R}_+^{NT} \rightarrow \mathcal{W}_i^T$. At the end of the communication, receiver i uses the vector $(\vec{Y}_{i,1}, \vec{Y}_{i,2}, \dots, \vec{Y}_{i,NT})^\top$ to obtain an estimate of the message indices

$$(\widehat{W}_i^{(1)}, \widehat{W}_i^{(2)}, \dots, \widehat{W}_i^{(T)}) = \psi_i(\vec{Y}_{i,1}, \vec{Y}_{i,2}, \dots, \vec{Y}_{i,NT}), \quad (5)$$

where $\widehat{W}_i^{(t)}$ is an estimate of the message index sent during block $t \in \{1, 2, \dots, T\}$. The decoding error probability in the two-user G-IC-NOF during block t of a codebook of block-length N , denoted by $P_e^{(t)}(N)$, is given by

$$P_e^{(t)}(N) = \max\left(\Pr\left[\widehat{W}_1^{(t)} \neq W_1^{(t)}\right], \Pr\left[\widehat{W}_2^{(t)} \neq W_2^{(t)}\right]\right). \quad (6)$$

The definition of an achievable rate pair $(R_1, R_2) \in \mathbb{R}_+^2$ is given below.

Definition 1 (Achievable Rate Pairs): A rate pair $(R_1, R_2) \in \mathbb{R}_+^2$ is achievable if there exists at least one pair of codebooks \mathcal{X}_1^N and \mathcal{X}_2^N with codewords of length N , and the corresponding encoding functions $f_1^{(1)}, \dots, f_1^{(N)}$ and $f_2^{(1)}, \dots, f_2^{(N)}$ such that the decoding error probability $P_e^{(t)}(N)$ can be made arbitrarily small by letting the block-length N grow to infinity, for all blocks $t \in \{1, \dots, T\}$.

The two-user G-IC-NOF in Figure 1 can be fully described by six parameters: $\overrightarrow{\text{SNR}}_i$, $\overleftarrow{\text{SNR}}_i$, and INR_{ij} , with $i \in \{1, 2\}$ and $j \in \{1, 2\} \setminus \{i\}$, which are defined as follows:

$$\overrightarrow{\text{SNR}}_i = \vec{h}_{ii}^2, \quad (7)$$

$$\text{INR}_{ij} = h_{ij}^2 \text{ and} \quad (8)$$

$$\overleftarrow{\text{SNR}}_i = \overleftarrow{h}_{ii}^2 (\vec{h}_{ii}^2 + 2\vec{h}_{ii}h_{ij} + h_{ij}^2 + 1). \quad (9)$$

III. MAIN RESULTS

This section introduces an achievable region (Theorem 1) and a converse region (Theorem 2), denoted by $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and $\overline{\mathcal{C}}_{\text{G-IC-NOF}}$ respectively, for the two-user G-IC-NOF with fixed parameters $\overrightarrow{\text{SNR}}_1, \overrightarrow{\text{SNR}}_2, \text{INR}_{12}, \text{INR}_{21}, \overleftarrow{\text{SNR}}_1$, and $\overleftarrow{\text{SNR}}_2$. In general, the capacity region of a given multi-user channel is said to be approximated to within a constant gap according to the following definition.

Definition 2 (Approximation to within ξ units): A closed and convex set $\mathcal{T} \subset \mathbb{R}_+^n$ is approximated to within ξ units by the sets $\underline{\mathcal{T}}$ and $\overline{\mathcal{T}}$ if $\underline{\mathcal{T}} \subseteq \mathcal{T} \subseteq \overline{\mathcal{T}}$ and for all $\mathbf{t} = (t_1, \dots, t_m) \in \overline{\mathcal{T}}$ then $((t_1 - \xi)^+, \dots, (t_m - \xi)^+) \in \underline{\mathcal{T}}$.

Denote by $\mathcal{C}_{\text{G-IC-NOF}}$ the capacity region of the 2-user G-IC-NOF. The achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and the converse region $\overline{\mathcal{C}}_{\text{G-IC-NOF}}$ approximate the capacity region $\mathcal{C}_{\text{G-IC-NOF}}$ to within 4.4 bits per channel use (Theorem 3).

A. An Achievable Region for the Two-User G-IC-NOF

The description of the achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ is presented using the constants $a_{1,i}$; the functions $a_{2,i} : [0, 1] \rightarrow \mathbb{R}_+$, $a_{3,i} : [0, 1]^2 \rightarrow \mathbb{R}_+$, with $l \in \{3, \dots, 6\}$; and $a_{7,i} : [0, 1]^3 \rightarrow \mathbb{R}_+$, which are defined as follows, for all $i \in \{1, 2\}$, with $j \in \{1, 2\} \setminus \{i\}$:

$$a_{1,i} = \frac{1}{2} \log \left(2 + \frac{\overrightarrow{\text{SNR}}_i}{\text{INR}_{ji}} \right) - \frac{1}{2}, \quad (10a)$$

$$a_{2,i}(\rho) = \frac{1}{2} \log \left(b_{1,i}(\rho) + 1 \right) - \frac{1}{2}, \quad (10b)$$

$$a_{3,i}(\rho, \mu) = \frac{1}{2} \log \left(\frac{\overleftarrow{\text{SNR}}_i (b_{2,i}(\rho) + 2) + b_{1,i}(1) + 1}{\overleftarrow{\text{SNR}}_i ((1-\mu)b_{2,i}(\rho) + 2) + b_{1,i}(1) + 1} \right), \quad (10c)$$

$$a_{4,i}(\rho, \mu) = \frac{1}{2} \log \left(((1-\mu)b_{2,i}(\rho) + 2) - \frac{1}{2} \right), \quad (10d)$$

$$a_{5,i}(\rho, \mu) = \frac{1}{2} \log \left(2 + \frac{\overrightarrow{\text{SNR}}_i}{\text{INR}_{ji}} + (1-\mu)b_{2,i}(\rho) \right) - \frac{1}{2}, \quad (10e)$$

$$a_{6,i}(\rho, \mu) = \frac{1}{2} \log \left(\frac{\overrightarrow{\text{SNR}}_i}{\text{INR}_{ji}} \left(((1-\mu)b_{2,j}(\rho) + 1) + 2 \right) - \frac{1}{2} \right), \quad (10f)$$

and

$$a_{7,i}(\rho, \mu_1, \mu_2) = \frac{1}{2} \log \left(\frac{\overrightarrow{\text{SNR}}_i}{\text{INR}_{ji}} \left(((1-\mu_i)b_{2,j}(\rho) + 1) + (1-\mu_j)b_{2,i}(\rho) + 2 \right) - \frac{1}{2} \right), \quad (10g)$$

where the functions $b_{l,i} : [0, 1] \rightarrow \mathbb{R}_+$, with $(l, i) \in \{1, 2\}^2$ are defined as follows:

$$b_{1,i}(\rho) = \overrightarrow{\text{SNR}}_i + 2\rho \sqrt{\overrightarrow{\text{SNR}}_i \text{INR}_{ij} + \text{INR}_{ij}} \text{ and} \quad (11a)$$

$$b_{2,i}(\rho) = (1-\rho)\text{INR}_{ij} - 1, \quad (11b)$$

with $j \in \{1, 2\} \setminus \{i\}$.

Note that the functions in (10) and (11) depend on $\overrightarrow{\text{SNR}}_1, \overrightarrow{\text{SNR}}_2, \text{INR}_{12}, \text{INR}_{21}, \overleftarrow{\text{SNR}}_1$, and $\overleftarrow{\text{SNR}}_2$, however as these parameters are fixed in this analysis, this dependence is not emphasized in the definition of these functions. Finally, using this notation, Theorem 1 is presented on the next page.

Proof: The proof of Theorem 1 is presented in [1]. ■

B. Comments on the Achievability

The achievable region is obtained using a random coding argument and combining three classical tools: rate splitting, superposition coding, and backward decoding. This coding scheme is described in [1] and it is specially designed for the two-user IC-NOF. Consequently, only the strictly needed number of superposition code-layers is used. Other achievable schemes, as reported in [2], can also be obtained as special cases of the more general scheme presented in [3]. However, in this more general case, the resulting code for the IC-NOF contains a handful of unnecessary superposing code-layers, which complicates the error probability analysis.

C. A Converse Region for the Two-User G-IC-NOF

The description of the converse region $\overline{\mathcal{C}}_{\text{G-IC-NOF}}$ is determined by the ratios $\frac{\text{INR}_{ij}}{\overrightarrow{\text{SNR}}_j}$, and $\frac{\text{INR}_{ji}}{\overrightarrow{\text{SNR}}_i}$, for all $i \in \{1, 2\}$, with $j \in \{1, 2\} \setminus \{i\}$. All relevant scenarios regarding these ratios

Theorem 1: The capacity region $\mathcal{C}_{\text{GIC-NOF}}$ contains the region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ given by the closure of the set of all possible non-negative achievable rate pairs (R_1, R_2) that satisfy

$$R_1 \leq \min \left(a_{2,1}(\rho), a_{6,1}(\rho, \mu_1) + a_{3,2}(\rho, \mu_1), a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{4,2}(\rho, \mu_1) \right), \quad (12a)$$

$$R_2 \leq \min \left(a_{2,2}(\rho), a_{3,1}(\rho, \mu_2) + a_{6,2}(\rho, \mu_2), a_{3,1}(\rho, \mu_2) + a_{4,1}(\rho, \mu_2) + a_{1,2} \right), \quad (12b)$$

$$R_1 + R_2 \leq \min \left(a_{2,1}(\rho) + a_{1,2}, a_{1,1} + a_{2,2}(\rho), a_{3,1}(\rho, \mu_2) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{7,2}(\rho, \mu_1, \mu_2), \right. \\ \left. a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1), a_{3,1}(\rho, \mu_2) + a_{7,1}(\rho, \mu_1, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{1,2} \right), \quad (12c)$$

$$2R_1 + R_2 \leq \min \left(a_{2,1}(\rho) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{7,2}(\rho, \mu_1, \mu_2), \right. \\ \left. a_{3,1}(\rho, \mu_2) + a_{1,1} + a_{7,1}(\rho, \mu_1, \mu_2) + 2a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1), a_{2,1}(\rho) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1) \right), \quad (12d)$$

$$R_1 + 2R_2 \leq \min \left(a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{2,2}(\rho) + a_{1,2}, a_{3,1}(\rho, \mu_2) + a_{7,1}(\rho, \mu_1, \mu_2) + a_{2,2}(\rho) + a_{1,2}, \right. \\ \left. 2a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{1,2} + a_{7,2}(\rho, \mu_1, \mu_2) \right), \quad (12e)$$

with $(\rho, \mu_1, \mu_2) \in \left[0, \left(1 - \max\left(\frac{1}{\text{INR}_{12}}, \frac{1}{\text{INR}_{21}}\right)\right)^+\right] \times [0, 1] \times [0, 1]$.

are described by two events denoted by $S_{l_1,1}$ and $S_{l_2,2}$, where $(l_1, l_2) \in \{1, \dots, 5\}^2$. The events are defined as follows:

$$S_{1,i}: \overrightarrow{\text{SNR}}_j < \min(\text{INR}_{ij}, \text{INR}_{ji}), \quad (13a)$$

$$S_{2,i}: \text{INR}_{ji} \leq \overrightarrow{\text{SNR}}_j < \text{INR}_{ij}, \quad (13b)$$

$$S_{3,i}: \text{INR}_{ij} \leq \overrightarrow{\text{SNR}}_j < \text{INR}_{ji}, \quad (13c)$$

$$S_{4,i}: \max(\text{INR}_{ij}, \text{INR}_{ji}) \leq \overrightarrow{\text{SNR}}_j < \text{INR}_{ij} \text{INR}_{ji}, \quad (13d)$$

$$S_{5,i}: \overrightarrow{\text{SNR}}_j \geq \max(\text{INR}_{ij}, \text{INR}_{ji}, \text{INR}_{ij} \text{INR}_{ji}). \quad (13e)$$

Note that for all $i \in \{1, 2\}$, the events $S_{1,i}$, $S_{2,i}$, $S_{3,i}$, $S_{4,i}$, and $S_{5,i}$ are mutually exclusive. This observation shows that given any 4-tuple $(\overrightarrow{\text{SNR}}_1, \overrightarrow{\text{SNR}}_2, \text{INR}_{12}, \text{INR}_{21})$, there always exists one and only one pair of events $(S_{l_1,1}, S_{l_2,2})$, with $(l_1, l_2) \in \{1, \dots, 5\}^2$, that identifies a unique scenario. Note also that the pairs of events $(S_{2,1}, S_{2,2})$ and $(S_{3,1}, S_{3,2})$ are not feasible. In view of this, twenty-three different scenarios can be identified using the events in (13). Once the exact scenario is identified, the converse region is described using the functions $\kappa_{l,i}: [0, 1] \rightarrow \mathbb{R}_+$, with $(l, i) \in \{1, \dots, 3\} \times \{1, 2\}$; $\kappa_l: [0, 1] \rightarrow \mathbb{R}_+$, with $l \in \{4, 5\}$; $\kappa_{6,l}: [0, 1] \rightarrow \mathbb{R}_+$, with $l \in \{1, \dots, 4\}$; and $\kappa_{7,i,l}: [0, 1] \rightarrow \mathbb{R}_+$, with $(i, l) \in \{1, 2\}^2$. These functions are defined as follows for all $i \in \{1, 2\}$, with $j \in \{1, 2\} \setminus \{i\}$:

$$\kappa_{1,i}(\rho) = \frac{1}{2} \log(b_{1,i}(\rho) + 1), \quad (14a)$$

$$\kappa_{2,i}(\rho) = \frac{1}{2} \log\left(1 + b_{5,j}(\rho)\right) + \frac{1}{2} \log\left(1 + \frac{b_{4,i}(\rho)}{1 + b_{5,j}(\rho)}\right), \quad (14b)$$

$$\kappa_{3,i}(\rho) = \frac{1}{2} \log\left(\frac{\overleftarrow{\text{SNR}}_j(b_{4,i}(\rho) + b_{5,j}(\rho) + 1)}{(b_{1,j}(1) + 1)(b_{4,i}(\rho) + 1)} + 1\right) \\ + \frac{1}{2} \log(b_{4,i}(\rho) + 1), \quad (14c)$$

$$\kappa_4(\rho) = \frac{1}{2} \log\left(1 + \frac{b_{4,1}(\rho)}{1 + b_{5,2}(\rho)}\right) + \frac{1}{2} \log(b_{1,2}(\rho) + 1), \quad (14d)$$

$$\kappa_5(\rho) = \frac{1}{2} \log\left(1 + \frac{b_{4,2}(\rho)}{1 + b_{5,1}(\rho)}\right) + \frac{1}{2} \log(b_{1,1}(\rho) + 1), \quad (14e)$$

$$\kappa_6(\rho) = \begin{cases} \kappa_{6,1}(\rho) & \text{if } (S_{1,2} \vee S_{2,2} \vee S_{5,2}) \\ & \wedge (S_{1,1} \vee S_{2,1} \vee S_{5,1}) \\ \kappa_{6,2}(\rho) & \text{if } (S_{1,2} \vee S_{2,2} \vee S_{5,2}) \\ & \wedge (S_{3,1} \vee S_{4,1}) \\ \kappa_{6,3}(\rho) & \text{if } (S_{3,2} \vee S_{4,2}) \\ & \wedge (S_{1,1} \vee S_{2,1} \vee S_{5,1}) \\ \kappa_{6,4}(\rho) & \text{if } (S_{3,2} \vee S_{4,2}) \wedge (S_{3,1} \vee S_{4,1}) \end{cases} \quad (14f)$$

$$\kappa_{7,i}(\rho) = \begin{cases} \kappa_{7,i,1}(\rho) & \text{if } (S_{1,i} \vee S_{2,i} \vee S_{5,i}) \\ \kappa_{7,i,2}(\rho) & \text{if } (S_{3,i} \vee S_{4,i}) \end{cases} \quad (14g)$$

where

$$\kappa_{6,1}(\rho) = \frac{1}{2} \log(b_{1,1}(\rho) + b_{5,1}(\rho) \text{INR}_{21}) - \frac{1}{2} \log(1 + \text{INR}_{12}) \\ + \frac{1}{2} \log\left(1 + \frac{b_{5,2}(\rho) \overleftarrow{\text{SNR}}_2}{b_{1,2}(1) + 1}\right) \\ + \frac{1}{2} \log(b_{1,2}(\rho) + b_{5,1}(\rho) \text{INR}_{21}) - \frac{1}{2} \log(1 + \text{INR}_{21}) \\ + \frac{1}{2} \log\left(1 + \frac{b_{5,1}(\rho) \overleftarrow{\text{SNR}}_1}{b_{1,1}(1) + 1}\right) + \log(2\pi e), \quad (15a)$$

$$\kappa_{6,2}(\rho) = \frac{1}{2} \log\left(b_{6,2}(\rho) + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overleftarrow{\text{SNR}}_2} (\overrightarrow{\text{SNR}}_2 + b_{3,2})\right) \\ - \frac{1}{2} \log(1 + \text{INR}_{12}) + \frac{1}{2} \log\left(1 + \frac{b_{5,1}(\rho) \overleftarrow{\text{SNR}}_1}{b_{1,1}(1) + 1}\right) \\ + \frac{1}{2} \log(b_{1,1}(\rho) + b_{5,1}(\rho) \text{INR}_{21}) - \frac{1}{2} \log(1 + \text{INR}_{21}) \\ + \frac{1}{2} \log\left(1 + \frac{b_{5,2}(\rho)}{\overleftarrow{\text{SNR}}_2} \left(\text{INR}_{12} + \frac{b_{3,2} \overleftarrow{\text{SNR}}_2}{b_{1,2}(1) + 1}\right)\right) \\ - \frac{1}{2} \log\left(1 + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overleftarrow{\text{SNR}}_2}\right) + \log(2\pi e), \quad (15b)$$

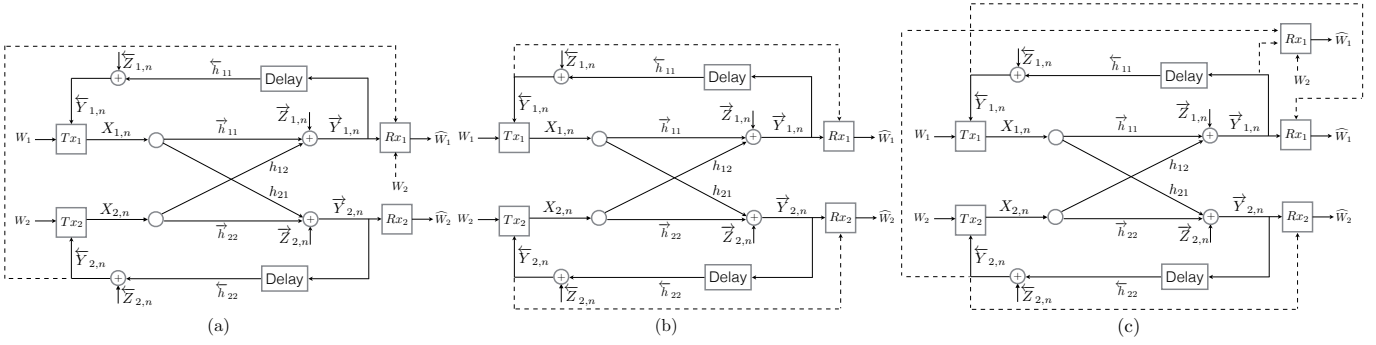


Fig. 2. Genie-Aided G-IC-NOF models for channel use n . (a) Model used to calculate the outer-bound on R_1 ; (b) Model used to calculate the outer-bound on $R_1 + R_2$; and (c) Model used to calculate the outer-bound on $2R_1 + R_2$

$$\begin{aligned} \kappa_{6,3}(\rho) &= \frac{1}{2} \log \left(b_{6,1}(\rho) + \frac{b_{5,1}(\rho) \overleftarrow{\text{SNR}}_{21}}{\overrightarrow{\text{SNR}}_1} (\overrightarrow{\text{SNR}}_1 + b_{3,1}) \right) \\ &\quad - \frac{1}{2} \log (1 + \text{INR}_{12}) + \frac{1}{2} \log \left(1 + \frac{b_{5,2}(\rho) \overleftarrow{\text{SNR}}_2}{b_{1,2}(1) + 1} \right) \\ &\quad + \frac{1}{2} \log (b_{1,2}(\rho) + b_{5,1}(\rho) \text{INR}_{21}) - \frac{1}{2} \log (1 + \text{INR}_{21}) \\ &\quad + \frac{1}{2} \log \left(1 + \frac{b_{5,1}(\rho)}{\overrightarrow{\text{SNR}}_1} \left(\text{INR}_{21} + \frac{b_{3,1} \overleftarrow{\text{SNR}}_1}{b_{1,1}(1) + 1} \right) \right) \\ &\quad - \frac{1}{2} \log \left(1 + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overrightarrow{\text{SNR}}_1} \right) + \log(2\pi e), \end{aligned} \quad (15c)$$

$$\begin{aligned} \kappa_{6,4}(\rho) &= \frac{1}{2} \log \left(b_{6,1}(\rho) + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overrightarrow{\text{SNR}}_1} (\overrightarrow{\text{SNR}}_1 + b_{3,1}) \right) \\ &\quad - \frac{1}{2} \log (1 + \text{INR}_{12}) - \frac{1}{2} \log (1 + \text{INR}_{21}) \\ &\quad + \frac{1}{2} \log \left(1 + \frac{b_{5,2}(\rho)}{\overrightarrow{\text{SNR}}_2} \left(\text{INR}_{12} + \frac{b_{3,2} \overleftarrow{\text{SNR}}_2}{b_{1,2}(1) + 1} \right) \right) \\ &\quad - \frac{1}{2} \log \left(1 + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overrightarrow{\text{SNR}}_2} \right) \\ &\quad - \frac{1}{2} \log \left(1 + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overrightarrow{\text{SNR}}_1} \right) \\ &\quad + \frac{1}{2} \log \left(b_{6,2}(\rho) + \frac{b_{5,1}(\rho) \text{INR}_{21}}{\overrightarrow{\text{SNR}}_2} (\overrightarrow{\text{SNR}}_2 + b_{3,2}) \right) \\ &\quad + \frac{1}{2} \log \left(1 + \frac{b_{5,1}(\rho)}{\overrightarrow{\text{SNR}}_1} \left(\text{INR}_{21} + \frac{b_{3,1} \overleftarrow{\text{SNR}}_1}{b_{1,1}(1) + 1} \right) \right) \\ &\quad + \log(2\pi e), \end{aligned} \quad (15d)$$

and

$$\begin{aligned} \kappa_{7,i,1}(\rho) &= \frac{1}{2} \log (b_{1,i}(\rho) + 1) - \frac{1}{2} \log (1 + \text{INR}_{ij}) \\ &\quad + \frac{1}{2} \log \left(1 + \frac{b_{5,j}(\rho) \overleftarrow{\text{SNR}}_j}{b_{1,j}(1) + 1} \right) \\ &\quad + \frac{1}{2} \log (b_{1,j}(\rho) + b_{5,i}(\rho) \text{INR}_{ji}) \\ &\quad + \frac{1}{2} \log (1 + b_{4,i}(\rho) + b_{5,j}(\rho)) - \frac{1}{2} \log (1 + b_{5,j}(\rho)) \\ &\quad + 2 \log(2\pi e), \end{aligned} \quad (16a)$$

$$\begin{aligned} \kappa_{7,i,2}(\rho) &= \frac{1}{2} \log (b_{1,i}(\rho) + 1) - \frac{1}{2} \log (1 + \text{INR}_{ij}) \\ &\quad - \frac{1}{2} \log (1 + b_{5,j}(\rho)) + \frac{1}{2} \log (1 + b_{4,i}(\rho) + b_{5,j}(\rho)) \\ &\quad + \frac{1}{2} \log \left(1 + (1 - \rho^2) \frac{\overleftarrow{\text{SNR}}_{ji}}{\overrightarrow{\text{SNR}}_j} \left(\text{INR}_{ij} + \frac{b_{3,j} \overleftarrow{\text{SNR}}_j}{b_{1,j}(1) + 1} \right) \right) \\ &\quad - \frac{1}{2} \log \left(1 + \frac{b_{5,i}(\rho) \text{INR}_{ji}}{\overrightarrow{\text{SNR}}_j} \right) \\ &\quad + \frac{1}{2} \log \left(b_{6,j}(\rho) + \frac{b_{5,i}(\rho) \text{INR}_{ji}}{\overrightarrow{\text{SNR}}_j} (\overrightarrow{\text{SNR}}_j + b_{3,j}) \right) \\ &\quad + 2 \log(2\pi e), \end{aligned} \quad (16b)$$

where the functions $b_{l,i}$, with $(l, i) \in \{1, 2\}^2$ are defined in (11); $b_{3,i}$ are constants; and the functions $b_{l,i} : [0, 1] \rightarrow \mathbb{R}_+$, with $(l, i) \in \{4, 5, 6\} \times \{1, 2\}$ are defined as follows, with $j \in \{1, 2\} \setminus \{i\}$:

$$b_{3,i} = \overrightarrow{\text{SNR}}_i - 2\sqrt{\overrightarrow{\text{SNR}}_i \text{INR}_{ji}} + \text{INR}_{ji}, \quad (17a)$$

$$b_{4,i}(\rho) = (1 - \rho^2) \overrightarrow{\text{SNR}}_i, \quad (17b)$$

$$b_{5,i}(\rho) = (1 - \rho^2) \text{INR}_{ij}, \quad (17c)$$

$$\begin{aligned} b_{6,i}(\rho) &= \overrightarrow{\text{SNR}}_i + \text{INR}_{ij} + 2\rho\sqrt{\text{INR}_{ij}} \left(\sqrt{\overrightarrow{\text{SNR}}_i} - \sqrt{\text{INR}_{ji}} \right) \\ &\quad + \frac{\text{INR}_{ij} \sqrt{\text{INR}_{ji}}}{\overrightarrow{\text{SNR}}_i} \left(\sqrt{\text{INR}_{ji}} - 2\sqrt{\overrightarrow{\text{SNR}}_i} \right). \end{aligned} \quad (17d)$$

Note that the functions in (14), (15), (16) and (17) depend on $\overrightarrow{\text{SNR}}_1$, $\overrightarrow{\text{SNR}}_2$, INR_{12} , INR_{21} , $\overleftarrow{\text{SNR}}_1$, and $\overleftarrow{\text{SNR}}_2$. However, these parameters are fixed in this analysis, and therefore, this dependence is not emphasized in the definition of these functions. Finally, using this notation, Theorem 2 is presented below.

Theorem 2: The capacity region $\mathcal{C}_{\text{GIC-NOF}}$ is contained within the region $\overline{\mathcal{C}}_{\text{G-IC-NOF}}$ given by the closure of the set of non-negative rate pairs (R_1, R_2) that for all $i \in \{1, 2\}$, with $j \in \{1, 2\} \setminus \{i\}$ satisfy:

$$R_i \leq \min(\kappa_{1,i}(\rho), \kappa_{2,i}(\rho)), \quad (18a)$$

$$R_i \leq \kappa_{3,i}(\rho), \quad (18b)$$

$$R_1 + R_2 \leq \min(\kappa_4(\rho), \kappa_5(\rho)), \quad (18c)$$

$$R_1 + R_2 \leq \kappa_6(\rho), \quad (18d)$$

$$2R_i + R_j \leq \kappa_{7,i}(\rho), \quad (18e)$$

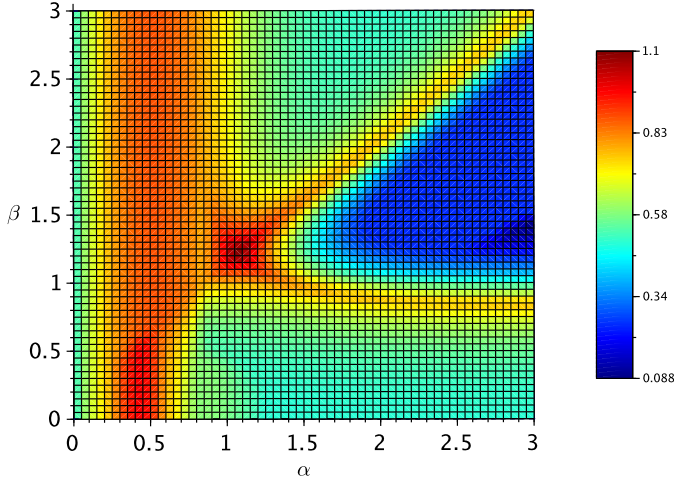


Fig. 3. Gap between the converse region $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$ and the achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ of the two-user G-IC-NOF, under symmetric channel conditions, i.e., $\overrightarrow{\text{SNR}}_1 = \overrightarrow{\text{SNR}}_2 = \overrightarrow{\text{SNR}}$, $\overrightarrow{\text{INR}}_{12} = \overrightarrow{\text{INR}}_{21} = \overrightarrow{\text{INR}}$, and $\overleftarrow{\text{SNR}}_1 = \overleftarrow{\text{SNR}}_2 = \overleftarrow{\text{SNR}}$, as a function of $\alpha = \frac{\log \overrightarrow{\text{INR}}}{\log \overrightarrow{\text{SNR}}}$ and $\beta = \frac{\log \overleftarrow{\text{SNR}}}{\log \overrightarrow{\text{SNR}}}$.

with $\rho \in [0, 1]$.

Proof: The proof of Theorem 2 is presented in [1]. ■

D. Comments on the Converse Region

The outer bounds (18a) and (18c) correspond to the outer bounds for the case of perfect channel-output feedback [4]. The bounds (18b), (18d) and (18e) correspond to new outer bounds that generalize those presented in [2] for the two-user symmetric G-IC-NOF. These new outer-bounds were obtained using the genie-aided models shown in Figure 2.

E. A Gap Between the Achievable Region and the Converse Region

Theorem 3 describes the gap between the achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and the converse region $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$ using the approximation notion described in Definition 2.

Theorem 3: The capacity region of the two-user G-IC-NOF is approximated to within 4.4 bits per channel use by the achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and the converse region $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$.

Proof: The proof of Theorem 3 is presented in [1]. ■

The gap, denoted by δ , between the sets $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$ and $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ can be approximated (Definition 2) as follows:

$$\delta \leq \max \left(\delta_{R_1}, \delta_{R_2}, \frac{\delta_{2R}}{2}, \frac{\delta_{3R_1}}{3}, \frac{\delta_{3R_2}}{3} \right), \quad (19)$$

where

$$\delta_{R_1} \triangleq \min \left(\kappa_{1,1}(\rho), \kappa_{2,1}(\rho), \kappa_{3,1}(\rho) \right) - \min \left(a_{2,1}(\rho), a_{6,1}(\rho, \mu_1) + a_{3,2}(\rho, \mu_1), a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{4,2}(\rho, \mu_1) \right), \quad (20a)$$

$$\delta_{R_2} \triangleq \min \left(\kappa_{1,2}(\rho), \kappa_{2,2}(\rho), \kappa_{3,2}(\rho) \right) - \min \left(a_{2,2}(\rho), a_{3,1}(\rho, \mu_2) + a_{6,2}(\rho, \mu_2), a_{3,1}(\rho, \mu_2) + a_{4,1}(\rho, \mu_2) + a_{1,2} \right), \quad (20b)$$

$$\delta_{2R} \triangleq \min \left(\kappa_4(\rho), \kappa_5(\rho), \kappa_6(\rho) \right) - \min \left(a_{2,1}(\rho) + a_{1,2}, a_{1,1} + a_{2,2}(\rho), a_{3,1}(\rho, \mu_2) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{7,2}(\rho, \mu_1, \mu_2), a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1), a_{3,1}(\rho, \mu_2) + a_{7,1}(\rho, \mu_1, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{1,2} \right), \quad (20c)$$

$$\delta_{3R_1} \triangleq \kappa_{7,1}(\rho) - \min \left(a_{2,1}(\rho) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{7,2}(\rho, \mu_1, \mu_2), a_{3,1}(\rho, \mu_2) + a_{1,1} + a_{7,1}(\rho, \mu_1, \mu_2) + 2a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1), a_{2,1}(\rho) + a_{1,1} + a_{3,2}(\rho, \mu_1) + a_{5,2}(\rho, \mu_1) \right), \quad (20d)$$

$$\delta_{3R_2} \triangleq \kappa_{7,2}(\rho) - \min \left(a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{2,2}(\rho) + a_{1,2}, a_{3,1}(\rho, \mu_2) + a_{7,1}(\rho, \mu_1, \mu_2) + a_{2,2}(\rho) + a_{1,2}, 2a_{3,1}(\rho, \mu_2) + a_{5,1}(\rho, \mu_2) + a_{3,2}(\rho, \mu_1) + a_{1,2} + a_{7,2}(\rho, \mu_1, \mu_2) \right). \quad (20e)$$

Note that δ_{R_1} and δ_{R_2} represent the gap between the active achievable single-rate bound and the active converse single-rate bound; δ_{2R} represents the gap between the active achievable sum-rate bound and the active converse sum-rate bound; and, δ_{3R_1} and δ_{3R_2} represent the gap between the active achievable weighted sum-rate bound and the active converse weighted sum-rate bound.

Finally, it is important to highlight that, as suggested in [2], [4], and [5], the gap between $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$ can be calculated more precisely. However, the choice in (19) eases the calculations at the expense of less precision.

Figure 3 presents the exact gap existing between the achievable region $\underline{\mathcal{C}}_{\text{G-IC-NOF}}$ and the converse region $\bar{\mathcal{C}}_{\text{G-IC-NOF}}$ for the case in which $\overrightarrow{\text{SNR}}_1 = \overrightarrow{\text{SNR}}_2 = \overrightarrow{\text{SNR}}$, $\overrightarrow{\text{INR}}_{12} = \overrightarrow{\text{INR}}_{21} = \overrightarrow{\text{INR}}$, and $\overleftarrow{\text{SNR}}_1 = \overleftarrow{\text{SNR}}_2 = \overleftarrow{\text{SNR}}$ as a function of $\alpha = \frac{\log \overrightarrow{\text{INR}}}{\log \overrightarrow{\text{SNR}}}$ and $\beta = \frac{\log \overleftarrow{\text{SNR}}}{\log \overrightarrow{\text{SNR}}}$. Note that in this case, the maximum gap is 1.1 bits per channel use and occurs when $\alpha = 1.05$ and $\beta = 1.2$.

IV. CONCLUSIONS

An achievable region and a converse region for the two-user G-IC-NOF have been introduced. It has been shown that these regions approximate the capacity region of the two-user G-IC-NOF to within 4.4 bits per channel use.

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