Bounds and Capacity Results for the Cognitive Z-interference Channel

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***Abstract*—We study the discrete memoryless Z-interference channel (ZIC) where the transmitter of the pair that suffers from interference is cognitive. We first provide upper and lower bounds on the capacity of this channel. We then show that, when the channel of the transmitter-receiver pair that does not face interference is noiseless, the two bounds coincide and therefore define the capacity region. The obtained results imply that, unlike in the Gaussian cognitive ZIC, in the considered channel superposition encoding at the non-cognitive transmitter as well as Gel'fand-Pinsker encoding at the cognitive transmitter are needed in order to minimize the impact of interference. As a byproduct of the obtained capacity region, we obtain the capacity result for a generalized Gel'fand-Pinsker problem.**

I. Introduction

The interference channel (IC) [1] is a simple network consisting of two transmitter-receiver pairs. Each pair wishes to reliably communicate at a certain rate, however, the two communications interfere with each other. A key issue in such scenarios then, is how to handle the interference introduced by the simultaneous transmissions. This issue is not yet fully understood, and the problem of finding the capacity region of the IC remains open, except in special cases [2]–[12]. For an overview on the capacity results of the IC, see [13]. The Z-interference channel (ZIC) is an IC where one transmitter-receiver pair is interference-free. Although this is a simpler channel model than the IC, capacity results are still known only in special cases [6, Section IV], [14]–[16].

In certain communication scenarios, such as cognitive radio networks, some transmitters are cognitive, i.e., are able to sense the environment and thus obtain side information about transmissions in their vicinity. Motivated by the promise of cognitive radio technology to improve bandwidth utilization and thus allow for new wireless services and a higher quality of service, the IC with one cognitive transmitter has recently received much attention [17]–[24]. Related channel models were also analyzed in [25], [26]. In the model considered in [17]–[25], it is assumed that due to the cognitive capabilities, the cognitive encoder noncausally obtains the full message of the non-cognitive transmitter. While this is a somewhat idealistic view of cognition in a wireless network, this model applies, for example, to scenarios where the cognitive transmitter is a base station. Then, it can obtain side information via backhaul (i.e., via a high-capacity link such as an optical cable). This side information then enables interference reduction [27] by precoding at the cognitive encoder. Furthermore, it enables cooperation with the non-cognitive pair. In fact, one of the main difficulties in finding the capacity region of the traditional IC comes from distributed encoding. The IC with one cognitive transmitter enables one-sided transmitter cooperation, and thus allows centralized encoding to some degree. This may be the reason why determining the capacity region of the cognitive IC is somewhat easier than the traditional IC. In particular, while the capacity region of the Gaussian IC in weak interference is not known (the sum capacity in certain weak interference regimes has recently been found in [28]–[30]), the capacity region of the *cognitive* Gaussian IC in weak interference has been determined [19], [20].

In this paper, we study a ZIC where the transmitter of the pair that suffers from interference is cognitive (see Fig. 1). The capacity region of such a cognitive ZIC in the Gaussian case is straightforward to obtain, since by using dirty-paper coding [31] at the cognitive encoder, both communicating pairs can achieve the interference-free, single-user rates. However, limiting the study of the cognitive ZIC to the Gaussian case leaves something lacking in the understanding of the problem. In particular, the Gaussian case does not provide intuition about how the interferer's rate affects the rate of the cognitive transmitter-receiver pair in a general channel. Nor does it provide insight into the optimal codebook structure for the non-cognitive encoder that minimizes interference to the cognitive pair.

Hence, in this paper, we study a *discrete* memoryless cognitive ZIC. We first derive an upper bound on the capacity region. To obtain the converse we use the technique of [34, page 314], which was introduced by Korner and Marton in [32], and was proven to be useful in the solution of several problems in multi-user information theory [15], [16], [32], [33], including the Gel'fand-Pinsker (GP) problem [27]. We apply this technique *twice* to obtain the upper bound on the capacity region. Next, we derive a lower bound on the capacity region where the non-cognitive pair uses superposition

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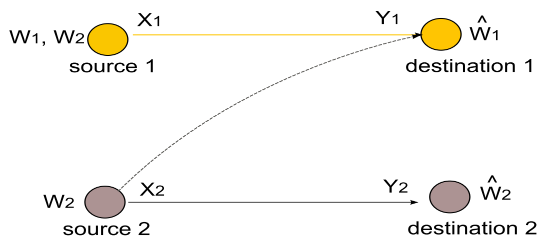

Fig. 1. Cognitive Z-interference channel.

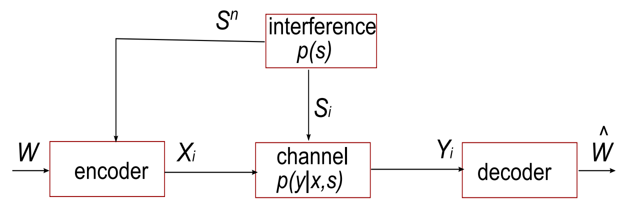

Fig. 2. Gel'fand-Pinsker problem.

encoding to control the amount of interference it causes to the cognitive pair. Unlike in the IC, this encoding approach has not been applied in the cognitive IC literature, with the exception of concurrent and independent work [23]. Finally, we show that the lower and upper bounds meet when the channel between the non-cognitive pair is noiseless. We denote this channel model as the cognitive ZIC with a noiseless non-cognitive link. From the capacity results, we conclude that it is optimal for the interference-causing (non-cognitive) pair to use superposition encoding; the inner codeword is decoded by the receiver of the cognitive pair while GP coding is performed against the outer codeword at the cognitive transmitter.

The capacity region of the discrete memoryless cognitive IC is known in some special cases [18], [19], [23]. The tight result we derive in this paper does not fall into these special cases, as explained in more detail in Section V. Furthermore, the cognitive ZIC with a noiseless non-cognitive link is the first channel model for which superposition encoding at the non-cognitive transmitter is optimal.

Note that, in general, the capacity region of the traditional ZIC in which the interference-free transmitter-receiver pair is noiseless is unknown. The most we know about this scenario is the sum capacity [15]. Thus, the results in this paper provide yet another example where finding the capacity region of the cognitive IC is easier than that of the traditional IC since centralized (joint) encoding can be employed at the cognitive transmitter.

The considered problem is also intimately related to the GP problem [27] where a transmitter-receiver pair communicates in the presence of interference noncausally known at the encoder (see Fig. 2). By viewing the non-cognitive encoder in the cognitive ZIC as a source of this interference, we obtain a generalized GP problem. Instead of the state being i.i.d. as in the GP problem, in the generalized GP model considered in this paper, the state is uniformly distributed on a set of size 2^{nR_2}, where R_2 is a number between 0 and the logarithm of the cardinality of the state space. The further generalization is that, unlike in [27], in our model one can optimize the set, i.e., the structure of the interference. Our results demonstrate that the optimal interference has a superposition structure.

II. System Model

Consider a ZIC with two transition probabilities $p(y_1|x_1,x_2)$ and $p(y_2|x_2)$. The input and output alphabets are $\mathcal{X}_1$, $\mathcal{X}_2$, $\mathcal{Y}_1$ and $\mathcal{Y}_2$.

Let W_1 and W_2 be two independent messages uniformly distributed on $\{1,2,\cdots,M_1\}$ and $\{1,2,\cdots,M_2\}$, respectively. Transmitter i wishes to send message W_i to Receiver i, $i=1,2$. Transmitter 1 is cognitive in the sense that, in addition to knowing W_1, it knows the message W_2. An (M_1,M_2,n,ϵ_n) code for this channel consists of a sequence of two encoding functions

$$f_1^n : \{1,2,\cdots,M_1\} \times \{1,2,\cdots,M_2\} \to \mathcal{X}_1^n, \tag{1}$$

$$f_2^n : \{1,2,\cdots,M_2\} \to \mathcal{X}_2^n, \tag{2}$$

and two decoding functions

$$g_i^n : \mathcal{Y}_i^n \to \{1,2,\cdots,M_i\}, \qquad i=1,2 \tag{3}$$

with probability of error

$$\epsilon_n = \max_{i=1,2} \frac{1}{M_1M_2}\sum_{w_1,w_2} \Pr\left[g_i^n(Y_i^n) \neq w_i | W_1=w_1, W_2=w_2\right]. \tag{4}$$

A rate pair (R_1,R_2) is said to be achievable if there exists a sequence of $\left(2^{nR_1},2^{nR_2},n,\epsilon_n\right)$ codes such that $\epsilon_n \to 0$ as $n\to\infty$. The capacity region of the cognitive ZIC is the closure of the set of all achievable rate pairs.

A cognitive ZIC with a noiseless non-cognitive link is a cognitive ZIC where the channel from X_2 to Y_2 is noiseless, i.e., $p(y_2|x_2)$ is a deterministic one-to-one function.

Throughout the paper, we use the following shorthand for random vectors: $K^i \triangleq K_1,K_2,\cdots,K_i$ and $K_{i+1}^n \triangleq K_{i+1},K_{i+2},\cdots,K_n$.

III. Converse

In this section, we provide an upper bound on the capacity region of the cognitive ZIC.

Theorem 1: Achievable rate pairs (R_1,R_2) belong to a union of rate regions given by

$$R_1 \leq I(U;Y_1|V) - I(U;Y_2|V) \tag{5}$$

$$R_2 \leq I(X_2;Y_2|V) + \min\{I(V;Y_1), I(V;Y_2)\} \tag{6}$$

where the union is over all probability distributions $p(v,u,x_2)p(x_1|u,x_2)$ and the mutual informations are calculated according to distribution

$$p(v,u,x_1,x_2,y_1,y_2) = p(v,u,x_2)p(x_1|u,x_2)p(y_1|x_1,x_2)p(y_2|x_2). \tag{7}$$

Proof: The proof is provided in Section VIII-A. ∎

This converse result is obtained by using the converse technique of Korner/Marton [34, page 314] two times, resulting in two auxiliary random variables.

IV. Achievability

The achievability scheme uses a combination of superposition encoding at the non-cognitive encoder and GP encoding against the outer codeword of interference at the cognitive encoder. The resulting rates are given in the following theorem.

Theorem 2: The union of rate regions given by

$$R_1 \leq I(U;Y_1|V) - I(U;X_2|V) \tag{8}$$
$$R_2 \leq I(X_2;Y_2|V) + \min\{I(V;Y_1), I(V;Y_2)\} \tag{9}$$

is achievable, where the union is over all probability distributions $p(v,u,x_2)p(x_1|u,x_2)$ and the mutual informations are calculated according to the distribution in (7).

Proof: Due to space limitations, the proof is omitted here but can be found in [35]. ■

Remark: The proposed achievability scheme is a special case of the independent and concurrent work [23, Theorem 2] by setting $U_{10} = V$, $(U_{11}, U_{10}) = (V_{11}, U_{10}) = X_1$, $V_{20} = \phi$, $V_{22} = U$, $L_{20} = R_{20} = 0$, $L_{11} = R_{11}$ and then swapping the indices of 1 and 2 since, in [23], the *second* transmitter-receiver pair is cognitive.

V. Capacity Region of the Cognitive ZIC with a Noiseless Non-cognitive Link

In general, the achievability results in (8)-(9) and the converse results in (5)-(6) do not meet, due to the fact that

$$I(U;X_2|V) \geq I(U;Y_2|V) \tag{10}$$

because the random variables satisfy (7), which implies that the Markov chain $U \rightarrow (V, X_2) \rightarrow Y_2$ holds. However, in the case where the channel output $Y_2 = X_2$, the achievability region and the converse region meet, yielding the capacity region. More specifically, we have the following capacity results for the cognitive ZIC.

Theorem 3: For the cognitive ZIC with a noiseless non-cognitive link, i.e., $p(y_2|x_2)$ is a deterministic one-to-one function, the capacity region is given by the union of rate regions:

$$R_1 \leq I(U;Y_1|V) - I(U;X_2|V) \tag{11}$$
$$R_2 \leq H(X_2|V) + \min\{I(V;Y_1), I(V;X_2)\} \tag{12}$$

where the union is over all probability distributions $p(v,u,x_2)p(x_1|u,x_2)$ and the mutual informations are calculated according to the distribution in (7).

Remark: Similar to the solution of the GP problem, one may restrict $p(x_1|u,x_2)$ to be a deterministic function, i.e., $p(x_1|u,x_2)$ only takes the values of 0 and 1 in the union in Theorem 3.

We conclude from Theorem 3 that, in the special case of a noiseless channel between the interference-free transmitter-receiver pair, to minimize the effect of interference caused to the cognitive transmitter-receiver pair, the non-cognitive pair uses superposition encoding, allowing the cognitive pair to decode the inner codeword. In contrast to the Han-Kobayashi scheme [9] for the traditional ZIC, where the outer codeword of the interferer is treated as noise, here, due to the cognitive capability of the transmitter that faces interference, GP encoding is performed against the outer codeword to further reduce the effect of interference.

We now provide some intuition as to why we are able to obtain capacity results *only* when the channel between the non-cognitive pair is noiseless. In the achievable scheme of Theorem 2, the cognitive transmitter treats the outer codeword as i.i.d. (conditioned on the inner codeword), and performs GP coding against it. When the channel $p(y_2|x_2)$ is noiseless, the outer codebook is decodable at Y_2 with full rate, i.e., $2^{nH(X_2|V)}$. This indicates that, conditioned on the inner codeword, the outer codeword is indeed very close to i.i.d. However, when $p(y_2|x_2)$ is noisy, to ensure decodability at Y_2, the outer codebook cannot have full rate, and therefore the outer codeword is not as random as in the i.i.d. case. Thus, it is suboptimal to treat it as i.i.d. and perform GP coding.

The capacity region of the discrete memoryless cognitive IC is known in some special cases [18], [19], [23]. However, our results fall outside these previous works. In particular, the cognitive ZIC with a noiseless non-cognitive link is not a special case of [18, Theorem 3] as it does not satisfy either of the two conditions of strong interference. It satisfies Assumption 3.1 but not Assumption 3.2 in [19], and therefore its capacity region is not characterized by [19, Theorem 3.4]. The capacity result in Theorem 3 is also not a special case of [23, Theorem 5] as the received signal of the cognitive pair is not a deterministic function of the two channel inputs. Rather, in the cognitive ZIC with a noiseless non-cognitive link, the received signal of the non-cognitive pair is a deterministic function. Furthermore, it does not satisfy the mutual information inequality required in [23, Theorem 5].

VI. Application to the Generalized GP Problem

Consider the following generalized GP problem: A transmitter, with channel input X_1, wishes to communicate via channel $p(y_1|x_1,x_2)$ with a receiver, which observes channel output Y_1, where X_2 is the channel state that affects this communication. The transmitter knows the realization of the channel state noncausally. Instead of the state (random parameters of the channel) being i.i.d. as in the original GP problem (Fig. 2), the state X_2^n is uniformly distributed on a set of size 2^{nR_2}. Furthermore, we are allowed the freedom to not only design the codebook of the transmitter, but also the structure of the set where the states lie, in order to maximize the number of bits transmitted between the transmitter-receiver pair. In other words, we are interested in the capacity of the transmitter-receiver pair, denoted as $C(R_2)$, which is a function of R_2.

The problem described above is exactly the same as the communication problem of Transmitter 1 and Receiver 1 in the cognitive ZIC where the channel from X_2 to Y_2 is noiseless and the rate of communication between Transmitter 2 and Receiver 2 is R_2. Thus, $C(R_2)$ in the generalized GP problem is the maximum rate at which Transmitter 1 and Receiver 1 can communicate given that Transmitter 2 and Receiver 2 are communicating at rate R_2 in the cognitive ZIC problem with a noiseless non-cognitive link. Therefore, we can use the capacity region in Theorem 3 to conclude that the capacity in the generalized GP problem is

$$C(R_2) = \max_{p(v,u,x_2),p(x_1|u,x_2)} I(U;Y_1|V) - I(U;X_2|V) \quad (13)$$

where the maximum is over all distributions $p(v, u, x_2)$, $p(x_1|u, x_2)$ that satisfy

$$H(X_2|V) + \min\{I(V;Y_1), I(V;X_2)\} \geq R_2. \quad (14)$$

Based on the proof of achievability in Theorem 3, we see that in the generalized GP problem, when given the rate of the possible channel states R_2, the optimal interference has a superposition structure, resulting in the highest R_1.

Remark: When $R_2 = \log|\mathcal{X}_2|$, $C(R_2)$ reduces to the GP rate where the state is i.i.d. and uniformly distributed on set $\mathcal{X}_2$.

VII. Conclusions

We have characterized the capacity region of the discrete Z-interference channel where the transmitter of the pair that suffers from interference is cognitive, and the channel between the interference-free pair is noiseless. In contrast to the Gaussian case, our results demonstrate that under certain conditions, superposition encoding is the optimal way to minimize interference, even if the transmitter of the interference-suffering pair has cognitive capabilities. Our results also apply to a generalized Gel'fand-Pinsker problem where a transmitter-receiver pair communicates in the presence of interference noncausally known at the encoder. The results not only provide new capacity theorems, but also shed light on the optimal structure of the interference with respect to capacity for more general multiterminal networks.

VIII. Appendix

A. Proof of Theorem 1

Following from Fano's inequality [36], we have

$$nR_1 \leq H(Y_1^n) - H(Y_1^n|W_1) + n\epsilon_n \quad (15)$$

and

$$\begin{aligned} nR_2 &\leq H(Y_2^n) - H(Y_2^n|W_2) + n\epsilon_n && (16)\\ &\leq H(Y_2^n) - H(Y_2^n|W_2, X_2^n) + n\epsilon_n && (17)\\ &= H(Y_2^n) - H(Y_2^n|X_2^n) + n\epsilon_n && (18)\\ &= H(Y_2^n) - \sum_{i=1}^n H(Y_{2i}|X_{2i}) + n\epsilon_n && (19) \end{aligned}$$

where (18) follows from the Markov Chain $W_2 \rightarrow X_2^n \rightarrow Y_2^n$, and (19) follows from the memoryless property of the channel $p(y_2|x_2)$.

Applying the technique [34, page 314, eqn (3.34)] twice, we obtain

$$\begin{aligned} H(Y_1^n) - H(Y_2^n) = \sum_{i=1}^n & H(Y_{1i}|Y_1^{i-1}, Y_{2(i+1)}^n) \\ & - H(Y_{2i}|Y_1^{i-1}, Y_{2(i+1)}^n), \quad (20) \end{aligned}$$

$$\begin{aligned} H(Y_1^n|W_1) - H(Y_2^n|W_1) = \sum_{i=1}^n & H(Y_{1i}|Y_1^{i-1}, Y_{2(i+1)}^n, W_1) \\ & - H(Y_{2i}|Y_1^{i-1}, Y_{2(i+1)}^n, W_1). \quad (21) \end{aligned}$$

Define auxiliary random variables as

$$V_i = Y_1^{i-1}, Y_{2(i+1)}^n, \qquad i = 1, 2, \cdots, n. \quad (22)$$

Further define Q to be an auxiliary random variable that is independent of everything else and uniform on the set $\{1, 2, \cdots, n\}$, and

$$\begin{aligned} V = (V_Q, Q), \quad U = (V, W_1), \quad X_1 = X_{1Q}, \\ X_2 = X_{2Q}, \quad Y_1 = Y_{1Q}, \quad Y_2 = Y_{2Q}. \quad (23) \end{aligned}$$

It is straightforward to check that the random variables thus defined satisfy (7).

Following from (20) and (21), we have

$$\frac{1}{n}\left(H(Y_1^n) - H(Y_2^n)\right) = H(Y_1|V) - H(Y_2|V) \quad (24)$$

$$\frac{1}{n}\left(H(Y_1^n|W_1) - H(Y_2^n|W_1)\right) = H(Y_1|U) - H(Y_2|U). \quad (25)$$

Notice that (24) implies that there exists a number γ where

$$\frac{1}{n}H(Y_1^n) = H(Y_1|V) + \gamma, \ \frac{1}{n}H(Y_2^n) = H(Y_2|V) + \gamma \quad (26)$$

$$0 \leq \gamma \leq \min\{I(V;Y_1), I(V;Y_2)\} \quad (27)$$

where (27) follows because $H(Y_1^n) \leq nH(Y_1)$ and $H(Y_2^n) \leq nH(Y_2)$ and

$$\begin{aligned} H(Y_1^n) = \sum_{i=1}^n H(Y_{1i}|Y_1^{i-1}) &\geq \sum_{i=1}^n H(Y_{1i}|Y_1^{i-1}, Y_{2(i+1)}^n) \\ &= nH(Y_1|V) \quad (28) \end{aligned}$$

Following from (19) and omitting the ϵ_n's, we have

$$\begin{aligned} R_2 &= \frac{1}{n}H(Y_2^n) - \frac{1}{n}\sum_{i=1}^n H(Y_{2i}|X_{2i}) \\ &= H(Y_2|V) + \gamma - H(Y_2|X_2, Q) && (29)\\ &= H(Y_2|V) + \gamma - H(Y_2|X_2) && (30)\\ &\leq H(Y_2|V) + \min\{I(V;Y_1), I(V;Y_2)\} - H(Y_2|X_2) && (31)\\ &= I(X_2;Y_2|V) + \min\{I(V;Y_1), I(V;Y_2)\} && (32) \end{aligned}$$

where (29) follows from (26) and the definition of the random variables in (23); (30) follows by the memoryless nature of the channel $p(y_2|x_2)$; (31) follows from (27); and (32) follows because the random variables satisfy (7) which implies that the Markov chain $V \rightarrow X_2 \rightarrow Y_2$ holds.

Following from (15) and omitting the ϵ_n's, we have

$$\begin{aligned}
R_1 &\leq \frac{1}{n}H(Y_1^n) - \frac{1}{n}H(Y_1^n|W_1) \\
&= \frac{1}{n}H(Y_2^n) + H(Y_1|V) - H(Y_2|V) - \frac{1}{n}H(Y_2^n|W_1) \\
&\quad - H(Y_1|U) + H(Y_2|U) \qquad (33) \\
&= H(Y_1|V) - H(Y_2|V) - H(Y_1|U) + H(Y_2|U) \qquad (34) \\
&= I(U;Y_1|V) - I(U;Y_2|V) \qquad (35)
\end{aligned}$$

where (33) follows from (24) and (25); (34) follows from the fact that Y_2^n only depends on X_2^n and the channel noise induced by $p(y_2^n|x_2^n)$, and is therefore independent of W_1; and (35) follows because the random variables satisfy (7) which implies that the Markov chain $V \to U \to (Y_1, Y_2)$ holds.

We obtain the desired upper bound on the capacity region from (32) and (35).

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