On the Capacity Region of the Partially Cooperative Relay Cognitive Interference Channel

Mohammad Kazemi
University of Rochester
Rochester, NY, USA
mkazemi@ece.rochester.edu

Azadeh Vosoughi
University of Central Florida
Orlando, FL, USA
azadeh@ucf.edu

***Abstract*—We derive a new upper bound on the capacity region of the discrete memoryless partially cooperative relay cognitive interference channel (PC-RCIC). We show that our new upper bound is the capacity region of the semideterministic discrete memoryless PC-RCIC, where the channel output observed by the relay is a deterministic function of the channel inputs.**

I. Introduction

The discrete memoryless cognitive interference channel (CIC) was the channel setup introduced in [1], [2] to study the fundamental limits of communications in cognitive radio channels. Interference, which undeniably arises in cognitive radio networks, affects adversely the data communication rates. Therefore, cooperative relay CIC (RCIC) was introduced in [3], [4] to study cooperative relaying of information as a powerful technique to improve the reliability and throughput of CICs.

In this paper, we study the discrete memoryless partially cooperative RCIC (PC-RCIC) which, as shown in Fig. 1, is a network with two sources communicating two independent and uniformly distributed messages to two destinations. Source 1, referred to as the cognitive source, knows both messages 1 and 2, whereas source 2, referred to as the primary source, knows only message 2. Destination 1 decodes both messages 1 and 2, while destination 2 decodes only message 1. In addition, destination 1 acts as a standard relay node [5]–[7] and assists destination 2 by transmitting cooperative information through a relay link.

We derive a new upper bound on the capacity of the general PC-RCIC. we also characterize the capacity region of the semideterministic PC-RCIC, where the channel output observed by destination 1 (relay) is a deterministic function of the channel inputs.

Discrete memoryless PC-RCIC was also considered in [3], where a lower bound was derived on the capacity region of the general case (not necessarily semideterministic). This lower bound is based on rate splitting [8] and superposition coding [9] at the cognitive source and decode-and-forward scheme [6] at the relay node. Furthermore, it was shown that this lower bound achieves the capacity region of a degraded version of PC-RCIC.

A. Vosoughi is supported by the National Science Foundation under Grant CCF-0915969.

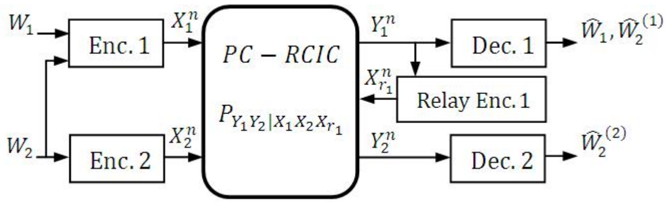

Fig. 1: The general SD-CIC

The paper is organized as follows. In Section II we provide a formal definition for the discrete memoryless PC-RCIC. In section III we establish a new upper bound on the capacity region of the general PC-RCIC. The capacity region of the semideterministic PC-RCIC is characterized in section IV.

II. Notations and Definitions

A. Notations

Random variables are indicated by upper case letters, (e.g. X) and their realizations are shown by the respective lower case letters (e.g. x). The probability mass function (p.m.f.) of a random variable X over its corresponding finite alphabet set $\mathcal{X}$ is indicated by $p_X(x)$ where occasionally subscript X is omitted. The conditional p.m.f. of a random variable X given random variable Y is denoted by $p_{X|Y}(x|y)$. Random vector $(X_1, X_2, ..., X_n)$ is indicated by X^n or $\boldsymbol{X}$; a sequence of random variables $(X_i, X_{i+1}, ..., X_{j-1}, X_j)$ is denoted by X_i^j. For brevity, X^j is used instead of X_1^j. Entropy of a RV, differential entropy of a RV and mutual information between two RVs are indicated by $H(\cdot)$, $h(\cdot)$ and $I(\cdot;\cdot)$, respectively.

B. Definitions

Definition 1. The general discrete memoryless PC-RCIC, as shown in Fig. 1, consists of two finite discrete source input alphabets $\mathcal{X}_1$, $\mathcal{X}_2$, a finite discrete relay input alphabet $\mathcal{X}_{r_1}$, two discrete output alphabets $\mathcal{Y}_1$ and $\mathcal{Y}_2$ and a set of transition probability distributions $p(y_1, y_2|x_1, x_2, x_{r_1})$ describing the relationship between transmitted symbols $(x_1, x_2, x_{r_1}) \in \mathcal{X}_1 \times \mathcal{X}_2 \times \mathcal{X}_{r_1}$ and received symbols $(y_1, y_2) \in \mathcal{Y}_1 \times \mathcal{Y}_2$.

Definition 2. A $(2^{nR_1}, 2^{nR_2}, n)$ code for the PC-RCIC consists of the following: (1) Two message sets $\mathcal{W}_i = \{1, 2, ..., 2^{nR_i}\}$, $i = 1, 2$; (2) Two messages W_1 and W_2 which are independent random variables uniformly distributed over

$\mathcal{W}_1$ and $\mathcal{W}_2$, respectively; (3) encoder $f_1 : \mathcal{W}_1 \times \mathcal{W}_2 \to \mathcal{X}_1^n$, which maps message pair $(\omega_1, \omega_2) \in \mathcal{W}_1 \times \mathcal{W}_2$ to a codeword $x_1^n \in \mathcal{X}_1^n$, encoder $f_2 : \mathcal{W}_2 \to \mathcal{X}_2^n$ which maps message $\omega_2 \in \mathcal{W}_2$ to a codeword $x_2^n \in \mathcal{X}_2^n$ and a set of relay functions $\{\varphi_i\}_{i=1}^n$ such that $x_{r_1,i} = \varphi_i(y_{1,1}^{i-1})$, $i = 1, ..., n$; (4) Decoder $g_1 : \mathcal{Y}_1^n \to \mathcal{W}_1 \times \mathcal{W}_2$, which maps a received sequence y_1^n to a message $(\widehat{\omega}_1, \widehat{\omega}_2^{(1)}) \in \mathcal{W}_1 \times \mathcal{W}_2$, and decoder $g_2 : \mathcal{Y}_2^n \to \mathcal{W}_2$, which maps a received sequence y_2^n to a message $\widehat{\omega}_2^{(2)} \in \mathcal{W}_2$.

Definition 3. The rate pair (R_1, R_2) is said to be achievable for the PC-RCIC if there exists a sequence of $(2^{nR_1}, 2^{nR_2}, n)$ codes such that the average error probability $P_e^{(n)} = Pr(g_1(Y_1^n) \neq (W_1, W_2) \text{ or } g_2(Y_2^n) \neq W_2) \to 0$ as n goes to infinity. The capacity is defined as the closure of the set of achievable rate pairs (R_1, R_2).

III. New Upper Bound for the General PC-RCIC

In this section, we derive a new upper bound on the capacity region of the general PC-RCIC. This new upper bound will be used later when we derive the capacity region of the discrete memoryless semideterministic PC-RCIC.

Theorem 1. *Achievable rate pairs (R_1, R_2) belong to the union of rate regions given by*

$$R_1 < I(X_1; Y_1|X_2, X_{r_1}) \quad \text{(1a)}$$

$$R_2 < \min\{I(V, X_2, X_{r_1}; Y_2), I(V, X_2; Y_1|X_{r_1})\} \quad \text{(1b)}$$

$$R_1 + R_2 < \min\{I(V, X_2, X_{r_1}; Y_2), I(V, X_2; Y_1|X_{r_1})\} + I(X_1; Y_1|V, X_2, X_{r_1}), \quad \text{(1c)}$$

where the union is over all joint probability mass functions $p(v, x_1, x_2, x_{r_1}, y_1, y_2)$ which satisfies the Markov chain

$$V \to (X_1, X_2, X_{r_1}, Y_1) \to Y_2. \quad (2)$$

Proof. Consider a $(2^{nR_1}, 2^{nR_2}, n)$ code with average error probability $P_e^{(n)}$. The probability distribution on the joint ensemble space $\mathcal{W}_1 \times \mathcal{W}_2 \times \mathcal{X}_1^n \times \mathcal{X}_2^n \times \mathcal{X}_{r_1}^n \times \mathcal{Y}_1^n \times \mathcal{Y}_2^n$ is given by:

$$\begin{aligned} p(\omega_1, \omega_2, x_1^n, x_2^n, x_{r_1}^n, y_1^n, y_2^n) = \\ p(\omega_1)p(\omega_2)p(x_1^n|\omega_1, \omega_2)p(x_2^n|\omega_2) \\ \times \prod_{i=1}^n p(x_{r_1,i}|y_1^{i-1})p(y_{1,i}, y_{2,i}|x_{1,i}, x_{2,i}, x_{r_1,i}). \quad (3) \end{aligned}$$

By Fano's inequality, we have

$$H(W_1, W_2|Y_1^n) \leq n(R_1 + R_2)P_e^{(n)} + 1 \triangleq n\delta_{1,n} \quad \text{(4a)}$$

$$H(W_2|Y_2^n) \leq nR_2P_e^{(n)} + 1 \triangleq n\delta_{2,n}, \quad \text{(4b)}$$

where $\delta_{1,n}$ and $\delta_{2,n}$ tends to zero when n goes to infinity. We define the auxiliary random variable

$$V_i = (W_2, Y_1^{i-1}, Y_{2,i+1}^n) \quad (5)$$

for $i \in \{1, ..., n\}$. We first upper bounds R_2 as follows:

$$\begin{aligned} nR_2 - n\delta_{2,n} &= H(W_2) - n\delta_(2, n) \\ &\leq I(W_2; Y_2^n) = \sum_{i=1}^n I(W_2; Y_{2,i}|Y_{2,i+1}^n) \quad (6) \\ &\leq \sum_{i=1}^n H(Y_{2,i}) - H(Y_{2,i}|Y_1^{i-1}, Y_{2,i+1}^n, W_2) \quad (7) \\ &= \sum_{i=1}^n H(Y_{2,i}) - H(Y_{2,i}|Y_1^{i-1}, Y_{2,i+1}^n, W_2, X_{2,i}, X_{r_1,i}) \quad (8) \\ &= \sum_{i=1}^n I(V_i, X_{2,i}, X_{r_1,i}; Y_{2,i}), \quad (9) \end{aligned}$$

where (6) follows from the chain rule, (7) follows from the fact that conditioning does not increase the entropy, (8) follows because $X_{r_1,i}$ is a deterministic function of Y_1^{i-1}, and $X_{2,i}$ is a deterministic function of W_2, and (9) follows from the definition of V_i, given in (5).

We can similarly derive the following upper bound on R_2:

$$\begin{aligned} nR_2 - n\delta_{1,n} &= H(W_2) - n\delta_{1,n} \leq I(W_2; Y_1^n) \\ &= \sum_{i=1}^n I(W_2; Y_{1,i}|Y_1^{i-1}) \\ &= \sum_{i=1}^n I(W_2; Y_{1,i}|Y_1^{i-1}, X_{r_1,i}) \quad (10) \\ &\leq \sum_{i=1}^n I(W_2, Y_1^{i-1}, Y_{2,i+1}^n, X_{2,i}; Y_{1,i}|X_{r_1,i}) \quad (11) \\ &= \sum_{i=1}^n I(V_i, X_{2,i}; Y_{1,i}|X_{r_1,i}), \quad (12) \end{aligned}$$

where (10) is due to the fact that $X_{r1,i}$ is a deterministic function of Y_1^{i-1}, and (11) follows because conditioning does not increase the entropy.

We then bound R_1 as follows

$$\begin{aligned} nR_1 - n\delta_{1,n} &= H(W_1) - n\delta_{1,n} \leq I(W_1; Y_1^n|W_2) \quad (13) \\ &= \sum_{i=1}^n I(W_1; Y_{1,i}|W_2, Y_1^{i-1}) \quad (14) \\ &= \sum_{i=1}^n I(W_1; Y_{1,i}|W_2, Y_1^{i-1}, X_{2,i}, X_{r_1,i}) \quad (15) \\ &\leq \sum_{i=1}^n [H(Y_{1,i}|X_{2,i}, X_{r_1,i}) \\ &\quad - H(Y_{1,i}|W_1, W_2, Y_1^{i-1}, X_{1,i}, X_{2,i}, X_{r_1,i})] \quad (16) \\ &= \sum_{i=1}^n [H(Y_{1,i}|X_{2,i}, X_{r_1,i}) \\ &\quad - H(Y_{1,i}|X_{1,i}, X_{2,i}, X_{r_1,i})] \quad (17) \\ &= \sum_{i=1}^n I(X_{1,i}; Y_{1,i}|X_{2,i}, X_{r_1,i}), \quad (18) \end{aligned}$$

where (13) follows since W_1 and W_2 are independent, (14) follows from the chain rule, (15) is due to the fact that $X_{r_1,i}$ is a deterministic function of Y_1^{i-1} and $X_{2,i}$ is a deterministic function of W_2, (16) follows because conditioning does not increase the entropy, and finally (17) follows from the Markov chain $(W_1, W_2, Y_1^{i-1}) \to (X_{1,i}, X_{2,i}, X_{r_1,i}) \to Y_{1,i}$.

For the sum rate, we now obtain the following bound:

$$\begin{aligned}
&n(R_1+R_2)-n(\delta_{1,n}+\delta_{2,n})\\
&=H(W_1,W_2)-n(\delta_{1,n}+\delta_{2,n})\\
&\le I(W_2;Y_2^n)+I(W_1;Y_1^n|W_2) && (19)\\
&=\sum_{i=1}^{n}[I(W_2;Y_{2,i}|Y_{2,i+1}^n)+I(W_1;Y_{1,i}|W_2,Y_1^{i-1})] && (20)\\
&\le\sum_{i=1}^{n}[I(W_2,Y_1^{i-1};Y_{2,i}|Y_{2,i+1}^n)\\
&\quad -I(Y_1^{i-1};Y_{2,i}|W_2,Y_{2,i+1}^n)\\
&\quad +I(W_1,Y_{2,i+1}^n;Y_{1,i}|W_2,Y_1^{i-1})]\\
&=\sum_{i=1}^{n}[I(W_2,Y_1^{i-1};Y_{2,i}|Y_{2,i+1}^n)\\
&\quad -I(Y_1^{i-1};Y_{2,i}|W_2,Y_{2,i+1}^n)\\
&\quad +I(Y_{2,i+1}^n;Y_{1,i}|W_2,Y_1^{i-1})\\
&\quad +I(W_1;Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n)] && (21)\\
&=\sum_{i=1}^{n}[I(W_2,Y_1^{i-1};Y_{2,i}|Y_{2,i+1}^n)\\
&\quad +I(W_1;Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n)] && (22)\\
&\le\sum_{i=1}^{n}[I(W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i};Y_{2,i})\\
&\quad +I(W_1;Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n)] && (23)\\
&=\sum_{i=1}^{n}[I(W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i};Y_{2,i})\\
&\quad +I(W_1;Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i})] && (24)\\
&\le\sum_{i=1}^{n}[I(W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i};Y_{2,i})\\
&\quad +H(Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i})\\
&\quad -H(Y_{1,i}|W_1,W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{1,i},X_{2,i},X_{r_1,i})] && (25)\\
&=\sum_{i=1}^{n}[I(W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i};Y_{2,i})\\
&\quad +H(Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{2,i},X_{r_1,i})\\
&\quad -H(Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{1,i},X_{2,i},X_{r_1,i})] && (26)\\
&=\sum_{i=1}^{n}[I(V_i,X_{2,i},X_{r_1,i};Y_{2,i})\\
&\qquad +I(X_{1,i};Y_{1,i}|V_i,X_{2,i},X_{r_1,i})], && (27)
\end{aligned}$$

where (19) follows as W_1 and W_2 are independent, (20) follows from the chain rule, (22) follows from applying Csiszar-Koener's Lemma [10] to (21); (23) is due to the fact that conditioning does not increase the entropy, (24) follows because $X_{r_1,i}$ is a deterministic function of Y_1^{i-1}, and $X_{2,i}$ is a deterministic function of W_2 and finally (26) follows from the Markov chain $(W_1,W_2,Y_1^{i-1})\to(X_{1,i},X_{2,i},X_{r_1,i})\to Y_{1,i}$, so we can remove W_1 from (25).

Finally, we consider the bound on the sum rate R_1+R_2:

$$\begin{aligned}
&n(R_1+R_2)-n\delta_{1,n}=H(W_1,W_2)-n\delta_{1,n}\\
&\le I(W_1,W_2;Y_1^n)\\
&=\sum_{i=1}^{n}I(W_1,W_2;Y_{1,i}|Y_1^{i-1}) && (28)\\
&=\sum_{i=1}^{n}I(W_1,W_2;Y_{1,i}|Y_1^{i-1},X_{r_1,i}) && (29)\\
&\le\sum_{i=1}^{n}[H(Y_{1,i}|X_{r_1,i})\\
&\qquad -H(Y_{1,i}|W_1,W_2,Y_1^{i-1},X_{1,i},X_{2,i},X_{r_1,i})] && (30)\\
&=\sum_{i=1}^{n}[H(Y_{1,i}|X_{r_1,i})\\
&\qquad -H(Y_{1,i}|W_2,Y_1^{i-1},X_{1,i},X_{2,i},X_{r_1,i})] && (31)\\
&=\sum_{i=1}^{n}[H(Y_{1,i}|X_{r_1,i})\\
&\qquad -H(Y_{1,i}|W_2,Y_1^{i-1},Y_{2,i+1}^n,X_{1,i},X_{2,i},X_{r_1,i})] && (32)\\
&=\sum_{i=1}^{n}I(V_i,X_{1,i},X_{2,i};Y_{1,i}|X_{r_1,i}), && (33)
\end{aligned}$$

where (28) follows from the chain rule, (29) is due to $X_{r_1,i}$ is a deterministic function of Y_1^{i-1}, (30) and (32) follows because conditioning does not increase the entropy, and (31) follows from the Markov chain $(W_1,W_2,Y_1^{i-1})\to(X_{1,i},X_{2,i},X_{r_1,i})\to Y_{1,i}$.

Now, we define $V=(V_Q,Q)$, $X_{r_1}=X_{r_1,Q}$, $X_m=X_{m,Q}$ and $Y_m=Y_{m,Q}$ for $m=1,2$, where auxiliary random variable Q is independent of every other random variable and is distributed uniformly over $\{1,2,...,n\}$. Following standard steps, it is straightforward to show that applying the defined random variables to (9), (12), (18), (27) and (33) results in the single letter bounds presented in Theorem 1.

IV. Capacity Region of Semideterministic PC-CIC

In this section, we characterize the capacity region of the discrete memoryless semideterministic PC-RCIC. The discrete memoryless PC-RCIC is semideterministic if the channel output observed by destination 1 (relay) is a deterministic function of the channel inputs, i.e.,

$$Y_1=f(X_1,X_2,X_{r_1}) \tag{34}$$

where $f(\cdot)$ is a deterministic function, while the output at the destination 2 is any random function of the channel inputs. We show when the condition (34) holds, rate splitting and superposition encoding at the cognitive source and decode-and-forward strategy at the relay node make the upper bound derived in Theorem 1 achievable.

Theorem 2. *For the semideterministic PC-RCIC, the ca-*

pacity region is given by the union of rate regions

$$R_1 < H(Y_1|X_2, X_{r_1}) \tag{35a}$$
$$R_2 < \min\{I(V, X_2, X_{r_1}; Y_2), I(V, X_2; Y_1|X_{r_1})\} \tag{35b}$$
$$R_1 + R_2 < \min\{I(V, X_2, X_{r_1}; Y_2), I(V, X_2; Y_1|X_{r_1})\} + H(Y_1|V, X_2, X_{r_1}), \tag{35c}$$

where the union is over all joint p.m.fs of the form

$$p(v, x_1, x_2, x_{r_1}, y_1, y_2) = p(x_{r_1})p(x_2|x_{r_1})p(v|x_2, x_{r_1}) \times p(x_1|v, x_2, x_{r_1})p(y_1, y_2|x_1, x_2, x_{r_1}). \tag{36}$$

Proof. We first introduce the following lemma that will be useful for achievability proof.

Lemma 1. *The capacity region of the general discrete memoryless PC-RCIC contains the union of rate-pairs (R_1, R_2) satisfying*

$$R_1 < I(X_1; Y_1|U, X_2, X_{r_1}) \tag{37a}$$
$$R_2 < \min\{I(U, V, X_2, X_{r_1}; Y_2), I(U, V, X_2; Y_1|X_{r_1})\} \tag{37b}$$
$$R_1 + R_2 < \text{RHS of } (37b) + I(X_1; Y_1|U, V, X_2, X_{r_1}), \tag{37c}$$

where the union is over all joint probability mass functions of the form

$$p(u, v, x_1, x_2, x_{r_1}, y_1, y_2) = p(x_{r_1})p(u, x_2|x_{r_1})p(v|u, x_2, x_{r_1}) \times p(x_1|u, v, x_2, x_{r_1})p(y_1, y_2|x_1, x_2, x_{r_1}). \tag{38}$$

Proof. See [1, Theorem 1].

Therefore, Achievability follows by setting $U = \emptyset$ in Lemma 1. To prove the converse, first we note that by applying the condition (34) to the upper bound derived in Theorem 1, we have

$$H(Y_2|V, X_1, X_2, X_{r_1}) = H(Y_2|V, X_1, X_2, X_{r_1}, Y_1) \tag{39}$$
$$= H(Y_2|X_1, X_2, X_{r_1}, Y_1) \tag{40}$$
$$= H(Y_2|X_1, X_2, X_{r_1}), \tag{41}$$

where (39) and (41) follows from (34), (40) follows from (2). Hence, (41) implies the Markov chain $V \to (X_1, X_2, X_{r_1}) \to (Y_1, Y_2)$, i.e., by applying (34), $p(v, x_1, x_2, x_{r_1}, y_1, y_2)$ satisfies the same Markov chain for both the upper bound and the lower bound, so the converse proof follows from Theorem 1 by setting $H(Y_1|X_1, X_2, X_{r_1}) = 0$.

Remark 1. Although by setting $U = \emptyset$ the lower bound (37) has the same form as the upper bound (1), the joint p.m.f. $p(v, x_1, x_2, x_{r_1}, y_1, y_2)$ in Theorem 1 does not satisfy the same Markov chain as it does in Lemma 1. This is because the auxiliary random variable V_i in Theorem 1 is defined to include $Y_{2,i+1}^n$ which is affected by $X_{r_1,i+1}^n$; $X_{r_1,i+1}^n$ is a deterministic function of Y_1^i, so $Y_{1,i}$ can be correlated with V_i even conditioned on the current channel inputs $X_{1,i}$, $X_{2,i}$ and $X_{r,i}$. Hence, although $V^n, X_1^n, X_2^n, X_{r_1}^n, Y_1^n$ and Y_2^n satisfy

$$V_i \to (X_{1,i}, X_{2,i}, X_{r_1,i}, Y_{1,i}) \to Y_{2,i}, \tag{42}$$

they do not satisfy

$$V_i \to (X_{1,i}, X_{2,i}, X_{r_1,i}) \to (Y_{1,i}, Y_{2,i}), \tag{43}$$

in general. Thus, the upper bound established in Theorem 1 does not coincide with the lower bound presented in Lemma 1 for the general PC-RCIC.

V. Conclusions

We derived a new upper bound on the capacity region of the discrete memoryless partially cooperative relay cognitive interference channel (PC-RCIC). We showed that our new upper bound is the capacity region of the semideterministic discrete memoryless PC-RCIC, where the channel output observed by the relay is a deterministic function of the channel inputs.

References

[1] N. Devroye, P. Mitran, and V. Tarokh, “Achievable rates in cognitive channels,” IEEE Trans. Info. Theory, vol. 52, no. 5, pp. 1813-1827, May 2006.

[2] Y. Liang, A. Somekh-Baruch, H. Vincent Poor, S. Shamai (Shitz), and S. Verd, “Capacity of cognitive interference channels with and without secrecy,” IEEE Trans. Info. Theory, vol. 55, no. 2, pp. 604-619, Feb. 2009.

[3] M. Kazemi, M. R. Aref, and M. A. Attari, “Cooperative Relay Cognitive Interference Channel,” In Proc. IEEE Inter. Conf. on Information Theory and Information Security, pages 1064-1069, Sep. 2010.

[4] M. Kazemi, M. Mirmohseni, and M. R. Aref, “Cooperative Relay Cognitive Interference Channels with Causal Channel State Information,” In Proc. of IEEE Inter. Conf. on Information Theory and Information Security, pages 1070-1075, Sep. 2010.

[5] E. C. van der Meulen, “Three-terminal communication channels,” Advances in Applied Probability, vol. 3, pp. 120-154, 1971.

[6] T. M. Cover and A. A. E. Gamal, “Capacity theorems for the relay channel,” IEEE Trans. Info. Theory, vol. 25, no. 5, pp. 572-584, Sep. 1979.

[7] A. A. El Gamal and M. Aref, “The capacity of the semideterministic relay channel,” IEEE Trans. Info. Theory, vol. 28, no. 3, pp.536 1982.

[8] T. S. Han and K. Kobayashi, “A new achievable rate region for the interference channel,” IEEE Trans. Info. Theory, vol. 27, no. 1, pp. 4960, Jan. 1981.

[9] A. El Gamal and Y.-H. Kim, Network Information Theory. Cambridge University Press, 2011.

[10] I. Csiszar and J. Korner, “Broadcast Channels with Confidential Messages,” IEEE Trans. Info. Theory, vol. 24, no. 3, pp. 339-348, May 1978.