The Discrete Memoryless Compound Multiple Access Channel With Conferencing Encoders

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***Abstract*— A multi-access problem is considered where two encoders wish to communicate their messages to two decoders. The encoders can further cooperate via a conference, as introduced by Willems for multi-access channels. The capacity region of this channel is determined and shown to be closely related to the capacity region of the multi-access channel with partially cooperating encoders.**

I. Introduction

A problem in which encoders partially cooperate over dedicated links in a discrete memoryless multiple access channel (MAC) has been introduced and solved by Willems [1]. We consider a network in which two separate encoders wish to communicate with two different decoders. We assume that there exist two communication links with known capacities between the two encoders, allowing them to partially cooperate to send their intended messages. The amount of information exchanged between the transmitters is bounded by the capacities C_{12} and C_{21} of the communication links. The communications system is shown in Figure 1. The proposed channel model enables investigation of the gains obtained using transmitter cooperation.

Without communication links C_{12}, C_{21}, the channel in Figure 1 reduces to the interference channel [2], [3], for which the capacity region is known in the case of *strong interference* [4] satisfying

$$I(X_1;Y_1|X_2) \leq I(X_1;Y_2|X_2) \quad (1)$$

$$I(X_2;Y_2|X_1) \leq I(X_2;Y_1|X_1) \quad (2)$$

for all inputs X_1 and X_2. This class of channels includes the *very strong interference channel* [5], [6] for which

$$I(X_1;Y_1|X_2) \leq I(X_1;Y_2) \quad (3)$$

$$I(X_2;Y_2|X_1) \leq I(X_2;Y_1). \quad (4)$$

The capacity region for both cases coincides with the capacity region of the two-sender, two-receiver channel in which both messages are decoded at both receivers. It was shown by Ahlswede [7] that this region is an intersection of the capacity regions of two MAC channels $(\mathcal{X}_1, \mathcal{X}_2, \mathcal{Y}_1, p(y_1|x_1,x_2))$ and $(\mathcal{X}_1, \mathcal{X}_2, \mathcal{Y}_2, p(y_2|x_1,x_2))$. In this paper, we will consider such a communication situation requiring both messages to be decoded at both receivers. We refer to this channel as a *compound multiple access channel with conferencing encoders* and denote it $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_1,y_2|x_1,x_2), \mathcal{Y}_1 \times \mathcal{Y}_2)$.

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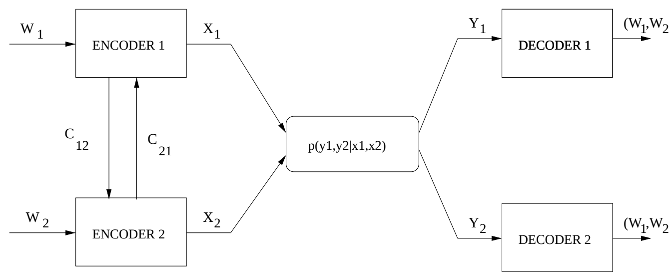

Fig. 1. Compound MAC with conferencing encoders.

For a two-sender, two-receiver Gaussian network, the rate improvements due to node cooperation were demonstrated in [8]–[12]. In [8], transmitters fully cooperate by exchanging their intended messages and then jointly encode them using dirty paper coding. More involved cooperation schemes were analyzed in [9]–[11]. In this paper, we find the capacity region of the compound MAC with conferencing encoders. For an input distribution with a specific Markov property, the rate region is an intersection of two rate regions of the MAC with partially cooperating encoders [1]. The capacity region is the union of all such rate regions. For $C_{12} = C_{21} = 0$, it becomes the capacity region of the two-sender, two-receiver channel with non-cooperating encoders [7].

II. Channel model and statement of result

The channel consists of finite sets $\mathcal{X}_1, \mathcal{X}_2, \mathcal{Y}_1, \mathcal{Y}_2$ and a conditional probability distribution $p(y_1,y_2|x_1,x_2)$. Symbols $(x_1,x_2) \in \mathcal{X}_1 \times \mathcal{X}_2$ are channel inputs and $(y_1,y_2) \in \mathcal{Y}_1 \times \mathcal{Y}_2$ are corresponding channel outputs. Each encoder t, $t = 1,2$, wishes to send a message $W_t \in \{1,\ldots,M_t\}$ to both decoders in N channel uses. The channel is memoryless and time-invariant in the sense that

$$p(y_{1,n}, y_{2,n}|\mathbf{x}_1^n, \mathbf{x}_2^n, \mathbf{y}_1^{n-1}, \mathbf{y}_2^{n-1}) = p(y_{1,n}, y_{2,n}|x_{1,n}, x_{2,n}) \quad (5)$$

where $\mathbf{x}_t^n = \begin{bmatrix} x_{t,1}, & \ldots, & x_{t,n} \end{bmatrix}$. To simplify notation, we drop the superscript when $n = N$.

Encoders use the communication links in the form of a *conference* [1]. A conference is given by two sets of K

communicating functions $\{h_{t,1}, \quad \ldots, \quad h_{t,K}\}$, $t = 1, 2$. Each function $h_{t,k}$ maps the message W_t and the sequence of previously received communications from the other encoder into the kth communication $V_{t,k}$, where $V_{t,k}$ ranges over a finite alphabet $\mathcal{V}_{t,k}$, for $k = 1, \ldots, K$,

$$h_{1,k} : \mathcal{W}_1 \times \mathcal{V}_2^{k-1} \to \mathcal{V}_{1,k}, \quad v_{1,k} = h_{1,k}(W_1, V_2^{k-1}) \quad (6)$$

$$h_{2,k} : \mathcal{W}_2 \times \mathcal{V}_1^{k-1} \to \mathcal{V}_{2,k}, \quad v_{2,k} = h_{2,k}(W_2, V_1^{k-1}). \quad (7)$$

The amount of information that can be exchanged during the conference is bounded by the capacities C_{12} and C_{21}. A conference is (C_{12}, C_{21})-permissible if

$$\sum_{k=1}^{K} \log(|\mathcal{V}_{1,k}|) \leq NC_{12} \quad (8)$$

$$\sum_{k=1}^{K} \log(|\mathcal{V}_{2,k}|) \leq NC_{21}. \quad (9)$$

An encoding function f_t maps the message W_t and what was learned from the conference into a codeword $\mathbf{x}_t$. An (M_1, M_2, N, K, P_e) code for the channel consists of two sets of K communicating functions (6)-(7), two encoding functions

$$f_1 : \mathcal{W}_1 \times \mathcal{V}_2^K \to \mathcal{X}_1^N \quad (10)$$

$$f_2 : \mathcal{W}_2 \times \mathcal{V}_1^K \to \mathcal{X}_2^N \quad (11)$$

generating codewords

$$\mathbf{x}_1 = f_1(w_1, v_2^K) \quad (12)$$

$$\mathbf{x}_2 = f_2(w_2, v_1^K) \quad (13)$$

and two decoding functions

$$g_1 : \mathcal{Y}_1^N \to \mathcal{W}_1 \times \mathcal{W}_2 \quad (14)$$

$$g_2 : \mathcal{Y}_2^N \to \mathcal{W}_1 \times \mathcal{W}_2 \quad (15)$$

such that the average probability of error of the code is

$$P_e = \sum_{(w_1,w_2)\in\mathcal{W}_1\times\mathcal{W}_2} \frac{1}{M_1 M_2} P\left[\left\{g_1(Y_1^N) \neq (w_1, w_2)\right\} \cup \left\{g_2(Y_2^N) \neq (w_1, w_2)\right\} |(w_1, w_2) \text{ sent}\right]. \quad (16)$$

A rate pair (R_1, R_2) is achievable if, for any $\epsilon > 0$, there exists an (M_1, M_2, N, K, P_e) code such that

$$M_t \geq 2^{NR_t} \quad t = 1, 2, \text{ and } P_e \leq \epsilon. \quad (17)$$

The capacity region of the *compound multiple access channel with conferencing encoders* is the closure of the set of all achievable rate pairs (R_1, R_2).

The next theorem is the main result of this paper. It shows that the capacity region of the compound multiple access channel with conferencing encoders is an intersection of two capacity regions of the MAC with partially cooperating encoders, as determined by Willems [1].

Theorem 1: For the compound multiple access channel $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_1, y_2|x_1, x_2), \mathcal{Y}_1 \times \mathcal{Y}_2)$ with communication links with capacities C_{12} and C_{21} the capacity region $\mathcal{R}(C_{12}, C_{21})$ is given by

$$\begin{aligned}\mathcal{R}(C_{12}, C_{21}) = \bigcup \{(R_1, R_2) :&\\ R_1 &\leq \min\{I(X_1; Y_1|X_2, U), I(X_1; Y_2|X_2, U)\} + C_{12}\\ R_2 &\leq \min\{I(X_2; Y_1|X_1, U), I(X_2; Y_2|X_1, U)\} + C_{21}\\ R_1 + R_2 &\leq \min\{I(X_1, X_2; Y_1|U), I(X_1, X_2; Y_2|U)\}\\ &\quad + C_{12} + C_{21}\\ R_1 + R_2 &\leq \min\{I(X_1, X_2; Y_1), I(X_1, X_2; Y_2)\}\end{aligned} \quad (18)$$

where the union is over all joint distributions that factor as

$$p(u)p(x_1|u)p(x_2|u)p(y_1, y_2|x_1, x_2).$$

III. Converse

The considered channel $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_1, y_2|x_1, x_2), \mathcal{Y}_1 \times \mathcal{Y}_2)$ defines two MACs:

- MAC_1 $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_1|x_1, x_2), \mathcal{Y}_1)$,
- MAC_2 $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_2|x_1, x_2), \mathcal{Y}_2)$,

where

$$p(y_1|x_1, x_2) = \sum_{y_2\in\mathcal{Y}_2} p(y_1, y_2|x_1, x_2) \quad (19)$$

and

$$p(y_2|x_1, x_2) = \sum_{y_1\in\mathcal{Y}_1} p(y_1, y_2|x_1, x_2). \quad (20)$$

An (M_1, M_2, N, K, P_{et}) code for MAC_t is given by the encoding functions (10) and (11) and a corresponding decoding function g_t given by (14) for $t = 1$ and (15) for $t = 2$. The corresponding error probabilities are

$$P_{e1} = \sum_{(w_1,w_2)} \frac{1}{M_1 M_2} P[g_1(\mathbf{Y}_1) \neq (w_1, w_2)|(w_1, w_2) \text{ sent}] \quad (21)$$

$$P_{e2} = \sum_{(w_1,w_2)} \frac{1}{M_1 M_2} P[g_2(\mathbf{Y}_2) \neq (w_1, w_2)|(w_1, w_2) \text{ sent}] \quad (22)$$

where $(w_1, w_2) \in \mathcal{W}_1 \times \mathcal{W}_2$. By comparing (21) and (22) with (16), we conclude that

$$\max\{P_{e1}, P_{e2}\} \leq P_e. \quad (23)$$

Next consider an (M_1, M_2, N, K, P_e) code for the $(\mathcal{X}_1 \times \mathcal{X}_2, p(y_1, y_2|x_1, x_2), \mathcal{Y}_1 \times \mathcal{Y}_2)$ compound MAC with conferencing encoders. From (23), the necessary condition for $P_e \to 0$ is that $P_{e1} \to 0$ and $P_{e2} \to 0$. From Willems' result [1, Sec. III], to guarantee that $P_{et} \to 0$, for $t = 1, 2$, the rates have to satisfy

$$\begin{aligned} R_1 &\leq I(X_1; Y_t|X_2, U) + C_{12} + \epsilon_{tN}\\ R_2 &\leq I(X_2; Y_t|X_1, U) + C_{21} + \epsilon_{tN}\\ R_1 + R_2 &\leq I(X_1, X_2; Y_t|U) + C_{12} + C_{21} + \epsilon_{tN}\\ R_1 + R_2 &\leq I(X_1, X_2; Y_t) + \epsilon_{tN}\end{aligned} \quad (24)$$

for a joint distribution $p(u)p(x_1|u)p(x_2|u)p(y_t|x_1, x_2)$ and

$$\epsilon_{tN} = (P_{et} \log(M_1 M_2 - 1) + h(P_{et}))/N \quad (25)$$

where $h(\cdot)$ denotes the binary entropy function. Note that $\epsilon_{1N} \to 0$ and $\epsilon_{2N} \to 0$ as $P_{e1} \to 0$ and $P_{e2} \to 0$.

Alternatively, we can obtain the same result by applying Fano's inequality to the message estimate $(\hat{W}_1, \hat{W}_2)$ at each receiver. We then use the approach of Willems [1, Section III] to obtain

$$\begin{aligned}
R_1 &\le \frac{1}{N} \sum_{n=1,N} I(X_{1n}; Y_{tn} | X_{2n}, U_n) + C_{12} + \epsilon_{tN} \\
R_2 &\le \frac{1}{N} \sum_{n=1,N} I(X_{2n}; Y_{tn} | X_{1n}, U_n) + C_{21} + \epsilon_{tN} \\
R_1 + R_2 &\le \frac{1}{N} \sum_{n=1,N} I(X_{1n}, X_{2n}; Y_{tn} | U_n) + C_{12} + C_{21} \\
&\quad + \epsilon_{tN} \\
R_1 + R_2 &\le \frac{1}{N} \sum_{n=1,N} I(X_{1n}, X_{2n}; Y_{tn}) + \epsilon_{tN}. \qquad (26)
\end{aligned}$$

We proceed as in [1] and show that the region of Theorem 1 is convex. We define a region $\mathcal{R}^8$ by upperbounding each coordinate by a term in (18)

$$\begin{aligned}
\mathcal{R}^8 \triangleq \{&(R_1, \ldots, R_8), t = 1, 2 : \\
&R_{t+2k} \le I(X_1; Y_t | X_2, U) + C_{12} & k = 0 \\
&R_{t+2k} \le I(X_2; Y_t | X_1, U) + C_{21} & k = 1 \\
&R_{t+2k} \le I(X_1, X_2; Y_t | U) + C_{12} + C_{21} & k = 2 \\
&R_{t+2k} \le I(X_1, X_2; Y_t) & k = 3\} \quad (27)
\end{aligned}$$

for $p(u)p(x_1|u)p(x_2|u)p(y_1, y_2|x_1, x_2)$. Applying the approach in [13, Appendix A] we can show that the region $\mathcal{R}^8$ is convex, and thus rates (26) belong to the region $\mathcal{R}^8$. From the definition of $\mathcal{R}^8$ and $\mathcal{R}$ in (27) and (18), it then follows that rates (R_1, R_2) belong to $\mathcal{R}(C_{12}, C_{21})$. □

IV. Achievability

In a conference, transmitters cooperate over the communication links with capacities C_{12} and C_{21} using the strategy proposed by Willems [1, Sec. IV]. Specifically, the set $\{1, \ldots, M_1\}$ is partitioned into $2^{NR_{12}}$ cells, labeled $s_1 \in \{1, \ldots, 2^{NR_{12}}\}$, each with $2^{N(R_1 - R_{12})}$ elements labeled $t_1 \in \{1, \ldots, 2^{N(R_1 - R_{12})}\}$. When w_1 belongs to cell s_1, we let $c_1(w_1) = s_1$. The same type of partitioning is done for messages W_2. Rates R_{12}, R_{21} are chosen such that $R_{12} = \min\{R_1, C_{12}\} \le C_{12}$, $R_{21} = \min\{R_2, C_{21}\} \le C_{21}$ ensuring that during the communication, the partial information

$$w'_0 = (w'_{01}, w'_{02}) = (c_1(w_1), c_2(w_2))$$

$(c_1(w_1), c_2(w_2)) \in \{1, \ldots, 2^{NR_{12}}\} \times \{1, \ldots, 2^{NR_{21}}\}$ can be exchanged between the encoders. We refer to W'_0 as a *common* message.

The part of the original message unknown to the other encoder is given by

$$\begin{aligned}
w'_1 &= t_1(w_1) \in \{1, \ldots, 2^{N(R_1 - R_{12})}\} \\
w'_2 &= t_2(w_2) \in \{1, \ldots, 2^{N(R_2 - R_{21})}\}.
\end{aligned}$$

The obtained system is shown in Figure 2. Thus, after the

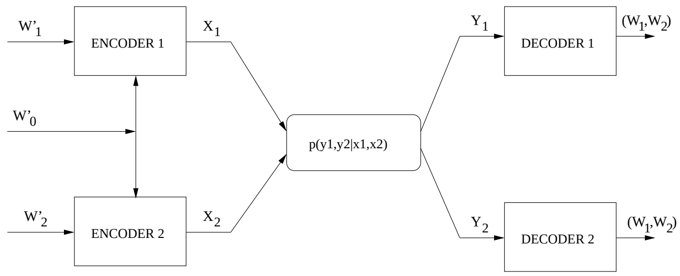

Fig. 2. Compound MAC with conferencing encoders after the conference.

conference, the coding has to be done for a common message with alphabet $\mathcal{W}'_0$

$$w'_0 \in \{1, \ldots, M'_0\} \qquad (28)$$

and private messages

$$w'_1 \in \{1, \ldots, M'_1\} \qquad (29)$$

$$w'_2 \in \{1, \ldots, M'_2\} \qquad (30)$$

with corresponding alphabets $\mathcal{W}'_1$ and $\mathcal{W}'_2$. We used notation $M'_0 = 2^{N(R_{12} + R_{21})}$, $M'_1 = 2^{N(R_1 - R_{12})}$ and $M'_2 = 2^{N(R_2 - R_{21})}$.

In the case of a single receiver, the channel after the conference reduces to a MAC with common and private messages at the encoders, as in [1]. The capacity region of this channel is known [14] and guarantees that the rates in [1, Sec. II.] are achievable. The result [14] was proved in a more direct way in [13]. It is straightforward to show that the encoding and decoding strategy proposed by Willems in [13] can be adopted for our system to guarantee the achievability of the rates (18).

Specifically, we use the codebook in [13, Section 3] constructed as follows:

Fix the distribution $p(u, x_1, x_2) = p(u)p(x_1|u)p(x_2|u)$.

1) Generate M'_0 sequences $\mathbf{u}$ each with probability $p(\mathbf{u}) = \prod_{n=1}^{N} p(u_n)$. Label them $\mathbf{u}(w'_0), w'_0 \in \{1, \ldots, M'_0\}$.
2) For each $\mathbf{u}(w'_0)$, generate M'_t sequences $\mathbf{x}_t$ with probability $P(\mathbf{x}_t|\mathbf{u}) = \prod_{n=1}^{N} p(x_{tn}|u_n)$ where $t = 1, 2$. Label them $\mathbf{x}_t(w'_0, w'_t), w'_t \in \{1, \ldots, M'_t\}$.

Encoding. To send a common message w'_0 and a private message w'_t encoder t sends the codeword $\mathbf{x}_t(w'_0, w'_t)$.

Decoding. At each decoder, we use the decoding scheme of [13]: After receiving $\mathbf{y}_t$, decoder t determines unique $(\hat{w}'_0, \hat{w}'_1, \hat{w}'_2)$ such that

$$(\mathbf{u}(\hat{w}'_0), \mathbf{x}_1(\hat{w}'_0, \hat{w}'_1), \mathbf{x}_2(\hat{w}'_0, \hat{w}'_2), \mathbf{Y}_t) \in A_\epsilon(\mathbf{U}, \mathbf{X}_1, \mathbf{X}_2, \mathbf{Y}_t)$$

where $A_\epsilon(\mathbf{U}, \mathbf{X}_1, \mathbf{X}_2, \mathbf{Y}_t)$ is the set of ϵ-typical N-sequences $(\mathbf{u}, \mathbf{x}_1, \mathbf{x}_2, \mathbf{y}_t)$ as defined in [15, Section 14.2].

The probability of error.

We apply the union bound to (16) to obtain

$$P_e \le P_{e1} + P_{e2} \qquad (31)$$

where P_{e1} and P_{e2} are given by (21) and (22). From the analysis of the probability of error in [13], it follows that both

P_{e1} and P_{e2} can made arbitrarily small when the rates satisfy (18). From (31) it then follows that the probability of error P_e can be made arbitrarily small. □

V. IMPLICATIONS

For $C_{12} = C_{21} = 0$, the capacity region (18) of the compound MAC with conferencing encoders becomes the capacity region of the two-sender, two-receiver channel established by Ahlswede [7]. Rates (18) qualify the improvement due to transmitter cooperation over the dedicated communication links with capacities C_{12} and C_{21}.

Furthermore, the rates (18) give inner bounds on the rates achievable in an interference channel in which users partially cooperate and each decoder decodes a message sent from a single encoder. It would be interesting to characterize the class of interference channels for which these rates in fact give the capacity region.

Finally, we apply (18) to a Gaussian network with channel outputs

$$y_{1i} = x_{1i} + \sqrt{h_{12}}x_{2i} + z_{1i} \tag{32}$$

$$y_{2i} = \sqrt{h_{21}}x_{1i} + x_{2i} + z_{2i} \tag{33}$$

where Z_t is zero-mean, variance N_t noise. The code definition is the same as that given in Section II with the addition of the power constraints

$$\frac{1}{N}\sum_{i=1}^{N} x_{ji}^2 \le P_j, \qquad j = 1, 2. \tag{34}$$

The power expended for the conference is thus not considered. We have the following result.

Corollary 1: The capacity region of the Gaussian compound MAC with conferencing encoders is given by

$$\mathcal{R}(C_{12}, C_{21}) = \bigcup\{(R_1, R_2) :$$

$$0 \le R_1 \le \min_{j\in\{1,2\}} C\left(\frac{h_{j1}\bar{a}P_1}{N_j}\right) + C_{12} \tag{35}$$

$$0 \le R_2 \le \min_{j\in\{1,2\}} C\left(\frac{h_{j2}\bar{b}P_2}{N_j}\right) + C_{21} \tag{36}$$

$$R_1 + R_2 \le \min_{j\in\{1,2\}} C\left(\frac{h_{j1}\bar{a}P_1 + h_{j2}\bar{b}P_2}{N_j}\right) + C_{12} + C_{21} \tag{37}$$

$$0 \le R_1 + R_2 \le \min_j C\left(\frac{h_{j1}P_1 + h_{j2}P_2 + 2\sqrt{h_{j1}aP_1h_{j2}bP_2}}{N_j}\right)\} \tag{38}$$

where the union is over all a, b, for $0 \le a \le 1, 0 \le b \le 1$, $\bar{a} = 1 - a$, $\bar{b} = 1 - b$, and $h_{11} = h_{22} = 1$,.

Figure 3 shows the capacity region for a symmetric case where $C_{12} = C_{21} = c = 0.5$, $P_1 = P_2 = P = 10$, $N_1 = N_2 = 1$, $h_{12} = h_{21} = h = 0.8$. Due to the symmetry, we choose $a = b$. To illustrate the cooperation benefit, also shown are the rates achievable when there is no cooperation ($c = 0$).

The bounds (35)-(37) are maximized for $a = 0$. As a increases, these bounds decrease, but the bound on the sum rate (38) increases. The sum rate is maximized when a is chosen such that (37) and (38) are the same. The capacity region is the union of all the pentagons obtained for different values of a.

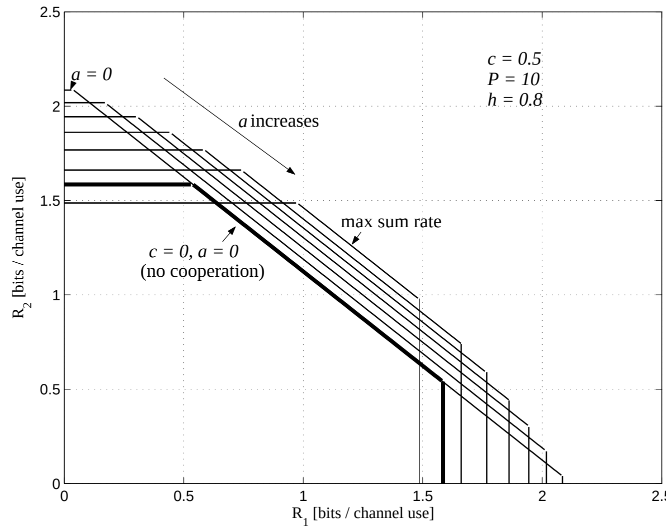

Fig. 3. The Gaussian Compound MAC with conferencing encoders capacity region.

REFERENCES

[1] F. M. J. Willems, "The discrete memoryless multiple channel with partially cooperating encoders," *IEEE Trans. on Inf. Theory*, vol. 29, no. 3, pp. 441–445, May 1983.

[2] H. Sato, "Two user communication channels," *IEEE Trans. on Inf. Theory*, vol. 23, no. 3, p. 295, May 1977.

[3] A. B. Carleial, "Interference channels," *IEEE Trans. on Inf. Theory*, vol. 24, no. 1, p. 60, Jan. 1978.

[4] M. H. M. Costa and A. A. E. Gamal, "The capacity region of the discrete memoryless interference channel with strong interference," *IEEE Trans. on Inf. Theory*, vol. 33, no. 5, pp. 710–711, Sept. 1987.

[5] H. Sato, "On the capacity region of a discrete two-user channel for strong interference," *IEEE Trans. on Inf. Theory*, vol. 24, no. 3, pp. 377–379, May 1978.

[6] H. Sato and M. Tanabe, "A discrete two-user channel with strong interference," in *Trans. Inst. Electron. Commun. Eng., Japan*, vol. 61, Nov. 1978, pp. 880–884.

[7] R. Ahlswede, "The capacity region of a channel with two senders and two receivers," *Annals of Probability*, vol. 2, no. 5, pp. 805–814, 1974.

[8] N. Jindal, U. Mitra, and A. Goldsmith, "Capacity of ad-hoc networks with node cooperation," in *IEEE Int. Symp. Inf. Theory*, 2004, p. 271.

[9] A. Høst-Madsen, "A new achievable rate for cooperative diversity based on generalized writing on dirty paper," in *IEEE Int. Symp. Inf. Theory*, June 2003, p. 317.

[10] ——, "On the achievable rate for receiver cooperation in ad-hoc networks," in *IEEE Int. Symp. Inf. Theory*, June 2004, p. 272.

[11] ——, "On the capacity of cooperative diversity," *IEEE Trans. on Inf. Theory, submitted.*

[12] C. Ng and A. Goldsmith, "Transmitter cooperation in ad-hoc wireless networks: Does dirty-paper coding beat relaying?" in *IEEE Inf. Theory Workshop*, Oct. 2004.

[13] F. M. J. Willems, "Informationtheoretical results for the discrete memoryless multiple access channel," *Ph.D. dissertation, Katholieke Universiteit Leuven, Belgium*, Oct. 1982.

[14] D. Slepian and J. K. Wolf, "A coding theorem for multiple access channels with correlated sources," *Bell Syst. Tech. J.*, vol. 52, pp. 1037–1076, 1973.

[15] T. Cover and J. Thomas, *Elements of Information Theory*. John Wiley Sons, Inc., 1991.