On the Capacity of a General Multiple-Access Channel and of a Cognitive Network in the Very Strong Interference Regime

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Abstract—The capacity of the multiple-access channel with any distribution of messages among the transmitting nodes was determined by Han in 1979 and the expression of the capacity region contains a number of rate bounds and that grows exponentially with the number of messages. We derive a more compact expression for the capacity region of this channel in which the number of rate bounds depends on the distribution of the messages at the encoders. Using this expression we prove capacity for a class of general cognitive network that we denote as “very strong interference” regime. In this regime there is no rate loss in having all the receivers decode all the messages and the capacity region reduces to the capacity of the compound multiple-access channel. This result generalizes the “very strong interference” capacity results for the interference channel, the cognitive interference channel, the interference channel with a cognitive relay and many others.

Index Terms—multiple access channel, cognitive network, strong interference, superposition coding, cut-set bound.

I. INTRODUCTION

The multiple access channel is a well studied channel model where multiple transmitters communicate with a single receiver. The capacity region of the two-users multiple-access channel was characterize in 1971 by Ahlswede and Liao. Slepian and Wolf studied a more general two-users channel where the transmitters, in addition to their own message, also cooperate in communicating a common message. Han generalized all the previously known results and derived the capacity region of a general multiple-access channel with any distribution of the messages at the encoders. The expression of the capacity region contains an auxiliary random variables for each of the messages to be transmitted and a number of rate bounds that grows exponentially with the number of messages. Despite of this result, it is known that, in certain special cases, it is possible to describe the capacity region with less rate bounds and fewer random variables. Two such examples are the multiple-access channel with independent messages and the degraded multiple-access channel. Gündüz and Simeone derived a compact expression for the capacity region of a multiple-access channel with a specific distribution of the messages among the transmitters that encompasses the examples above. The authors also describe an algorithmic procedure to convert a general multiple access channel in a multiple-access channel with the specific message distribution they consider, but provide no closed form expression for the general case.

One can sometimes exploit the available capacity results for the general multiple-access channel to derive the capacity for a subclass of general channels in what is generally referred to as the “very strong interference” regime. This regime is characterized by the fact that the level of the interference at each decoder is so high to allow for the decoding of all the interfering signals and the complete cancelation of the interference. As a result, the capacity region of the channel reduces to the intersection of the multiple-access channels between the transmitters and each receiver. The first “very strong interference” result was derived for the two user interference channel Carleial and Sato. Inspired by this result, similar “very strong interference” capacity results was proved for the two user cognitive interference channel, the interference channel with a cognitive relay and others. An interesting “very strong interference” result is provided by Sridharan et al. for the Gaussian symmetric K-user interference channel by employing lattice codes: here the receivers do not decode each interfering signal separately, but instead decode their total sum. We note that this result heavily relies on the structure Gaussian channel and does not extend to a general channel model.

Contributions and Paper Organization:

Sec. I—We introduce a general cognitive network and the notation used throughout the paper.

Sec. II—We provide inner and outer bounds for the general cognitive network. The outer bounds is reminiscent of the cut-set outer bound and the inner bound is based on rate splitting and superposition coding.

Sec. III—We provide a compact characterization of the capacity for a general multiple-access channel which requires less rate bounds than and is valid for a general distribution of messages, unlike [6].

Sec. IV—We show capacity for a general cognitive network in “very strong interference” regime in which capacity is achieved using superposition coding and having all the decoders decode all the messages.

Sec. V—We provide an example of our results by deriving capacity in the “very strong interference” regime for the interference channel where each transmitter is sending a private and a common message.
II. NETWORK MODEL

We consider the general cognitive multiple-terminal network in [12] where $N_{TX}$ transmitting nodes want to communicate with $N_{RX}$ receiving nodes. A given node may only be a transmitting or a receiving node, that is, the network is single-hop and without feedback or cooperation. The transmitting node $k, k \in [1 : N_{TX}]$, inputs $X_k$ to the channel, while the receiving node $z, z \in [1 : N_{RX}]$, has access to the channel output $Y_z$. The channel transition probability is indicated with $P_{Y_z | X_k} | X_k : X_{NTX}$ and the channel is assumed to be memoryless. The subset of transmitting nodes $i, i \in \mathcal{P}_{N_{TX}}$, is interested in sending the message $W_{i-j}$ to the subset of receiving nodes $j \in \mathcal{P}_{N_{RX}}$ over $N$ channel uses. The message $W_{i-j}, (i,j) \in \mathcal{P}_{N_{TX}} \times \mathcal{P}_{N_{RX}}$, uniformly distributed Random Variable (RV) in the interval $[0 : 2^N R_{i-j} - 1]$, where $N$ is the block-length and $R_{i-j}$ the transmission rate.

A rate vector $\mathbf{R} = \{ R_{i-j}, \forall (i,j) \in \mathcal{P}_{N_{TX}} \times \mathcal{P}_{N_{RX}} \}$ is said to be achievable if there exists a sequence of encoding functions

$$X_k^N = X_k^N, \{(W_{i-j}, \text{ s.t. } R_{i-j} \in \mathbf{R}, k \in i)\},$$

and a sequence of decoding functions

$$\hat{W}_{i-j} = \hat{W}_{i-j}(Y_z^N) \text{ if } z \in j,$$

such that

$$\lim_{N \to \infty} \max_{i,j,z} \mathbb{P} [ \hat{W}_{i-j} \neq W_{i-j} ] = 0.$$ 

The capacity region $\mathcal{C}(\mathbf{R})$ is the convex closure of the region of all achievable rates in the vector $\mathbf{R}$-pairs.

The general network model we consider is a variation to the network model in [13, Ch. 14] but we allow for messages to be distributed to more than one user while disregarding feedback. The transmitting or a receiving node, that is, the network is single-hop and without feedback or cooperation. The transmitting node $k, k \in [1 : N_{TX}]$, inputs $X_k$ to the channel, while the receiving node $z, z \in [1 : N_{RX}]$, has access to the channel output $Y_z$. The channel transition probability is indicated with $P_{Y_z | X_k} | X_k : X_{NTX}$ and the channel is assumed to be memoryless. The subset of transmitting nodes $i, i \in \mathcal{P}_{N_{TX}}$, is interested in sending the message $W_{i-j}$ to the subset of receiving nodes $j \in \mathcal{P}_{N_{RX}}$ over $N$ channel uses. The message $W_{i-j}, (i,j) \in \mathcal{P}_{N_{TX}} \times \mathcal{P}_{N_{RX}}$, uniformly distributed Random Variable (RV) in the interval $[0 : 2^N R_{i-j} - 1]$, where $N$ is the block-length and $R_{i-j}$ the transmission rate.

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III. INNER AND OUTER BOUNDS FOR A GENERAL COGNITIVE NETWORK

We begin by stating outer bounds for the general cognitive network model in Sec. II that was originally devised in [4, Th. 5.1]. This outer bound generalizes the outer bound in [5, Th. 3.2] to any number of users and is reminiscent of the cut-set bound in [13, Th. 14.10.1] when extended to the case where messages are distributed among the users.

**Corollary III.1. Cut-Set Bound for a General Cognitive Network** If the rate vector $\mathbf{R}$ is achievable for the general multi-terminal network in Sec. II, the following must hold

$$0 \leq \sum_{(i,j) \in S} R_{i-j} \leq \sum_{z \in \mathcal{R}_{X_{S}}} I(Y_z; \{X_k, \forall k\})$$

$$\big| \{X_k, \forall k \in \mathcal{R}_{X_{S}}\}, \{U_{i-j}, (i,j) \in S^c \} \big|,$$

for every $S$ as defined in (2) and any partition $\{S^z\}$ of $S$ with

$$(i,j) \in S^z \implies z \in j,$$

and any distribution

$$P_{\{X_k, \forall k\}, \{U_{i-j}, (i,j)\}} = \prod_{(i,j)} P_{U_{i-j}} \prod_k P_{X_k | \{U_{i-j}, k \in i\}}.$$ 

*Proof: See [4] for a complete proof. In essence Fano’s inequality is applied to any set of messages $W_{i-j}, (i,j) \in S$ as

$$\sum_{(i,j) \in S} R_{i-j} \leq \sum_{z \in \mathcal{R}_{X_{S}}} I(Y_z; \{W_{i-j} \in S^z\})$$

$$\leq \sum_{z \in \mathcal{R}_{X_{S}}} I(Y_z; \{W_{i-j} \in S^z\} | \{W_{i-j} \in S^c\}),$$

where $S^z$ determines which $W_{i-j}$ are decoded at receiver $z$ (note that the complement of $S$ is taken with respect to all the messages in the network). The single letterization follows
from the memoryless property of the channel and the bound in \([5]\) is obtained defining the auxiliary RV \(Y_1 = W_i - W_j\).

We now derive a general achievable region obtained with the chain graph representation of an achievable scheme in \([12]\).

**Corollary III.2. An Achievable Region Based on Superposition Coding and Rate Splitting** A rate vector \(R\) is achievable in the general network in Sec. \([7]\) if there exists a rate vector \(R_{all}\) such that

\[
R_{i-j} = \sum_j R_{i-j},
\]

that satisfies

\[
\sum_{(i,j) \in S'} R_{i-j} \leq I \left( Y; \{ X_k, \forall k \} \mid \{ U_{i-j} \}, (i,j) \in S' \right),
\]

for all the subsets \(S' \subset \{ (i,j) \mid (i,j) \in R_{all} \}\) such that

\[
(i,j) \in S' \implies (l,j) \in S', \quad \forall l \neq i,
\]

for all decoders \(z\) and for any distribution

\[
P(X_k, \forall k; \{ U_{i-j} \}, (i,j) \in R_{all}) = \prod_{(i,j)} P(U_{i-j} \mid (i,j) \in R_{all}) \cdot \prod_k P(X_k \mid (U_{i-j} \mid k \in i)).
\]

**Proof:** The theorem is a special case of the general achievable region in \([12]\). All the messages \(W_{i-j}\) are decoded at all receivers. The messages transmitted by the same set of encoders \(i\) are encoded in the codeword \(U_{i-j}^{\prime} \mid j \neq all\) with rate \(R_{i-j}\), where subscript \(j\) indicates that the codeword is decoded by all receivers. Equation \([9]\) describe the rate splitting strategy where all the messages are decoded at all the receiver. For this reason, the messages known at the same set of encoders \(i\) can be encoded in the same codeword \(U_{i-j}^{\prime} \mid j \neq all\) with rate \(R_{i-j}\). The two codewords \(U_{i-j}^{\prime} \mid j \neq all\) are then superposed the one on top of the other if the bottom codeword is known at a larger set of encoders than the top codeword. Intuitively, each rate bounds corresponds with the event that the all the codewords \(U_{i-j}^{\prime} \mid j \neq all\) in \(S'\) in \([10]\) has been incorrectly decoded while the codewords in \(S'\) are correctly decoded. Not all the possible decoding errors are possible, though. When a codeword \(U_{i-j}^{\prime} \mid j \neq all\) has been incorrectly decoded, all the codewords superposed to \(U_{i-j}^{\prime} \mid j \neq all\) are incorrectly decoded as well. This condition is expressed by \([11]\).

**IV. A New Formulation of Capacity for a General Multiple-Access Channel**

We begin by stating the formulation of the capacity region of a general MAC derived in \([4]\) Th. 5.1]

**Corollary IV.1. The Capacity Region of a General Multiple-Access Channel** \([4]\) Th. 5.1] The capacity of the general MAC is

\[
\sum_{(i,z) \in S} R_{i-z} \leq I \left( Y; \{ X_k, \forall k \} \mid \{ U_{i-z}, (i,z) \in S \} \right),
\]

for all the sets \(S\) in \([2]\) and taken the union over all the distributions in \([7]\).

**Theorem IV.2. Compact Formulation of the Capacity Region of the Multiple Access Channel** The capacity of the general MAC is given by \([13]\) for all the sets \(S\) such that \([11]\) for \(S = S'\) holds and taken the union over all the distributions in \([12]\) for \(U_{i-z} = U_{i-j}^{\prime} \mid j \neq all\).

**Proof:** We show capacity by matching each of the rate bounds in the inner bound expression in \([10]\) with a outer bound expression in \([5]\) and then consider the union over all the possible distributions \(P_{i-j}\) in the two regions. Since there is only decoder in the network, \(z\), one only permutation \(\{S'\}\) is possible and it is \(S' = S\). Again, given that there is only one decoder, we have that \(j\) is \(z\) and thus we can match each \(S\) in Cor. \([12]\) with the set \(S = S'\) in Cor. \([11]\) and \(U_{i-z} = U_{i-j}^{\prime} \mid j \neq all\). This shows that for each rate bound in Cor. \([11]\) there exists a matching outer bound in Cor. \([12]\). The proof concludes by noting that the distribution of the auxiliary RVs \(U_{i-j}\) in the inner bound, \([12]\) has a more general form that the distribution in the outer bound, \([7]\).

The result in Th. \([IV.2]\) is a extension of \([6]\) Th 3.2] to the general MAC channel. Note that the number of bounds in the formulation of the capacity region in Cor. \([IV.1]\) grows exponentially with the number of messages since the possible sets \(S\) are obtained from all the permutations in \([2]\). On the other hand the expression of the capacity region in Th. \([IV.2]\) grow, in general, much less since one needs to consider only the permutations of \(S\) for which \([11]\) holds.

**Remark IV.3.** It interesting to compare the region in Cor. \([IV.1]\) with the region in Th. \([IV.2]\) in the of region Cor. \([IV.1]\) the number of bounds increases exponentially with the number of messages but the auxiliary RVs \(U_{i-z}\) are independent. For the region in Th. \([IV.2]\) is more compact but the auxiliary RVs \(U_{i-z}\) are no longer independent. It appears that one can trade a simpler expression in the capacity region at the cost of using correlated RVs in the expression of this region.

**V. Capacity for a General Cognitive Network**

In this section we utilize the expression of capacity of the general MAC channel in Th. \([V.2]\) to derive the capacity of the general network in the “very strong interference” regime, where there is no loss of optimality in having all the receivers decodes all messages. In this class of channels the inner expression in Cor. \([V.2]\) and outer bound expression of Cor. \([III.1]\) can both be simplified and shown to be equivalent.

We begin by deriving the conditions under which the outer bound expression can be simplified by replacing the bounds in \([5]\). The outer bound obtained in this case is sometimes referred to as “strong interference” outer bound.
Corollary V.1. Strong Interference Outer Bound
Consider a set $S$ in Cor. III.2 and a partition \( \{ S^z \} \), if
\[
\sum_{z \in \mathbb{R}^S} I(Y_z; \{ X_k, \forall k \} | \{ U_{i-j}, (i,j) \in S^z \}) \\
\leq I(Y_z; \{ X_k, \forall k \} | \{ U_{i-j}, (i,j) \in S \}) ,
\]  
for all the distributions of \( \{ X_k, \forall k \} \) and \( \{ U_{i-j}, (i,j) \in S \} \) in (7) and for some \( z' \), then the bound in (5) for \( S, \{ S^z \} \) and \( z \) can be eliminated from the outer bound while the following bound is introduced
\[
\sum_{(i,j) \in S} R_{i-j} \geq I(Y_z; \{ X_k, \forall k \} | \{ U_{i-j}, (i,j) \in S \}) .
\]

Proof: The complete proof can found in [14].

Corollary V.2. Simplified Inner Bound Consider a set \( S' \) in Cor. III.2 if
\[
I(Y_z; \{ X_k, \forall k \} | \{ U'_{i-j}, (i,j) \in S' \}) \\
\geq \sum_{(S', Z_y)} I(Y_z; \{ X_k, \forall k \} | \{ U'_{i-j}, (i,j) \in S' \}) ,
\]
for some set \( \{ S' \} \supset S' \) such that (11) hold for every \( S' \) and for all the distributions of \( \{ U_{i-j}, (i,j) \in \mathbb{R} \} \) in (12) and for some set of output \( \{ Z_y \} \), then the bound in (10) for \( S' \) and \( z \) can be eliminated from the achievable region.

Proof: The complete proof can found in [14]: the theorem states the conditions under which a rate bound in the inner bound in Th. V.2 can be eliminated because it is larger than a linear combination of other rate bounds in the achievable region. The each set \( S' \) corresponds to a rate bound in (10) for a channel output \( Z_y \). The collection of sets \( \{ S' \} \) corresponds then to the summation of different bounds that is larger than rate bound in (10) for \( S' \) and \( Z_y \).

By combining the results in Cor. V.1 and Cor. V.2 we can finally prove capacity for a general cognitive network in the “very strong interference” regime.

Theorem V.3. Very Strong Interference Capacity Results
Consider the achievable region in Cor. III.2 with the assignment
\[
U'_{i-j} = \{ U_{i-j}, (i,j) \in \mathbb{R} \} ,
\]
so that the set \( S' \) in Cor. III.2 coincides with the set \( S \) for
\[
S = \{ (i,j), i \in S', j \in \mathbb{R} \} ,
\]
and the rate vector \( \mathbb{R} \) is obtained from the rate vector \( R_{all} \) with (9). This region is capacity if, for each \( S \) in (19) and each \( z \), one of the following conditions holds

i) \( z \in \bigcap_{(i,j) \in S} j \) so that we can set \( \{ S^z \} = S \),

ii) there exists a partition \( \{ S^z \} \) and some \( z' \) for which condition (14) holds, or

iii) there exists a set \( \{ S_{all}, \tilde{Y}_z \} \) for which condition (17) holds.

Proof: The complete proof can found in [14].

Remark V.4. From Th. V.3 one concludes that capacity can be determined by imposing different conditions on \( Y_z \) and \( U_{i-j}'s \). Not all the choices will be feasible though and some choices will be unfeasible for all channels but some degenerate channel.

VI. AN EXAMPLE: THE INTERFERENCE CHANNEL WITH COMMON MESSAGES

We now apply the results of Th. V.3 to a sample channel: the Interference Channel with two common messages (IFC-2CM). The IFC-2CM is a classical interference channel where each transmitter is also sending a common message to the two decoders. A graphical representation of this channel ran be found in Fig. 2.
encoded by transmitter one and are thus encoded in the same codeword $U^N_{1(1,2)}$, since $j_{\text{all}} = \{1,2\}$, for $R'_{i(1,2)} = R_{i(1,2)} + R_{i(1,2)}$. The same reasoning can be applied to the messages of the second user. The achievable region with the rate-splitting in (13) is

$$R'_{i(1,2)} \leq I(Y_i; X_1, X_2 | U^N_{i(1,2)}),$$

$$R_{i(1,2)} + R'_{i(1,2)} \leq I(Y_i; X_1, X_2),$$

for $P_{U, U_i(1,2)}$ and $i \in \{1,2\}$. With the assignment in (13) and (13) we obtain the achievable region

$$R_{i(1,2)} + R_{i(1,2)} \leq I(Y_i; X_1, X_2 | U^N_{i(1,2)}, U_{i(1,2)}) \quad (20a)$$

$$R_{i(1,2)} + R_{i(1,2)} \leq I(Y_i; X_1, X_2 | U^N_{i(1,2)}), \quad (20b)$$

$$R_{i(1,2)} + R_{i(1,2)} + R_{i(1,2)} \leq I(Y_i; X_1), \quad (20c)$$

$$R_{i(1,2)} + R_{i(1,2)} + R_{i(1,2)} \leq I(Y_i; X_1, X_2), \quad (20d)$$

We now match the inner bound expression in (20) with the outer bound in Cor. III.1. By consider $S = S^k = \{(1,1), (1, \{2\})\}$ in Cor. III.1 we obtain the bound

$$R_{i(1,2)} + R_{i(1,2)} \leq I(Y_i; U_{i(1,2)}, U_{i(1,2)} | U_{i(1,2)}),$$

which is equivalent to the bound in (20a). The bound for (20d) is obtained from $S = S^2 = \{(2,2), (1, \{2\})\}$ in a similar manner. The bound in (20d) cannot be matched with an outer bound from Cor. III.1 since the decoders are not required to decode all the messages. From Cor. III.1 we can obtain sum rates bounds of the form

$$R_{\text{sum}} \leq I(Y; X_1, X_2 | U^N_{i(1,2)}, U_{i(1,2)}, U_{i(1,2)}), \quad (21a)$$

$$R_{\text{sum}} \leq I(Y; X_1, X_2 | U^N_{i(1,2)}, U_{i(1,2)}), \quad (21b)$$

$$R_{\text{sum}} \leq I(Y; X_1, X_2 | U^N_{i(1,2)}, U_{i(1,2)}), \quad (21c)$$

$$R_{\text{sum}} \leq I(Y; X_1, X_2 | U^N_{i(1,2)}), \quad (21d)$$

and for $R_{\text{sum}} = R_{i(1,2)} + R_{i(1,2)} + R_{i(1,2)}$ To show that the region in (20), we can impose conditions as in Cor. VII.2 and Cor. VII.1. This can be done in different ways:

- **Remove two sum rates from the inner bound** by imposing (20a) + (20b) \leq \max\{20c, 20d\},

- **Remove a sum rate from the inner bound and add a sum rate in the outer bound** by setting (20d) \geq (20c) and one of the following conditions (20d) \geq (21b), (20c) \geq (21b), (21c) \geq (21d), or (20c) \geq (21d), in which case the capacity region reduces to (20a), (20b), and (20c). One can also consider the symmetric conditions obtained by setting (20c) \geq (20d) and change the other conditions accordingly.

- **Add two sum rates in the outer bounds** by setting, for example, either (21a) \geq \max\{20e, 20d\} or (21a) \geq (20k), (21b) \geq (20d) or (21c) \geq (20c), (21d) \geq (20b) and so on.

**VII. Conclusion**

In this paper we derive the a compact representation of the capacity of a general multiple-access channel with any number of transmitters and any distribution of messages among the transmitters. From this result we derive a capacity result in a certain class of a general class of channels with any number of transmitters, receivers, and any distribution of messages. In this class of channels, that we denote as in “very strong interference”, there is no rate loss in having every encoder decode all the messages and the capacity region reduces to the intersection of the multiple-access channels from all the encoders to each decoder. To exemplify this result we derive capacity in the “very strong interference” regime for the interference channel where each decoder is sending a message to the intended receiver and also a message to both receivers.

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