On the capacity regions of broadcast channel problems with receiver side information

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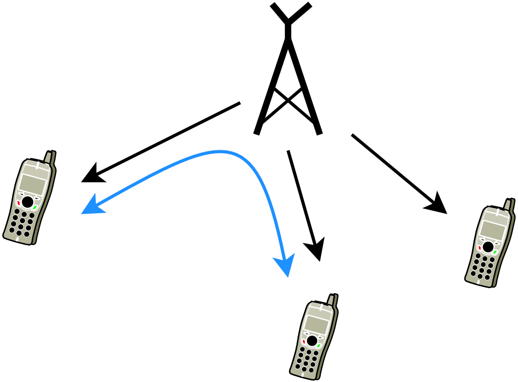
Motivation: In-cell Commnunication

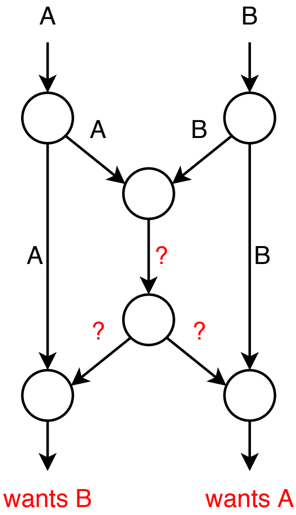


- Two nodes want to communicate within a cell.
- Provider does not allow direct communication.
  - Uplink: Messages send & decoded at basestation (MAC).
  - **Advanced downlink:** (Partial) messages cognition at receiver.

Outline

1. Introduction
   - Motivation
   - Basic Idea of Network Coding
   - Capacity Region of the Bidirectional Broadcast Channel
   - Vector-valued Gaussian case
2. Bidirectional BC with Random States
   - Achievable Region
   - Capacity Region if State is also known at one Receiver
   - Gaussian Channel
3. Three User Broadcast Channel with Message Cognition
   - Coding Strategy
   - Capacity Results for Special Cases
   - Look into a Converse for Less Noisy
4. Concluding Remarks

Basic Idea of Network Coding

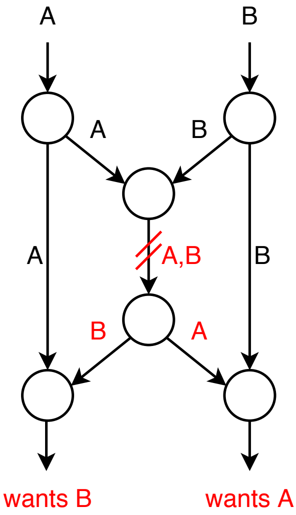


Example: **Butterfly Network**

- Problem: Bits A and B should be transfered.
- Constraint: Each P2P link has 1 bit capacity.

- Network coding: Ahlswede et al, "Network Information Flow" T-IT 00.

Basic Idea of Network Coding



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  $\Rightarrow$ **Two channel uses!**

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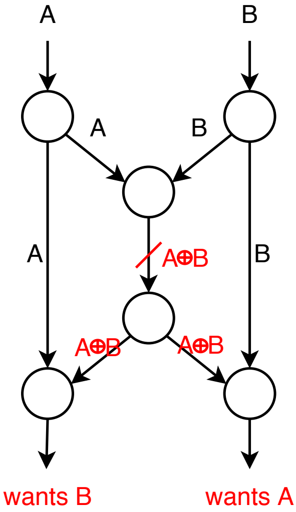
Basic Idea of Network Coding



Example: **Butterfly Network**

- Problem: Bits A and B should be transfered.
- Constraint: Each P2P link has 1 bit capacity.
- Routing: Forward A and B
  $\Rightarrow$ **Two channel uses!**
- Network coding: Forward $A \oplus B$
  $\Rightarrow$ **One channel use!**

Idea: Allow computation at nodes!

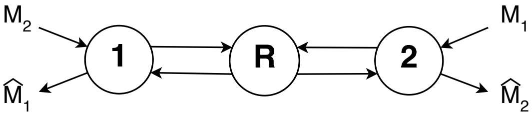
Paradigm Shift

Information flows $\neq$ incompressible fluids!

- Network coding: Ahlswede et al, "Network Information Flow" T-IT 00.

Bidirectional Relaying

- Two nodes want to exchange messages with the help of a relay.
  - For scenarios where the direct link is not good enough!
  - *Half-duplex assumption*: Nodes can either transmit or receive.

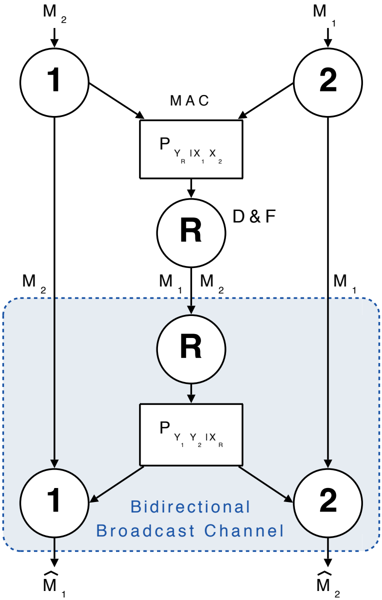


- Different **processing strategies** at relay node:
  - amplify-and-forward, decode-and-forward (here), compress-and-forward, compute-and-forward, ...
  - **optimal strategy unknown**

Bidirectional Broadcast Channel

Restricted decode & forward bidirectional relaying

1. Phase: MAC [Ahlswede '71]
2. Phase: BiBC: BC with RX message cognition



Bidirectional Broadcast Channel

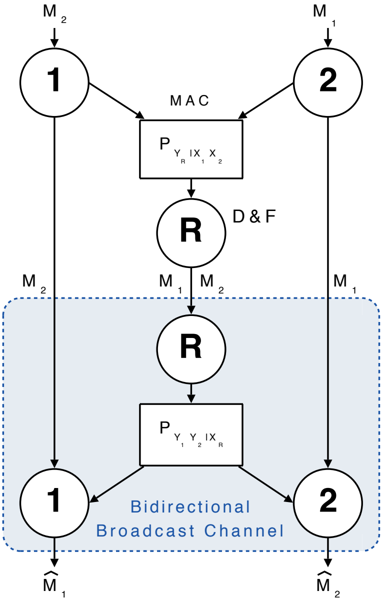
DM-BiBC capacity region [T-IT '08]

Union of all $[R_1, R_2]$ over p_{X_R}:

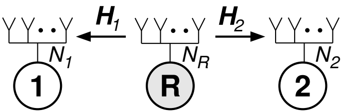
$$0 \leq R_1 \leq I(X_R; Y_1)$$
$$0 \leq R_2 \leq I(X_R; Y_2)$$

Proof ideas:

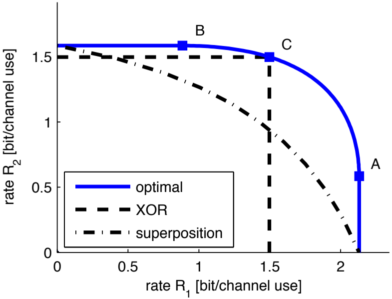
- Coding which combines information flows at relay (network coding idea).
- Converse: Take side information into account.



Gaussian Multi-Antenna Bidirectional Relaying



BC phase



Capacity Region [ISIT '08]

$$C_{\text{BC}} := \bigcup_{\operatorname{tr}\boldsymbol{Q}\le P,\ \boldsymbol{Q}\succeq 0} \left\{[R_1, R_2] \in \mathbb{R}_+^2 \ :\ R_1 \le C_1(\boldsymbol{Q}), R_2 \le C_2(\boldsymbol{Q})\right\}$$

with

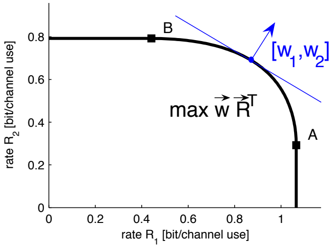
$$C_i(\boldsymbol{Q}) := \log\det\left(\boldsymbol{I}_{N_i} + \tfrac{1}{\sigma^2}\boldsymbol{H}_i^H \boldsymbol{Q} \boldsymbol{H}_i\right), \quad i = 1, 2.$$

Transmit Covariance Optimization Problem

Boundary characterized by

$$\underset{\operatorname{tr} \boldsymbol{Q} \leq P,\, \boldsymbol{Q} \succeq 0}{\arg\max} \sum_{i=1}^{2} w_i \log\det\left(\boldsymbol{I}_{N_i} + \frac{1}{\sigma^2} \boldsymbol{H}_i^H \boldsymbol{Q} \boldsymbol{H}_i\right)$$

➠ **Convex opt. problem!**



Closed form results/procedures are available:

- **MISO case** [T-SP '09]
  - Rank one optimality of transmit covariance matrix $\boldsymbol{Q}$.
- **MIMO case** [T-COM '09]
  - Generalized water-filling solution for high SNR and non-degenerate channels ($(\boldsymbol{H}_i \boldsymbol{H}_i^H)^{-1}$ exists)

Lesson learned so far

Paradigm shift

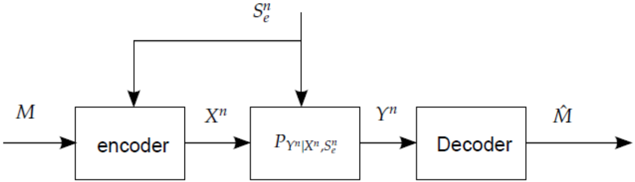
Information flow $\neq$ fluids.

- **Communication principle:** Convey as much information to the receiving nodes which allows them to conclude on the message using their side information.

$\Rightarrow$ **Bidirectional broadcast channel:**
Single information flow used by both users.

- **Trade-off:** Optimal input distribution need not be optimal for both users (vector optimization problem).

Channel Coding with States

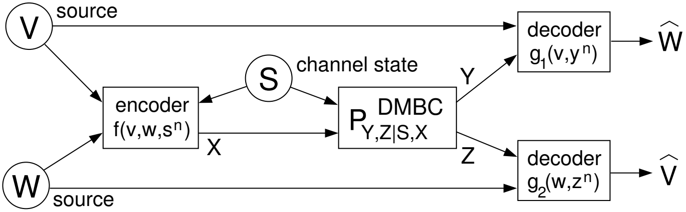


- Channel coding with states known non-causally at the encoder [Gel'fand, Pinsker '80]

$$C = \max_{P_{X|U,S}P_{U|S}} [I(U;Y) - I(U;S)] \quad (\geq \max_{P_{X|U,S}P_U} I(U;Y))$$

- Extension to broadcast channel with state [Steinberg '05] and [Steinberg, Shamai '05]
  - Capacity result for degraded case.
  - General case open - similar results as for BC

Bidirectional DMBC with Random States



Definition: DMBC with random states

$$P_{Y^nZ^n|S^nX^n}(y^n, z^n|s^n, x^n) = \prod_{i=1}^{n} P_{YZ|SX}(y_i, z_i|s_i, x_i), \quad P_S^n(s^n) = \prod_{i=1}^{n} P_S(s_i)$$

Achievable Rate Region

- Extension of Gel'fand Pinsker coding results for BC with receiver side information (bidirectional BC) [accepted T-IT]:

Achievable Rate Region

Convex hull of the set of all rate pairs $[R_1, R_2]$ such that

$$R_1 \leq [I(U;Y) - I(U;S)]_+ , \quad R_2 \leq [I(U;Z) - I(U;S)]_+$$

for some $U - (X,S) - (Y,Z)$ with $p_{X|US}$ deterministic and $|\mathcal{U}| \leq |\mathcal{S}||\mathcal{X}| + 1$ sufficient.

Trivial Outer Bound

Set of all rate pairs $[R_1, R_2]$ such that

$$R_1 \leq \max_{P_{U,X|S}} [I(U;Y) - I(U;S)] , \quad R_2 \leq \max_{P_{U,X|S}} [I(U;Z) - I(U;S)]$$

Sketch of coding scheme

- **Random codebook:** Generate $2^{n(R_1+R_2+\tilde{R})}$ iid sequences $u^n(v,w,\ell) \sim P_{\mathrm{U}}$, $1 \le v \le 2^{nR_1}$, $1 \le w \le 2^{nR_2}$, $1 \le \ell \le 2^{n\tilde{R}}$.
- **Encoding:** To send (v,w) after observing s^n look for some $\ell \ : \ (u^n(v,w,\ell), s^n) \in \mathcal{T}_\varepsilon^{(n)}(P_{\mathrm{US}})$.
  - Probability of success tends to one with n if $\tilde{R} > I(U;S)$.
- **Decoding:** Decoder g_1 knows v and searches for a unique pair $(\hat{w},\hat{\ell})$ such that $(u^n(v,\hat{w},\hat{\ell}), y^n) \in \mathcal{T}_\varepsilon^{(n)}(P_{\mathrm{UY}})$.
  - Probability of failure vanishes with n if $R_1 + \tilde{R} < I(U;Y)$.

  Likewise, decoder g_2 knows w and searches for a unique pair $(\hat{v},\hat{\ell})$ such that $(u^n(\hat{v},w,\hat{\ell}), z^n) \in \mathcal{T}_\varepsilon^{(n)}(P_{\mathrm{UZ}})$.
  - Probability of failure vanishes with n if $R_2 + \tilde{R} < I(U;Z)$.

Channel State additionally known at Decoder one

Capacity Region

Set of all rate pairs $[R_1, R_2]$ such that

$$R_1 \leq I(X;Y|S), \quad R_2 \leq I(U;Z) - I(U;S)$$

for some $U - (X,S) - (Y,Z)$ with $p_{X|US}$ deterministic.

- **Equivalent representation of region (crucial):**
  - Consider output $\tilde{Y} = (Y,S)$

$$I(\tilde{Y};U) - I(S;U) = I(Y,S;U) - I(S;U) = I(Y;U|S)$$

  - Since $p_{X|US}$ deterministic $\Rightarrow X - (U,S) - Y$, we have

$$I(U;Y|S) = I(X,U;Y|S) - \underbrace{I(X;Y|U,S)}_{=0, X-(U,S)-Y} = I(X;Y|S) + \underbrace{I(U;Y|X,S)}_{=0, U-(X,S)-Y} = I(X;Y|S)$$

- Previous gives achievability; standard arguments the converse

Scalar Complex Gaussian Channel

$$Y = X + S + N_1, \qquad Z = X + S + N_2$$

- Power constraint $\mathbb{E}\{X^2\} \le P$
- State $S \sim \mathcal{CN}(0, Q)$ and channel noise $N_i \sim \mathcal{CN}(0, \sigma_i^2)$, $i = 1, 2$.

Costa's choice of RV $\boldsymbol{U = X + \alpha S}$, $X \sim \mathcal{CN}(0, Q)$, $X \perp S$:

$$R_i(\alpha) = \log\left(\frac{P(P + Q + \sigma_i^2)}{PQ(1-\alpha)^2 + \sigma_i^2(P + \alpha^2 Q)}\right),$$

maximized at $\alpha_i^* = P/(P + \sigma_i^2)$, $i = 1, 2$.

- *Remark:* If $\sigma_1^2 \neq \sigma_2^2$ then $\alpha_1^* \neq \alpha_2^*$...

Channel State additionally known at Decoder one

Capacity region

Set of rate pairs $[R_1, R_2]$ such that

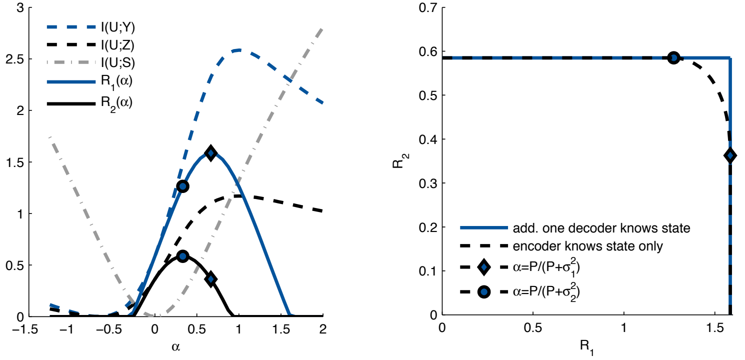
$$\begin{aligned} R_1 \leq R_1(\alpha_2^*) &= I(U; X + S + N_1 | S) \\ &= I(X + \alpha_2^* S; X + N_1 | S) \\ &= I(X; X + N_1) = \log\left(1 + P/\sigma_1^2\right), \end{aligned}$$

$$\begin{aligned} R_2 \leq R_2(\alpha_2^*) &= I(X; X + S + N_2 | S) \\ &= I(X; X + N_2) = \log\left(1 + P/\sigma_2^2\right). \end{aligned}$$

On each link the AWGN single-user capacity can be achieved.

$\Rightarrow$ Capacity region

Illustration



- If only the encoder knows channel state sequence, than each single-user capacity is achievable, but not simultaneously.
- If additionally one decoder knows the channel state sequence, both user can simultaneously achieve single-user capacity

Looking backward, looking forward

Backward:

- 2-user broadcast channel with receiver message cognition
- 2-user broadcast channel with receiver message cognition and random state

Forward:

- 3-user broadcast channel with partial message cognition and degraded message sets

Three User Extension

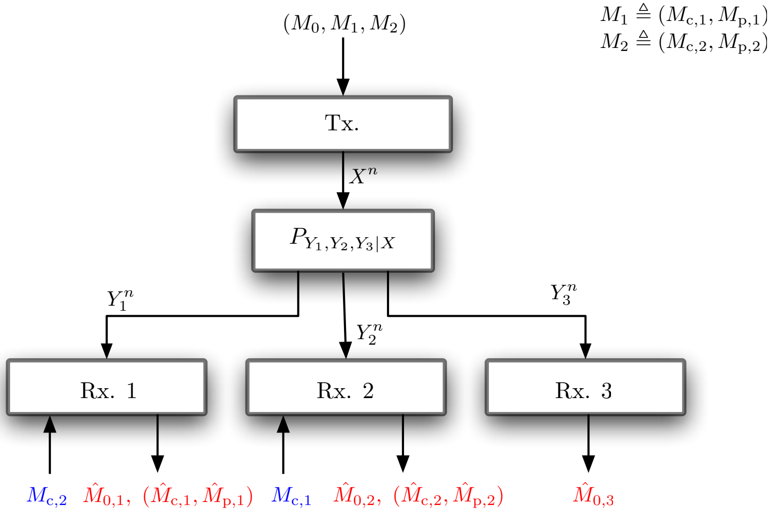
- Capacity results are found for the general 2 receiver BC with
  - full message cognition, called *bidirectional broadcast channel* [T-IT '08]
  - partial message cognition and degraded message set [Kramer, Shamai, '07]
  - degraded message sets [Körner, Marton, '77]

- Some results on the capacity for 3 receiver BC, degraded message set, no message cognition [Nair, El Gamal, '09]

Question: Can we obtain capacity results for the 3 receiver BC, degraded message set, and full/partial message cognition?

Answer: For special cases/classes only.

Problem: BC with Partial Message Cognition



- Problem includes the general 2 receiver BC!

Broadcast Channel Class: Less Noisy

Definition [Körner, Marton, '75]

- Y is **less noisy** than Z (notation: $Y \succeq Z$) if

$$I(U;Y) \geq I(U;Z) \qquad \text{for all } U - X - (Y,Z).$$

Capacity result for

- 2 receiver less noisy BC [Körner, Marton, '75]
- 3 receiver less noisy BC [Nair, Wang '11]

Key lemma [Nair, Wang, '11]

Let $X \to (Y,Z)$ be DM-BC with $Y \succeq Z$ and M any RV such that $M - X^n - (Y^n, Z^n)$, then

1. $I(Y^{i-1}; Z_i | M) \geq I(Z^{i-1}; Z_i | M), \quad 1 \leq i \leq n.$
2. $I(Y^{i-1}; Y_i | M) \geq I(Z^{i-1}; Y_i | M), \quad 1 \leq i \leq n.$

Inner Bound

- $\mathcal{R}^{(1)}_{\text{in,part}}$ denotes the set of $(R_0, R_{1,\text{c}}, R_{1,\text{p}}, R_{2,\text{c}}, R_{2,\text{p}})$ satisfying

$$\begin{aligned} R_0 &\le I(U;Y_3) \\ R_{1,\text{p}} &\le I(X;Y_1|V) \\ R_0 + R_2 &\le \min\{I(V;Y_2), I(U;Y_3) + I(V;Y_2|U)\} \\ R_0 + R_1 + R_{2,\text{p}} &\le \min\{I(X;Y_1), I(U;Y_3) + I(X;Y_1|U)\} \end{aligned}$$

  for some (U,V,X) with $U - V - X - (Y_1, Y_2, Y_3)$.
- $\mathcal{R}^{(2)}_{\text{in,part}}$: Interchange indices 1 and 2.

- $|\mathcal{U}| \le |\mathcal{X}| + 4$ and $|\mathcal{V}| \le (|\mathcal{X}| + 4)(|\mathcal{X}| + 1)$ suffices.

Theorem: Achievable Rate Region $\mathcal{R}_{\text{in,part}}$ [ISIT'12]

$$C_{\text{part}} \supseteq \mathcal{R}_{\text{in,part}} \triangleq \text{convex hull}\left(\mathcal{R}^{(1)}_{\text{in,part}} \cup \mathcal{R}^{(2)}_{\text{in,part}}\right)$$

Proof of $\mathcal{R}^{(1)}_{\text{in,part}}$: Superposition Coding

- **Rate splitting** and **construct new messages**
  - private message $M_{2,\mathsf{p}} = (M^{(1)}_{2,\mathsf{p}}, M^{(2)}_{2,\mathsf{p}})$
  - cognizant messages: $M_{1,\mathsf{c}} = (M^{(1)}_{1,\mathsf{c}}, M^{(2)}_{1,\mathsf{c}})$, $M_{2,\mathsf{c}} = (M^{(1)}_{2,\mathsf{c}}, M^{(2)}_{2,\mathsf{c}})$

$$M^{(k)}_{\oplus} = \left(M^{(k)}_{1,\mathsf{c}} + M^{(k)}_{2,\mathsf{c}}\right) \text{ modulo } 2^{n \max\{R^{(k)}_{1,\mathsf{c}}, R^{(k)}_{2,\mathsf{c}}\}}, \quad k = 1, 2$$

Rx1: Decide on $M^{(k)}_{1,\mathsf{c}}$ using knowledge of $M^{(k)}_{2,\mathsf{c}}$

Rx2: Decide on $M^{(k)}_{2,\mathsf{c}}$ using knowledge of $M^{(k)}_{1,\mathsf{c}}$

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- **3 layer superposition coding with non-unique decoding**:

layer	codeword	M_0	$M^{(1)}_{\oplus}$	$M^{(1)}_{2,\text{p}}$	$M^{(2)}_{\oplus}$	$M^{(2)}_{2,\text{p}}$	$M_{1,\text{p}}$	used by
1	u^n iid $\sim P_U$	×	×	×				nodes 1,2,3
2	v^n iid $\sim P_{V\|U}$	×	×	×	×	×		nodes 1,2
3	x^n iid $\sim P_{X\|V}$	×	×	×	×	×	×	node 1

□

Less Noisy Capacity Results

Theorem: Capacity Region [ISIT'12]

If there is a *less-noisy ordering* between Y_1, Y_2, and Y_3, then

$$\mathcal{C}_{\text{part}} = \mathcal{R}_{\text{in,part}}.$$

In particular the description of $\mathcal{R}_{\text{in,part}}$ can be simplified, e.g.

- $Y_1 \succeq Y_2 \succeq Y_3 \quad \Rightarrow \quad \begin{array}{l} I(V;Y_2) \geq I(U;Y_3) + I(V;Y_2|U) \\ I(X;Y_1) \geq I(U;Y_3) + I(X;Y_1|U) \end{array}$

  Converse is proved for the following region, which includes the simplified achievable rate region.

$$\begin{aligned} R_0 &\leq I(U;Y_3) \\ R_{1,\text{p}} &\leq I(X;Y_1|V) \\ R_2 &\leq I(V;Y_2|U) \\ R_1 + R_{2,\text{p}} &\leq I(X;Y_1|U) \end{aligned}$$

Example: Gaussian Channel

$$Y_k = X + N_k, \qquad N_k \sim \mathcal{N}(0, \sigma_k^2), \quad k = 1, 2, 3$$

Corollary: Capacity Region Gaussian Channel

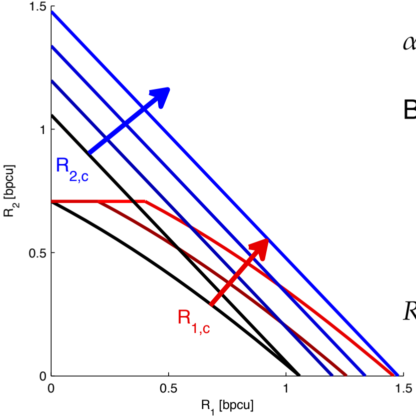
If $\sigma_3^2 \geq \sigma_2^2 \geq \sigma_1^2$, then C_{part} is given by

$$\begin{aligned}
R_0 &\leq \tfrac{1}{2}\log\left(1 + \tfrac{\alpha P}{(1-\alpha)P+\sigma_3^2}\right) \\
R_1 &\leq \tfrac{1}{2}\log\left(1 + \tfrac{(1-\alpha-\beta)P}{\sigma_1^2}\right) + R_{1,\mathrm{c}} \\
R_2 &\leq \tfrac{1}{2}\log\left(1 + \tfrac{\beta P}{(1-\alpha-\beta)P+\sigma_2^2}\right) \\
R_1 + R_2 &\leq \tfrac{1}{2}\log\left(1 + \tfrac{(1-\alpha)P}{\sigma_1^2}\right) + R_{2,\mathrm{c}} \qquad \alpha, \beta, \alpha+\beta \in [0,1]
\end{aligned}$$

Proof: Entropy power inequality & maximal entropy property.

Discussion: Gaussian Channel $\sigma_3^2 \geq \sigma_2^2 \geq \sigma_1^2$

Cognizant knowledge: $R_{2,\mathrm{c}} \rightarrow$ Rx 1, $R_{1,\mathrm{c}} \rightarrow$ Rx 2



α_0: $\quad R_0 = \frac{1}{2}\log\left(1 + \frac{\alpha_0 P}{(1-\alpha_0)P + \sigma_3^2}\right)$

Bounds on R_1 and R_2, $\beta \in [0, \alpha_0]$:

$$R_1 \leq \frac{1}{2}\log\left(1 + \frac{(1-\alpha_0-\beta)P}{\sigma_1^2}\right) + R_{1,\mathrm{c}}$$

$$R_2 \leq \frac{1}{2}\log\left(1 + \frac{\beta P}{(1-\alpha_0-\beta)P + \sigma_2^2}\right)$$

$$R_1 + R_2 \leq \frac{1}{2}\log\left(1 + \frac{(1-\alpha_0)P}{\sigma_1^2}\right) + R_{2,\mathrm{c}}$$

$\Rightarrow$ There might be no gain due to (more) message cognition!

Full Message Cognition: $M_{1,c} = M_1$ and $M_{2,c} = M_2$

- Two examples for which capacity is known. (3 more in [ISIT'12])
  - Cases which we cannot solve without full message cognition.

Theorem: Capacity Region

The capacity region for the full message cognition case if

(ii) Y_3 is *more capable* than Y_1 and Y_2:

$$R_0 + R_1 \le I(X; Y_1)$$
$$R_0 + R_2 \le I(X; Y_2)$$

(v) Y_3 is a *deterministic function* of X:

$$R_0 \le H(Y_3)$$
$$R_0 + R_1 \le I(X; Y_1)$$
$$R_0 + R_2 \le I(X; Y_2)$$

- Main task: Simplify achievable rate region. Converses are easy.

Look into a Converse for $Y_1 \succeq Y_2 \succeq Y_3$

$$n(R_1 + R_{2,\mathsf{p}}) - n\epsilon_n \overset{Fano}{\leq} \underbrace{I(M_1; Y_1^n | M_0, M_{2,\mathsf{c}})}_{\substack{=\sum_{i=1}^{n} I(M_1, Y_{2,i+1}^n; Y_{1,i} | M_0, M_{2,\mathsf{c}}, Y_1^{i-1}) \\ -I(Y_{2,i+1}^n; Y_{1,i} | M_0, M_1, M_{2,\mathsf{c}}, Y_1^{i-1})}} + \underbrace{I(M_{2,\mathsf{p}}; Y_2^n | M_0, M_1, M_{2,\mathsf{c}})}_{\substack{\leq \sum_{i=1}^{n} I(M_{2,\mathsf{p}}; Y_{2,i} | M_0, M_1, M_{2,\mathsf{c}}, Y_{2,i+1}^n, Y_1^{i-1}) \\ + I(Y_1^{i-1}; Y_{2,i} | M_0, M_1, M_{2,\mathsf{c}}, Y_{2,i+1}^n)}}$$

$$\overset{C.S.}{\leq} \sum_{i=1}^{n} I(M_1, M_{2,\mathsf{c}}, Y_{2,i+1}^n; Y_{1,i} | M_0, Y_1^{i-1}) + \underbrace{I(X_i; Y_{2,i} | M_0, M_1, M_{2,\mathsf{c}}, Y_{2,i+1}^n, Y_1^{i-1})}_{\overset{Y_1 \succeq Y_2}{\leq} I(X_i; Y_{1,i} | M_0, M_1, M_{2,\mathsf{c}}, Y_{2,i+1}^n, Y_1^{i-1})}$$

$$\leq \sum_{i=1}^{n} I(X_i; Y_{1,i} | M_0, Y_1^{i-1}) = \sum_{i=1}^{n} I(X_i; Y_{1,i} | M_0) - \underbrace{I(Y_{1,i}; Y_1^{i-1} | M_0)}_{\overset{N.W.Lemma}{\leq} I(Y_{1,i}; Y_2^{i-1} | M_0)}$$

$$\leq \sum_{i=1}^{n} I(X_i; Y_{1,i} | Y_2^{i-1}, M_0) = \sum_{i=1}^{n} I(X_i; Y_{1,i} | U_i)$$

using $(Y_{1,i}, Y_{2,i}) - X_i - (M_0, M_1, M_2, Y_1^{i-1}, Y_{2,i+1}^n)$ and $(Y_1^n, Y_2^n) - X^n - M_0$. $\square$

Concluding Remarks

- Capacity for general bidirectional BC is known, but extension to general 3 receiver BC with full receiver message cognition and degraded message sets appears to be difficult.
  - Problem: Extension of Csiszar sum lemma.
- *Observation:* (More) receiver message cognition might not enlarge capacity region.
  - RX cognition approach useful for genie aided converses?
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  - cellular communication
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Thank you for your attention! Questions?