Cognitive Radio: an information theoretic perspective

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COLLEGE OF ENGINEERING

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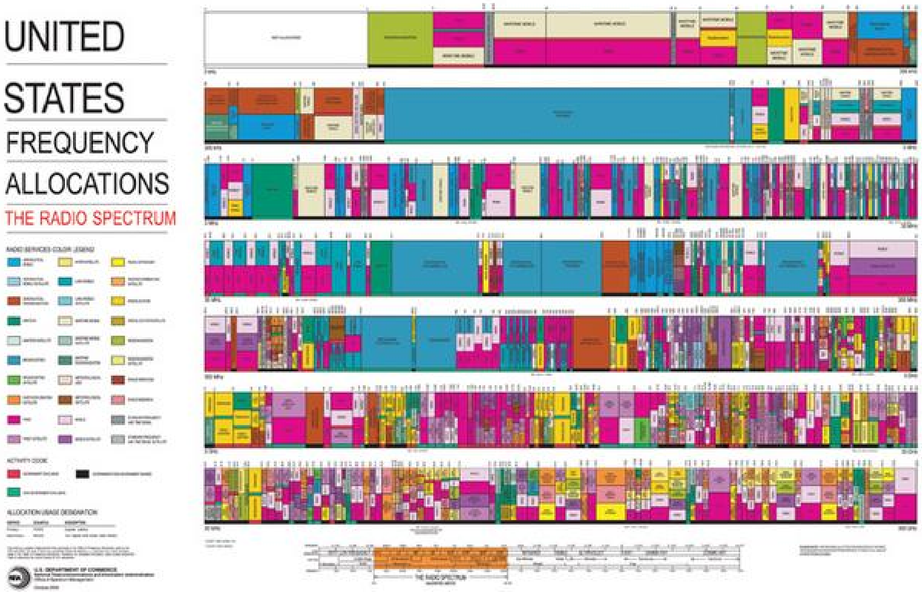
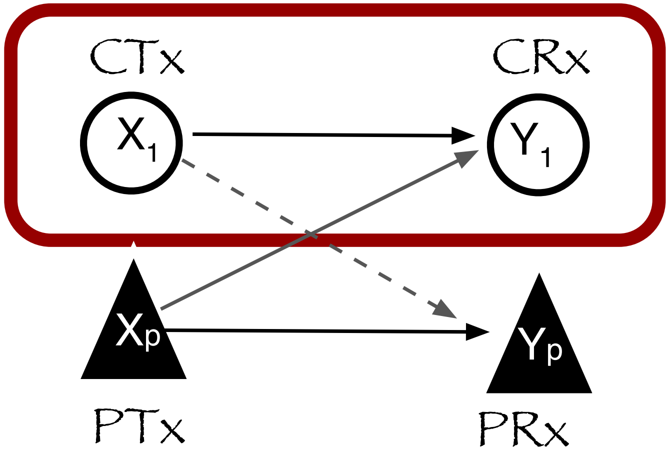
Motivations

- Coexisting devices on a radio channel interfere with one another.
- Prime frequency bands all licensed with almost no free band for new services.



Motivations

- Is it possible to coexist in overcrowded spectrum without degrading existing users/services?
- Idea: use smart devises with advanced sensing/processing capabilities.



Motivations

- Major problems: not technical but regulatory
- Currently, divide-and-set-aside:
  - spectrum divided into distinct bands;
  - regulated communication uses in each band;
  - license each band for exclusive use (ex, cellular, TV, radio, navigation, emergency, defense, etc).
- This approach has pros and cons ...

Motivations

- Some bands are shared/unlicensed to encourage innovation and reduce cost to purchase licensed spectrum (ex, 2.4GHz: Bluetooth, 802.11b/g/n WiFi, etc.).
- Killed by their own success? too much interference.

Motivations

- Cognitive radio aims to bring the advantages of unlicensed bands to licensed bands without disrupting existing services.
- But how?

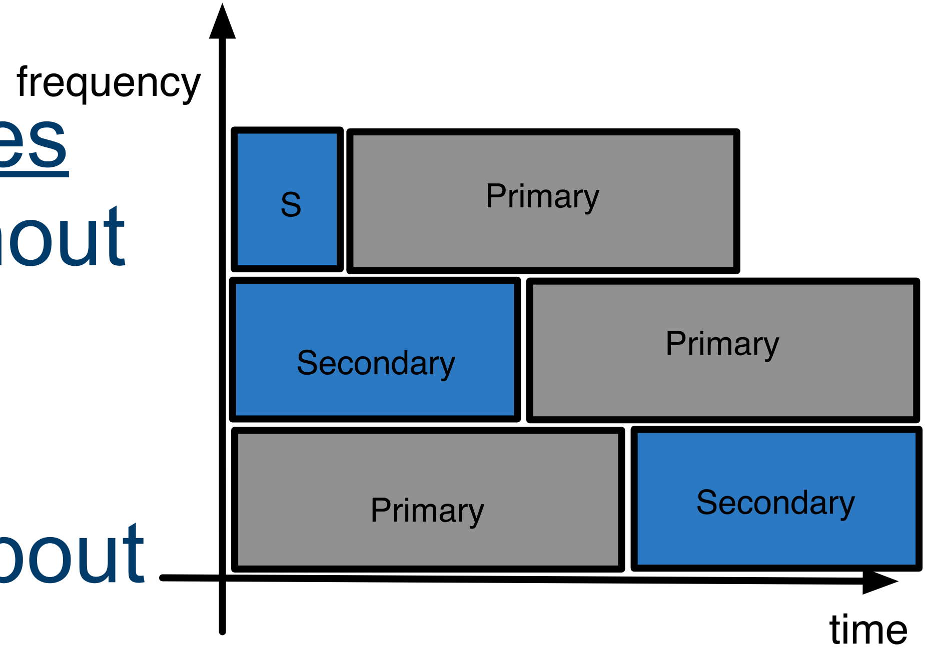
Cognitive Radio (CR)

- CR is a wireless communication system with <u>side information</u> about:
  - the channel activity,
  - channel conditions,
  - user' codebooks/messages.
- CR devices seek to **interweave, underlay** or **overlay** their signals with those of existing users without impacting their QoS.

Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective, Goldsmith et al, *Proceedings of IEEE*, 2009.

Interweave CR

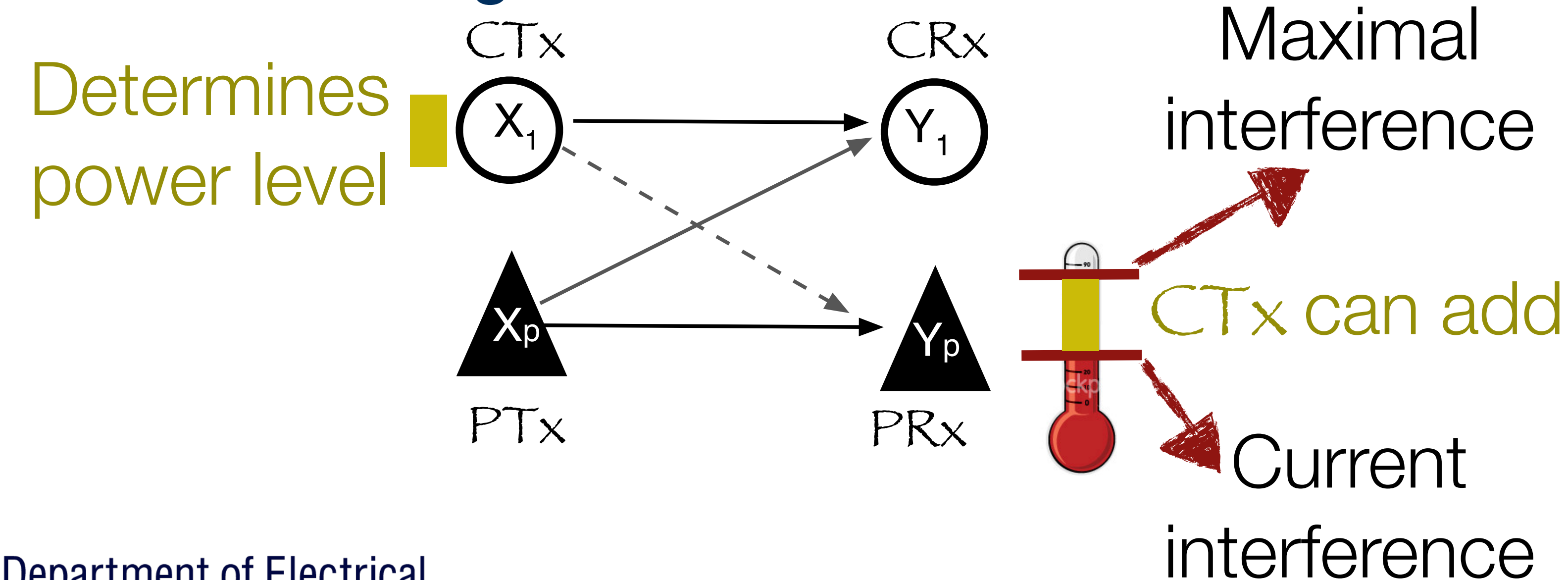
- CR opportunistically <u>exploits spectral holes</u> to communicate without disrupting primary transmissions.
- Needs knowledge about channel activity (extensively studied in CommTh and SigProc).



Joseph Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," PhD Dissertation, KTH, Sweden, December 2000

Underlay CR

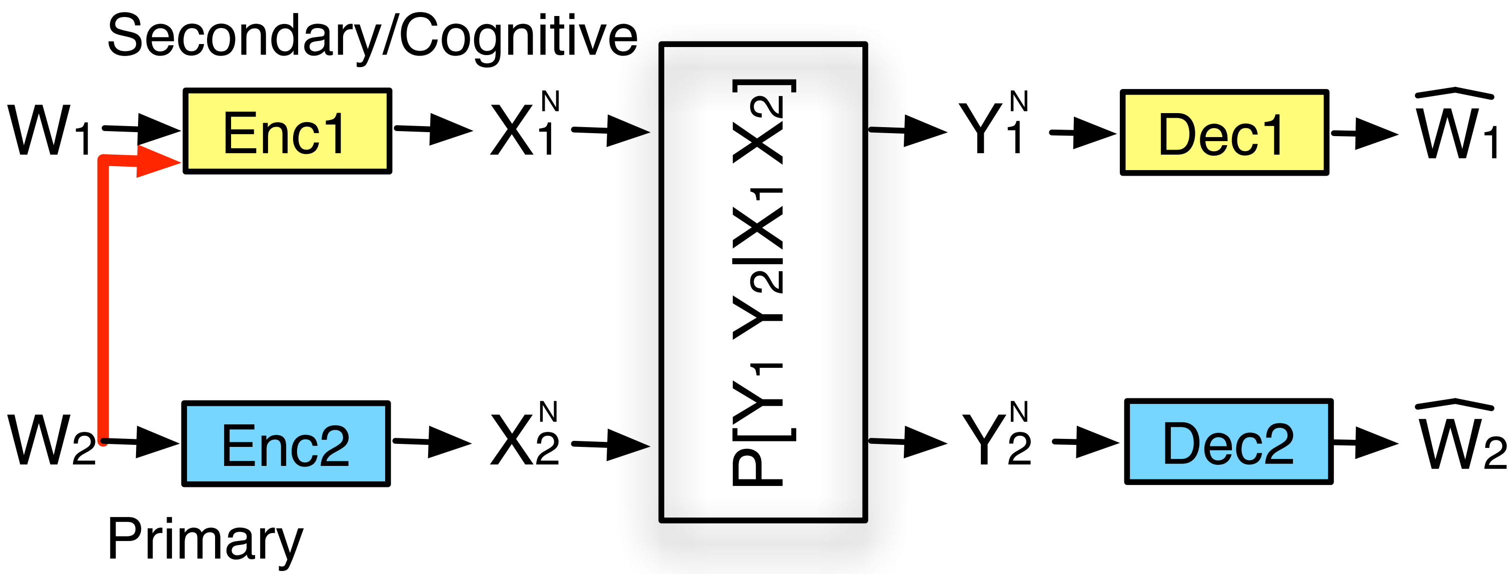
- CR sends if interference at PRx is below a fixed <u>interference margin</u> (MIMO or UWU)
  - Pros: primary users are protected
  - Cons: short range communication



Overlay CR

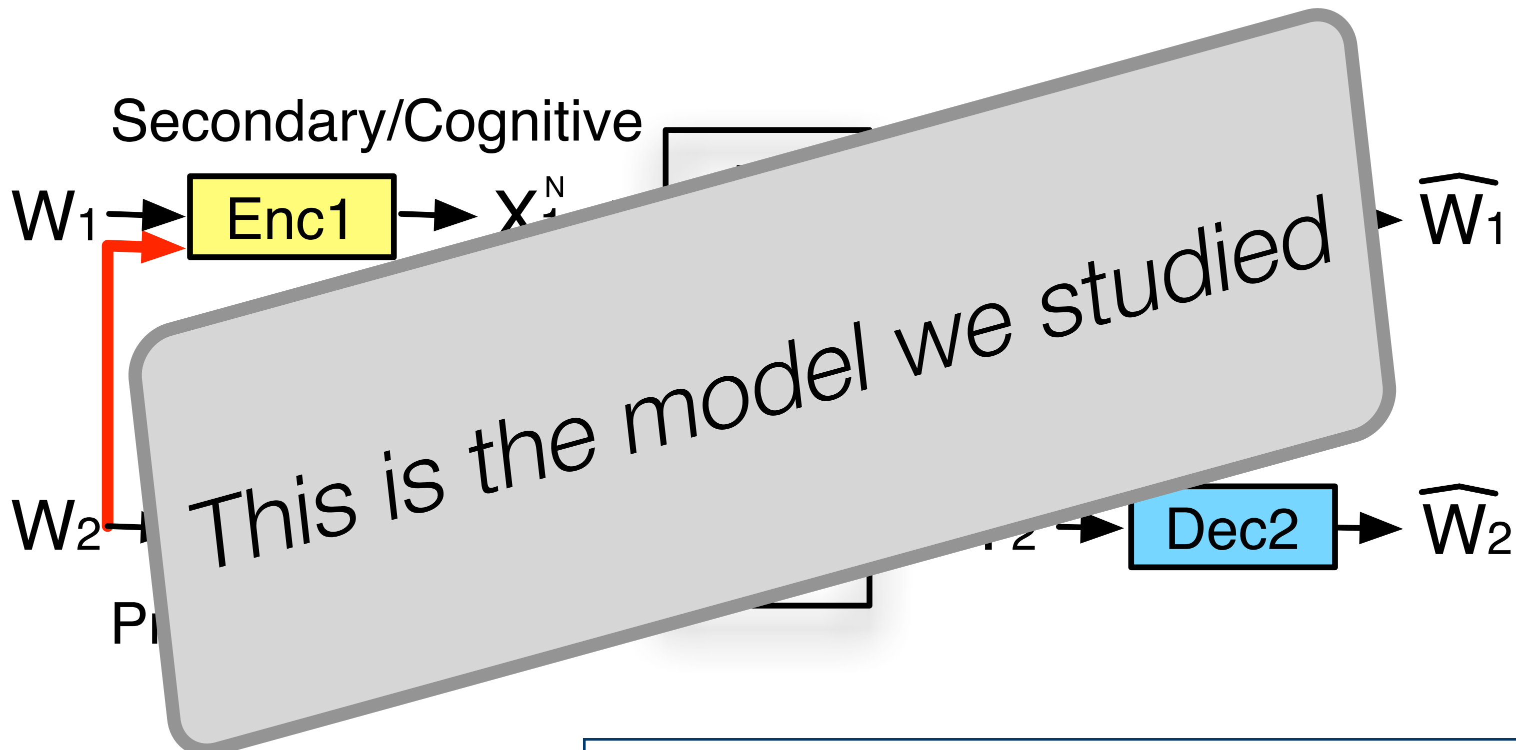
- CR uses sophisticated signal processing and coding to maintain or improve the communication of PR while achieving its own communication goals.
- Needs knowledge of primary codebooks (ex from standards) and possibly primary messages (ex after first transmission).

IT overlay CR



N. Devroye, P. Mitran, V. Tarokh, Achievable Rates in Cognitive Radio Channels," IEEE Transactions on Information Theory, vol. 52, pp. 1813–1827, May 2006

IT overlay CR



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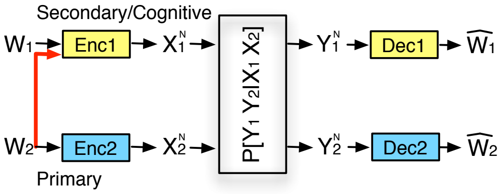
Past Work - outer bounds

the smaller, the better



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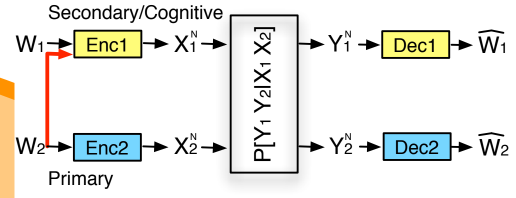

Devroye *et al* IT06
(Broadcast Channel)

Past Work - outer bounds

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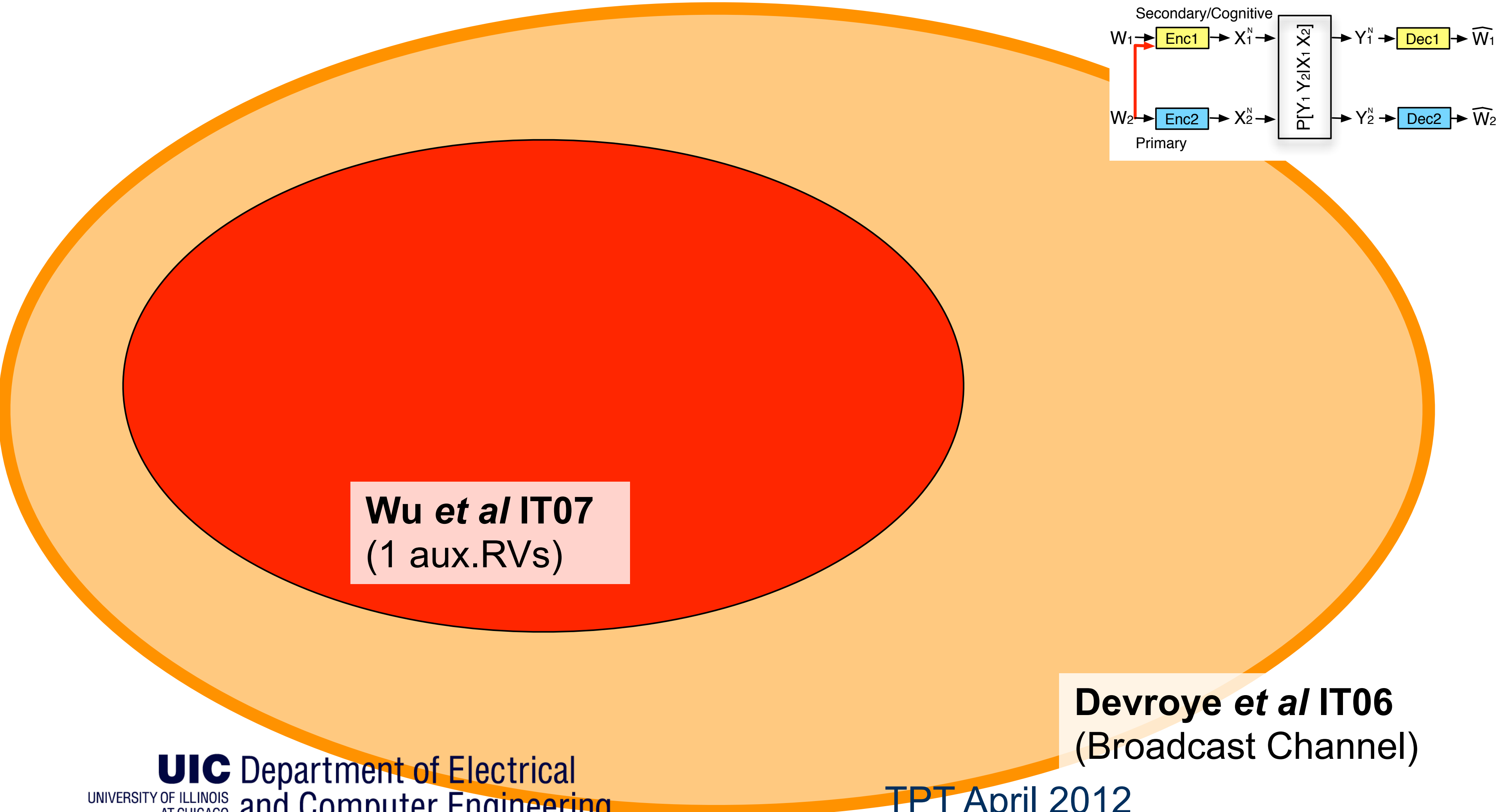
the better



Past Work - outer bounds

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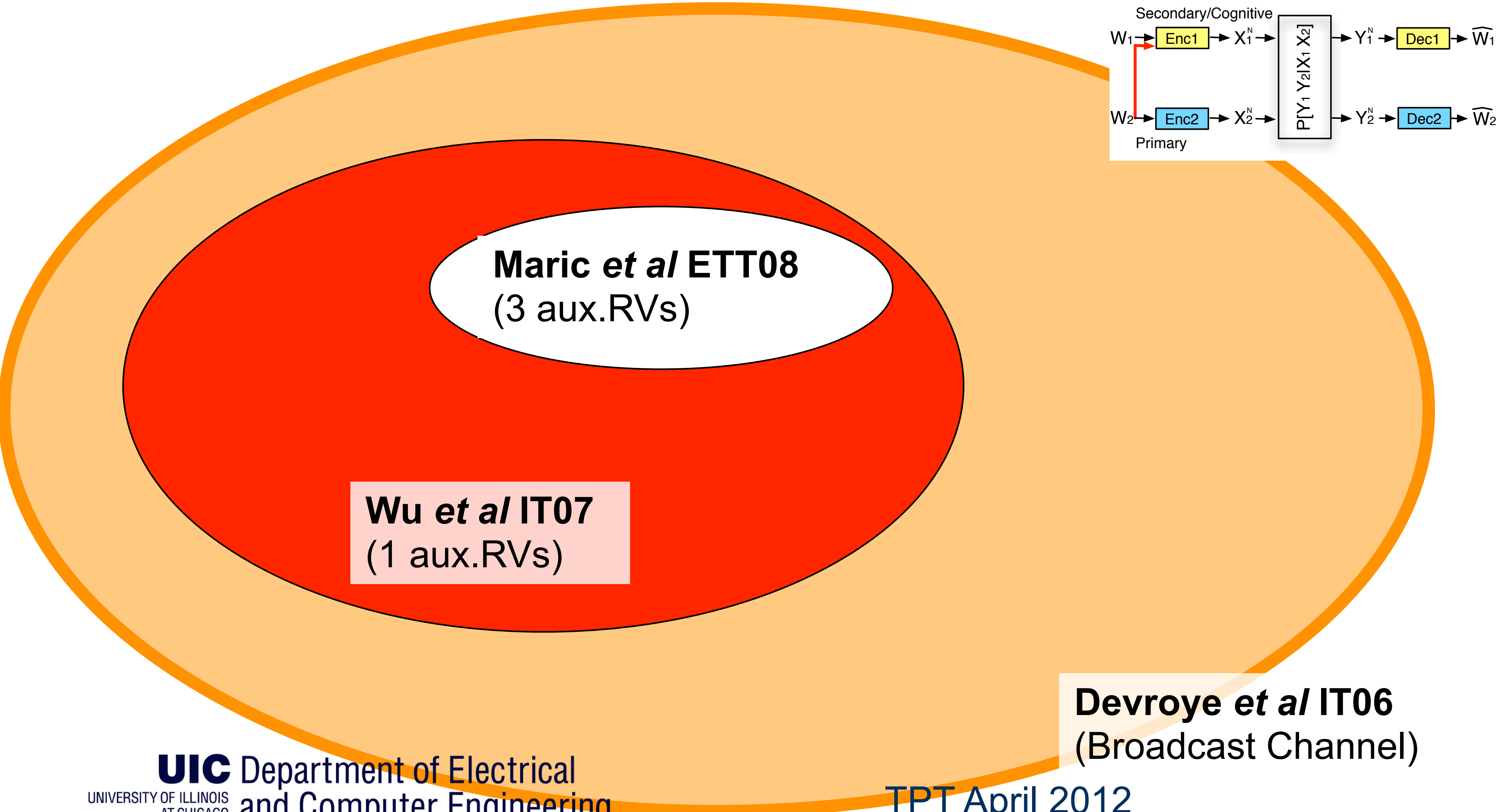

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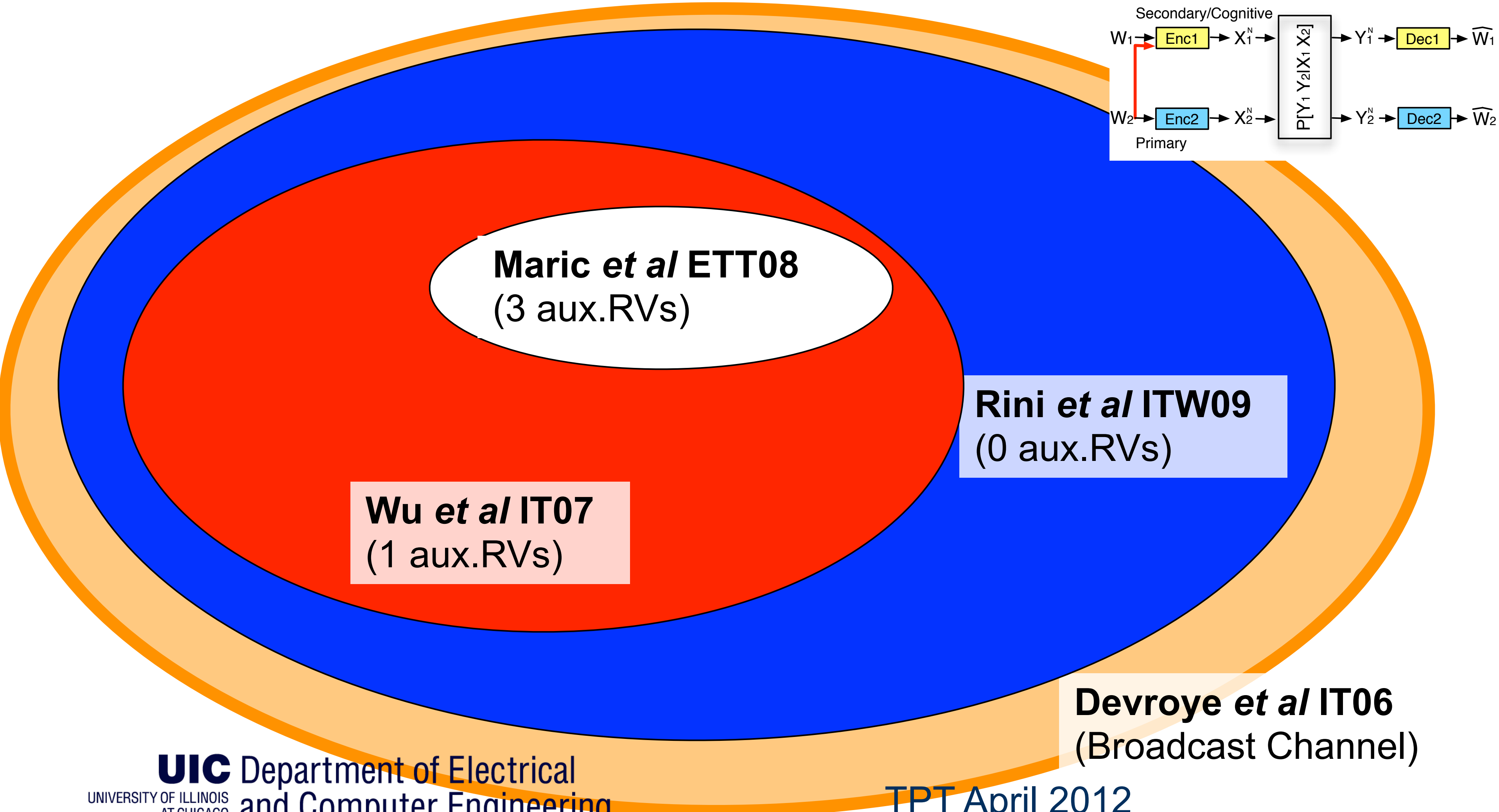

Past Work - inner bounds

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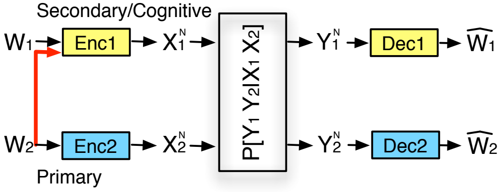

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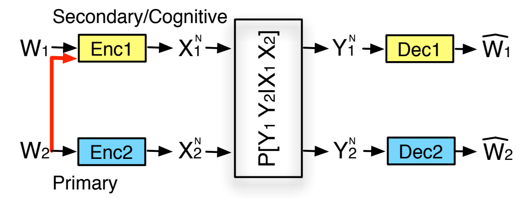
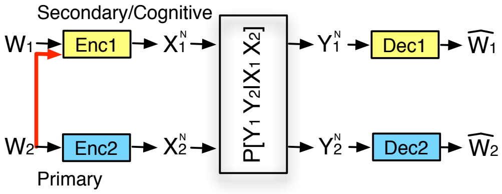
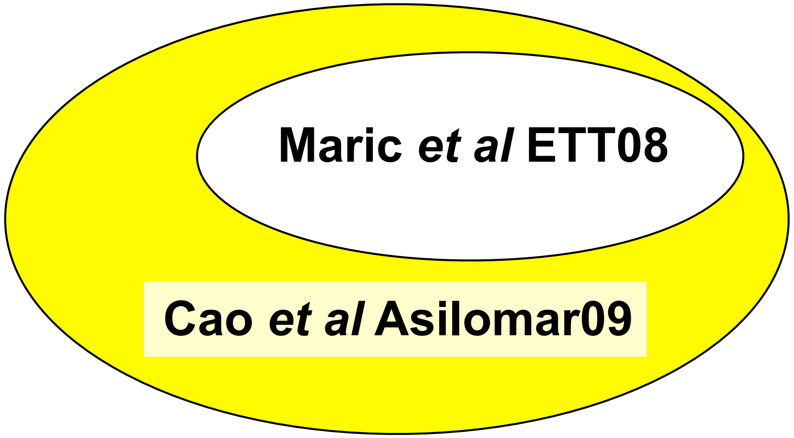


Maric *et al* ETT08

Past Work - inner bounds

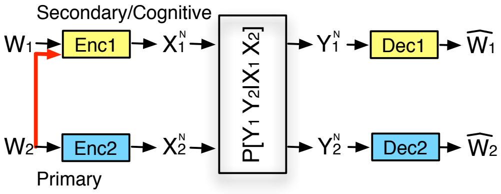
the larger, the better

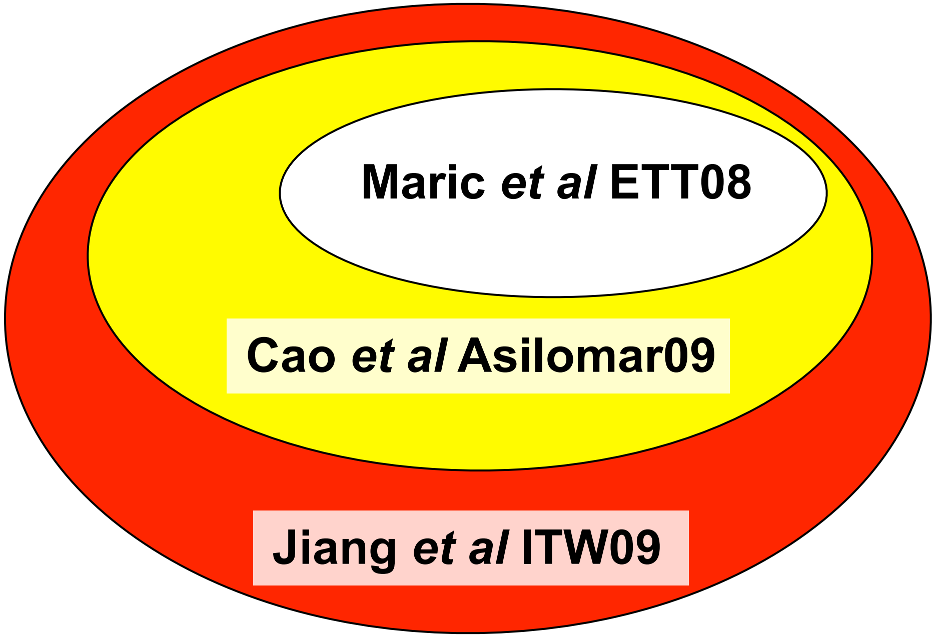




Past Work - inner bounds

the larger, the better





Past Work - inner bounds

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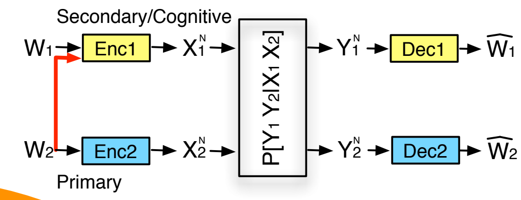

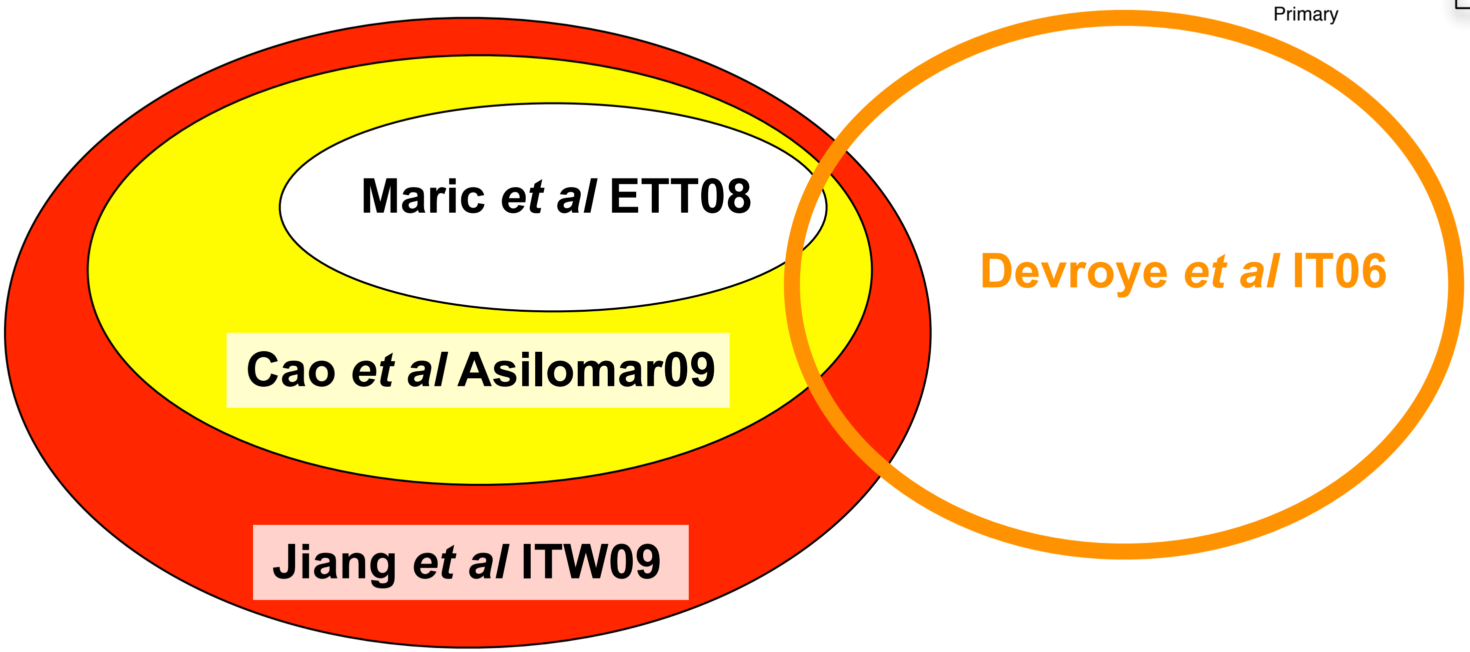

Past Work - inner bounds

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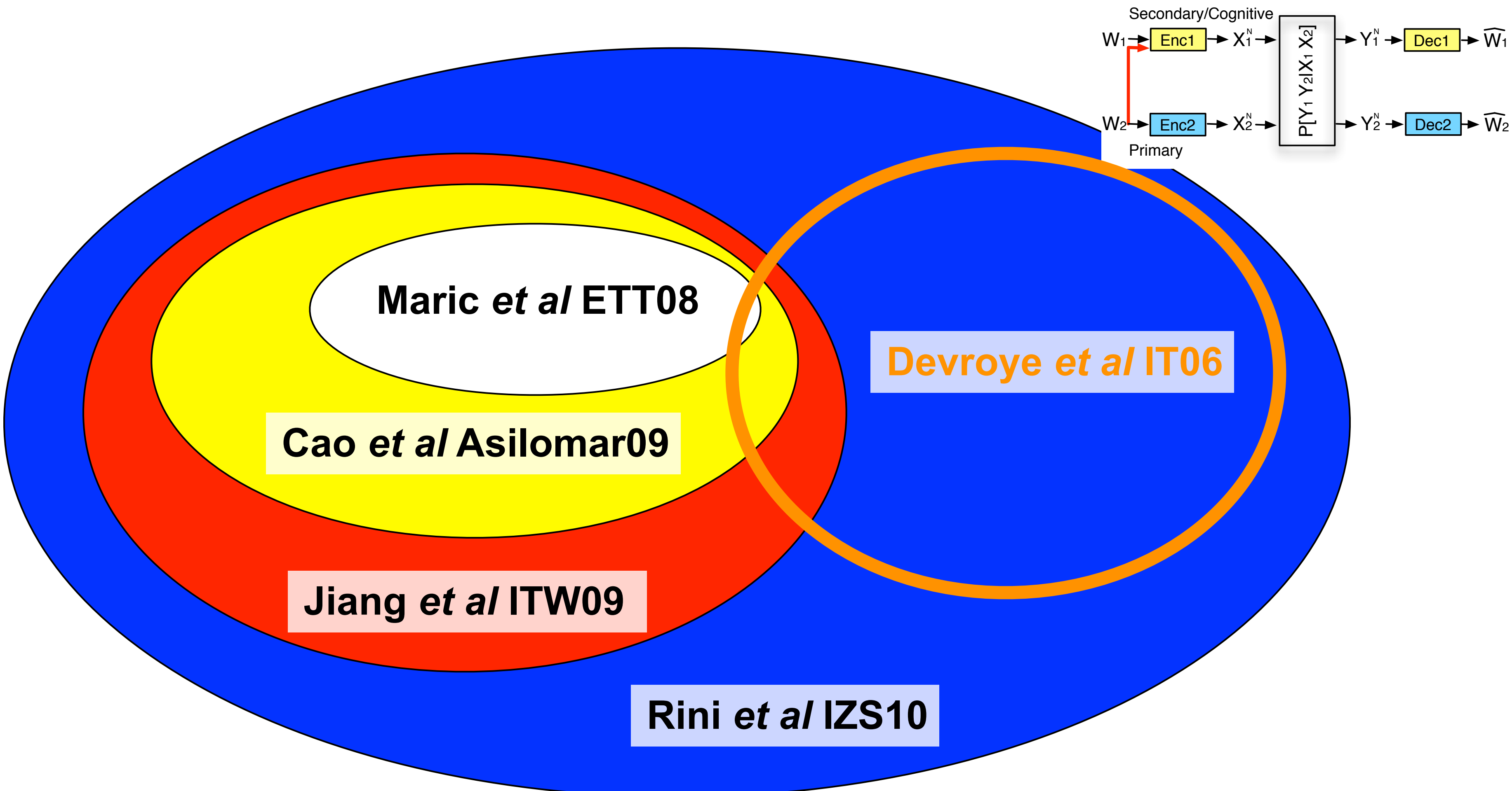
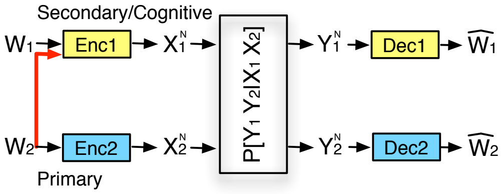


Past Work - capacity

- Weak interference [W. Wu et al IT 2007, Jovicic et al IT 2006 for AWGN]



- (Very) strong interference [I. Maric et al IT 2007]
- Some semi-deterministic [Y. Cao et al Asilomar 2009]
- Some Z-channel [N. Liu et al ISIT 2009]

Contributions: general CIFC

- Computable outer bound (the tightest is still by Maric et at ETT 2008)
- Largest inner bound
- Capacity in “better cognitive decoding”
- Capacity for semi-deterministic channels

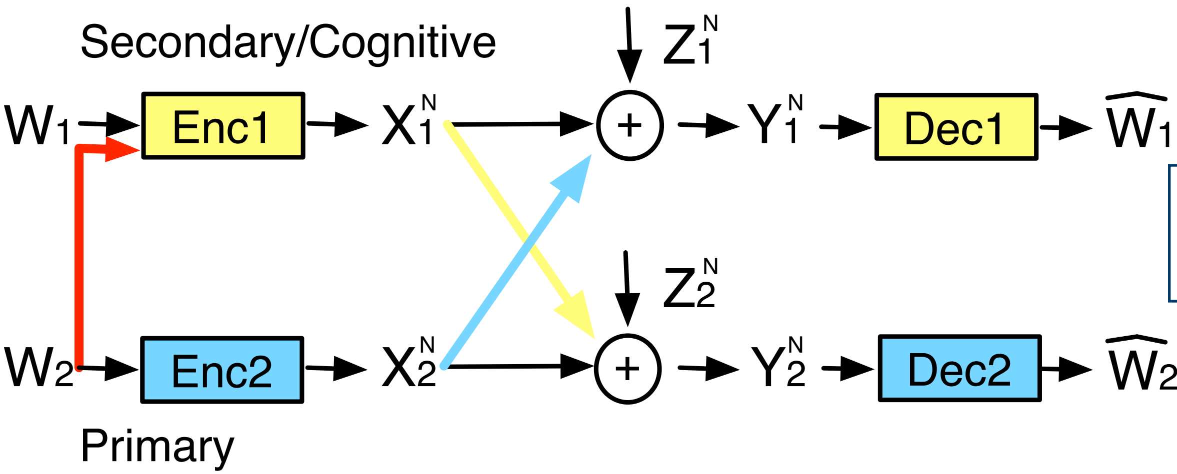
S. Rini et al, “New Inner and Outer Bounds for the Memoryless Cognitive Interference Channel and some Capacity Result”, IT 2011

Contributions: AWGN CIFC

- Unifying outer bound (for weak and strong interference)
- "BC with degraded message set" outer bound for strong interference
- Capacity in "primary decodes cognitive"
  [subset also presented by J. Jiang et al ICC 2011]
- Capacity for some Z-channels
  [extension claimed by M. Vaezi et al CWIT 2011]
- Capacity to within 1 bit or a factor 2

S. Rini et al, "Inner and Outer Bounds for the Gaussian Cognitive Interference Channel and New Capacity Results", IT 2012

AWGN CIFC

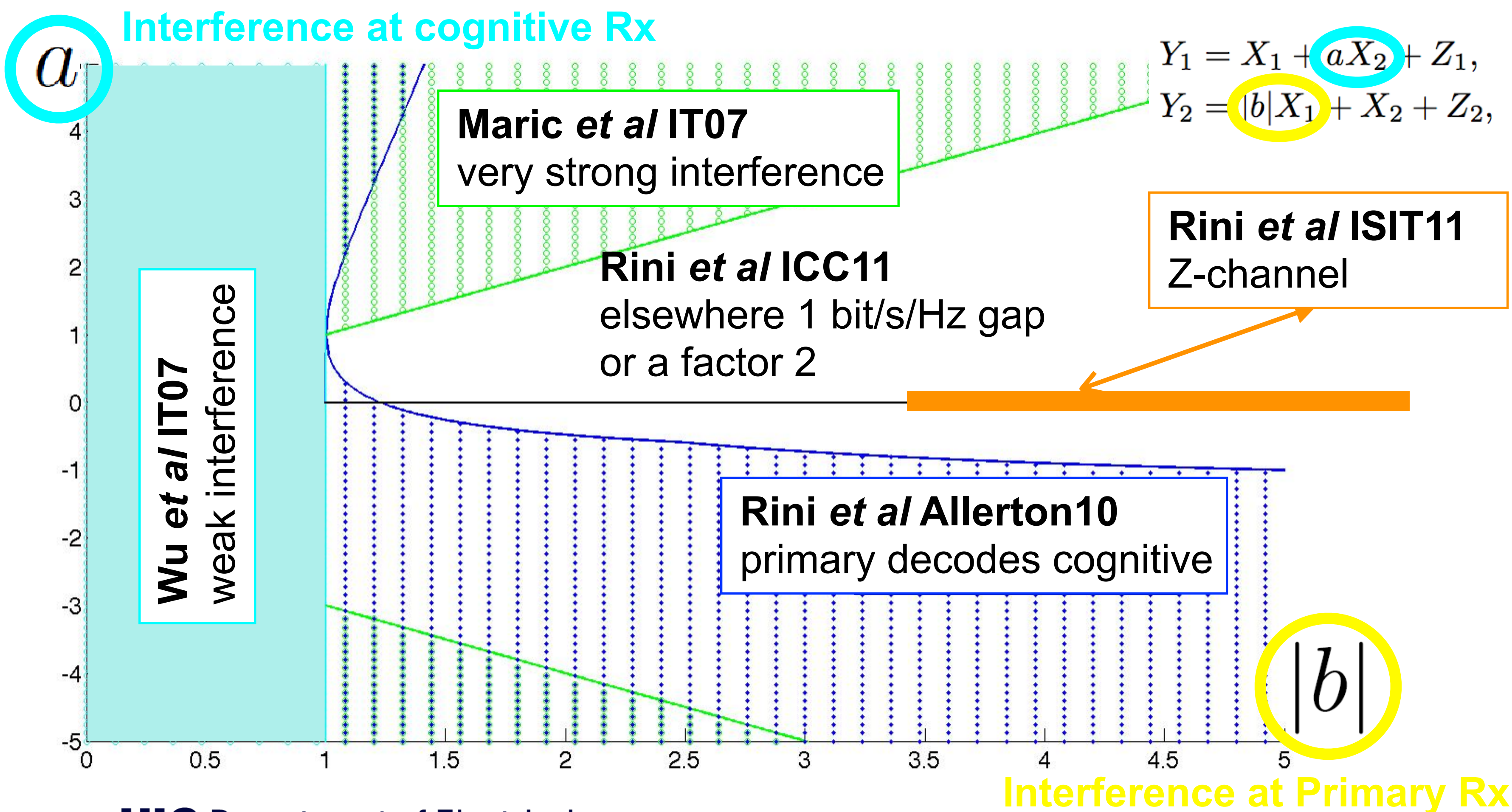


Most results extend to a general memoryless CIFC

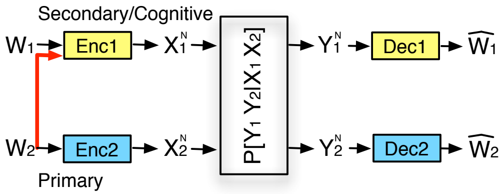
$$Y_1 = X_1 + aX_2 + Z_1,$$
$$Y_2 = |b|X_1 + X_2 + Z_2,$$

$$X_1^N = f_1(W_1, W_2) : \frac{1}{N}\sum_{t=1}^{N} \mathbb{E}[|X_{1,t}|^2] \le P_1,$$
$$X_2^N = f_2(\quad W_2) : \frac{1}{N}\sum_{t=1}^{N} \mathbb{E}[|X_{2,t}|^2] \le P_2,$$
$$Z_j \sim \mathcal{N}(0,1),\ j = 1,2.$$

Contributions: AWGN CIFC



Outer Bound



- Wu et al IT 07 (BC argument; not the tightest)

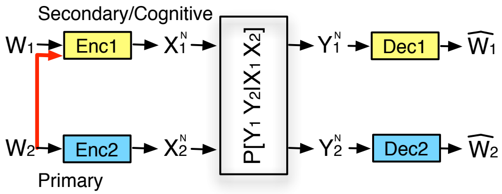
$$R_1 \leq I(Y_1; X_1 | X_2),$$

$$R_2 \leq I(U, X_2; Y_2),$$

$$R_1 + R_2 \leq I(U, X_2; Y_2) + I(Y_1; X_1 | U, X_2),$$

  - U: help from the cognitive to the primary
  - [Rini et al IT11] tight for "semi-deterministic" channels and for "better cognitive decoding"

Outer Bound

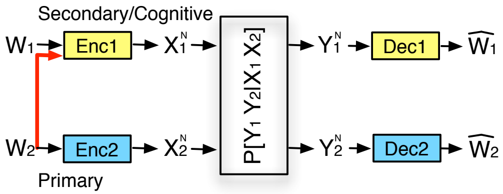


- Rini et al IT 11 (IFC argument)

$$
\begin{aligned}
R_1 &\le I(Y_1; X_1 | X_2), \\
R_2 &\le I(X_1, X_2; Y_2), \\
R_1 + R_2 &\le I(X_1, X_2; Y_2) + I(Y_1; X_1 | Y'_2, X_2),
\end{aligned}
$$

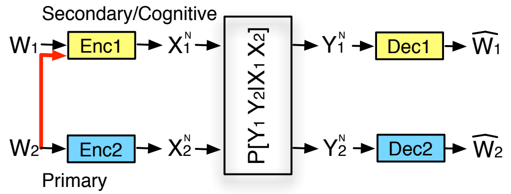
  - does not contain auxiliary RVs, hence it is computable
  - [Rini et al IT12]: it unifies weak and strong interference outer bounds for AWGN

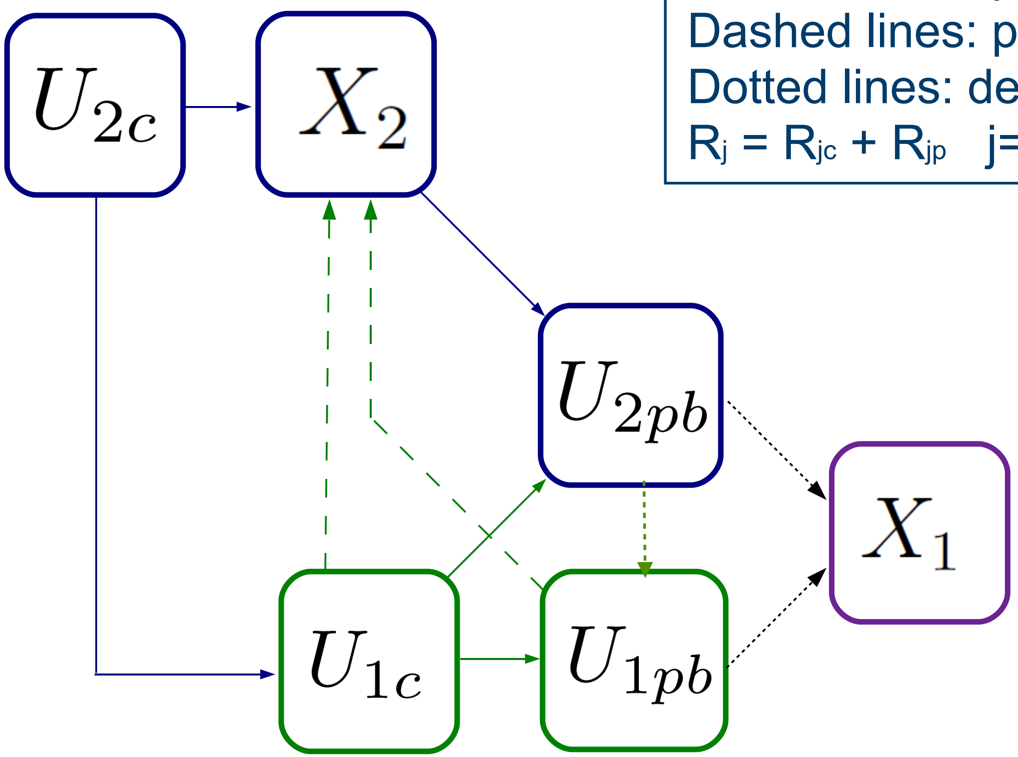
Inner Bound



- Rate splitting:
  - common message (decoded @ non intended destination)
  - private message (treated as noise @ non intended destination)
- Superposition coding/nesting: start with primary-common end with cognitive-private
- Interference pre-coding/binning: remove effect of interf. non-causally known at CTx

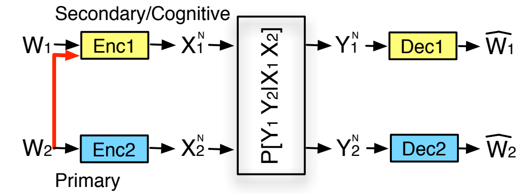
Inner Bound



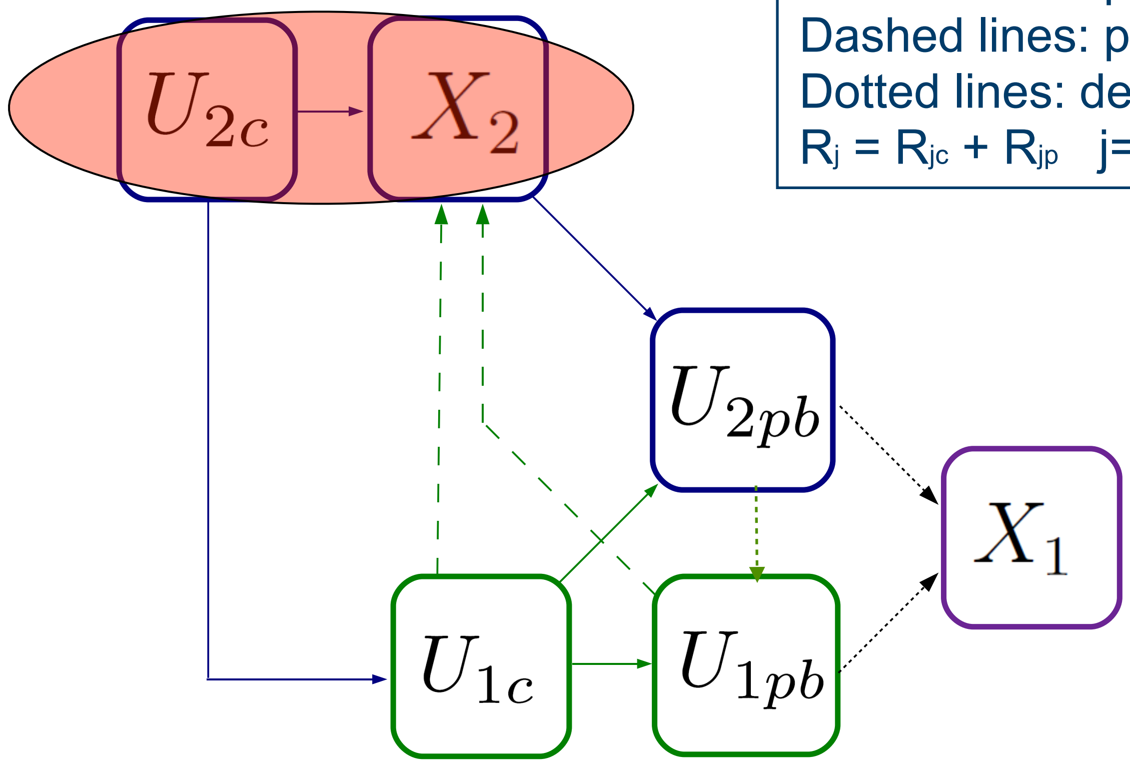


Thick lines: superposition
Dashed lines: pre-coding
Dotted lines: deterministic function
$R_j = R_{jc} + R_{jp}$ $j=1,2$

Inner Bound



@ primary Tx: common/private split



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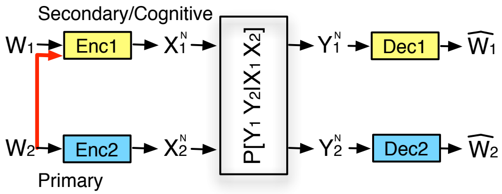
Inner Bound



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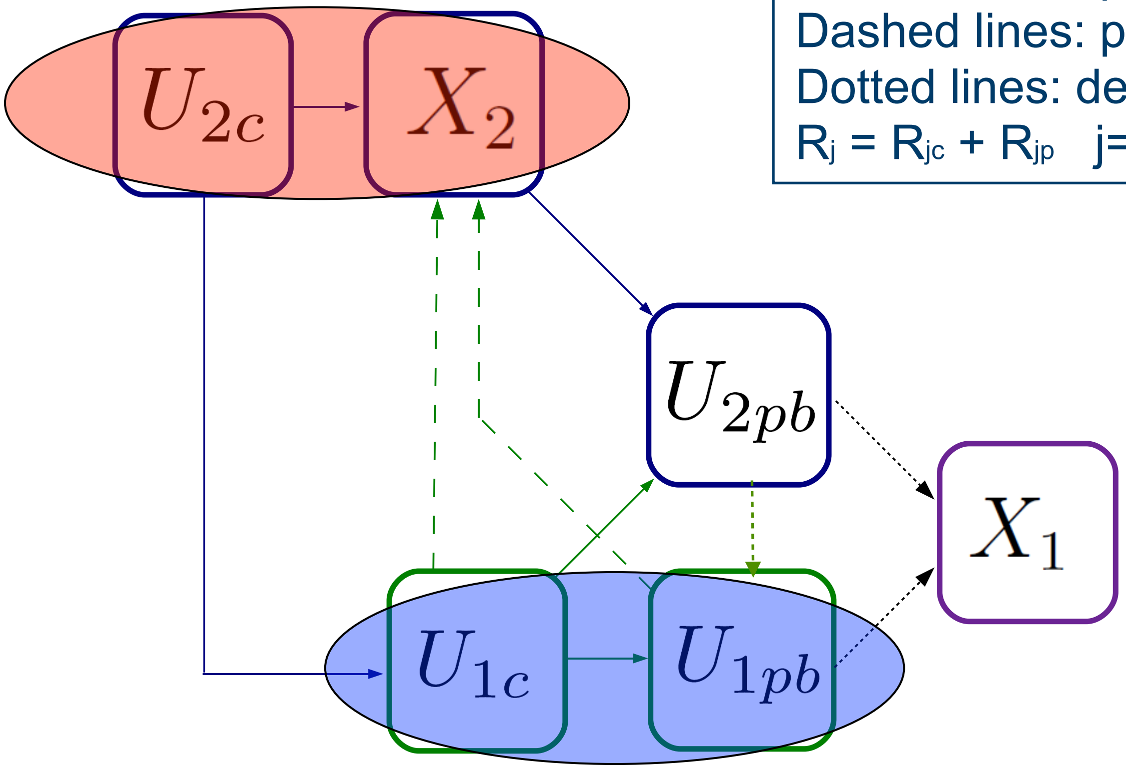

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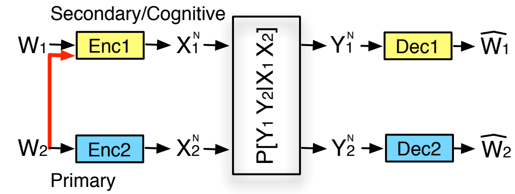
@ cognitive: common/private split

Inner Bound



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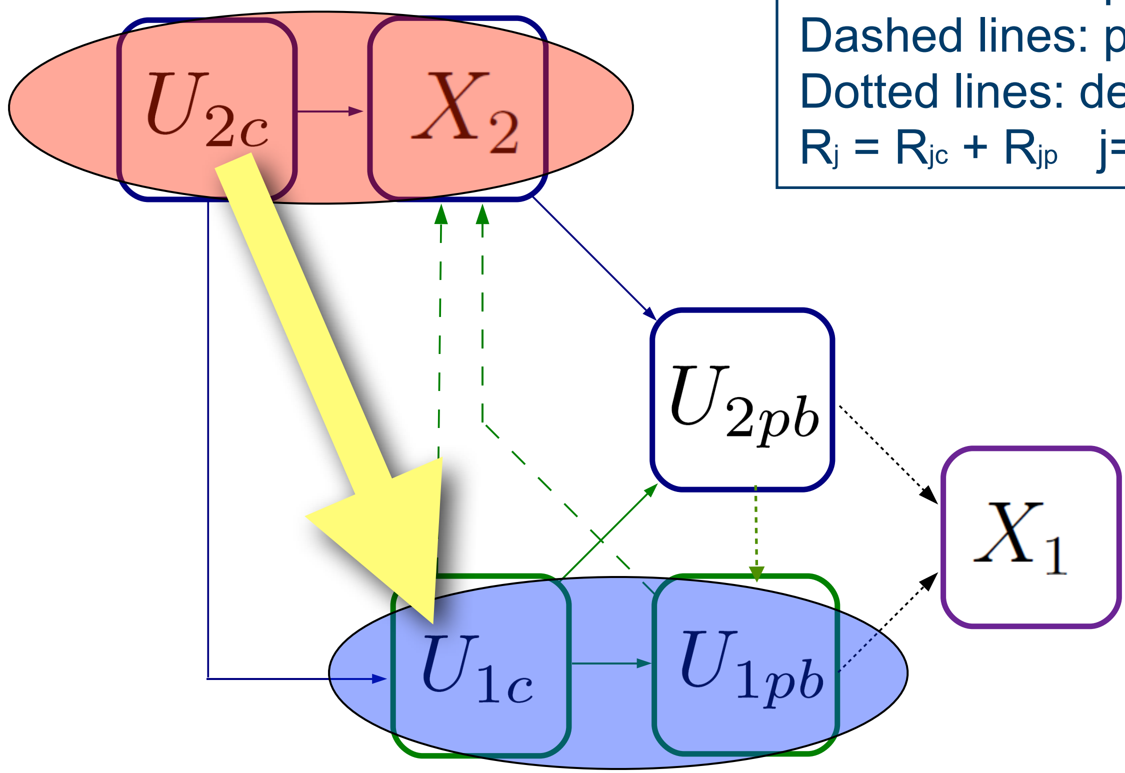

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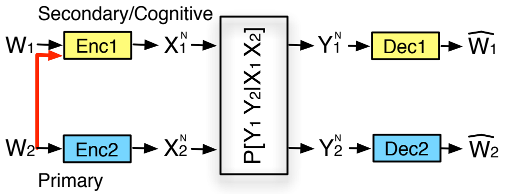
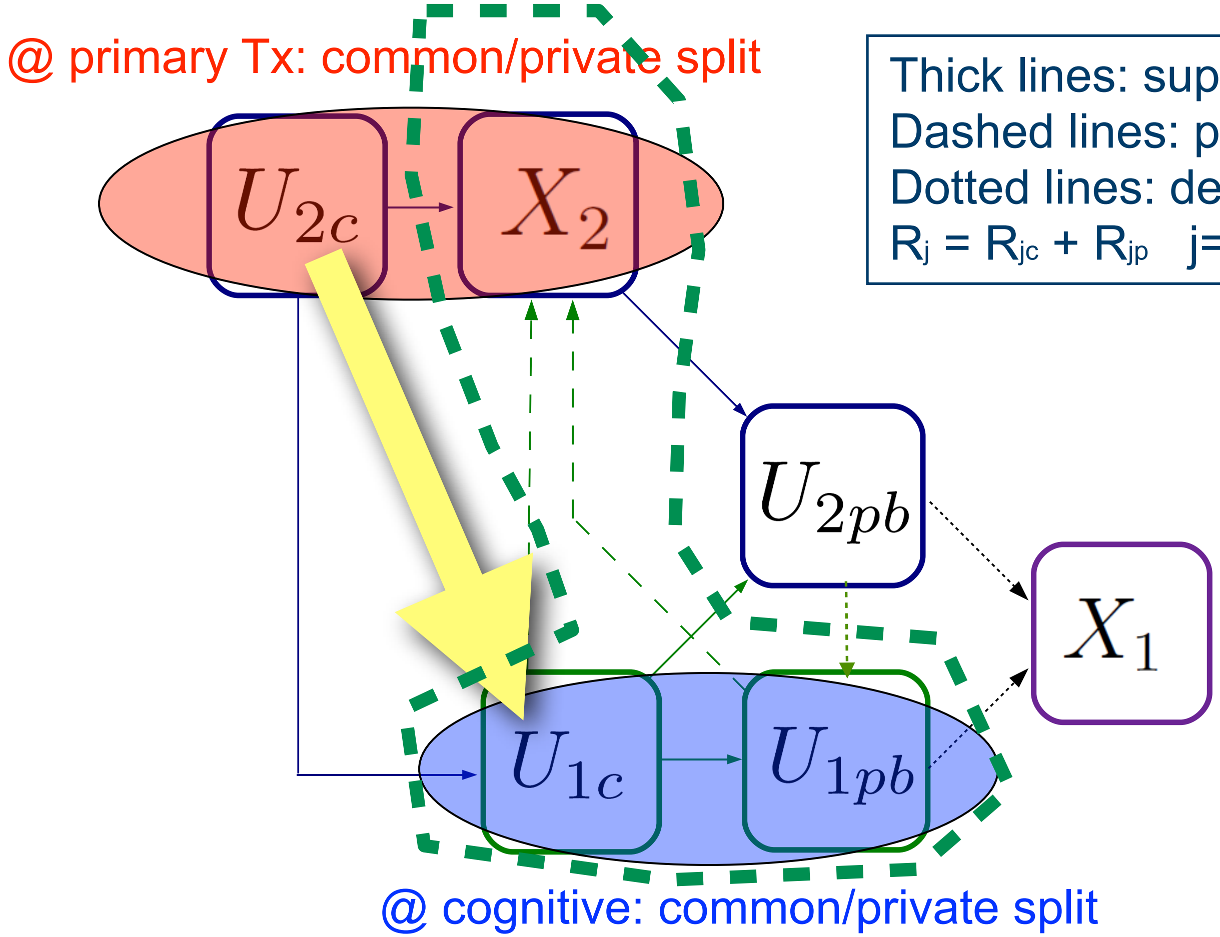
Inner Bound





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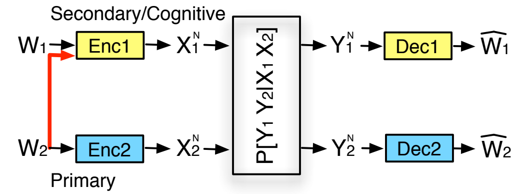

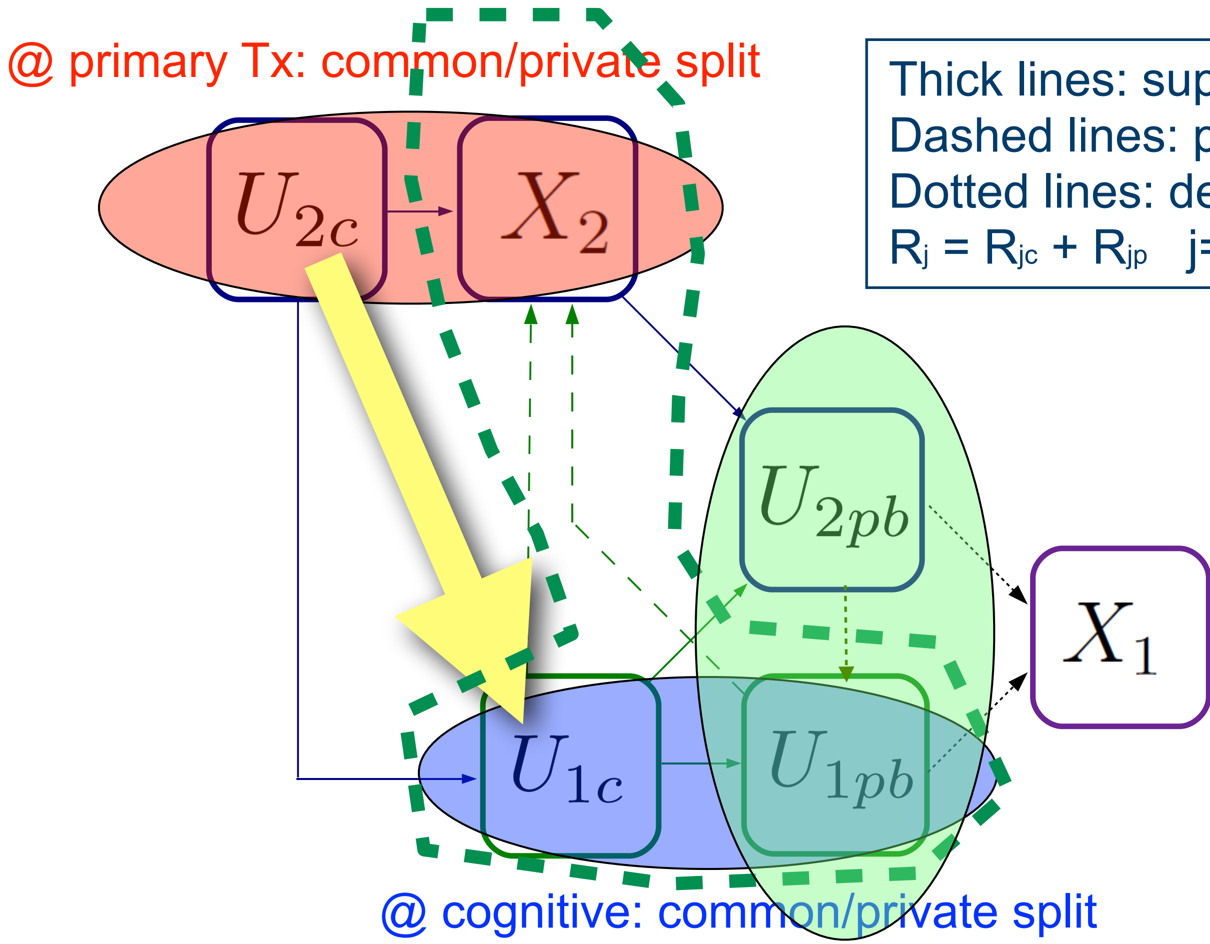

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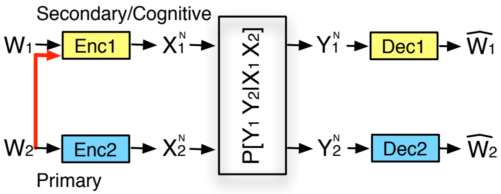
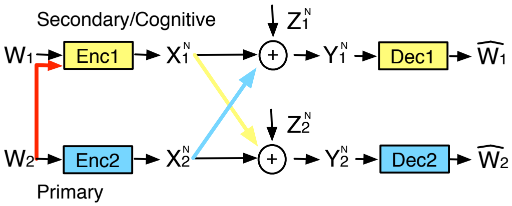
Inner Bound

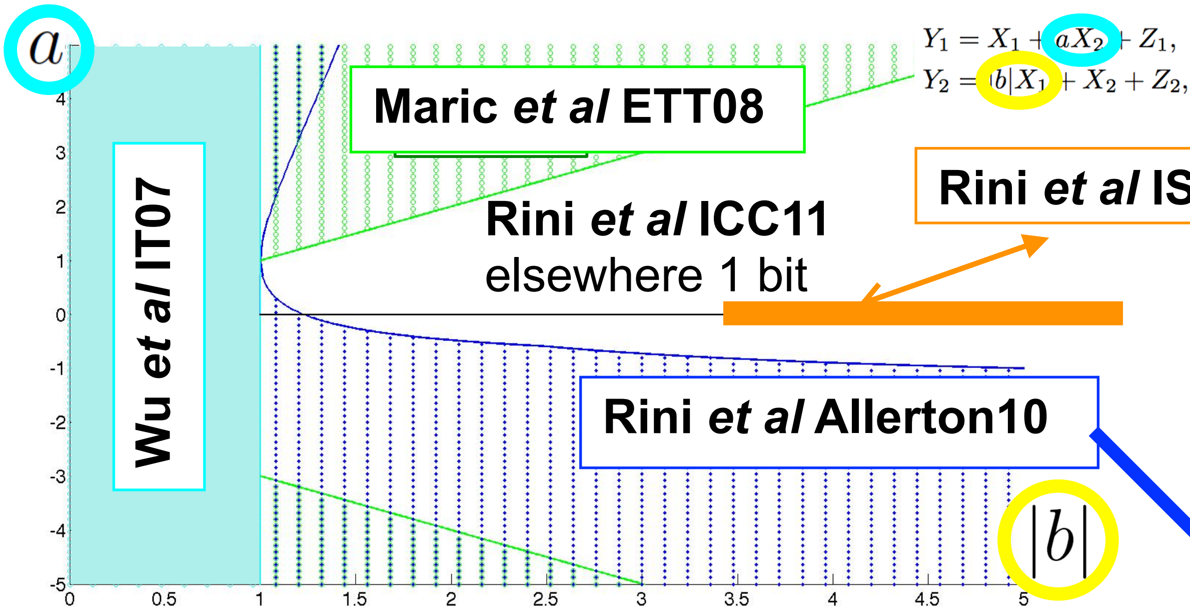


- Overall region (not that "ugly"...)

$$
\begin{aligned}
R_1 &\leq I(Y_1;U_{1pb},U_{1c}|U_{2c}) - I(U_{1pb},U_{1c};X_2|U_{2c}),\\
R_1 &\leq I(Y_1;U_{1pb}|U_{1c},U_{2c}) + I(Y_2;U_{2pb},U_{1c},X_2|U_{2c}) - I(U_{1pb};X_2|U_{1c},U_{2c}),\\
R_2 &\leq I(Y_2;U_{2pb},X_2,U_{1c},U_{2c}) + I(U_{1c};X_2|U_{2c}),\\
R_1+R_2 &\leq I(Y_1;U_{1pb},U_{1c},U_{2c}) + I(Y_2;U_{2pb},X_2|U_{1c},U_{2c}) - I(U_{1pb};U_{2pb},X_2|U_{1c},U_{2c}),\\
R_1+R_2 &\leq I(Y_1;U_{1pb}|U_{1c},U_{2c}) + I(Y_2;U_{2pb},X_2,U_{1c},U_{2c}) - I(U_{1pb};U_{2pb},X_2|U_{1c},U_{2c}),\\
2R_1+R_2 &\leq I(Y_1;U_{1pb},U_{1c},U_{2c}) + I(Y_1;U_{1pb}|U_{1c},U_{2c}) + I(Y_2;U_{2pb},U_{1c},X_2|U_{2c})\\
&\quad - I(U_{1pb};U_{2pb},X_2|U_{1c},U_{2c}) - I(U_{1pb},U_{1c};X_2|U_{2c}),
\end{aligned}
$$

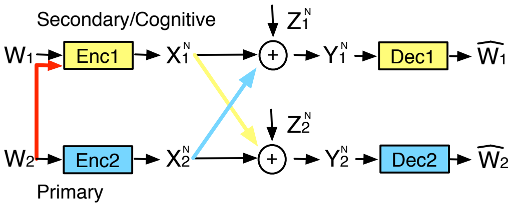
Capacity Results

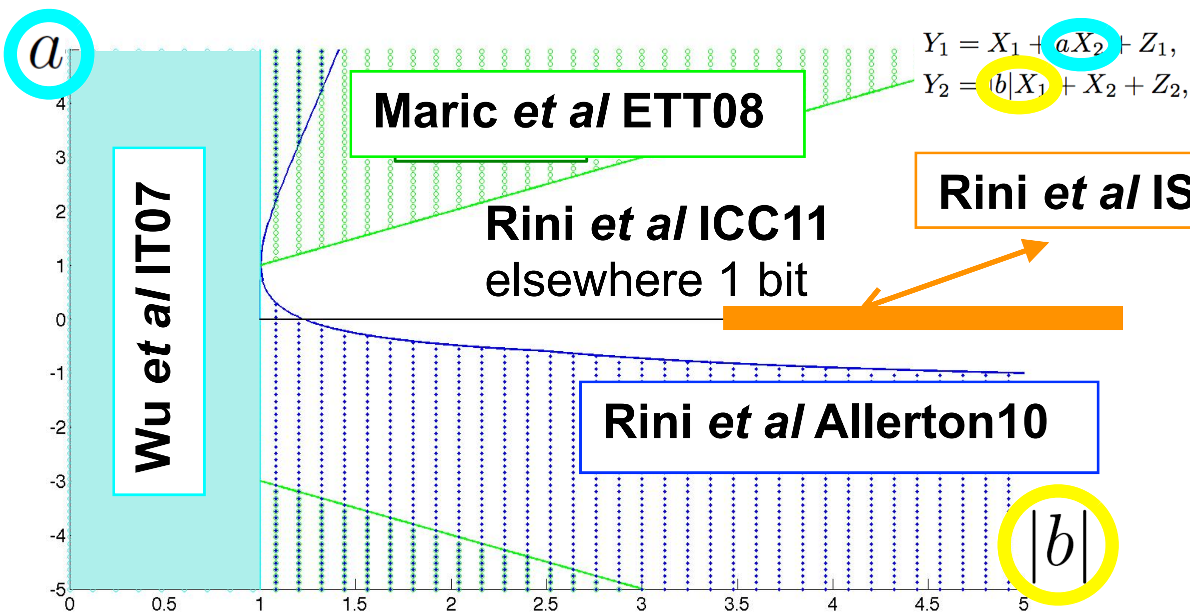




Primary decodes cognitive: cognitive msg is all common & impose conditions so that the computable outer bound and inner bound match

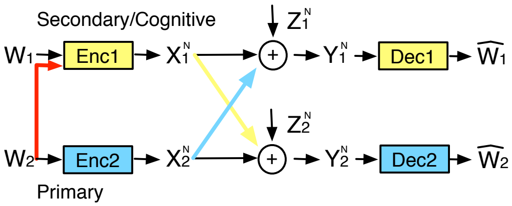
Capacity Results

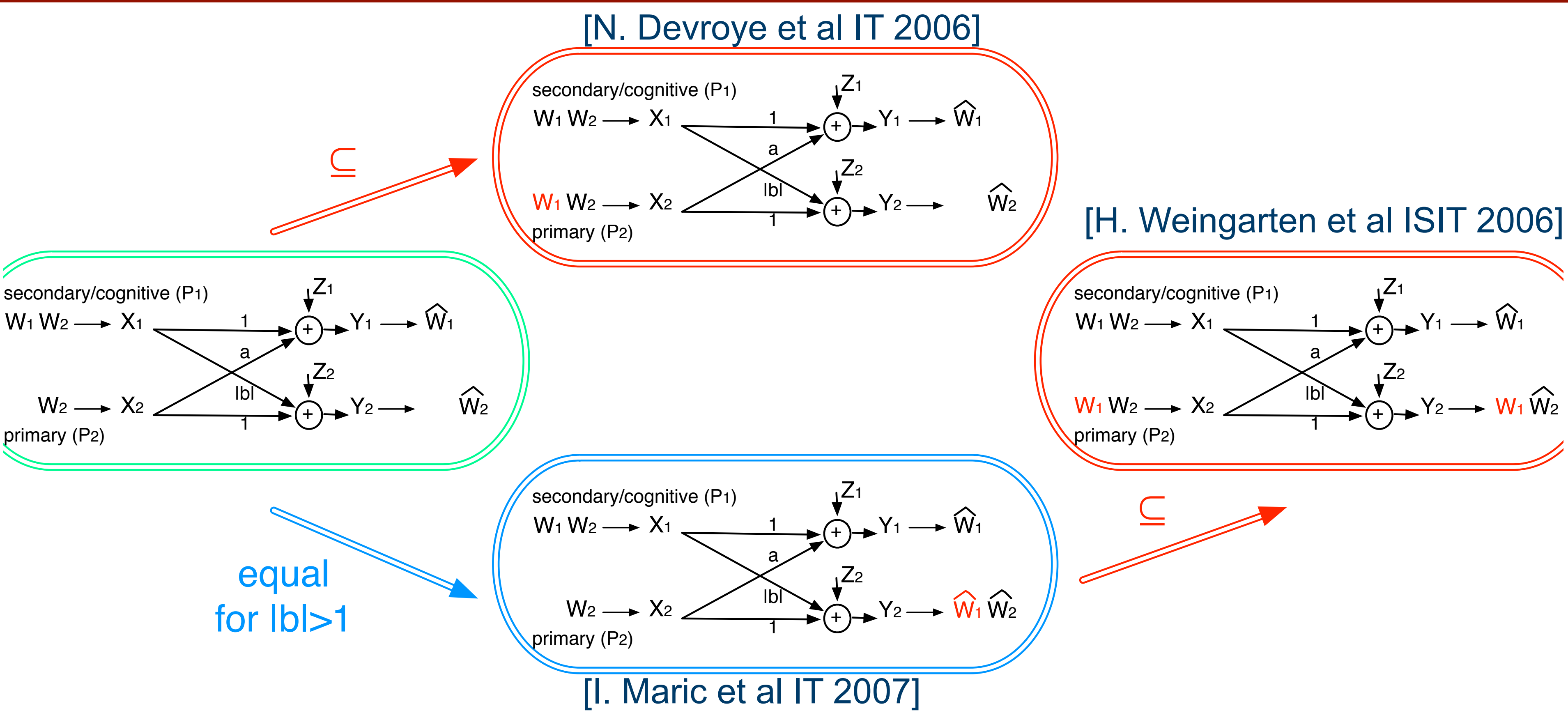




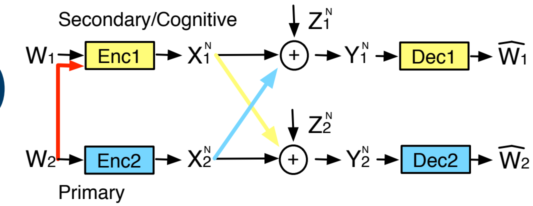
Z-channel: need new outer bound! This new outer bound only holds for AWGN ...

Capacity Results

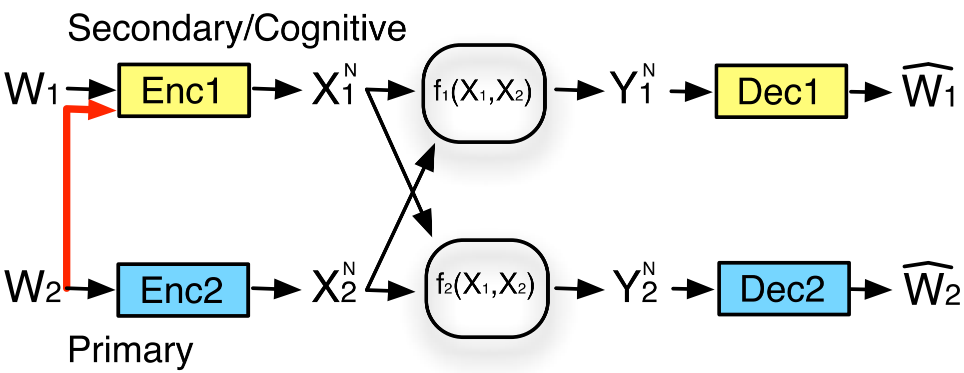


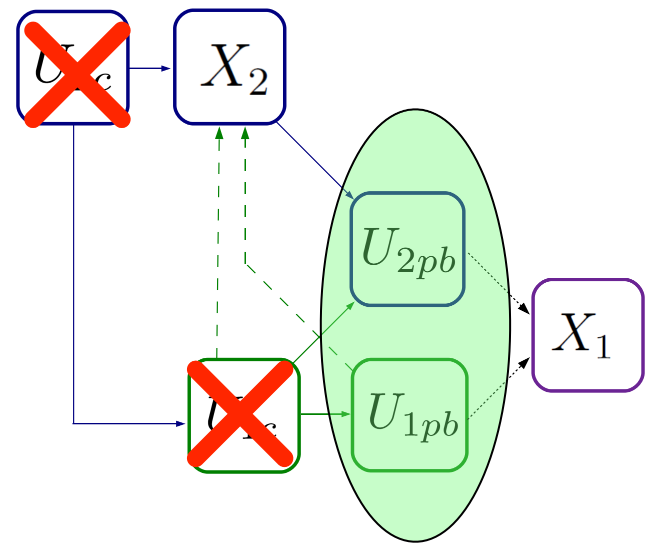


1bit additive gap



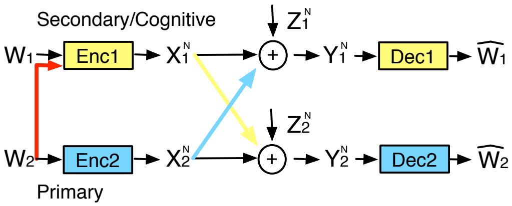
Inspired by the capacity achieving scheme for the deterministic channel: $U_{k,pb} = Y_k$





$$R_1 \le H(Y_1|X_2)$$
$$R_2 \le H(Y_2)$$
$$R_1 + R_2 \le H(Y_2) + H(Y_1|X_2, Y_2)$$

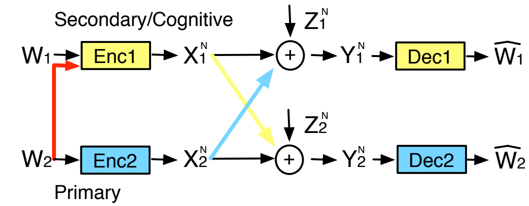
1bit additive gap

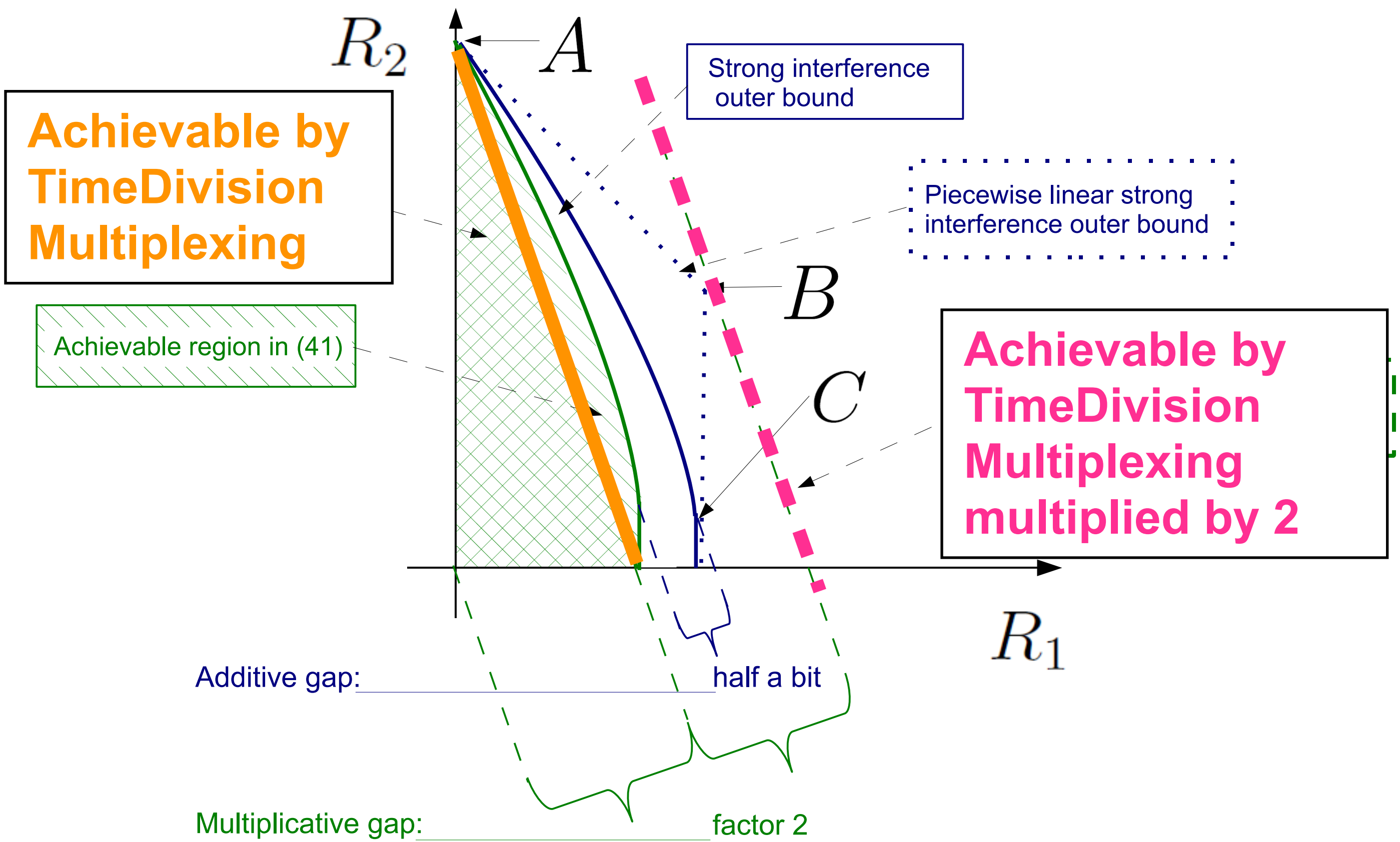


- Impossible to set $U_{k,pb} = Y_k$
- $U_{k,pb} \sim Y_k$ does the trick
- Why does it work?

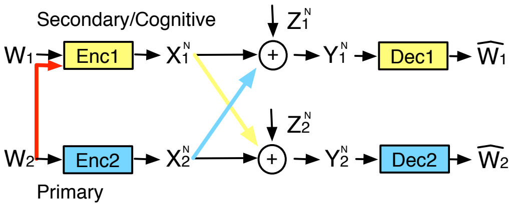
$$\text{Gap} = \log(1+ \text{Var}[Y_k]/(1+\text{Var}[U_{k,pb}]))$$
$$<= \log(1+1) = 1 \text{ bit}$$

factor 2 gap


Secondary/Cognitive
W1
Enc1
X1
Z1
Y1
Dec1
W2
Enc2
X2
Z2
Y2
Dec2
Primary

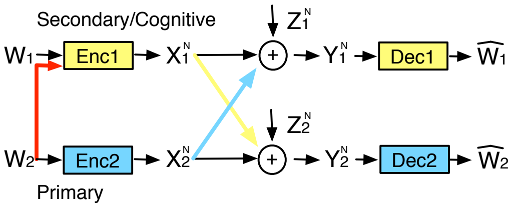

R2
A
Strong interference outer bound
Achievable by TimeDivision Multiplexing
Piecewise linear strong interference outer bound
B
Achievable region in (41)
C
Achievable by TimeDivision Multiplexing multiplied by 2
R1
Additive gap:
half a bit
Multiplicative gap:
factor 2

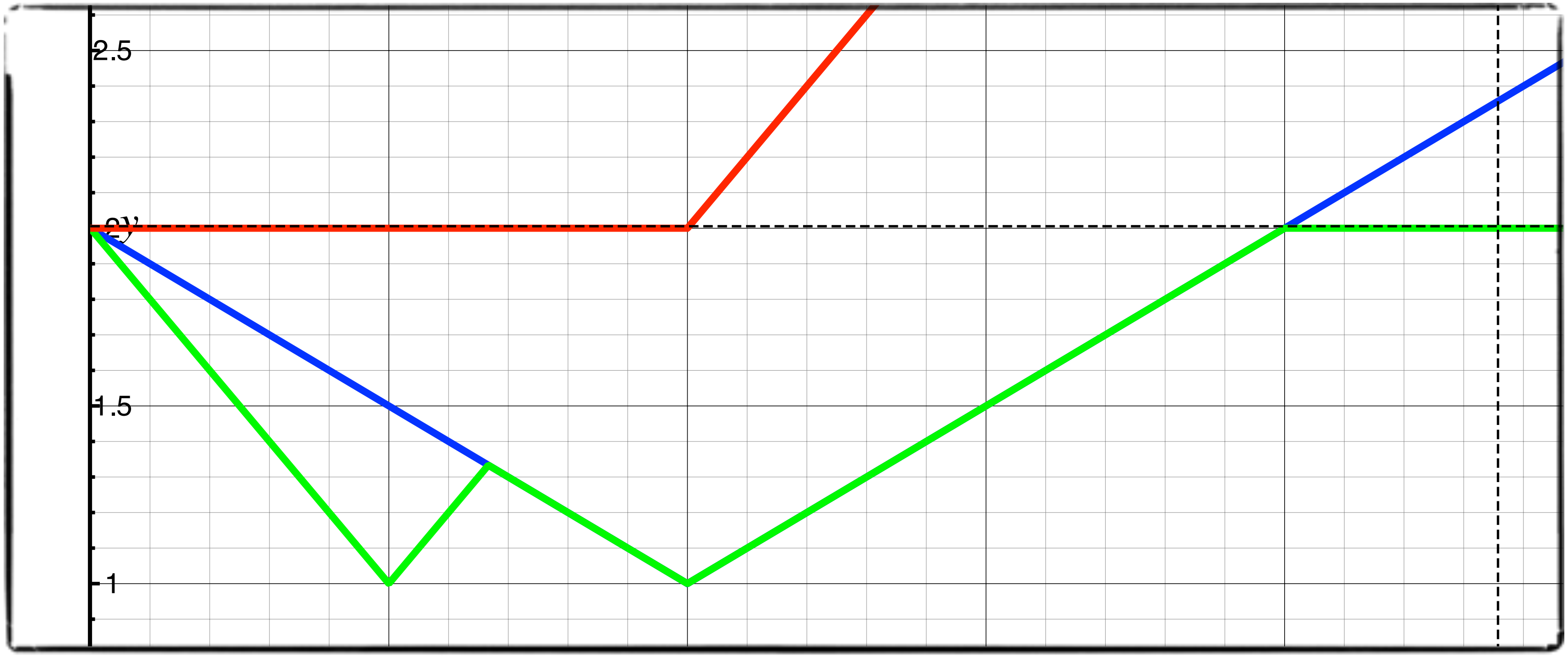
Generalized DoF



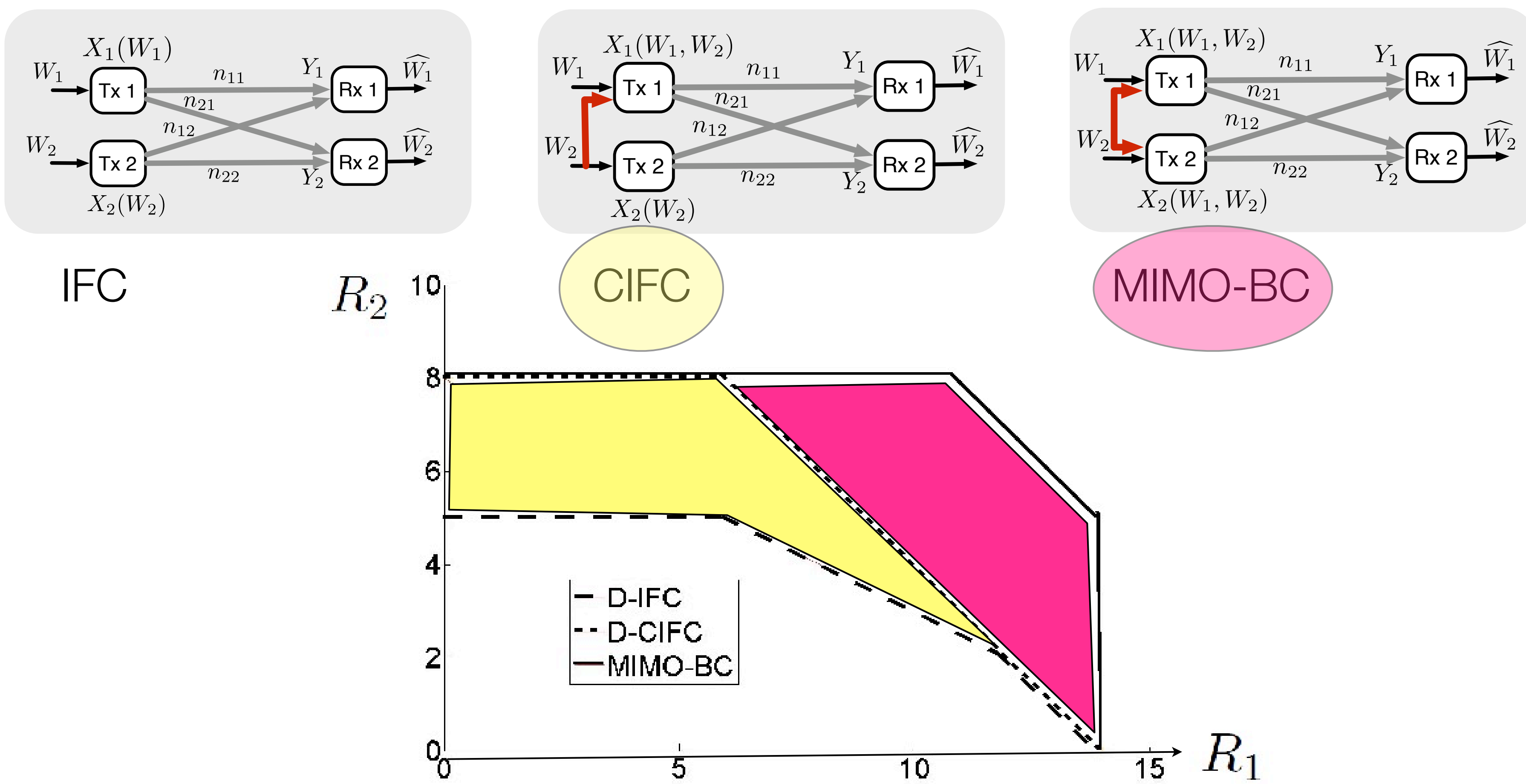
- Useful for gDoF:
  - $P_1 = P_2 := SNR$,
  - $b^2 P_1 = a^2 P_2 := SNR^{\alpha}$,
  - $d_{2\text{-CIFC}}(\alpha)$
    $:= \max(R_1+R_2)/\log(1+SNR)$
    $= 2\max(1,\alpha) - \alpha := V(\alpha)$

Generalized DoF



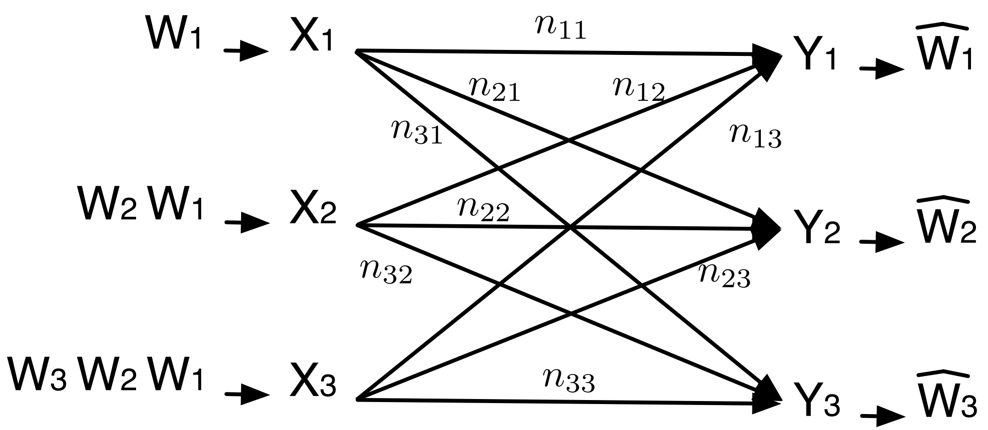


What is the value of cognition?



More than 2 pairs

- dGoF [Maamari et al, submitted to ISIT 2012]
  - sum-capacity for LDA-AWGN for K=3
  - $d_{K\text{-CIFC}}(\alpha) := K \max(1,\alpha) - \alpha$
  - $d_{K\text{-BC}}(\alpha) := K \max(1,\alpha)$



Current Work

- Cognitive channels with nested messages.
- Casal cognition, i.e., secondary users learn the primary message(s) -- a special case of cooperation/generalized feedback.
- Cognitive channels with oblivion constraints, i.e., primary users are unaware of the presence of the secondary users.

Thank you

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