Fundamental Limits of Cognitive Networks

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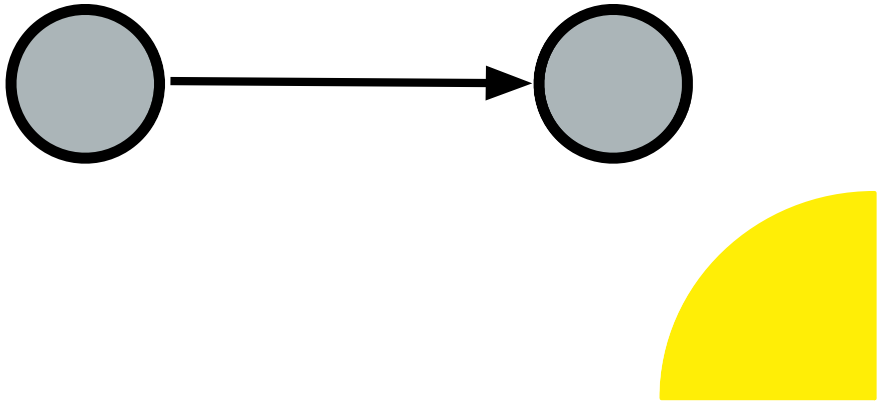
Efficient, reliable communication



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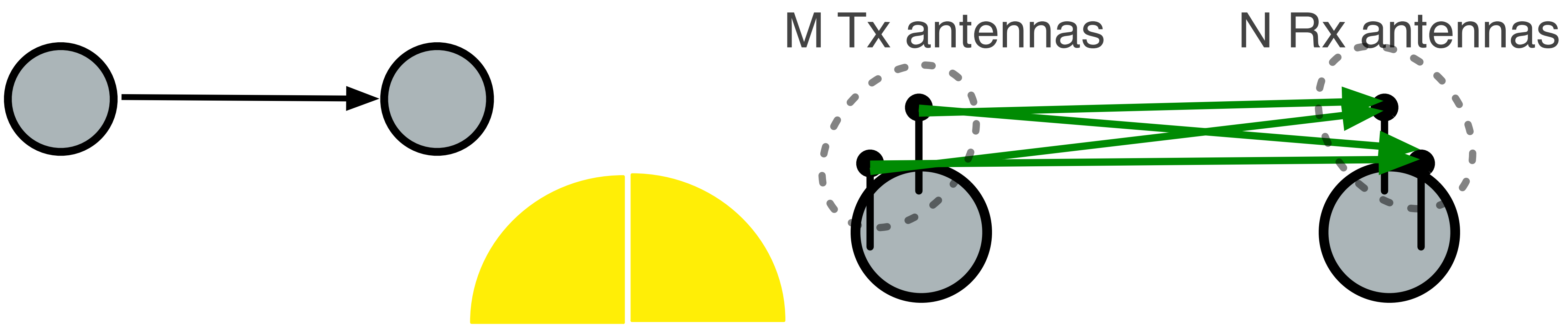
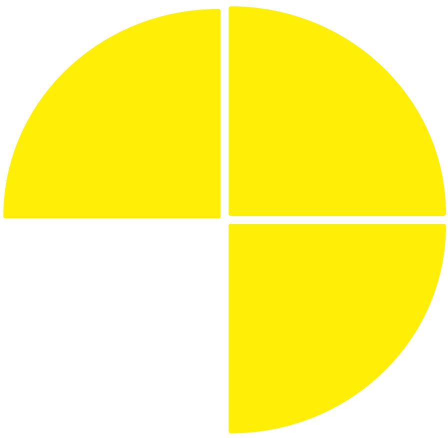
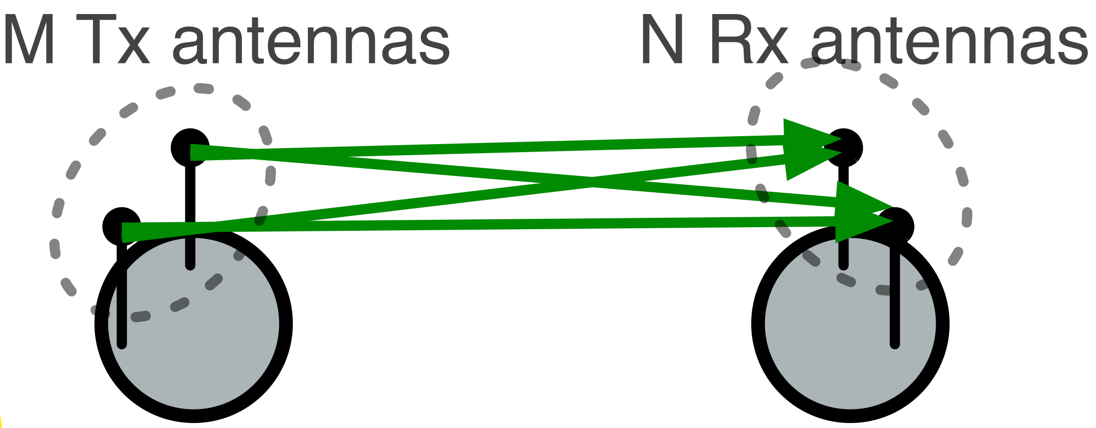


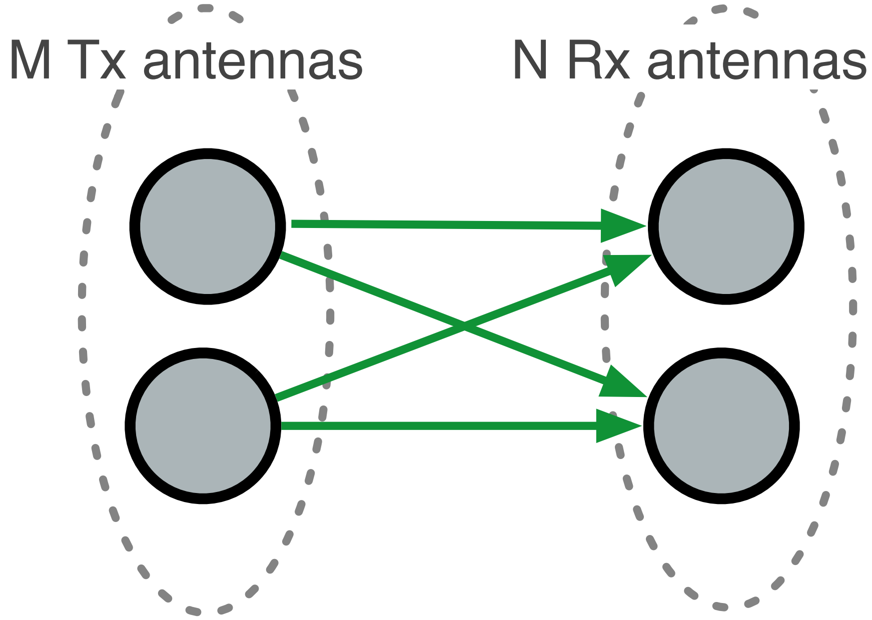
M Tx antennas

N Rx antennas

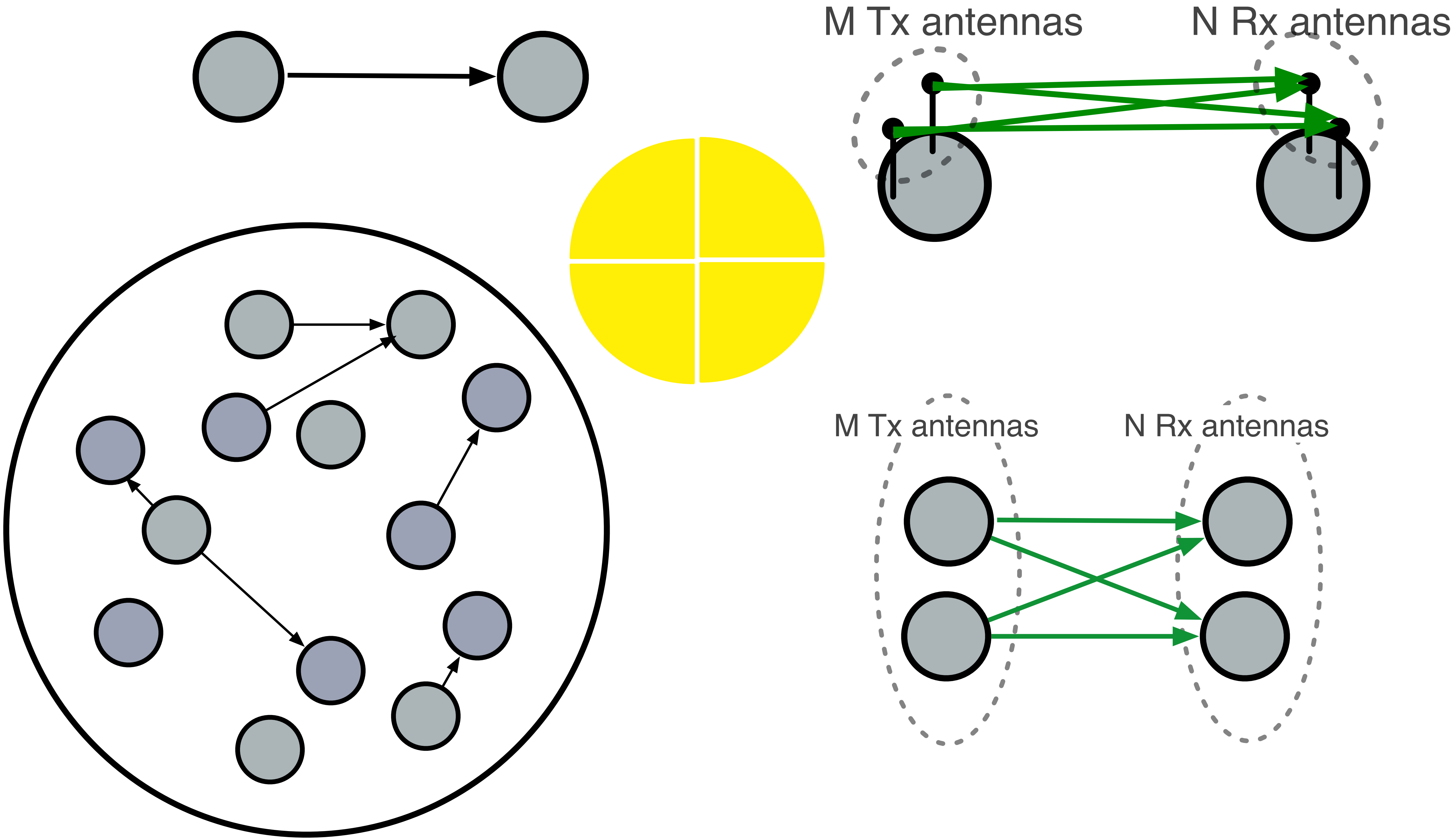
Efficient, reliable communication



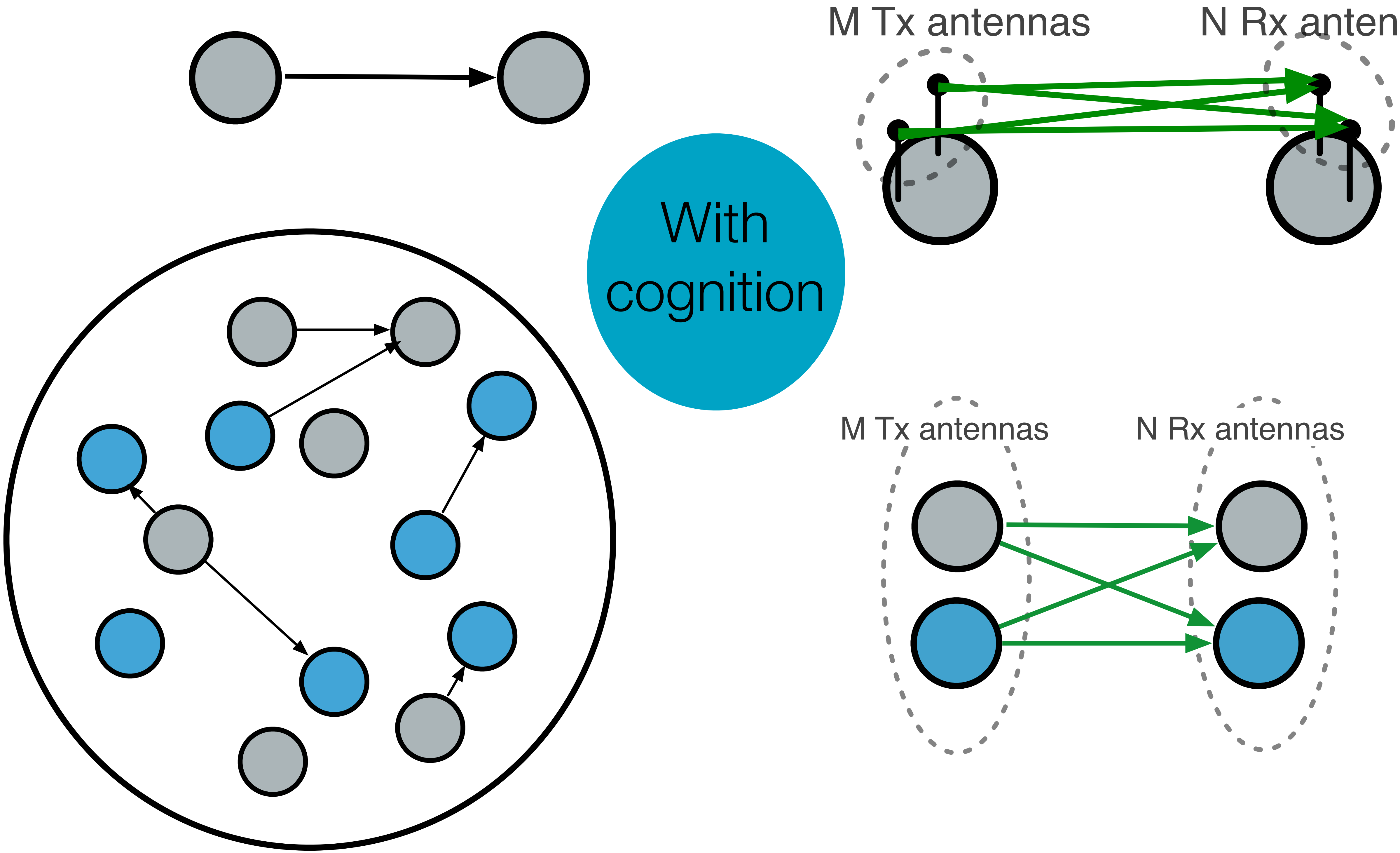




Efficient, reliable communication



Efficient, reliable communications



M Tx antennas

N Rx antennas

With cognition

M Tx antennas

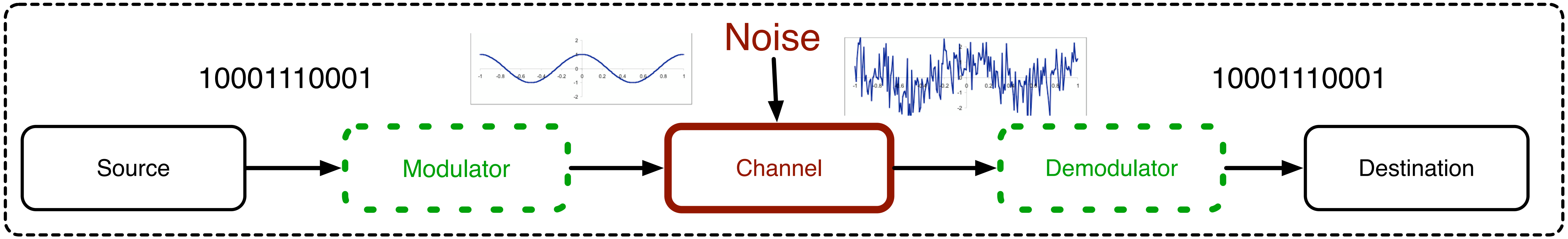
N Rx antennas

Radio

Software-defined Radio =SDR

Cognitive Radio = CR

Radio



10001110001

Noise

10001110001

Source

Modulator

Channel

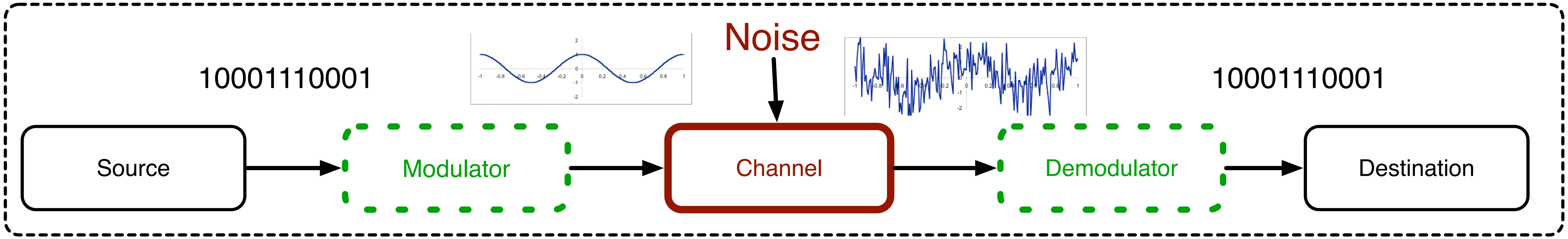
Demodulator

Destination

Software-defined Radio =SDR

Cognitive Radio = CR

Radio



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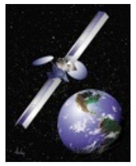
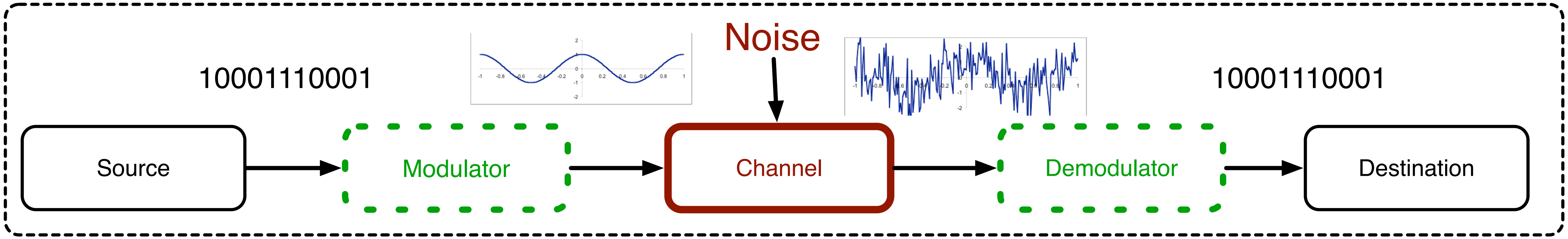




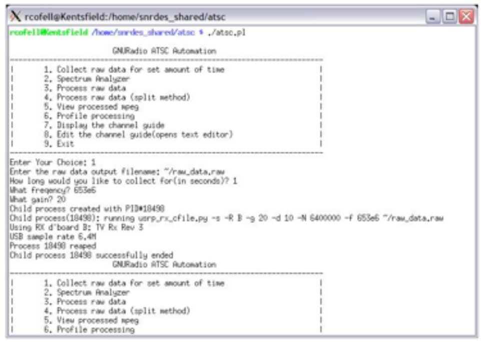
Noise

10001110001

10001110001

Source → Modulator → Channel → Demodulator → Destination

Software-defined Radio =SDR



```
rcofell@Kentsfield /home/snrdes_shared/atsc $ ./atsc.pl

                         GNURadio ATSC Automation
--------------------------------------------------------------------------
|       1. Collect raw data for set amount of time                       |
|       2. Spectrum Analyzer                                             |
|       3. Process raw data                                              |
|       4. Process raw data (split method)                               |
|       5. View processed mpeg                                           |
|       6. Profile processing                                            |
|       7. Display the channel guide                                     |
|       8. Edit the channel guide(opens text editor)                     |
|       9. Exit                                                          |
--------------------------------------------------------------------------
Enter Your Choice: 1
Enter the raw data output filename: ~/raw_data.raw
How long would you like to collect for(in seconds)? 1
What freqency? 653e6
What gain? 20
Child process created with PID#18498
Child process(18498): running usrp_rx_cfile.py -s -R B -g 20 -d 10 -N 6400000 -f 653e6 ~/raw_data.raw
Using RX d'board B: TV Rx Rev 3
USB sample rate 6.4M
Process 18498 reaped
Child process 18498 successfully ended
                         GNURadio ATSC Automation
--------------------------------------------------------------------------
|       1. Collect raw data for set amount of time                       |
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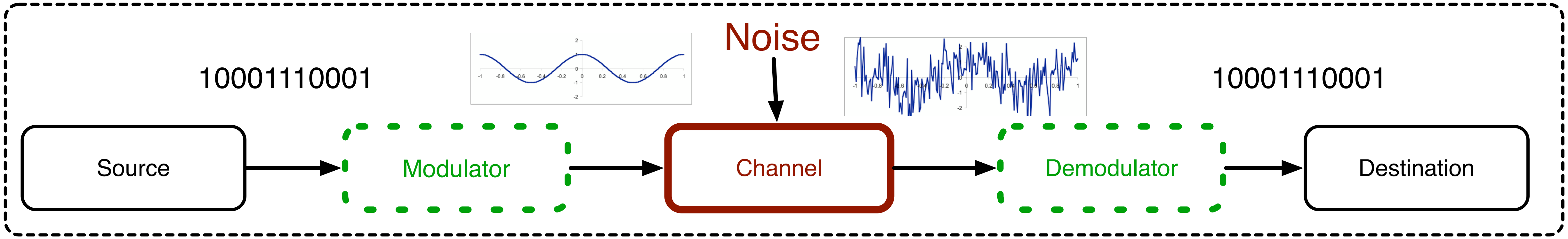
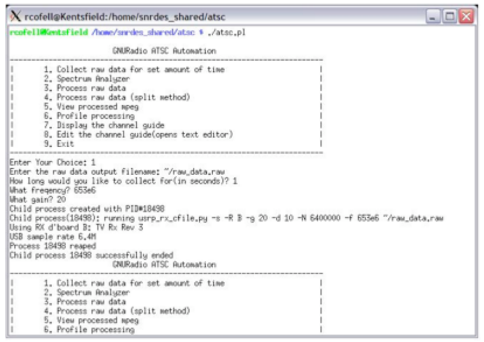
```

Cognitive Radio = CR

Radio



Software-defined Radio =SDR



```
rcofell@Kentsfield:/home/snrdes_shared/atsc
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                        GNURadio ATSC Automation
----------------------------------------------------------------------
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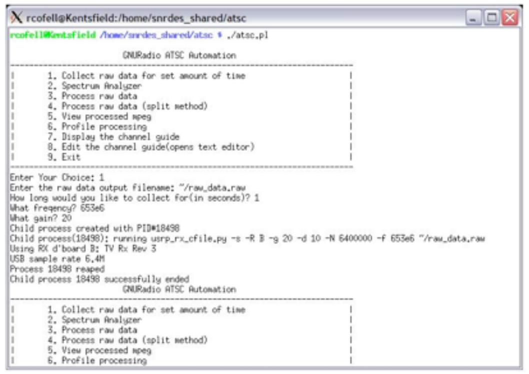
```

Cognitive Radio = CR



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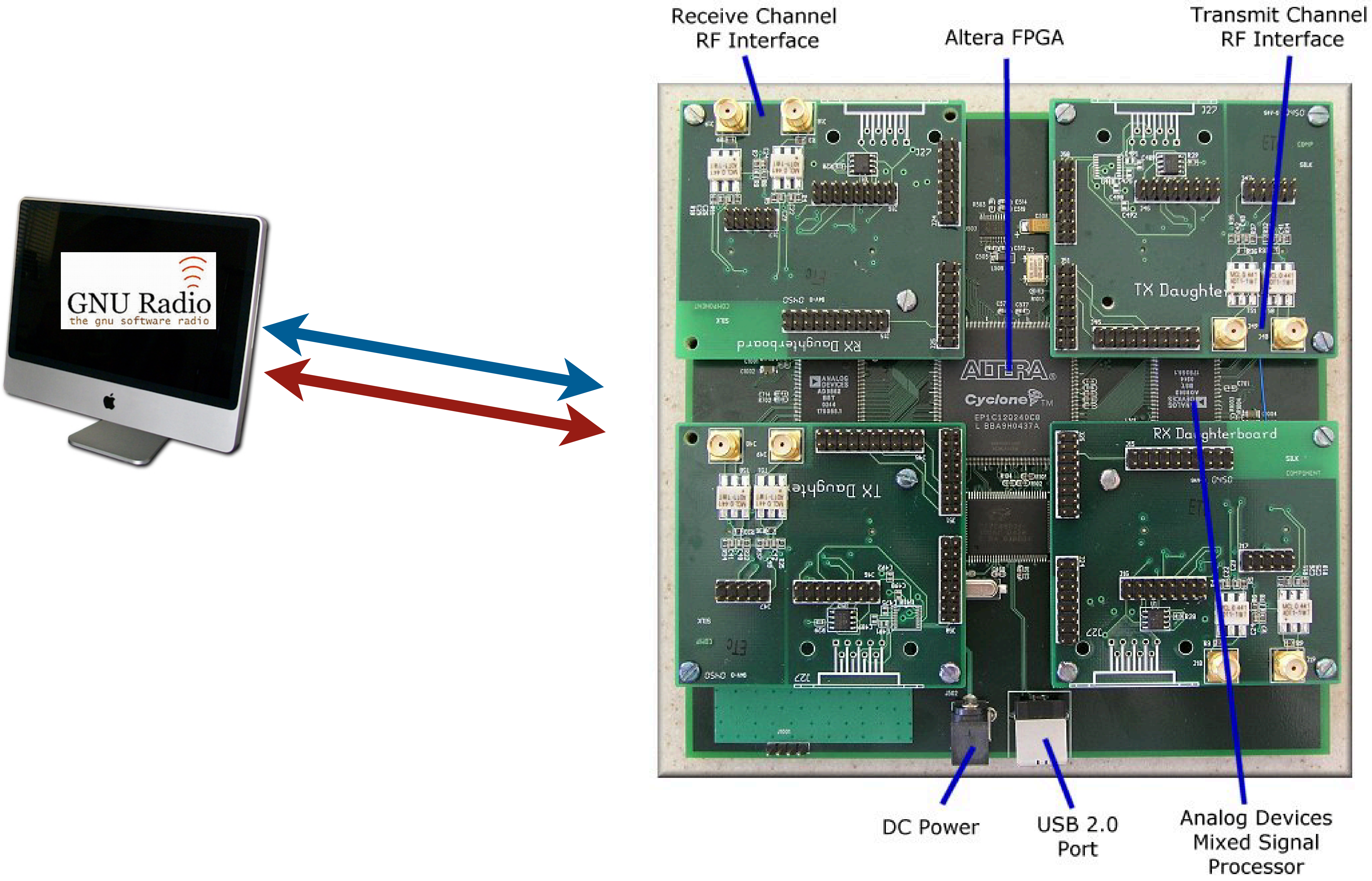
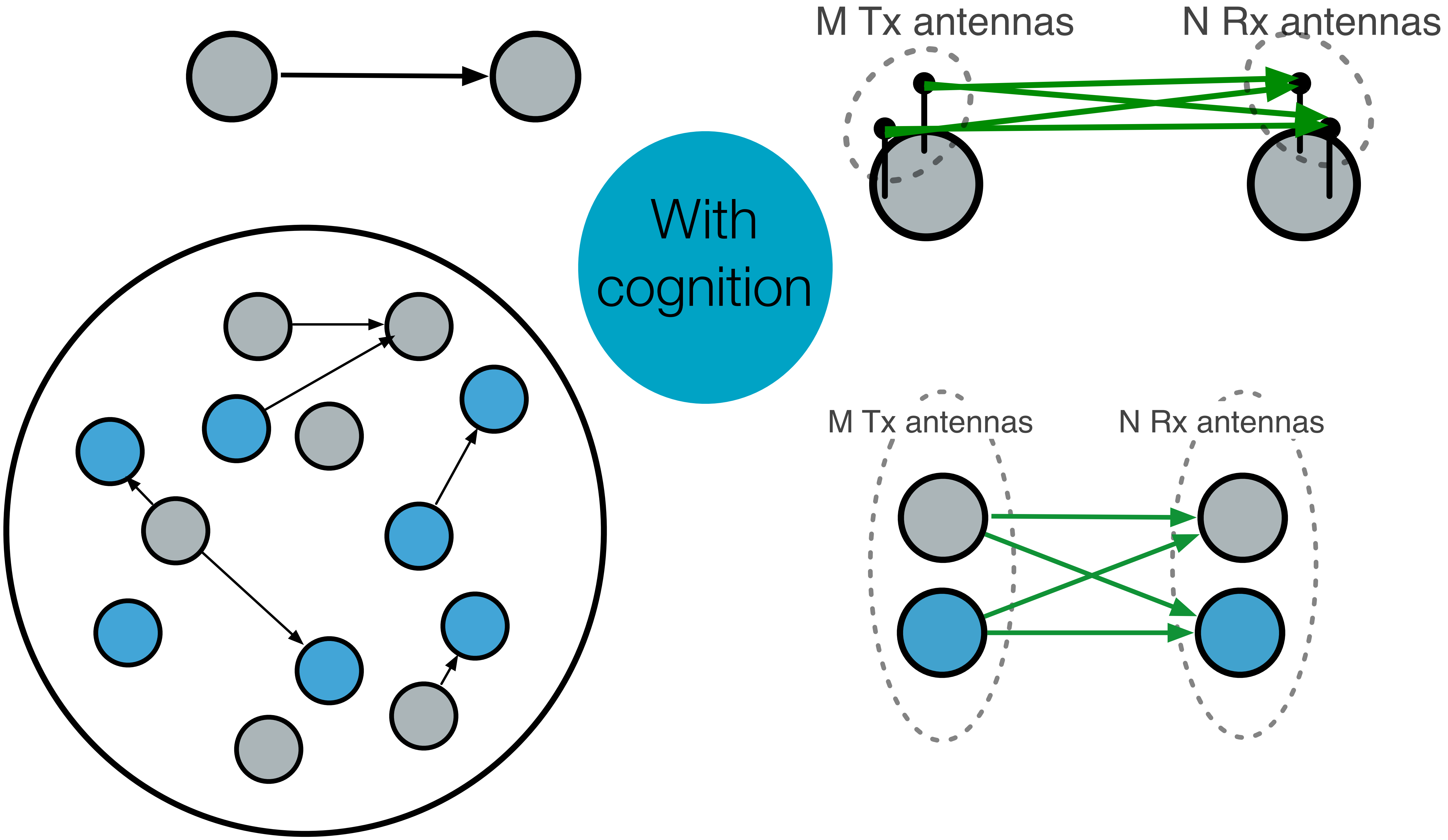
```

Example: GNU Radio+USRP




Ettus Research
USRP

Efficient, reliable communications



Capacity regions

↕

Fundamental Limits of Cognitive Networks

UIC University of Illinois at Chicago

Channel capacity

Channel capacity

Capacity $C = \max_{p(x)} I(X;Y)$ bits/channel use

Channel capacity

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$$I(X;Y) = \sum_{x,y} p(x,y) \log \left(\frac{p(x,y)}{p(x)p(y)} \right)$$

Channel capacity

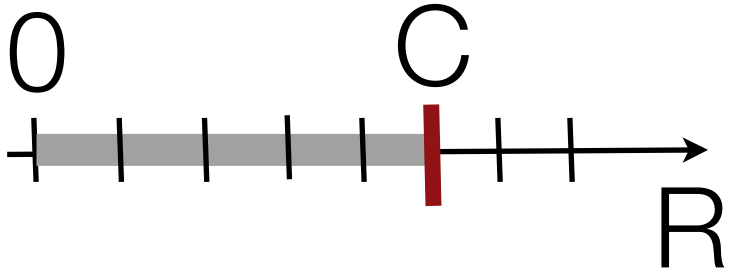
Capacity $$C = \max_{p(x)} I(X;Y)$$ bits/channel use

`Highest rate (bits/channel use) that can communicate at reliably`

Mathematical description of capacity

- Can achieve reliable communication for all transmission rates R:

$$R < C$$



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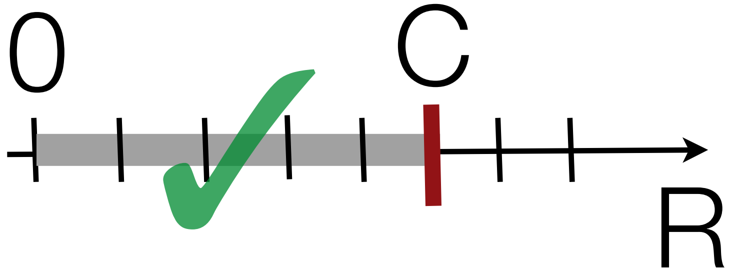

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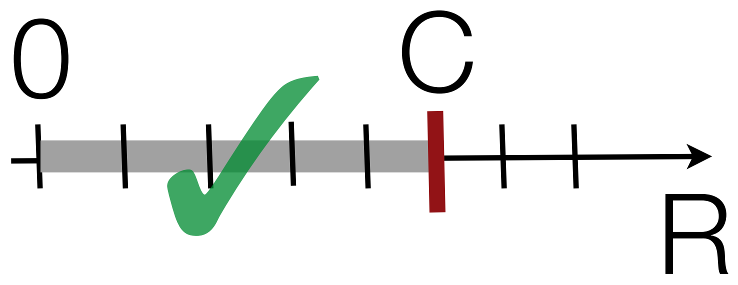
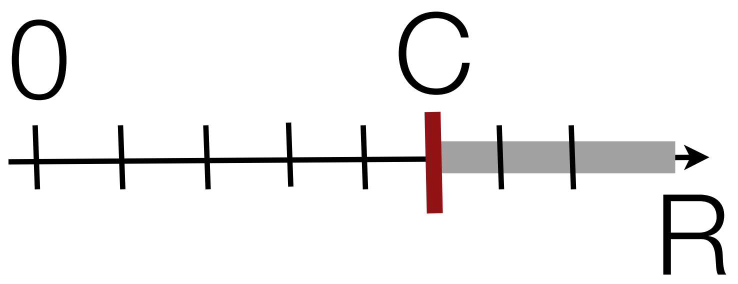


- BUT, probability of decoding error always bounded away from zero if

$R > C$



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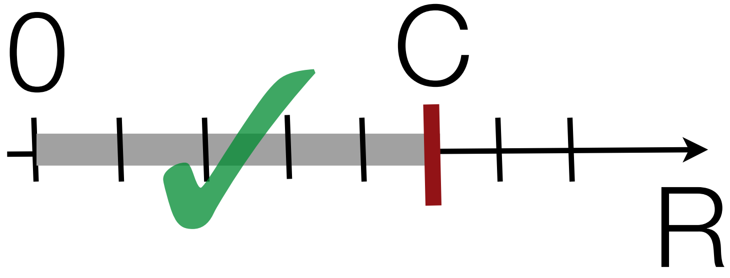

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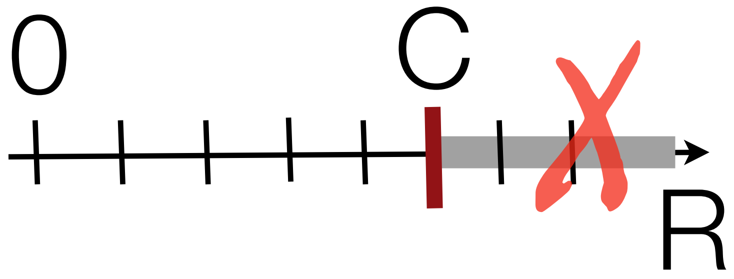
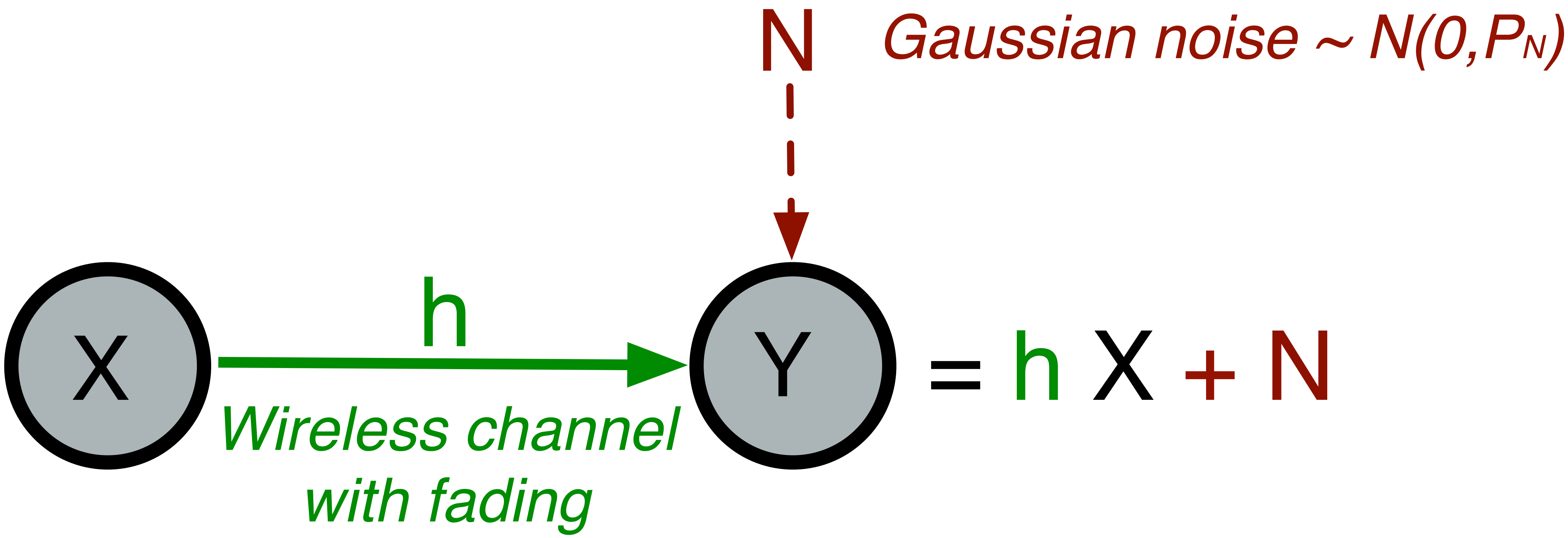


AWGN channel capacity



N *Gaussian noise ~ $N(0,P_N)$*

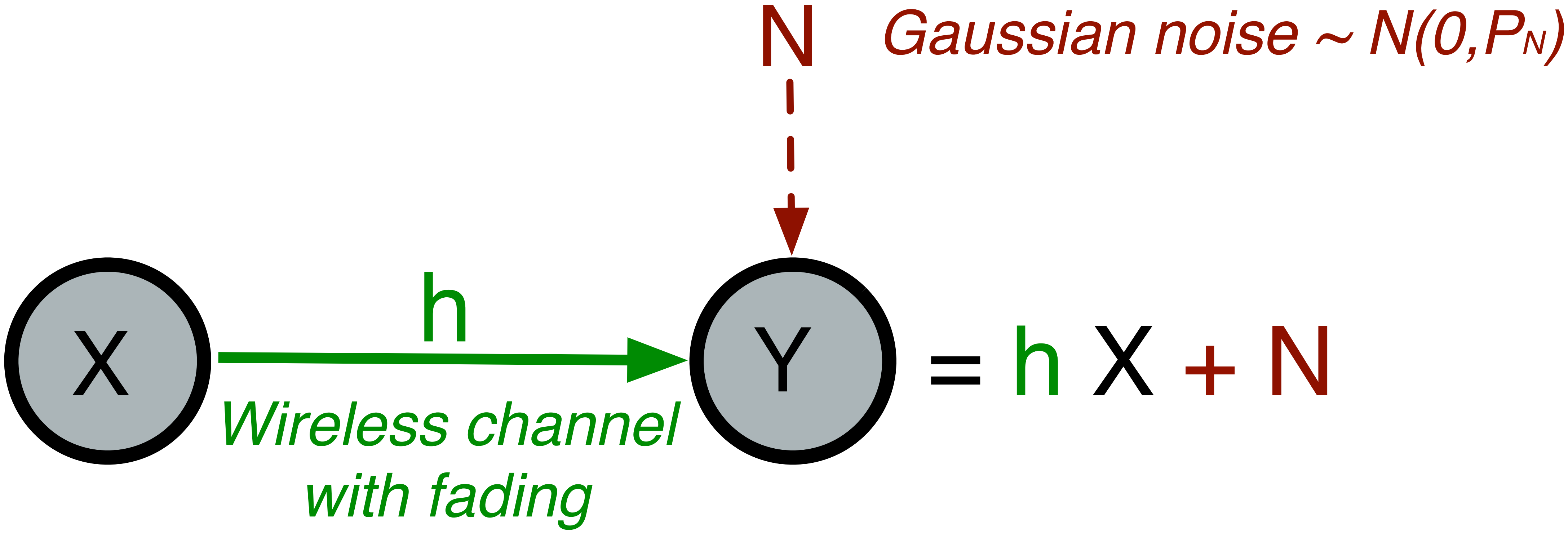
h

Wireless channel with fading

X

$Y = h X + N$

AWGN channel capacity



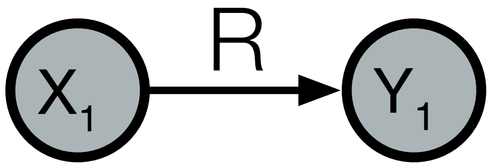
= h X + N

$$C = \frac{1}{2}\log\left(\frac{|h|^2 P + P_N}{P_N}\right)$$

$$= \frac{1}{2}\log(1 + SNR) \quad (\text{bits/channel use})$$

Capacity and capacity regions

- Point to point **capacity**



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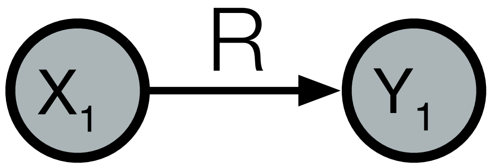
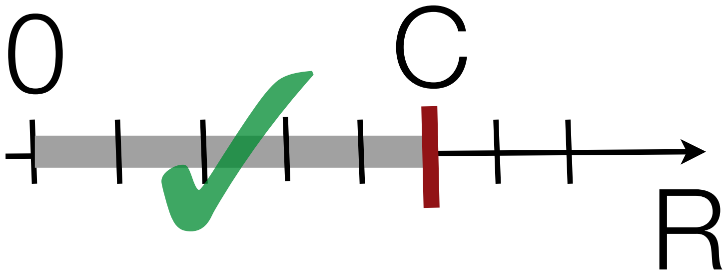
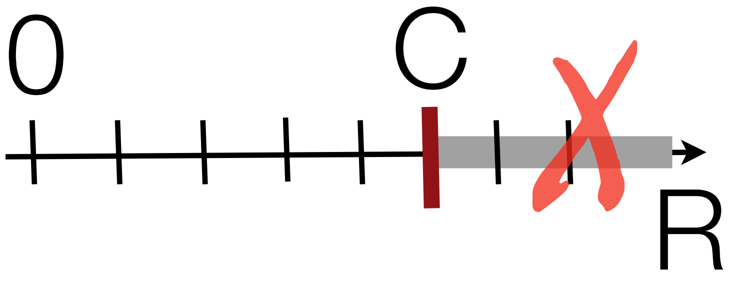
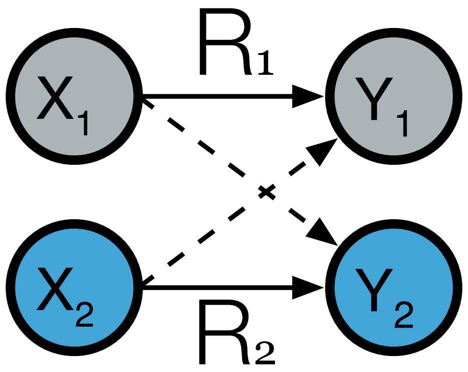
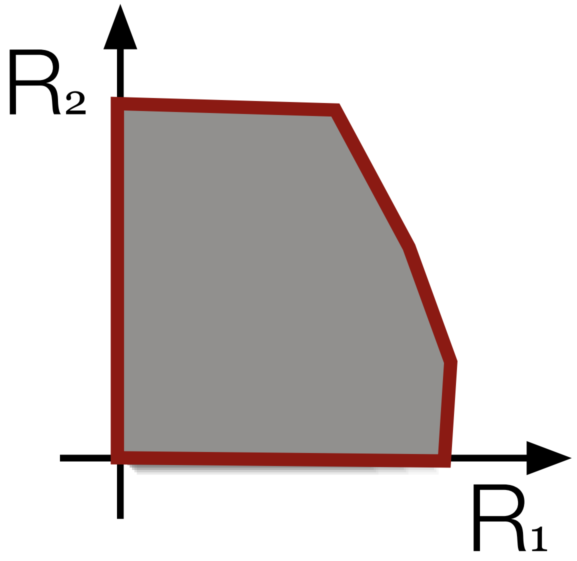


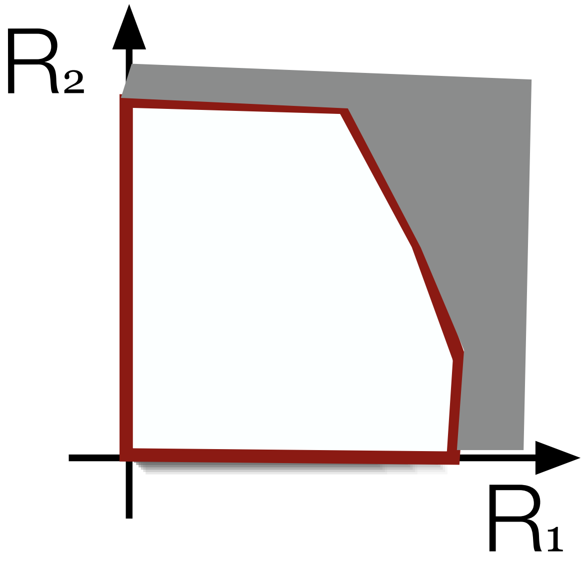




- Multi-user **capacity region**







Capacity and capacity regions

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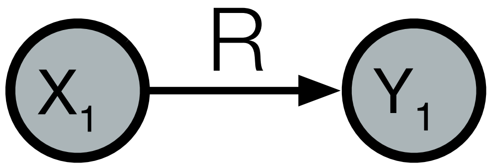

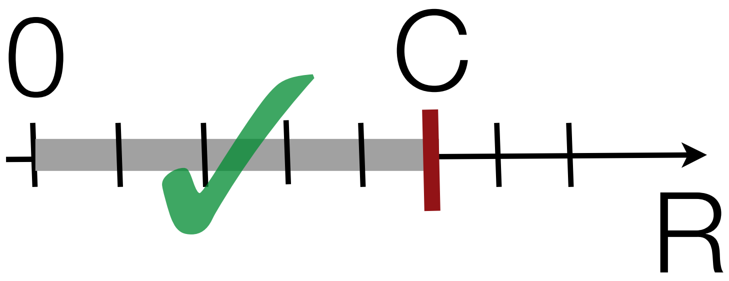

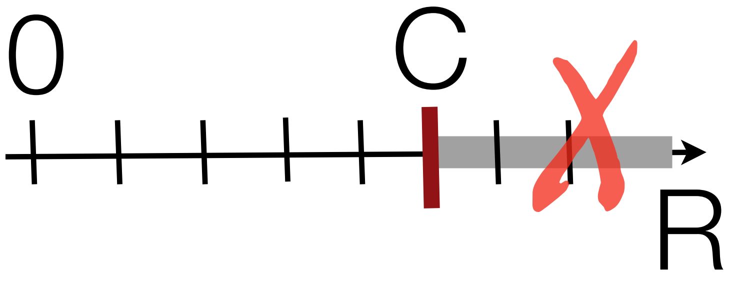

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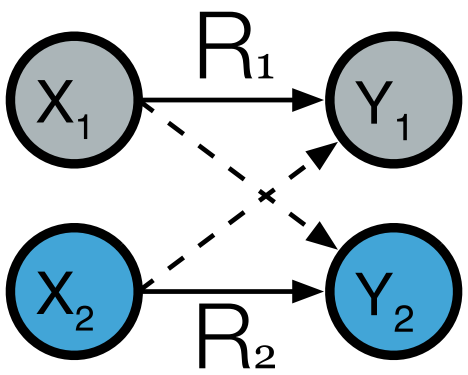

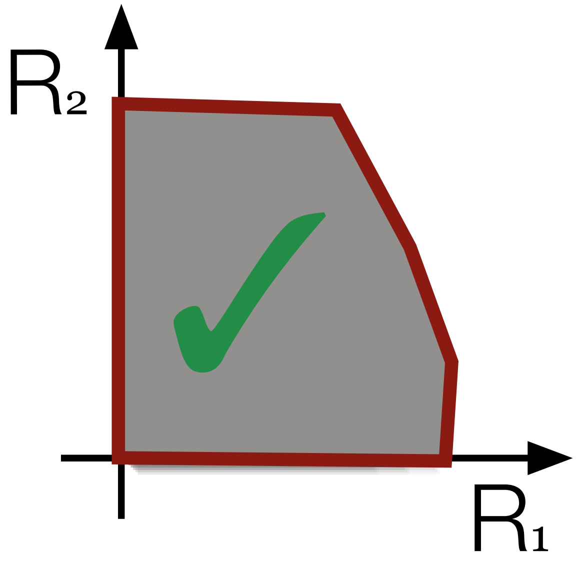

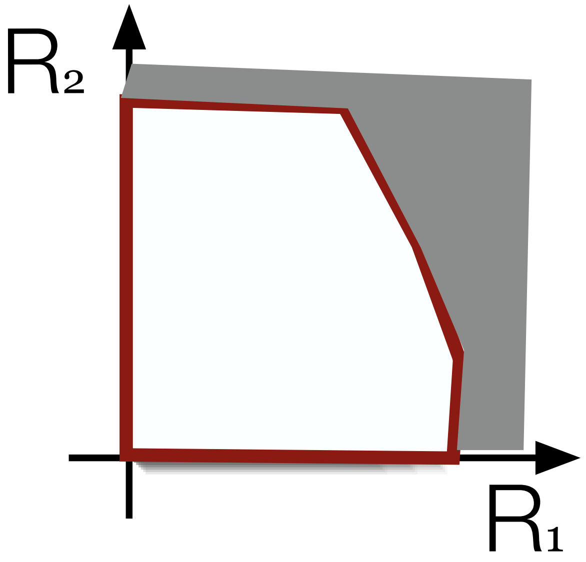

Capacity and capacity regions

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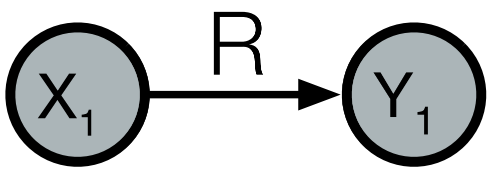

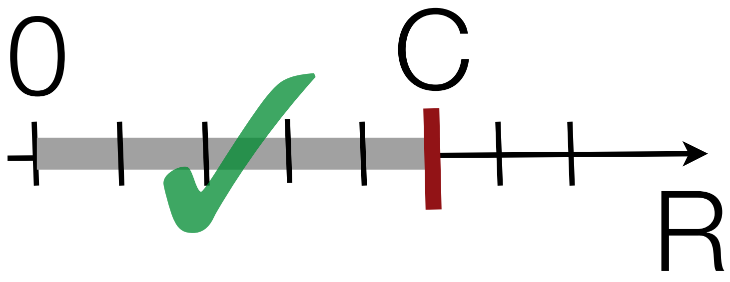

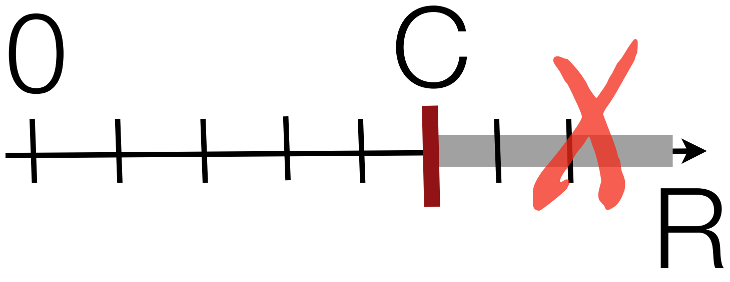

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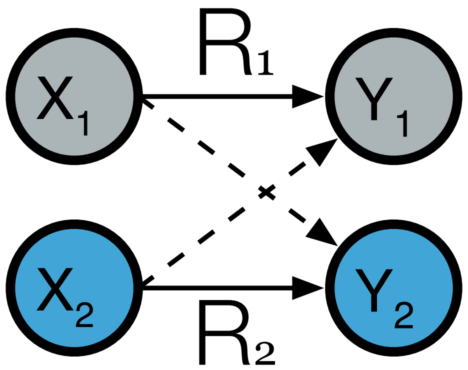
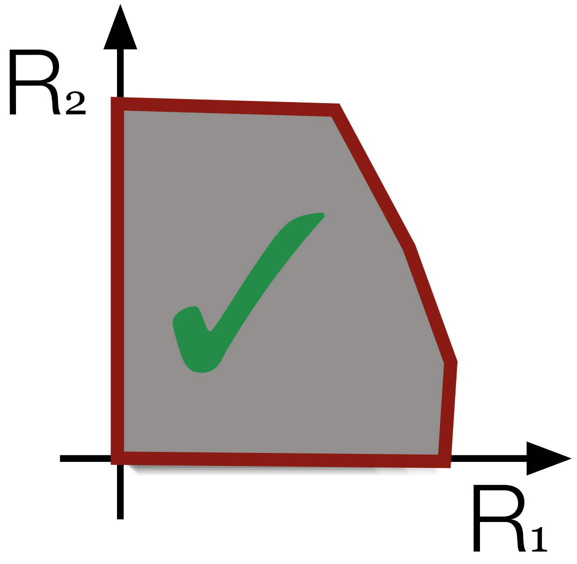
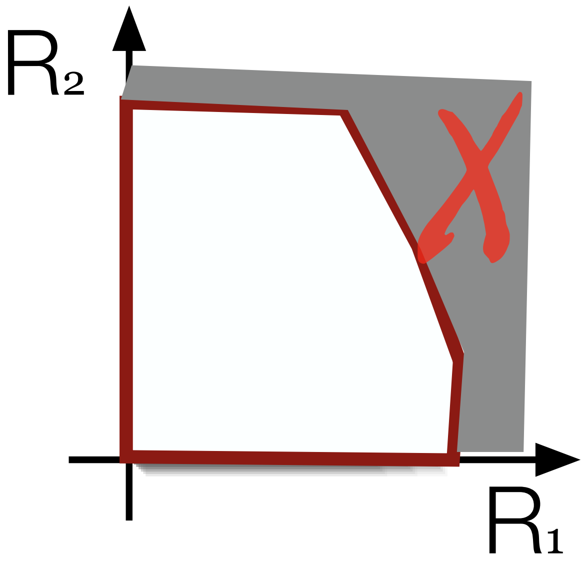
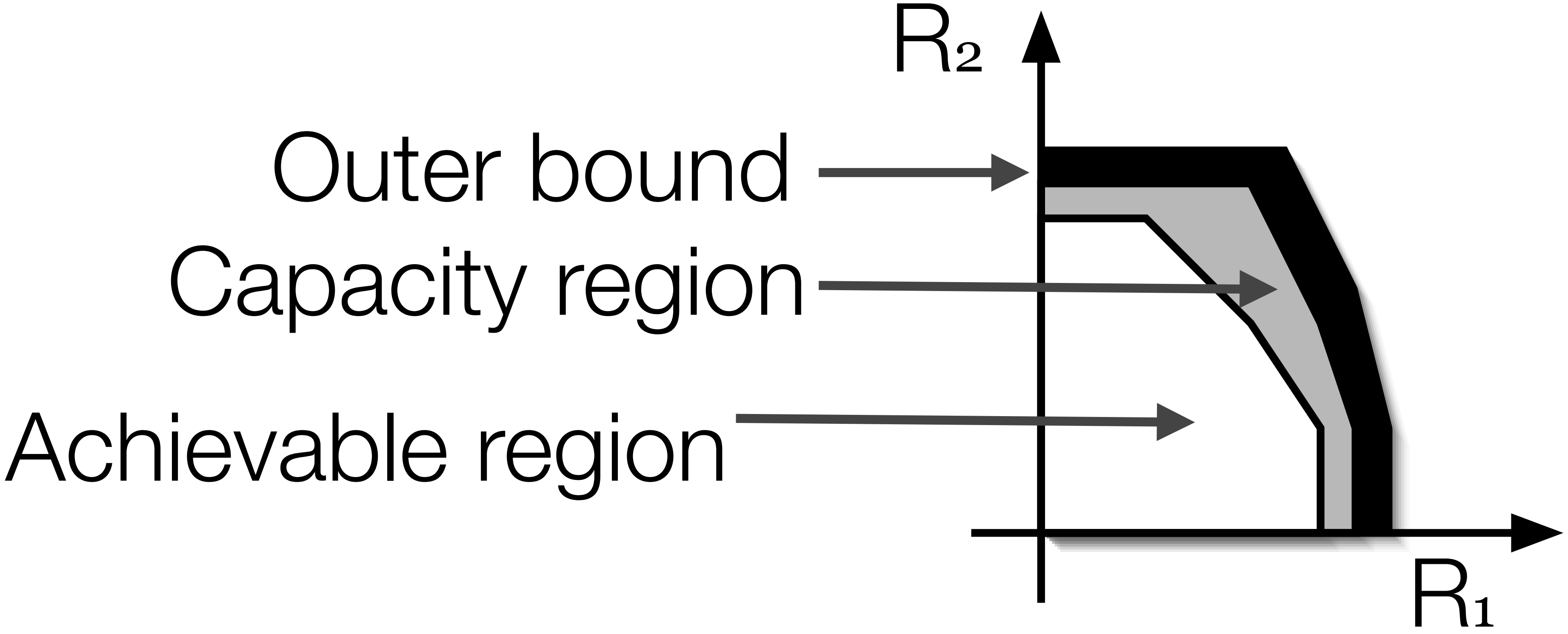






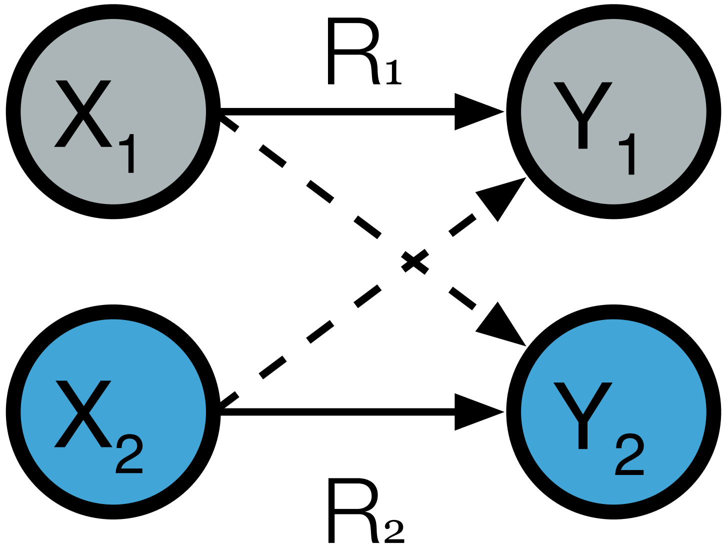
Capacity regions



Outer bound

Capacity region

Achievable region

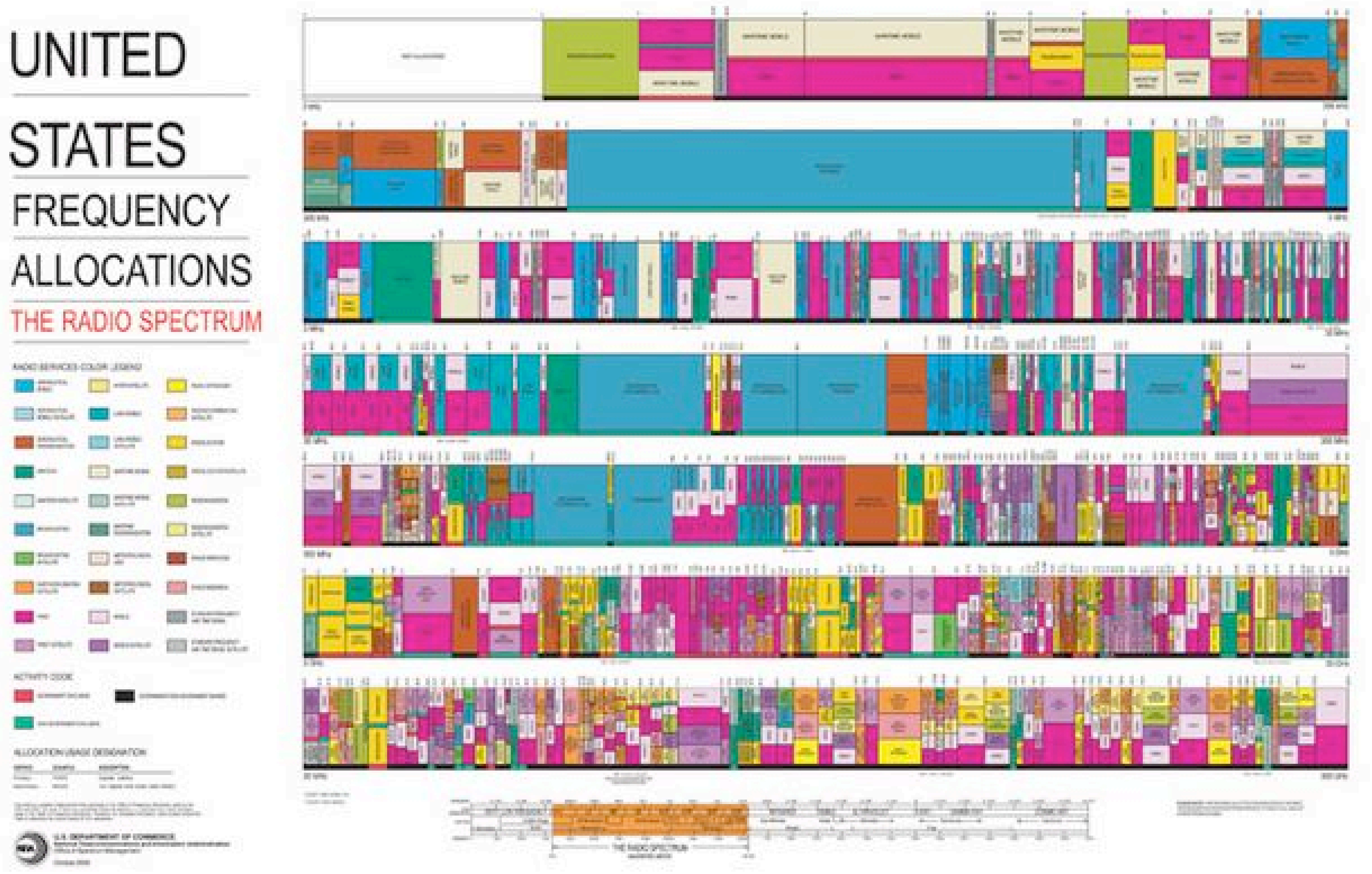


Fundamental Limits of Cognitive Networks

Motivation?

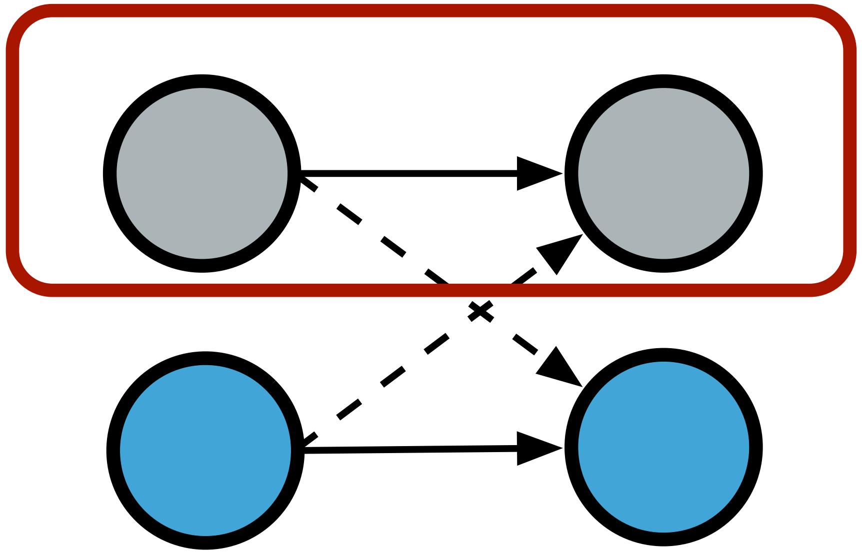
Motivation 1: smart cognitive devices

Motivation 2: spectral efficiency



Spectrum licensing: future

Primary users/ primary license holders



Spectrum licensing: future

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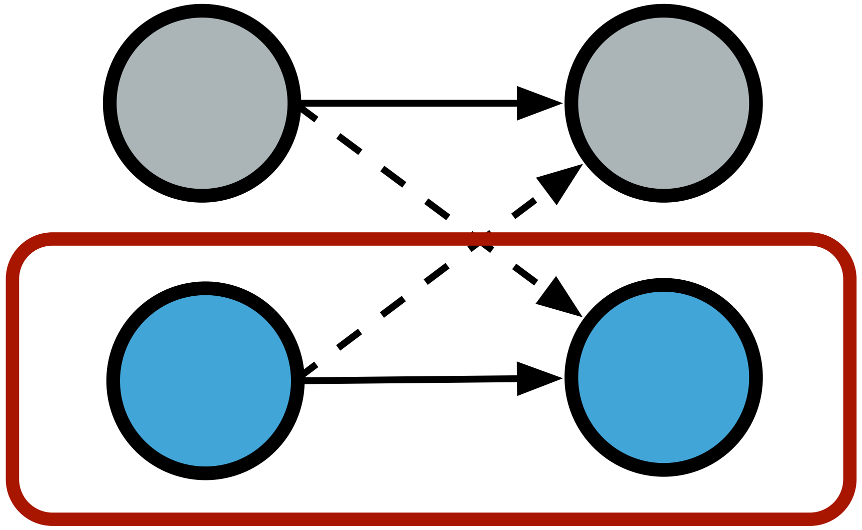
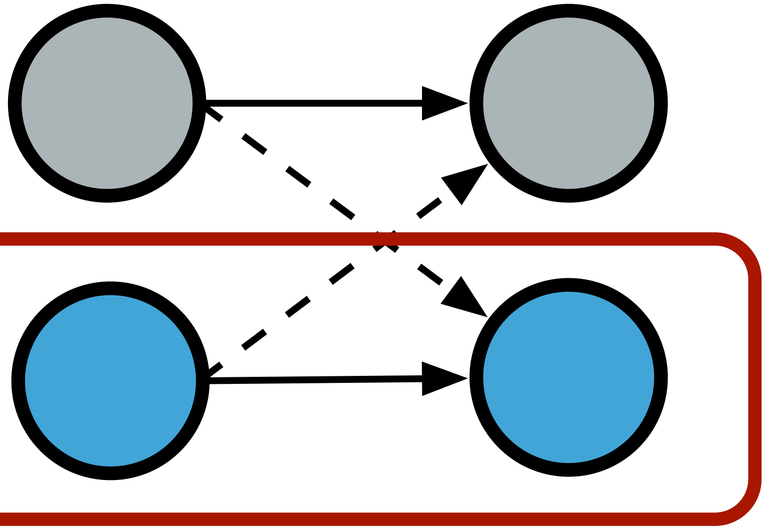


Secondary users

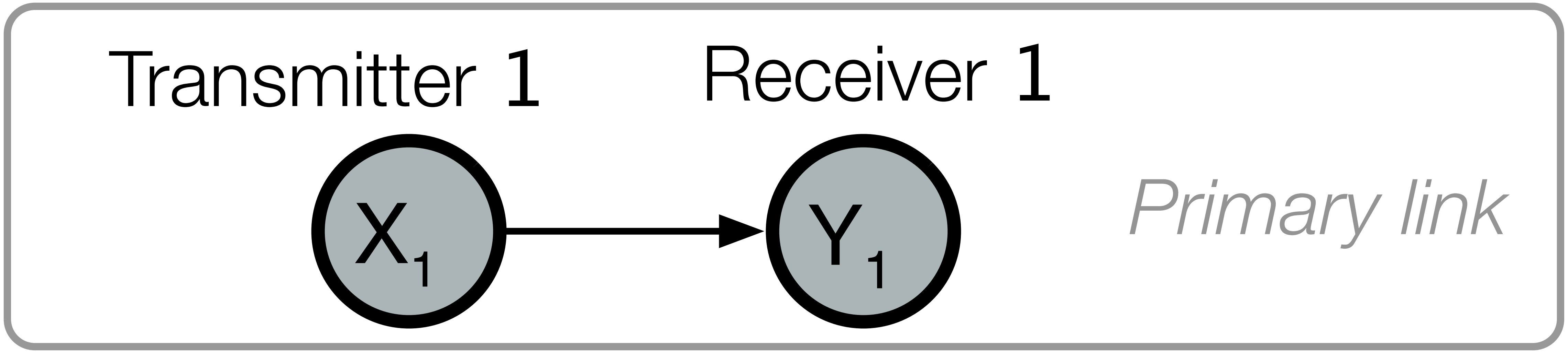
Spectrum licensing: future

Primary users/ primary license holders



Secondary users ⟷ Cognitive radios

Secondary spectrum usage



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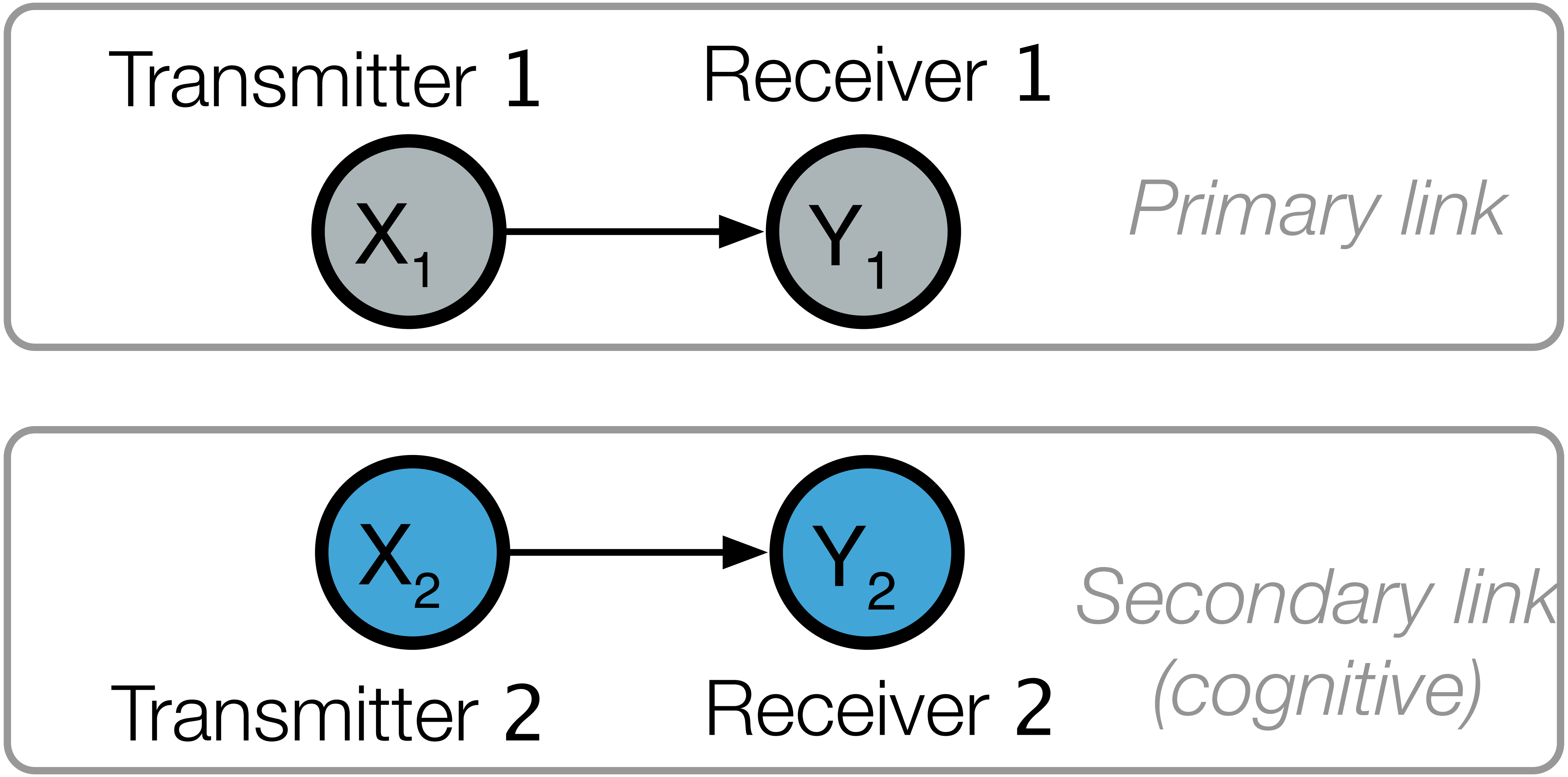


Transmitter 1

Receiver 1

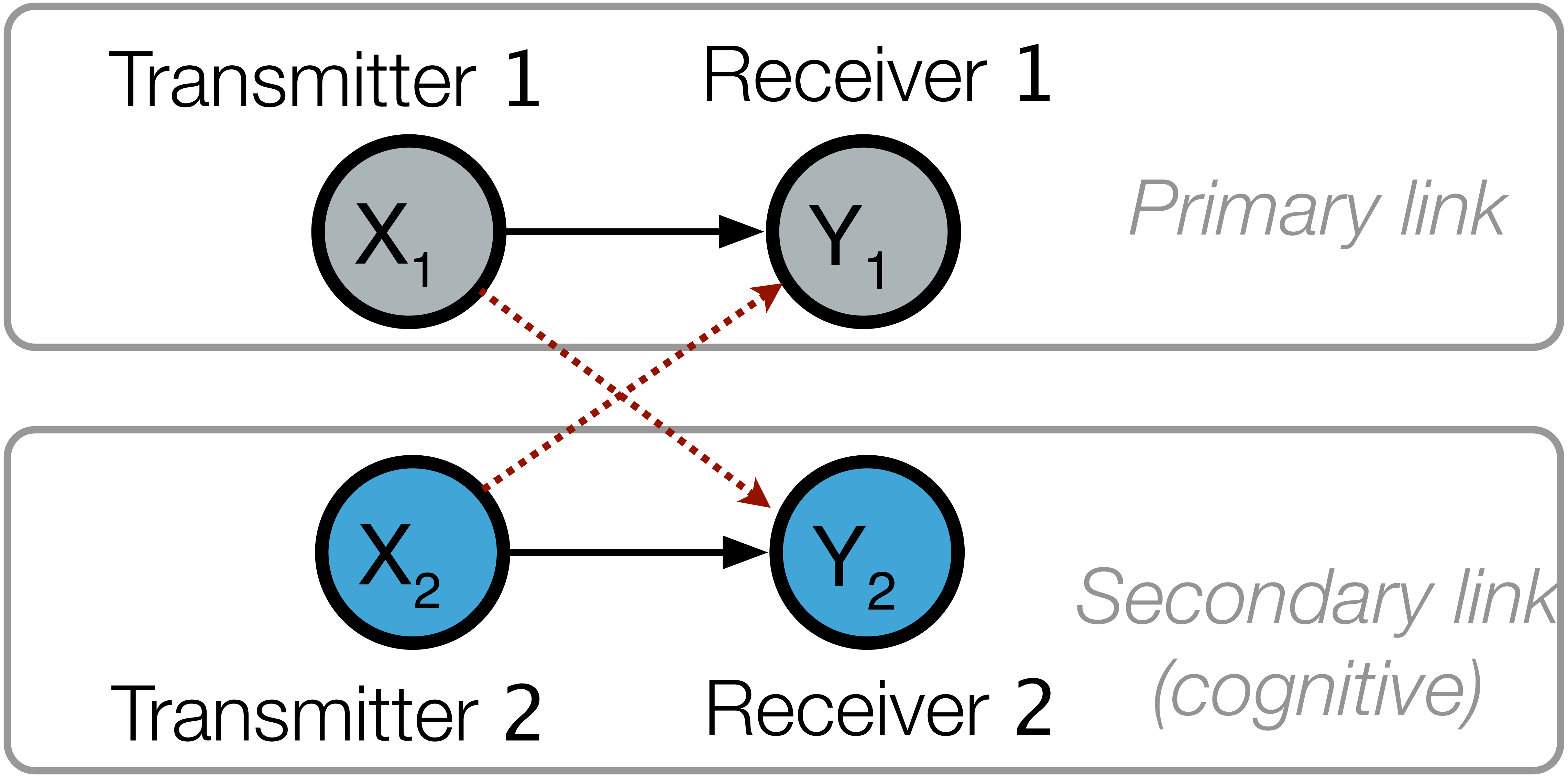
Primary link

Transmitter 2

Receiver 2

Secondary link (cognitive)

Secondary spectrum usage



Transmitter 1

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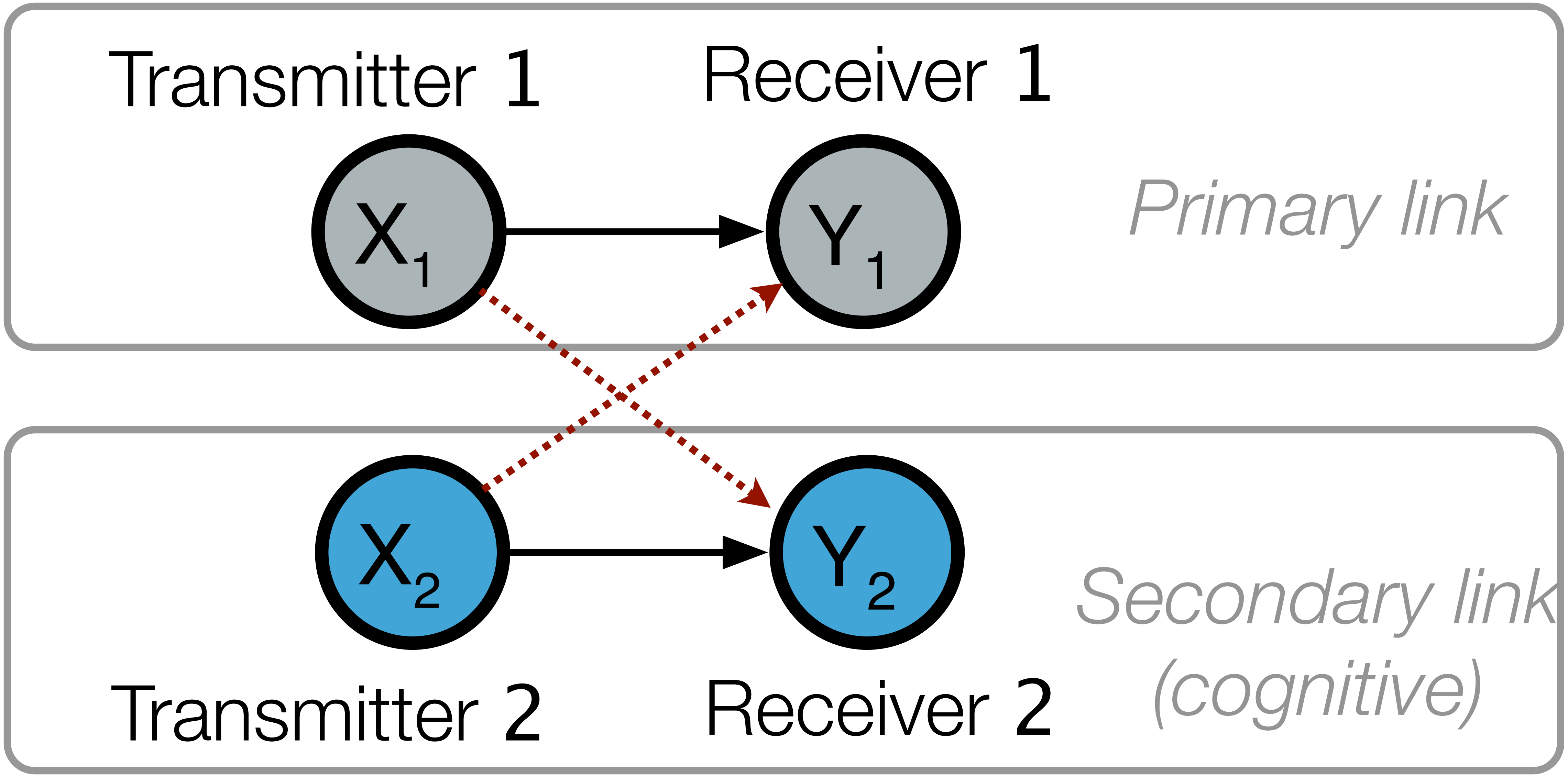
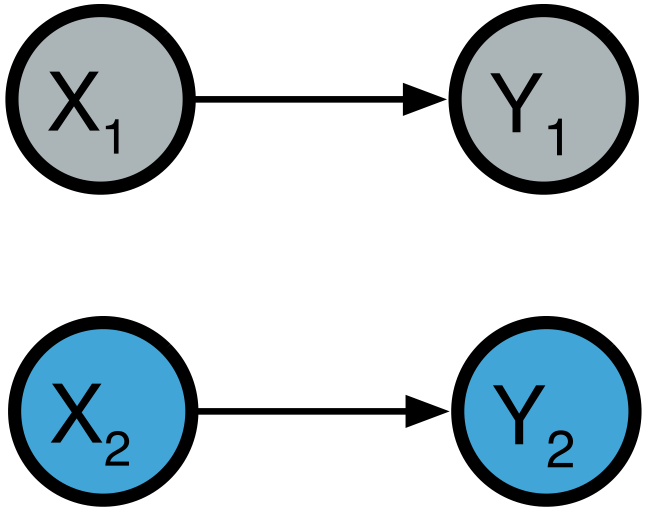
Secondary link (cognitive)

Secondary spectrum usage



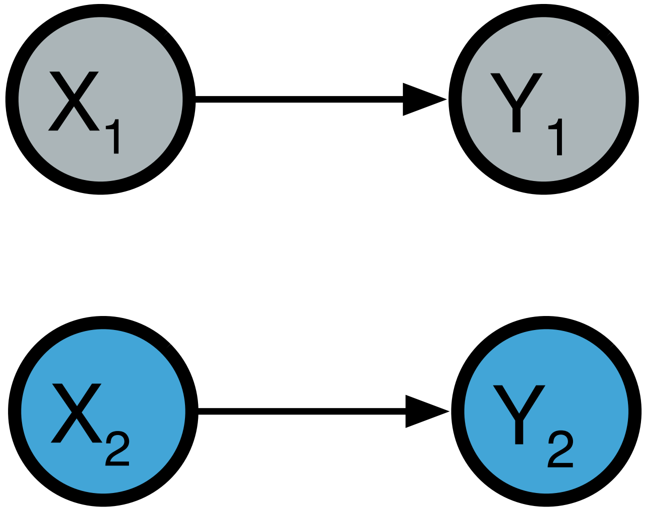
What can the cognitive link do?

Cognition



- Assumptions on primary/secondary models will dictate behavior + performance

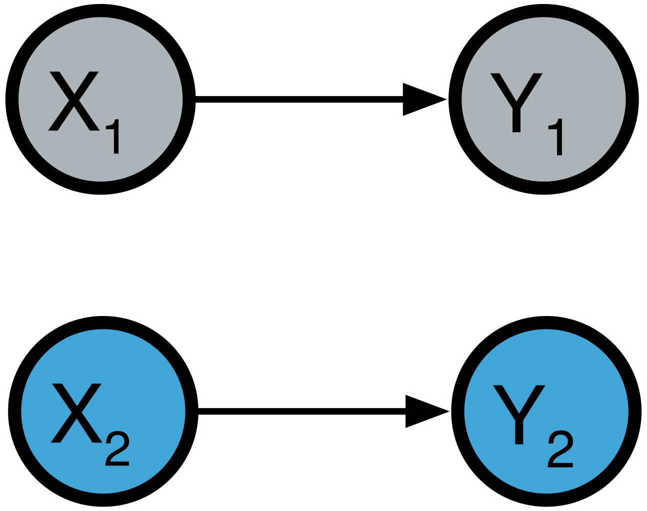
Cognition



- Assumptions on primary/secondary models will dictate behavior + performance

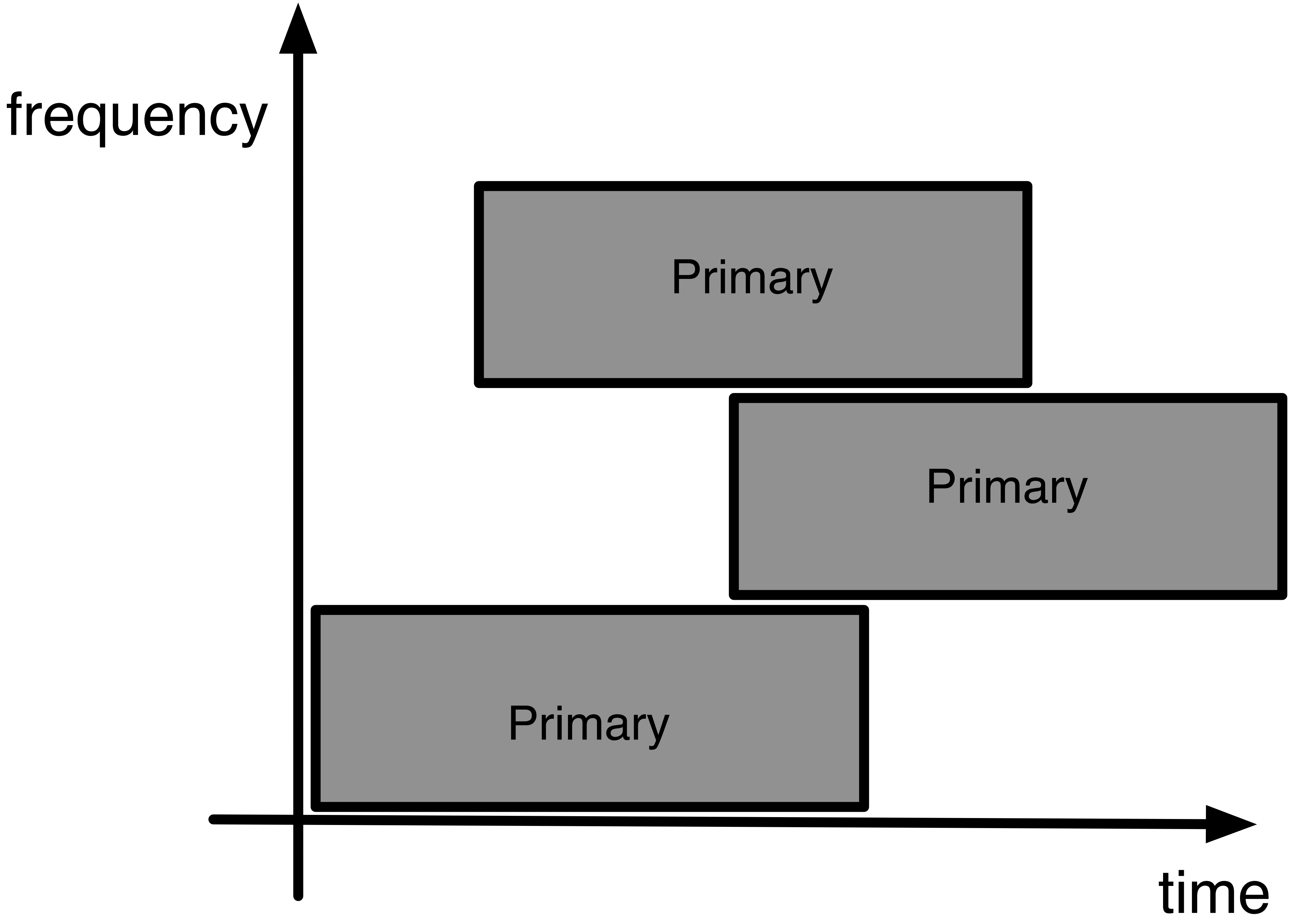
- Cognition boils down to **side-information** and how to use it

Cognition

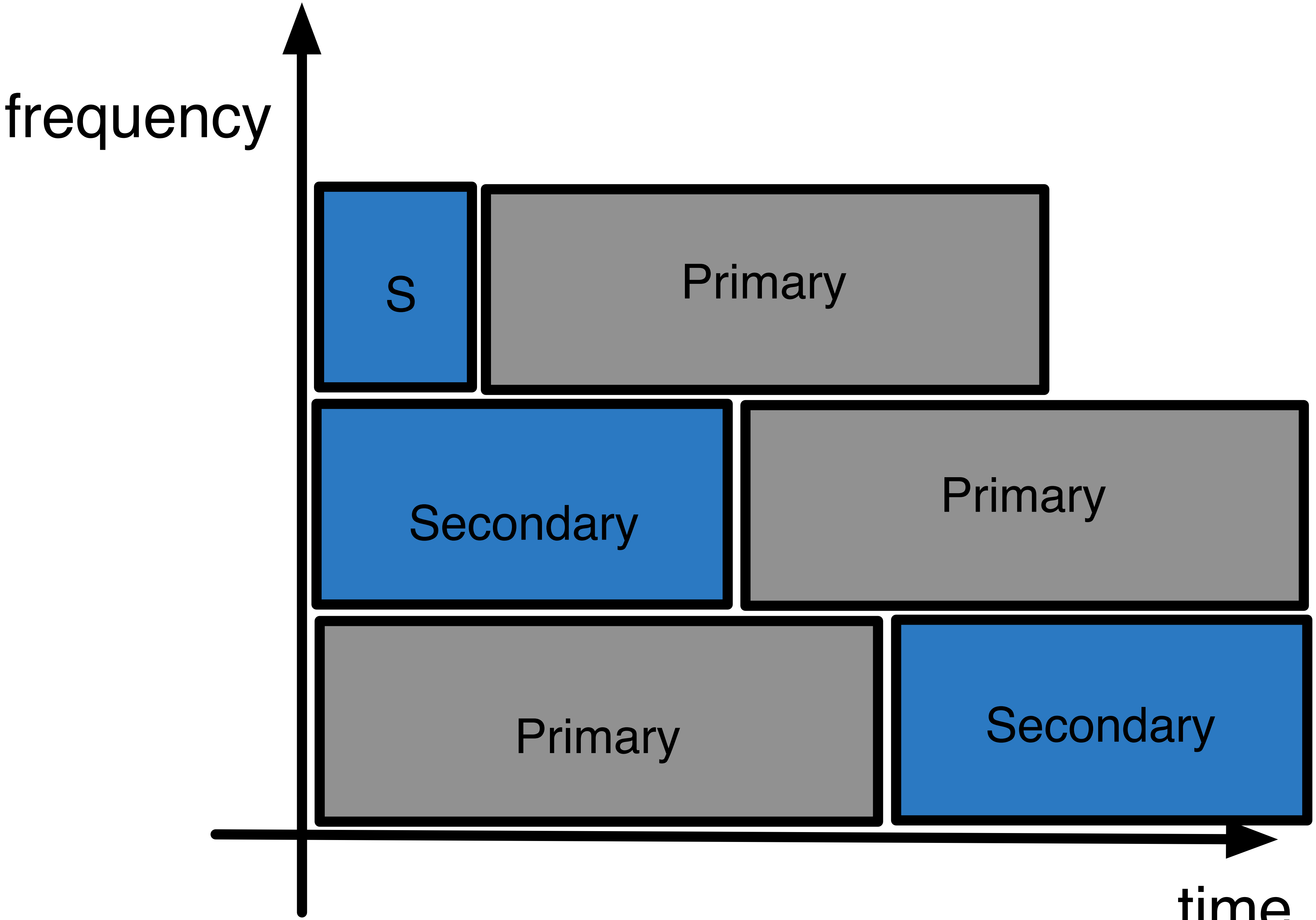


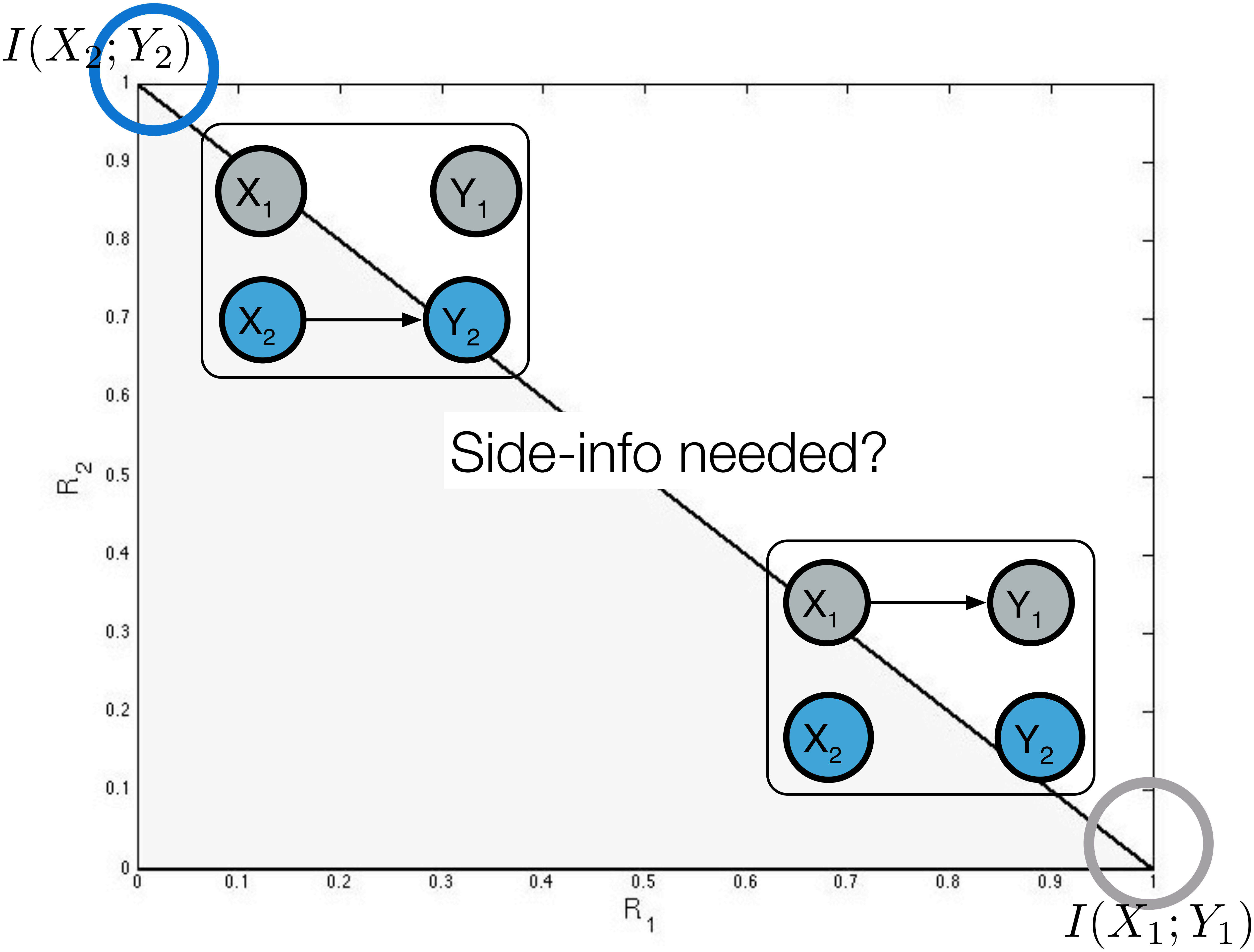
- Assumptions on primary/secondary models will dictate behavior + performance
- Cognition boils down to **side-information** and how to use it
- Use information theory to tell us which techniques are most promising

1. White spaces



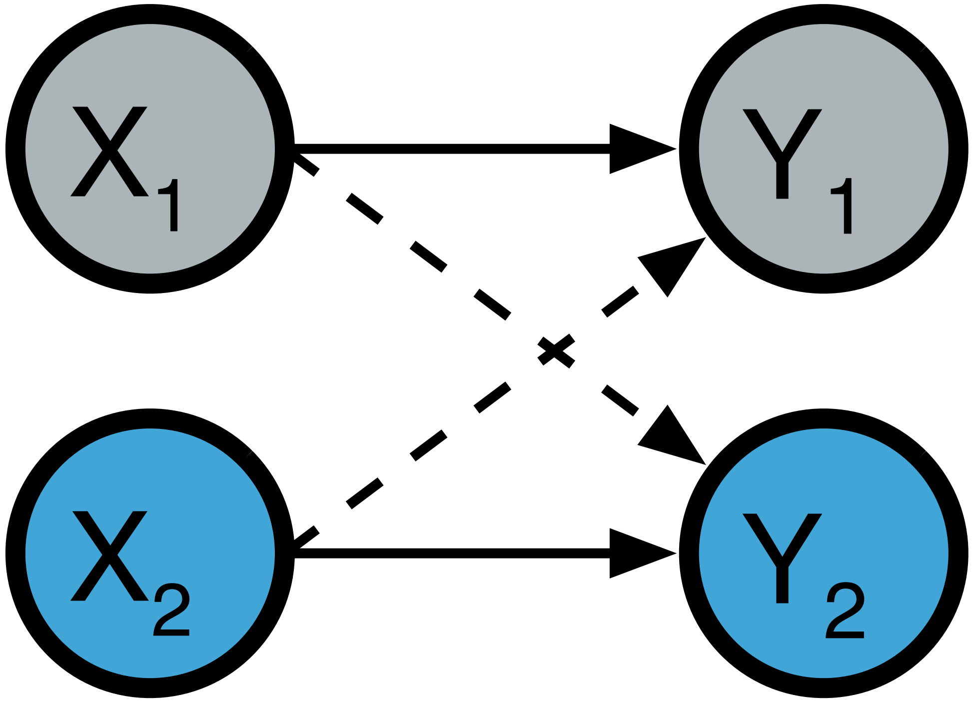
1. White spaces





Side-info needed?

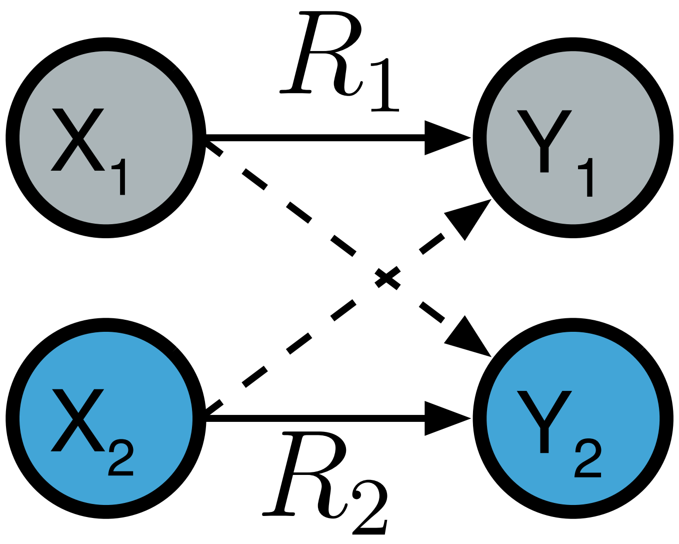
2. Just transmit



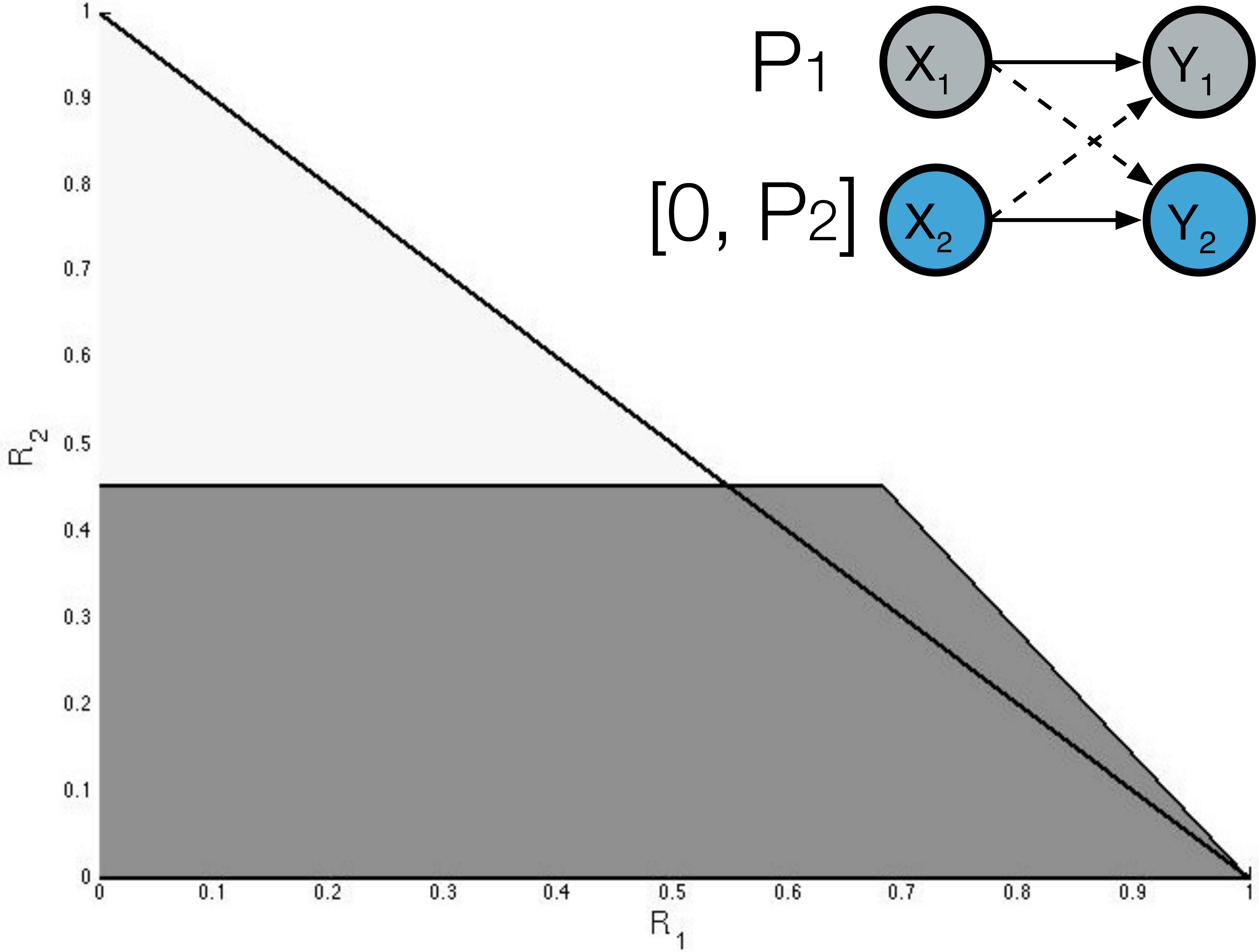
Interfere with each other!

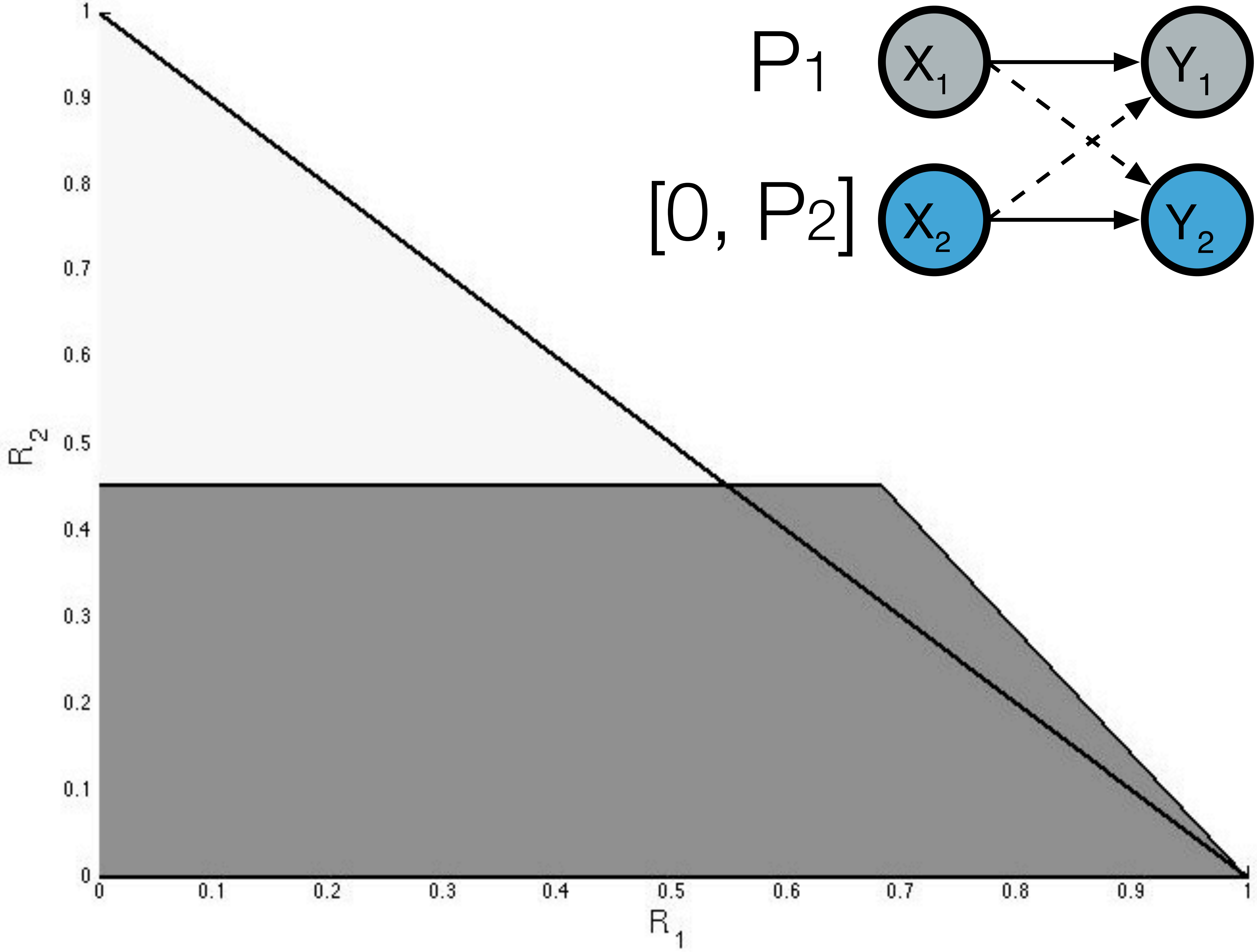
2. Just transmit

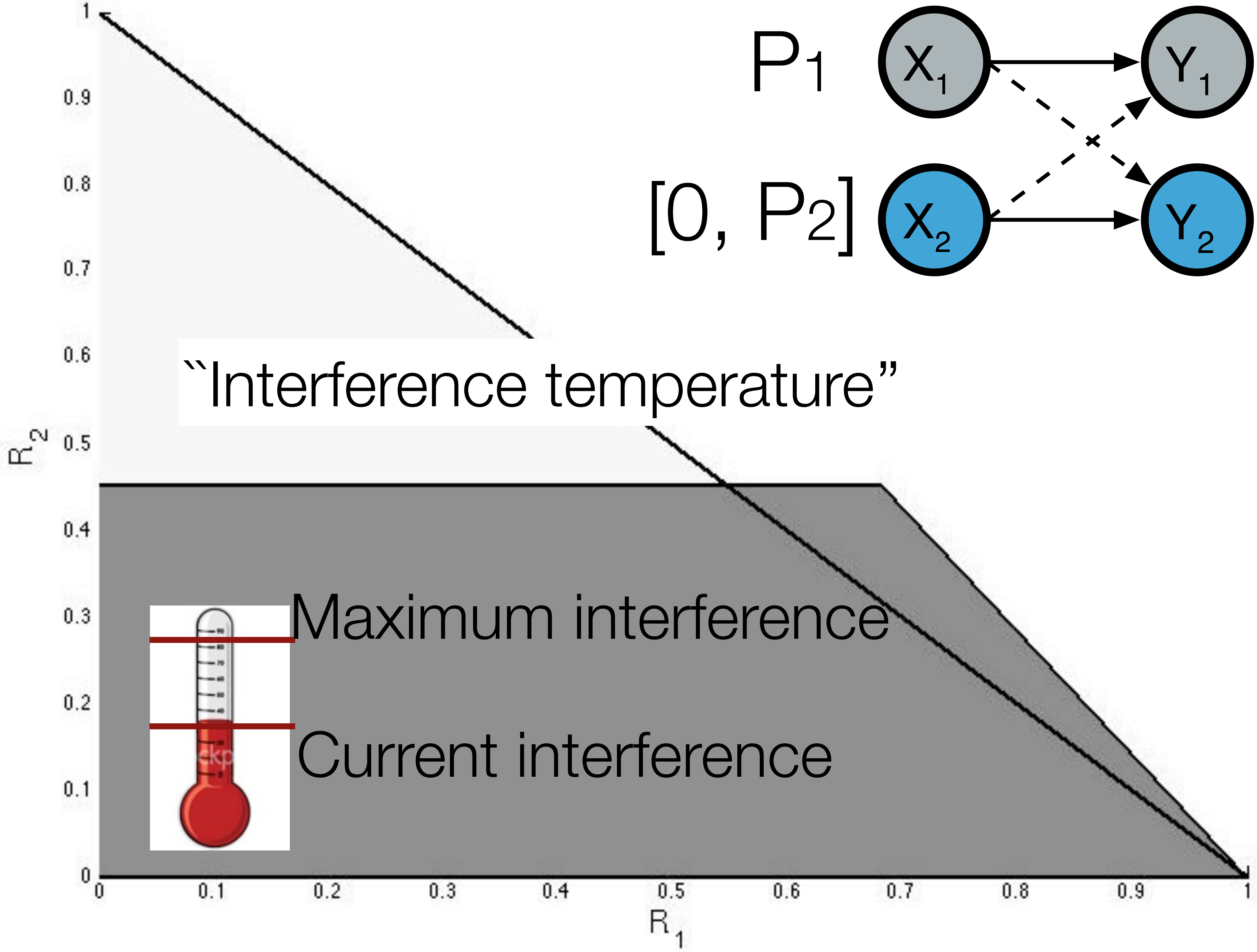
$$R_1 \le \frac{1}{2}\log_2\left(1 + \frac{\text{Power of signal 1}}{\text{Interference from signal 2} + \text{ Noise}}\right)$$



$$R_2 \le \frac{1}{2}\log_2\left(1 + \frac{\text{Power of signal 2}}{\text{Interference from signal 1} + \text{ Noise}}\right)$$


P1
[0, P2]
X1
X2
Y1
Y2
R2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
R1

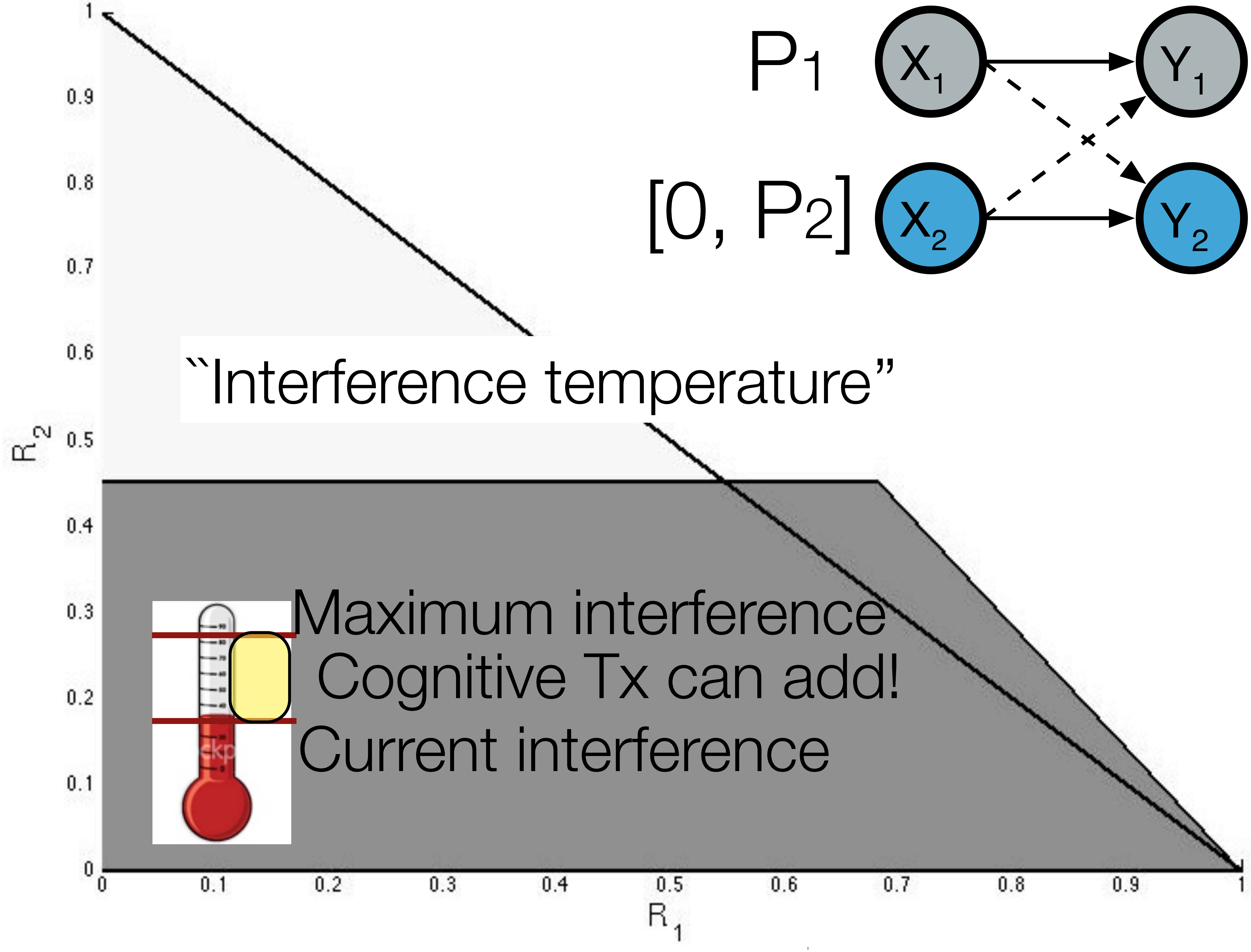

P1
[0, P2]
X_1
X_2
Y_1
Y_2
R_2
R_1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



“Interference temperature”

Maximum interference

Current interference

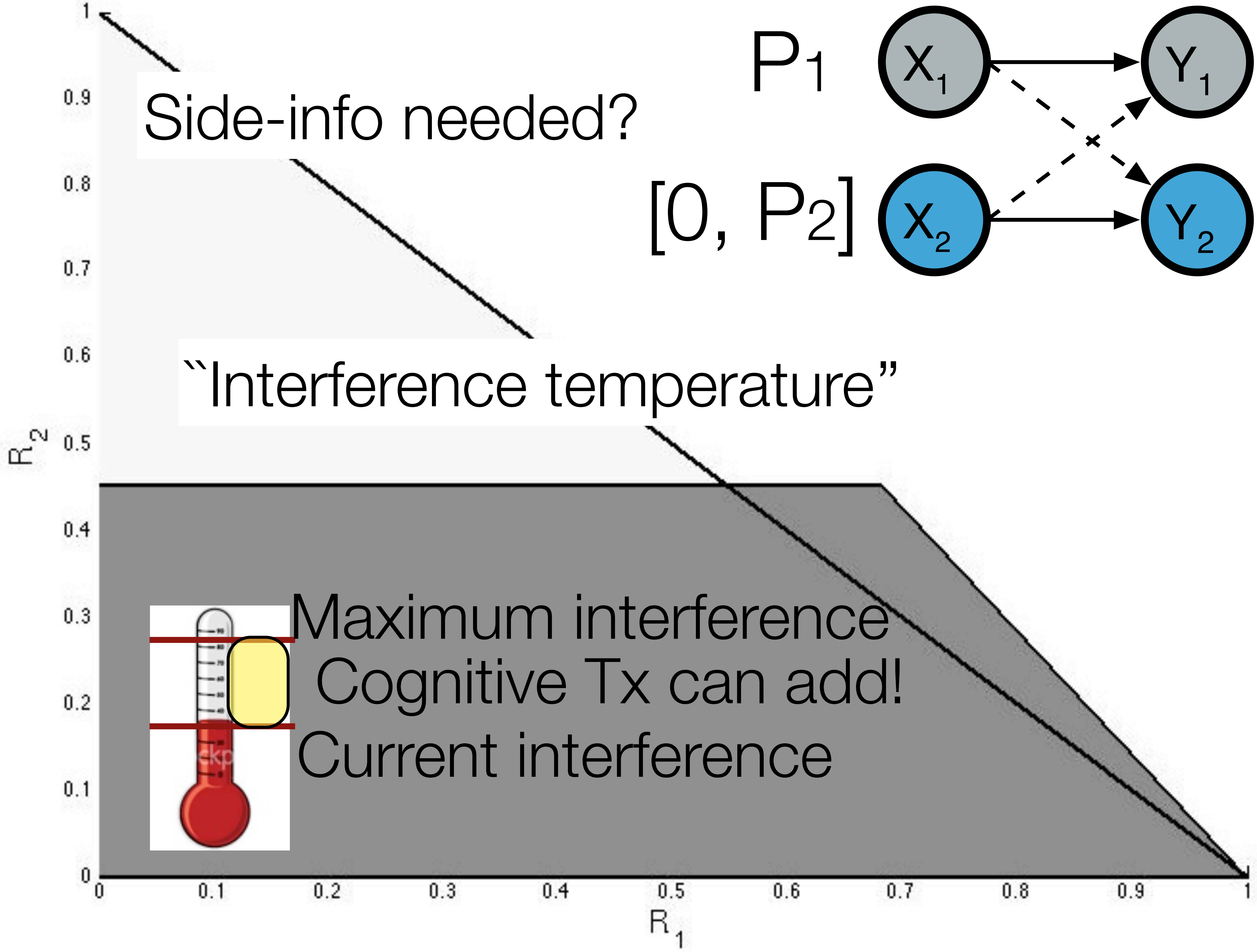


"Interference temperature"

Maximum interference

Cognitive Tx can add!

Current interference



Side-info needed?

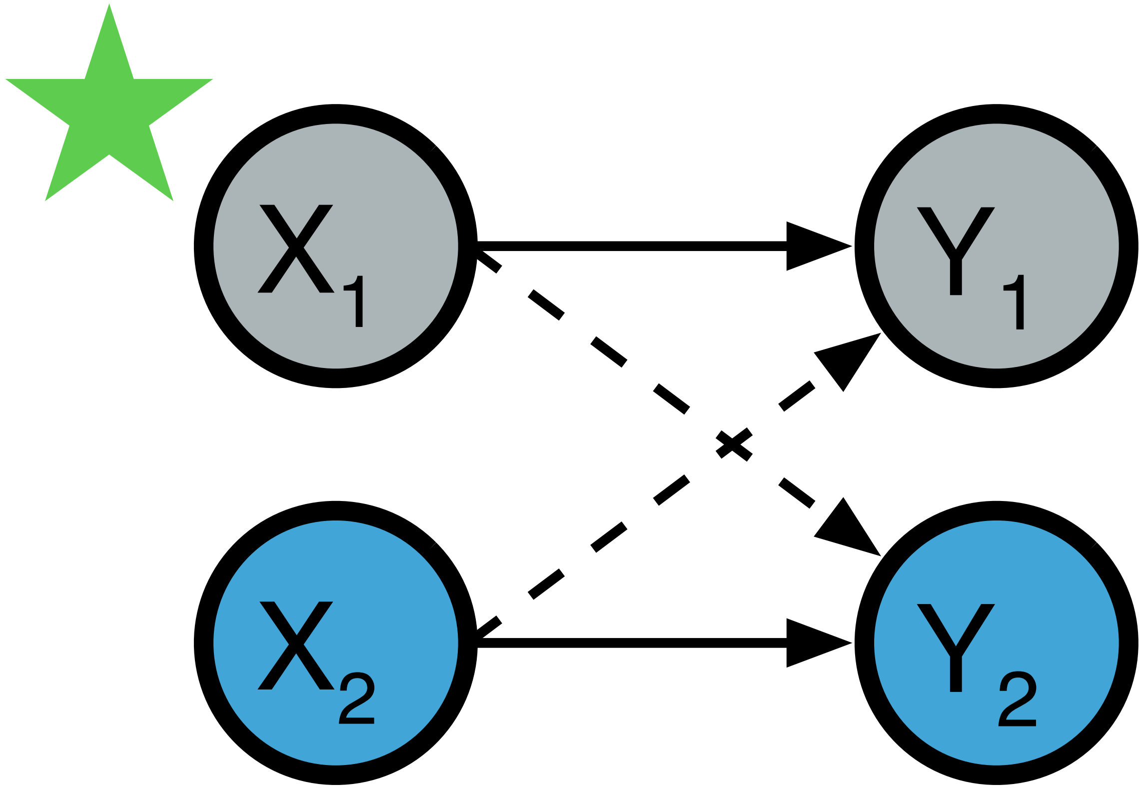
“Interference temperature”

Maximum interference

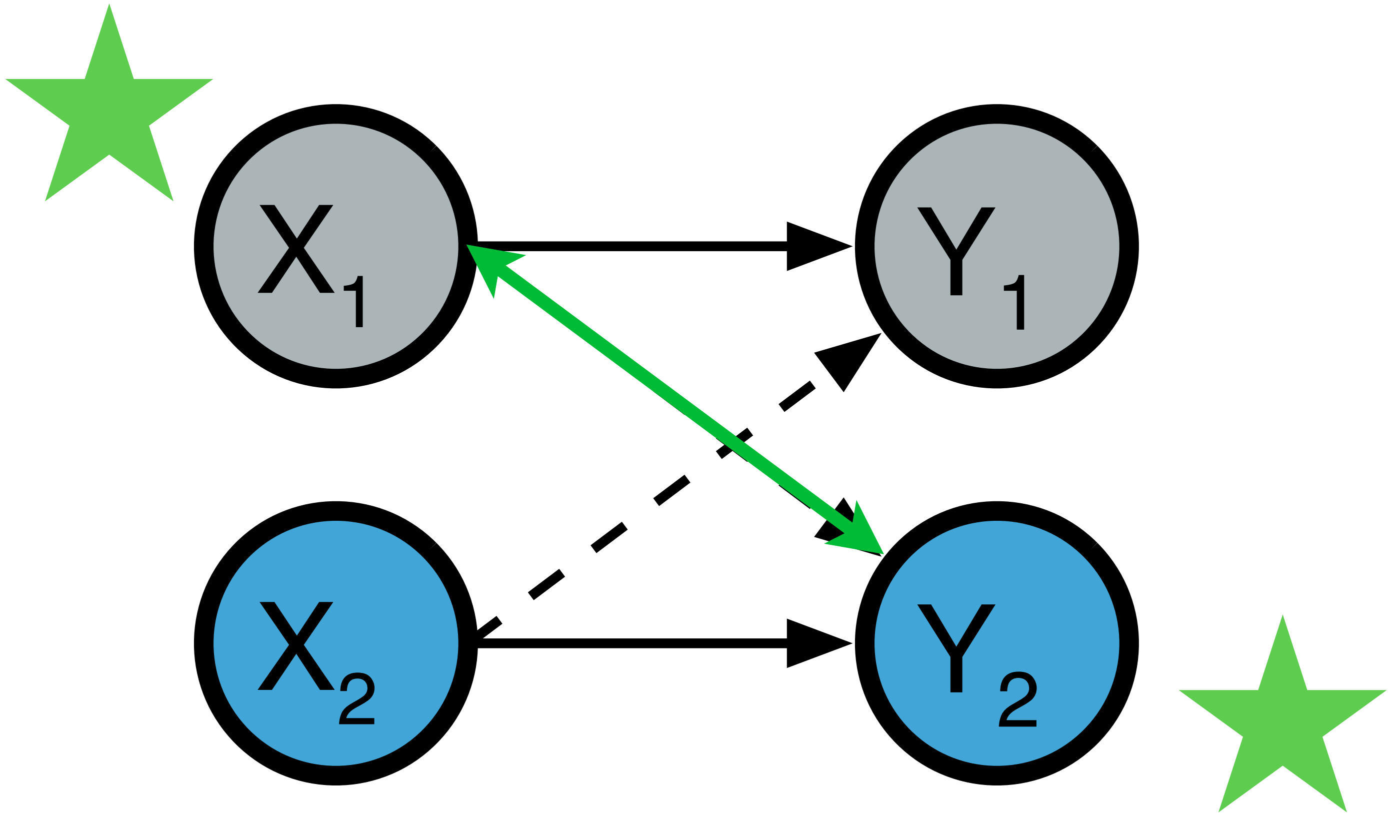
Cognitive Tx can add!

Current interference

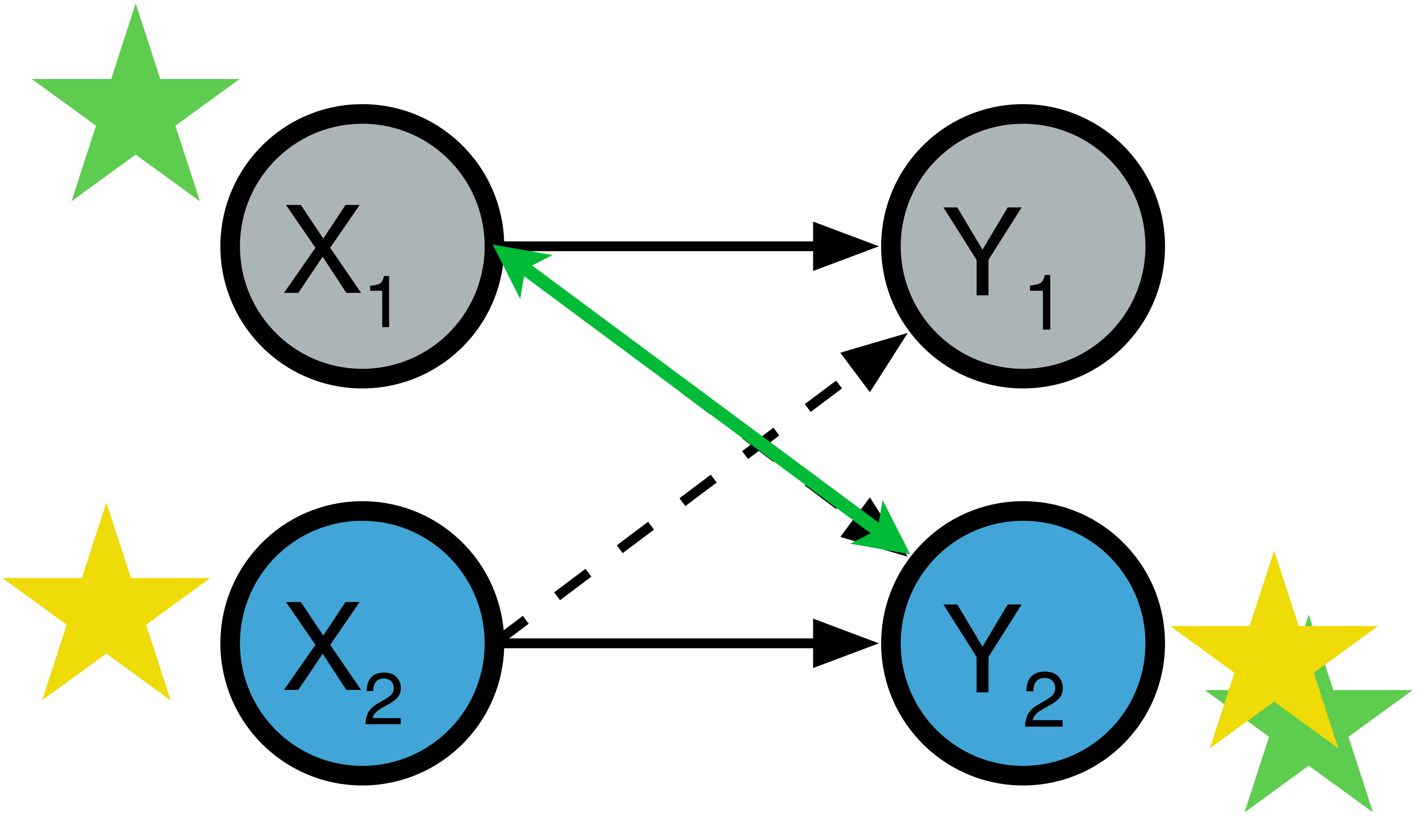
3. Opportunistic “cognitive” decoding



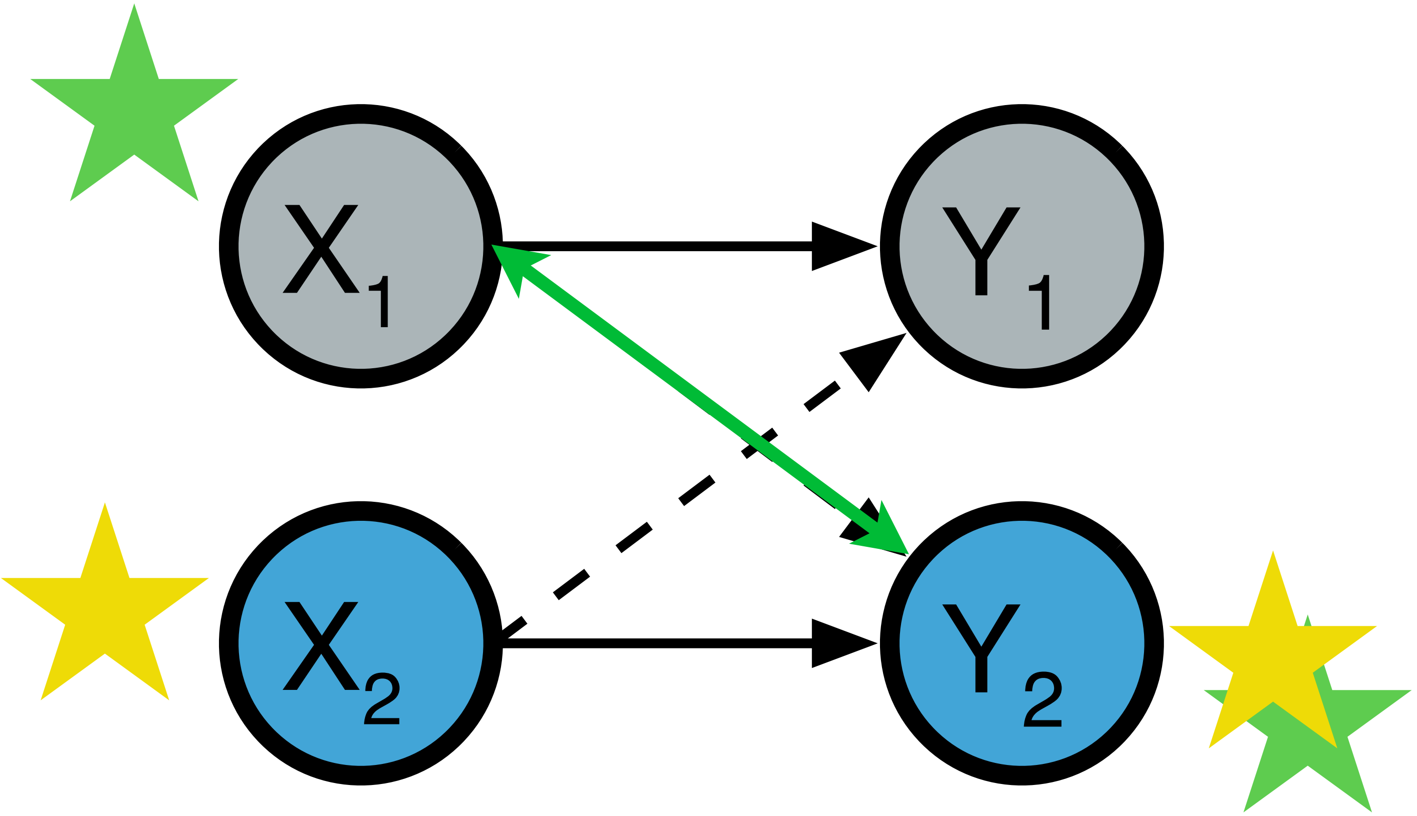
3. Opportunistic “cognitive” decoding



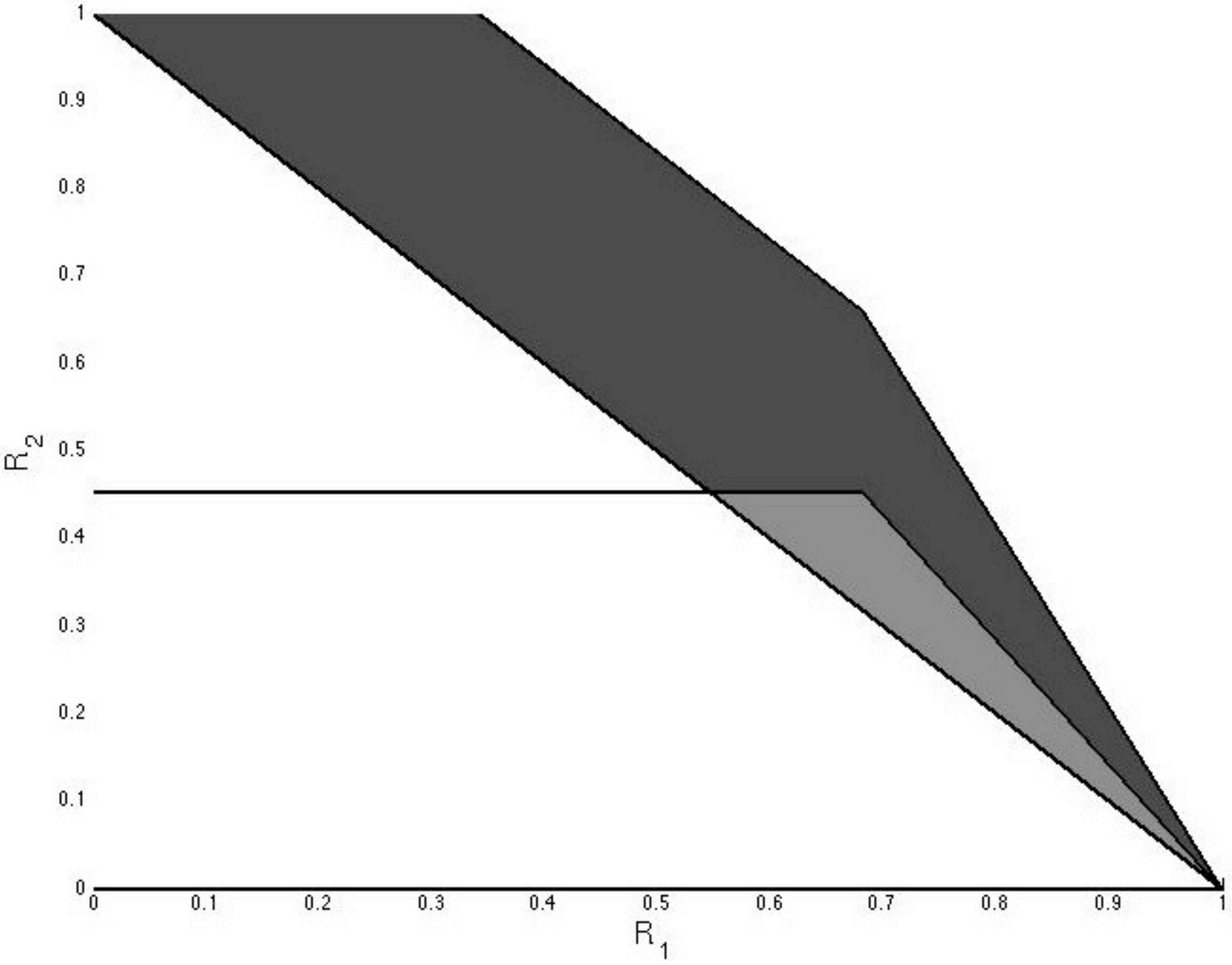
3. Opportunistic “cognitive” decoding



3. Opportunistic "cognitive" decoding

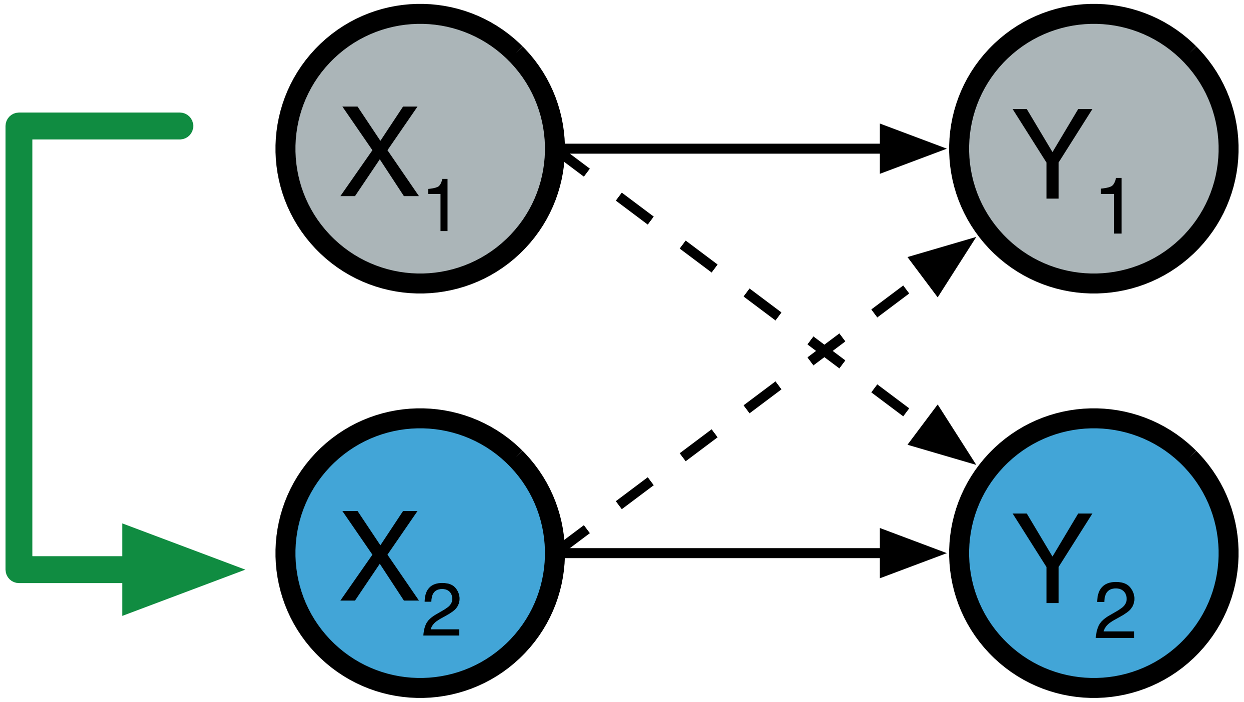


Side-info needed?



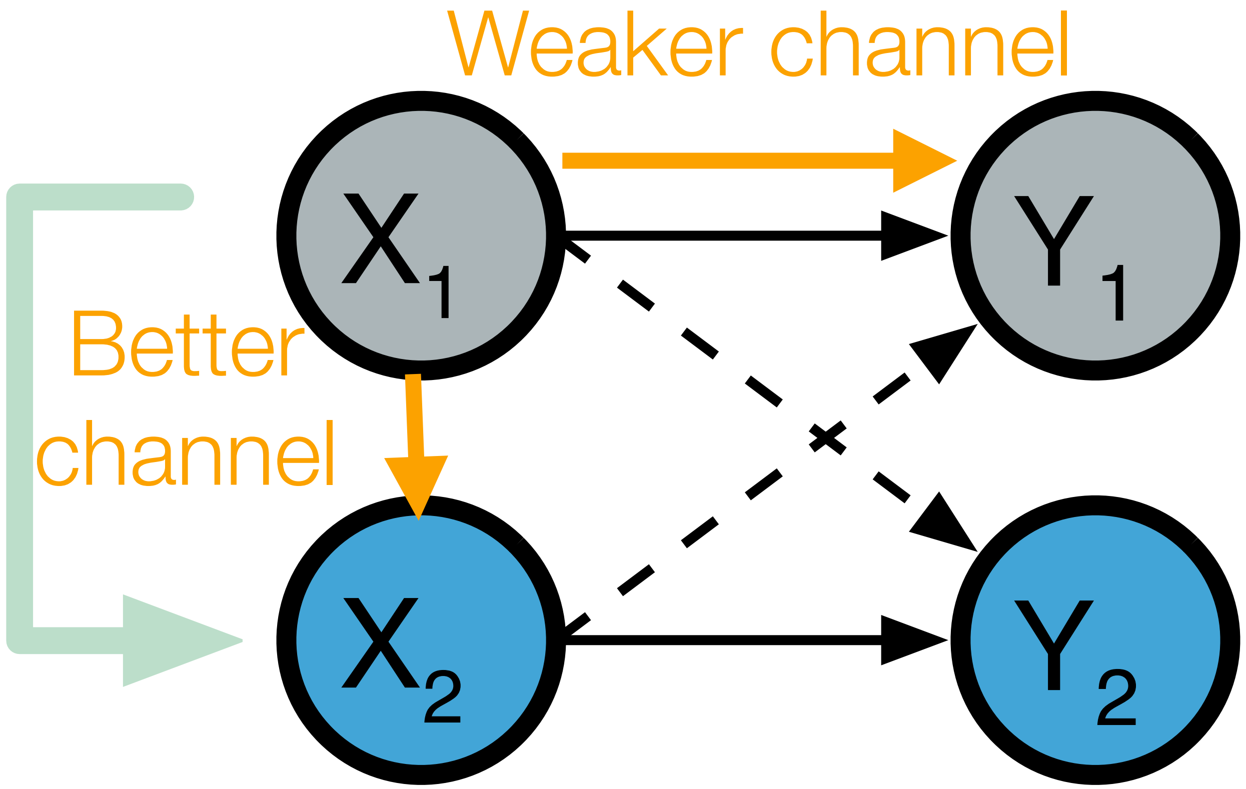
R_2
R_1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

4. Simultaneous Cognitive Transmission



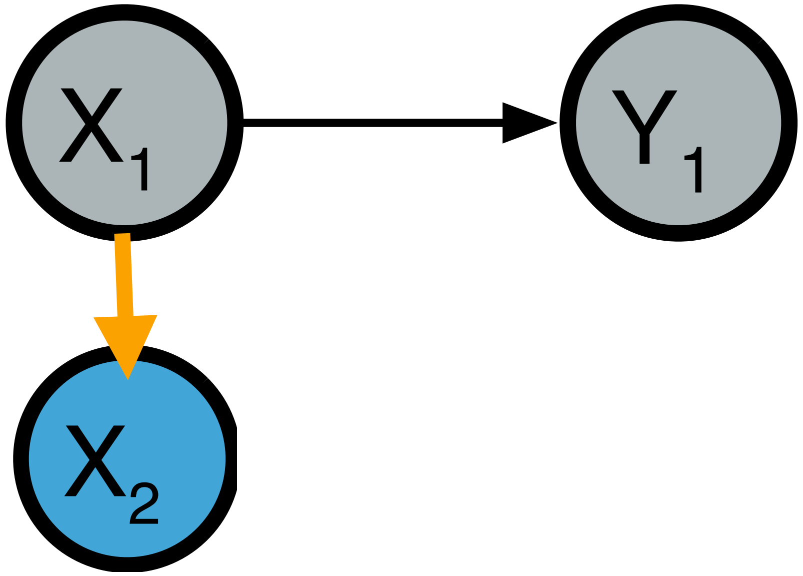
Assumption: Tx 2 knows message encoded by X_1 a-priori

4. Simultaneous Cognitive Transmission

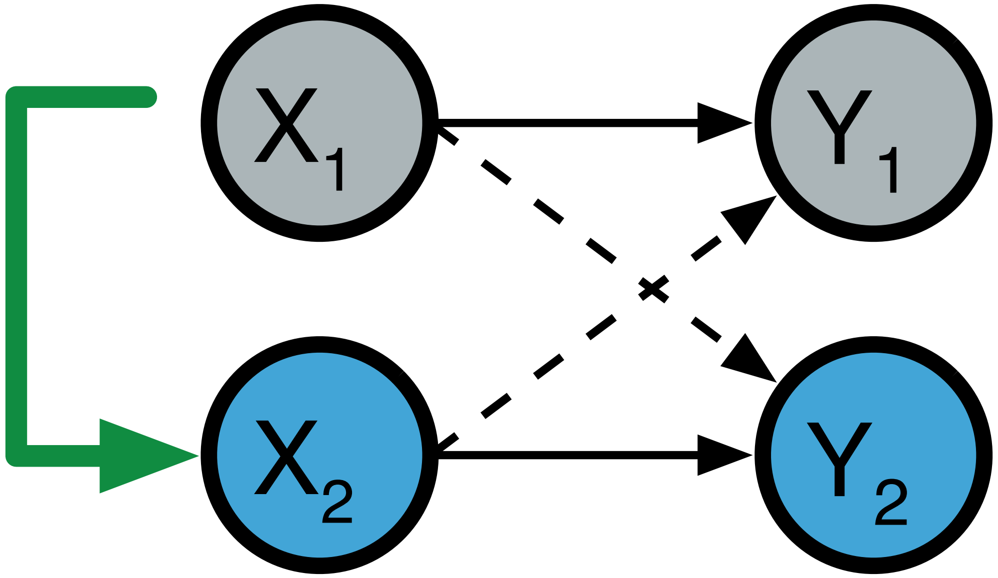


Cognitive Tx may obtain primary’s message in a fraction of the time

4. Simultaneous Cognitive Transmission

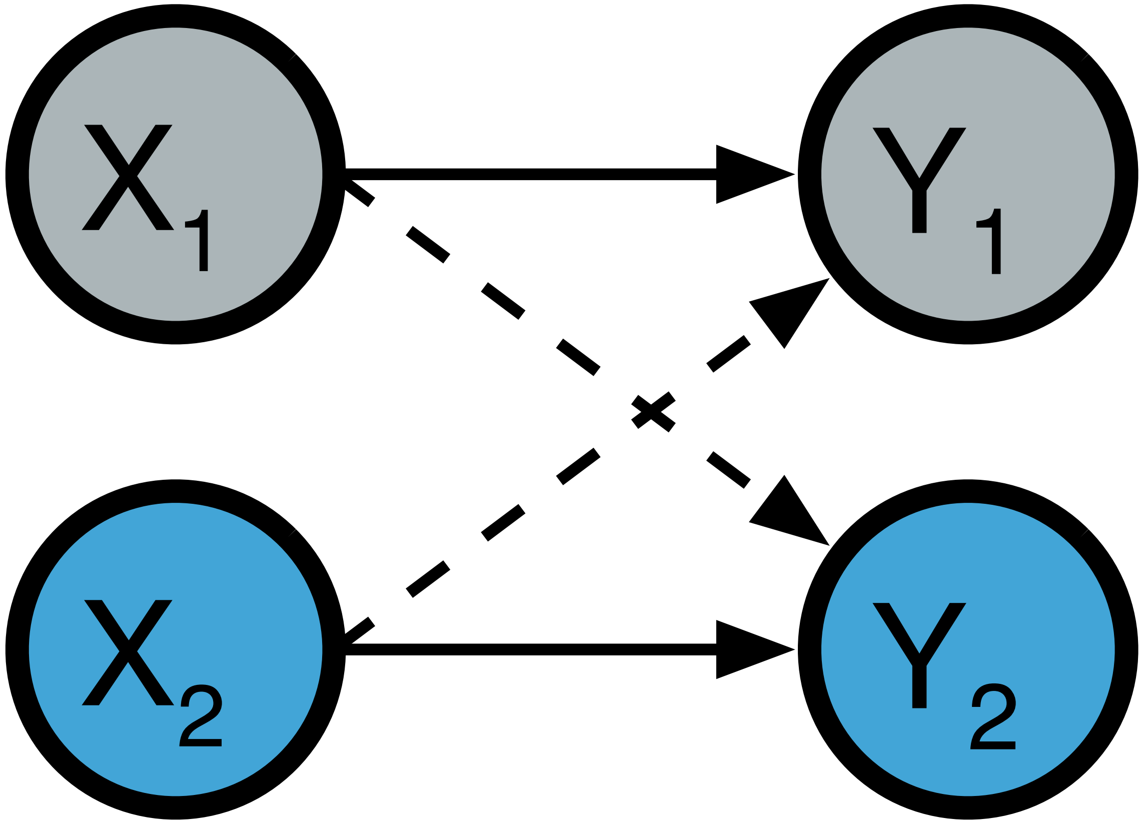


Primary transmission



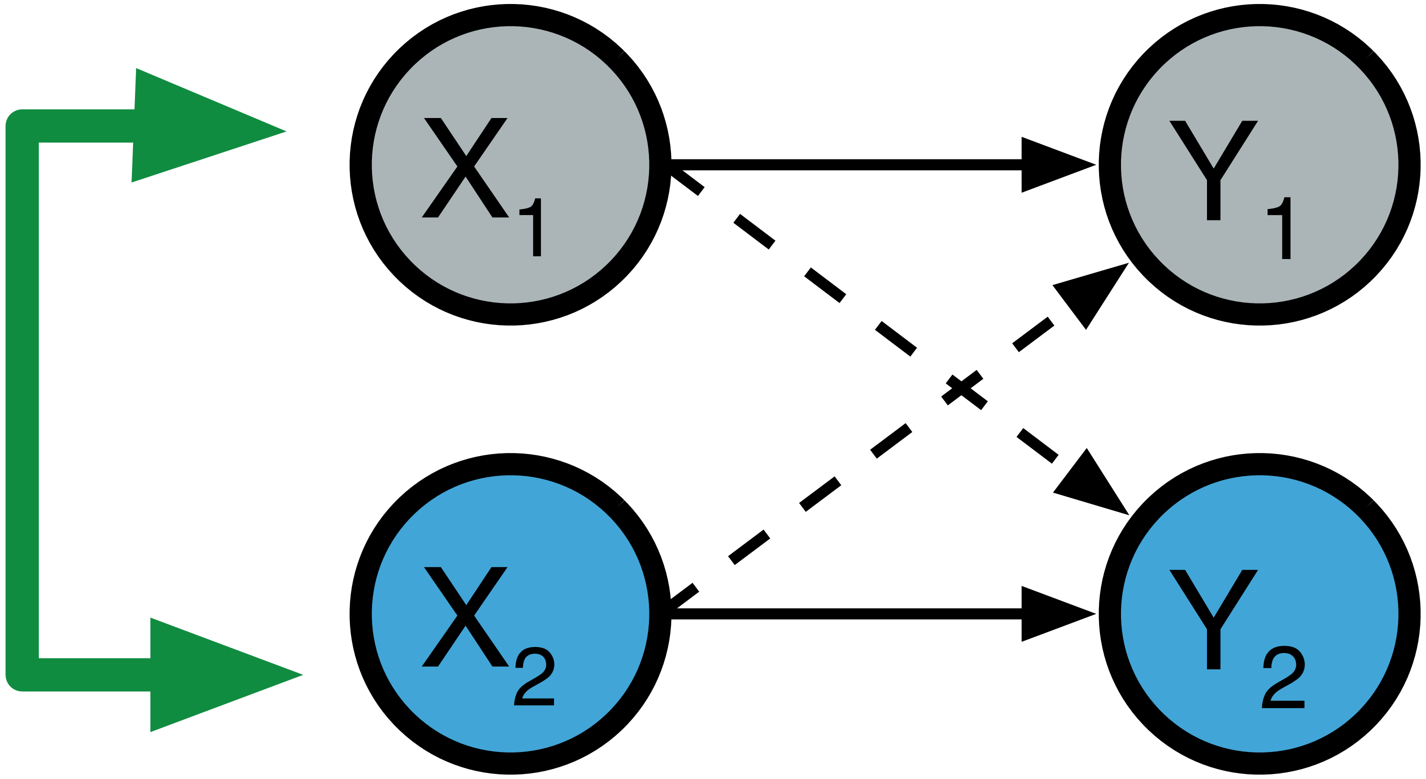
Re-transmission

Cognitive Tx may overhear primary's message



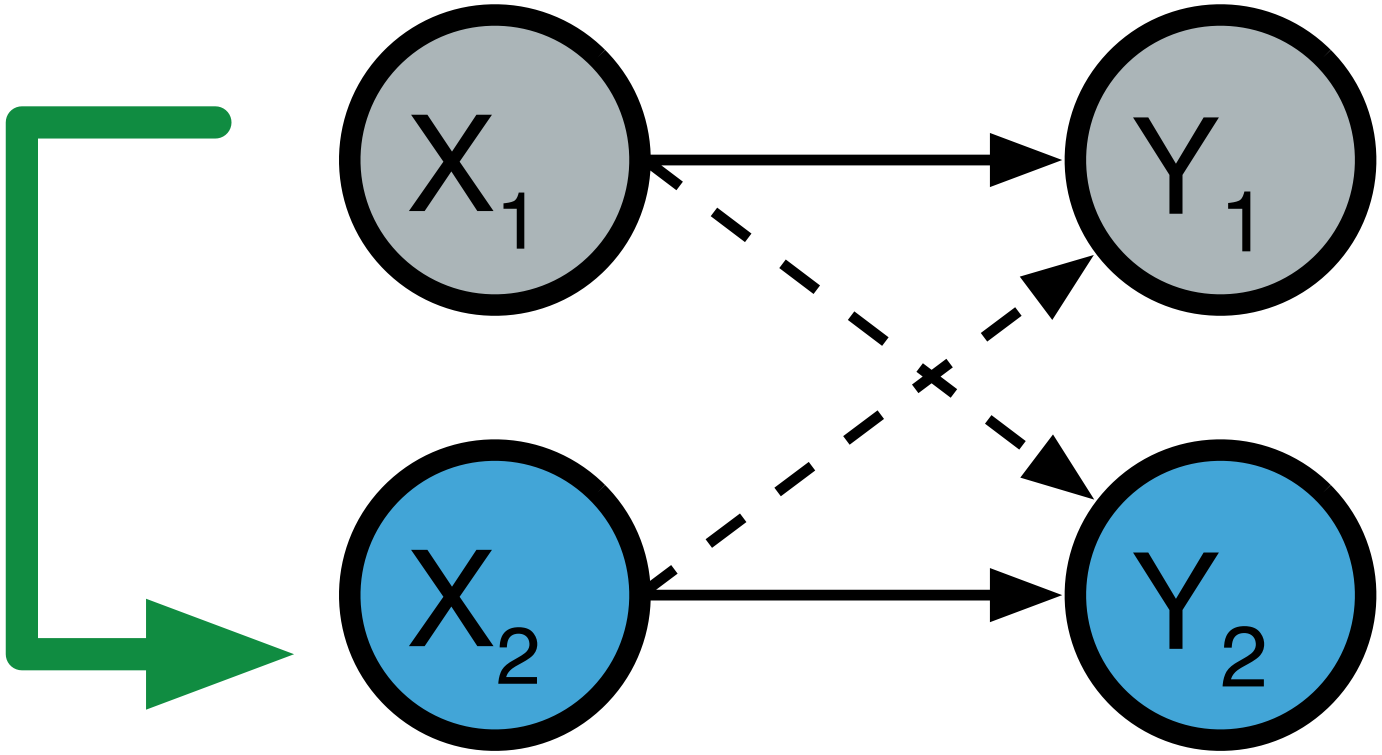
"Competitive"

Interference channel



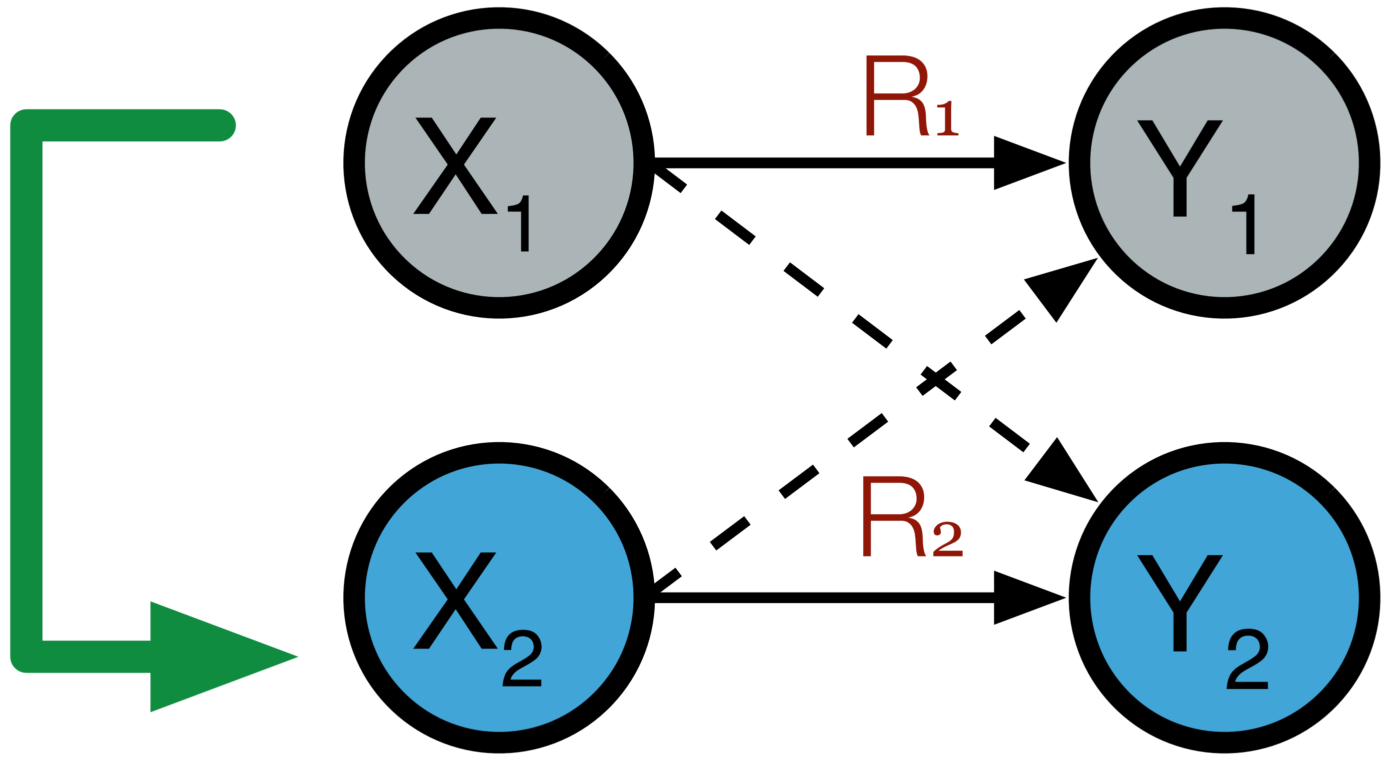
“Cooperative”

2 Tx antenna
Broadcast channel



“Cognitive”

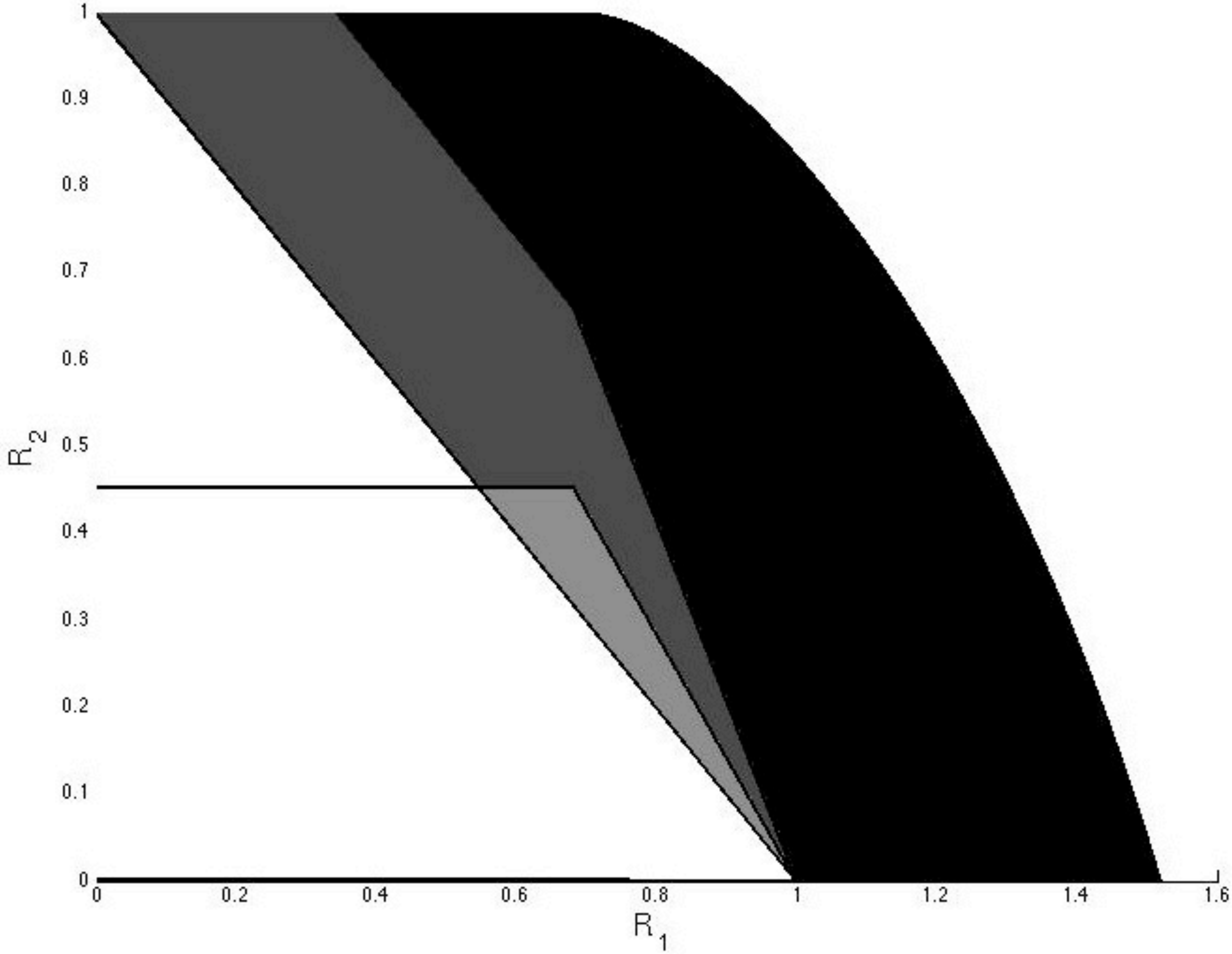
Cognitive channel



“Cognitive”

Cognitive channel

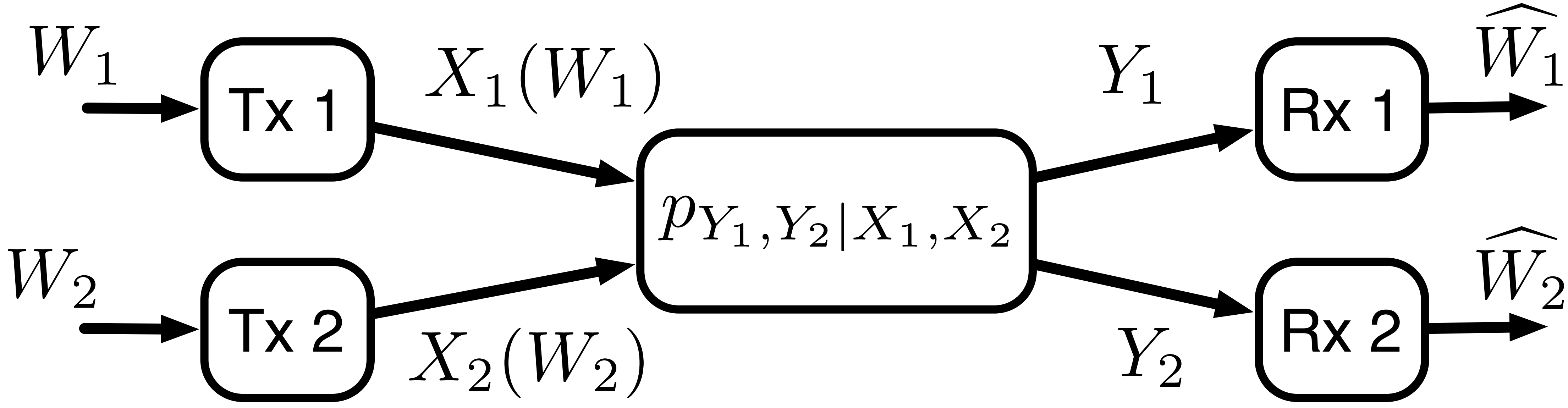
What rates (R_1, R_2) are achievable?



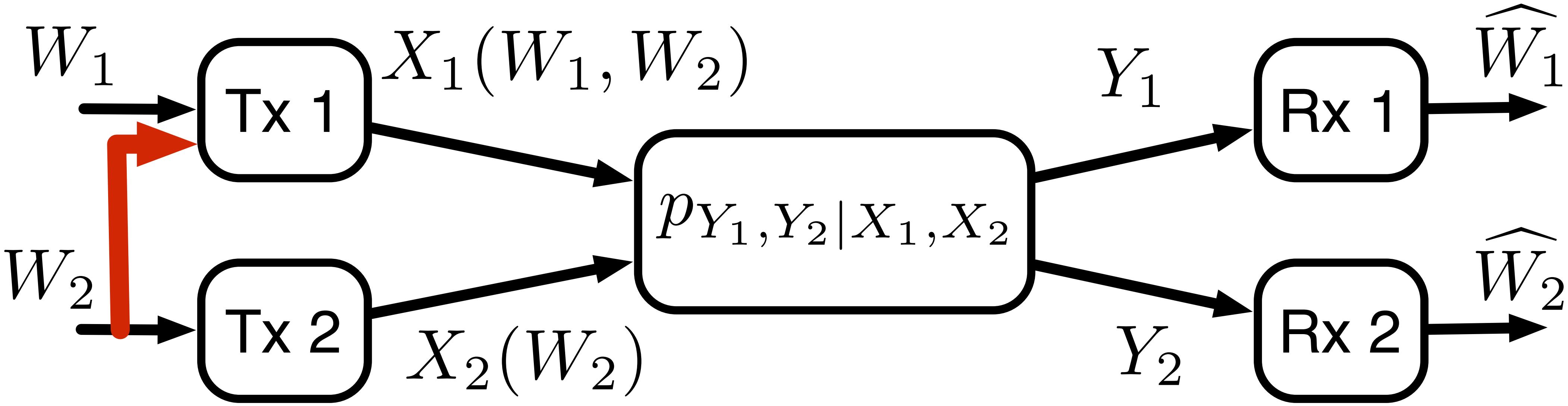
R_2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
R_1

Information theoretic abstraction

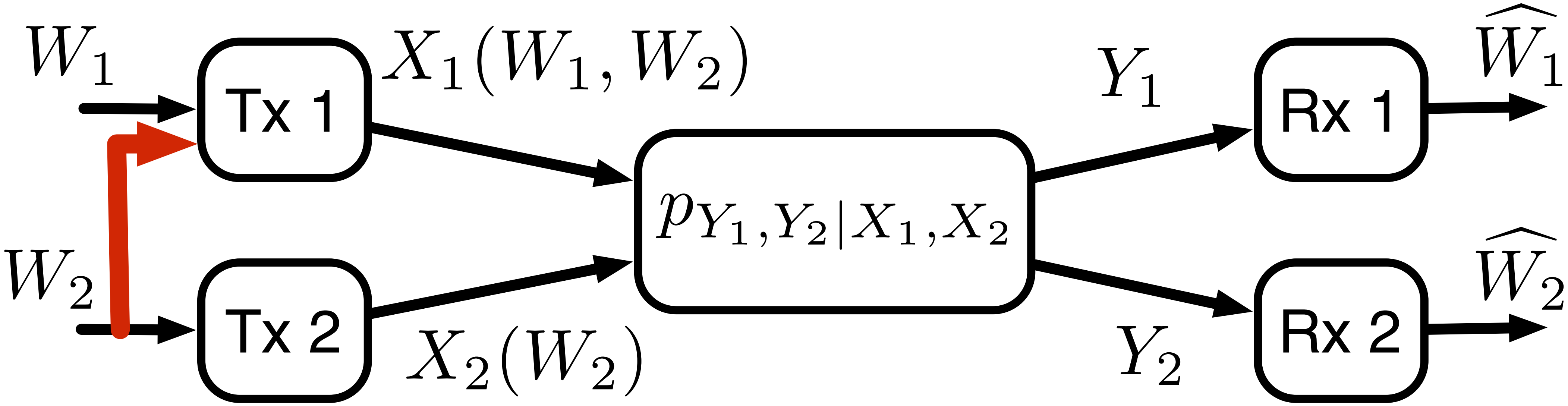
Interference channel



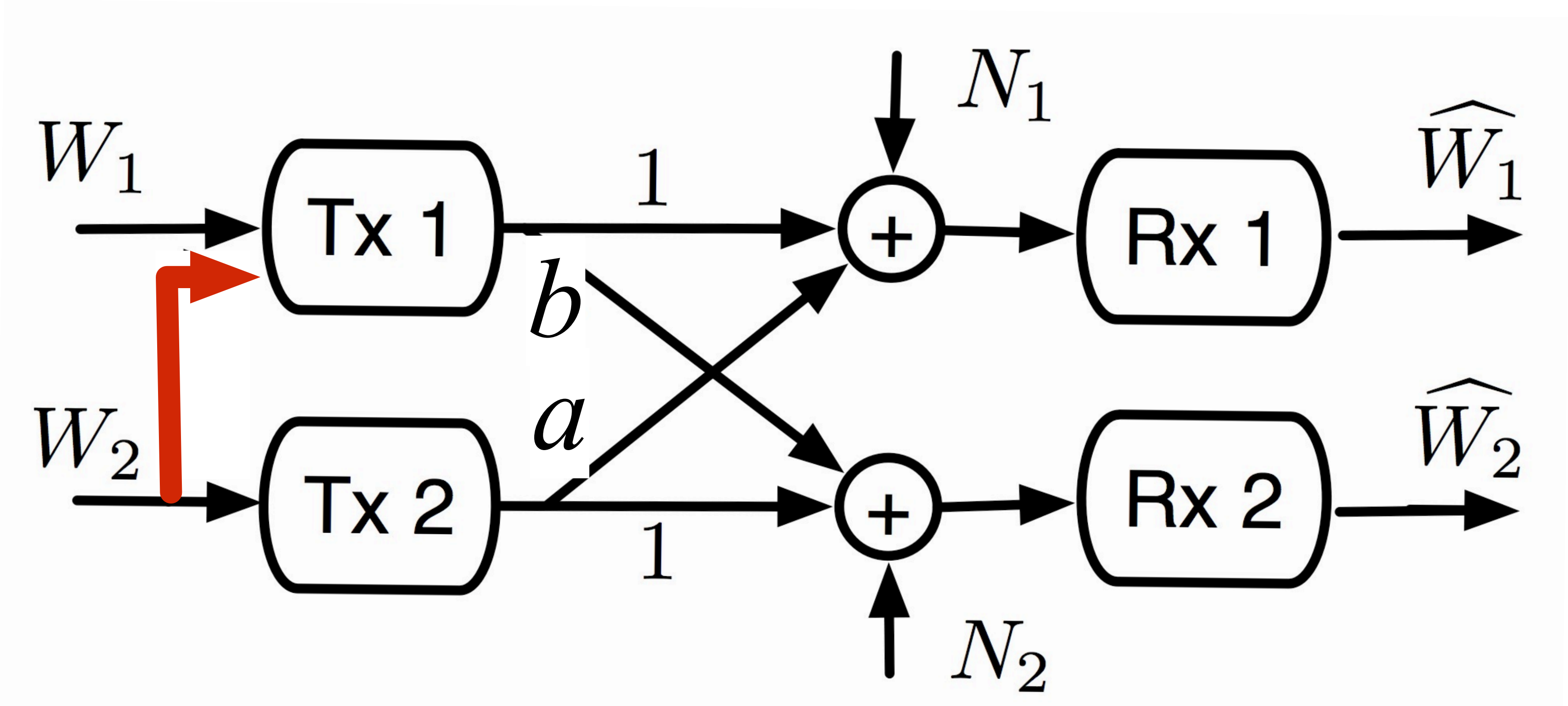
DM Cognitive interference channel



DM Cognitive interference channel



Gaussian Cognitive interference channel



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Large unified region

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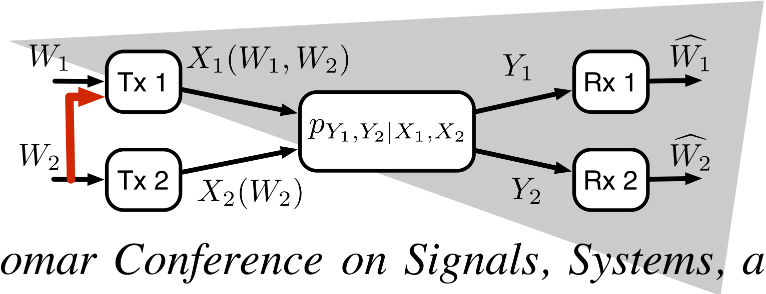
Broadcast channel is contained



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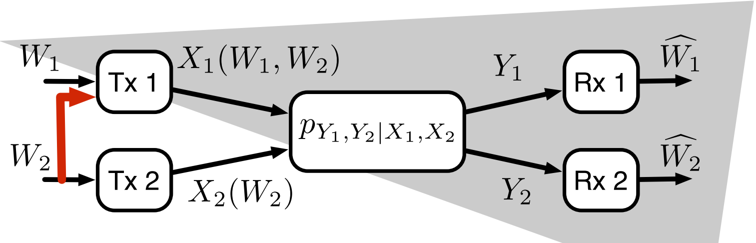

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Interference channel with cognitive relay

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Causal cognitive interference channel

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Cognitive interference channels with secrecy

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Cognitive Z interference channel

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Degrees of Freedom of Cognitive Channels

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Cognitive Z interference channel

N. Liu, I. Maric, A. Goldsmith, and S. Shamai, “The capacity region of the cognitive z-interference channel with one noiseless component,” *http://www.scientificcommons.org/38908274*, 2008. [Online]. Available: http://arxiv.org/abs/0812.0617

Degrees of Freedom of Cognitive Channels

Chiachi Huang, Syed A. Jafar, ``Degrees of Freedom of the MIMO Interference Channel with Cooperation and Cognition'', *IEEE Transactions on Information Theory*, Vol. 55, No. 9, Sep. 2009, Pages: 4211-4220.

Wyner-type cognitive networks

A. Lapidoth, N. Levy, S. Shamai (Shitz), and M. A. Wigger, ``A Cognitive Network with Clustered Decoding'', in *Proc. ISIT 2009*, Seoul, Korea, June 28-July 3, 2009.
A. Lapidoth, S. Shamai (Shitz), and M. A. Wigger, ``On Cognitive Interference Networks'', in *Proc. ITW 2007*, Lake Tahoe, USA, Sep. 2-6, 2007.
A. Lapidoth, S. Shamai (Shitz), and M. A. Wigger, ``A Linear Interference Network with Local Side-Information'', in *Proc. ISIT 2007,* Nice, France, June 24-29, 2007.

Causal cognitive interference channel

S. H. Seyedmehdi, Y. Xin, J. Jiang, and X. Wang, “An improved achievable rate region for the causal cognitive radio,” in *Proc. IEEE Int. Symp. Inf. Theory*, June 2009.

Semi-deterministic cognitive interference channel

Y. Cao and B. Chen, “Interference channel with one cognitive transmitter,” in *Asilomar Conference on Signals, Systems, and Computers*, Oct. 2008.

——, “Interference Channels with One Cognitive Transmitter,” *Arxiv preprint arXiv:09010.0899v1*, 2009.

Cognitive interference channels with secrecy

O. Simeone and A. Yener, “The cognitive multiple access wire-tap channel,” in *Proc. Conf. on Information Sciences and Systems (CISS)*, Mar. 2009.

Y. Liang, A. Somekh-Baruch, H. V. Poor, S. Shamai, and S. Verdú, “Capacity of cognitive interference channels with and without secrecy,” *IEEE Trans. on Inf. Theory*, vol. 55, no. 2, pp. 604–619, Feb. 2009.

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N. Liu, I. Maric, A. Goldsmith, and S. Shamai, “The capacity region of the cognitive z-interference channel with one noiseless component,” *http://www.scientificcommons.org/38908274*, 2008. [Online]. Available: http://arxiv.org/abs/0812.0617

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A. Lapidoth, S. Shamai (Shitz), and M. A. Wigger, ``A Linear Interference Network with Local Side-Information'', in *Proc. ISIT 2007,* Nice, France, June 24-29, 2007.

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O. Sahin and E. Erkip, “Achievable rates for the gaussian interference relay channel,” in *Proc. of IEEE Globecom*, Washington D.C., Nov. 2007.

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J. Jiang, I. Maric, A. Goldsmith, and S. Cui, “Achievable rate regions for broadcast channels with cognitive radios,” *Proc. of IEEE Information Theory Workshop (ITW)*, Oct. 2009.

S. Sridharan, S. Vishwanath, S. Jafar, and S. Shamai, “On the capacity of cognitive relay assisted gaussian interference channel,” in *Proc. IEEE Int. Symp. Information Theory, Toronto, Canada*, 2008, pp. 549–553.

Cognition

↕

Non-causal side information at Tx/Rxs

Contributions

Introduction

N. Devroye, P. Mitran, and V. Tarokh, “Achievable rates in cognitive radio channels,” in *39th Annual Conf. on Information Sciences and Systems (CISS)*, Mar. 2005.
——, “Achievable rates in cognitive radio channels,” *IEEE Trans. Inf. Theory*, vol. 52, no. 5, pp. 1813–1827, May 2006.
N. Devroye, “Information theoretic limits of cognition and cooperation in wireless networks,” Ph.D. dissertation, Harvard University, 2007.

Capacity in very weak interference

A. Jovicic and P. Viswanath, “Cognitive radio: An infomation-theoretic perspective,” *Proc. IEEE Int. Symp. Inf. Theory*, pp. 2413–2417, July 2006.

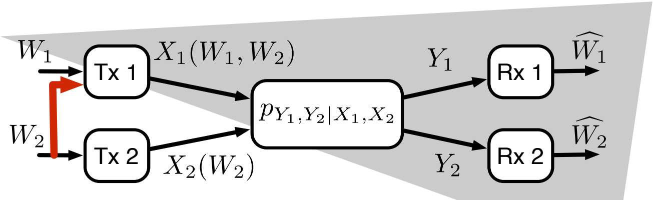
W. Wu, S. Vishwanath, and A. Arapostathis, “Capacity of a class of cognitive radio channels: Interference channels with degraded message sets,” *Information Theory, IEEE Transactions on*, vol. 53, no. 11, pp. 4391–4399, Nov. 2007.

Capacity in very strong interference

I. Maric, R. D. Yates, and G. Kramer, “Capacity of Interference Channels With Partial Transmitter Cooperation,” *IEEE Trans. Inf. Theory,* vol. 53, no. 10, pp.3536–3548, Oct. 2007.

Large unified region

I. Maric, A. Goldsmith, G. Kramer, and S. Shamai, “On the capacity of interference channels with a cognitive transmitter,” *European Transactions on Telecommunications*, vol. 19, pp. 405–420, Apr. 2008.



Broadcast channel is contained

Y. Cao and B. Chen, “Interference channel with one cognitive transmitter,” in *Asilomar Conference on Signals, Systems, and Computers*, Oct. 2008.
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Special case of broadcast channel with cognitive radios

J. Jiang, I. Maric, A. Goldsmith and S. Cui, “Achievable Rate Regions for Broadcast Channels with Cognitive Radios,” *IEEE Information Theory Workshop (ITW)*, Taormina, Italy, Oct. 2009.

Our recent result [Rini, Tuninetti, Devroye IZS 2010] = largest known achievable rate region

Contributions

Introduction

N. Devroye, P. Mitran, and V. Tarokh, “Achievable rates in cognitive radio channels,” in *39th Annual Conf. on Information Sciences and Systems (CISS)*, Mar. 2005.
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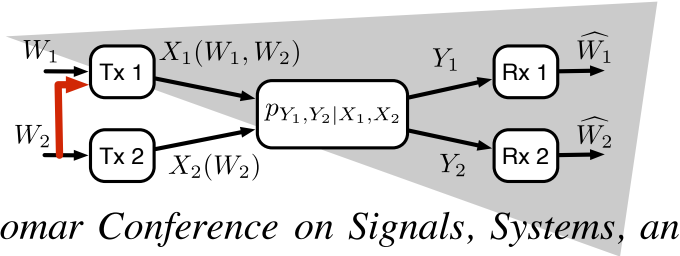

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In Gaussian noise, achieves within 1.87 bits from outer bound derived in

Contributions

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N. Devroye, P. Mitran, and V. Tarokh, “Achievable rates in cognitive radio channels,” in *39th Annual Conf. on Information Sciences and Systems (CISS)*, Mar. 2005.
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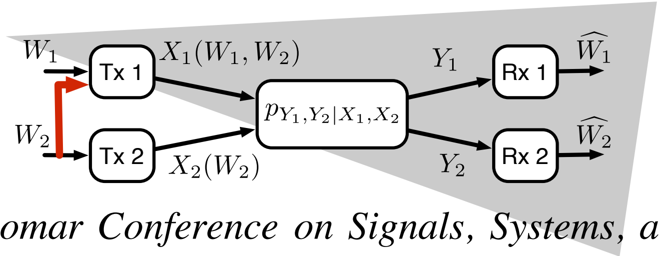

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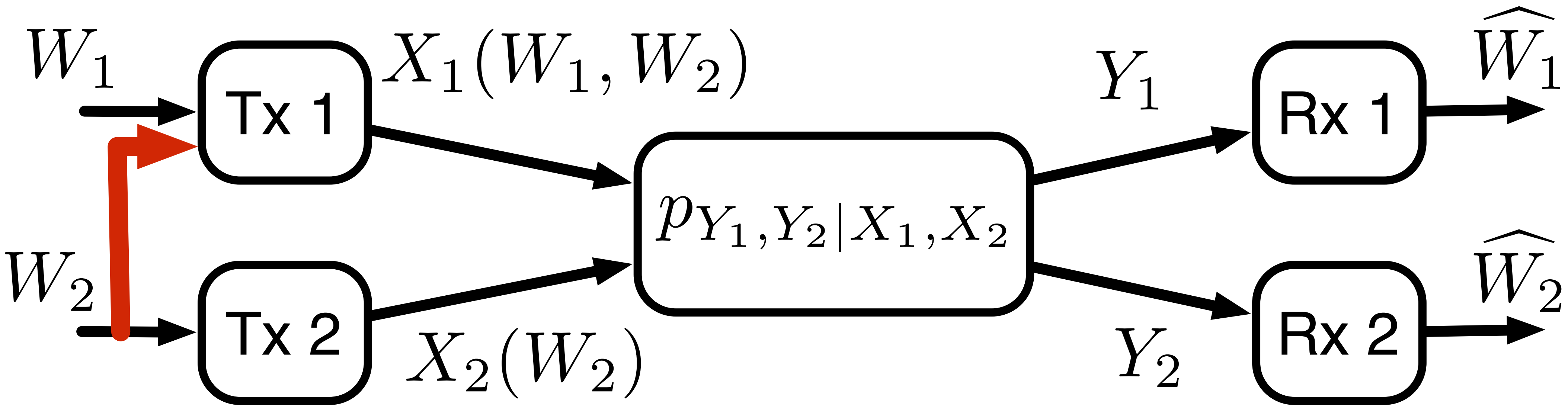
Special case of broadcast channel with cognitive radios

J. Jiang, I. Maric, A. Goldsmith and S. Cui, “Achievable Rate Regions for Broadcast Channels with Cognitive Radios,” *IEEE Information Theory Workshop (ITW)*, Taormina, Italy, Oct. 2009.

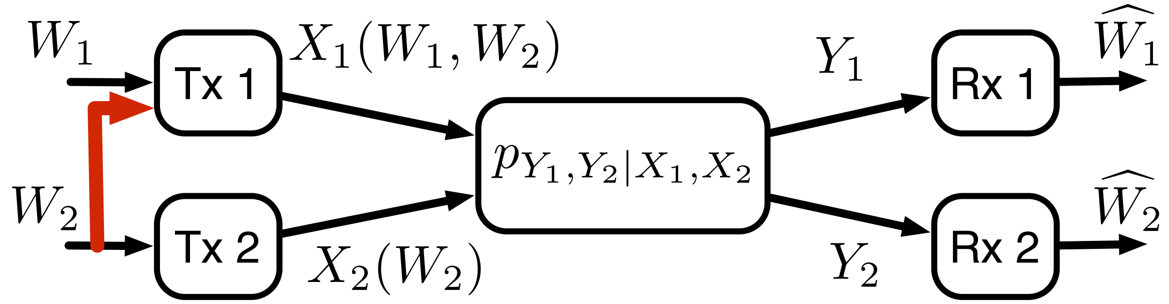
Capacity in certain (new) cases and channels - high SNR deterministic channel

Achievable scheme



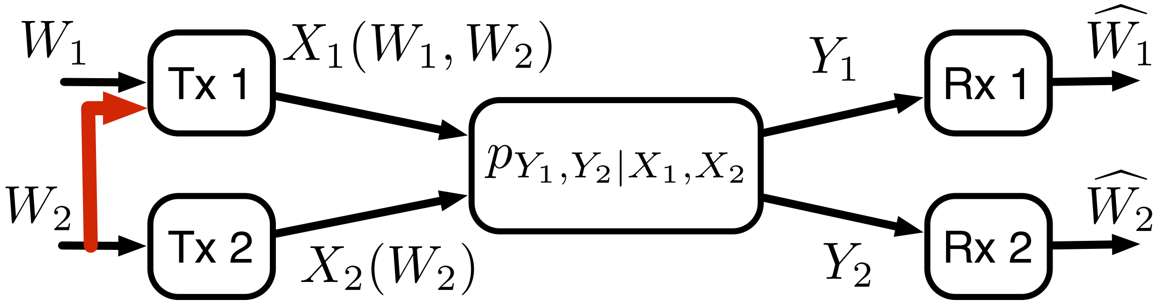
- rate-splitting
- superposition coding
- Gel’fand-Pinkser binning

Rate splitting

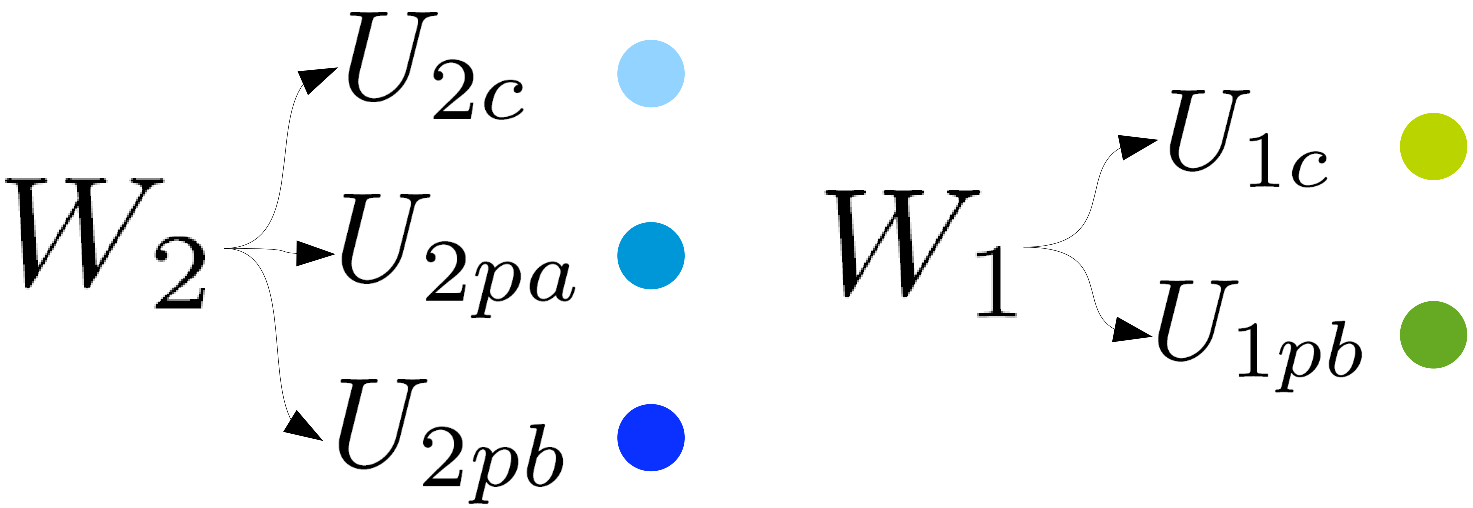


$$\begin{aligned} R_1 &= R_{1c} + R_{1pb}, \\ R_2 &= R_{2c} + R_{2pa} + R_{2pb}. \end{aligned}$$

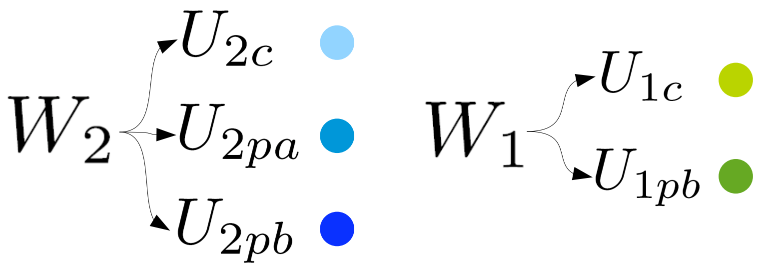
Rate splitting

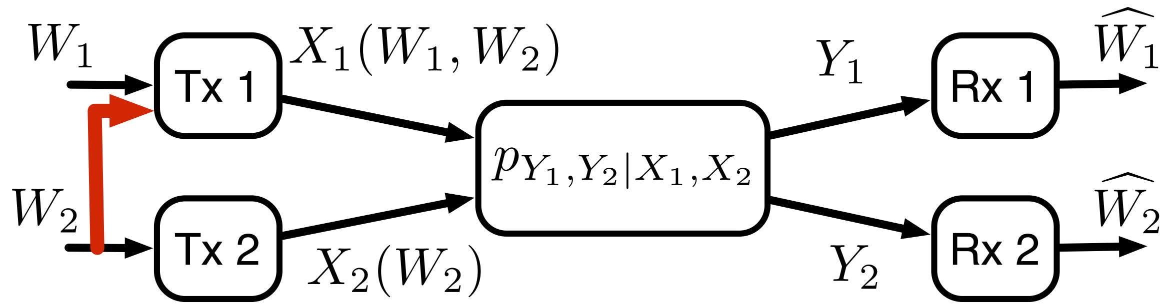


$$\begin{aligned} R_1 &= R_{1c} + R_{1pb}, \\ R_2 &= R_{2c} + R_{2pa} + R_{2pb}. \end{aligned}$$



c = *common*, *p* = *private*,
a = *alone*, *b* = *broadcast*





c = common, p = private,
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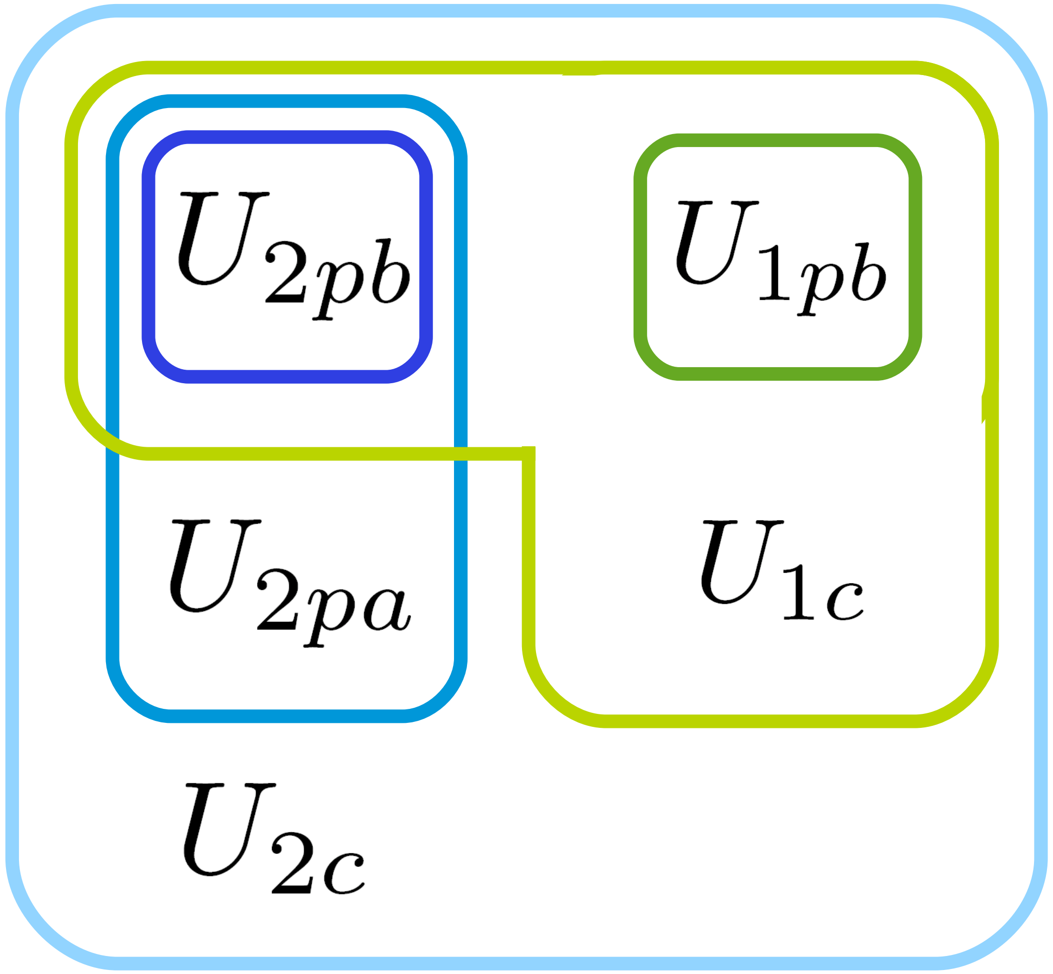
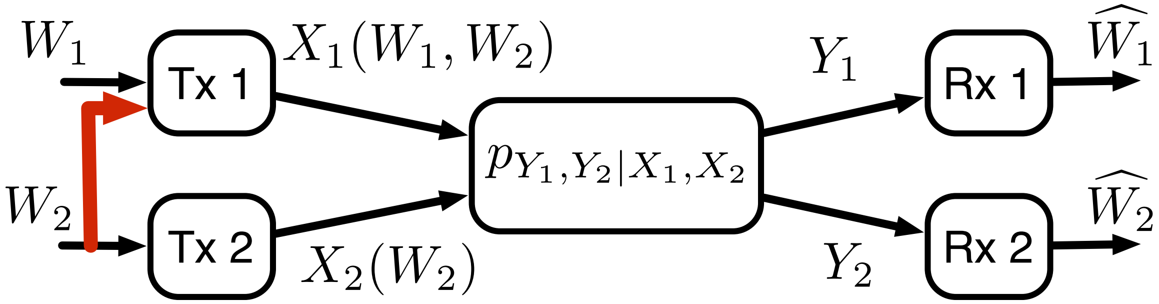


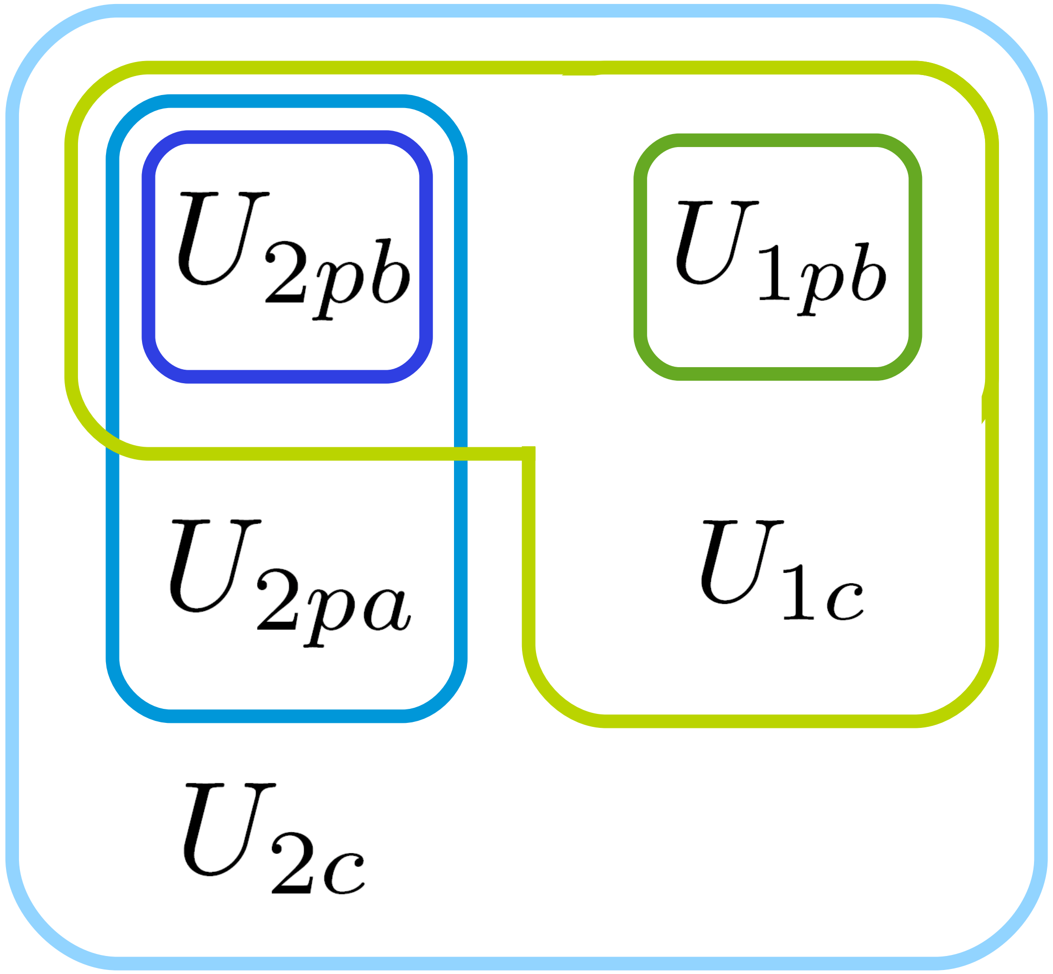
Superposition coding

W_2 → U_{2c} ●, U_{2pa} ●, U_{2pb} ●

W_1 → U_{1c} ●, U_{1pb} ●

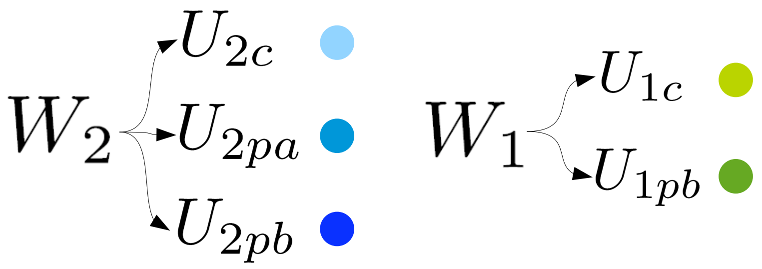
c = common, p = private,
a = alone, b = broadcast

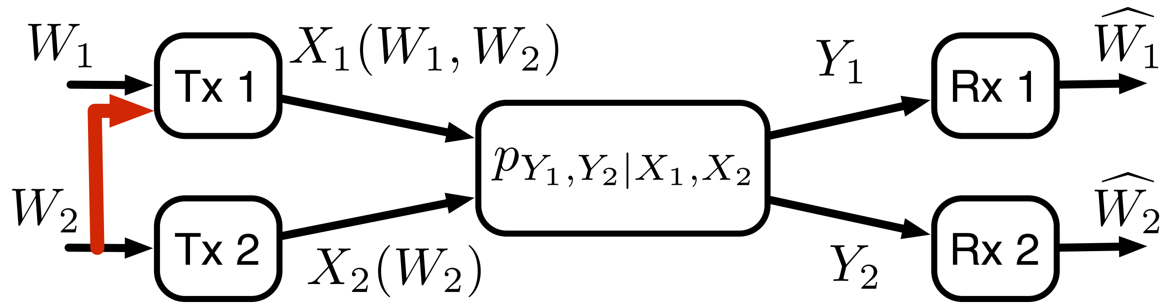




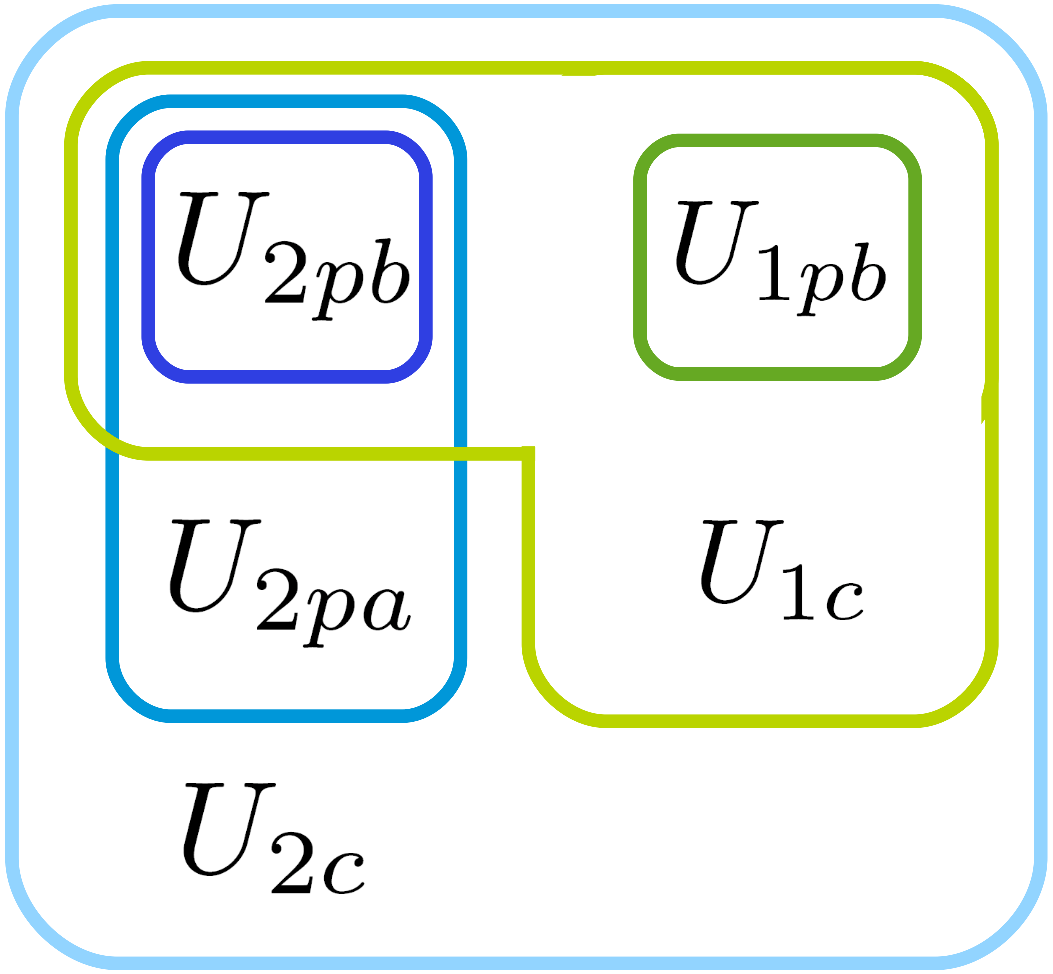
$p_{u_{2c}}$

Superposition coding





c = common, p = private,
a = alone, b = broadcast

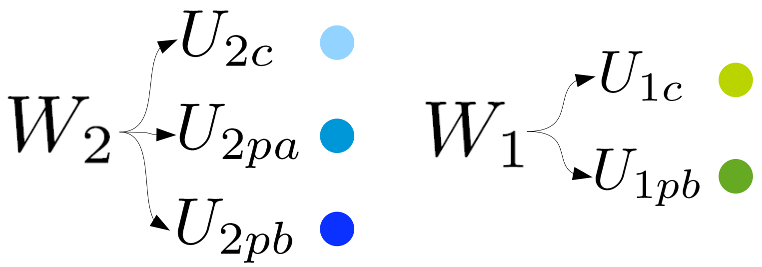


$p_{u_{2pa}|u_{2c}}$

$p_{u_{2c}}$

Superposition coding

Superposition coding



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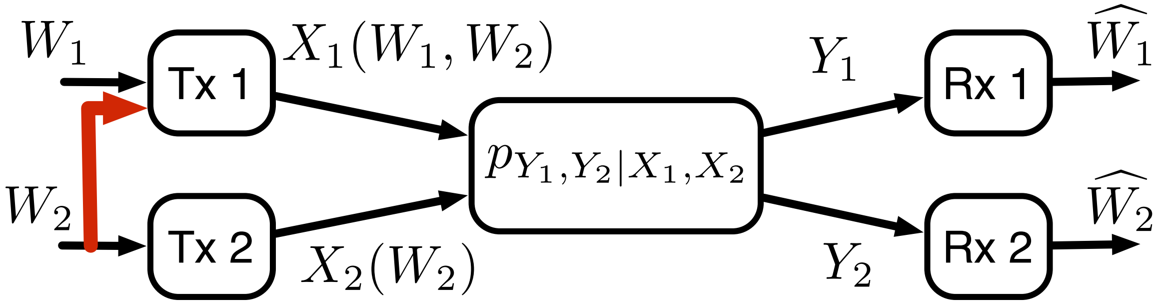
a = alone, b = broadcast

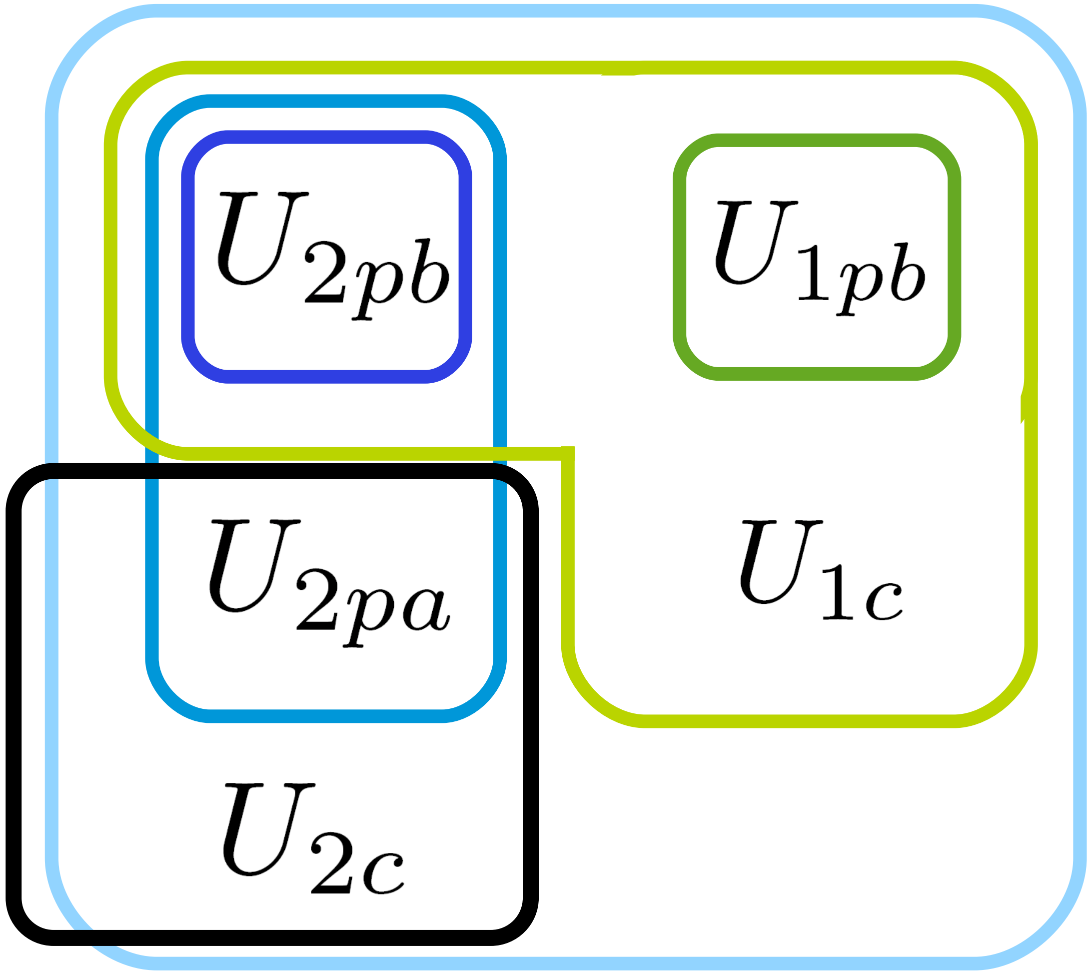


X_2

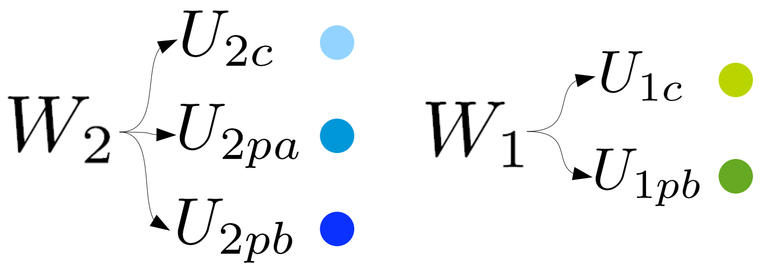
$p_{x_2|u_{2pa},u_{2c}}$

$p_{u_{2pa}|u_{2c}}$

$p_{u_{2c}}$



Superposition coding



c = common, p = private,
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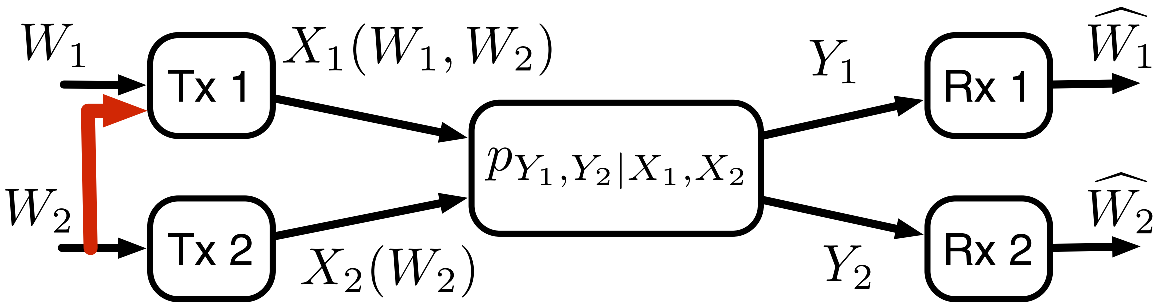
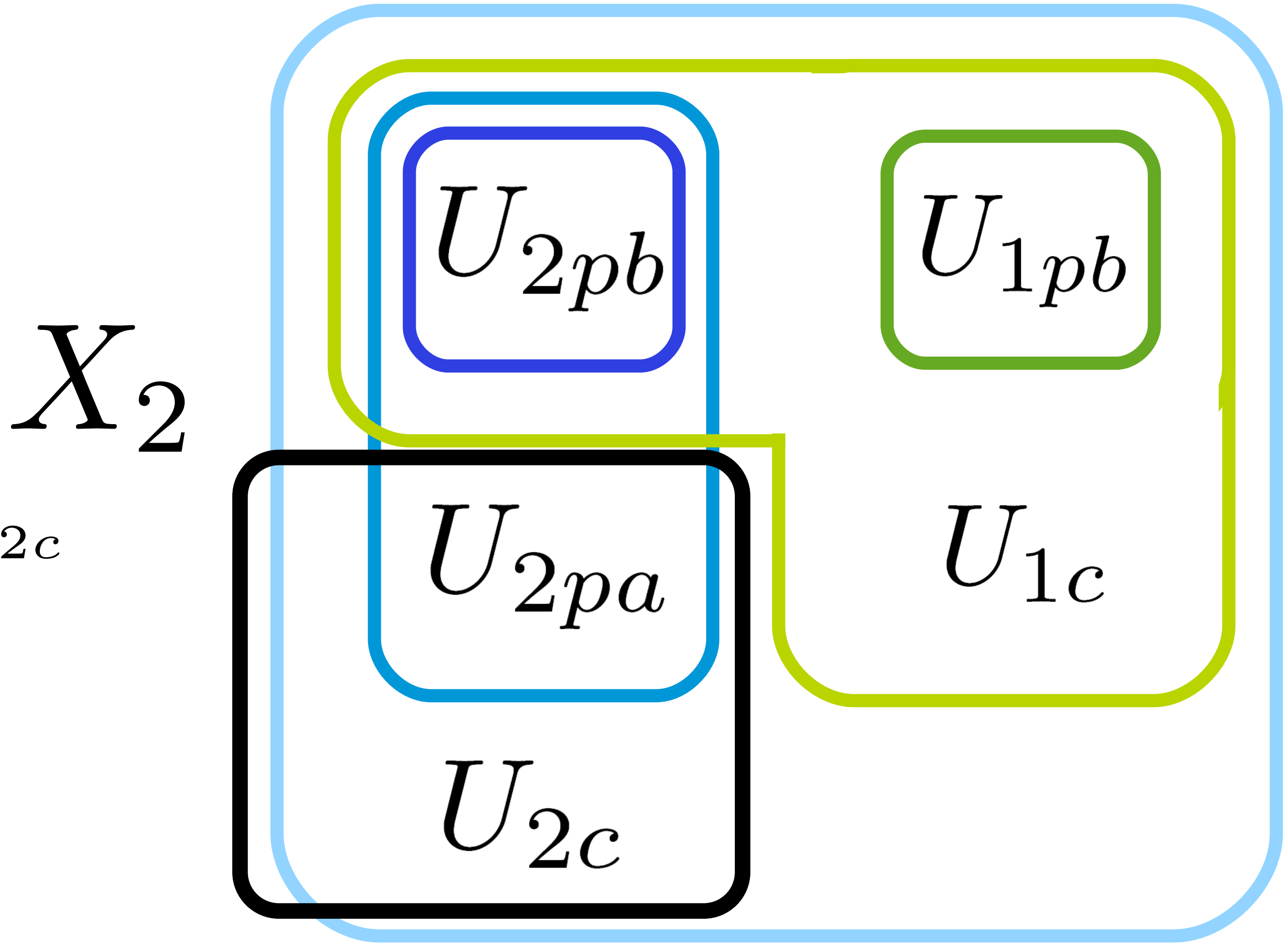


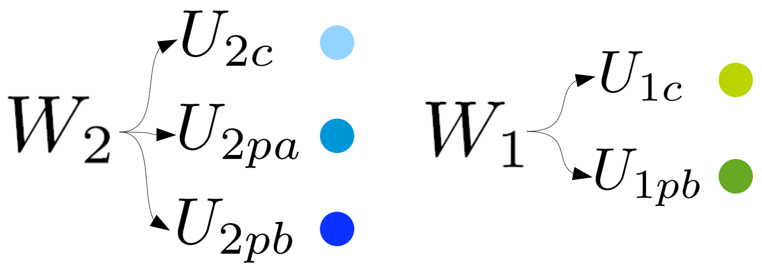


$p_{x_2|u_{2pa},u_{2c}}$

$p_{u_{2pa}|u_{2c}}$

$p_{u_{2c}}$

$p_{u_{1c}|u_{2c}}$



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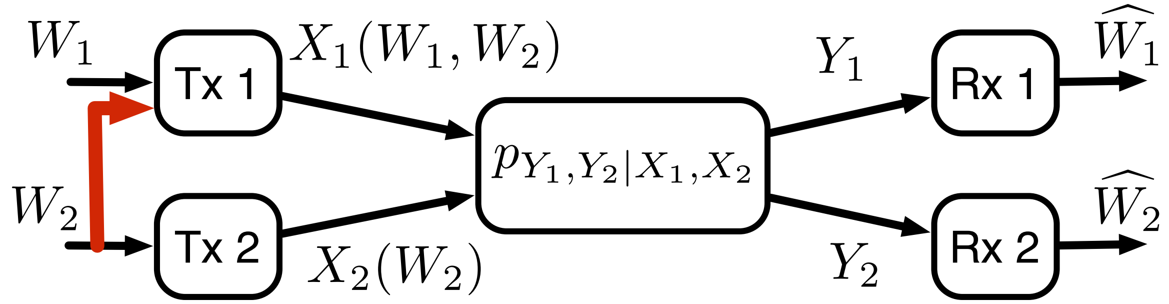
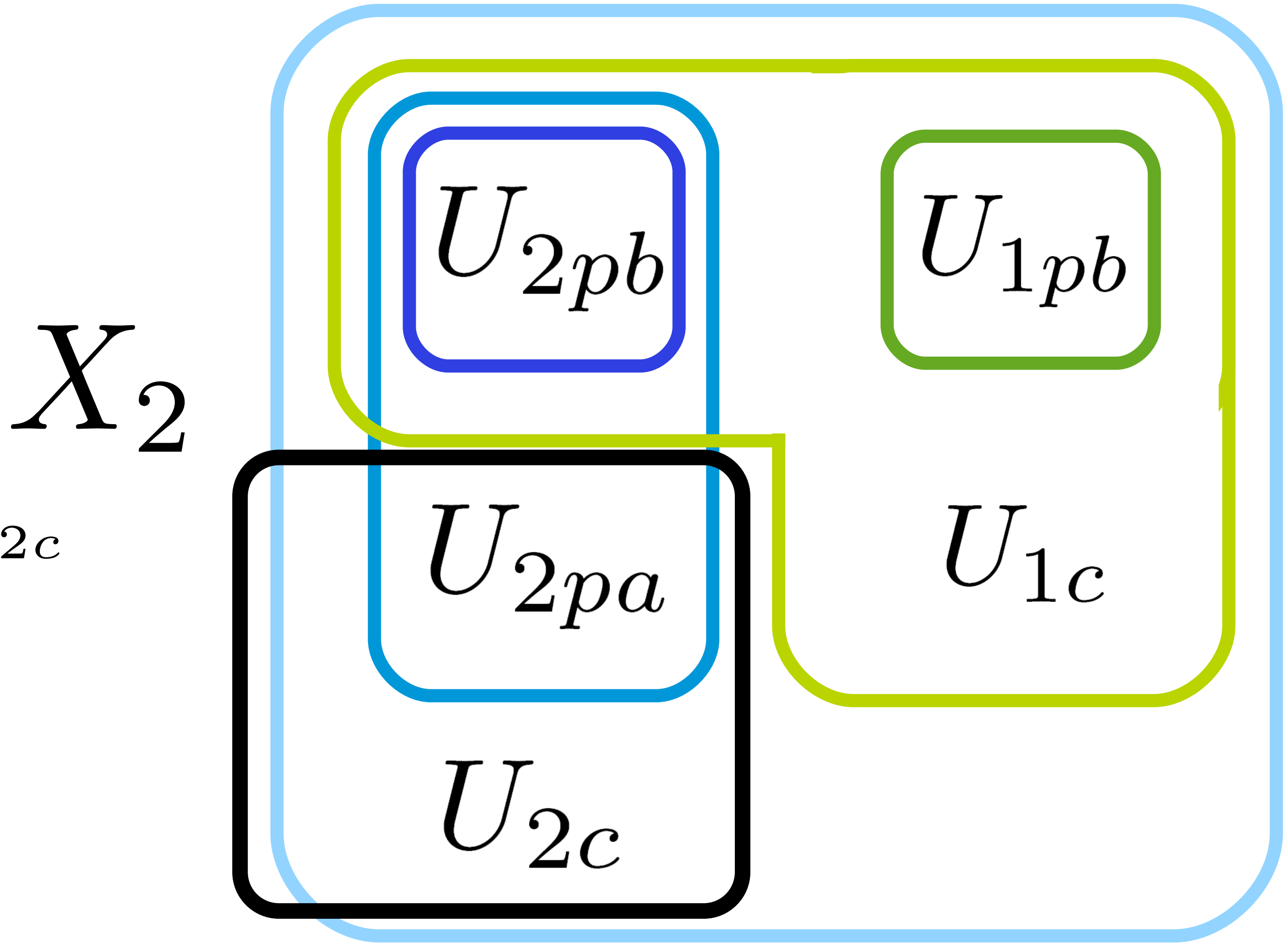
a = alone, b = broadcast





$$p_{u_{1pb}|u_{1c},u_{2c}}$$

$$p_{x_2|u_{2pa},u_{2c}}$$

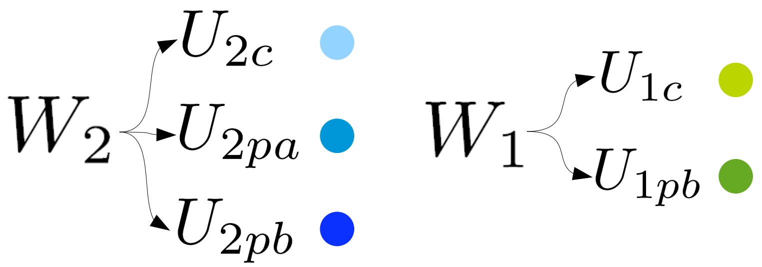
$$p_{u_{1c}|u_{2c}}$$

$$p_{u_{2pa}|u_{2c}}$$

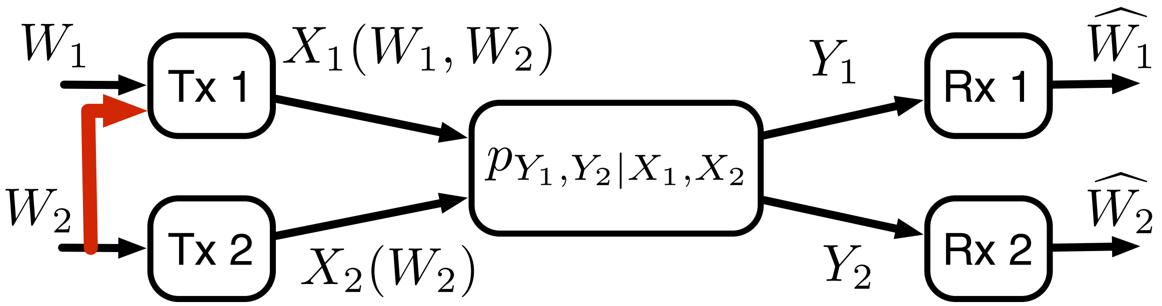
$$p_{u_{2c}}$$

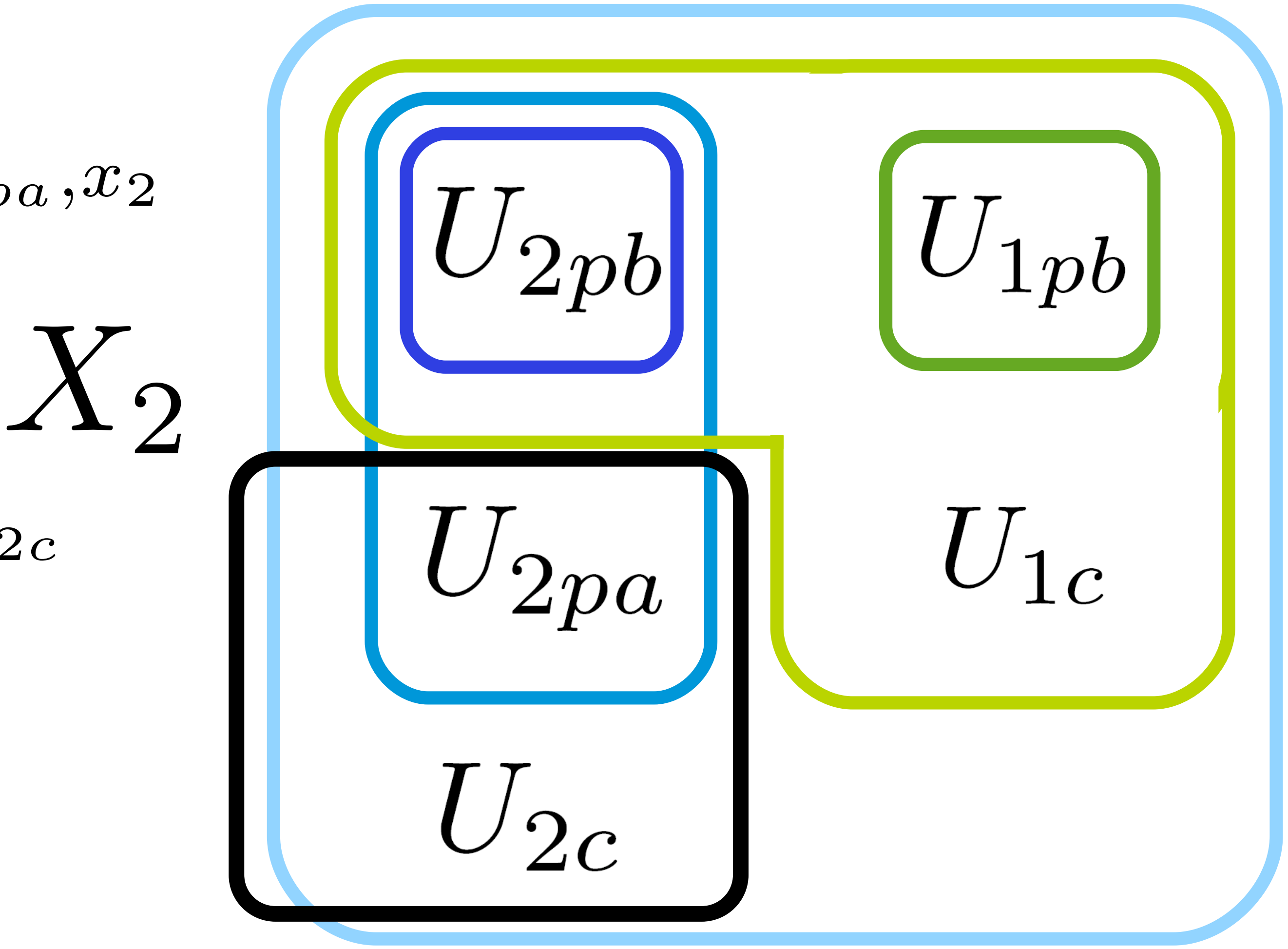
Superposition coding

Superposition coding



c = common, p = private,
a = alone, b = broadcast





$p_{u_{2pb}|u_{1c},u_{2c},u_{2pa},x_2}$

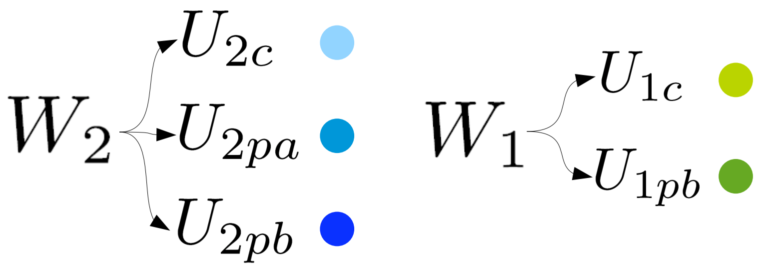
$p_{x_2|u_{2pa},u_{2c}}$

$p_{u_{2pa}|u_{2c}}$

$p_{u_{2c}}$

$p_{u_{1pb}|u_{1c},u_{2c}}$

$p_{u_{1c}|u_{2c}}$



c = common, p = private,
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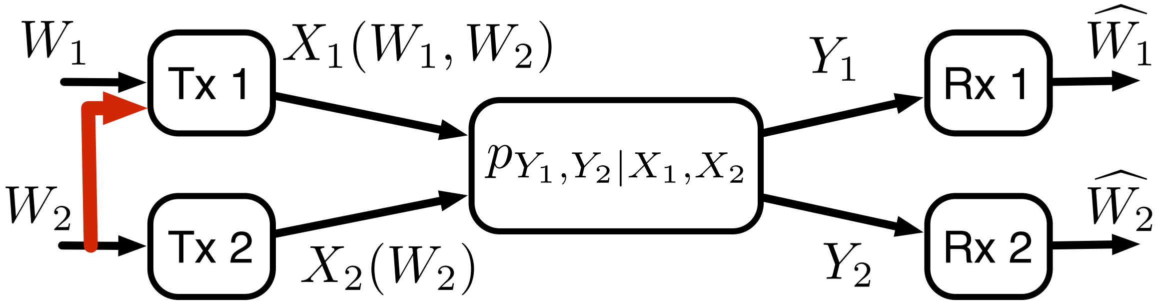
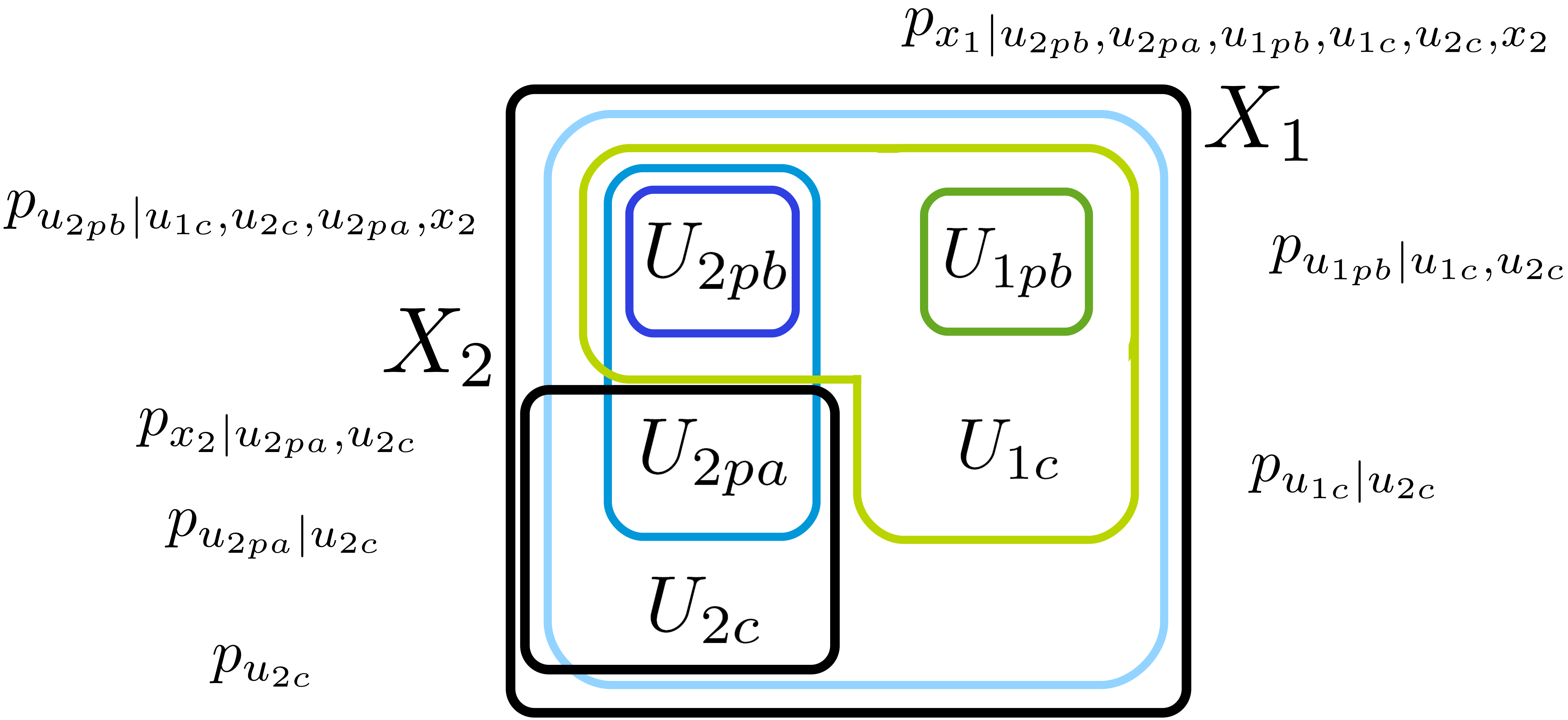




$p_{x_1|u_{2pb},u_{2pa},u_{1pb},u_{1c},u_{2c},x_2}$

$p_{u_{2pb}|u_{1c},u_{2c},u_{2pa},x_2}$

$p_{u_{1pb}|u_{1c},u_{2c}}$

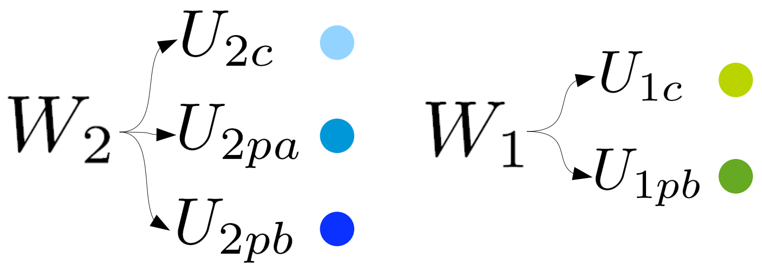
$p_{x_2|u_{2pa},u_{2c}}$

$p_{u_{2pa}|u_{2c}}$

$p_{u_{1c}|u_{2c}}$

$p_{u_{2c}}$

Superposition coding



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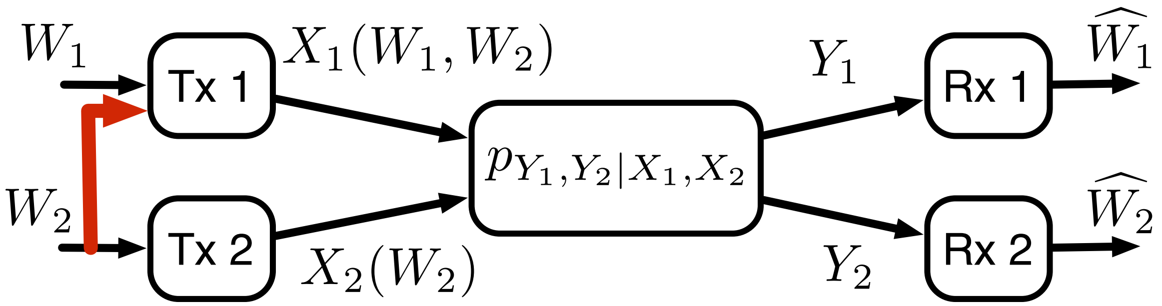
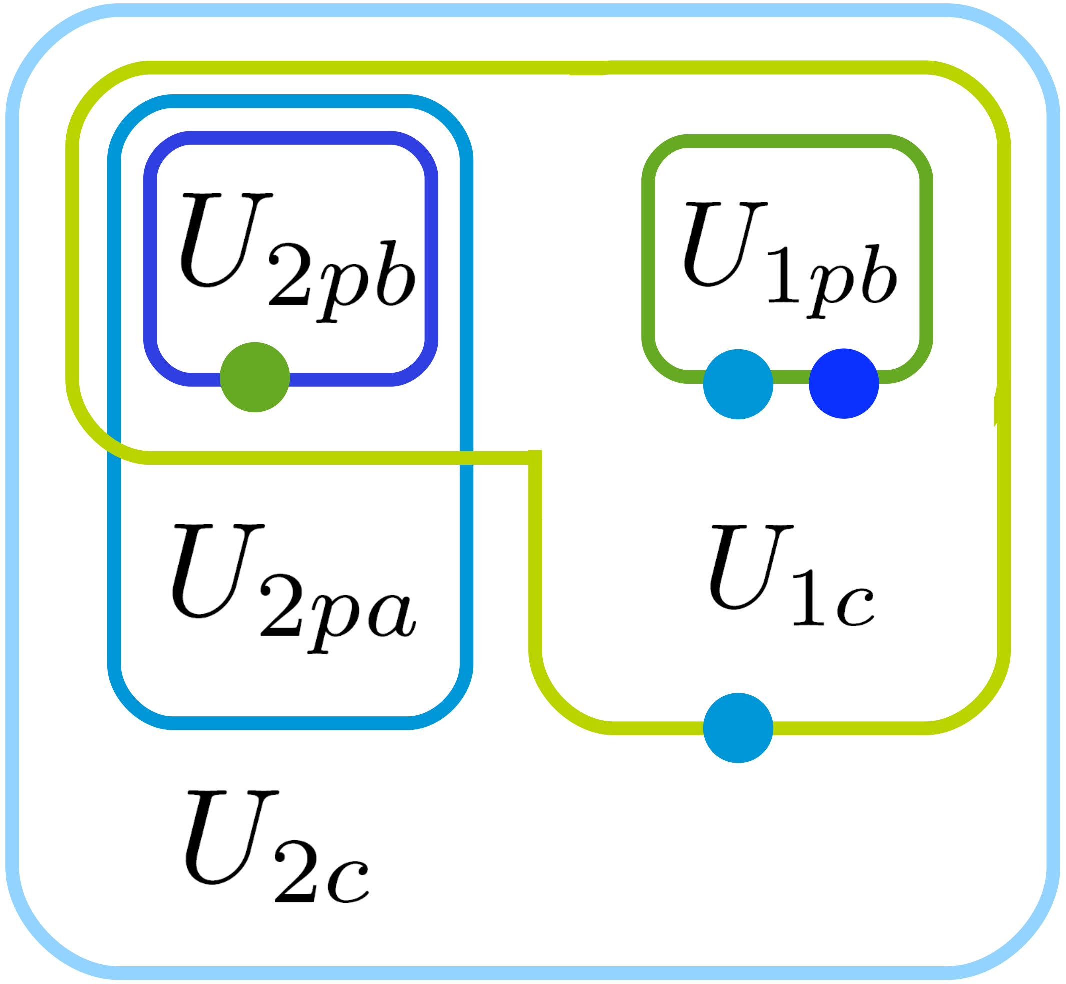
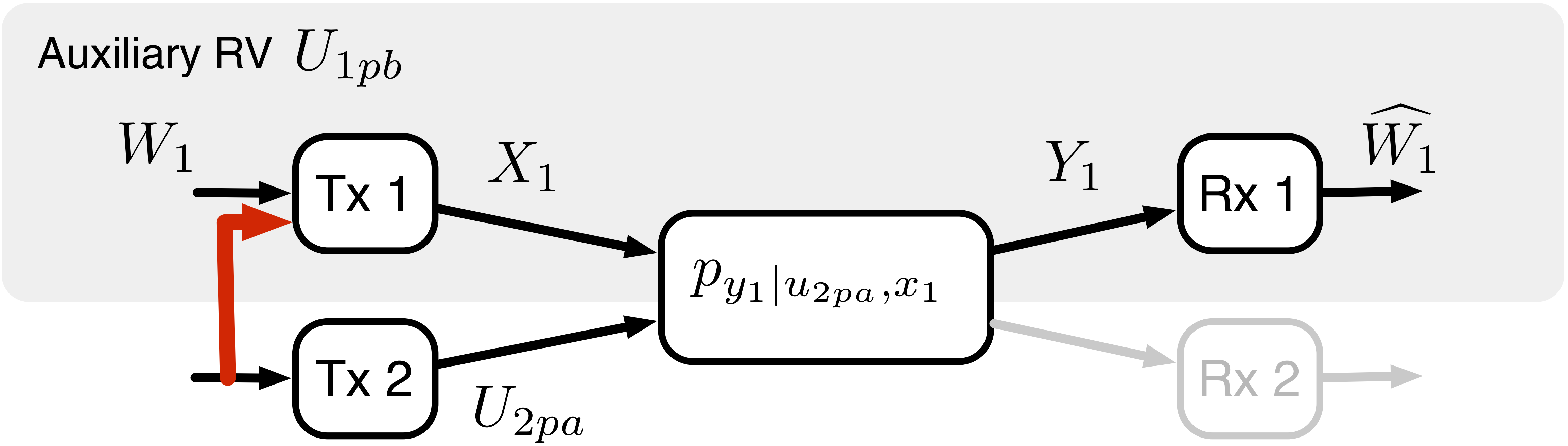
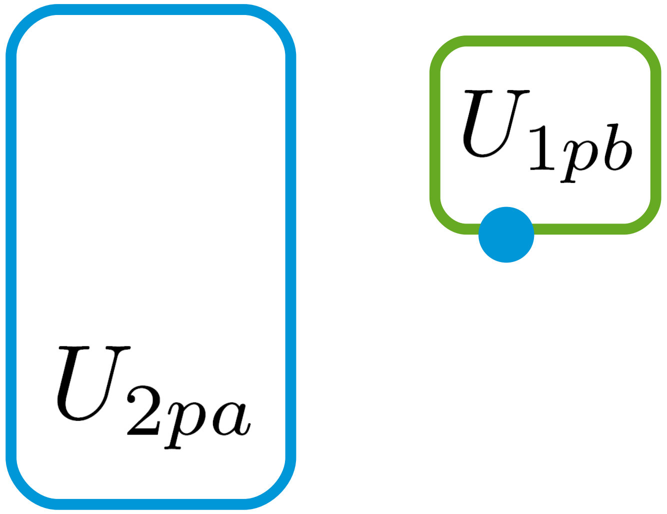




Gel’fand-Pinsker binning





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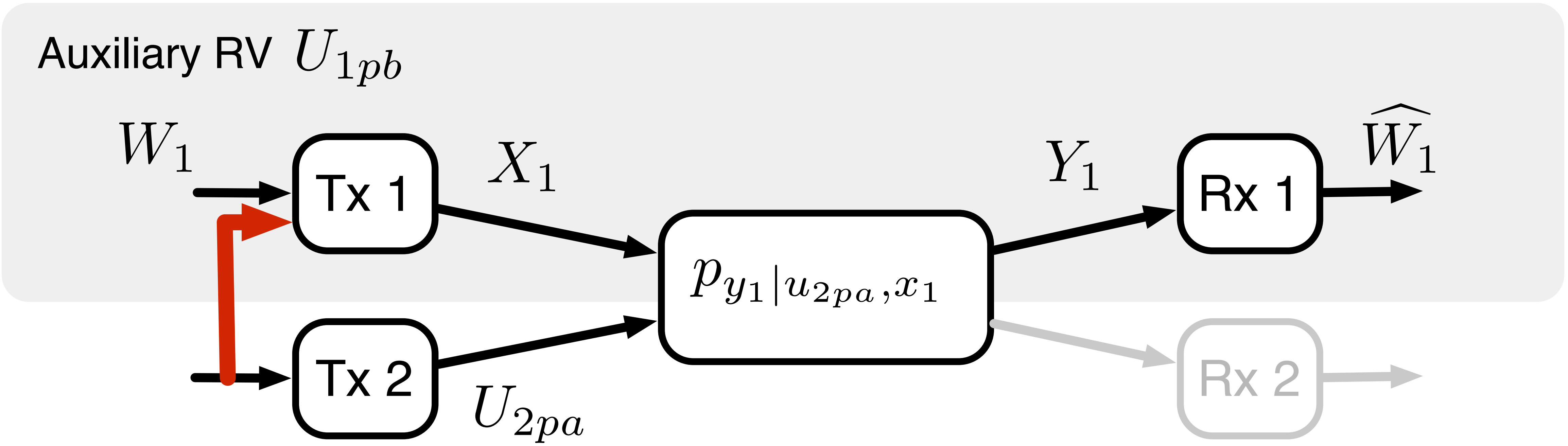
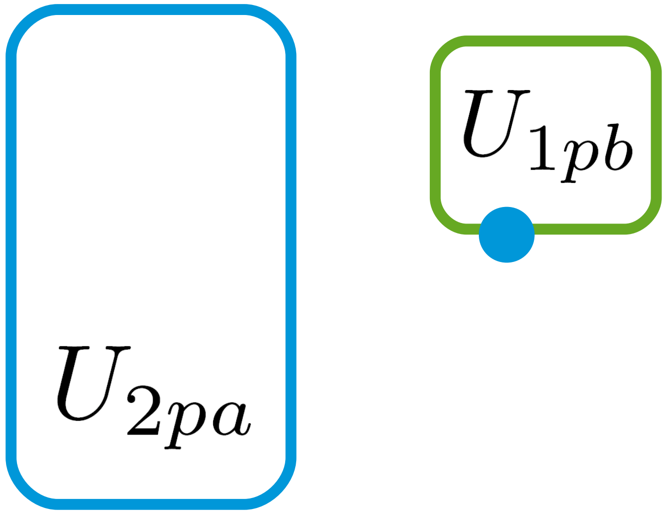
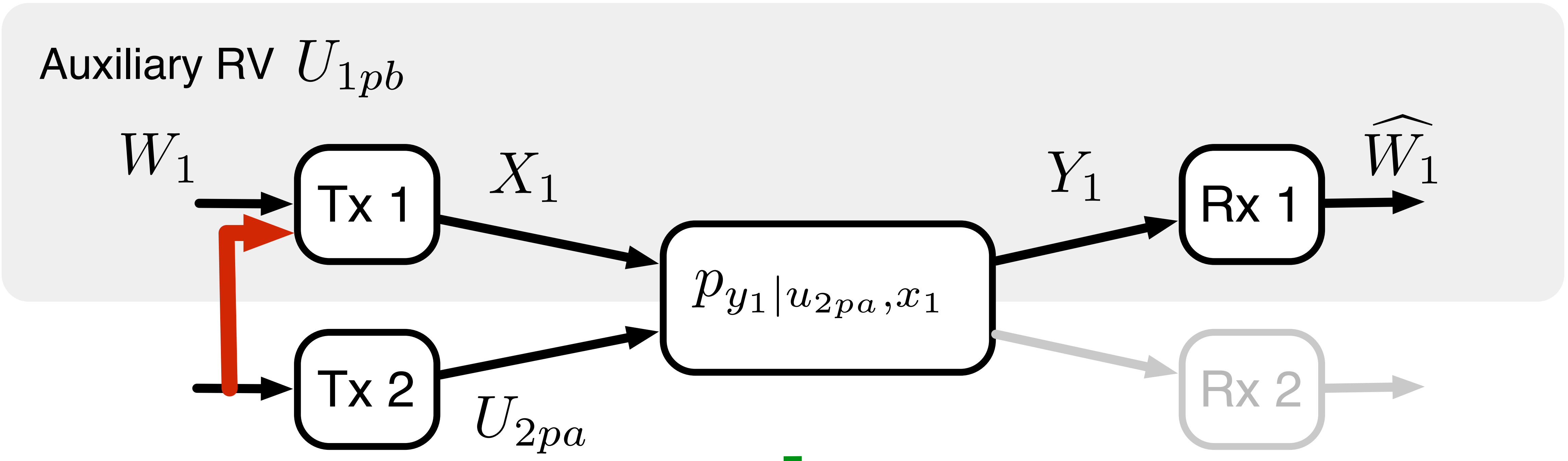


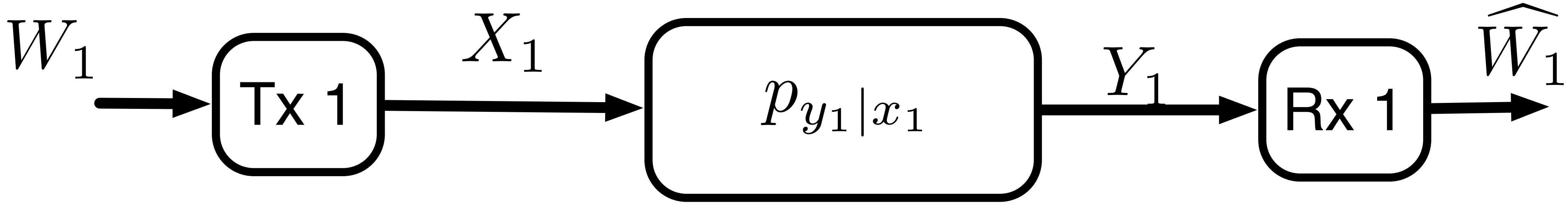


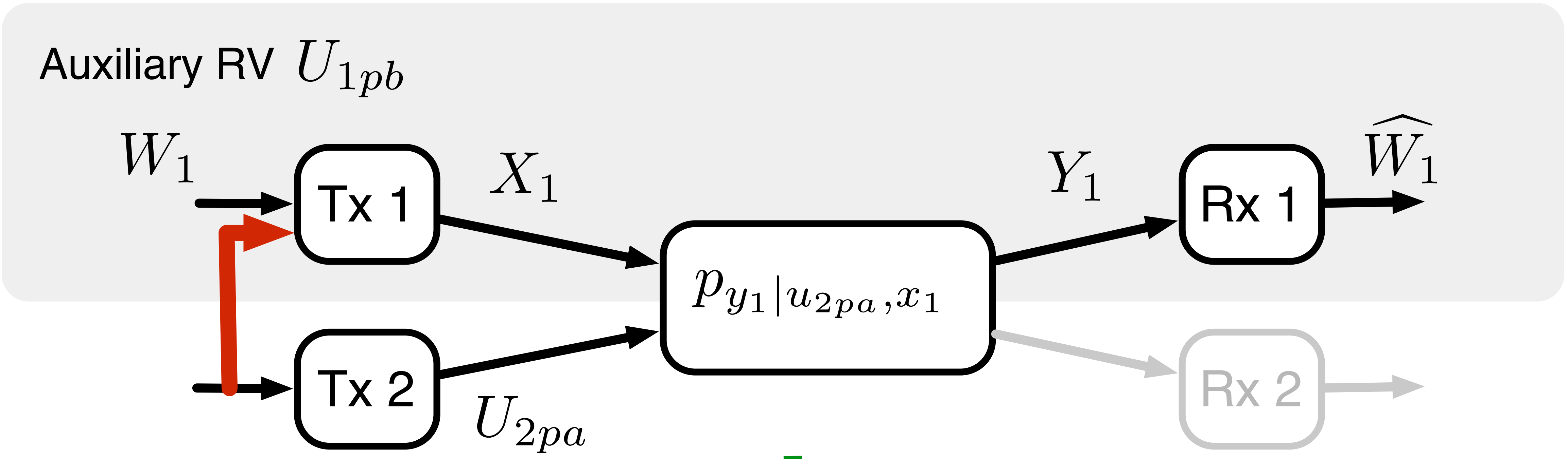
$$C_{1pb} = \max_{p_{u_{1pb},x_1|u_{2pa}}} I(U_{1pb};Y_1) - I(U_{1pb};U_{2pa})$$

Gel’fand-Pinsker binning

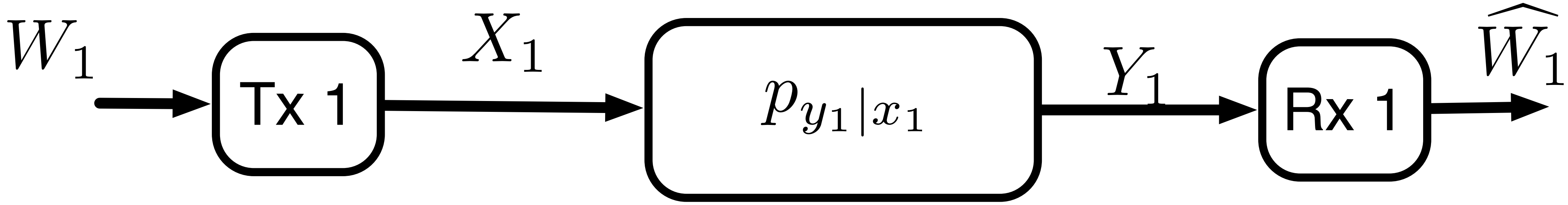


In Gaussian noise with ``proper” choice of auxiliary RV





In Gaussian noise with ``proper" choice of auxiliary RV



Gel'fand-Pinsker binning =
Dirty Paper Coding in Gaussian noise!

Dirty-paper coding

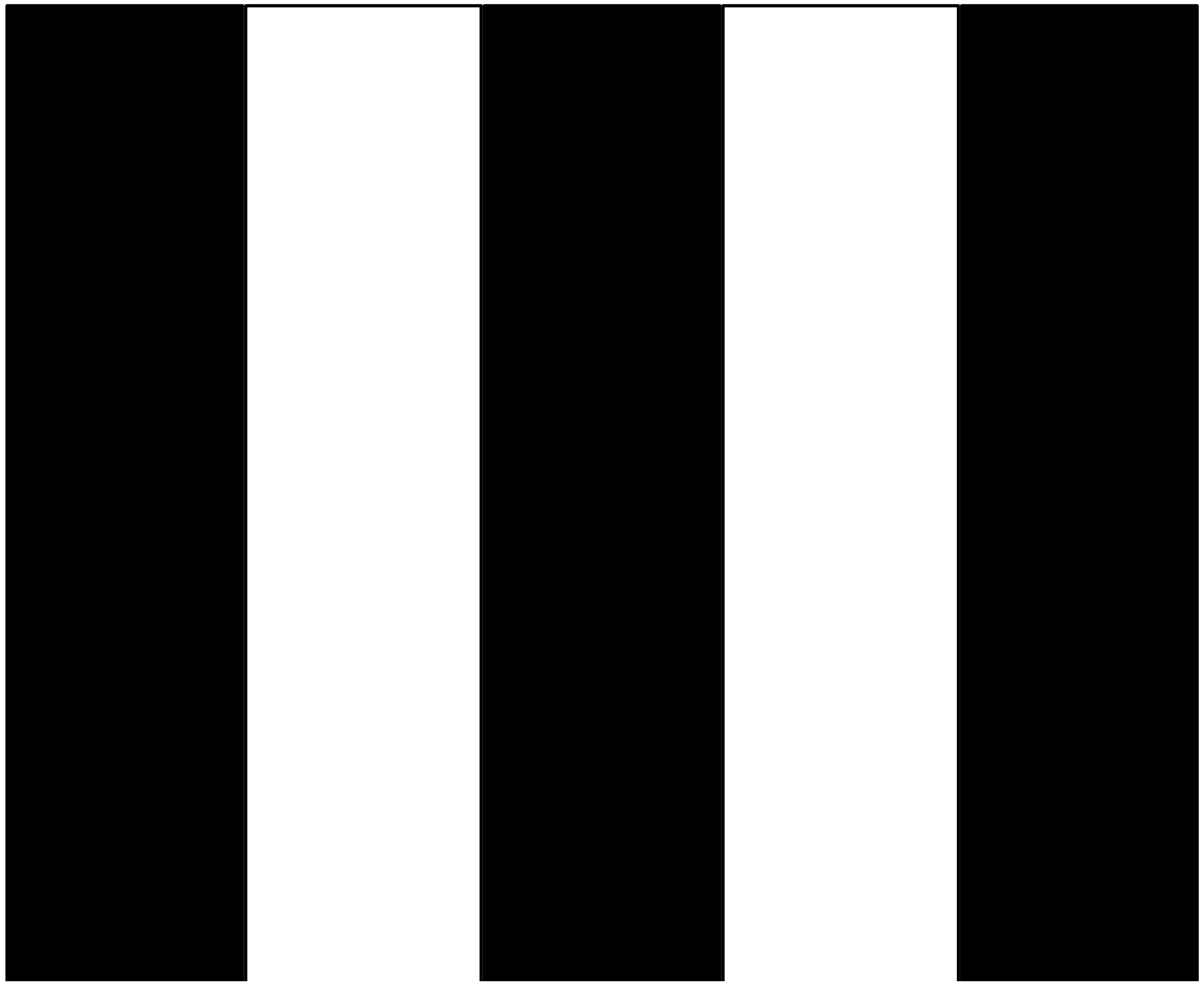
[Gel’fand, Pinsker, 1980]

[Costa, 1983]

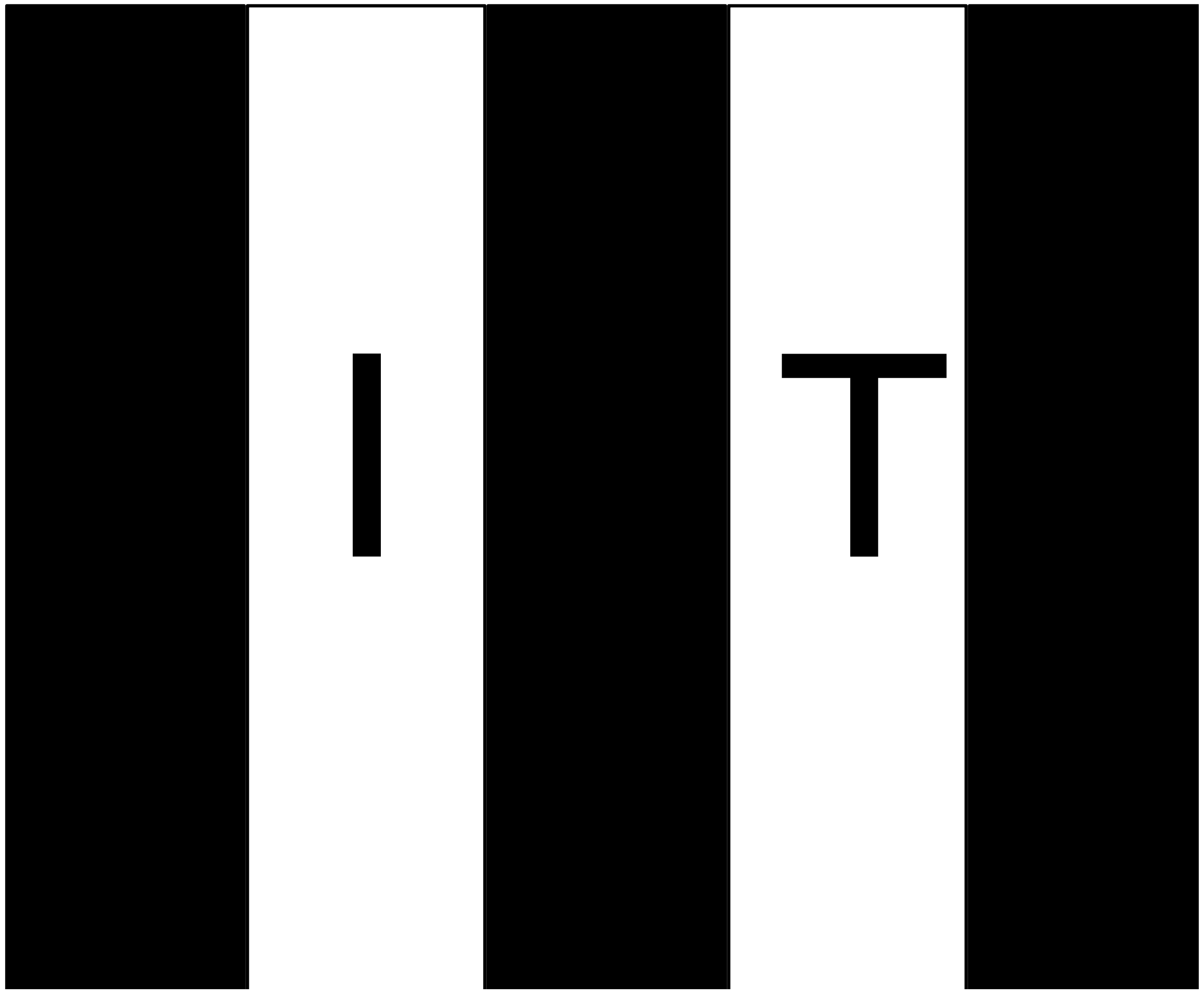
Dirty-paper coding

DIRTY

Dirty-paper coding



Dirty-paper coding

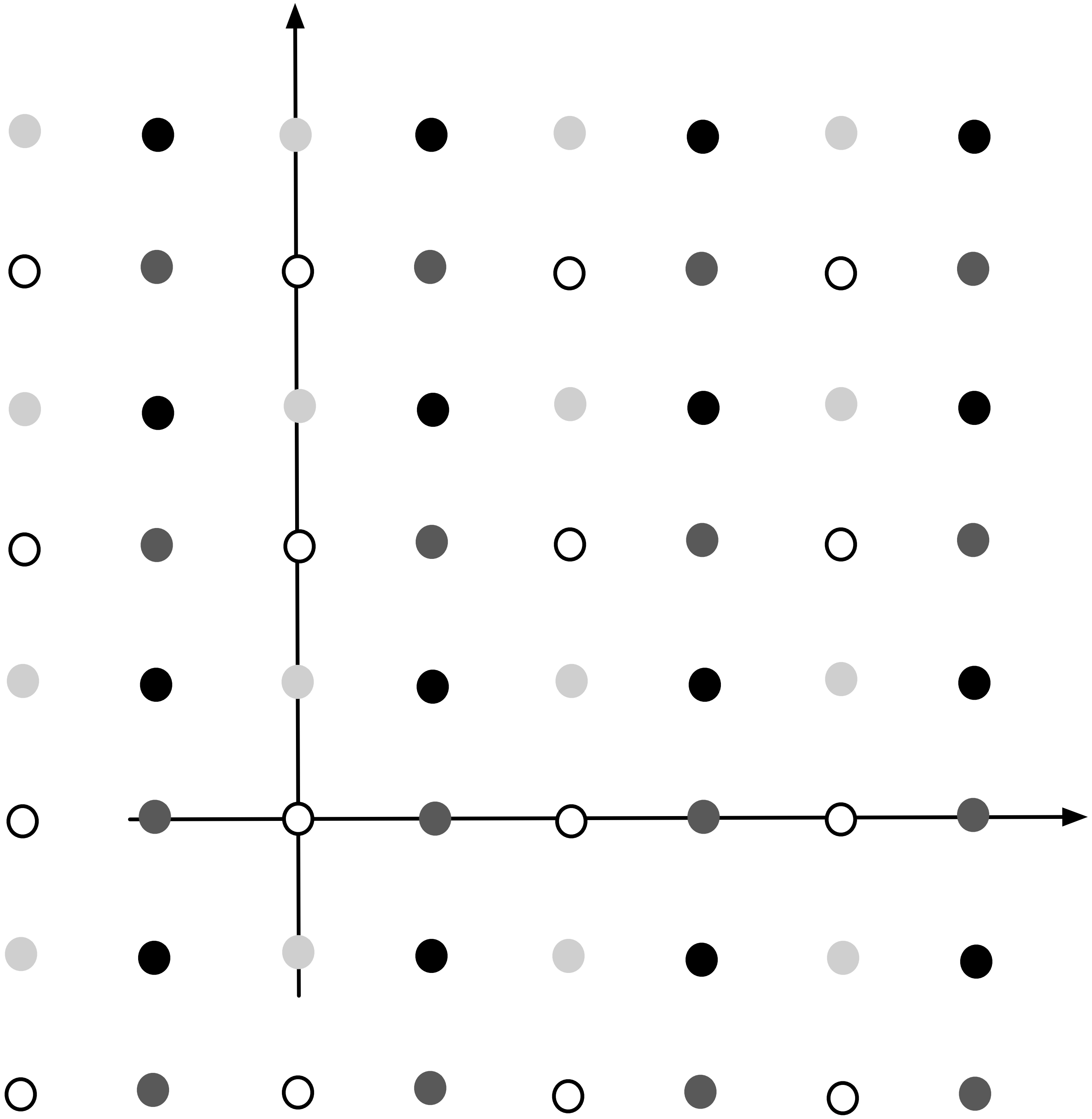


write in black ink?

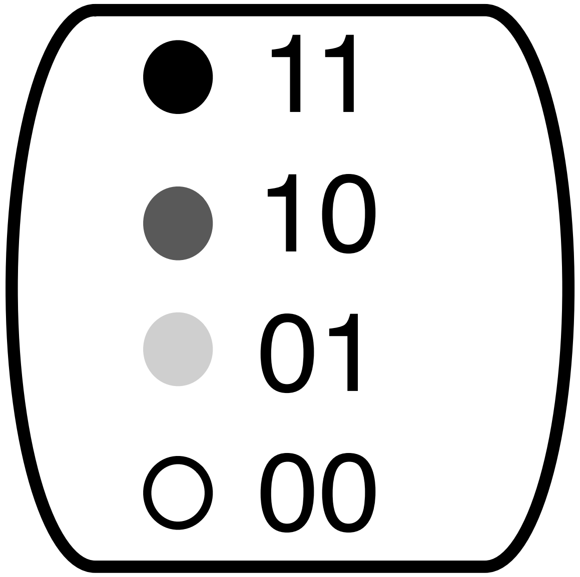
Dirty-paper coding

adjust your ink ✓

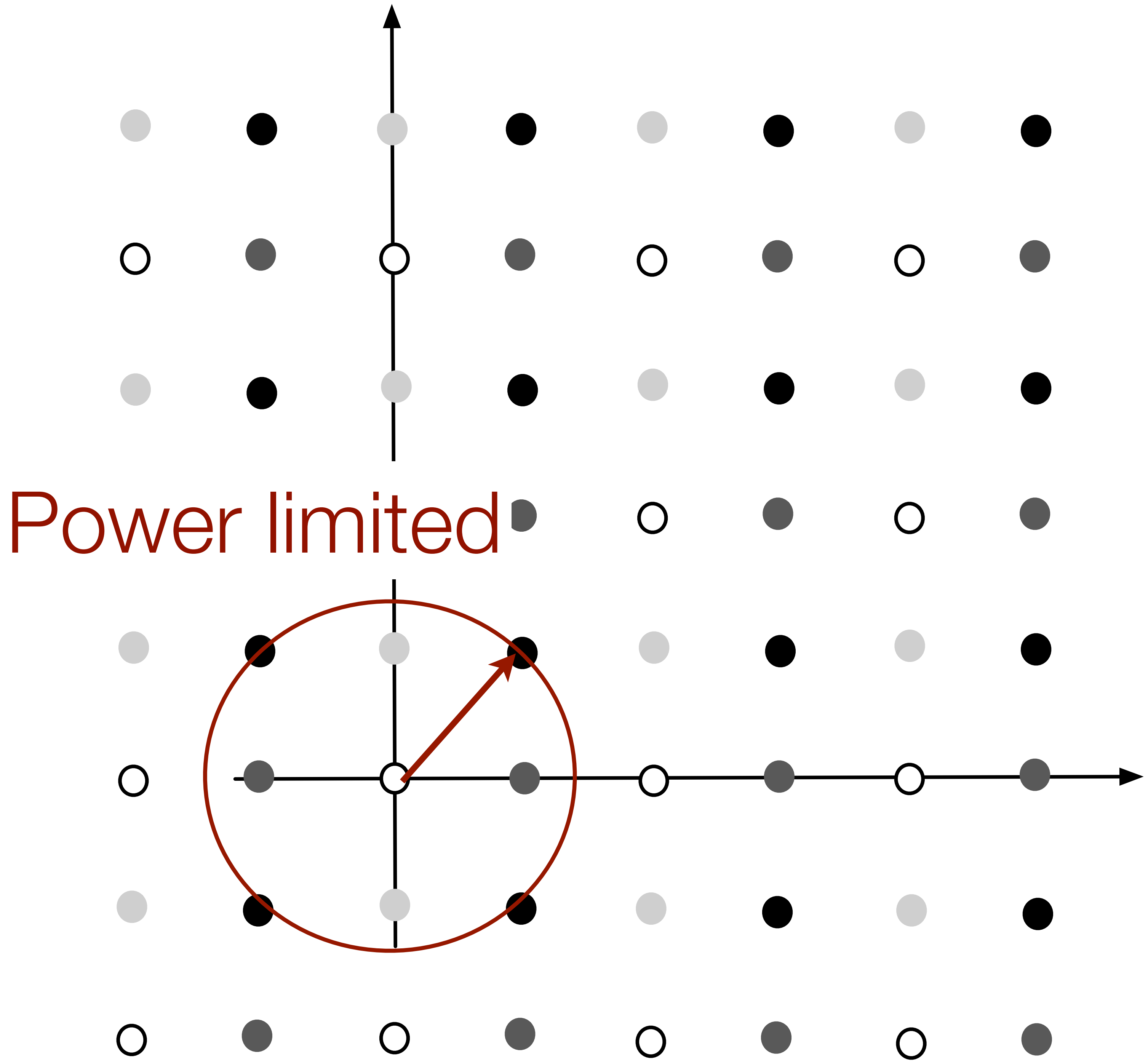
Example of dirty-paper coding



Send 2 bits:



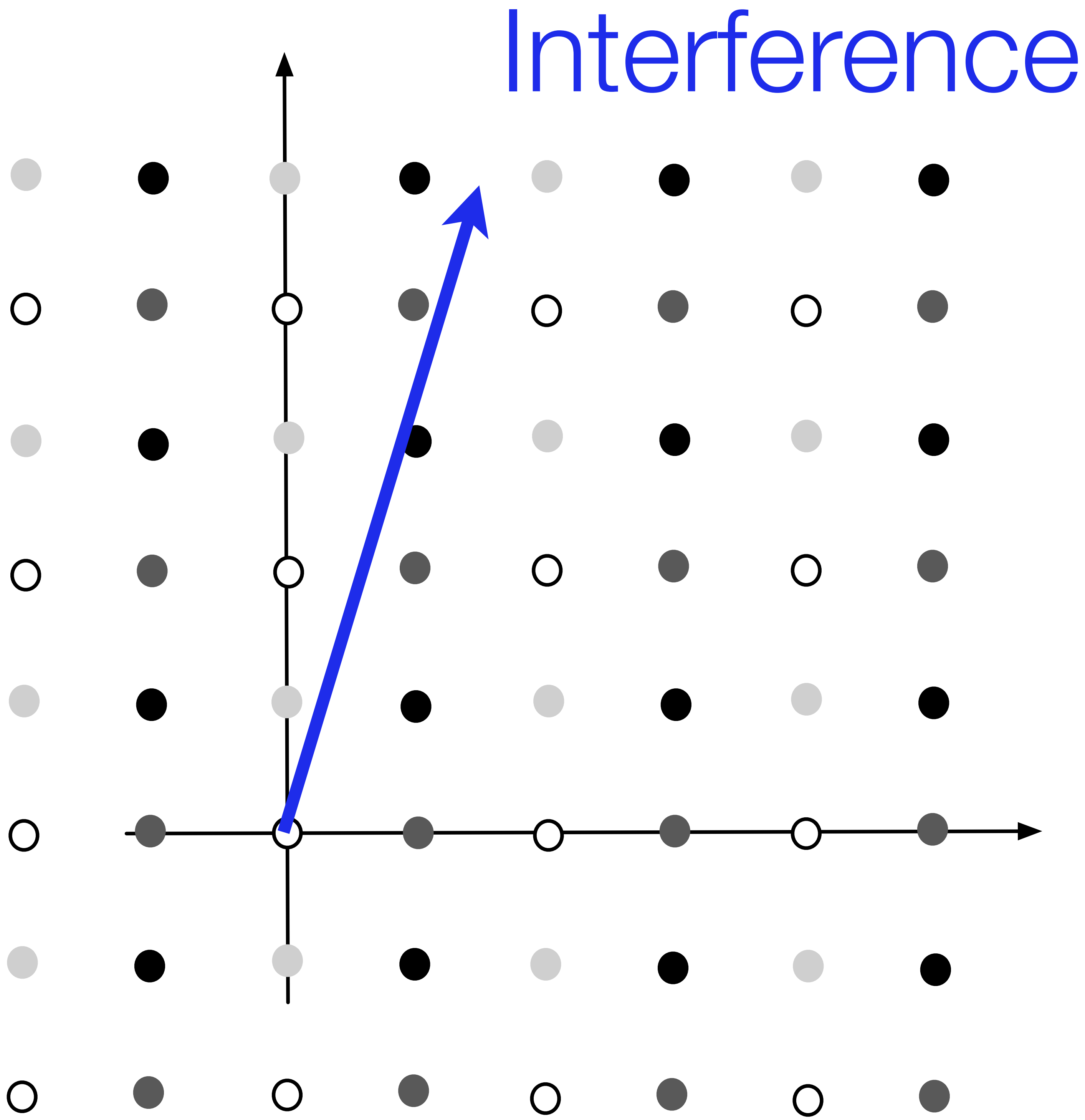
Example of dirty-paper coding



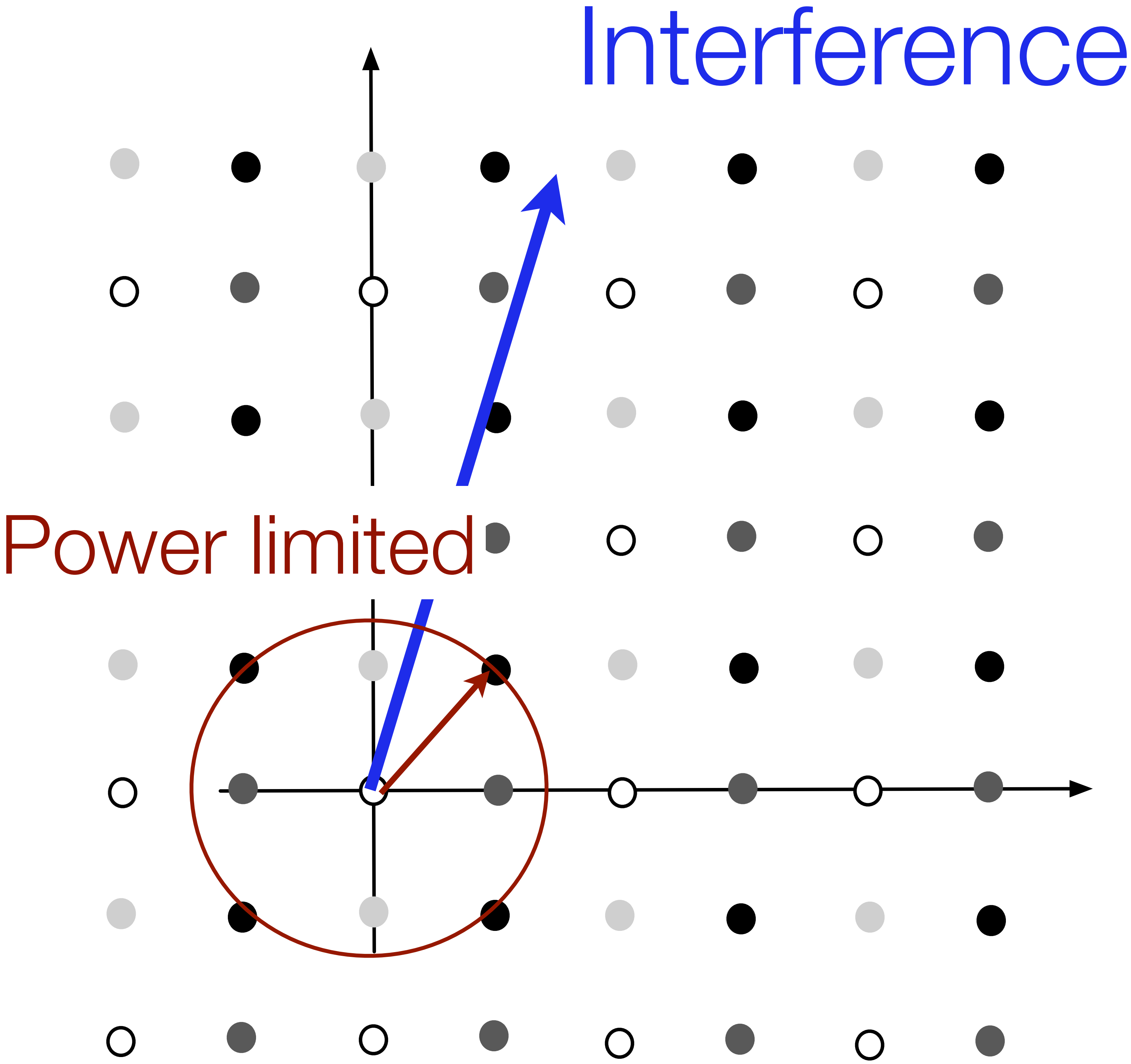
Send 2 bits:

● 11
▨ 10
░ 01
○ 00

Example of dirty-paper coding

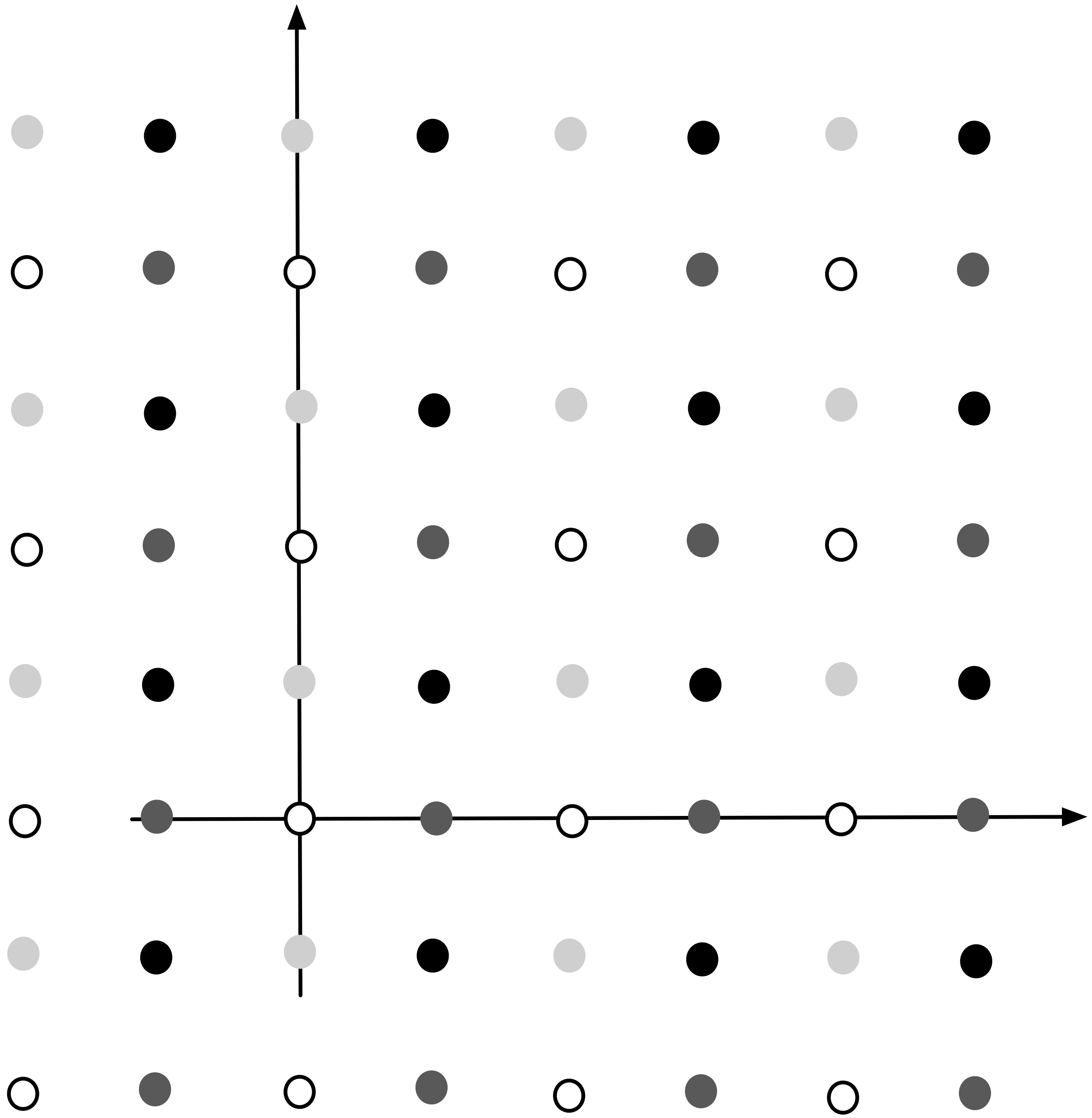


Example of dirty-paper coding



Do NOT have enough power to subtract off the interference!

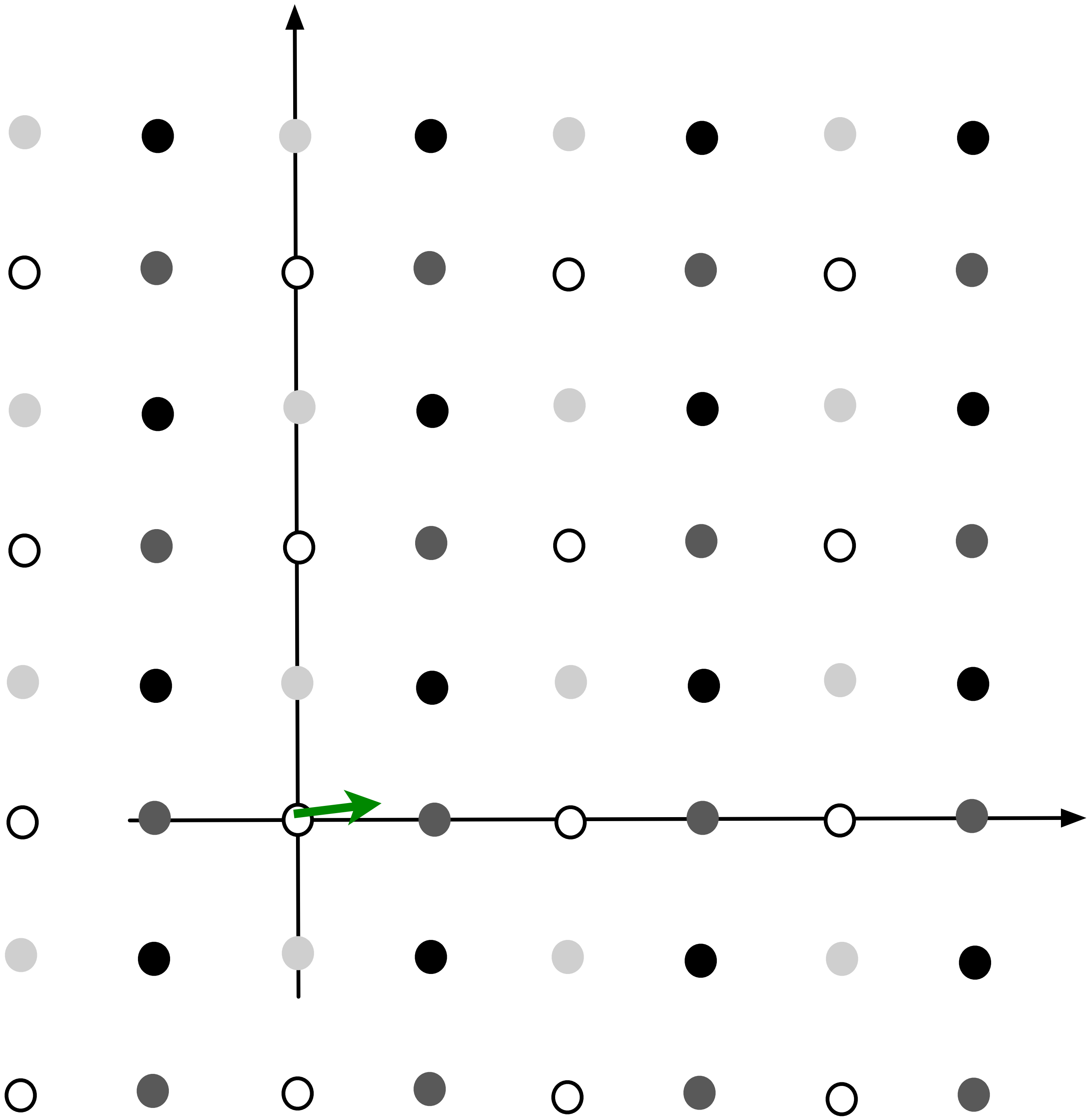
Example of dirty-paper coding



How to send 01?

● 11
◉ 10
◍ 01
○ 00

Example of dirty-paper coding



How to send 01?

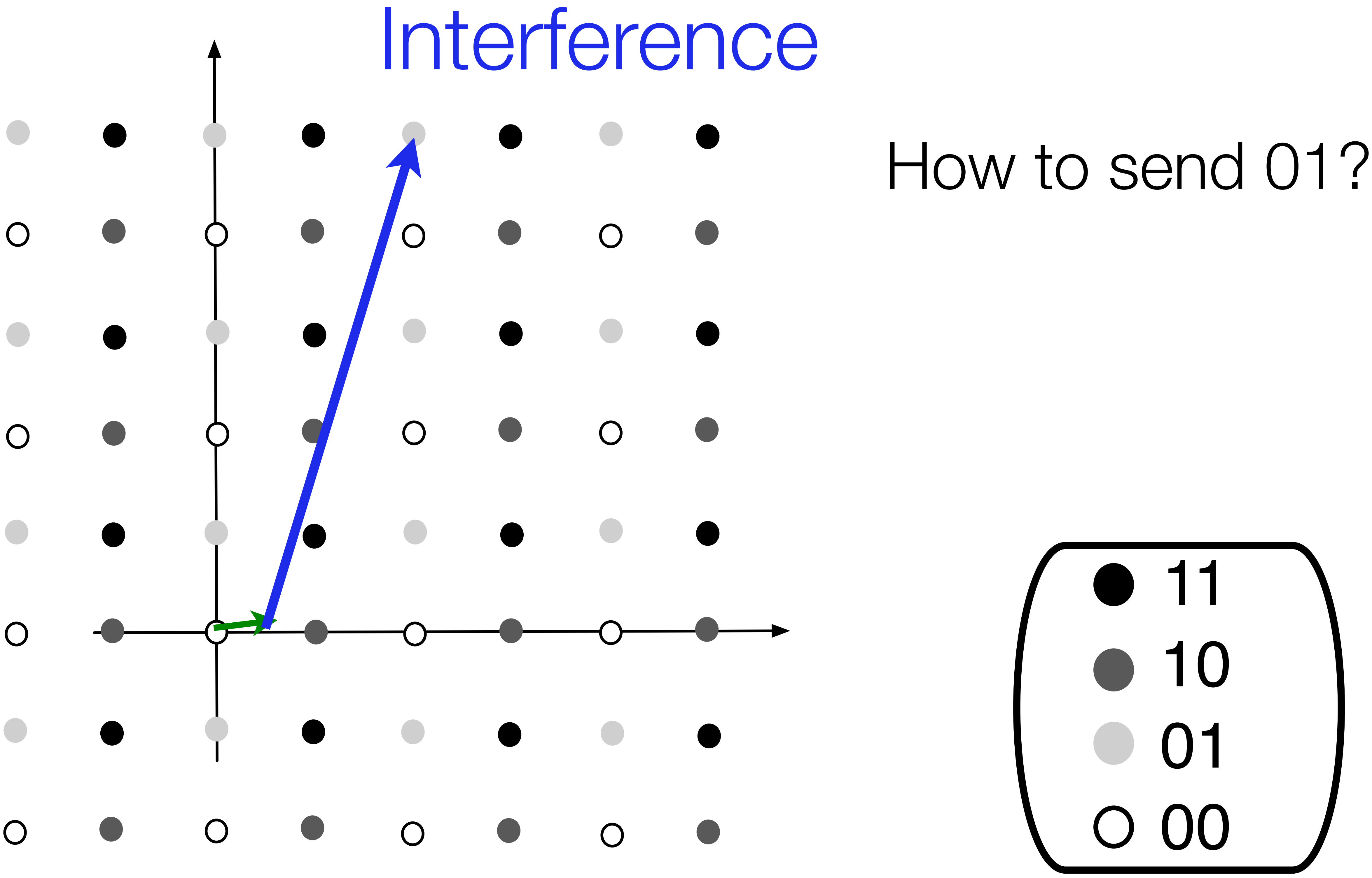
● 11

◍ 10

◌ 01

○ 00

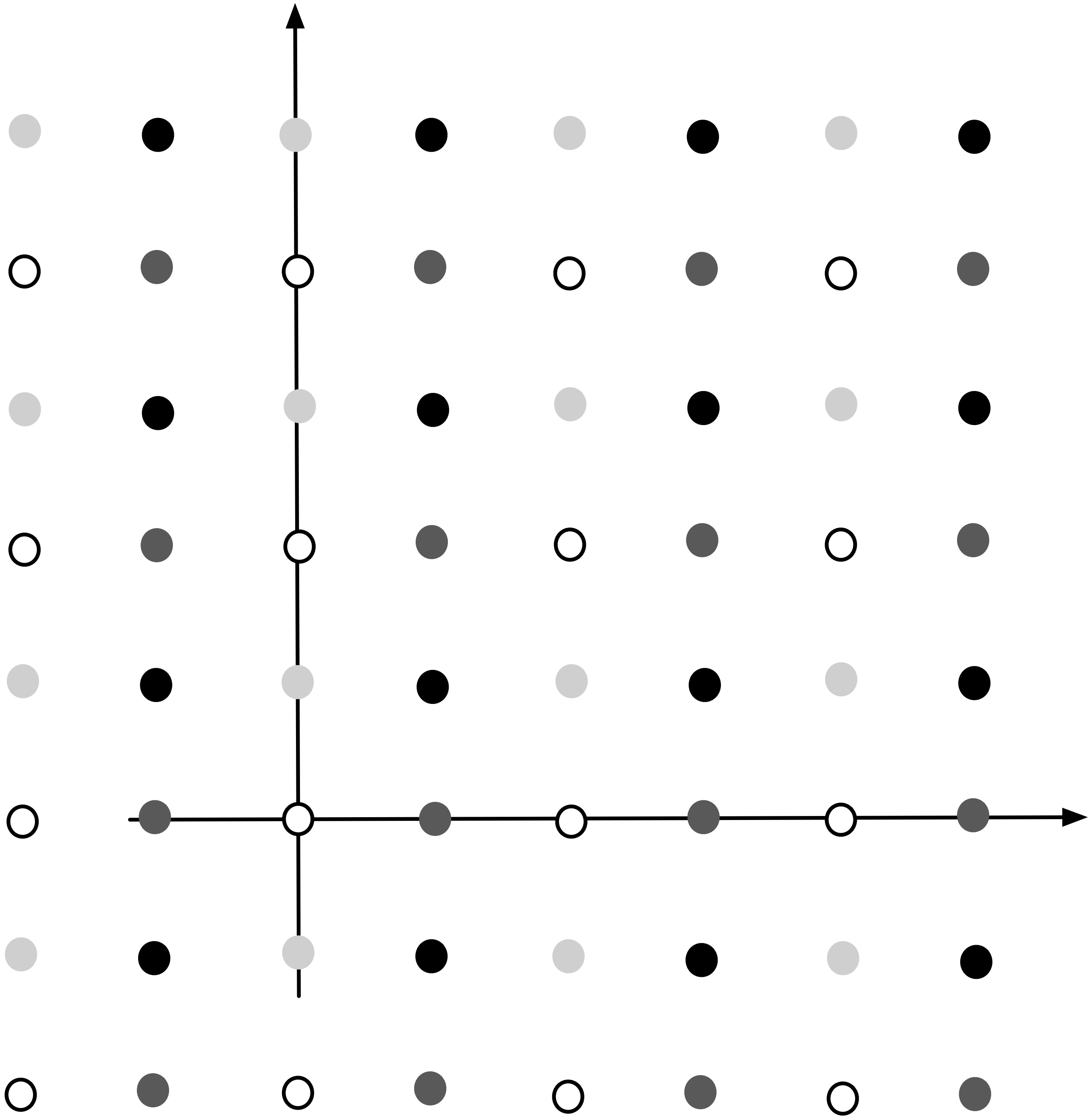
Example of dirty-paper coding



How to send 01?

- ● 11
- ● 10
- ● 01
- ○ 00

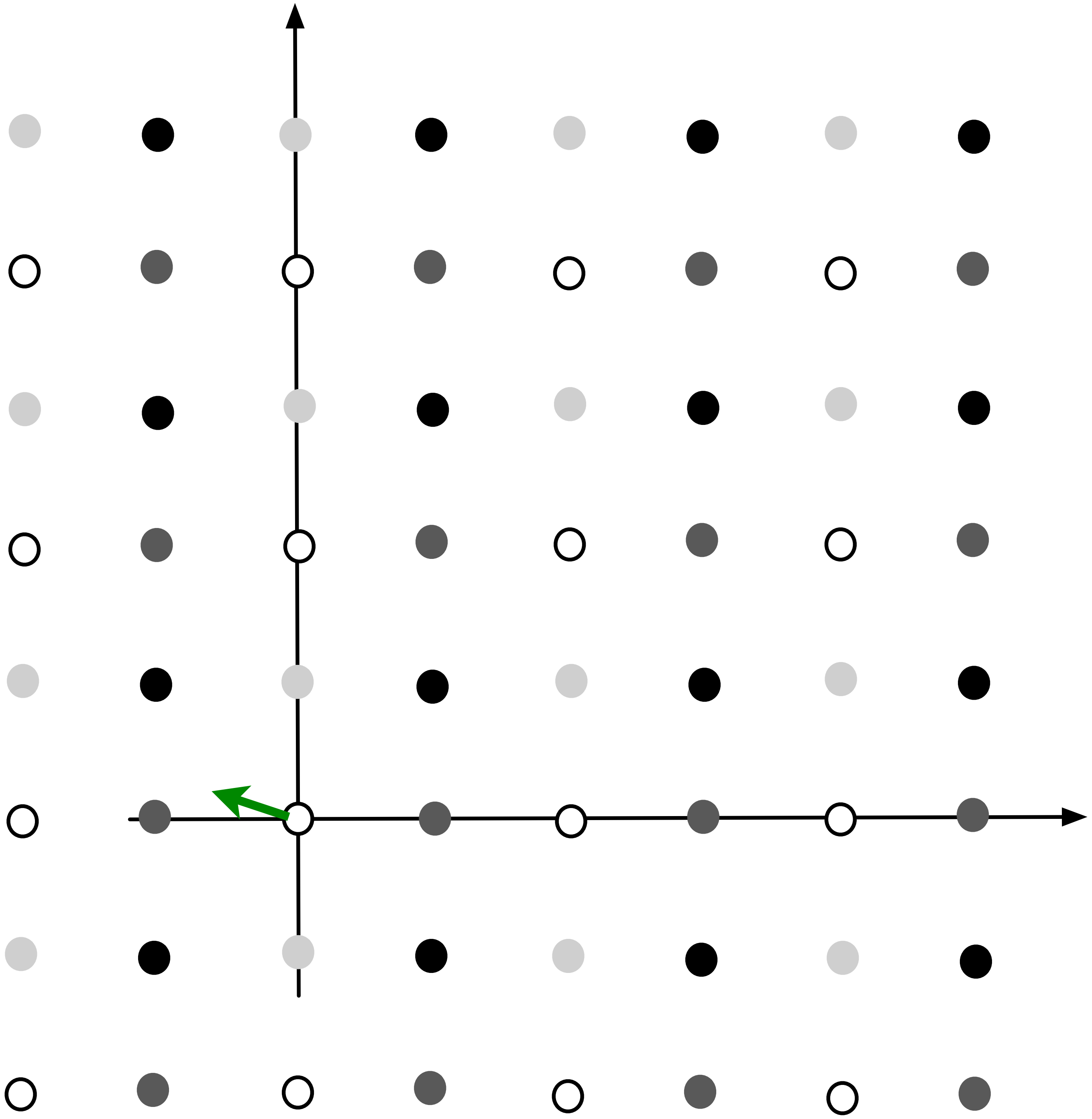
Example of dirty-paper coding



How to send 11?

● 11
◉ 10
◌ 01
○ 00

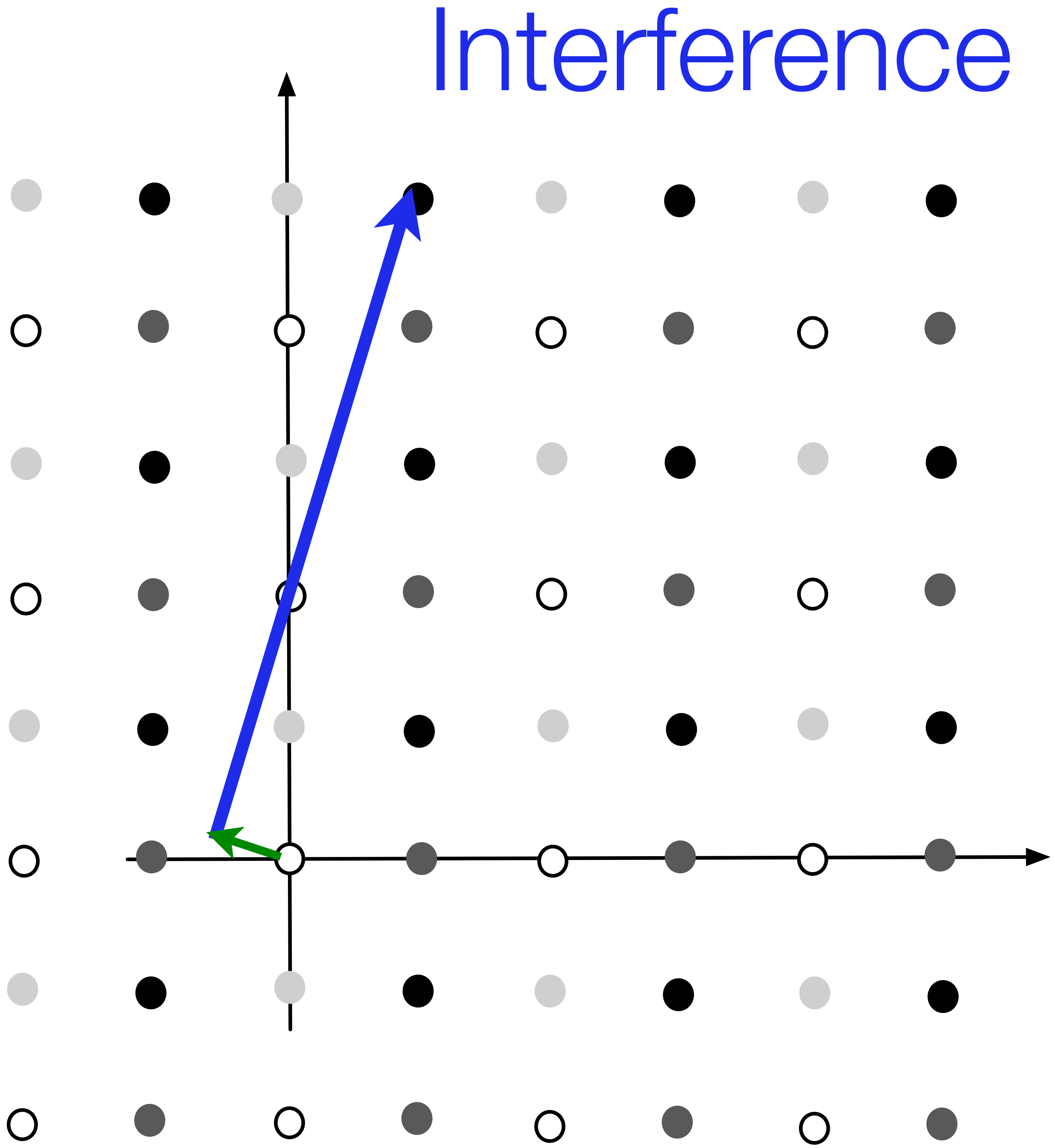
Example of dirty-paper coding



How to send 11?

● 11
● 10
● 01
○ 00

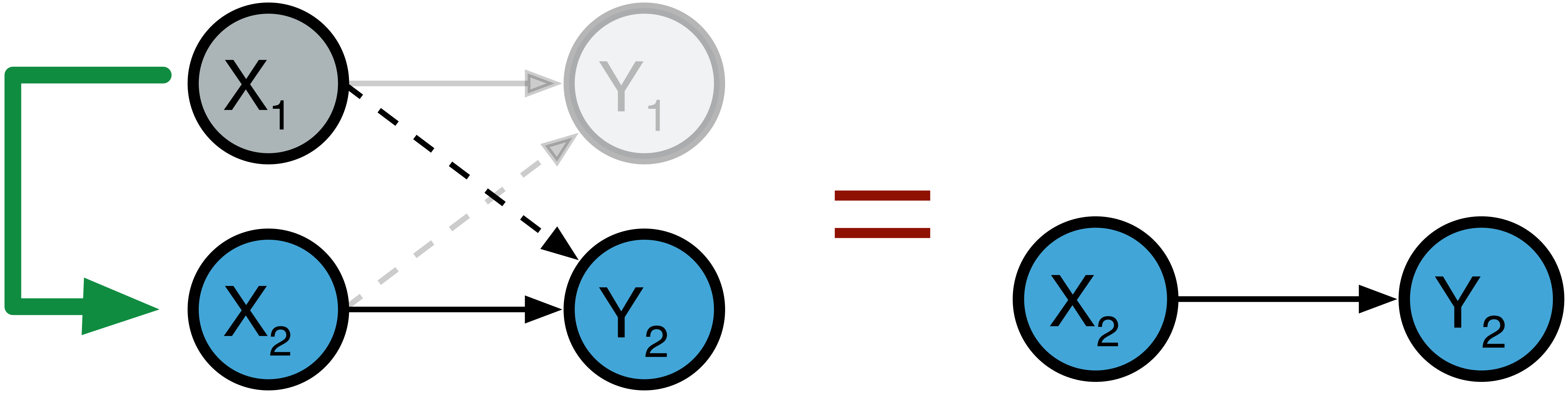
Example of dirty-paper coding



How to send 11?

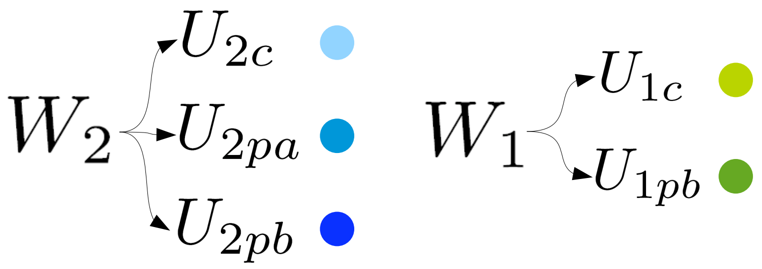
● 11
◍ 10
◌ 01
○ 00

Dirty-paper coding

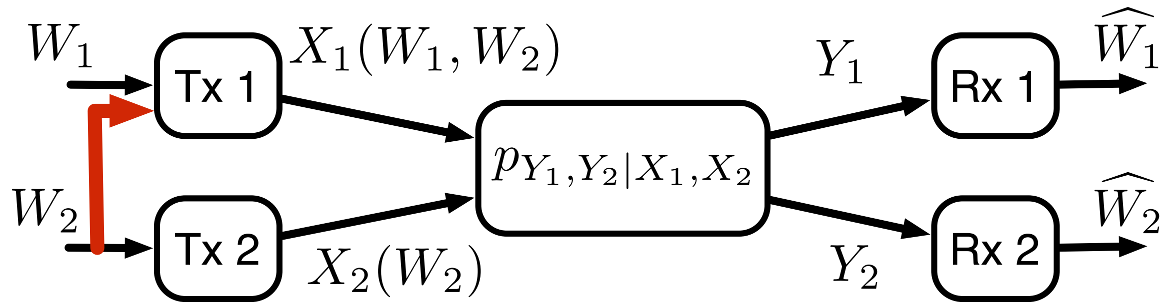


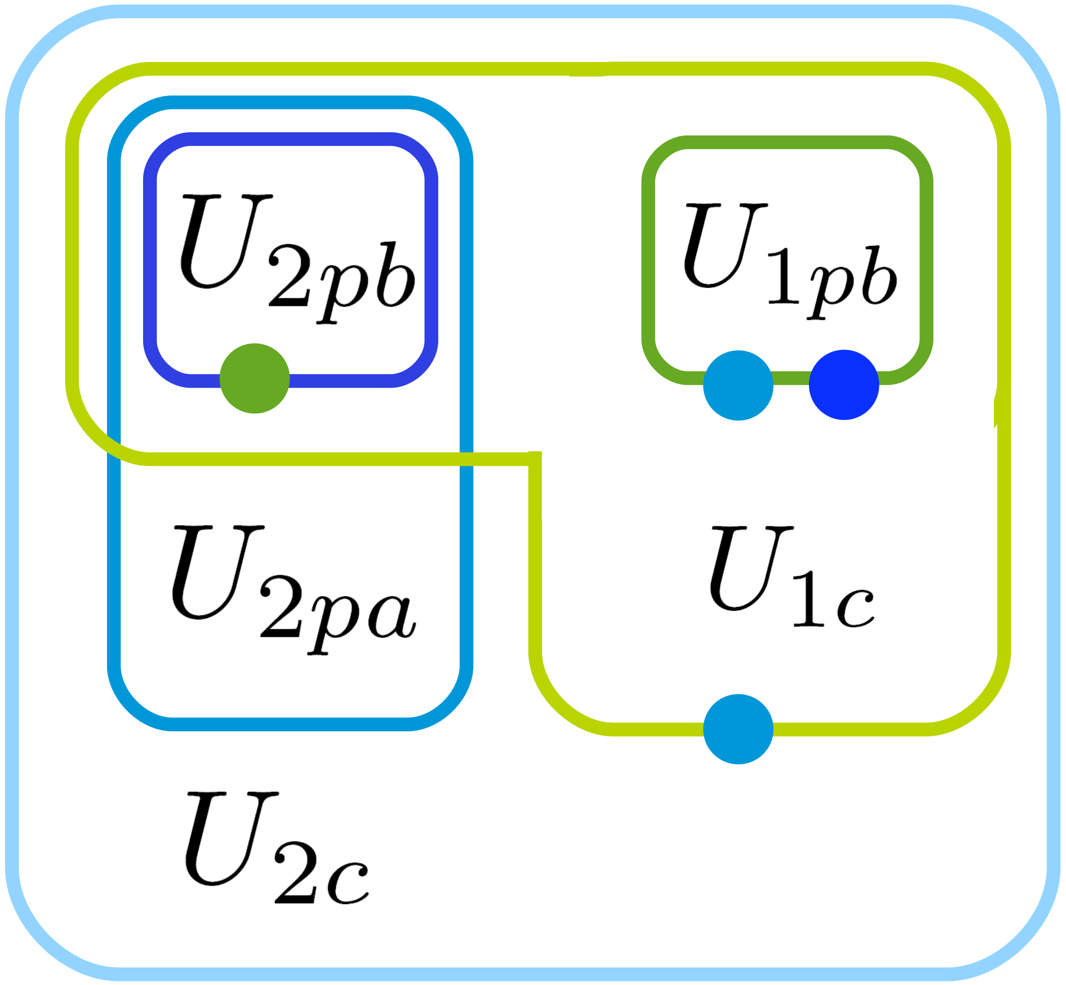
NO power penalty!

NOT subtracting off interference!

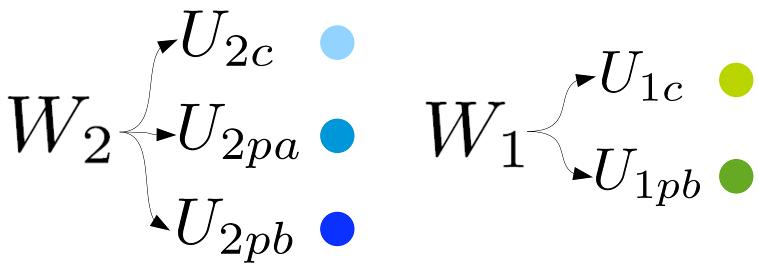


c = common, p = private,
a = alone, b = broadcast





Gel’fand-Pinsker binning



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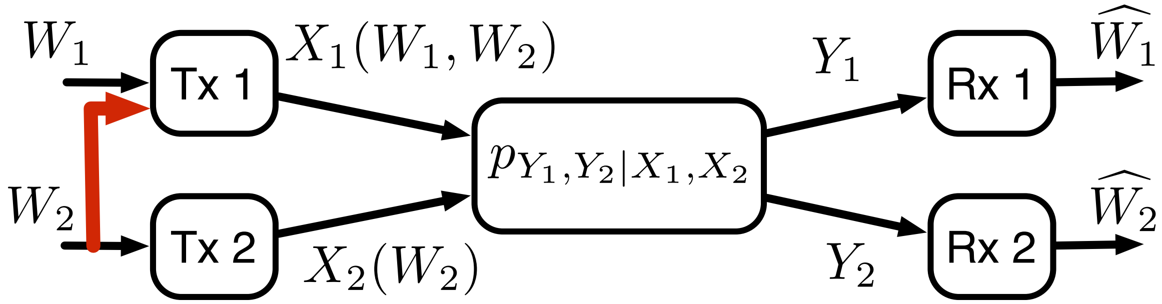
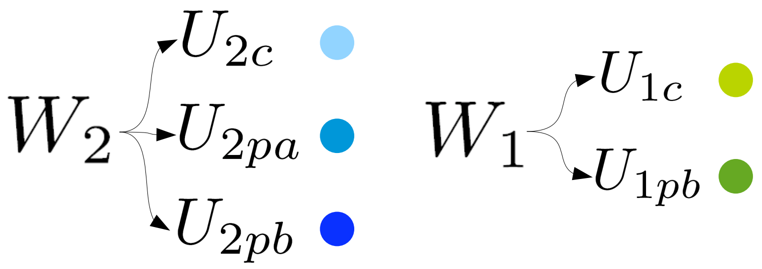
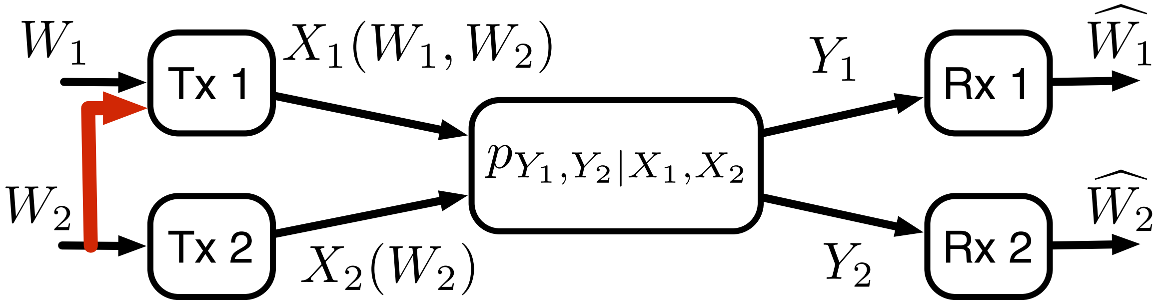


$$\begin{aligned}
R'_0 &\geq I(U_{1c};U_{2pa},X_2|U_{2c}) && \text{(3a)}\\
R'_0+R'_1+R'_2 &\geq I(U_{1c};U_{2pa},X_2|U_{2c})+I(U_{1pb};U_{2pa},U_{2pb},X_2|U_{2c},U_{1c}) && \\
&\quad +I(U_{2pb};X_2|U_{2c},U_{2pa},U_{1c}) && \text{(3b)}\\
R_{2c}+R_{1c}+R_{2pa}+R_{2pb}+R'_0+R'_2 &\leq I(Y_2;U_{1c},U_{2c},U_{2pa},U_{2pb})+I(U_{1c};U_{2pa}|U_{2c}) && \text{(3c)}\\
R_{1c}+R_{2pa}+R_{2pb}+R'_0+R'_2 &\leq I(Y_2;U_{1c},U_{2pa},U_{2pb}|U_{2c})+I(U_{1c};U_{2pa}|U_{2c}) && \text{(3d)}\\
R_{2pa}+R_{2pb}+R'_2 &\leq I(Y_2;U_{2pa},U_{2pb}|U_{2c},U_{1c})+I(U_{1c};U_{2pa}|U_{2c}) && \text{(3e)}\\
R_{1c}+R_{2pb}+R'_0+R'_2 &\leq I(Y_2;U_{1c},U_{2pb}|U_{2c},U_{2pa})+I(U_{1c};U_{2pa}|U_{2c}) && \text{(3f)}\\
R_{2pb}+R'_2 &\leq I(Y_2;U_{2pb}|U_{2c},U_{1c},U_{2pa})+I(U_{2pa};U_{1c}|U_{2c}) && \text{(3g)}\\
R_{2c}+R_{1c}+R_{1pb}+R'_0+R'_1 &\leq I(Y_1;U_{2c},U_{1c},U_{1pb}) && \text{(3h)}\\
R_{1c}+R_{1pb}+R'_0+R'_1 &\leq I(Y_1;U_{1c},U_{1pb}|U_{2c}) && \text{(3i)}\\
R_{1pb}+R'_1 &\leq I(Y_1;U_{1pb}|U_{2c},U_{1c}) && \text{(3j)}
\end{aligned}$$

over all input distributions of the form $p_{X_1,X_2,U_{1c},U_{2c},U_{2pa},U_{1pb},U_{2pb}}$



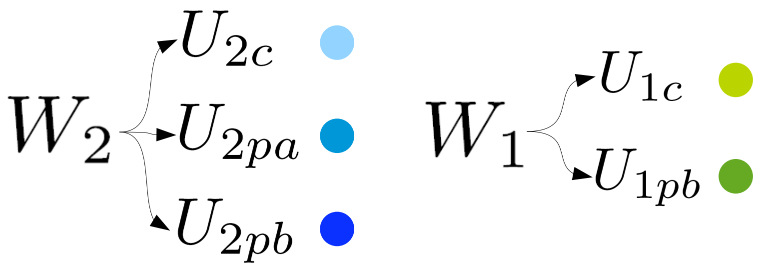


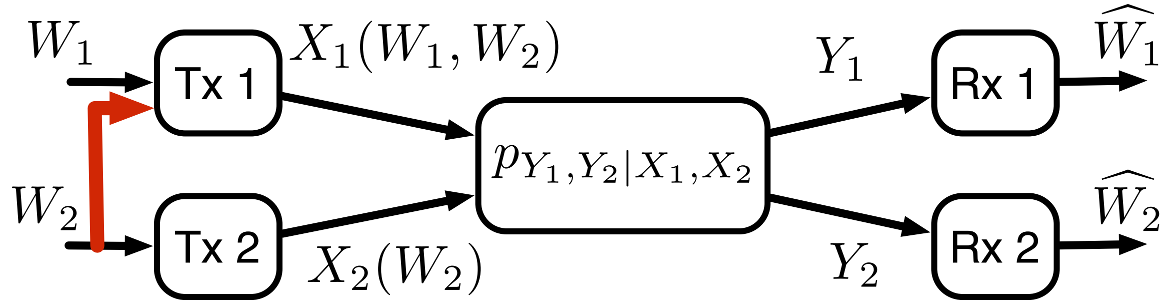
c = common, p = private,
a = alone, b = broadcast

Analytically shown to be largest known region

$$
\begin{aligned}
R'_0 &\geq I(U_{1c}; U_{2pa}, X_2|U_{2c}) && \text{(3a)}\\
R'_0 + R'_1 + R'_2 &\geq I(U_{1c}; U_{2pa}, X_2|U_{2c}) + I(U_{1pb}; U_{2pa}, U_{2pb}, X_2|U_{2c}, U_{1c}) \\
&\quad + I(U_{2pb}; X_2|U_{2c}, U_{2pa}, U_{1c}) && \text{(3b)}\\
R_{2c} + R_{1c} + R_{2pa} + R_{2pb} + R'_0 + R'_2 &\leq I(Y_2; U_{1c}, U_{2c}, U_{2pa}, U_{2pb}) + I(U_{1c}; U_{2pa}|U_{2c}) && \text{(3c)}\\
R_{1c} + R_{2pa} + R_{2pb} + R'_0 + R'_2 &\leq I(Y_2; U_{1c}, U_{2pa}, U_{2pb}|U_{2c}) + I(U_{1c}; U_{2pa}|U_{2c}) && \text{(3d)}\\
R_{2pa} + R_{2pb} + R'_2 &\leq I(Y_2; U_{2pa}, U_{2pb}|U_{2c}, U_{1c}) + I(U_{1c}; U_{2pa}|U_{2c}) && \text{(3e)}\\
R_{1c} + R_{2pb} + R'_0 + R'_2 &\leq I(Y_2; U_{1c}, U_{2pb}|U_{2c}, U_{2pa}) + I(U_{1c}; U_{2pa}|U_{2c}) && \text{(3f)}\\
R_{2pb} + R'_2 &\leq I(Y_2; U_{2pb}|U_{2c}, U_{1c}, U_{2pa}) + I(U_{2pa}; U_{1c}|U_{2c}) && \text{(3g)}\\
R_{2c} + R_{1c} + R_{1pb} + R'_0 + R'_1 &\leq I(Y_1; U_{2c}, U_{1c}, U_{1pb}) && \text{(3h)}\\
R_{1c} + R_{1pb} + R'_0 + R'_1 &\leq I(Y_1; U_{1c}, U_{1pb}|U_{2c}) && \text{(3i)}\\
R_{1pb} + R'_1 &\leq I(Y_1; U_{1pb}|U_{2c}, U_{1c}) && \text{(3j)}
\end{aligned}
$$

over all input distributions of the form $p_{X_1,X_2,U_{1c},U_{2c},U_{2pa},U_{1pb},U_{2pb}}$





c = common, p = private,
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Analytically shown to be largest known region

$$R'_0 \geq I(U_{1c}; U_{2pa}, X_2 | U_{2c}) \tag{3a}$$

$$\begin{aligned} R'_0 + R'_1 + R'_2 \geq\ & I(U_{1c}; U_{2pa}, X_2 | U_{2c}) + I(U_{1pb}; U_{2pa}, U_{2pb}, X_2 | U_{2c}, U_{1c}) \\ & + I(U_{2pb}; X_2 | U_{2c}, U_{2pa}, U_{1c}) \end{aligned} \tag{3b}$$

$$R_{2c} + R_{1c} + R_{2pa} + R_{2pb} + R'_0 + R'_2 \leq I(Y_2; U_{1c}, U_{2c}, U_{2pa}, U_{2pb}) + I(U_{1c}; U_{2pa} | U_{2c}) \tag{3c}$$

$$R_{1c} + R_{2pa} + R_{2pb} + R'_0 + R'_2 \leq I(Y_2; U_{1c}, U_{2pa}, U_{2pb} | U_{2c}) + I(U_{1c}; U_{2pa} | U_{2c}) \tag{3d}$$

$$R_{2pa} + R_{2pb} + R'_2 \leq I(Y_2; U_{2pa}, U_{2pb} | U_{2c}, U_{1c}) + I(U_{1c}; U_{2pa} | U_{2c}) \tag{3e}$$

$$R_{1c} + R_{2pb} + R'_0 + R'_2 \leq I(Y_2; U_{1c}, U_{2pb} | U_{2c}, U_{2pa}) + I(U_{1c}; U_{2pa} | U_{2c}) \tag{3f}$$

$$R_{2pb} + R'_2 \leq I(Y_2; U_{2pb} | U_{2c}, U_{1c}, U_{2pa}) + I(U_{2pa}; U_{1c} | U_{2c}) \tag{3g}$$

$$R_{2c} + R_{1c} + R_{1pb} + R'_0 + R'_1 \leq I(Y_1; U_{2c}, U_{1c}, U_{1pb}) \tag{3h}$$

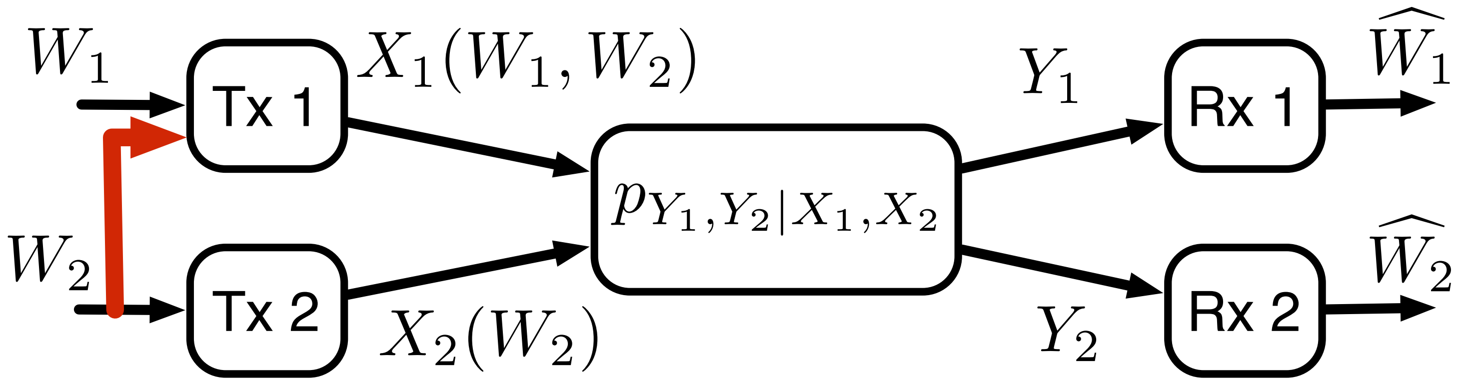
$$R_{1c} + R_{1pb} + R'_0 + R'_1 \leq I(Y_1; U_{1c}, U_{1pb} | U_{2c}) \tag{3i}$$

$$R_{1pb} + R'_1 \leq I(Y_1; U_{1pb} | U_{2c}, U_{1c}) \tag{3j}$$

over all input distributions of the form $p_{X_1, X_2, U_{1c}, U_{2c}, U_{2pa}, U_{1pb}, U_{2pb}}$

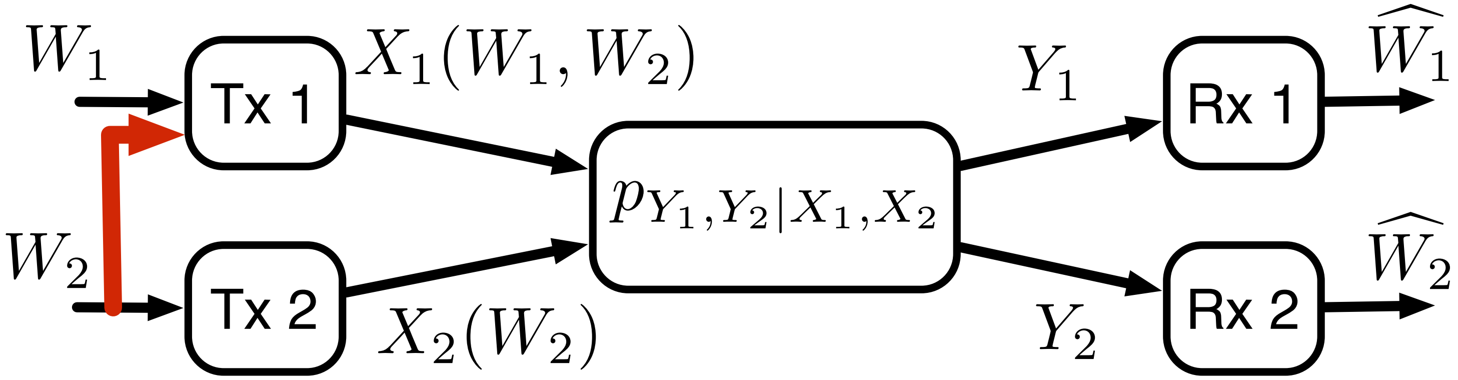
Reduces to capacity whenever capacity is known

Reduces to capacity whenever capacity is known



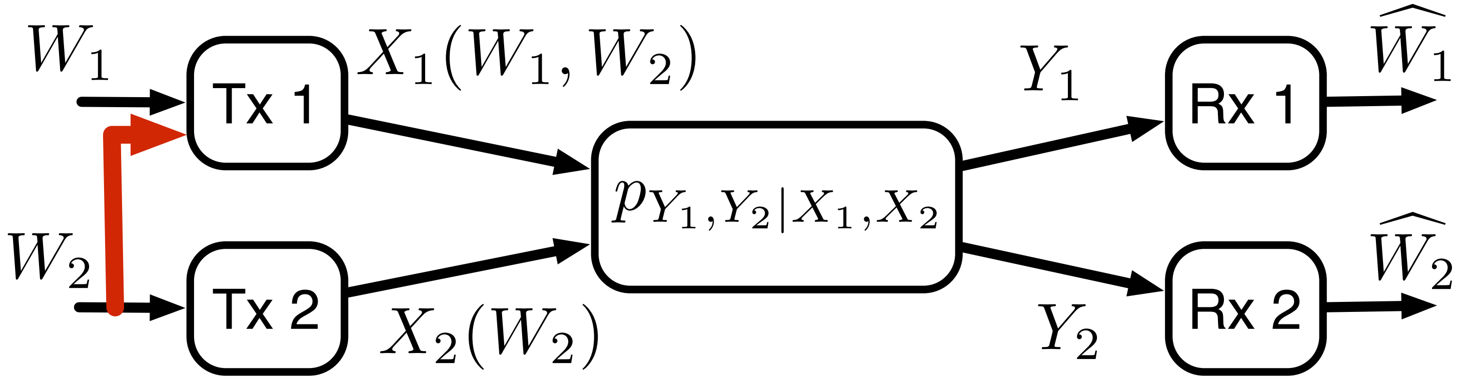
- Discrete memoryless channels - weak interference, very strong interference, **new classes of weak and strong interference**

Reduces to capacity whenever capacity is known



- Discrete memoryless channels - weak interference, very strong interference, **new classes of weak and strong interference**
- Deterministic channels - classes of semi-deterministic channels and **deterministic channels**

Reduces to capacity whenever capacity is known



- Discrete memoryless channels - weak interference, very strong interference, **new classes of weak and strong interference**
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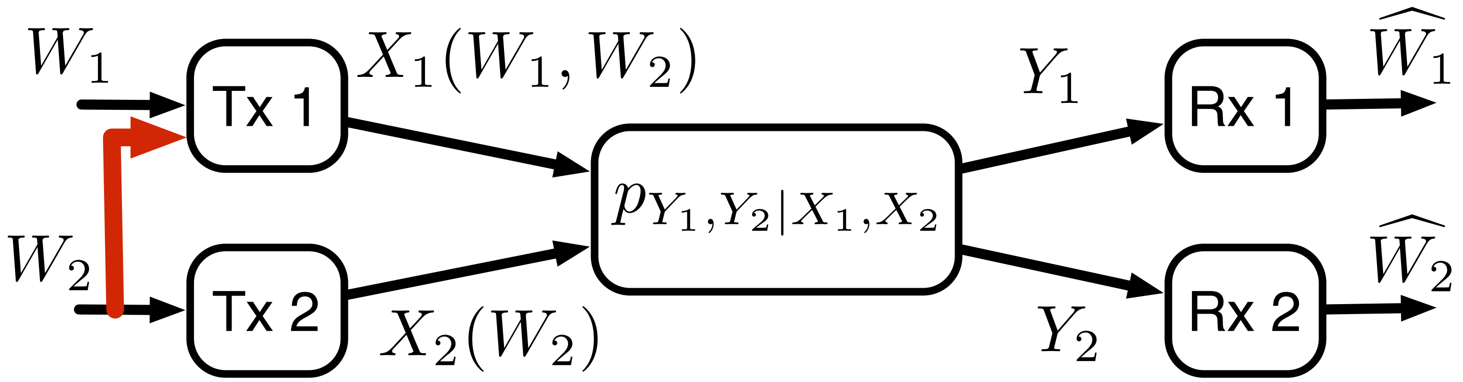
- **High-SNR deterministic approximation - capacity**

Reduces to capacity whenever capacity is known



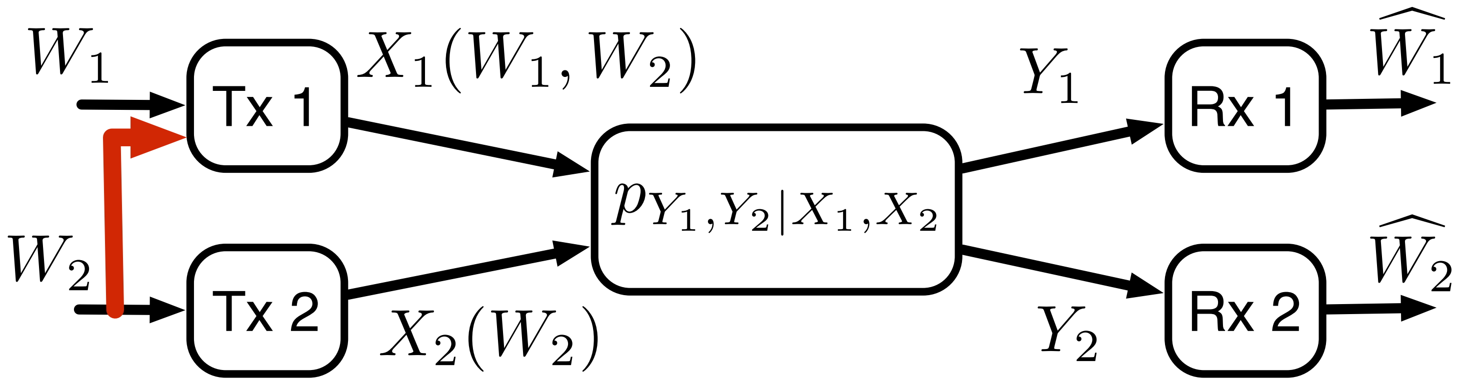
- Discrete memoryless channels - weak interference, very strong interference, **new classes of weak and strong interference**

- Deterministic channels - classes of semi-deterministic channels and **deterministic channels**

- **High-SNR deterministic approximation - capacity**

- Gaussian channels - weak interference, very strong interference, **constant gap in all other regimes**

Reduces to capacity whenever capacity is known



- Discrete memoryless channels - weak interference, very strong interference, **new classes of weak and strong interference**

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- **High-SNR deterministic approximation - capacity**

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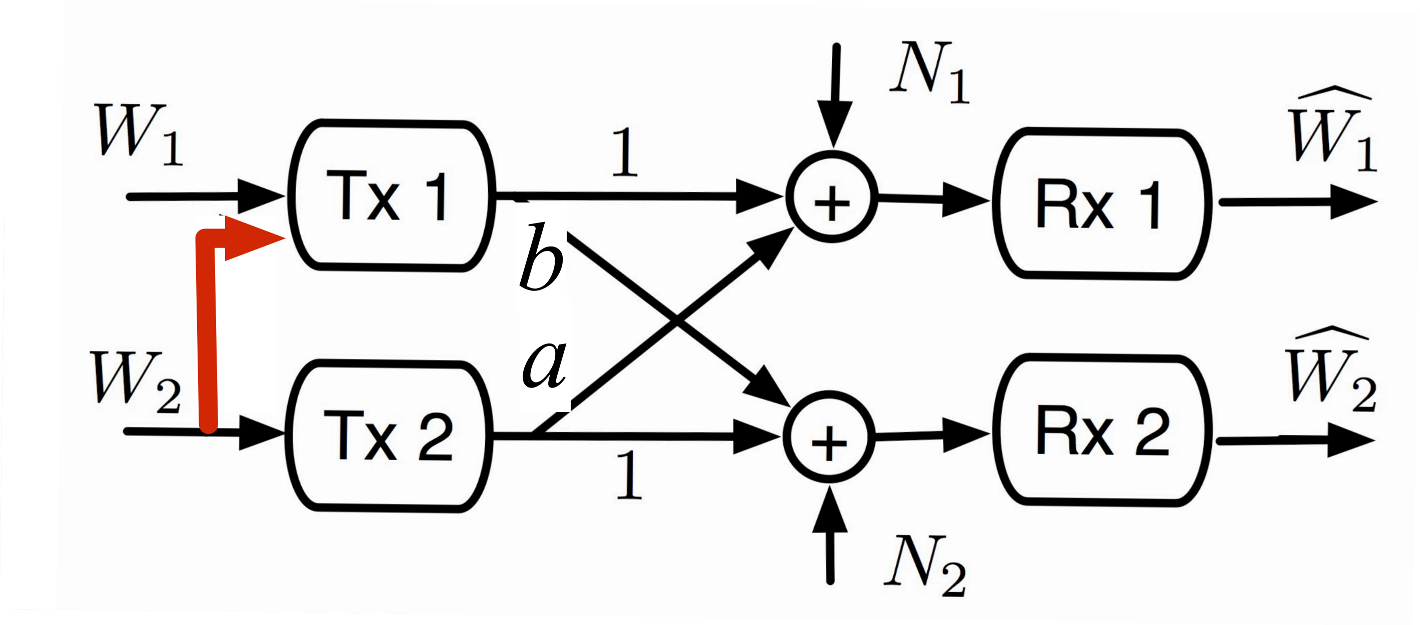
High-SNR linear deterministic cognitive interference channel

S. Rini, D. Tuninetti, and N. Devroye, “The capacity region of deterministic cognitive radio channels,” *r* *r* *t* *y*, vol.
Oct., 2009.



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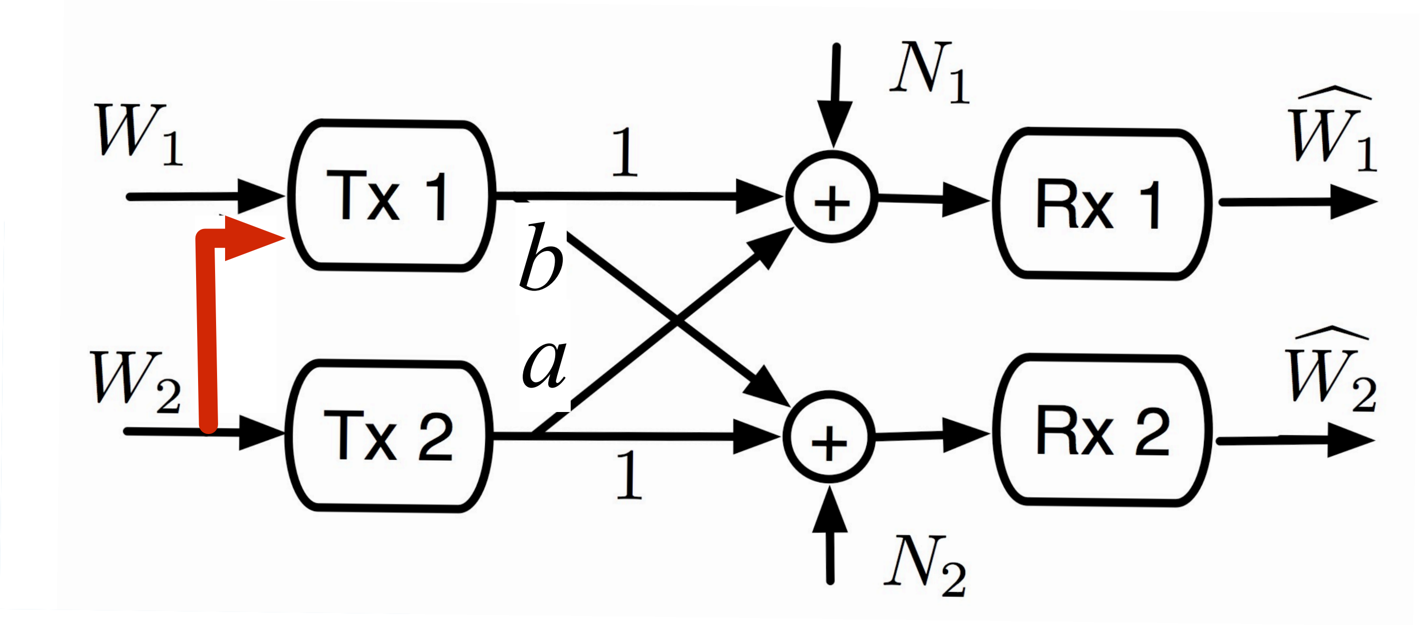
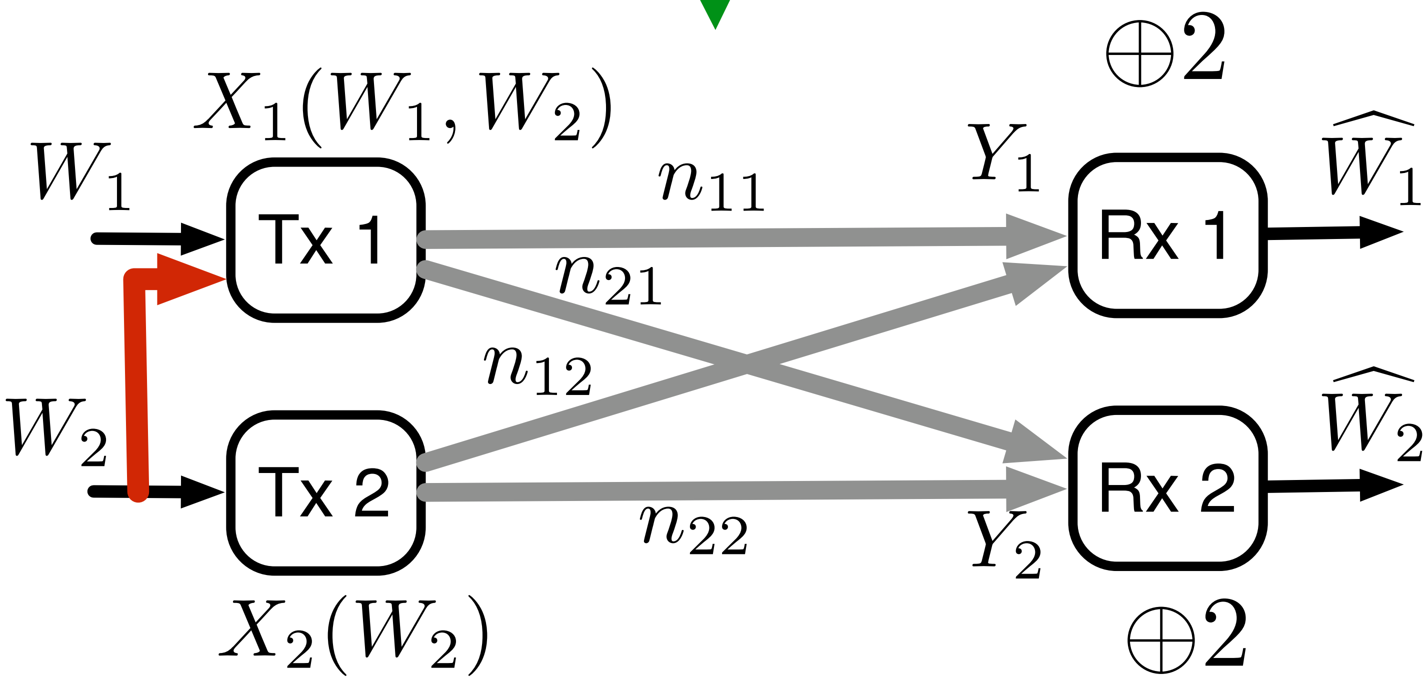


At high SNR



High-SNR deterministic models

A. Avestimehr, S. Diggavi, and D. Tse, "A deterministic approach to wireless relay networks," in *Proc. Allerton Conf. Commun., Control and Comp.*, Monticello, Sept. 2007.

——, "A deterministic model for wireless relay networks and its capacity," in *Proc. IEEE Inf. Theory Workshop*, Bergen, July 2007, pp. 6–11.

G. Bresler and D. Tse, "The two-user gaussian interference channel: A deterministic view," *European Transactions in Telecommunications*, vol. 19, pp. 333–354, Apr. 2008.

S. Rini, D. Tuninetti, and N. Devroye, "The capacity region of the gaussian cognitive radio channel at high SNR," in *Proc. IEEE Inf. Theory Workshop*, Taormina, Oct. 2009.

Constant gap results using deterministic intuition

R. Etkin, D. Tse, and H. Wang, "Gaussian interference channel capacity to within one bit," *IEEE Trans. Inf. Theory*, vol. 54, no. 12, pp. 5534–5562, Dec. 2008.

G. Bresler, A. Parekh, and D. Tse, "The approximate capacity of the many-to-one and one-to-many gaussian interference channels," 2008. [Online]. Available: http://arxiv.org/abs/0809.3554

S. Rini, D. Tuninetti, and N. Devroye, "The capacity region of gaussian cognitive radio channels to within 1.87 bits," *Proc. IEEE ITW Cairo, Egypt*, 2010, http://www.ece.uic.edu/∼devroye/conferences.html.

A. Avestimehr, A. Sezgin, and D. Tse, "Capacity region of the deterministic multi-pair bi-directional relay network," in *Proc. IEEE Inf. Theory Workshop*, Volos, June 2009.

——, "Approximate capacity of the two-way relay channel: a deterministic approach," in *Proc. Allerton Conf. Commun., Control and Comp.*, Monticello, IL, Sept. 2008, pp. 1582–1589.

M. Anand and P. Kumar, "On approximating gaussian relay networks by deterministic networks," 2009. [Online]. Available: http://arxiv.org/abs/0904.0828

V. Prabhakaran and P. Viswanath, "Interference channels with source cooperation," 2009. [Online]. Available: http://arxiv.org/abs/0905.3109

High-SNR linear deterministic cognitive interference channel

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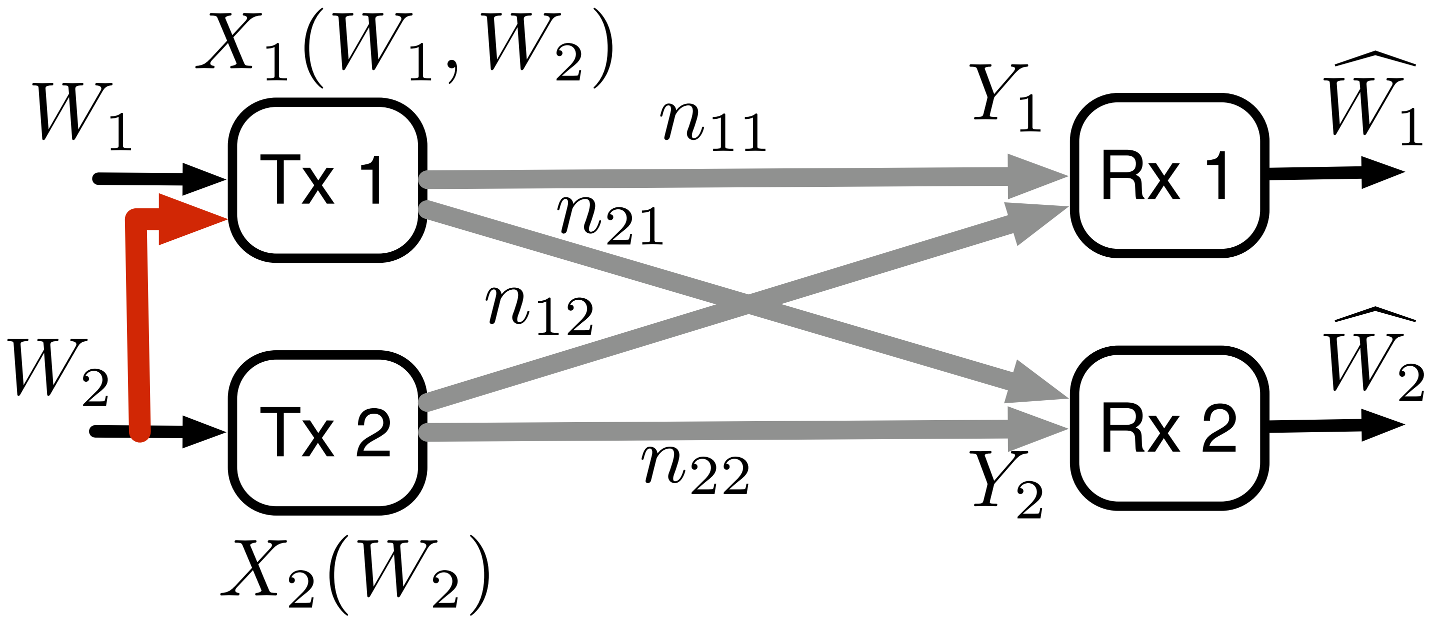

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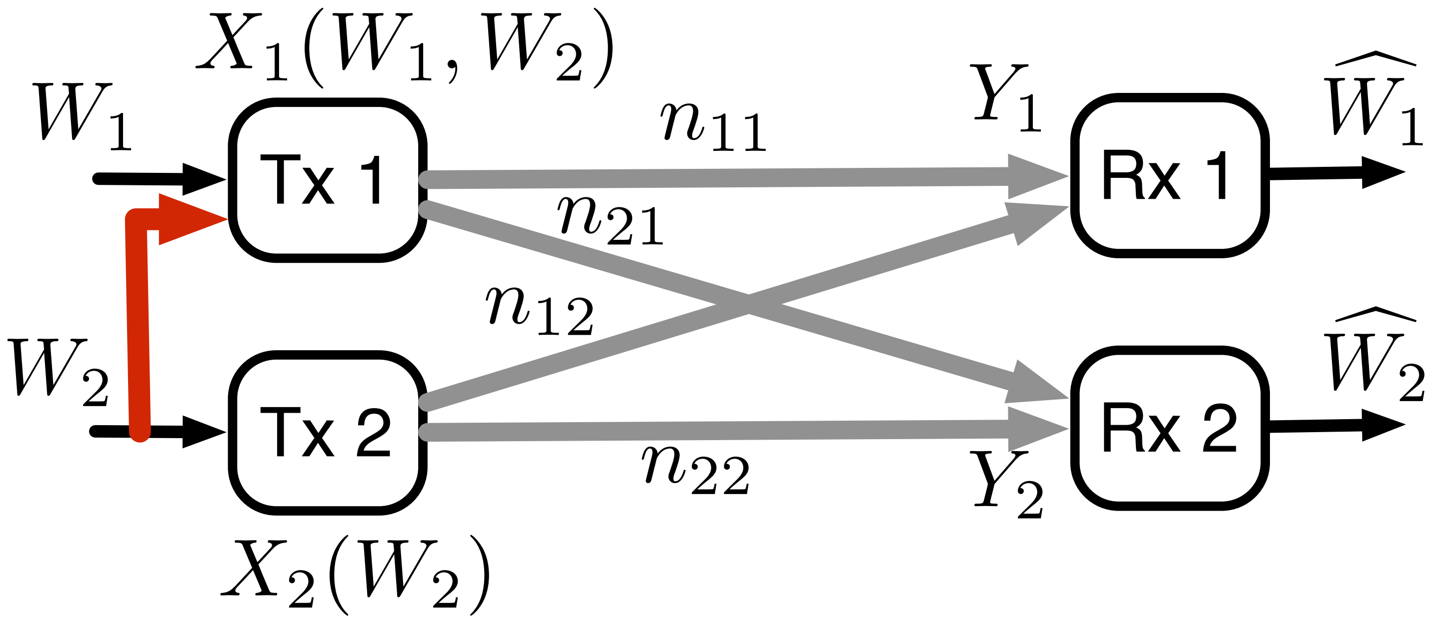
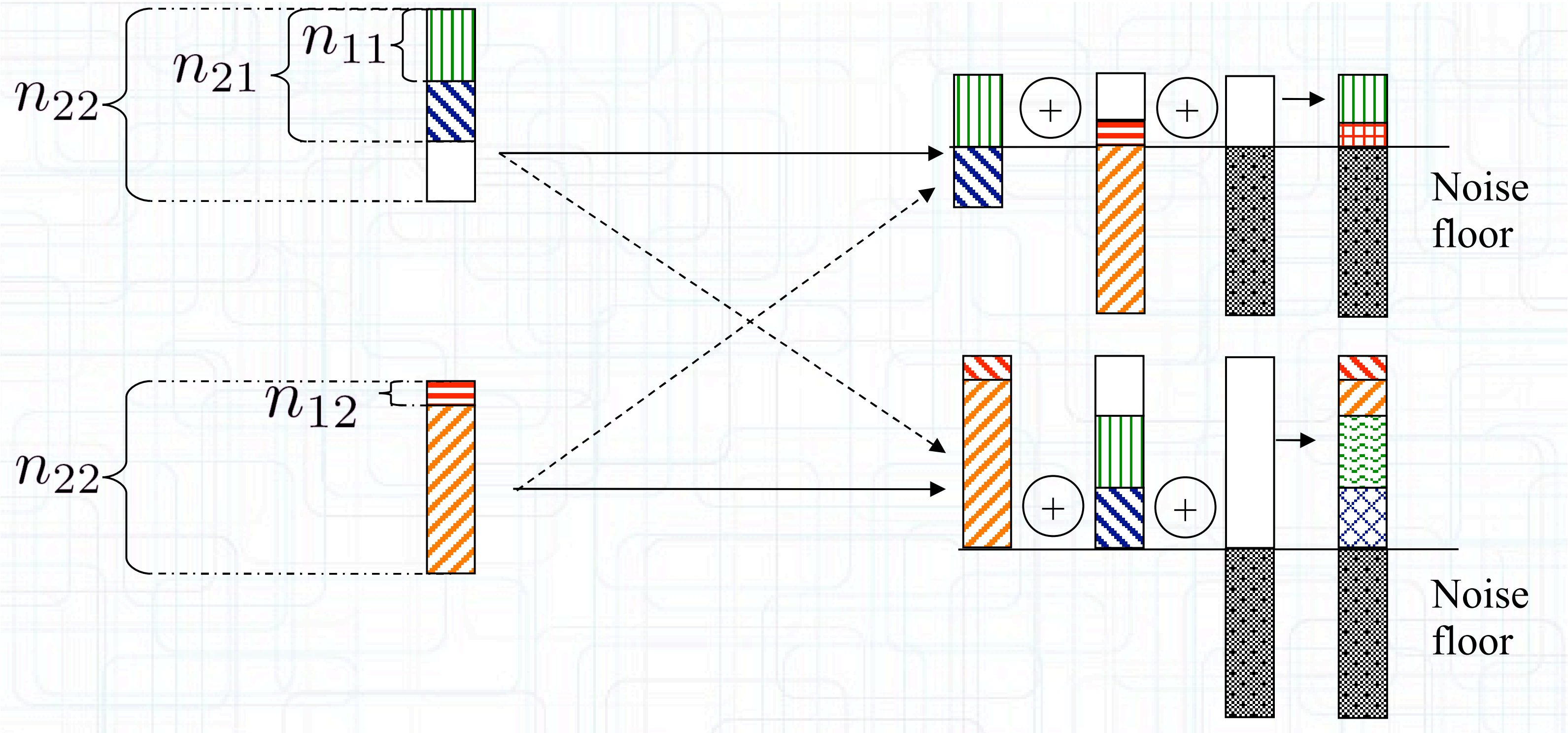
Oct., 2009.





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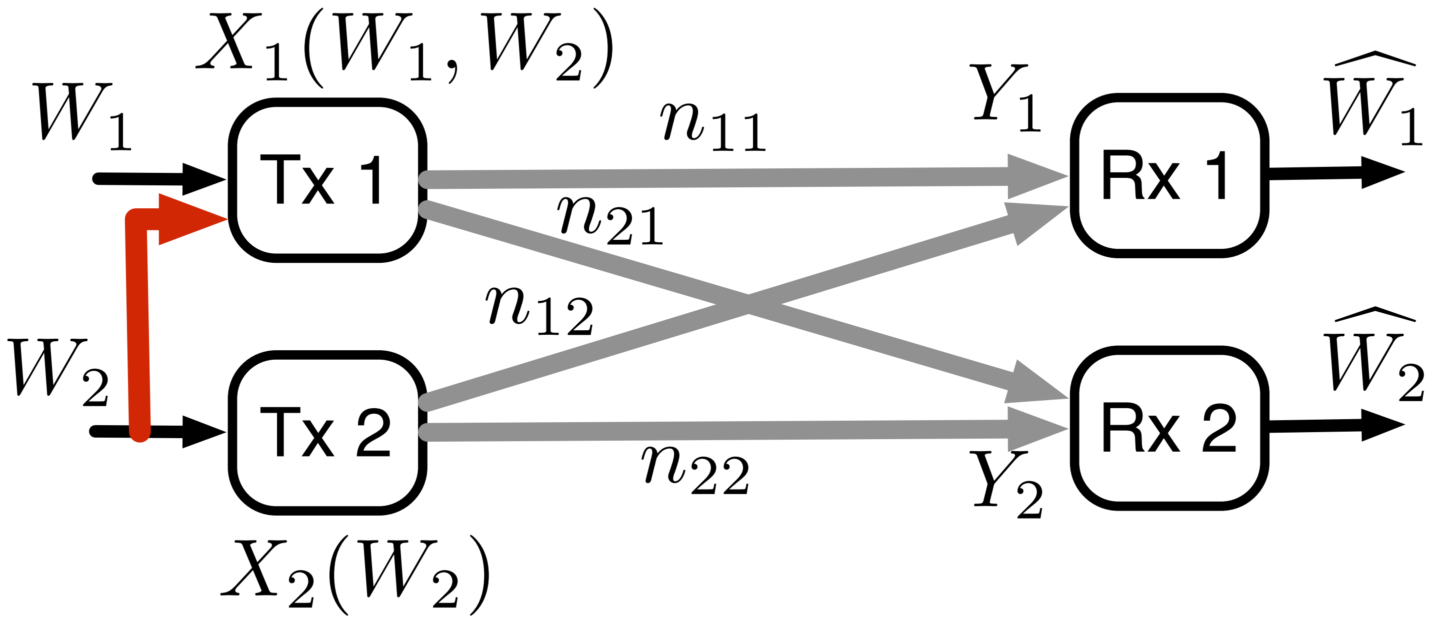


$$R_1 \leq n_{11}$$

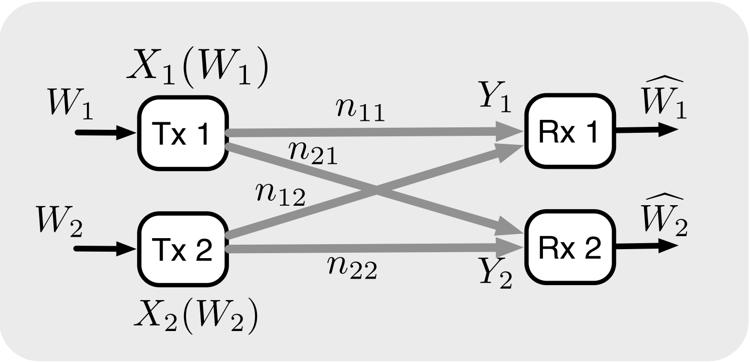
$$R_2 \leq \max\{n_{21}, n_{22}\}$$

$$R_1 + R_2 \leq \max\{n_{21}, n_{22}\} + [n_{11} - n_{21}]^+$$

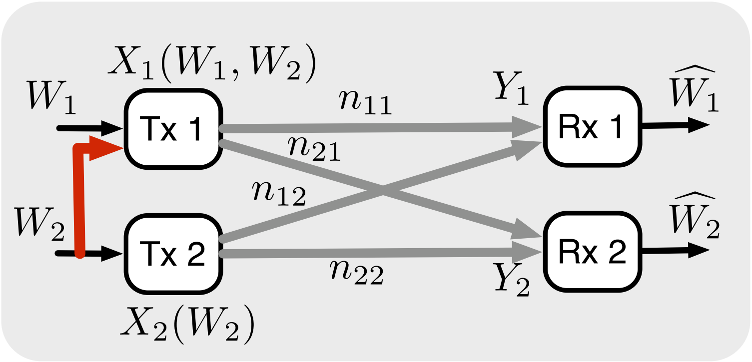
We have capacity!

High-SNR linear deterministic cognitive interference channel

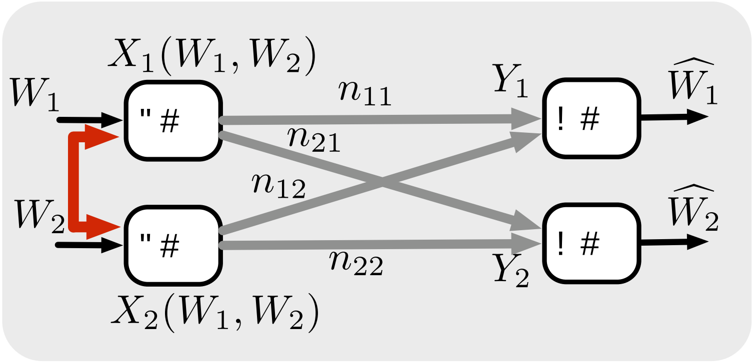
S. Rini, D. Tuninetti, and N. Devroye, “The capacity region of deterministic cognitive radio channels,” r r t y, vol. Oct., 2009.



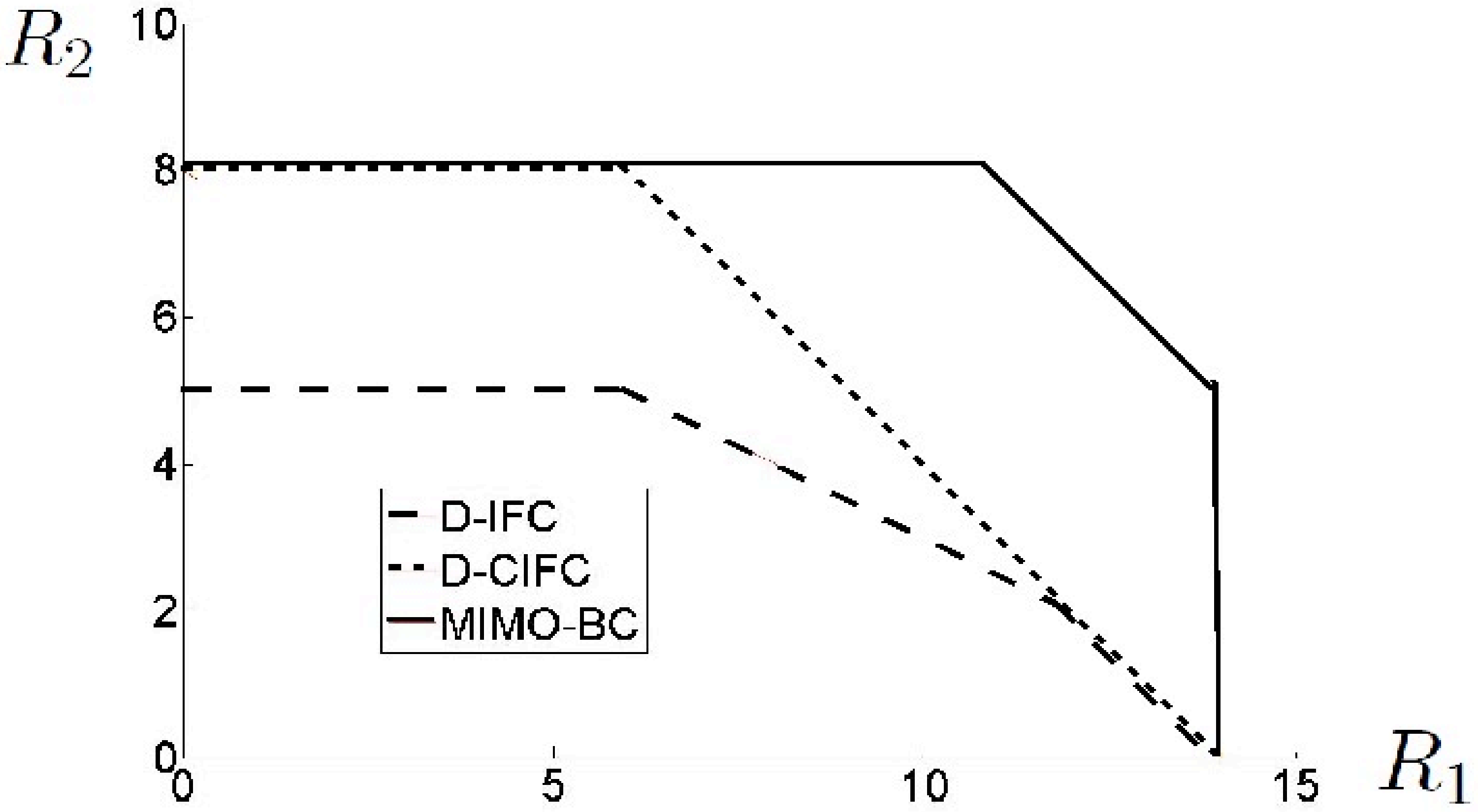
D-IFC



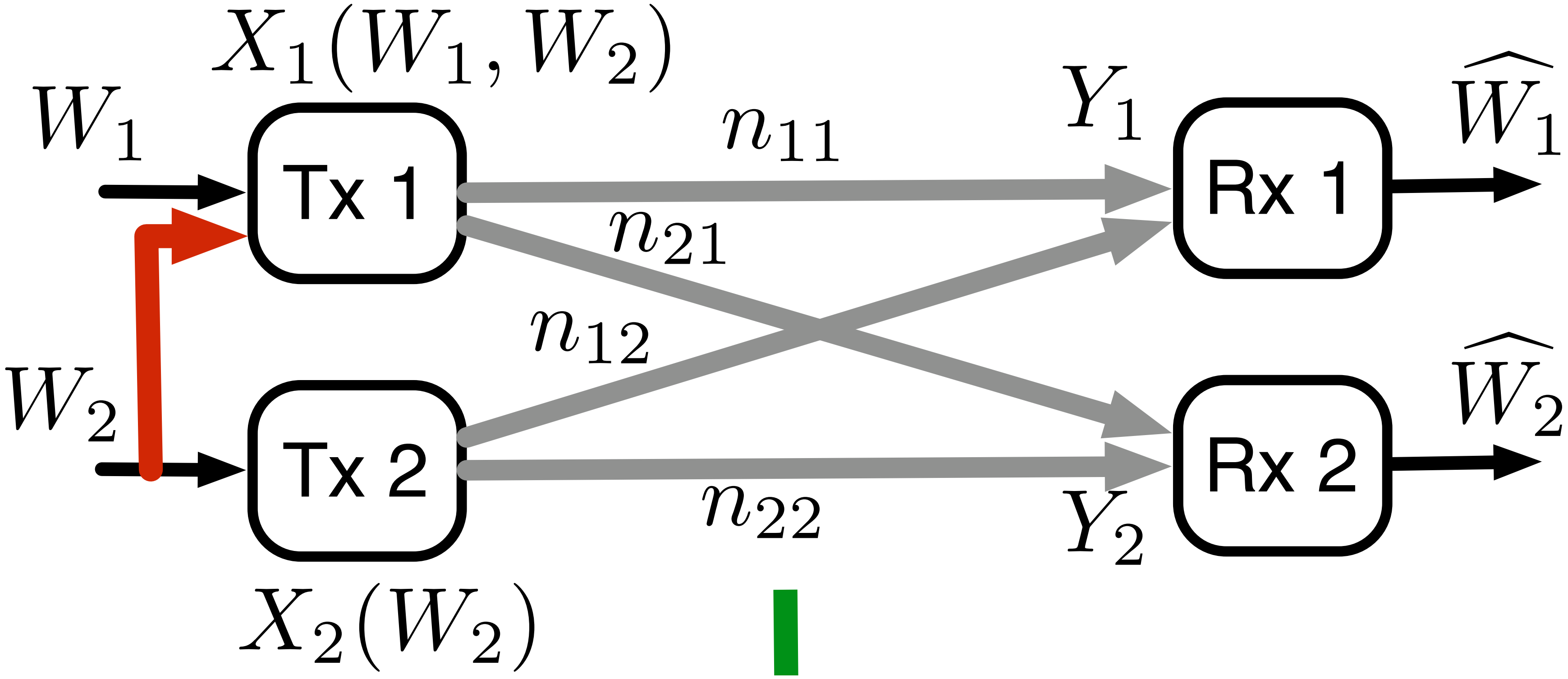
D-CIFC



D-MIMO-BC

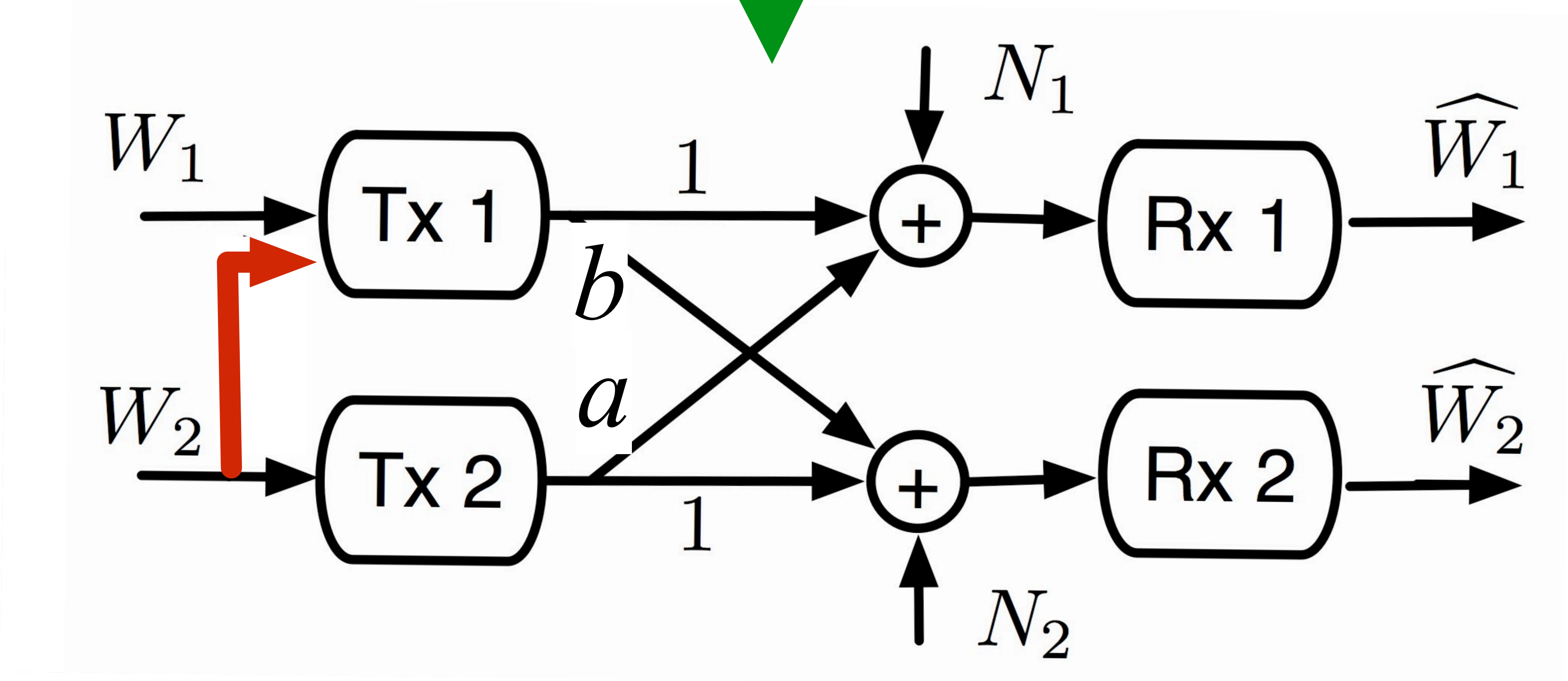


High-SNR deterministic C-IFC

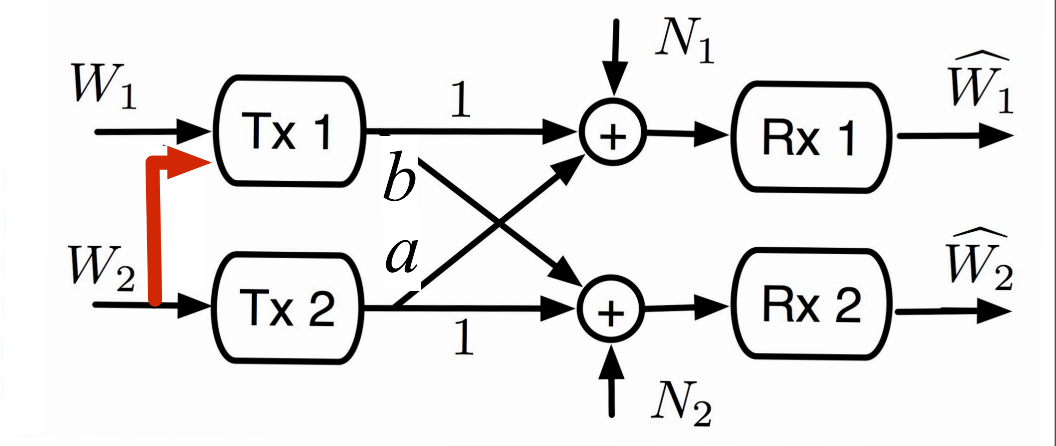


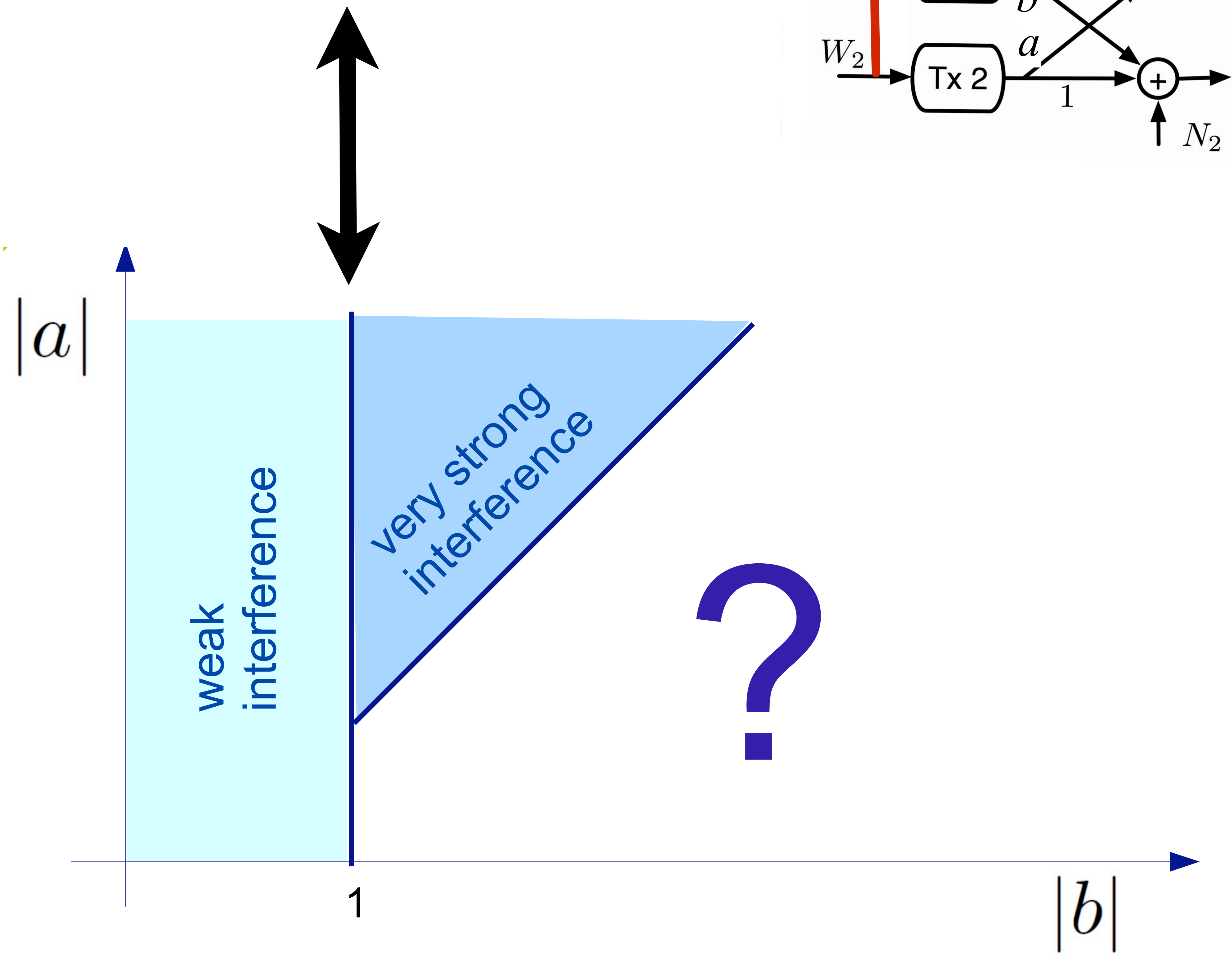
Intuition

Gaussian C-IFC

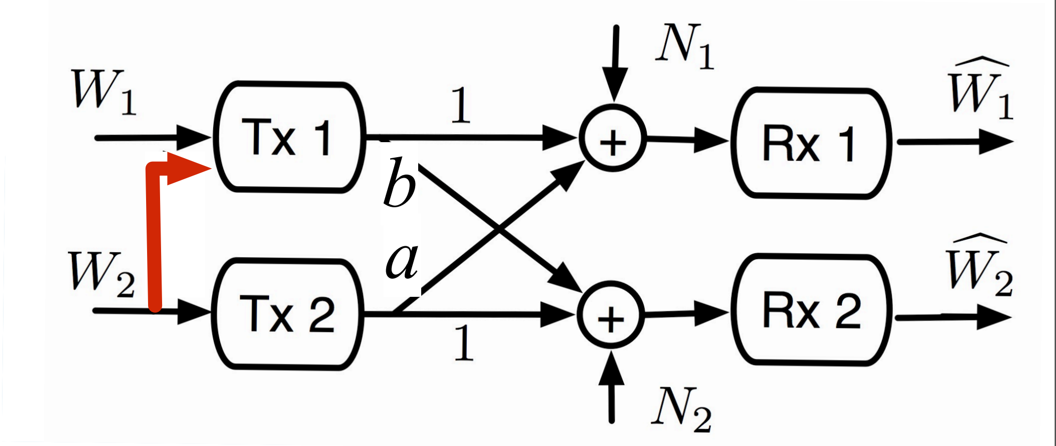


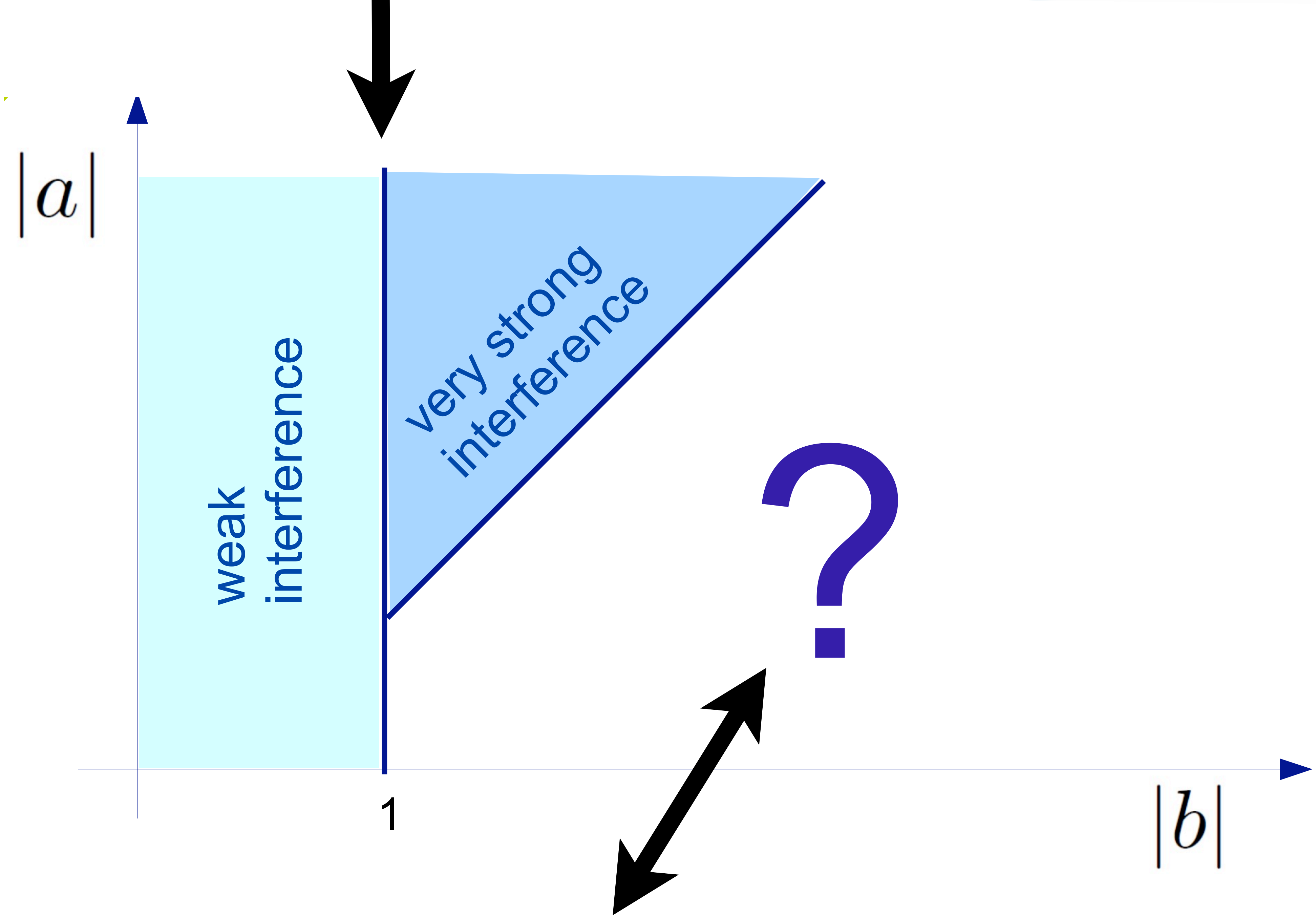
Known Gaussian results





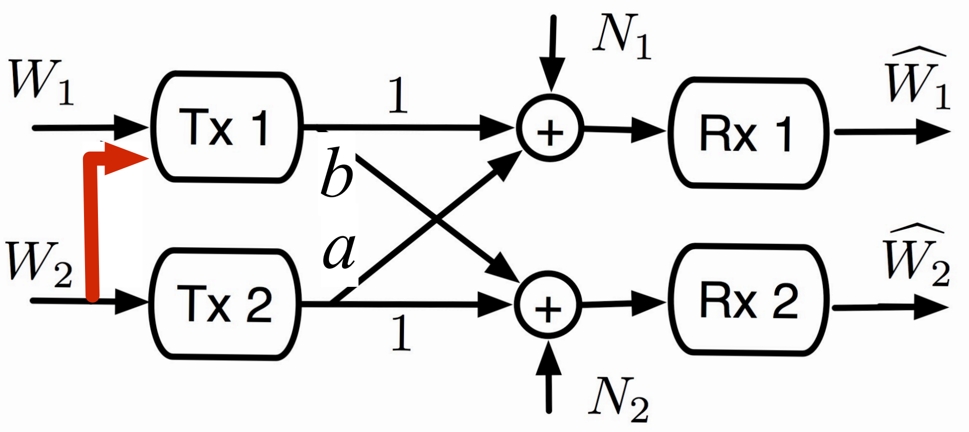
Known Gaussian results

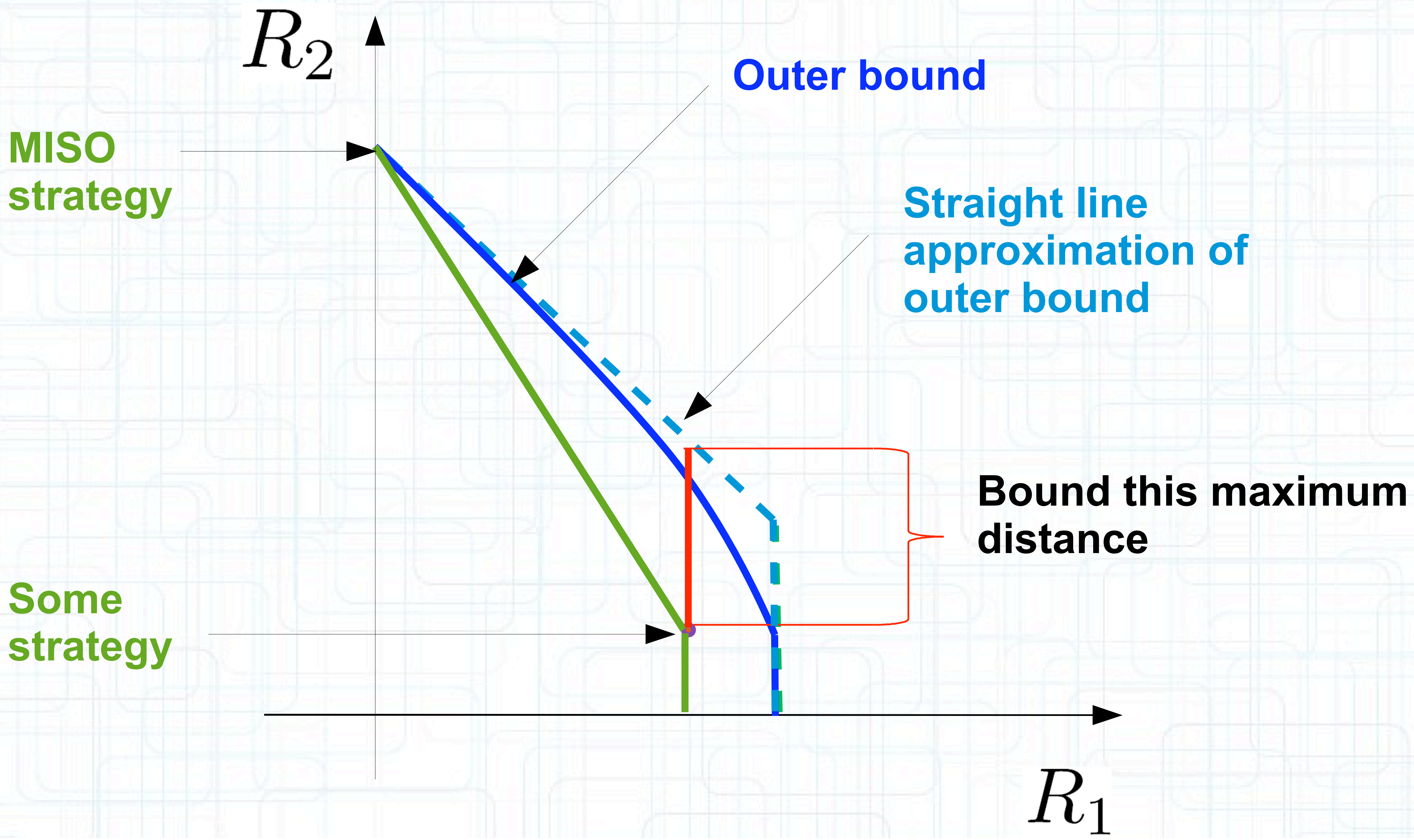




We prove a finite gap

Proving a finite gap





Outer bound

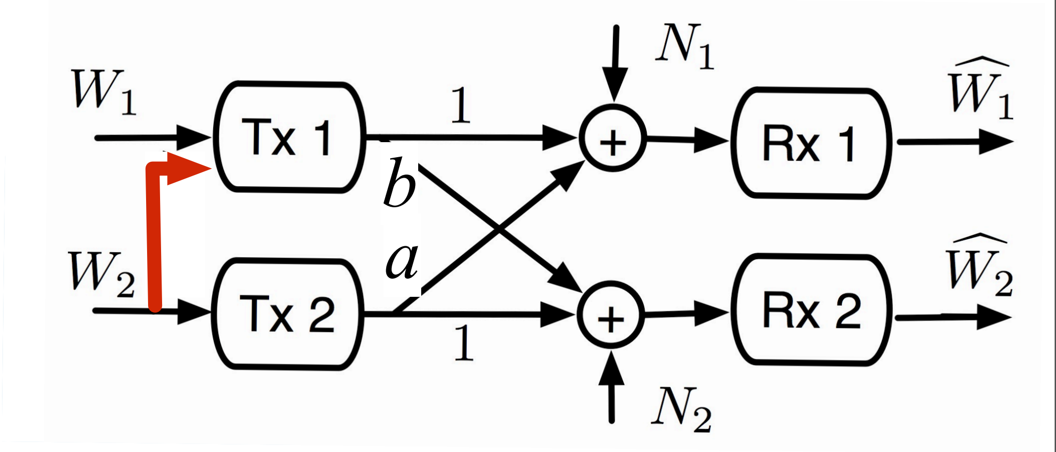
MISO strategy

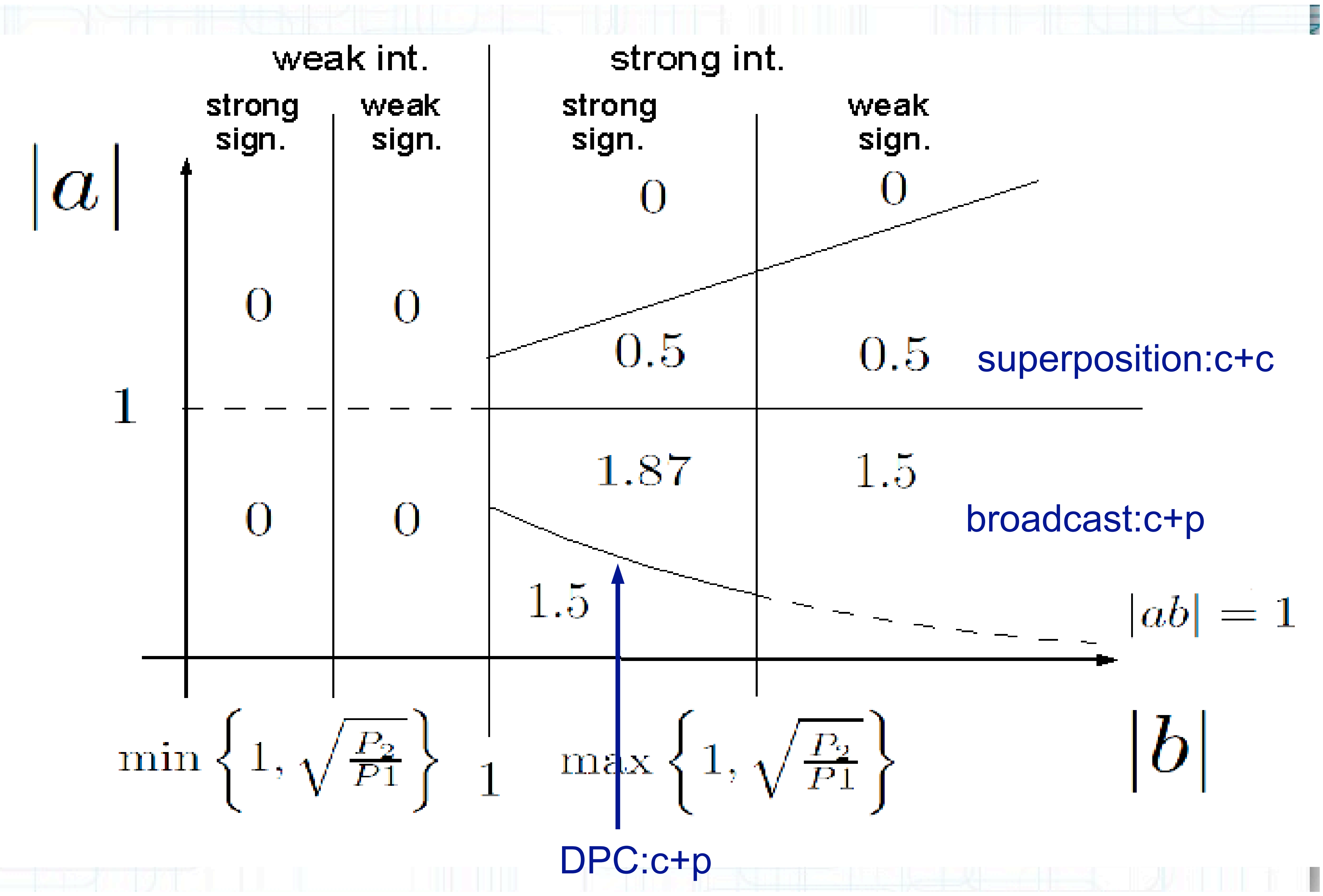
Straight line approximation of outer bound

Bound this maximum distance

Some strategy

Proving a finite gap

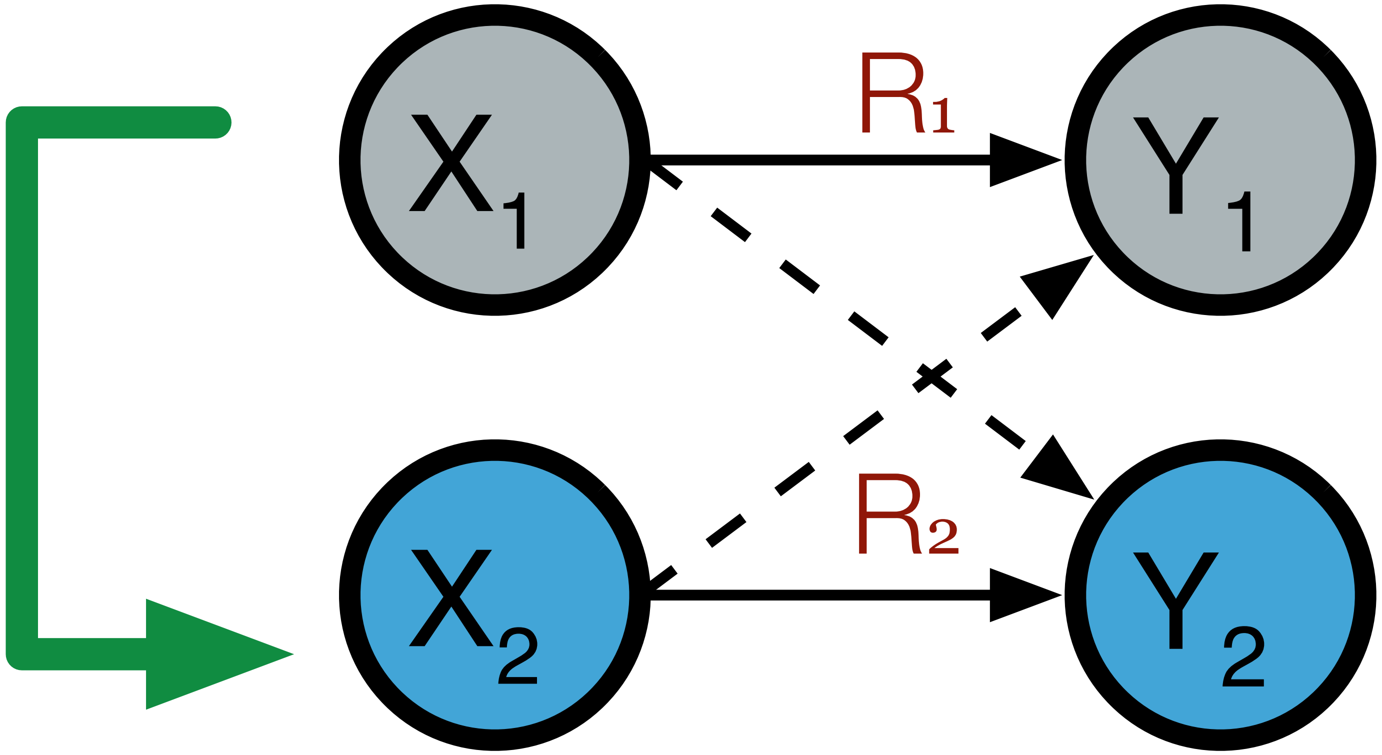




superposition:c+c

broadcast:c+p

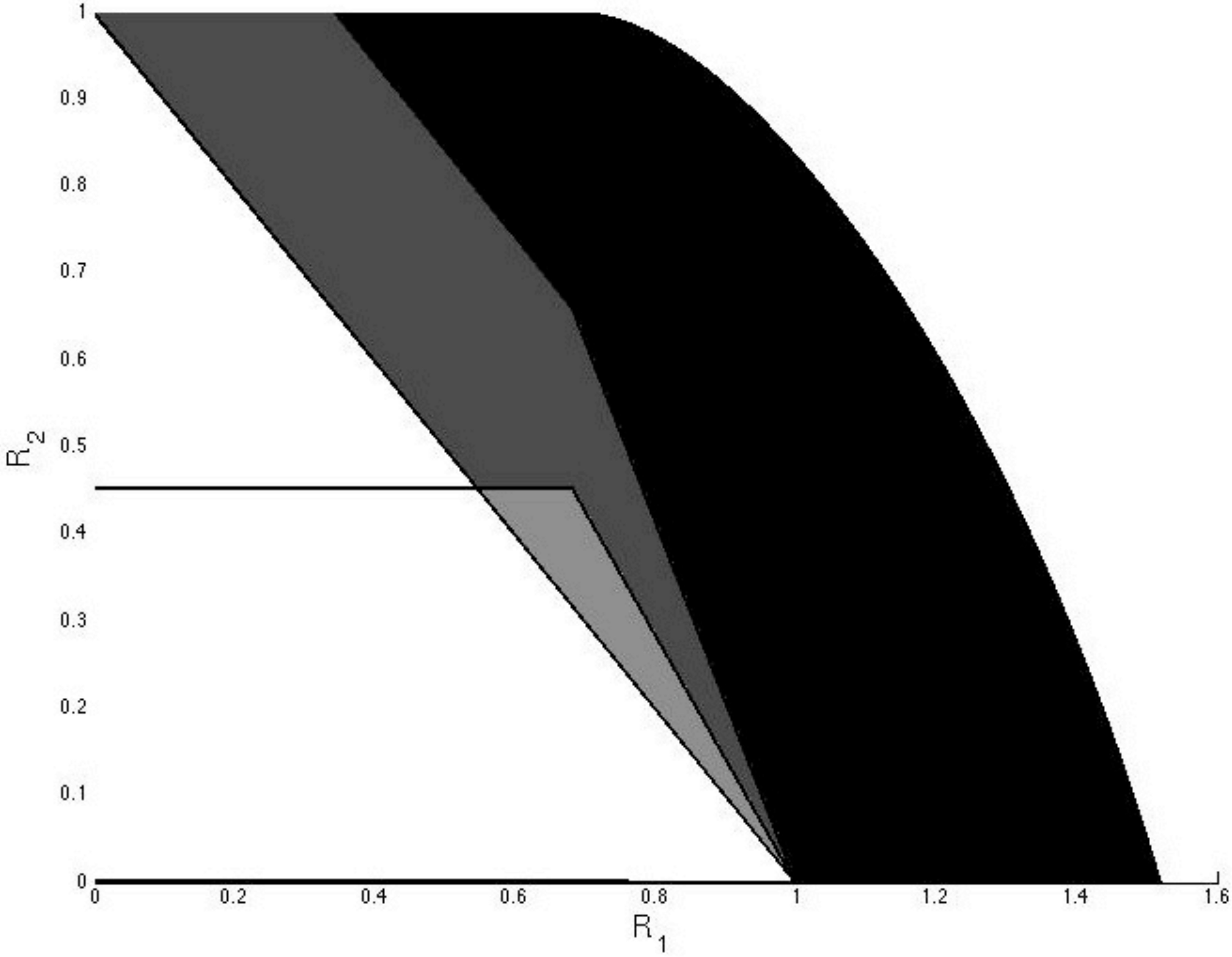
DPC:c+p



“Cognitive”

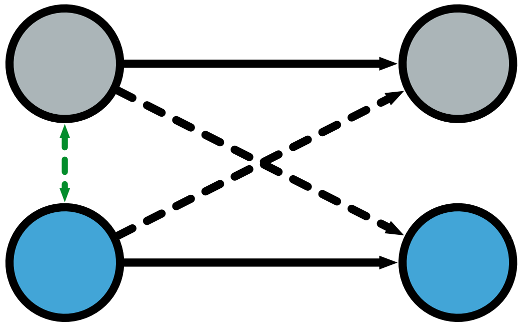
Cognitive channel

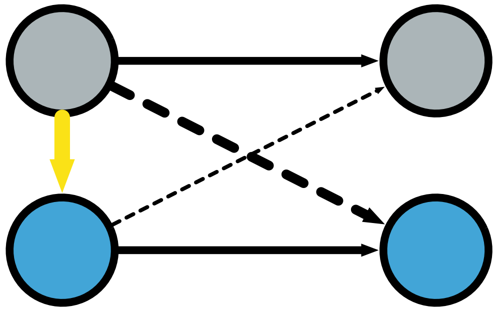
What rates (R_1, R_2) are achievable?


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R_2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
R_1

Extensions of “cognition” in multi-user IT

- causal versus non-causal cognition





Extensions of “cognition” in multi-user IT

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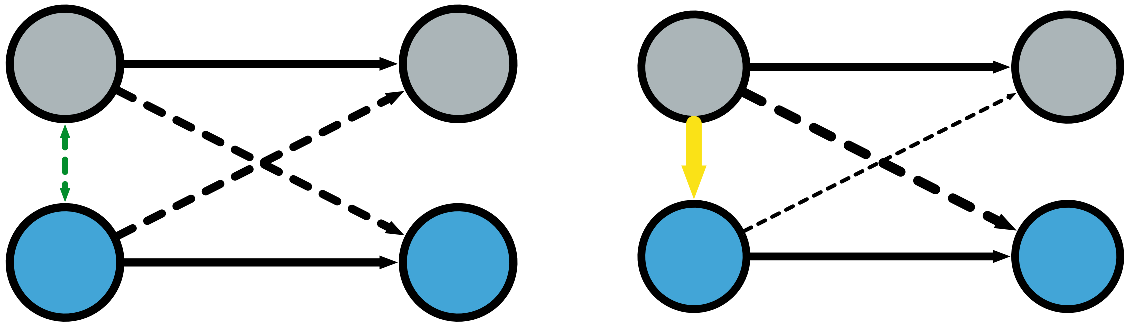
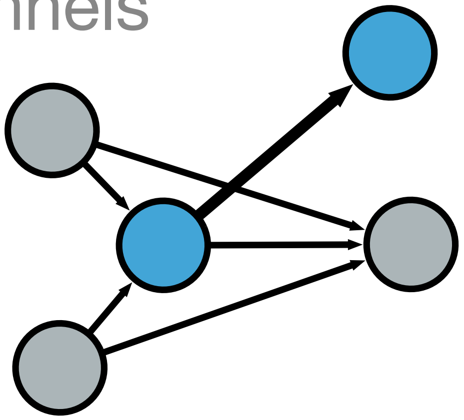
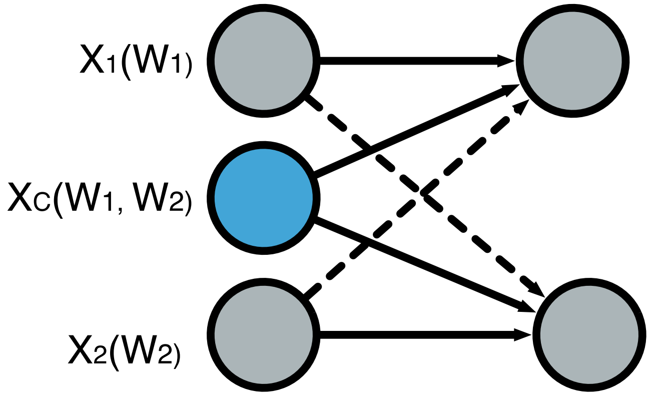


- cognitive relay: interference, relay channels





Extensions of “cognition” in multi-user IT

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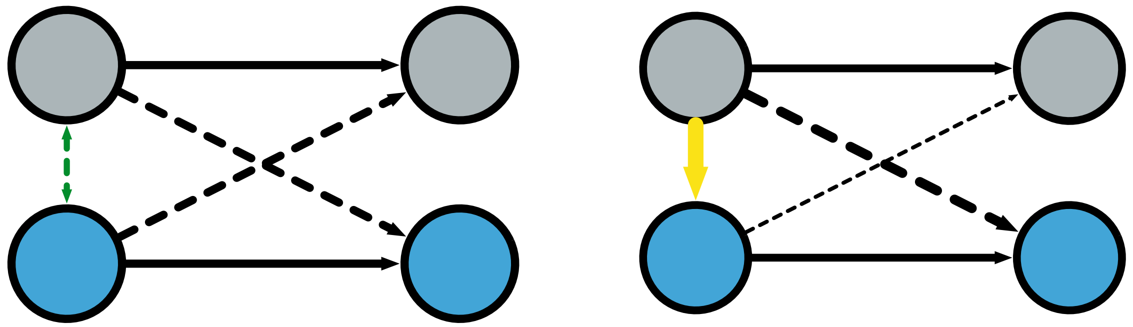

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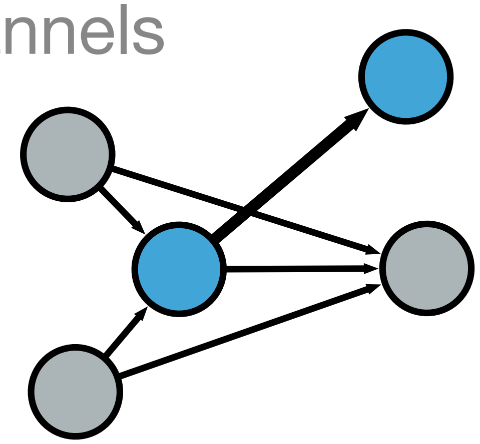
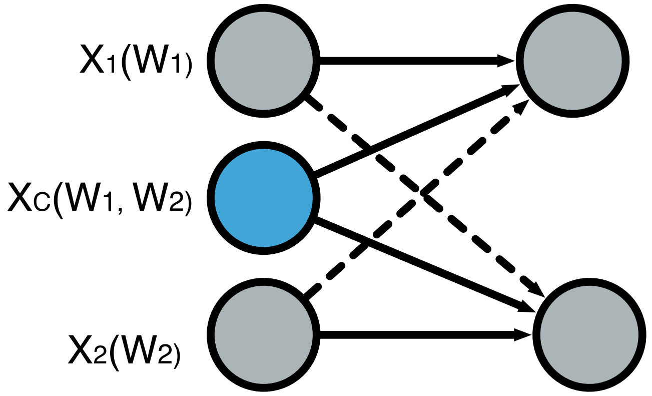
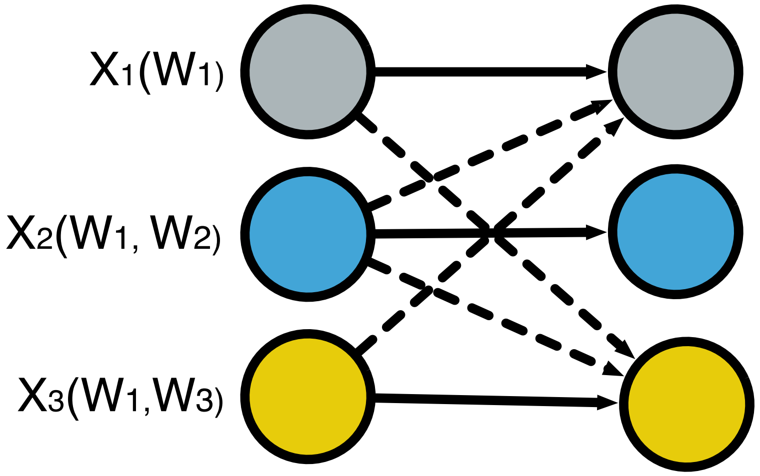
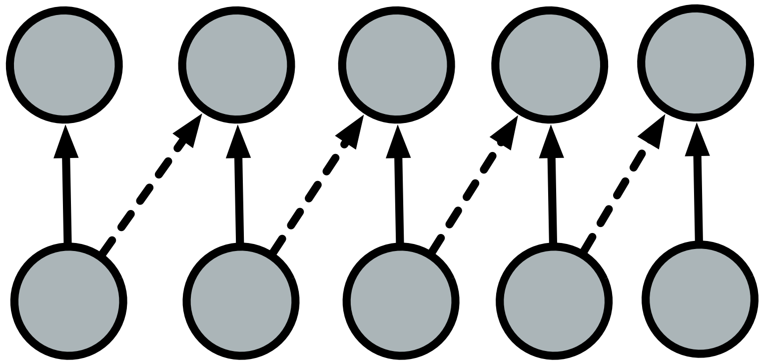
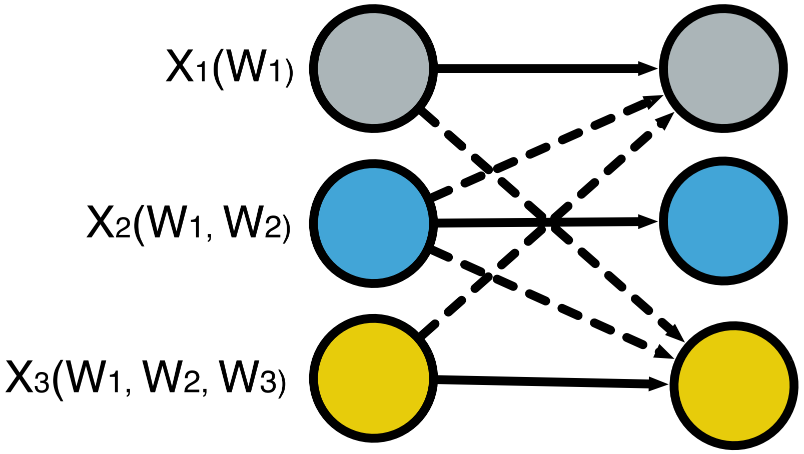




- more cognitive users, more scenarios....







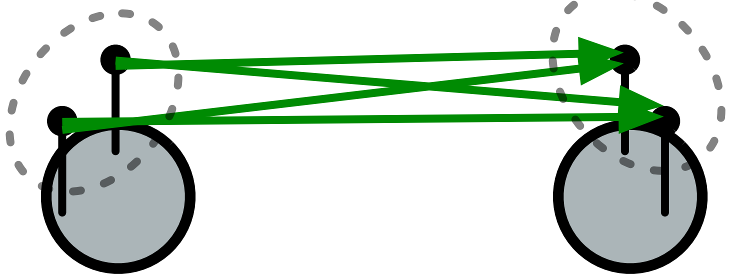
Degrees of freedom: classical

DOF = # “clean” channels in a multi-stream network

MIMO

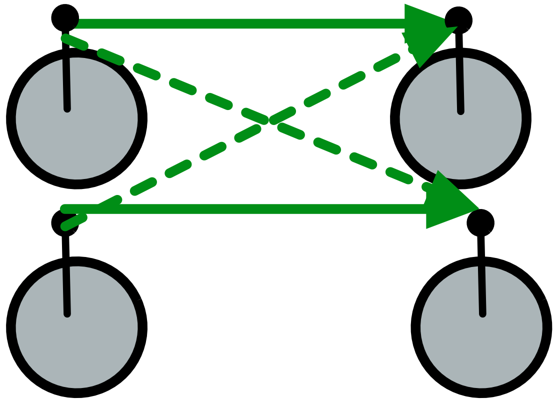
M Tx antennas

N Rx antennas



DOF = min(M,N)=2

Interference channel

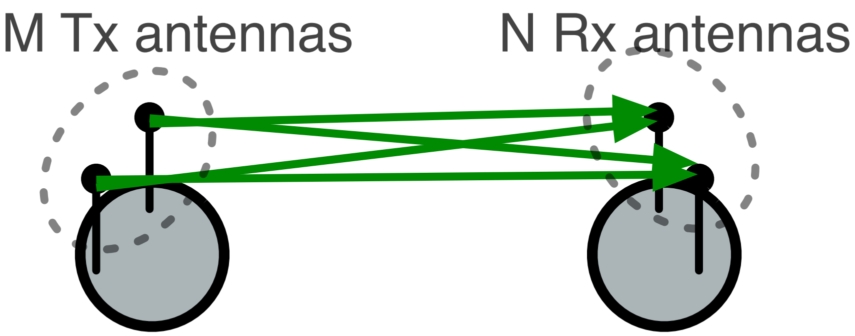


DOF = 1

Degrees of freedom: classical

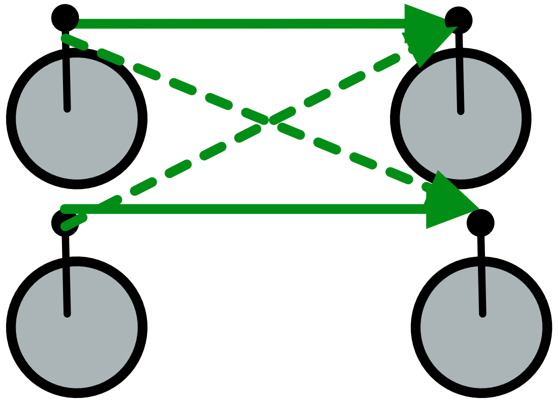
DOF = # “clean” channels in a multi-stream network

MIMO



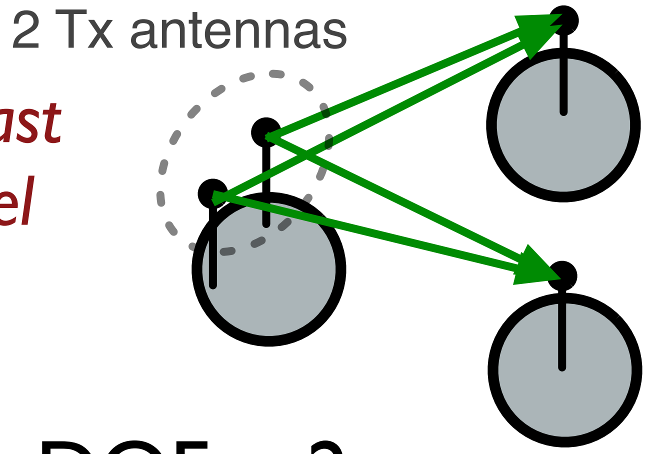
DOF = min(M,N)=2

Interference channel



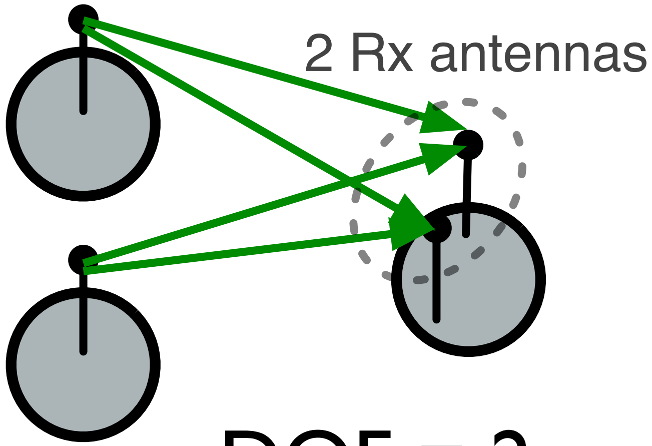
DOF = 1

Broadcast channel



DOF = 2

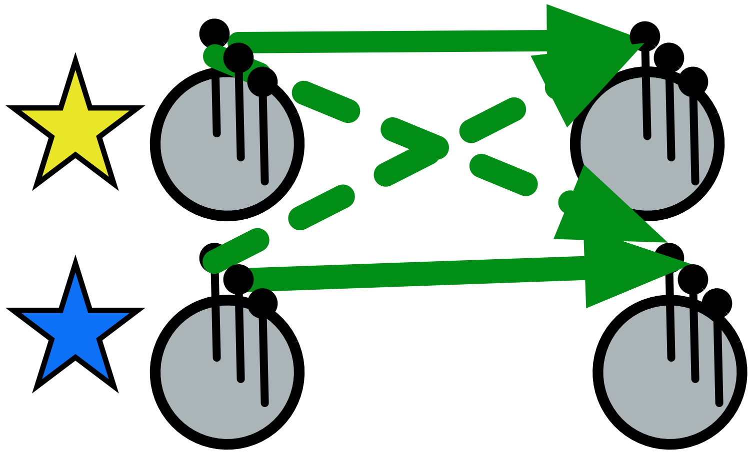
Multiple-access channel



DOF = 2

Degrees of freedom: cognitive, M antennas

MIMO interference channel

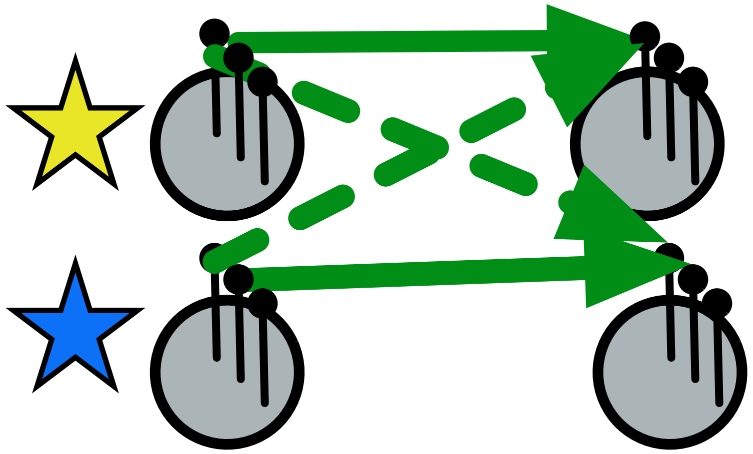


DOF = M

Syed A. Jafar, Shlomo Shamai, Degrees of Freedom Region for the MIMO X Channel , IEEE Transactions on Information Theory, Vol. 54, No. 1, Jan. 2008, Pages: 151-170.

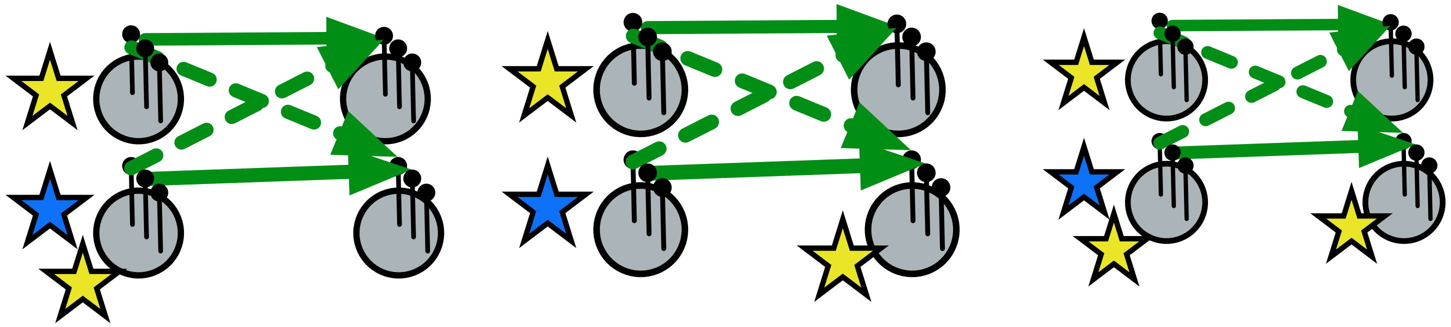
Degrees of freedom: cognitive, M antennas

MIMO interference channel



DOF = M

MIMO cognitive channel, cases a,b,c



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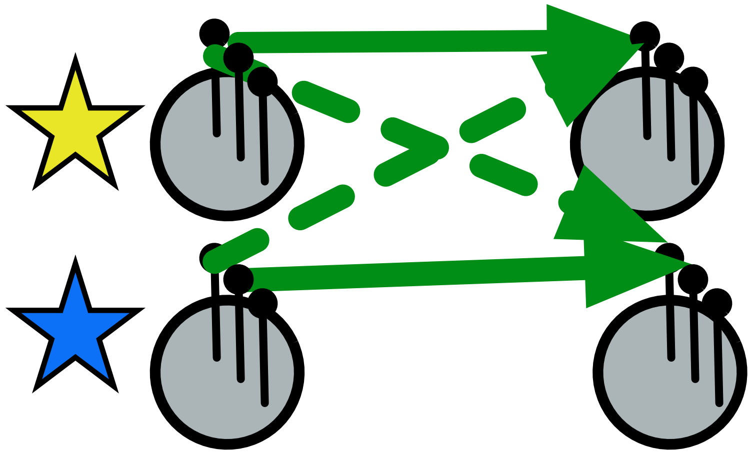
Syed A. Jafar, Shlomo Shamai, Degrees of Freedom Region for the MIMO X Channel , IEEE Transactions on Information Theory, Vol. 54, No. 1, Jan. 2008, Pages: 151-170.

Degrees of freedom: cognitive, M antennas

MIMO interference channel



DOF = M

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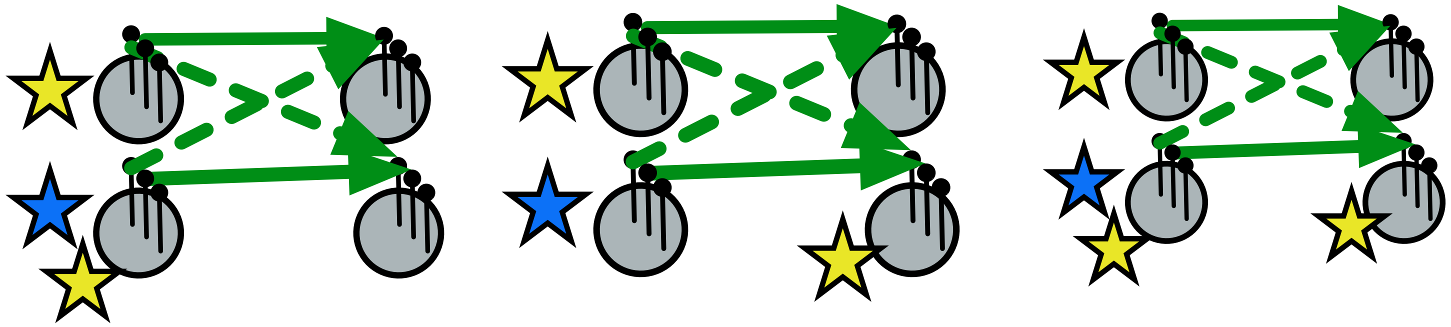
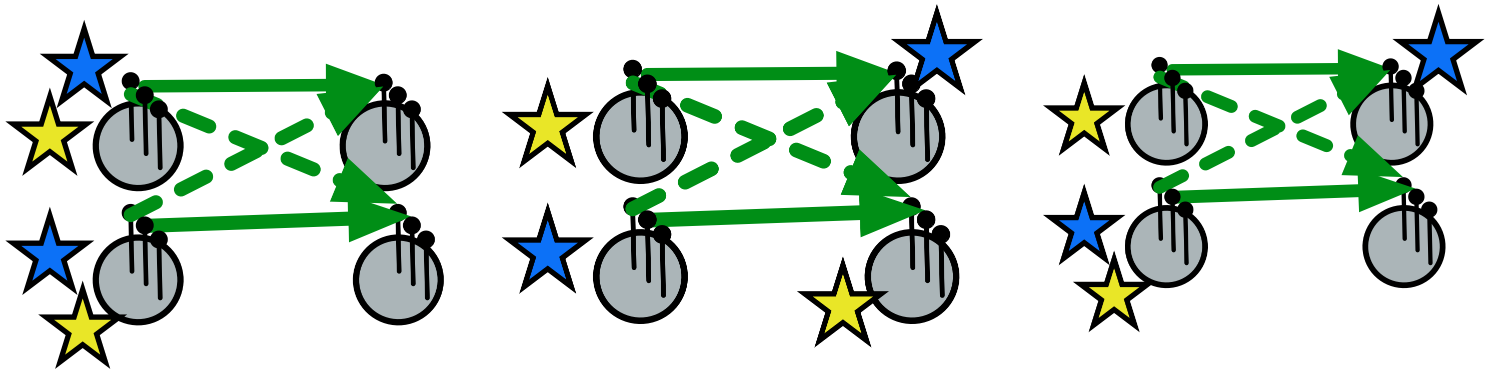


DOF = M

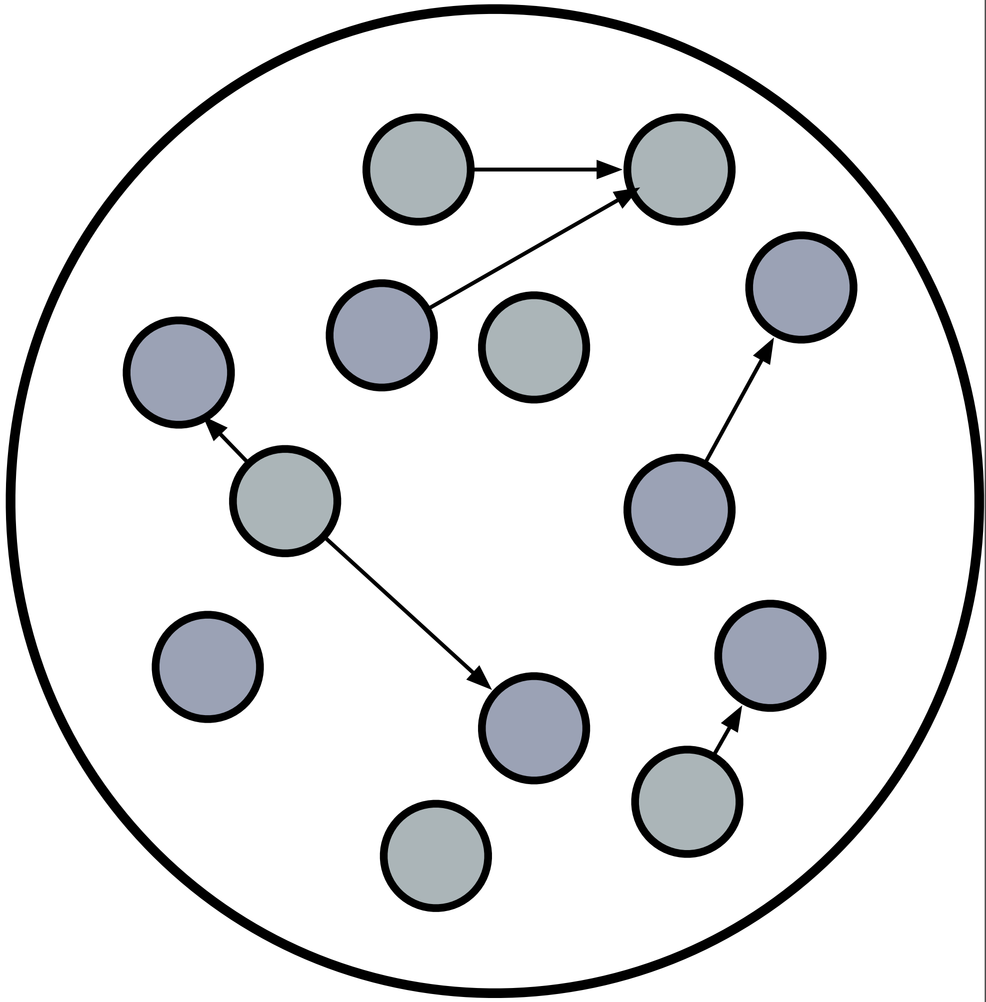
MIMO cognitive channel, cases d,e,f



DOF = 2M

Syed A. Jafar, Shlomo Shamai, Degrees of Freedom Region for the MIMO X Channel , IEEE Transactions on Information Theory, Vol. 54, No. 1, Jan. 2008, Pages: 151-170.

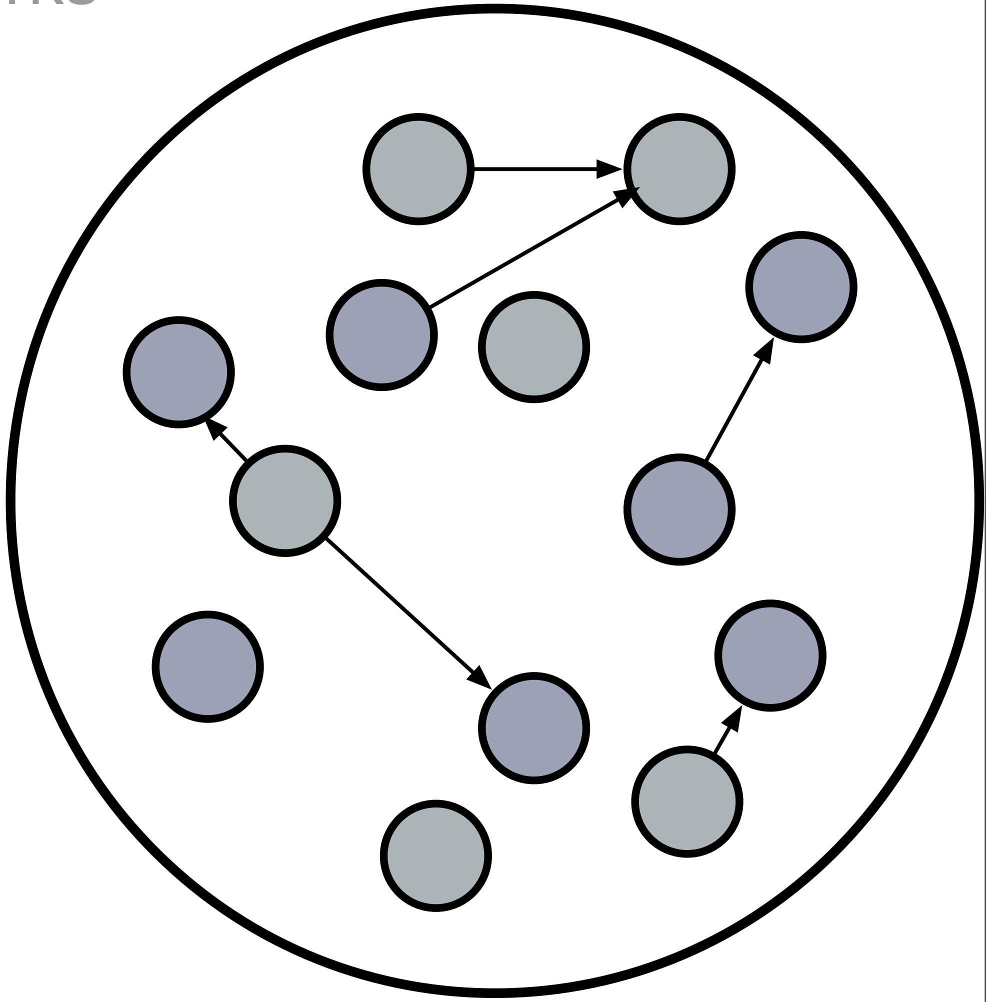
Scaling laws # nodes n → ∞



Scaling laws

nodes n → ∞

- [Gupta+Kumar 2000]: Non-cooperative ad hoc networks
  - per-node throughput ~ $O(1/\sqrt{n} \log(n))$
  - Degradation is due to multi-hop and interference between nodes



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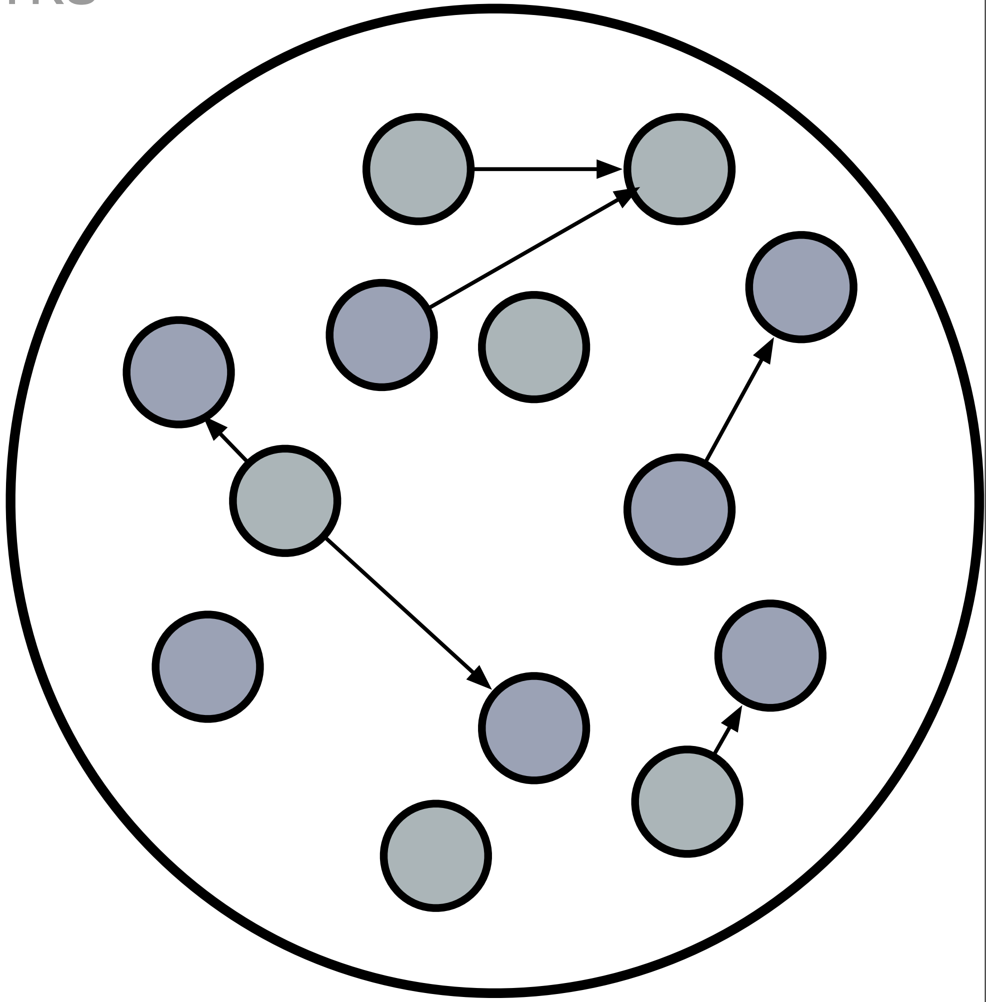
- [Franseschetti et al. 2000]: ad hoc networks
  - per-node throughput ~ $O(1/\sqrt{n})$
  - percolation theory



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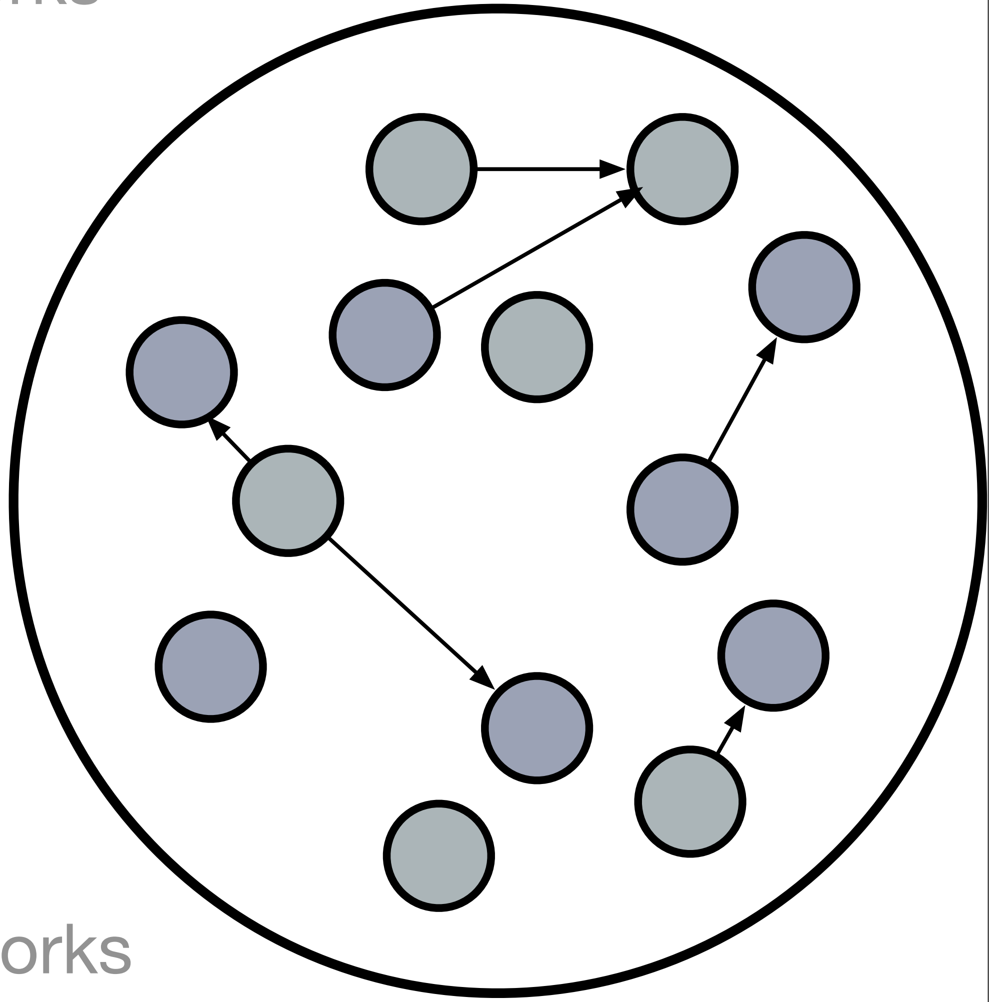

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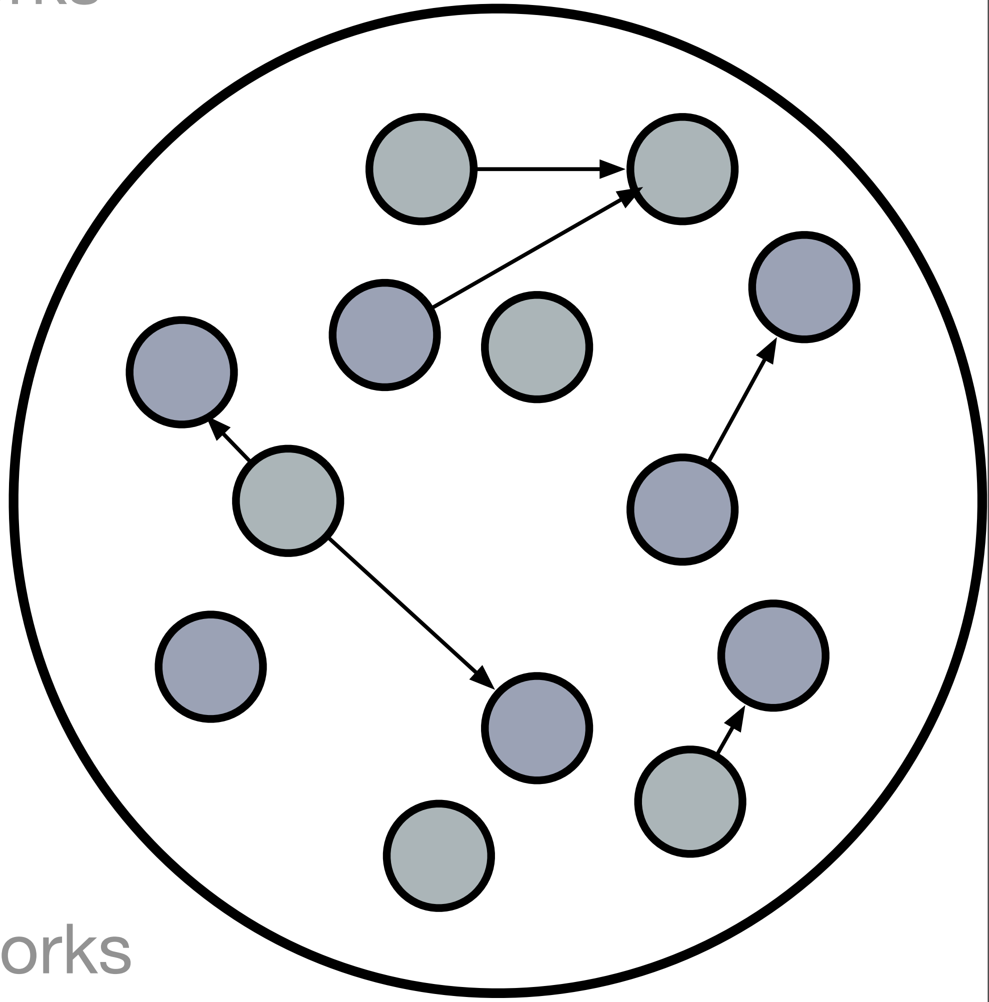
- [Ozgur, Leveque, Tse 2007]: Cooperative ad hoc networks
  - nodes may cooperate as in a MIMO system
  - per-node throughput ~ O(1) (constant)

Scaling laws # nodes n → ∞

- [Gupta+Kumar 2000]: Non-cooperative ad hoc networks
  - per-node throughput ~ O(1/√n log(n))
  - Degradation is due to multi-hop and interference between nodes



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- [Ozgur, Leveque, Tse 2007]: Cooperative ad hoc networks
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  - per-node throughput ~ O(1) (constant)

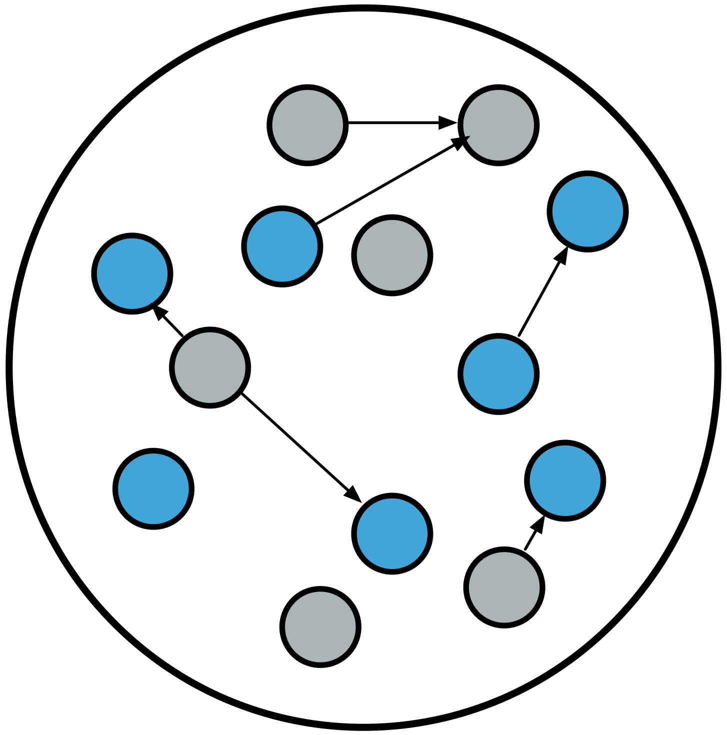
- Many many more...

Scaling laws: with cognition

- What we guarantee:

Primary nodes act as if cognitive network does not exist

Primary nodes achieve same scaling law as if cognitive network does not exist



Scaling laws: with cognition

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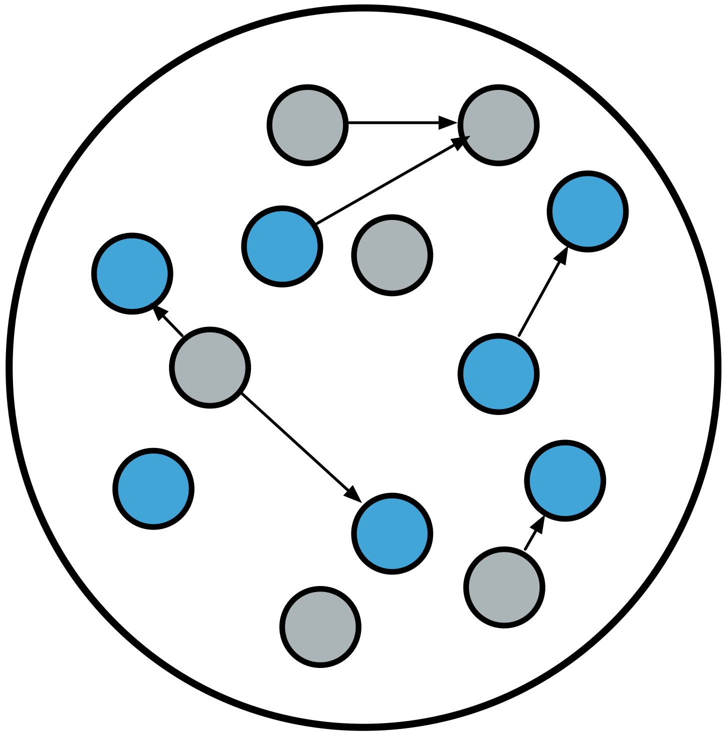
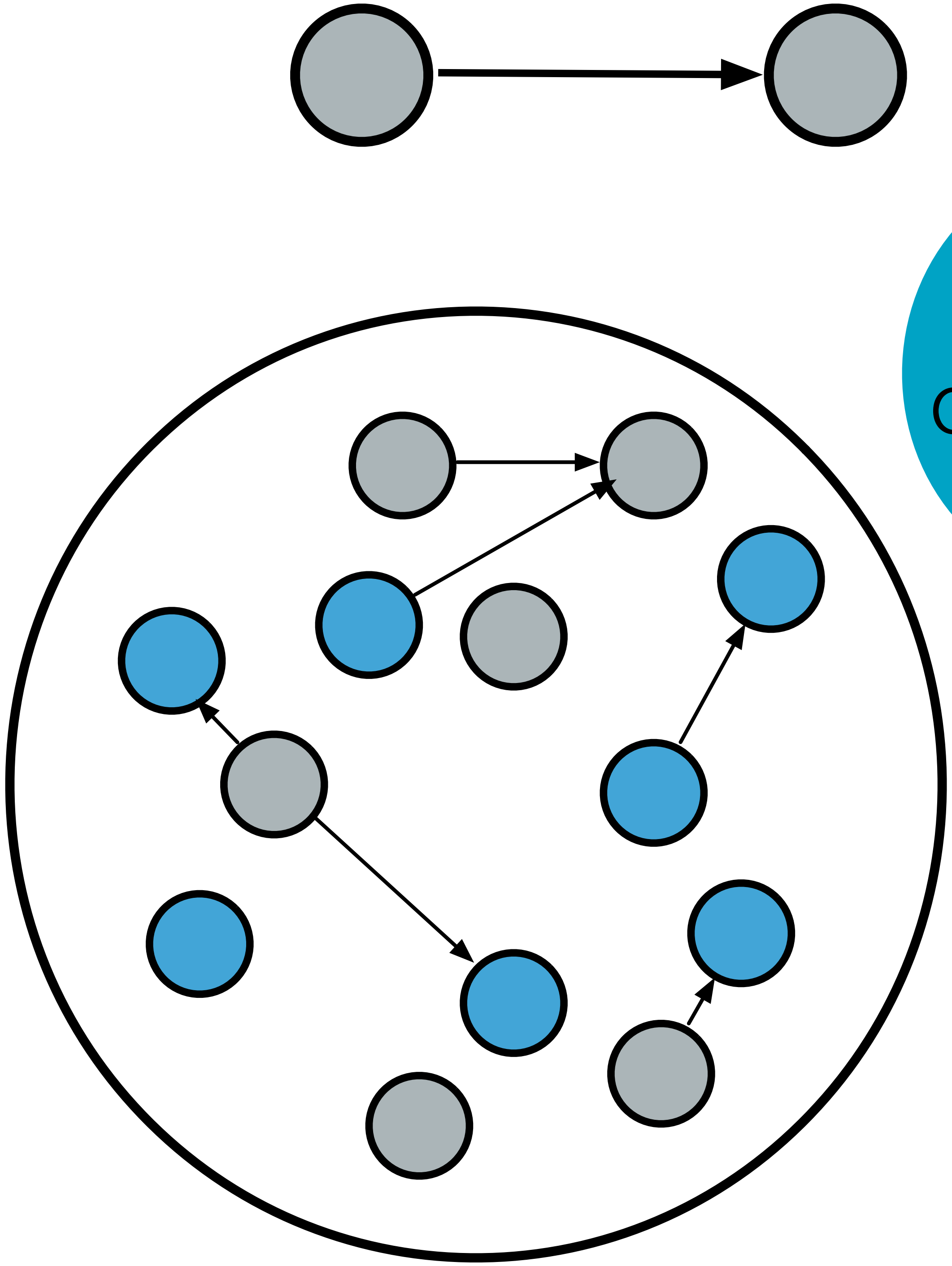


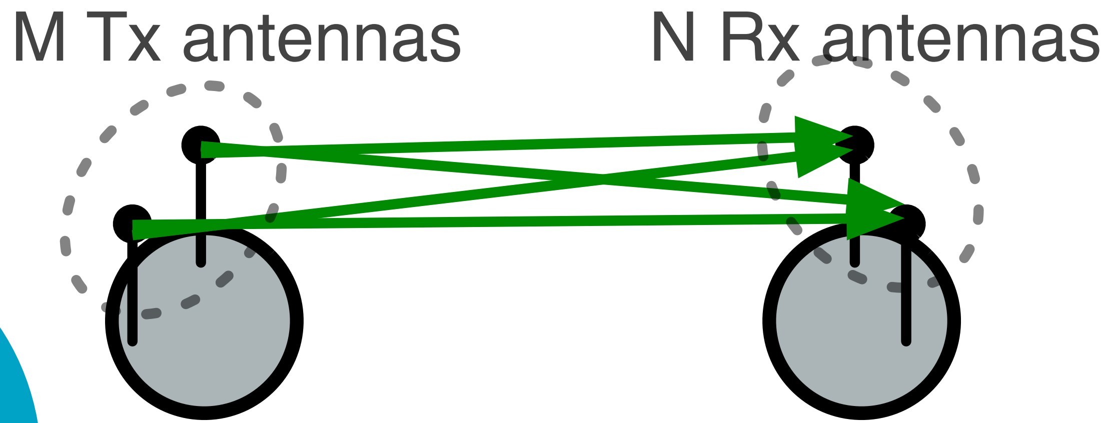
- What we prove:

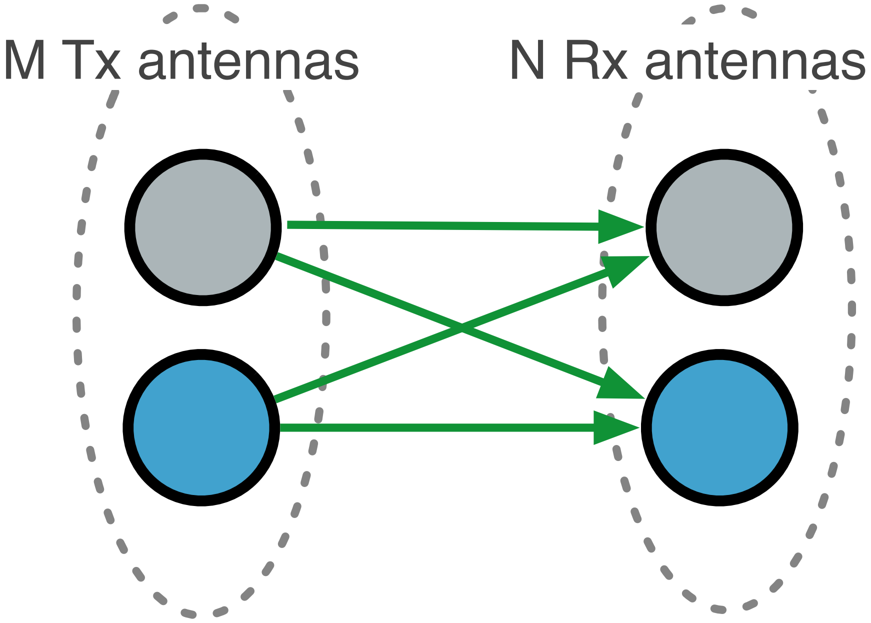
$$T_p(n) = \Theta\left(\sqrt{\frac{1}{n \log n}}\right), \quad T_s(m) = \Theta\left(\sqrt{\frac{1}{m \log m}}\right)$$

Efficient, reliable communications

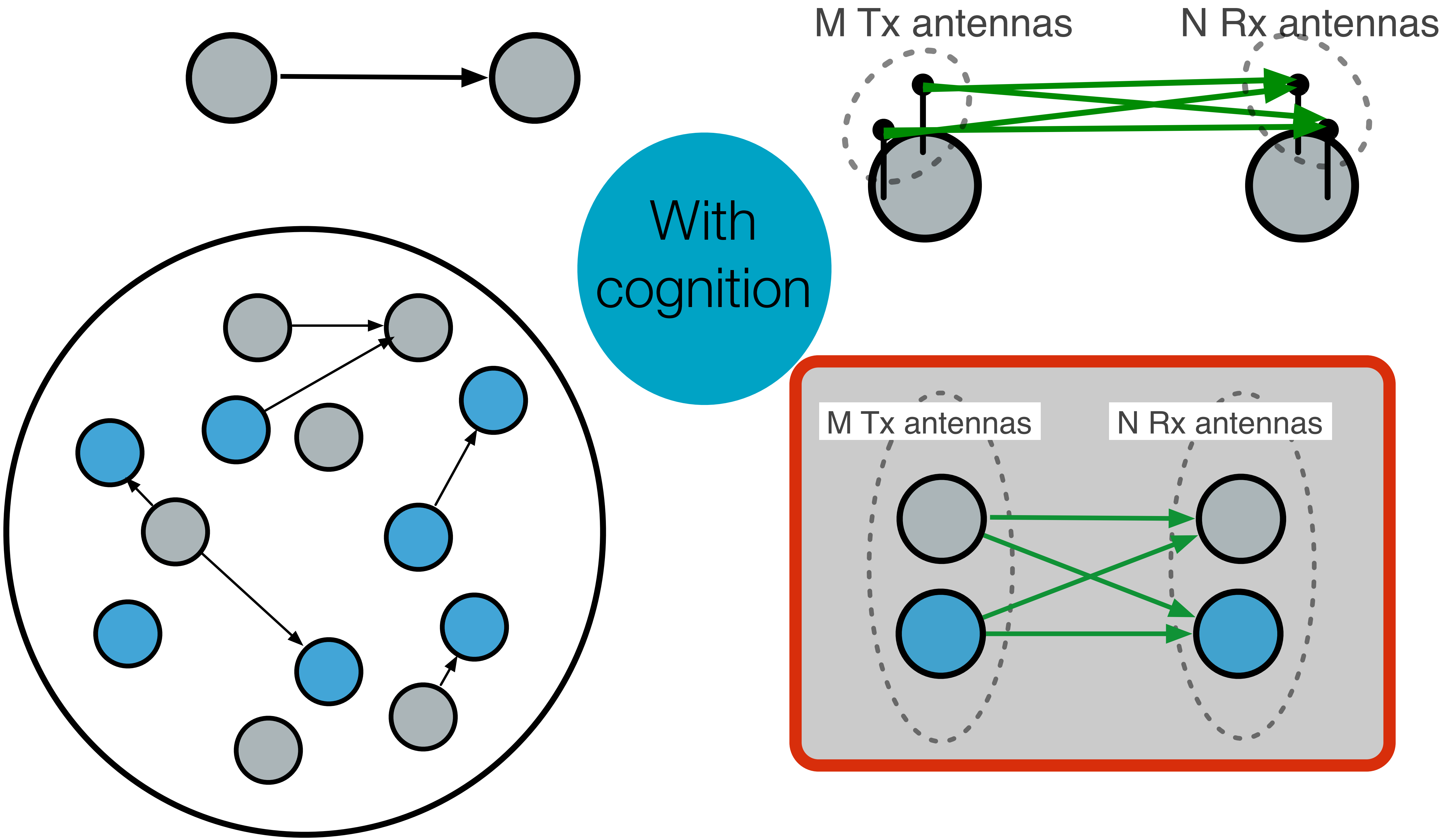


With cognition





Efficient, reliable communications



M Tx antennas

N Rx antennas

With cognition

M Tx antennas

N Rx antennas

Thank you

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http://www.ece.uic.edu/~devroye

Purdue University
Lecture Series on Science of Information
2/22/2010