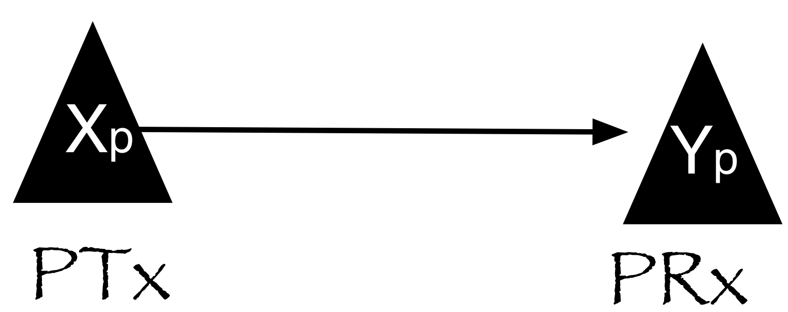
Receiver-side Opportunism in Cognitive Networks

Natasha Devroye, University of Illinois at Chicago
Petar Popovski, Aalborg University

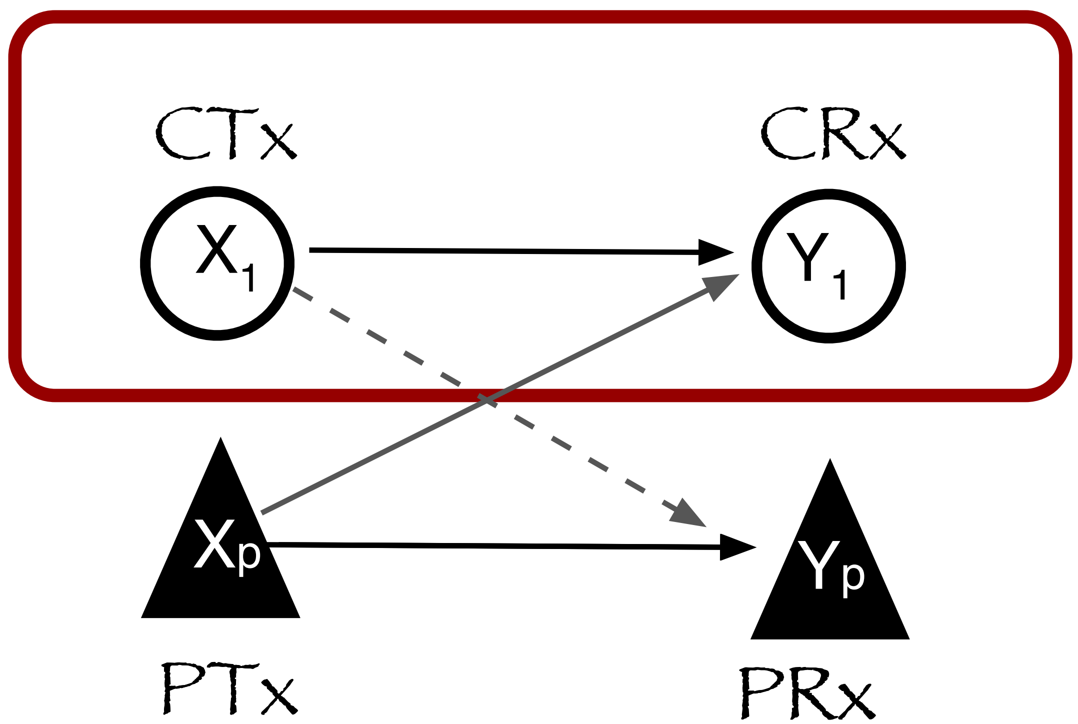
Secondary spectrum licensing



Primary users

Secondary spectrum licensing

Secondary users ⟷ Cognitive radios



Primary users

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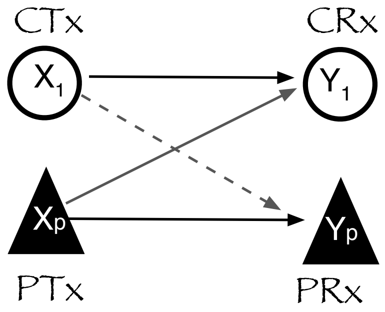
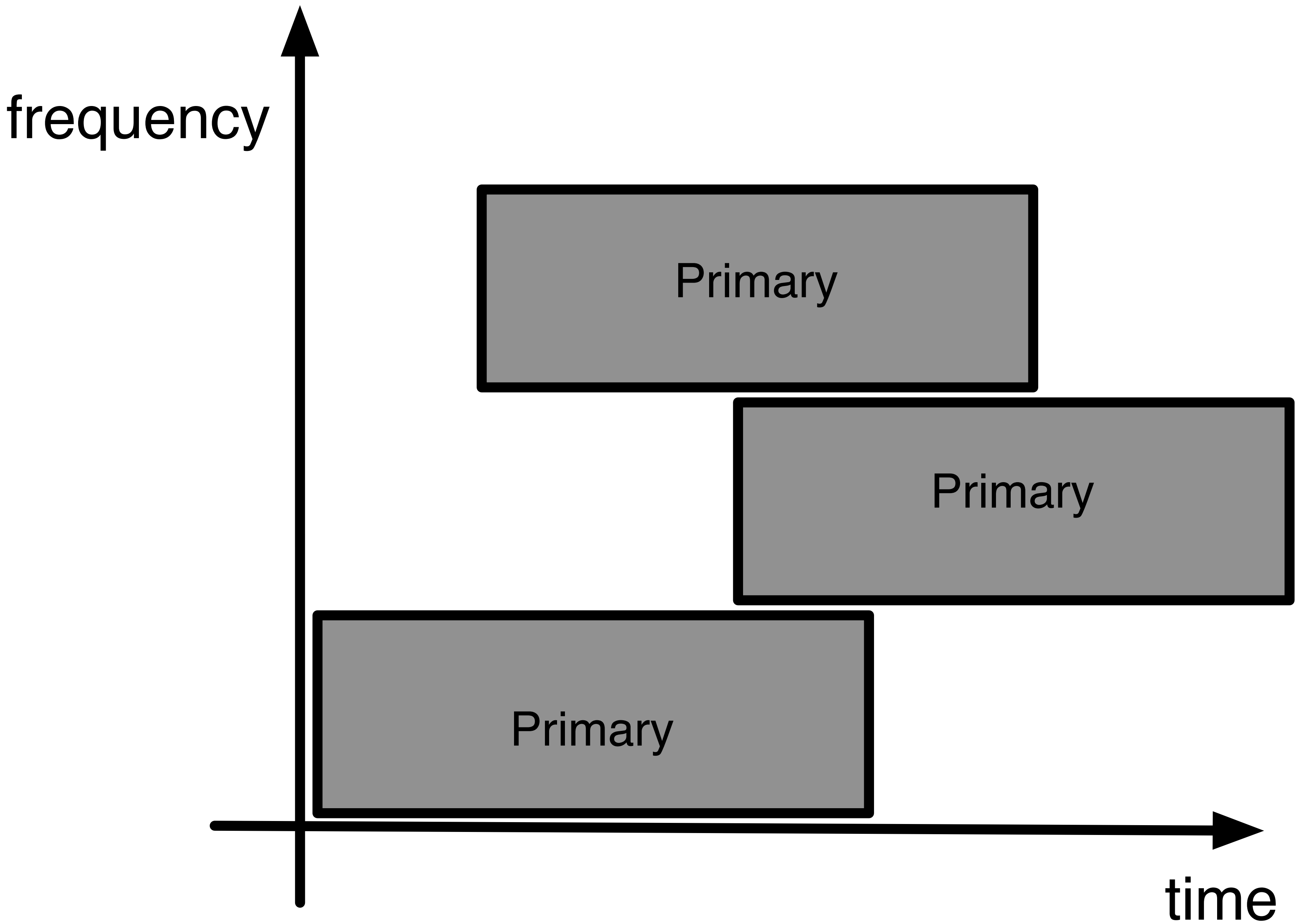


1. White-space filling



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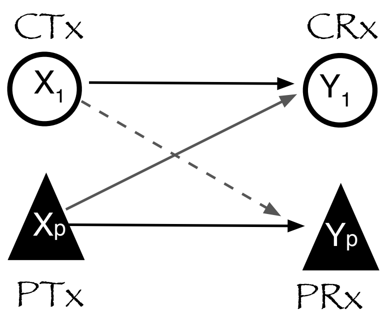

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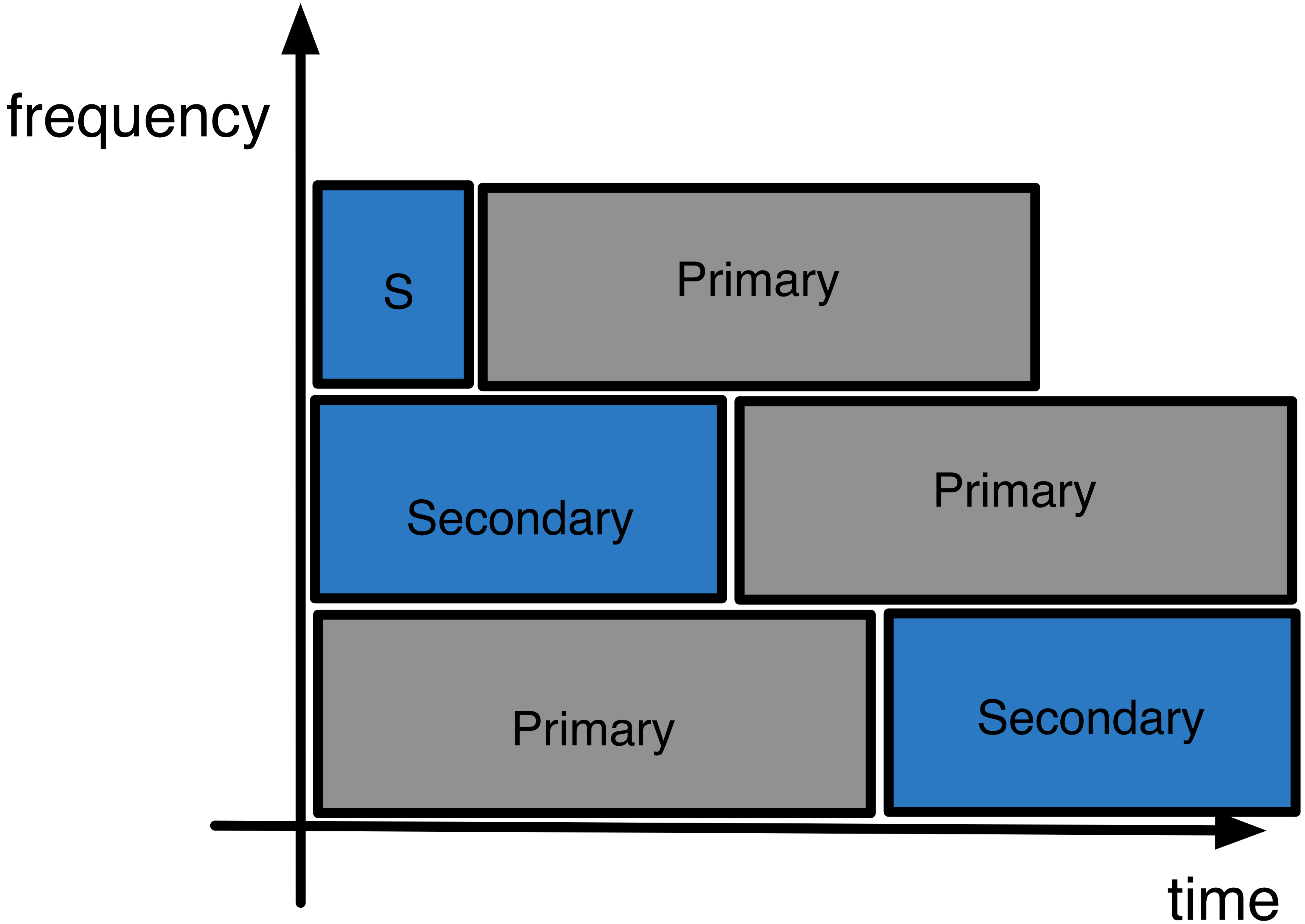

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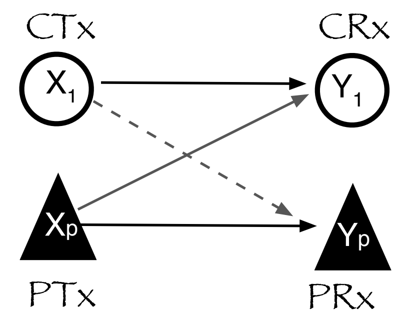

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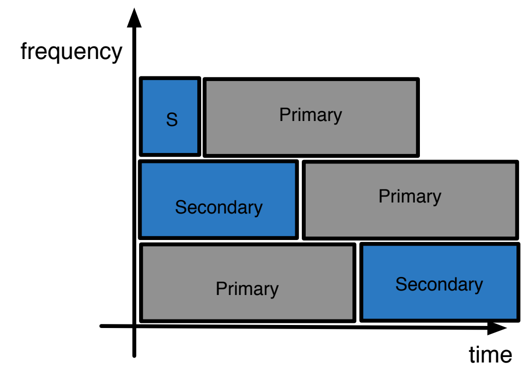
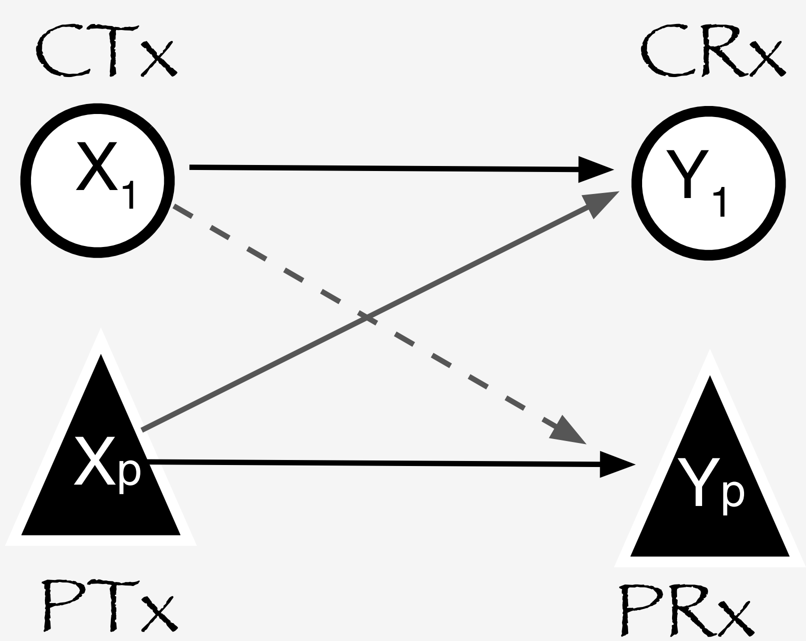


2. Underlay / interference-temperature



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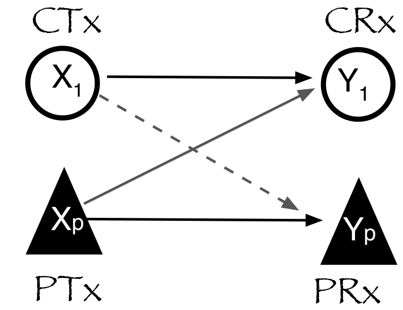

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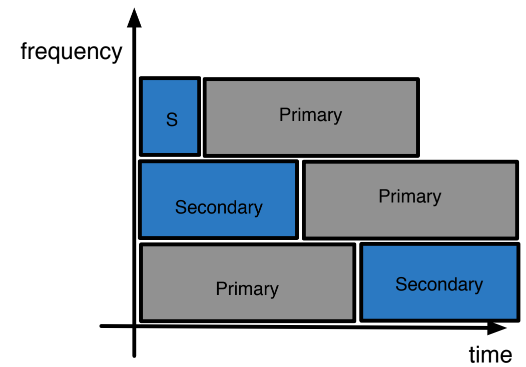

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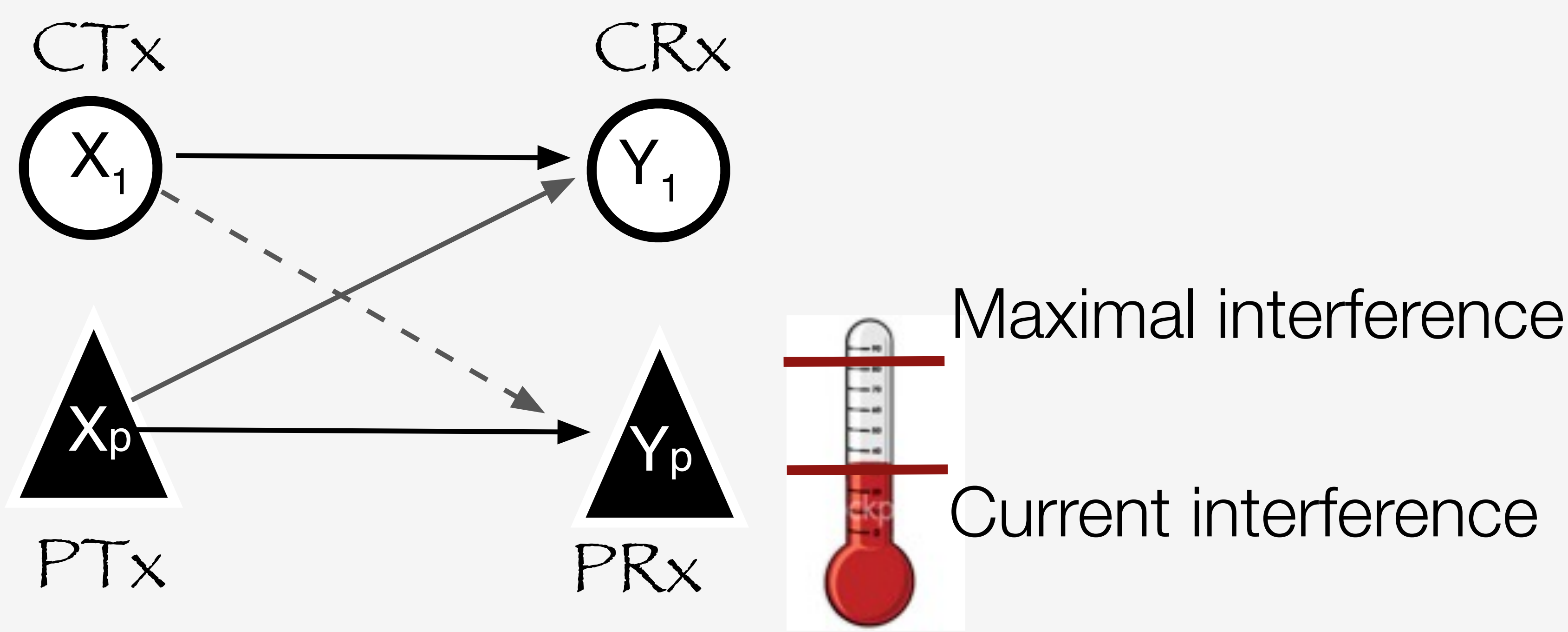

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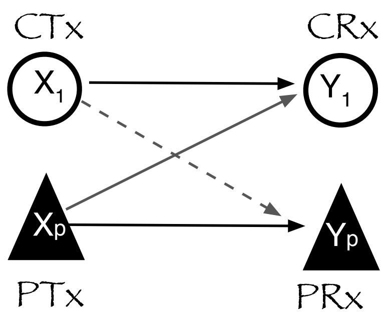

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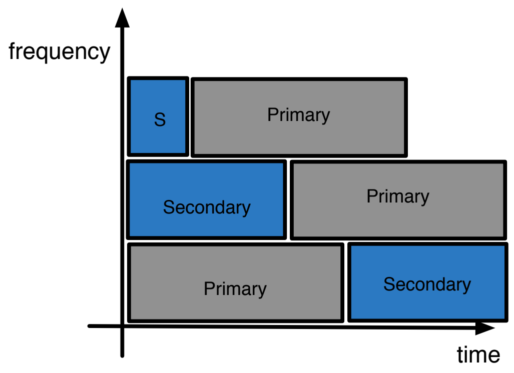

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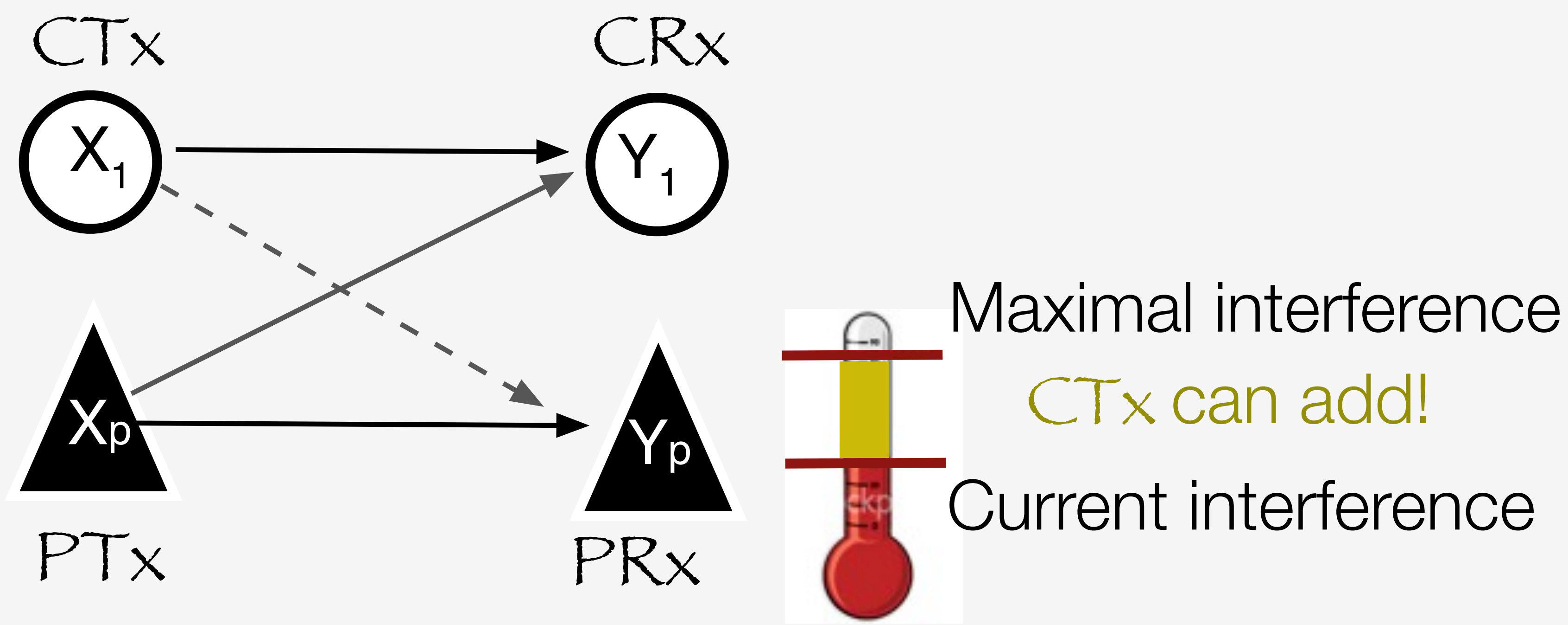

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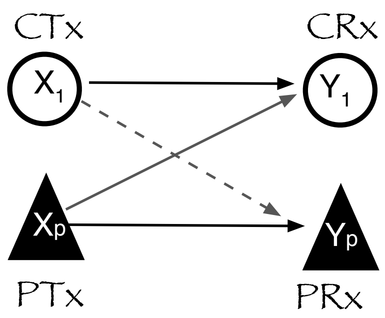

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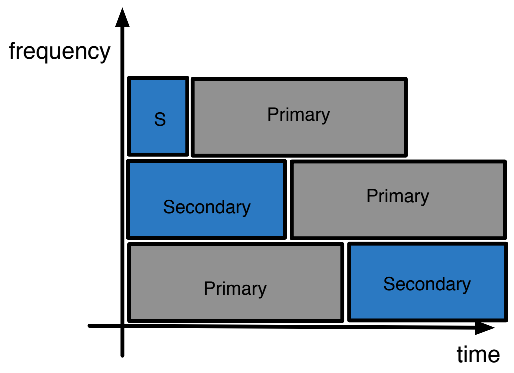
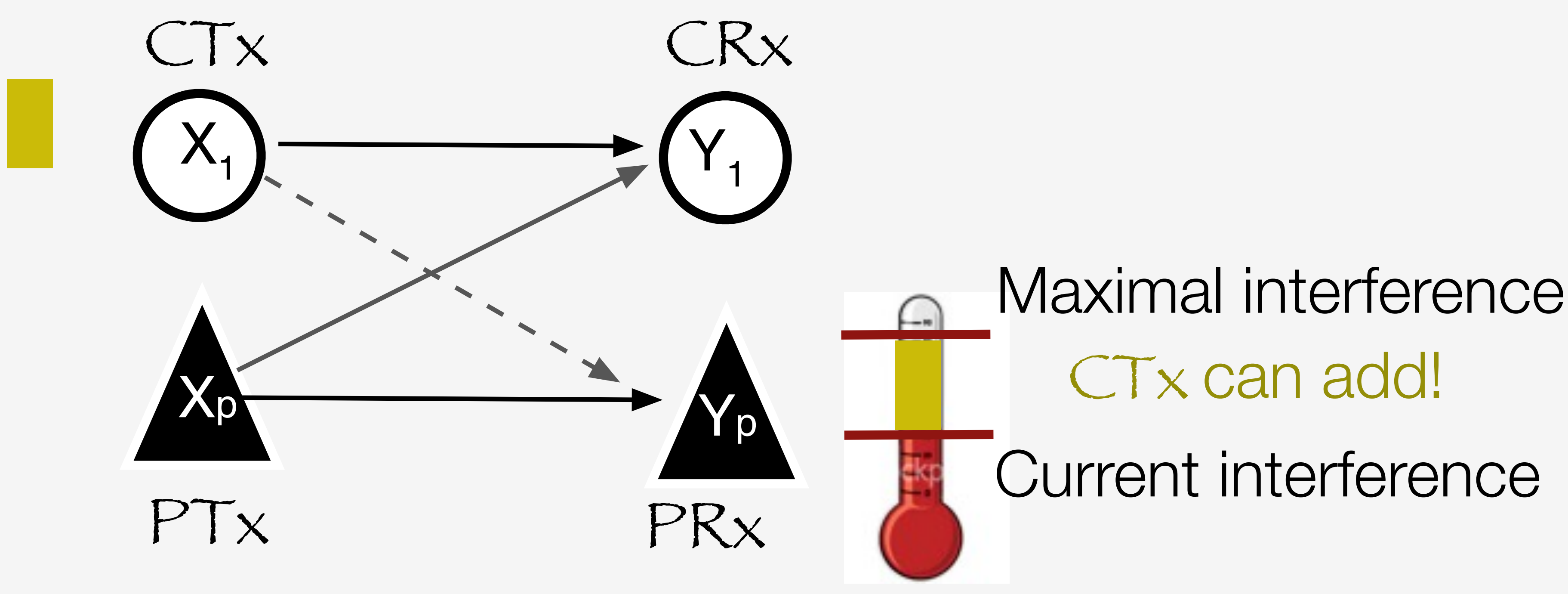


2. Underlay / interference-temperature

Determines power level



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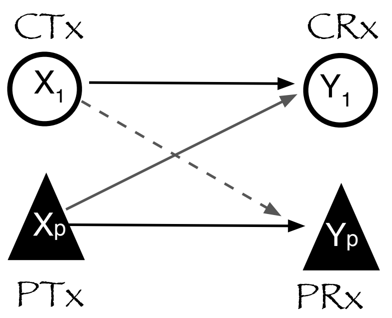

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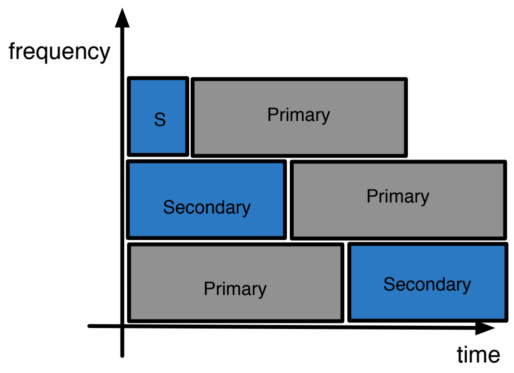

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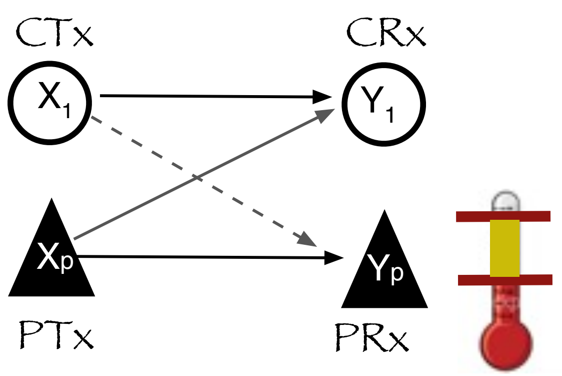
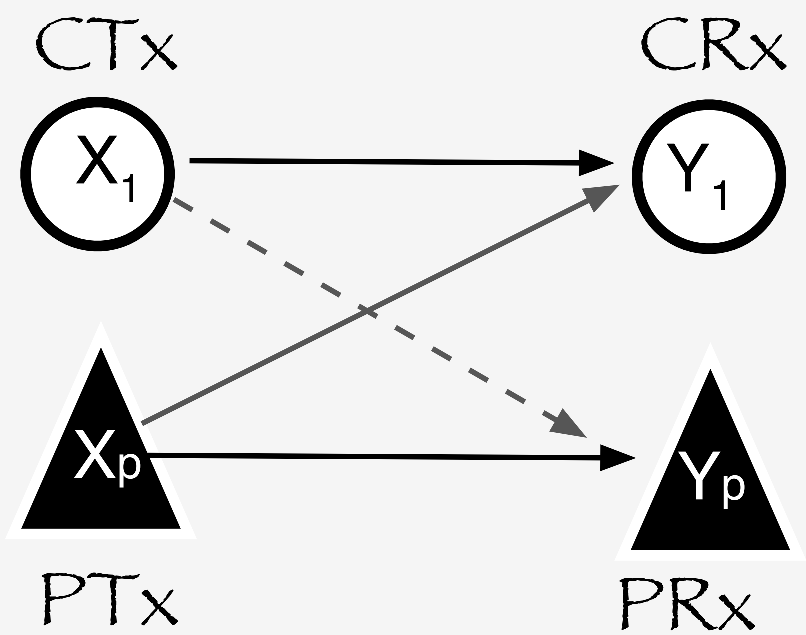
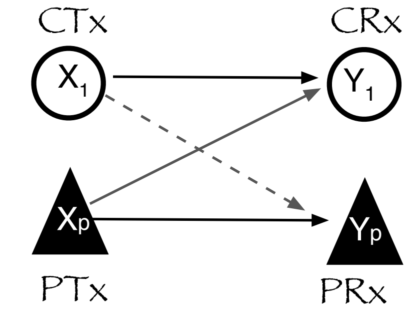


3. Overlay



Control interference

Secondary licensing



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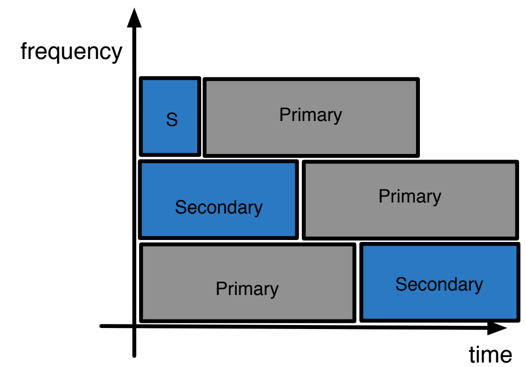

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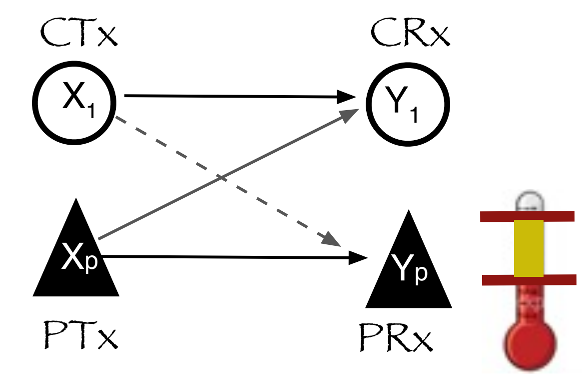

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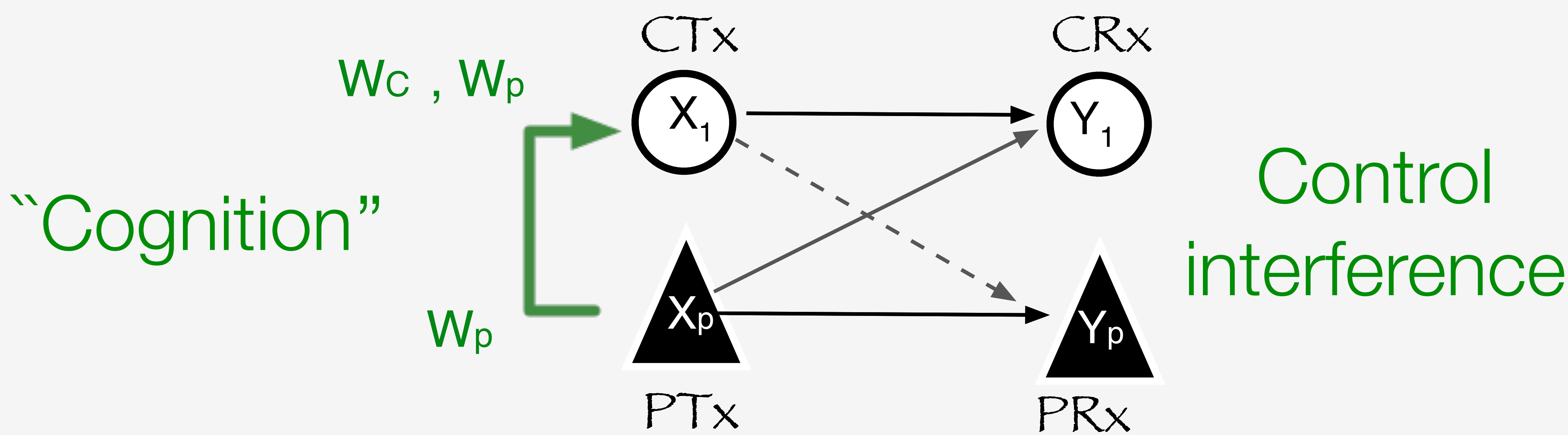
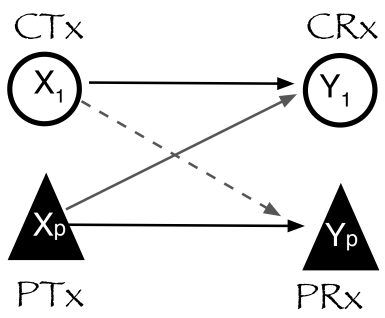


Emphasis on cognitive Tx, CTx!

Cognitive Tx?



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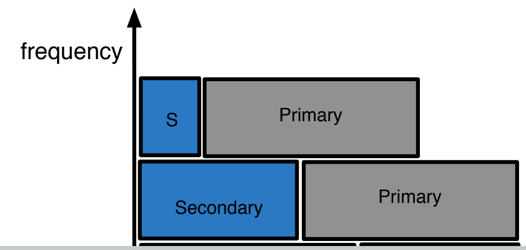
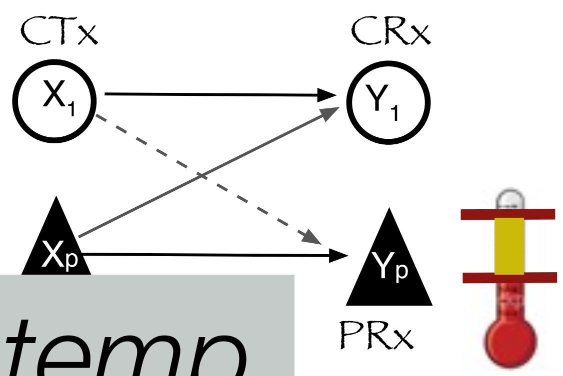


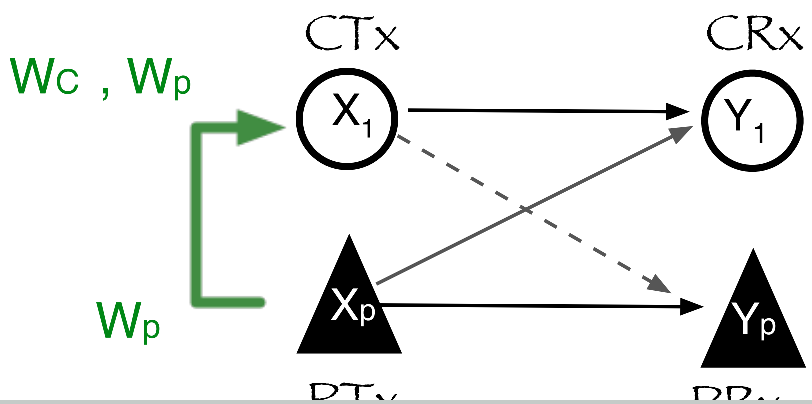
CTx senses spectral gaps + fills them

2. Underlay / interference-temperature



CTx adjusts power to interference temp.

3. Overlay



CTx controls interference

What about intelligent CRx behavior?

What about intelligent CRx behavior?

Opportunistic **I**nterference **C**ancelation!

OIC

Outline

- Past work: plain point-to-point cognitive channel with OIC
- This work: Multiple access channel with OIC
- This work: Interference channel with OIC
- This work: Broadcast channel with OIC

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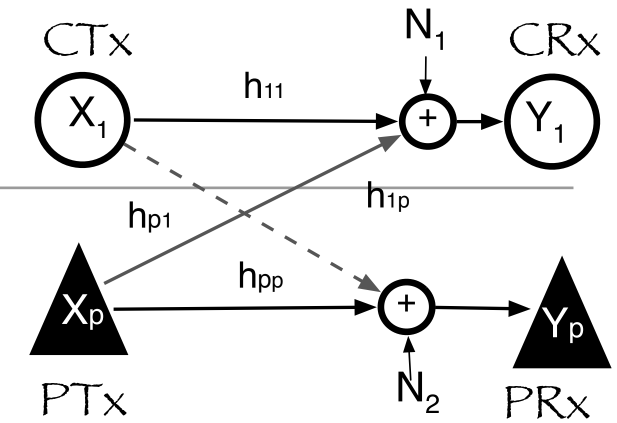

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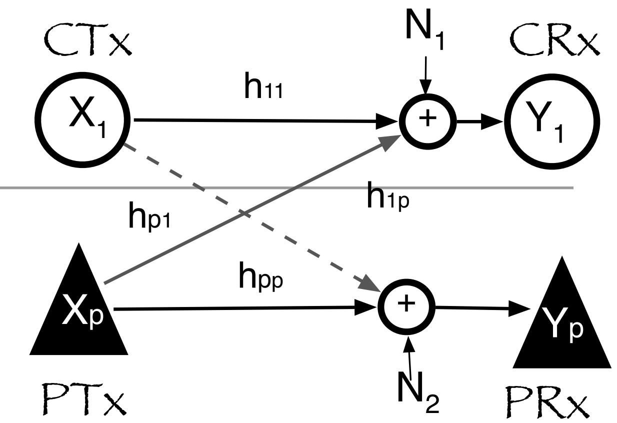

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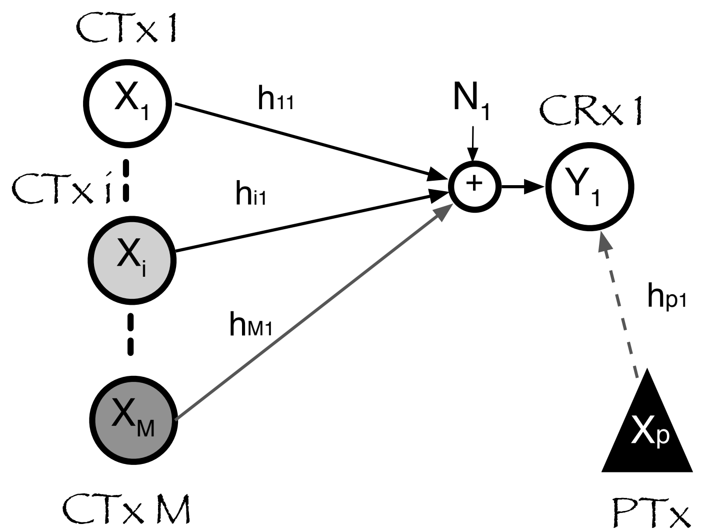

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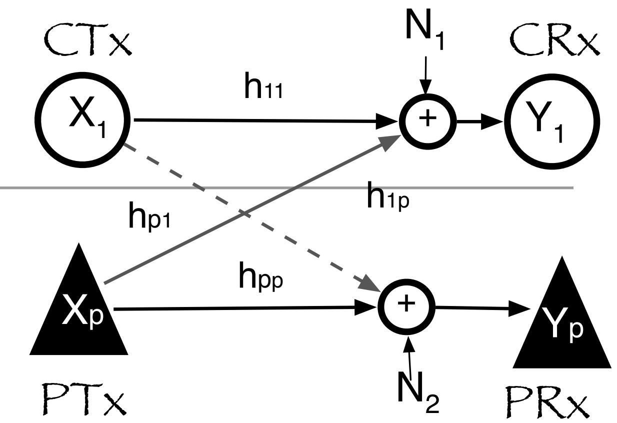

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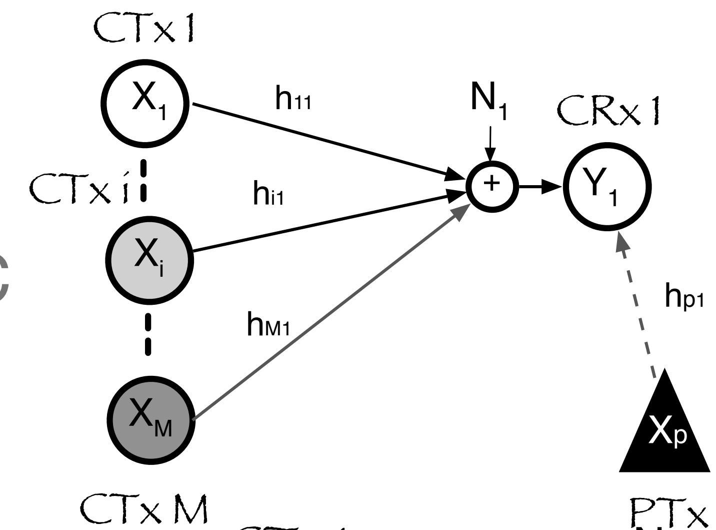

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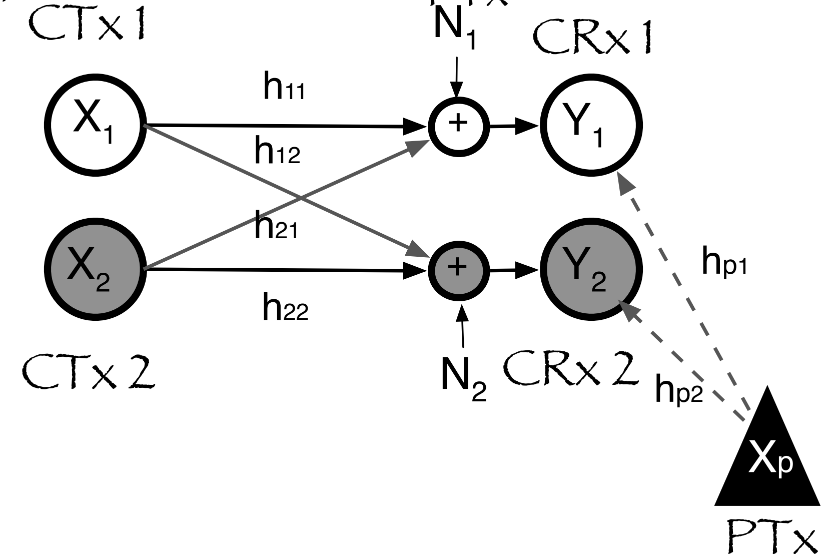

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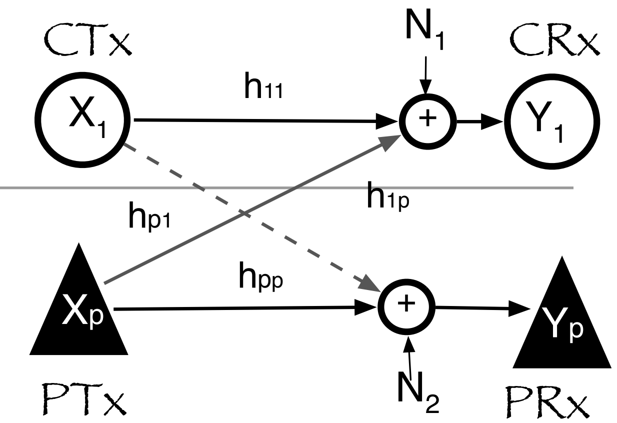

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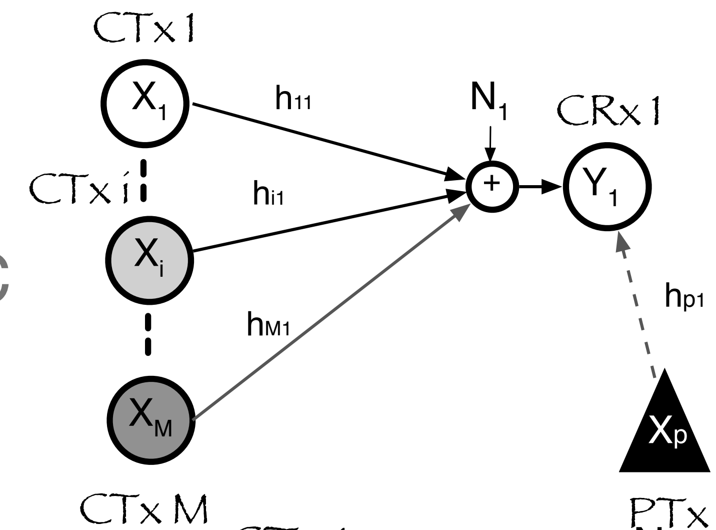

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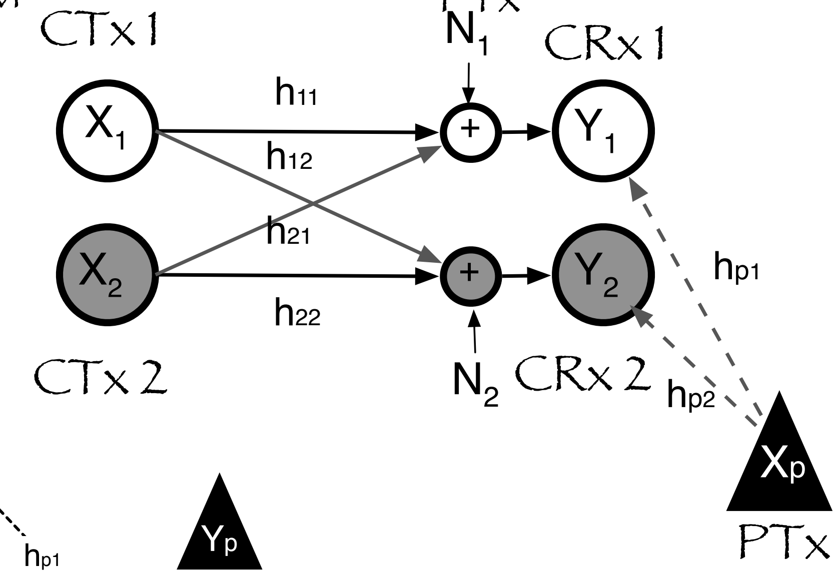
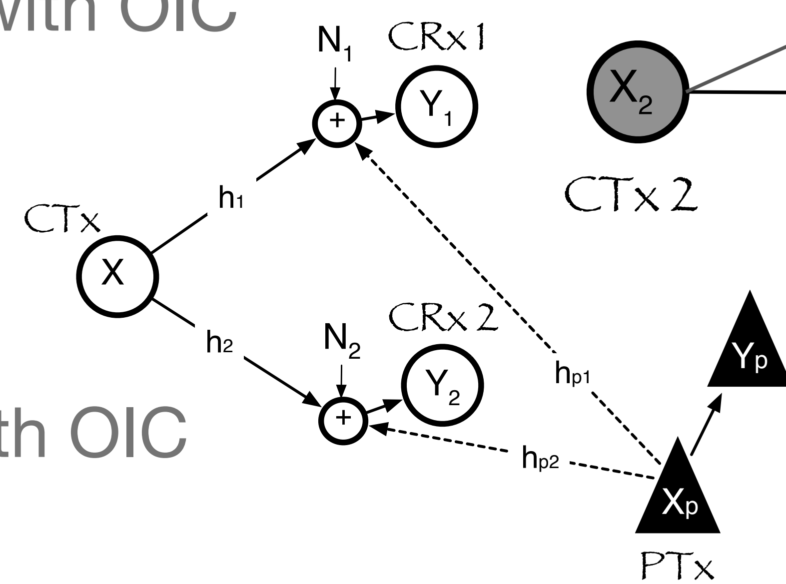
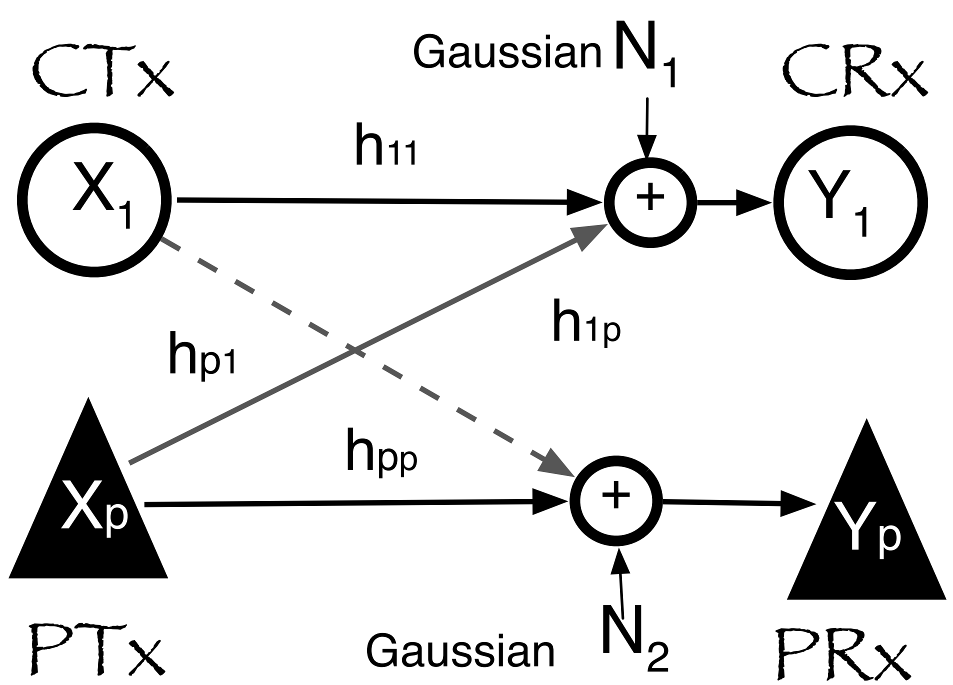


- This work: Broadcast channel with OIC



Opportunistic **I**nterference **C**ancelation (**OIC**)

- introduced by Popovski et al. *[P. Popovski, H. Yomo, K. Nishimori, R. D. Taranto, and R. Prasad, DYSPAN 2007]*



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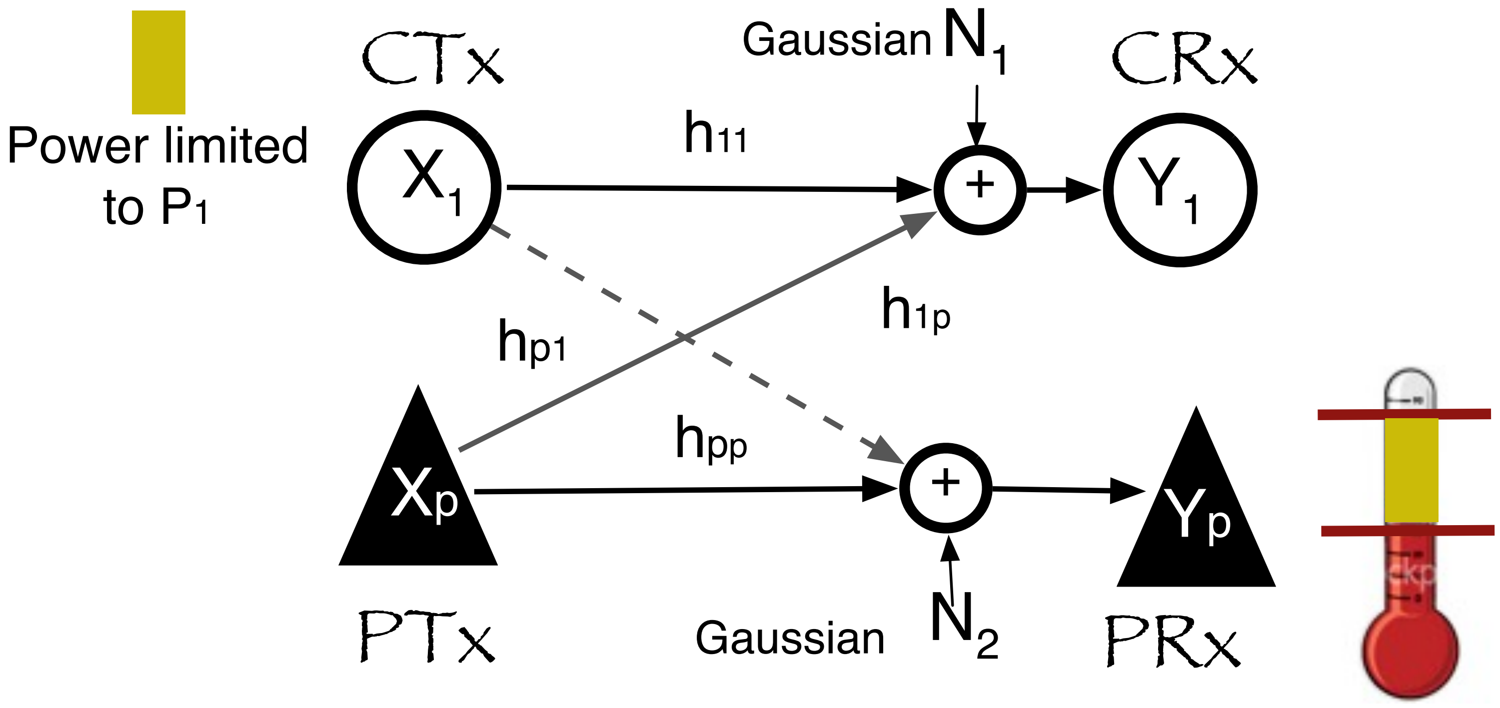

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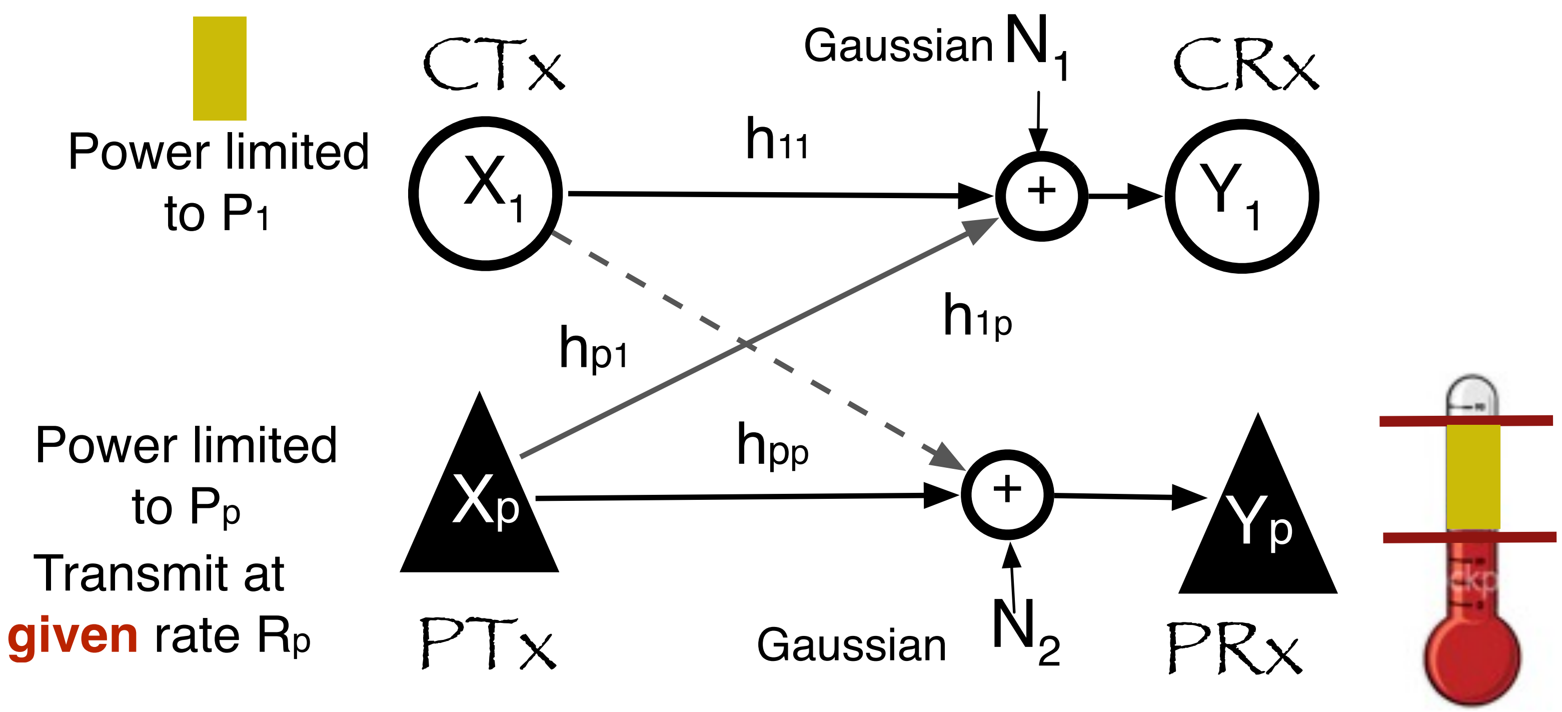

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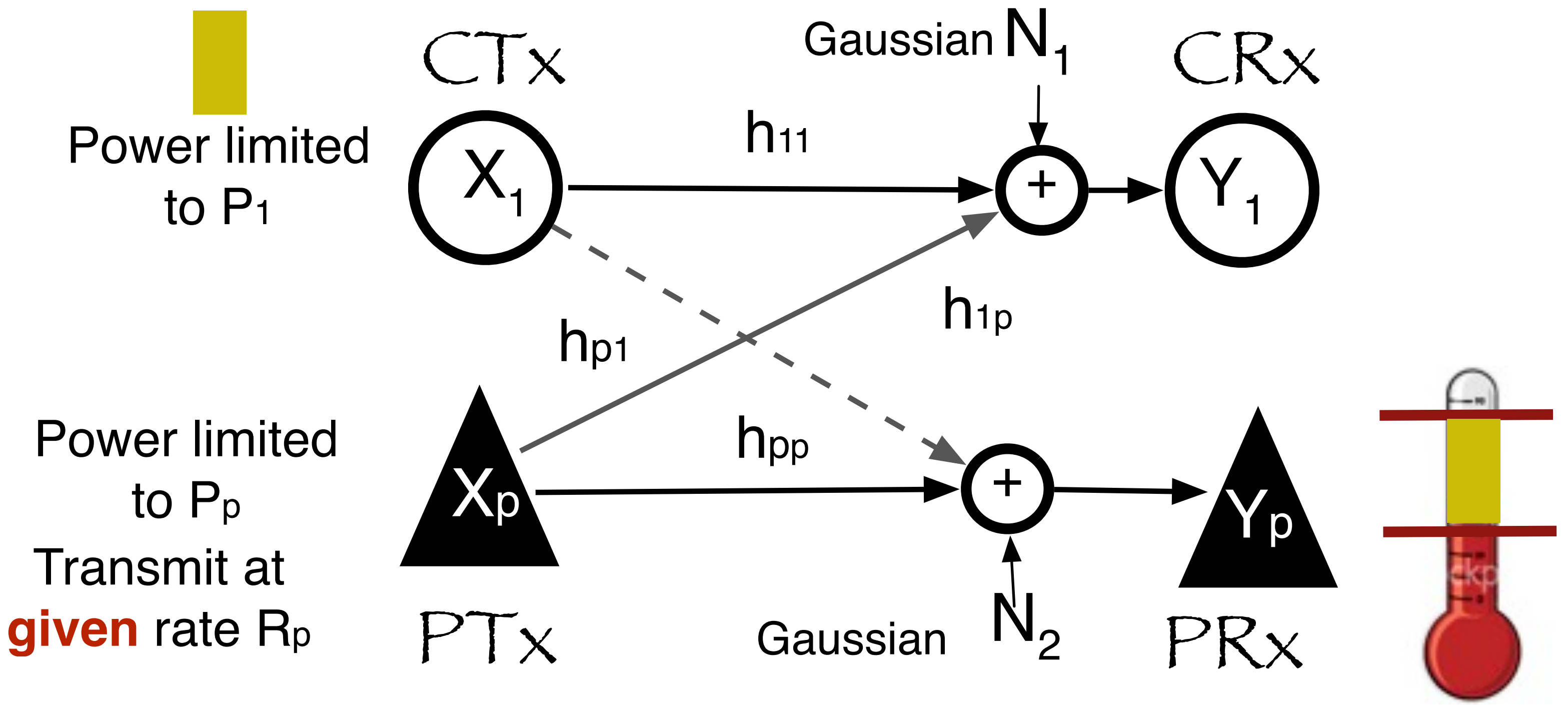
$$P_1^* \leq \min\{I_0/|h_{p1}|^2, P_1\}$$



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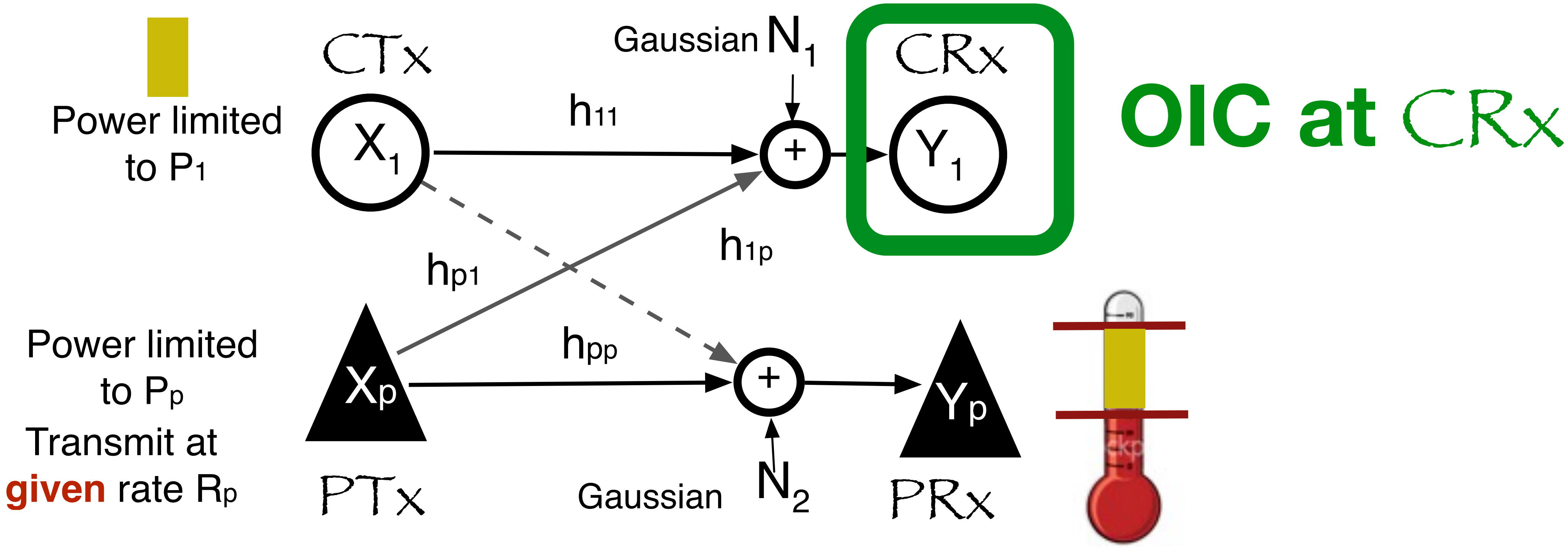

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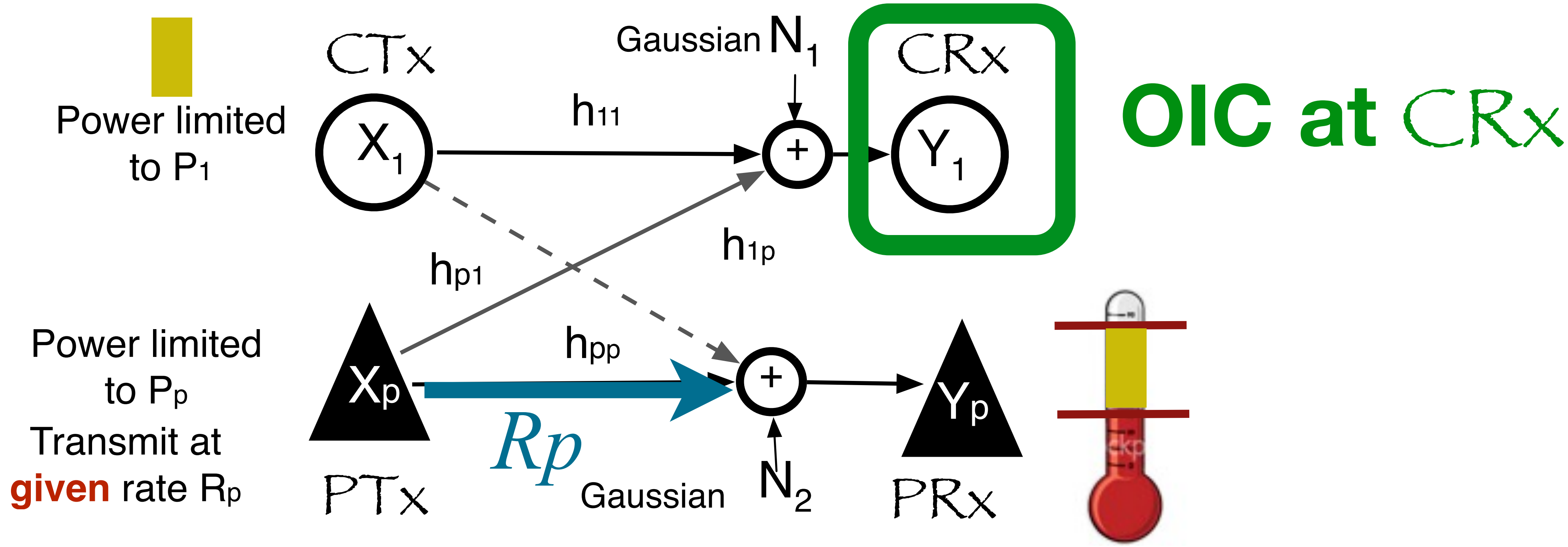
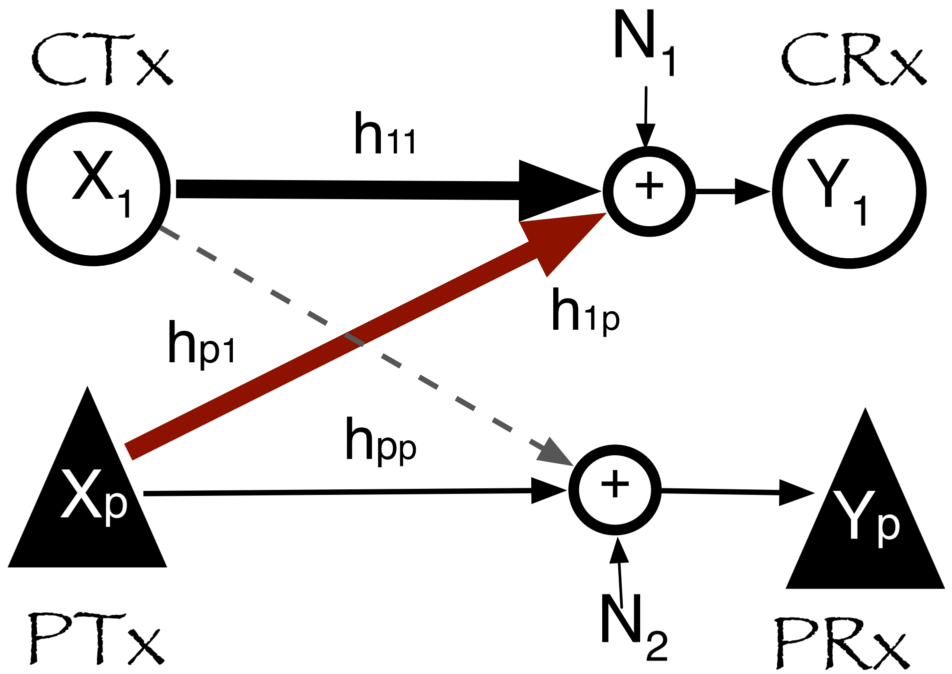


$$R_p = \log\left(1 + \frac{|h_{pp}|^2}{1+I_0}\right) \qquad \text{Interference margin } I_0$$

Opportunistic Interference Cancelation (OIC)



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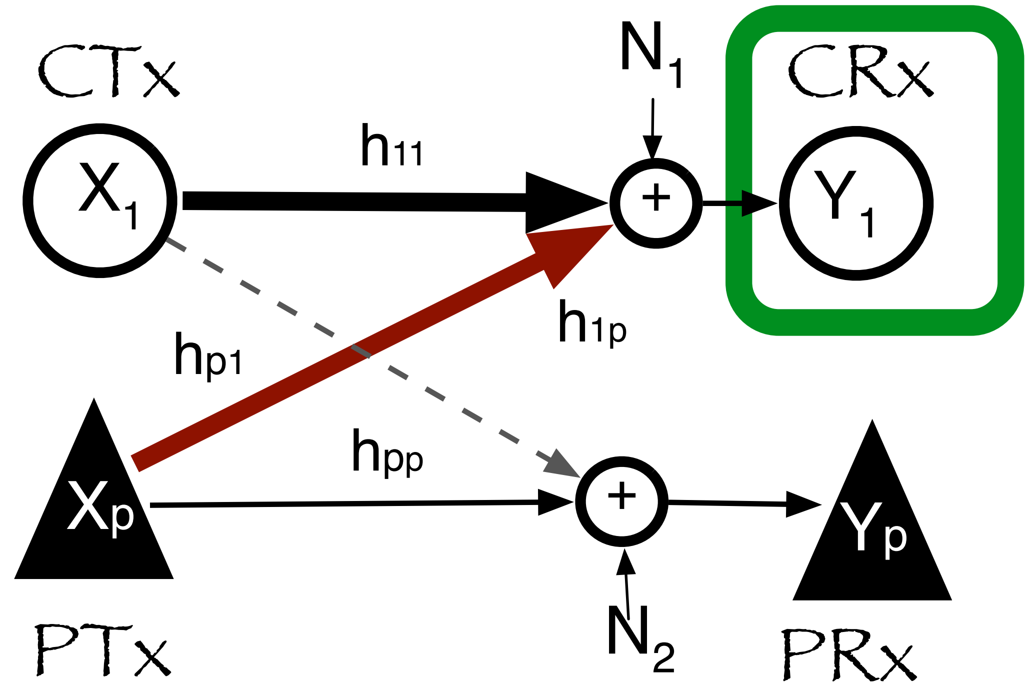
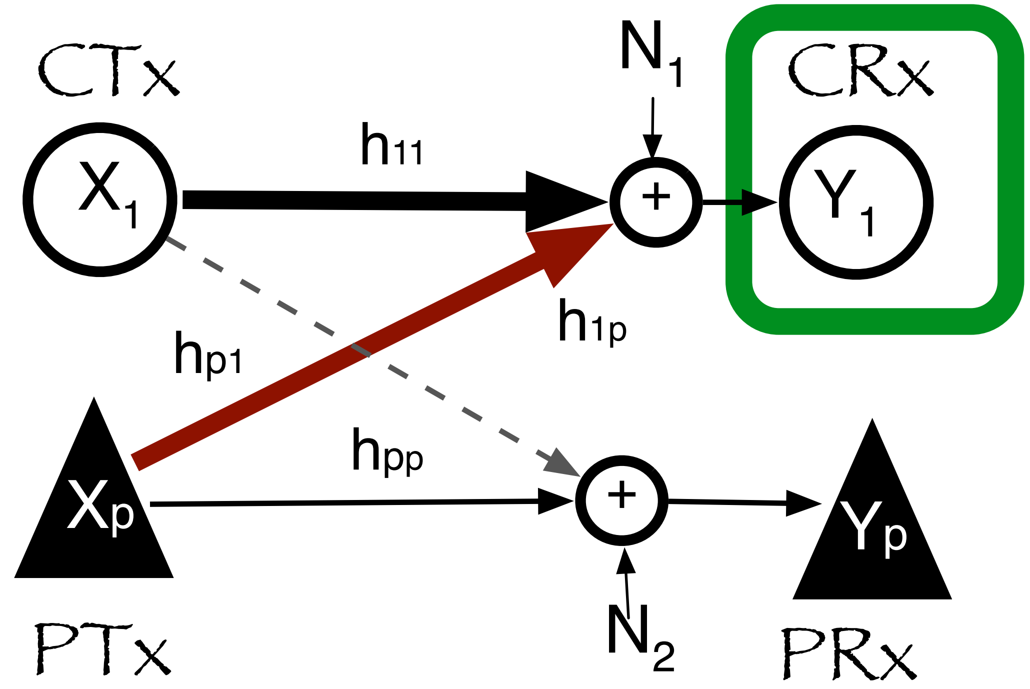


OIC at CRx

Opportunistic Interference Cancelation (OIC)

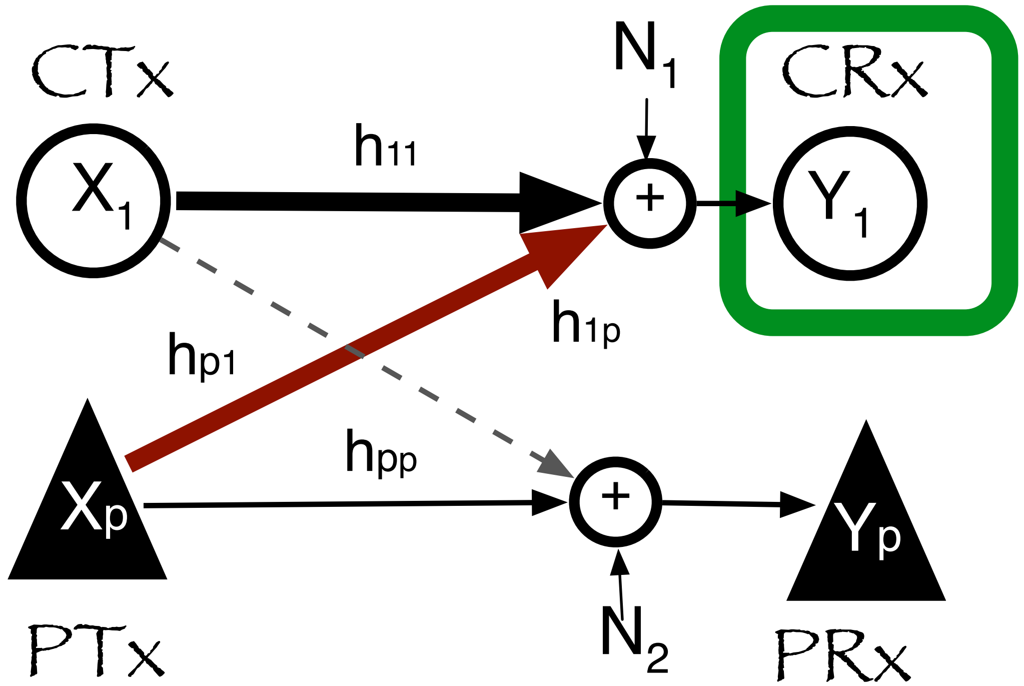


OIC at CRx

KEY ASSUMPTION:

CRx has codebook of (PTx,PRx)

Opportunistic Interference Cancelation (OIC)

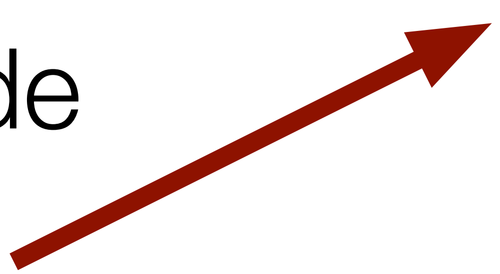


OIC at CRx

KEY ASSUMPTION:

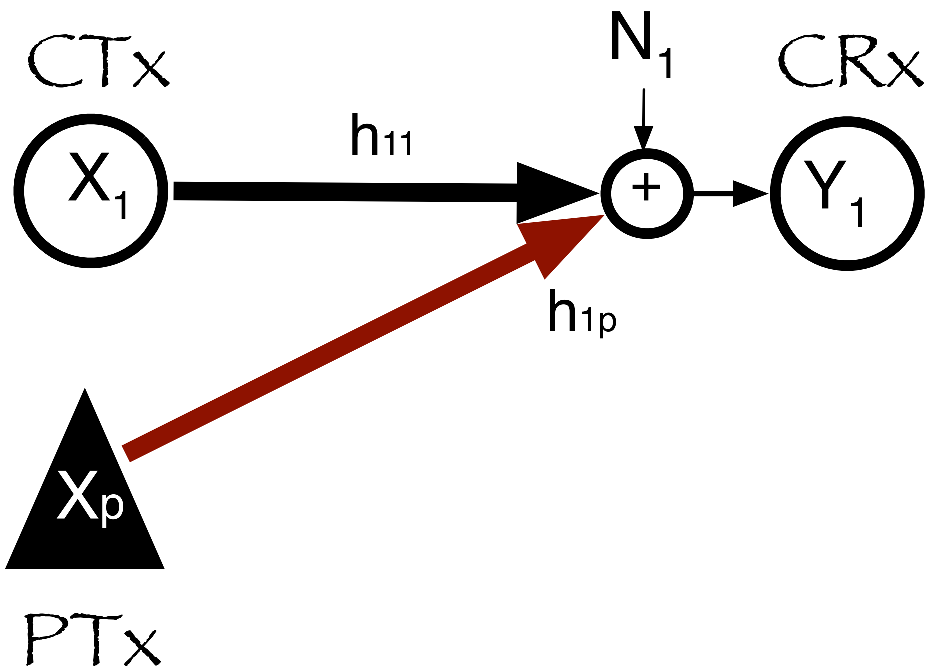
CRx has codebook of (PTx,PRx)

uses this to decode "opportunistically"



Decode PTx message **``opportunistically”**?

"Opportunistically:"

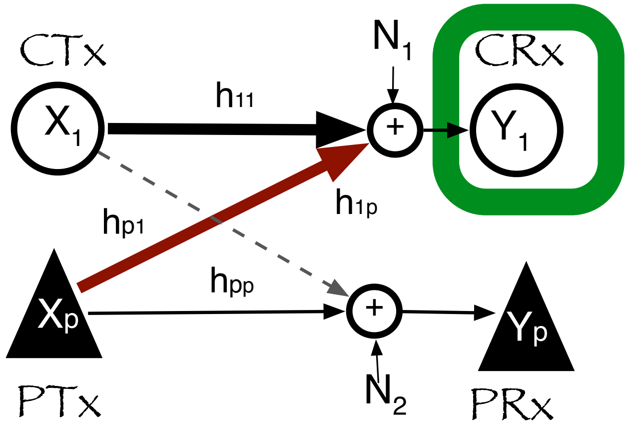


Constraint 1: R_p^* fixed by primary

Constraint 2: primary SNR at CRx depends on channel gain

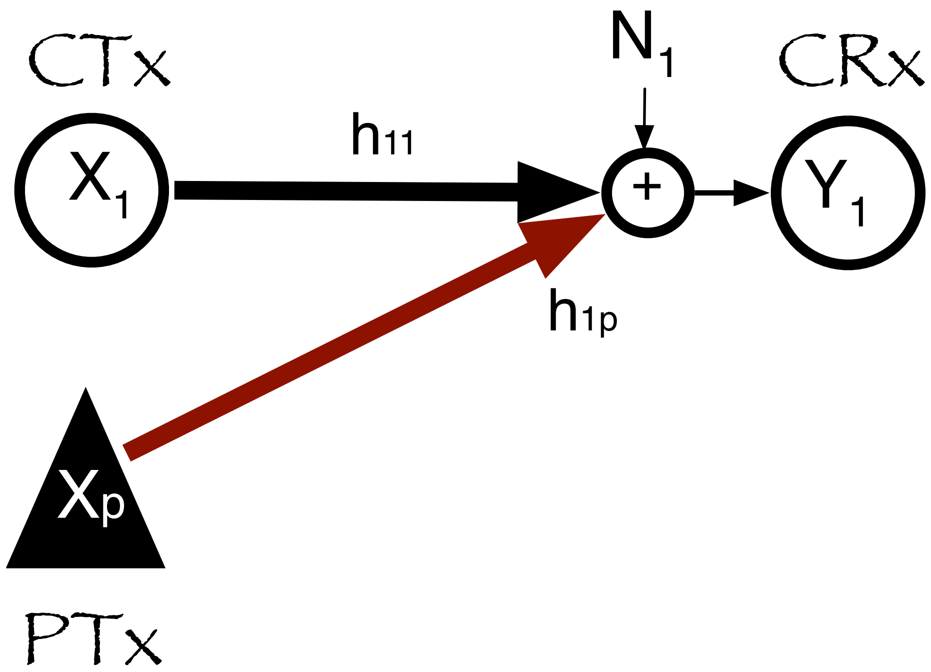
$$\gamma_{p1} := |h_{1p}|^2 P_p$$

"Opportunistically:"



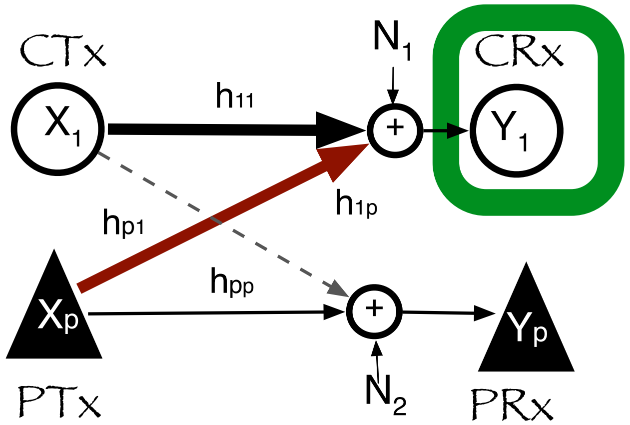
$$Y_1 = h_{11}X_1 + h_{p1}X_p + N_1$$

Multiple Access Channel, know capacity!



$$R_c \leq I(X_1; Y_1 | X_p)$$
$$R_p \leq I(X_p; Y_1 | X_1)$$
$$R_c + R_p \leq I(X_1, X_p; Y_1)$$

``Opportunistically:”



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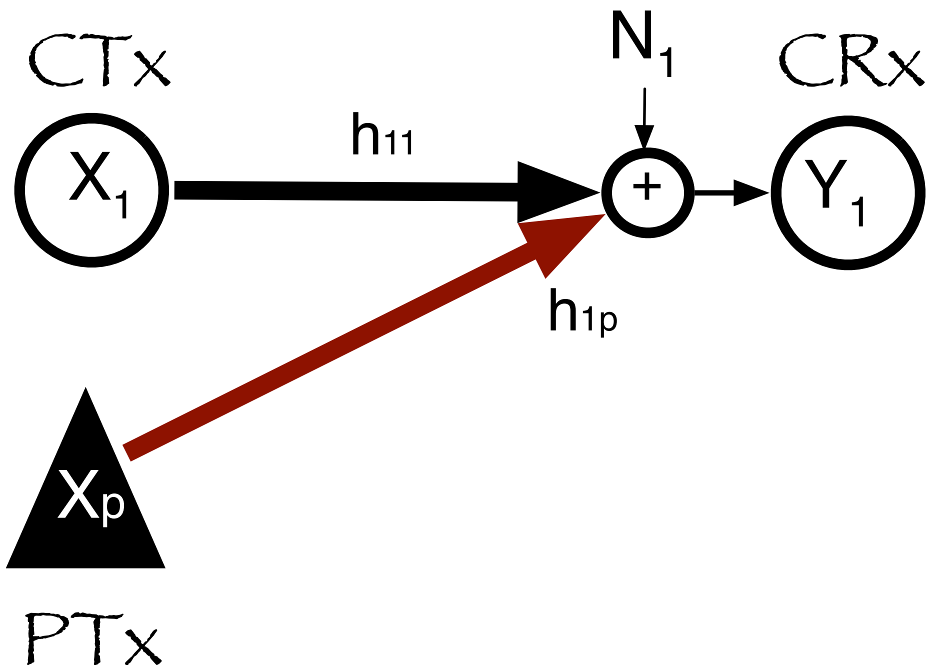
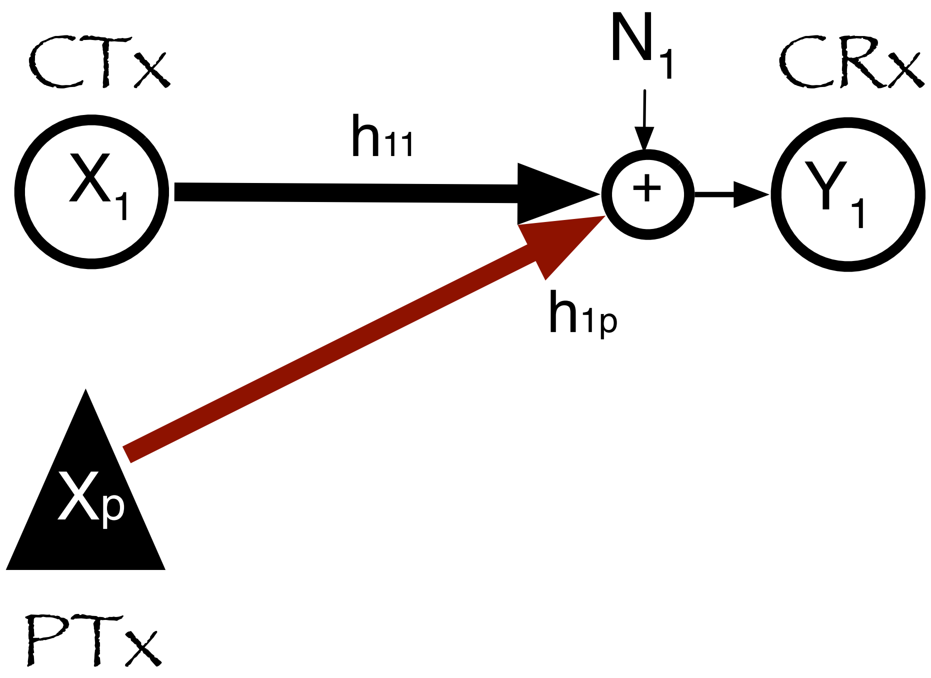


$$\begin{aligned} R_c &\le I(X_1; Y_1 | X_p) \\ R_p &\le I(X_p; Y_1 | X_1) \\ R_c + R_p &\le I(X_1, X_p; Y_1) \end{aligned}$$

Fixed to R_p^* $\Rightarrow$ find R_c

``Opportunistically:"



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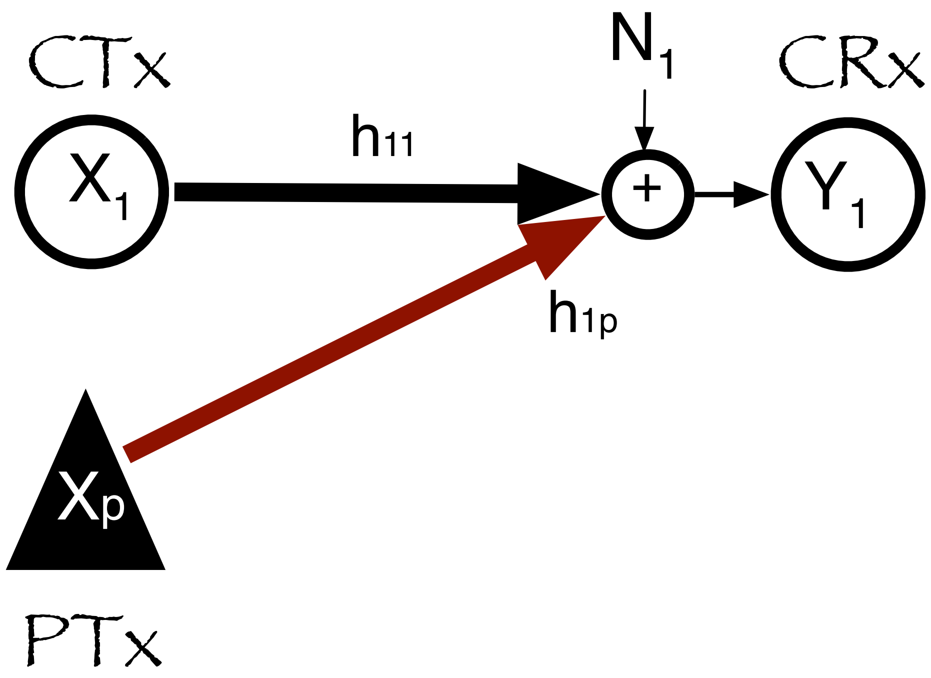
R_p^* fixed by primary

Case 1: γ_{p1} large , **opportunistically cancel** PTx **message**

$$Y_1 = h_{11} X_1 + h_{p1} X_p + N_1$$

``Opportunistically:"



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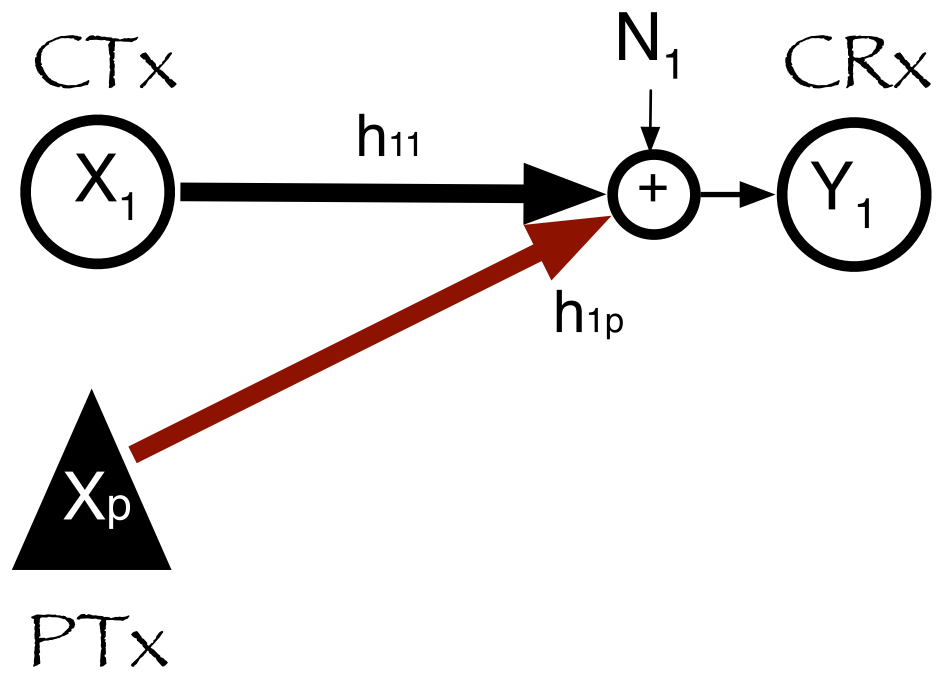

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R_p^* fixed by primary

Case 1: γ_{p1} large , **opportunistically cancel PTx message**

$$Y_1 = h_{11} X_1 + h_{p1} X_p + N_1$$

Case 2: γ_{p1} small , treat PTx message as noise

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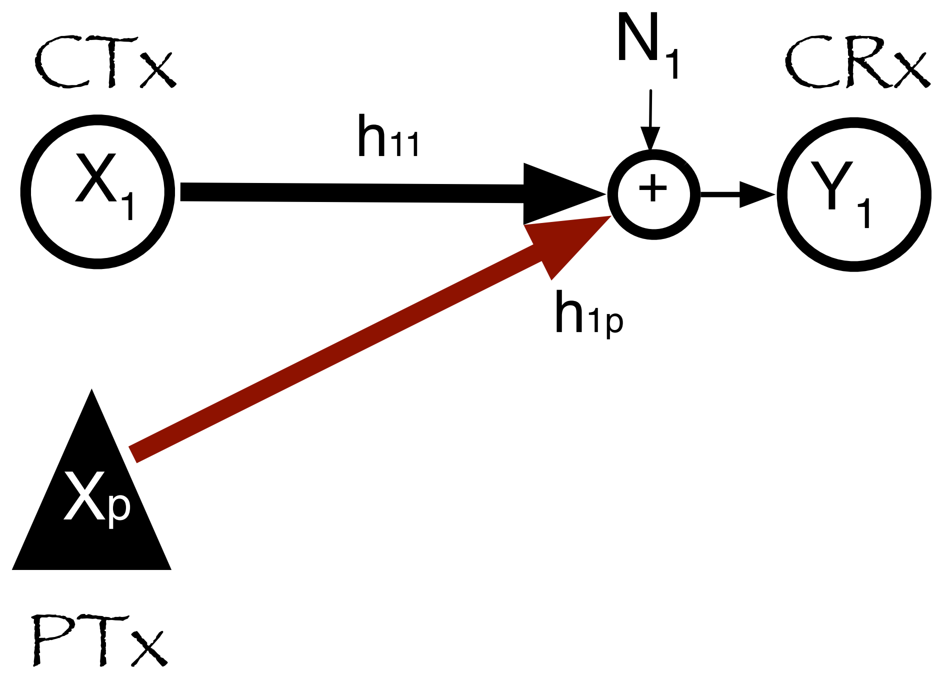

$$R_c \leq I(X_1; Y_1 | X_p)$$
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$$R_c + R_p \leq I(X_1, X_p; Y_1)$$

R_p^* fixed by primary

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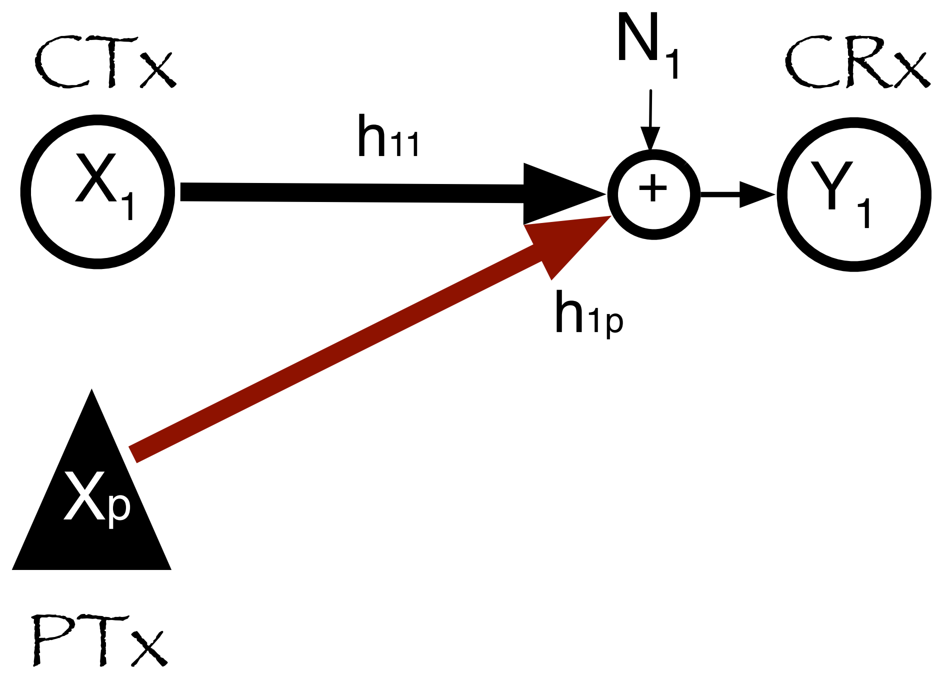

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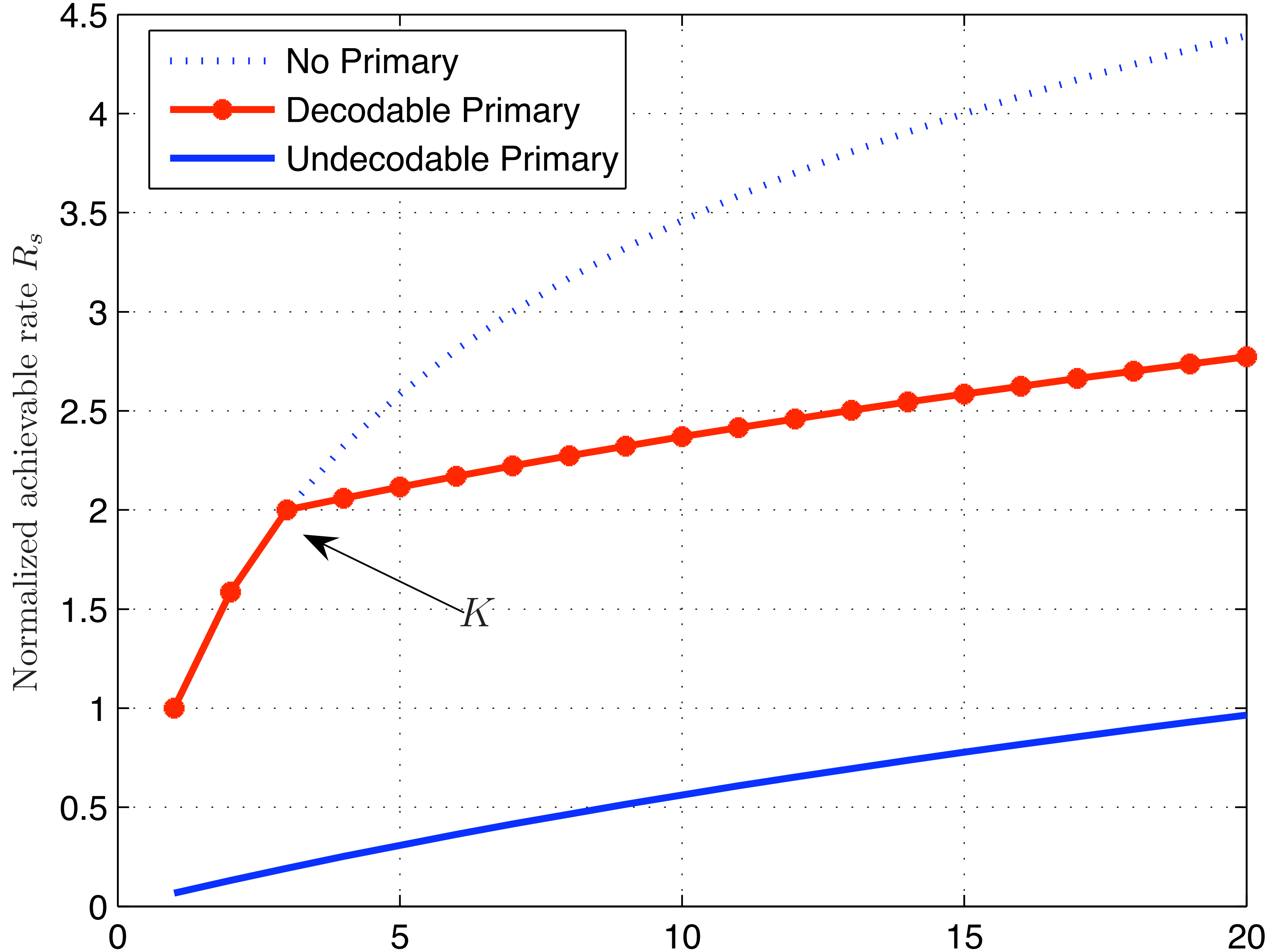
} gets rates Rc

[P. Popovski, H. Yomo, K. Nishimori, R. D. Taranto, and R. Prasad, DYSPAN 2007]



Primary signal SNR at CRx

What about **OIC** in *networks* of cognitive users?

What about **OIC** in *networks* of cognitive users?

Same idea - use primary codebook knowledge to **decode and cancel** primary message when channel conditions permit!

Networks with **OIC** assumptions

- **Interference margin:** single primary user operates at a positive I_0

$$R_p = \log\left(1 + \frac{|h_{pp}|^2}{1+I_0}\right)$$

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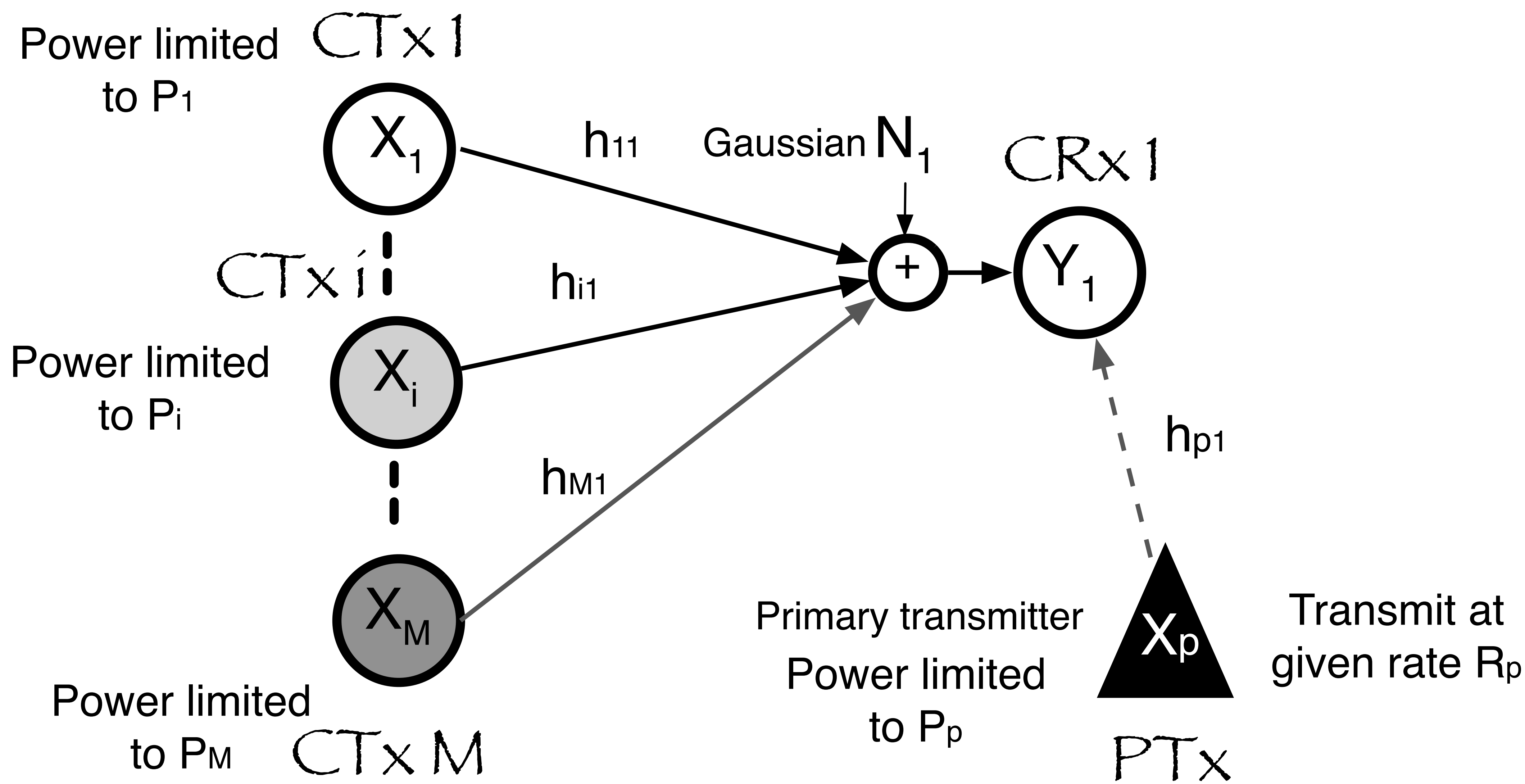
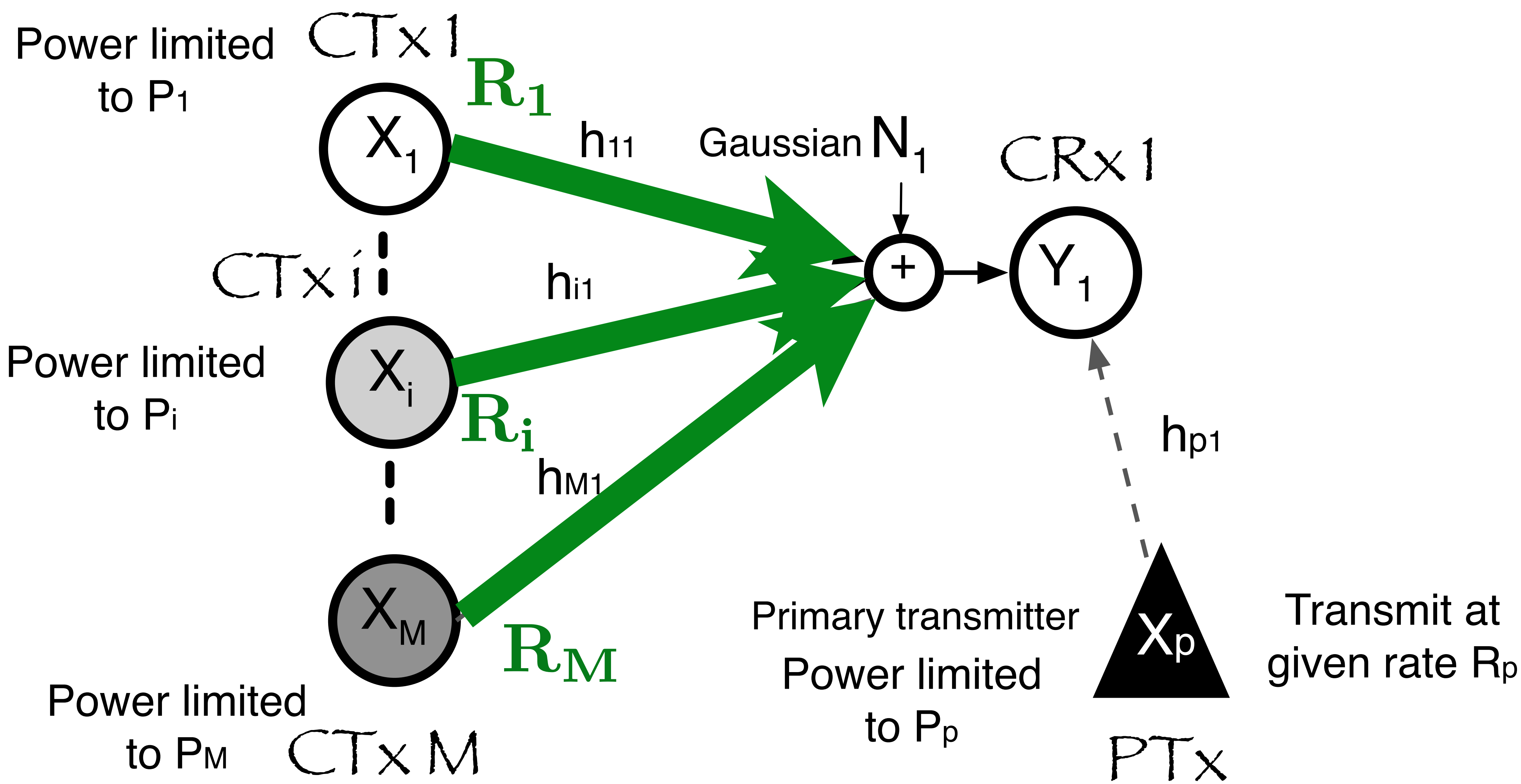
- **Channel knowledge assumption:** CTxs and CRxs assumed to know quasi-static channel gains h_{ij}

Multiple Access Channel with OIC

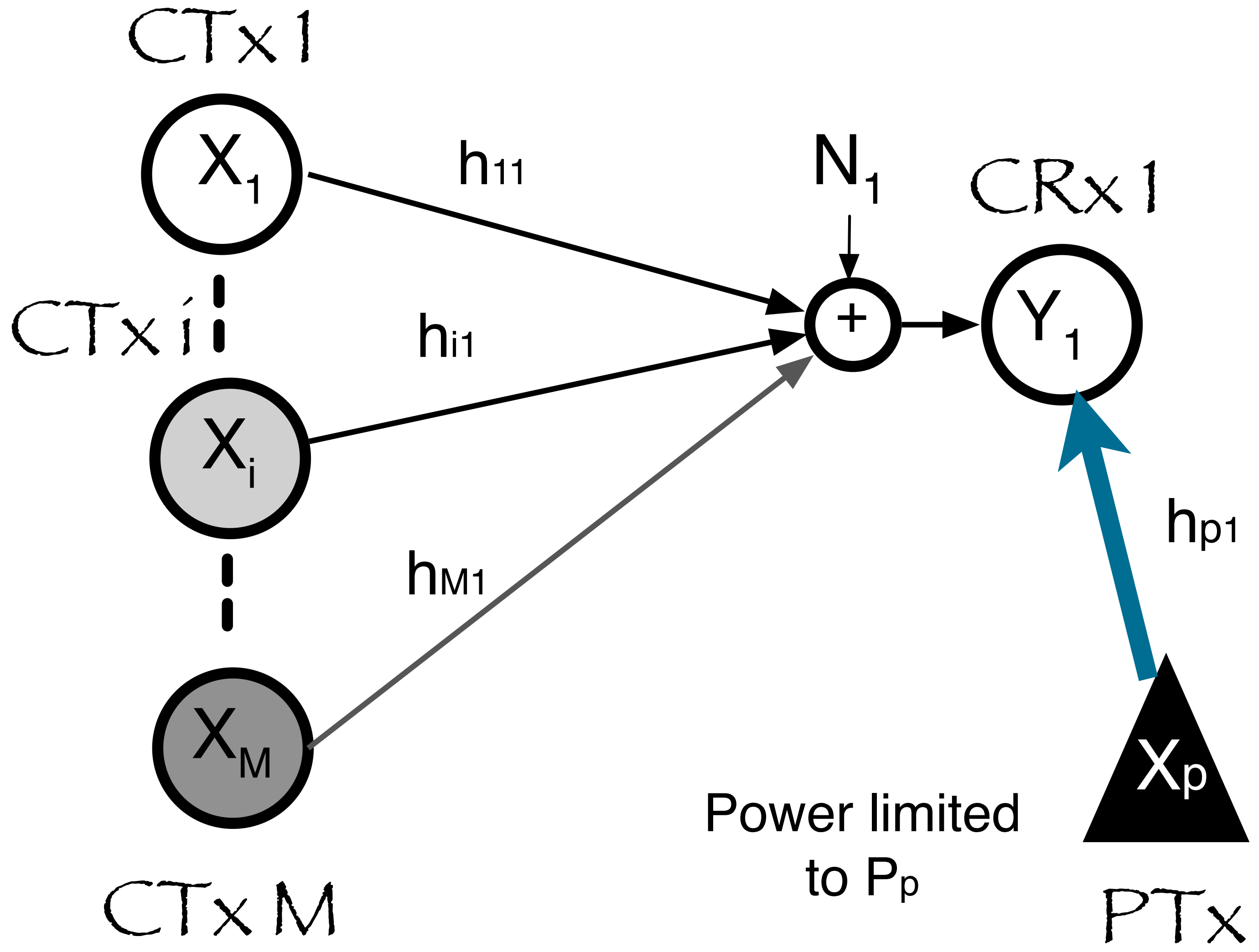


Multiple Access Channel with OIC



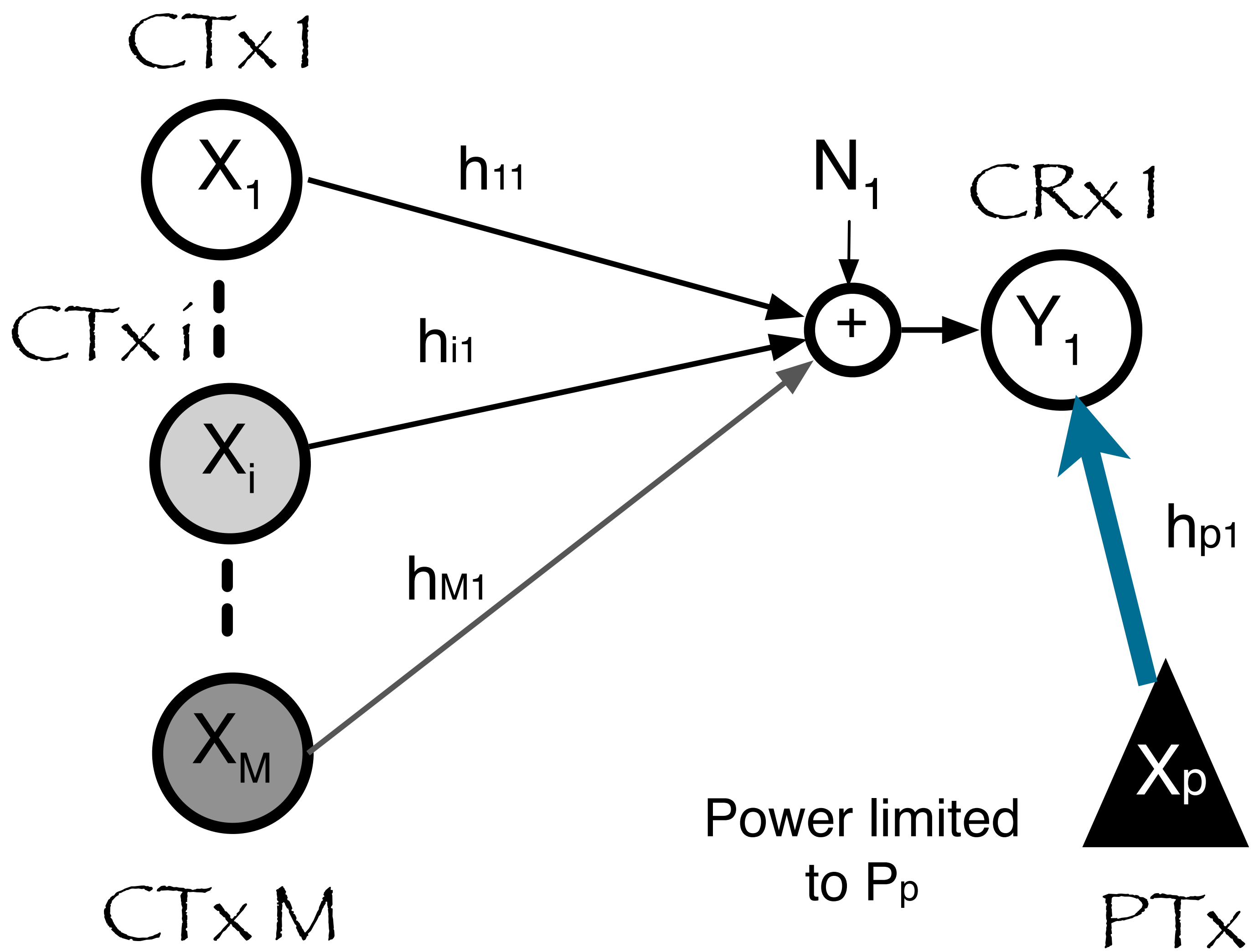
What secondary rates can we achieve?

Multiple Access Channel with OIC



$$\gamma_{p1} = |h_{p1}|^2 P_p$$

Multiple Access Channel with OIC



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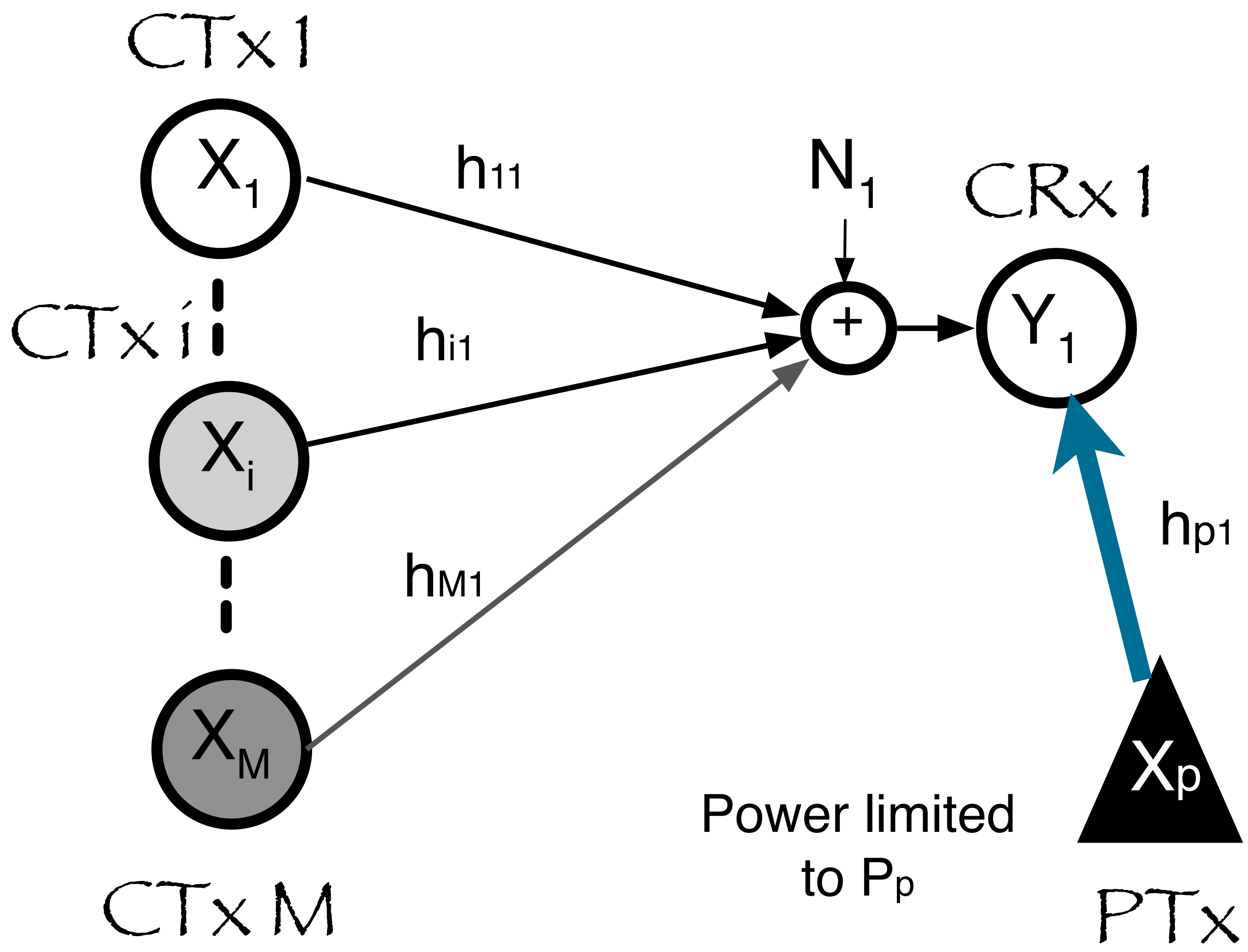
Primary rate set to R_p^*

Multiple Access Channel with OIC



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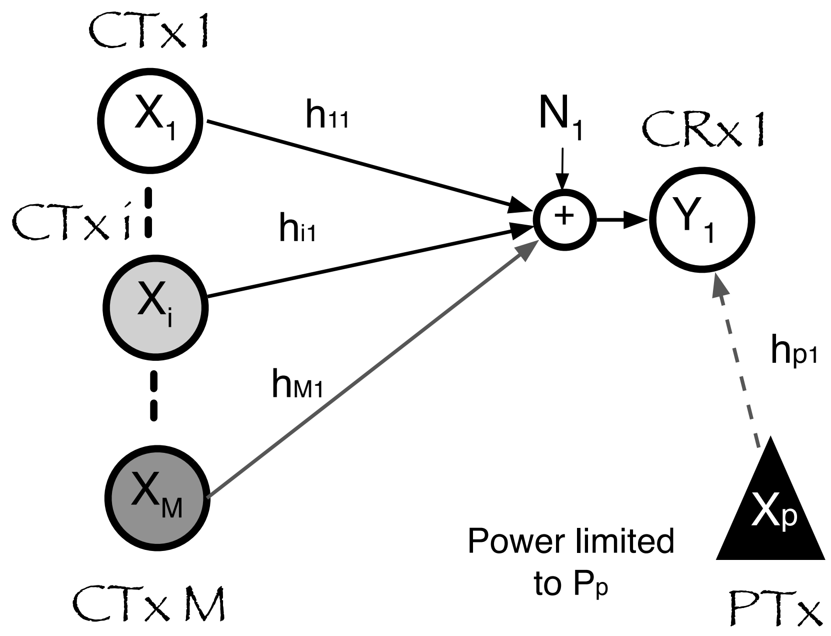
Relative values of γ_{p1} and R_p^* will allow/prevent OIC

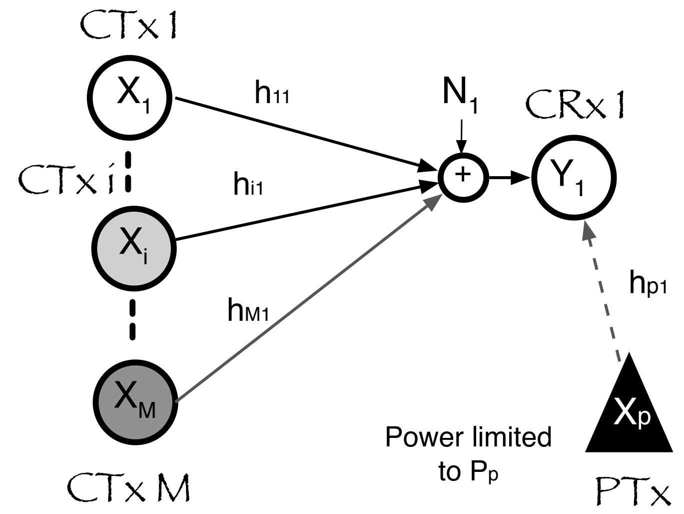
Multiple access channel with OIC



- divide into cases: decode PTx message at or not
- for each case, obtain region as M+1 user MAC channel with FIXED R_p^*
- take union over power constraints

$$P_{MAC} = \{(P_1, P_2, \cdots, P_M) \text{ such that } |h_{1p}|^2 P_1 + |h_{2p}|^2 P_2 + \cdots + |h_{Mp}|^2 P_M \leq I_{margin}\}.$$

(FAST)



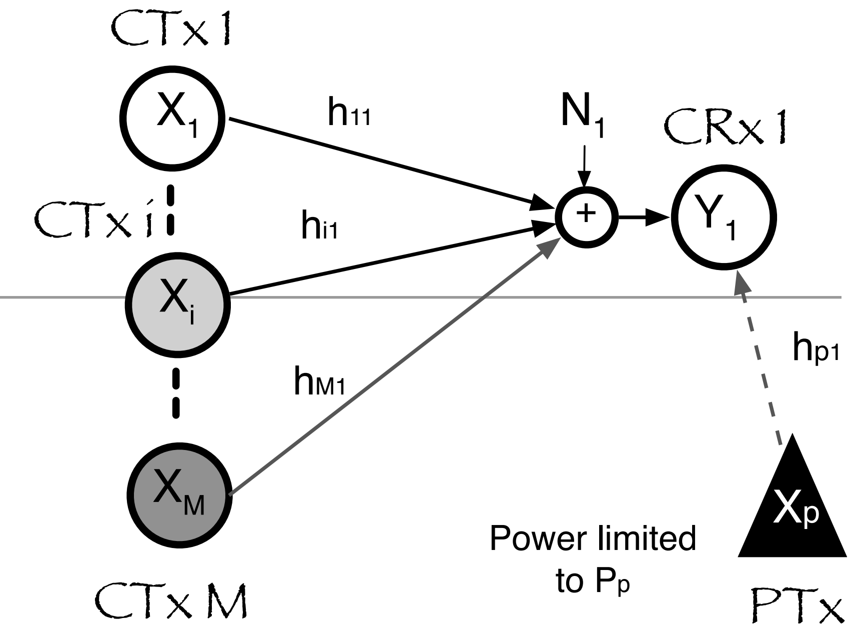
For a given R_p^*, γ_{p1}, an achievable rate region $\mathcal{R}_{MAC}$ is given by the convex hull of the union over all $\mathbf{P} = (P_1, P_2, \cdots, P_M) \in \mathcal{P}_{MAC}$ of the regions $\mathcal{R}(\mathbf{P}) = (R_1, R_2, \cdots, R_p)$ such that if $R_p^* \geq C(\gamma_{p1})$, the primary signal is treated as noise, resulting in the region:

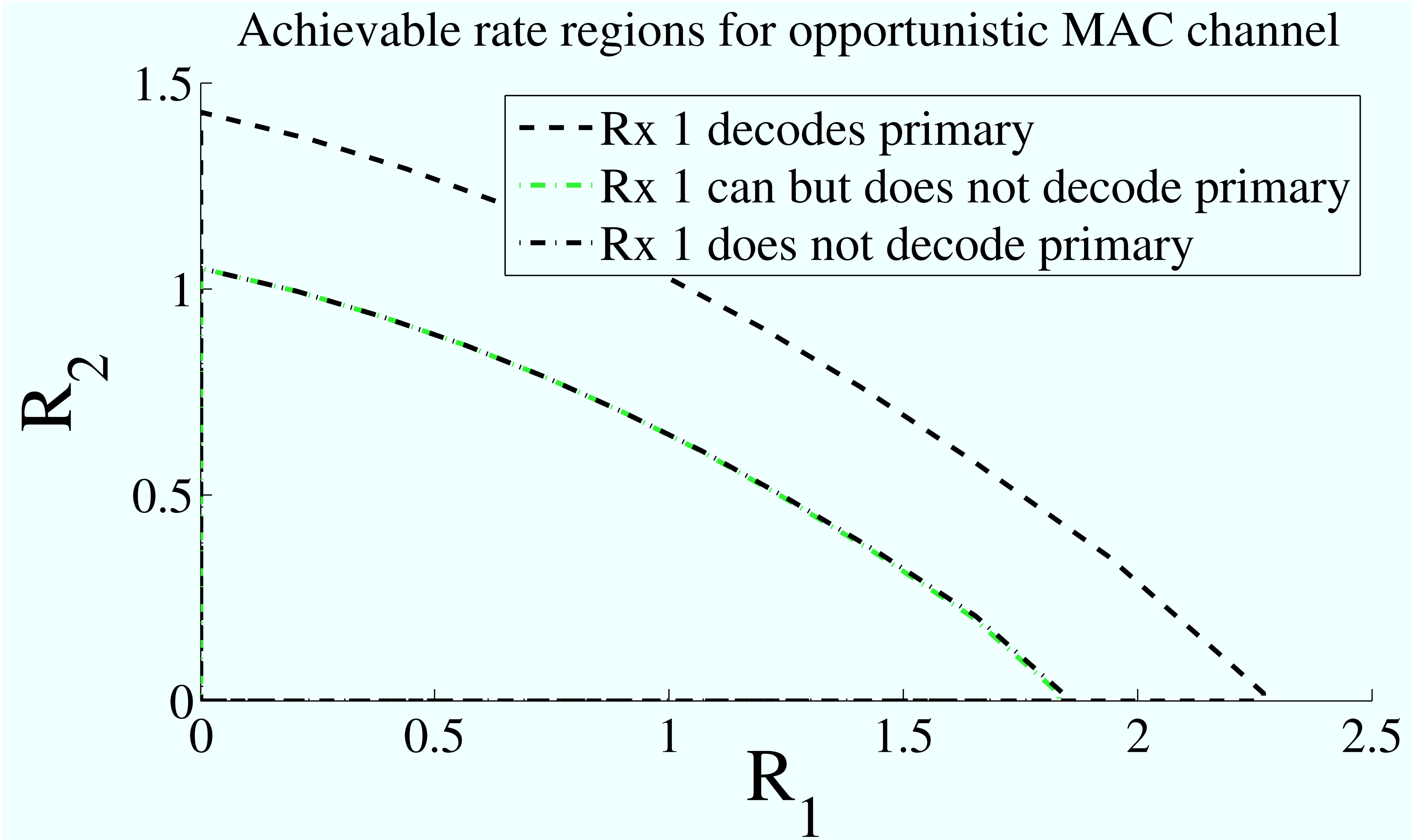
$$\bigcap_{T \subset \{1,2,\cdots M\}} \left(\sum_{t \in T} R_t \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}}),$$

and if $R_p^* < C(\gamma_{p1})$ then the primary signal may be decoded at CRx 1, resulting in the region

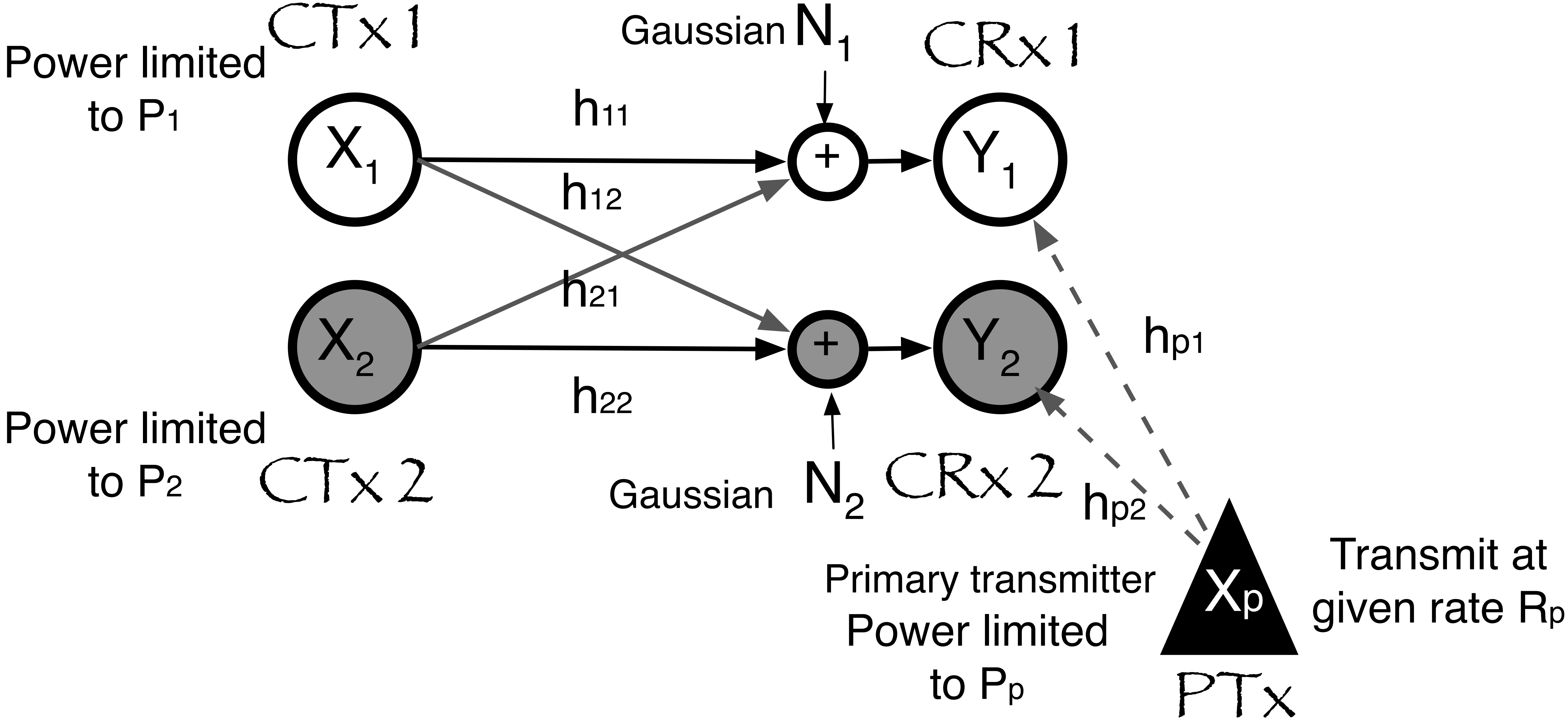
$$\bigcap_{\substack{T \subset \{1,2,\cdots M,p\} \\ T \neq \{p\}}} \left(\sum_{t \in T} R_t \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}}), \quad \text{where } R_p = R_p^*.$$

Multiple access channel with OIC

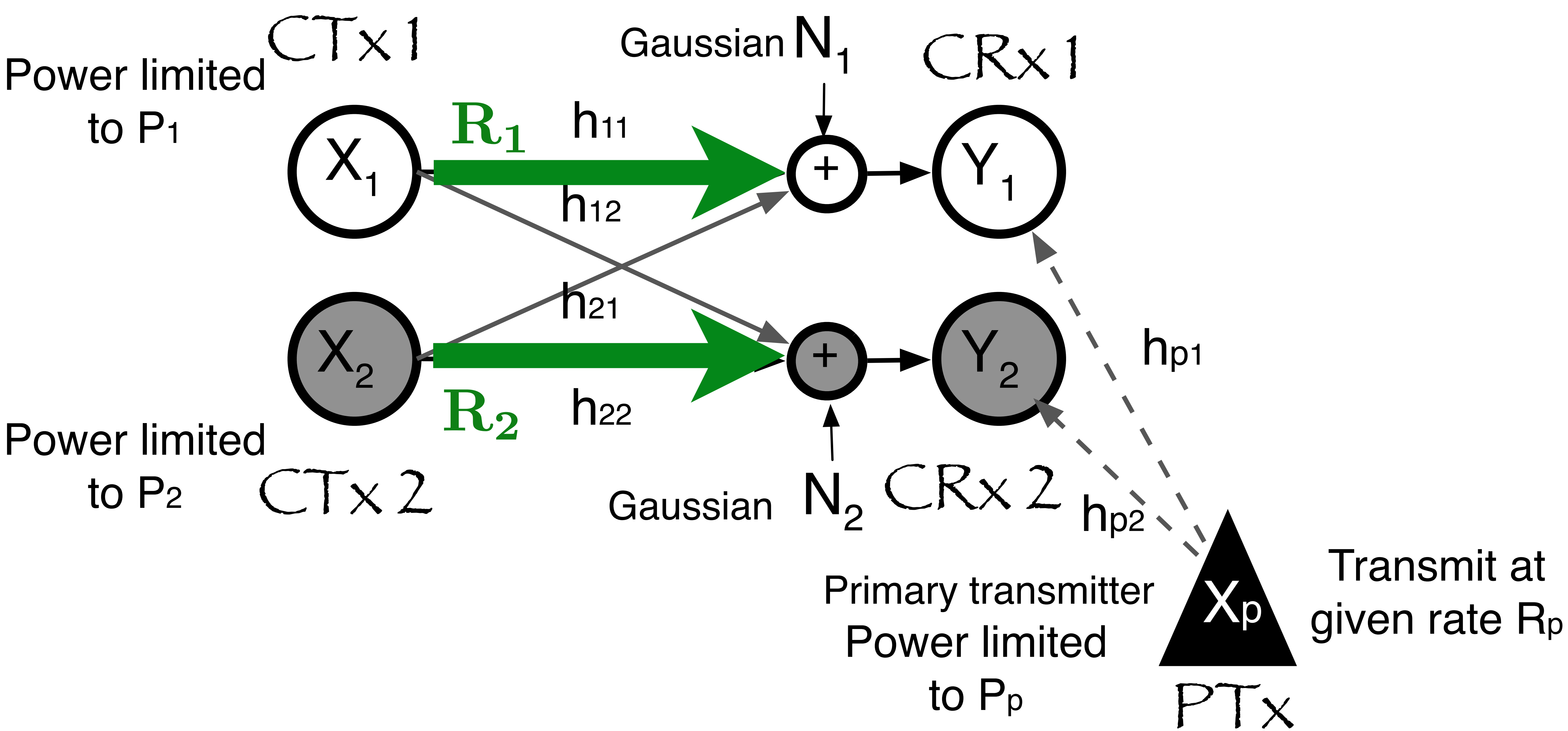




Interference channel with OIC



Interference channel with OIC



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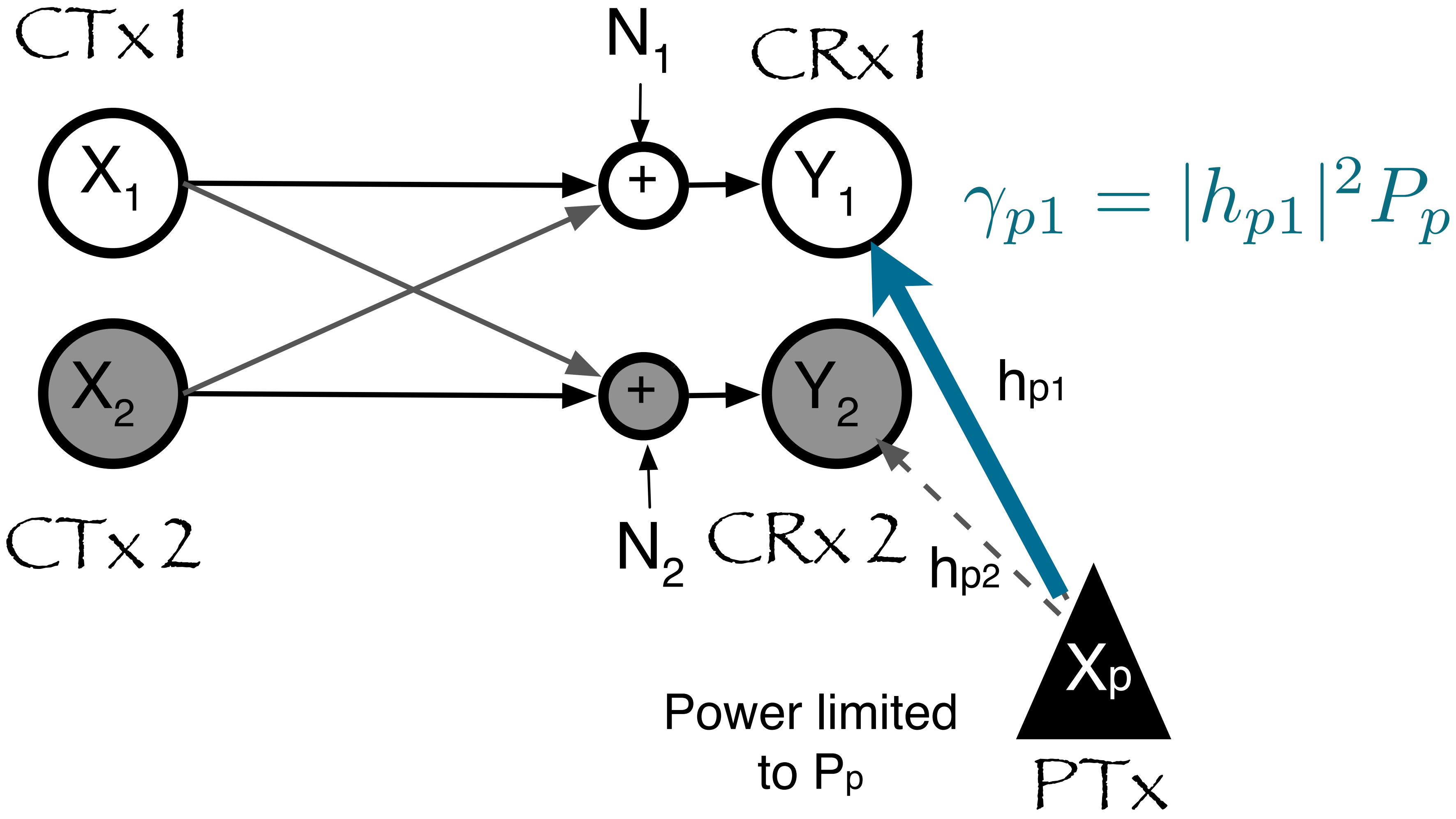
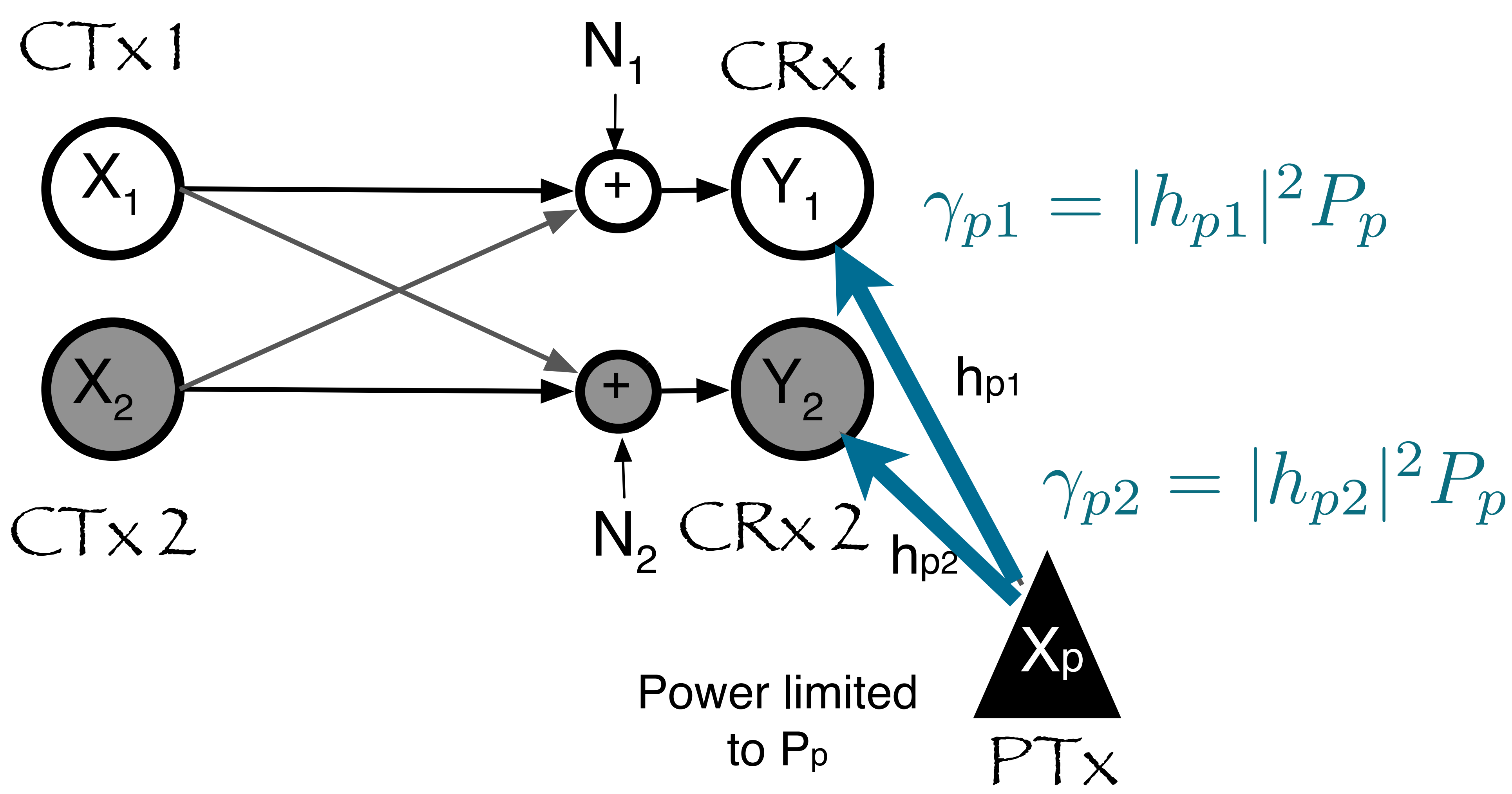
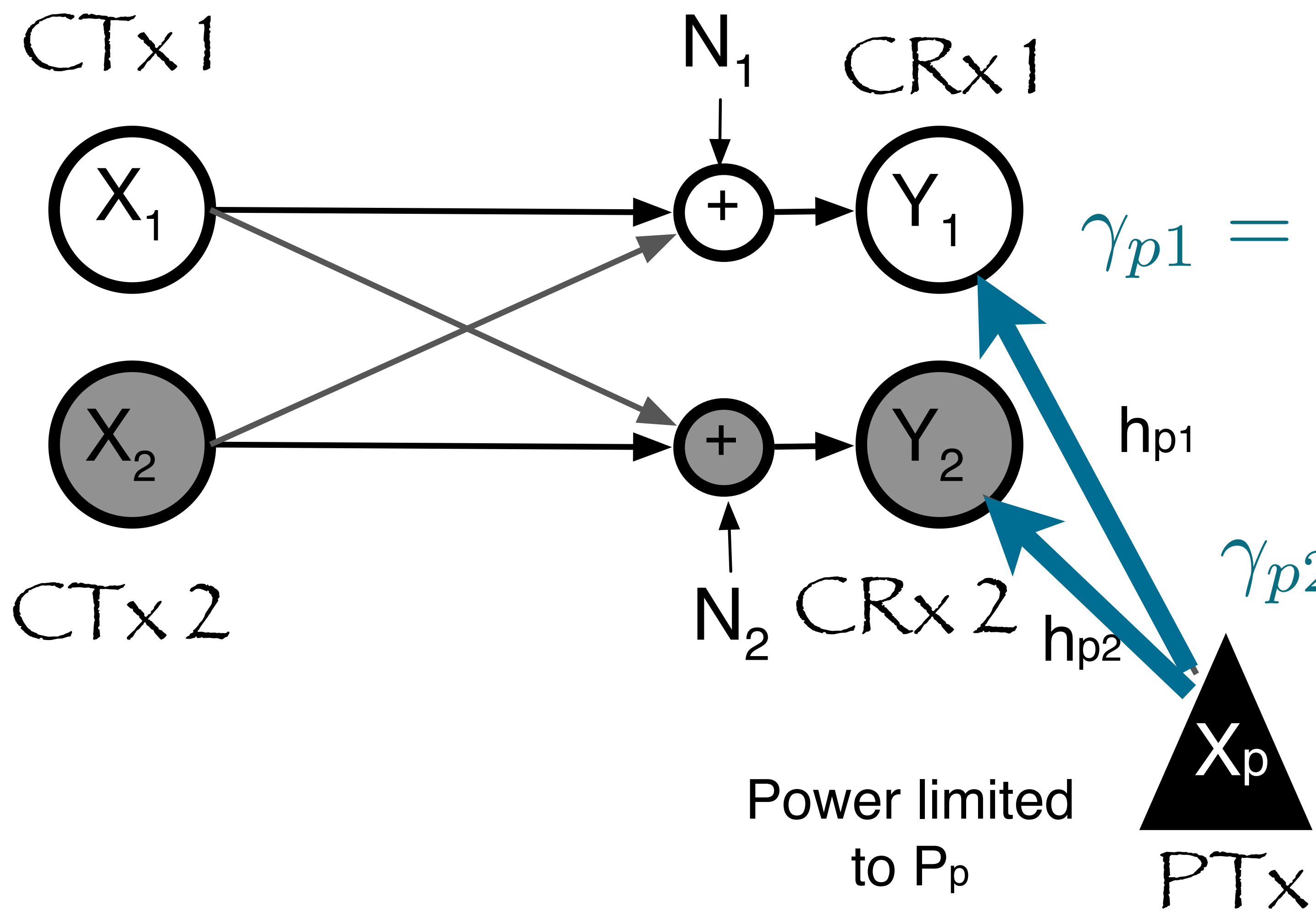
Interference channel with OIC



Interference channel with OIC



Interference channel with OIC

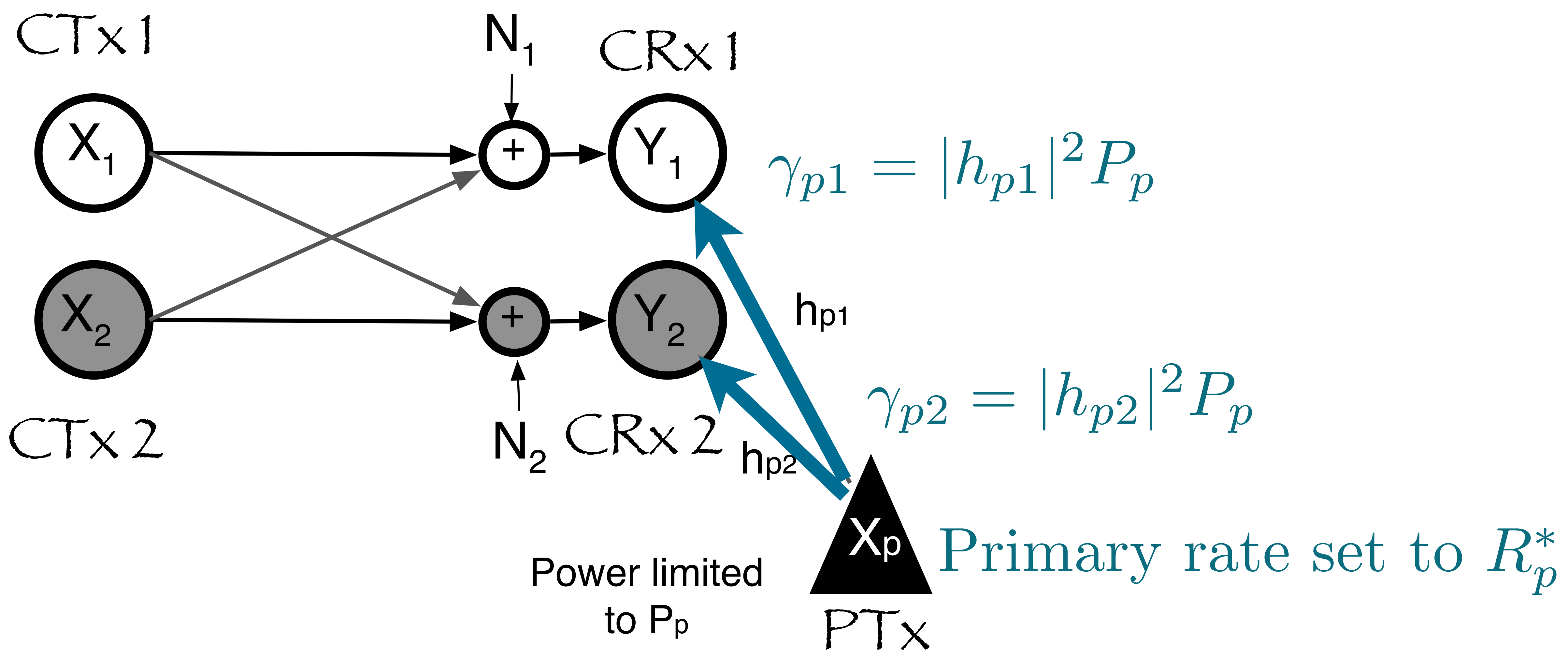


$\gamma_{p1} = |h_{p1}|^2 P_p$

$\gamma_{p2} = |h_{p2}|^2 P_p$

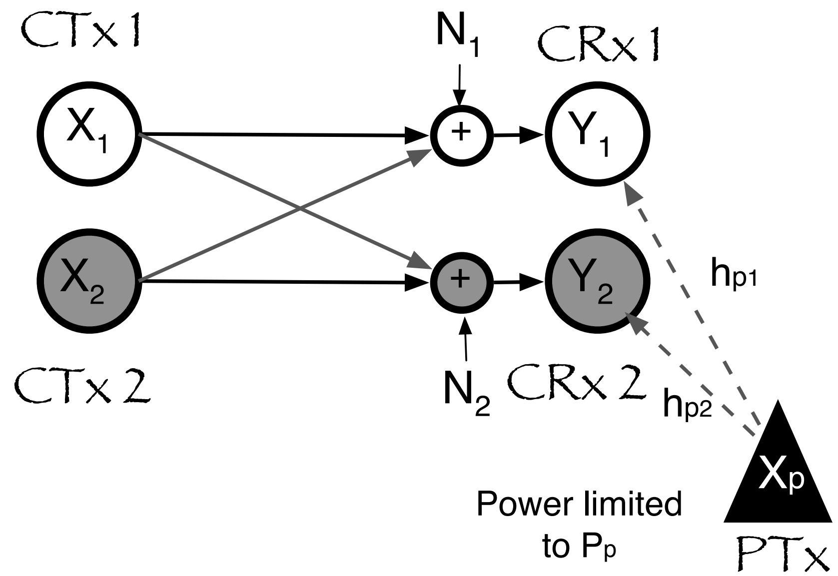
Primary rate set to R_p^*

Interference channel with OIC



Relative values of $\gamma_{p1}, \gamma_{p2}, R_p^*$ will allow/prevent OIC

Interference channel with OIC



- divide into cases: decode PTx message at one, both or neither CRx
- for each case, obtain region as known achievable rate region (3 user extension of Han + Kobayashi region for interference channel) with FIXED R_p^*
- take union over power constraints

$$P_{INT} = \left\{(P_1, P_2) \text{ such that } |h_{1p}|^2 P_1 + |h_{2p}|^2 P_2 \leq I_{margin}\right\}.$$

For a given R_p^*, γ_{p1} and γ_{p2}, an achievable rate region $\mathcal{R}_{INT}$ is given by the convex hull of the union over all $\mathbf{P} = (P_1, P_2) \in \mathcal{P}_{INT}$ of the regions $\mathcal{R}(\mathbf{P}) = (R_1 = R_{11} + R_{12}, R_2 = R_{21} + R_{22})$ such that:

1. If $R_p^* \geq \max(C(\gamma_{p1}), C(\gamma_{p2}))$ then the primary signal is treated as noise at both CRxs, with resulting region:

$$\bigcap_{T \subset T_1} \left(\sum_{t_1 \in T} R_{t_1} \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}}),$$

$$\bigcap_{T \subset T_2} \left(\sum_{t_2 \in T} R_{t_2} \right) \leq I(Y_2; \mathbf{X_T} | \mathbf{X_{\overline{T}}}).$$

2. If $C(\gamma_{p2}) < R_p^* < C(\gamma_{p1})$, then CRx 1 can decode the primary, while CRx 2 cannot, with resulting region:

$$\bigcap_{T \subset T_1^p, T \neq \{p\}} \left(\sum_{t_1 \in T} R_{t_1} \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}}), \text{ for } R_p = R_p^*$$
$$\bigcap_{T \subset T_2} \left(\sum_{t_2 \in T} R_{t_2} \right) \leq I(Y_2; \mathbf{X_T} | \mathbf{X_{\overline{T}}}).$$

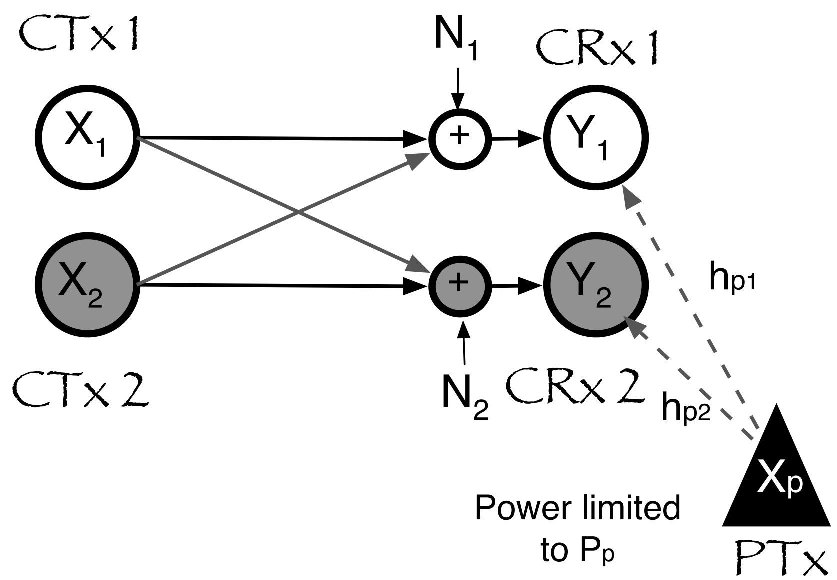
3. If $C(\gamma_{p1}) < R_p^* < C(\gamma_{p2})$, then CRx 2 can decode the primary, while CRx 1 cannot, with resulting region:

$$\bigcap_{T \subset T_1} \left(\sum_{t_1 \in T} R_{t_1} \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}})$$
$$\bigcap_{T \subset T_2^p, T \neq \{p\}} \left(\sum_{t_2 \in T} R_{t_2} \right) \leq I(Y_2; \mathbf{X_T} | \mathbf{X_{\overline{T}}}), \text{ for } R_p = R_p^*.$$

4. If $R_p^* < C(\gamma_{p1})$ and $R_p^* < C(\gamma_{p2})$ then both CRxs can decode the primary message, resulting in the region:

$$\bigcap_{T \subset T_1^p, T \neq \{p\}} \left(\sum_{t_1 \in T} R_{t_1} \right) \leq I(Y_1; \mathbf{X_T} | \mathbf{X_{\overline{T}}}), \text{ for } R_p = R_p^*$$

$$\bigcap_{T \subset T_2^p, T \neq \{p\}} \left(\sum_{t_2 \in T} R_{t_2} \right) \leq I(Y_2; \mathbf{X_T} | \mathbf{X_{\overline{T}}}), \text{ for } R_p = R_p^*.$$



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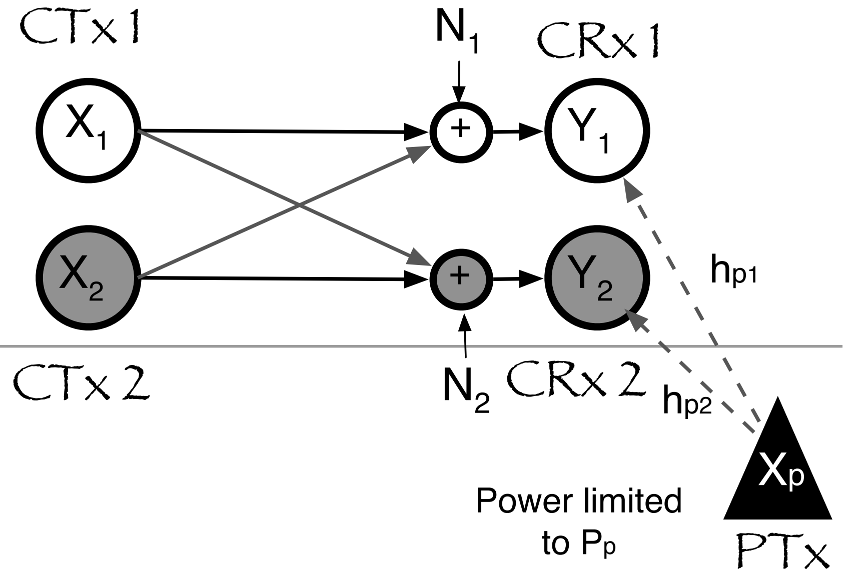
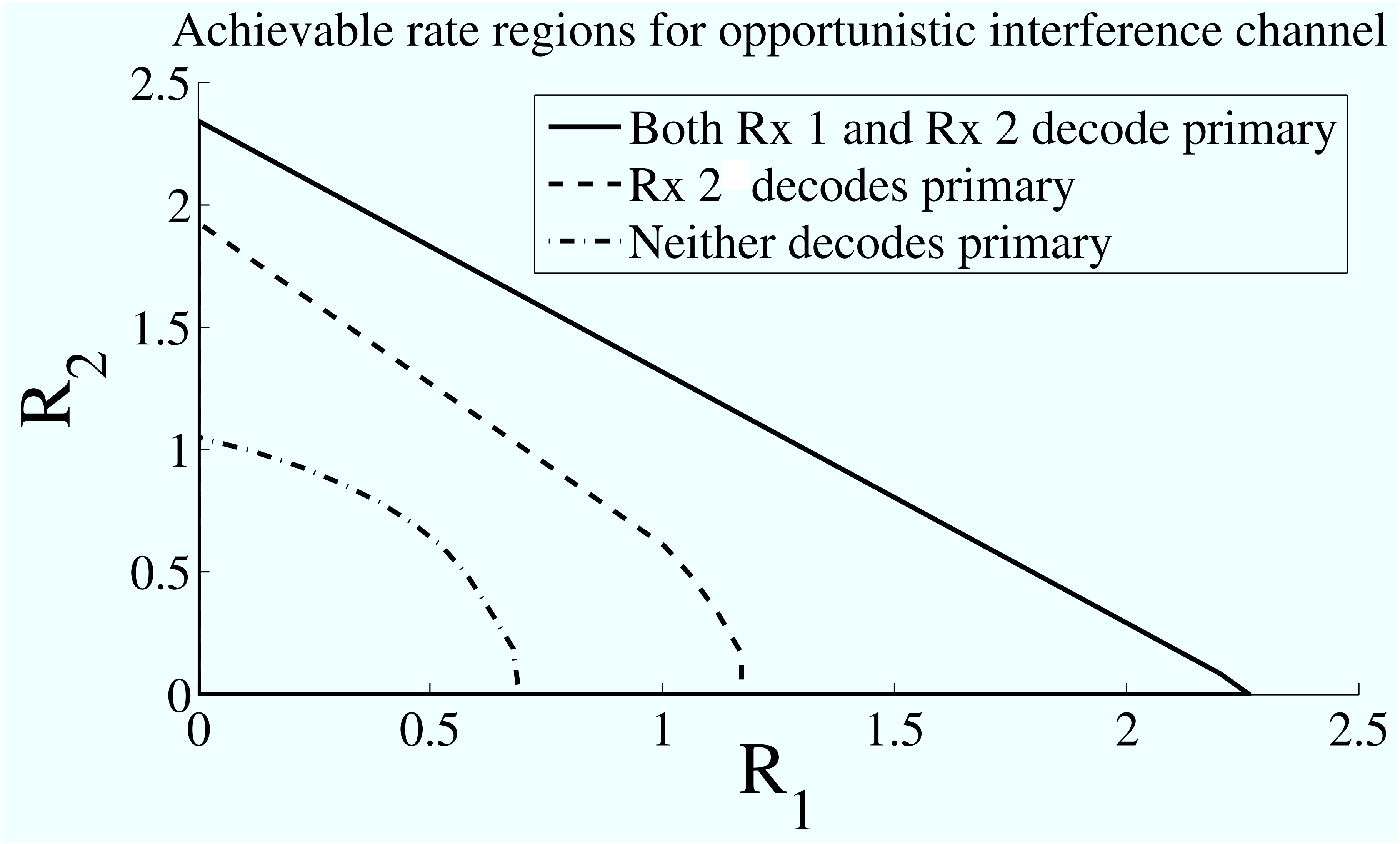
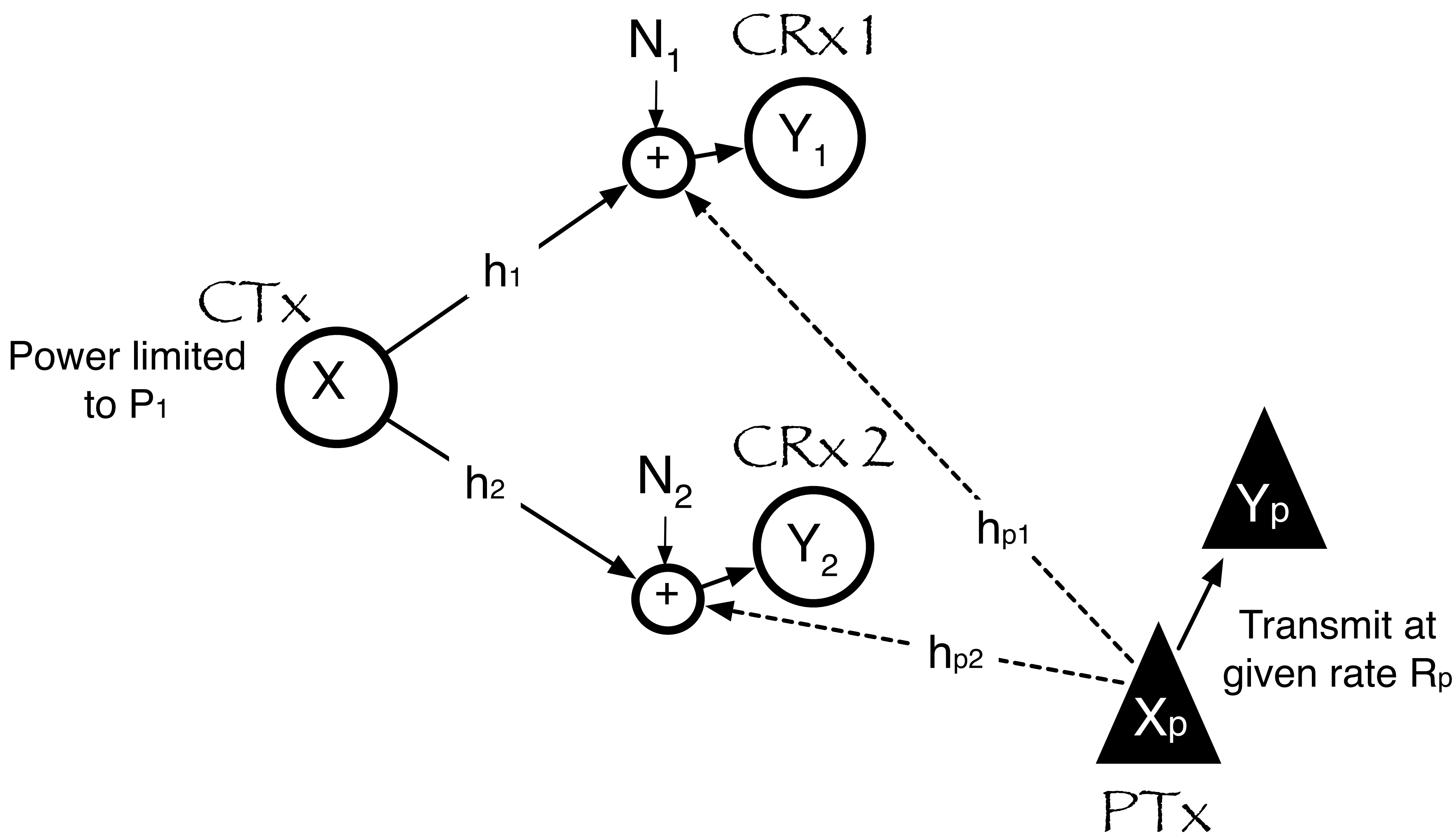
Interference channel with OIC





Broadcast Channel with OIC



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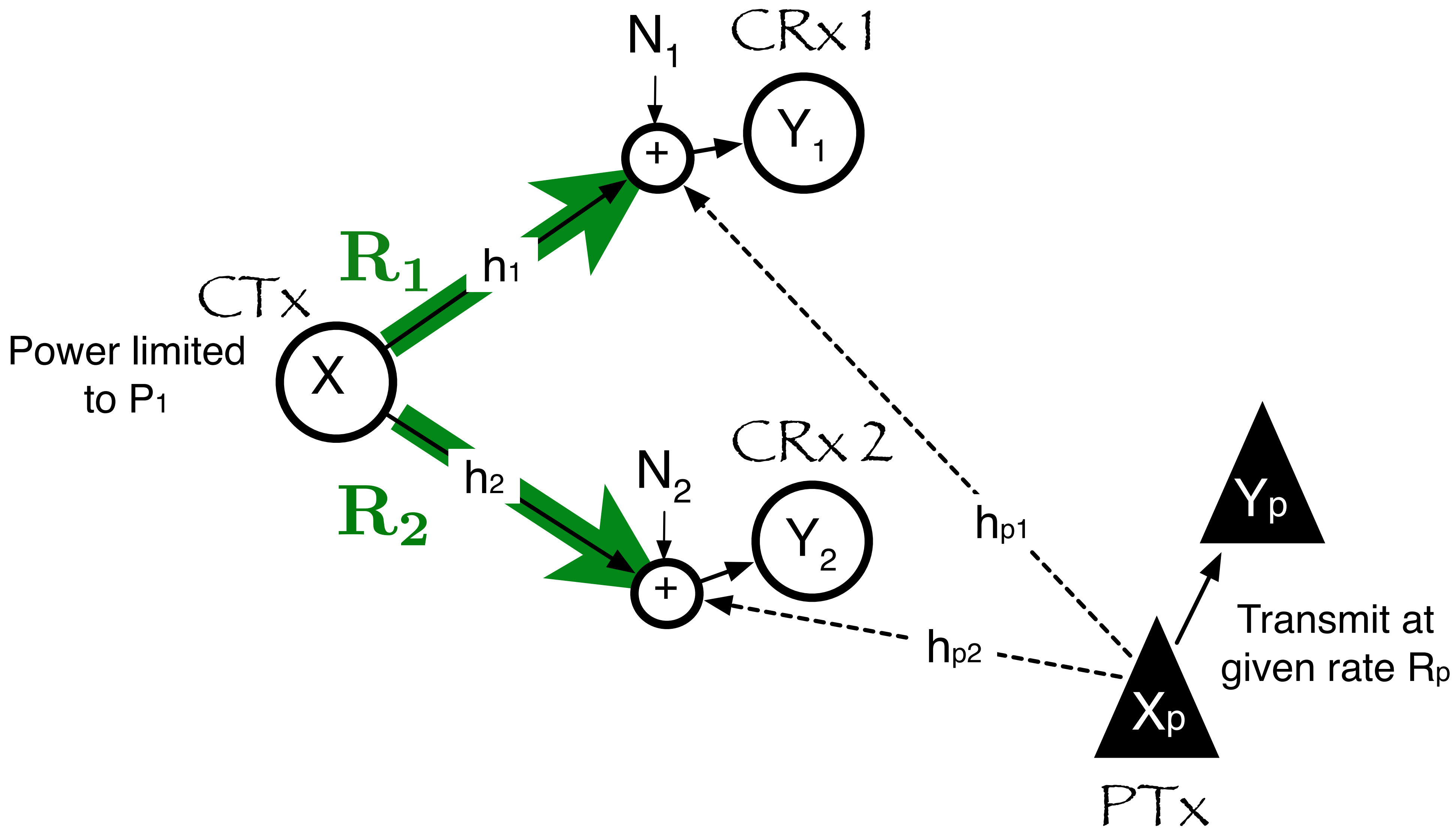

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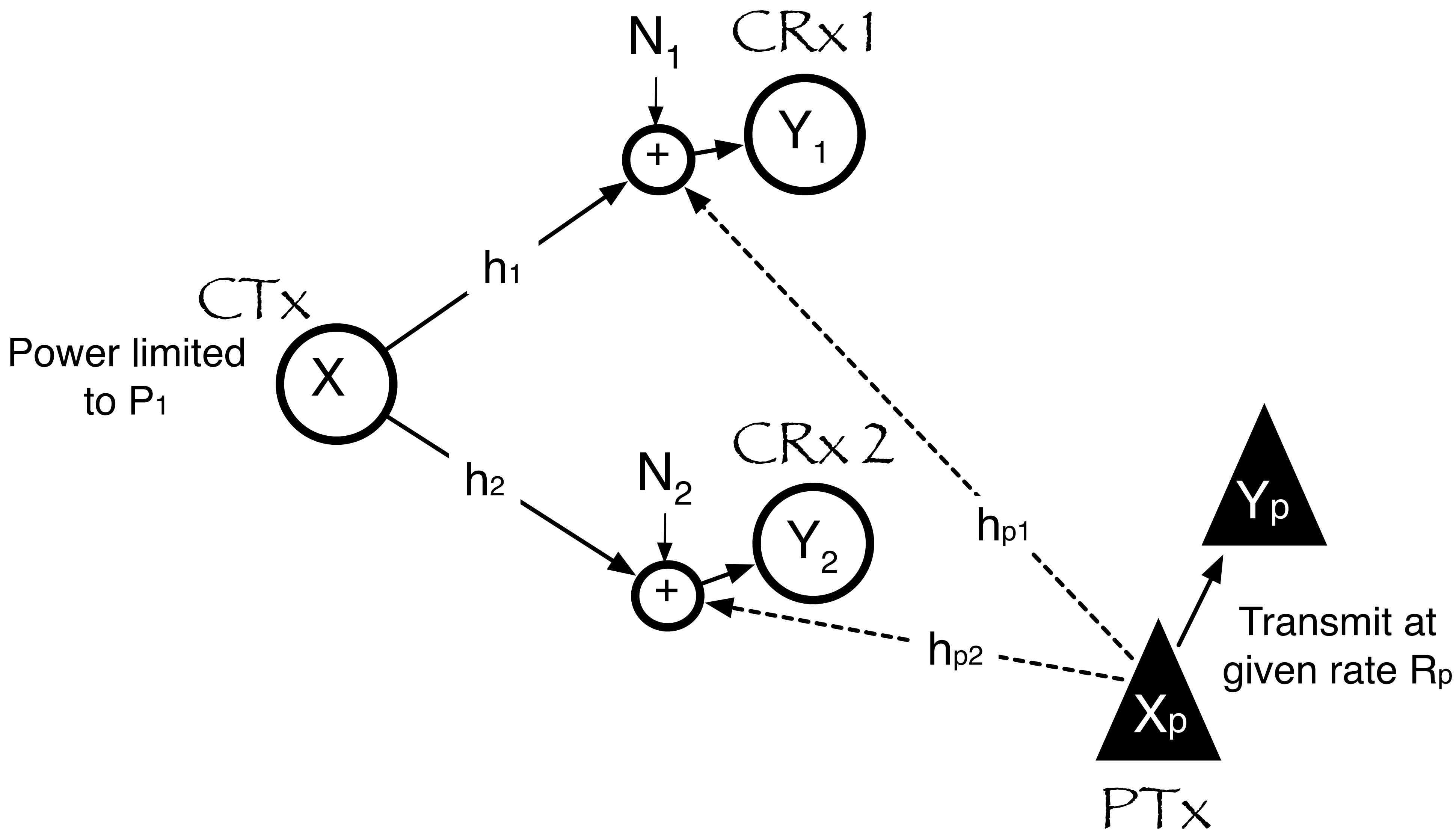
Broadcast Channel with OIC



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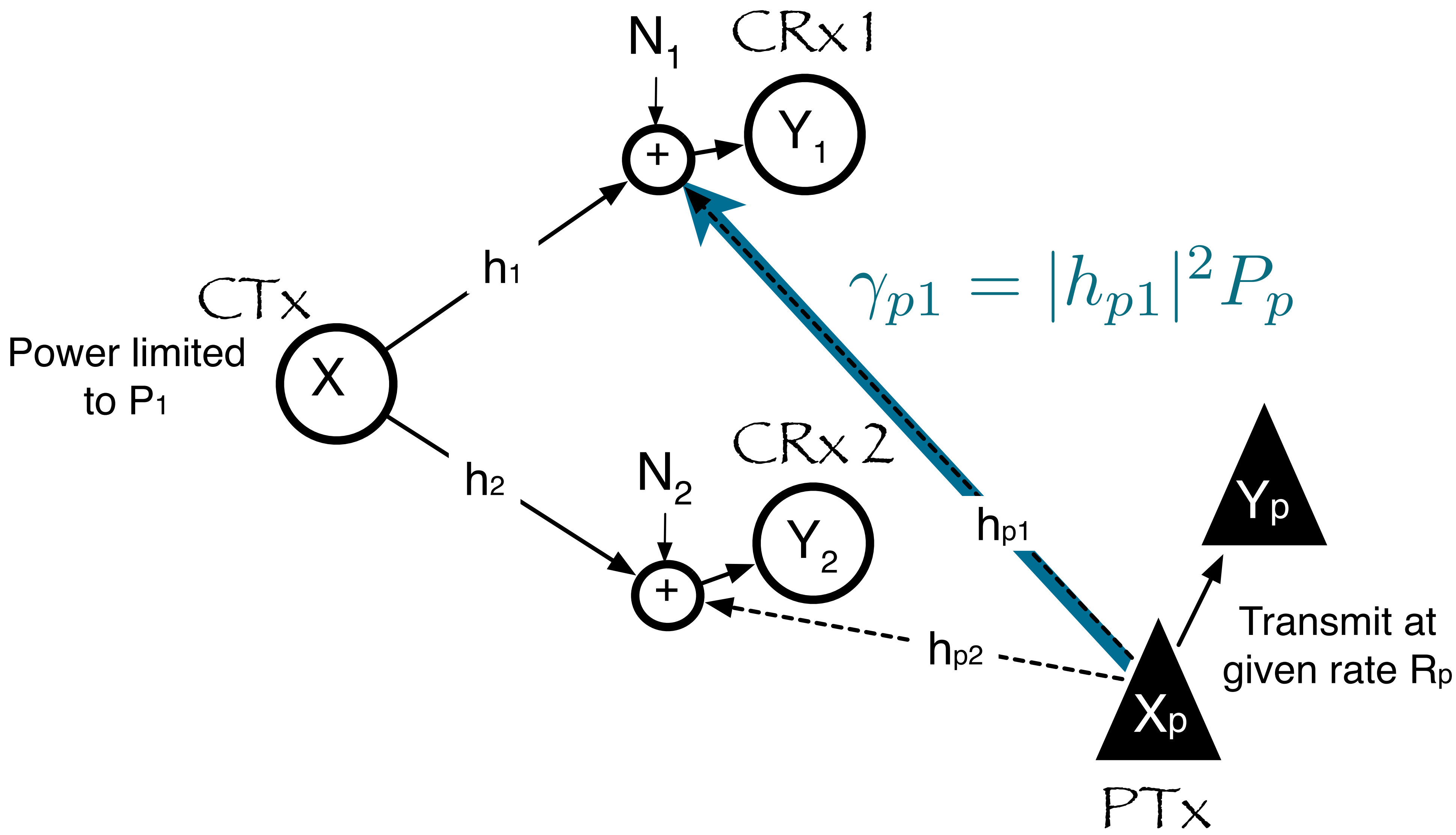
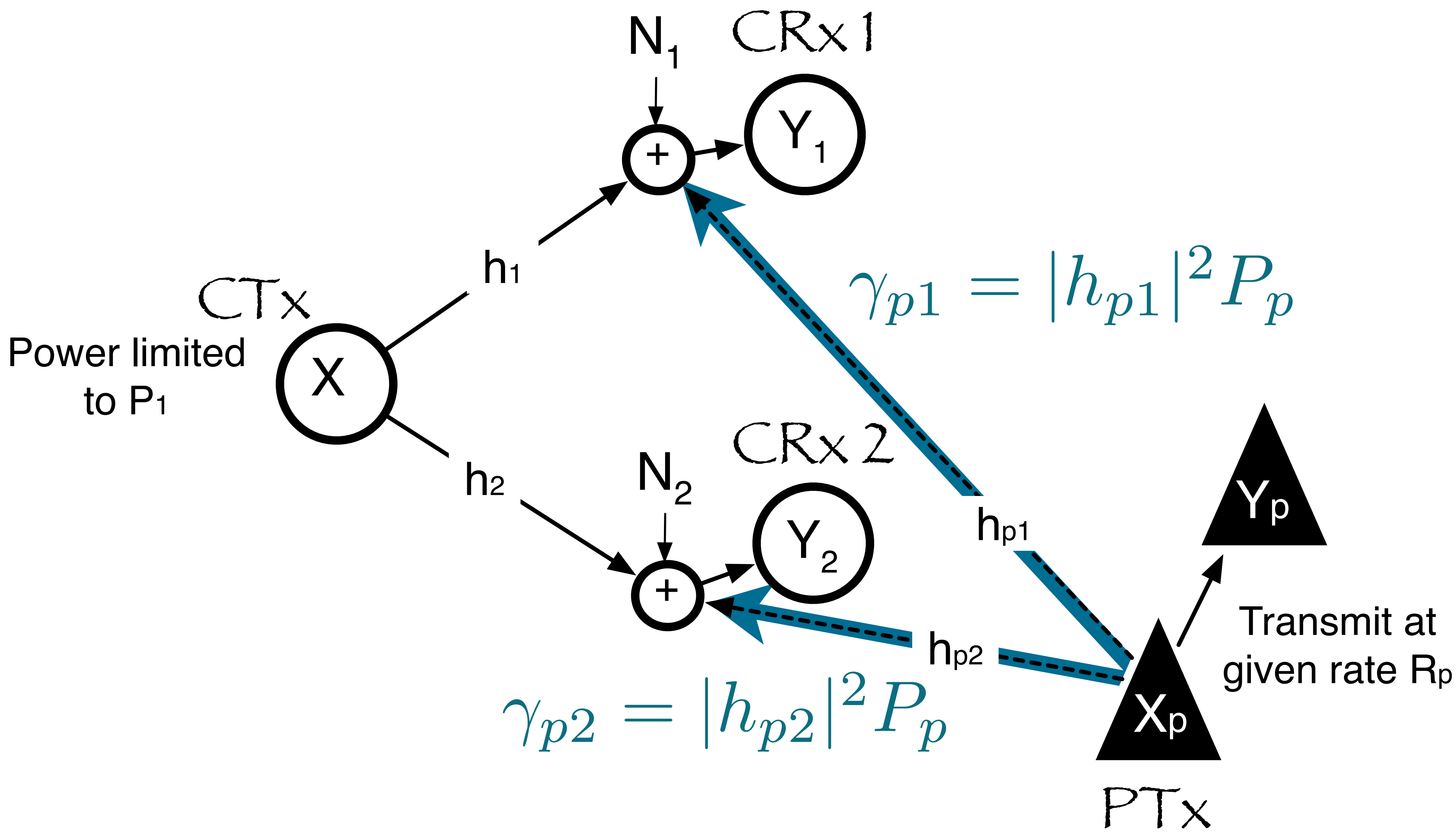


Broadcast Channel with OIC



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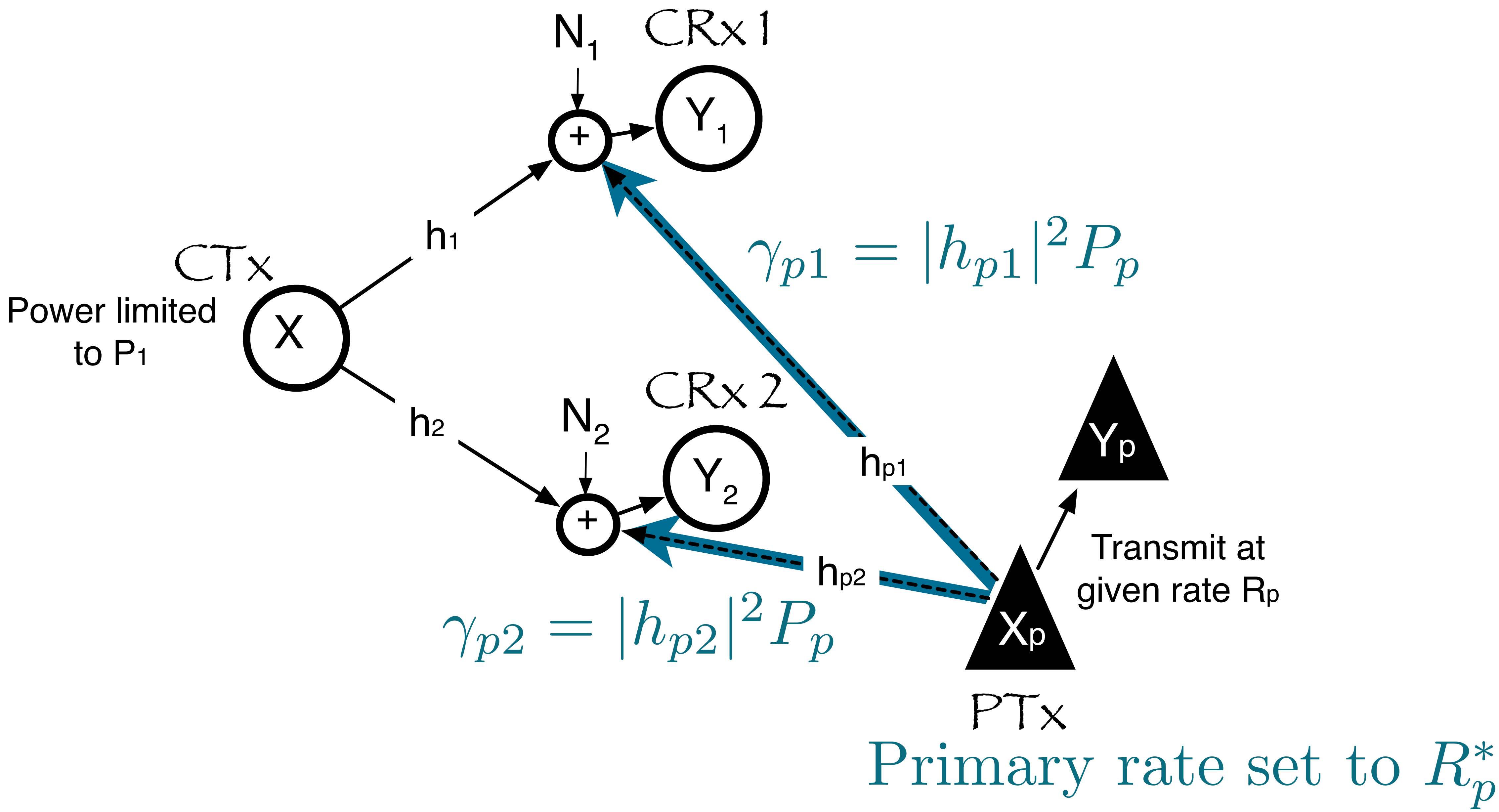

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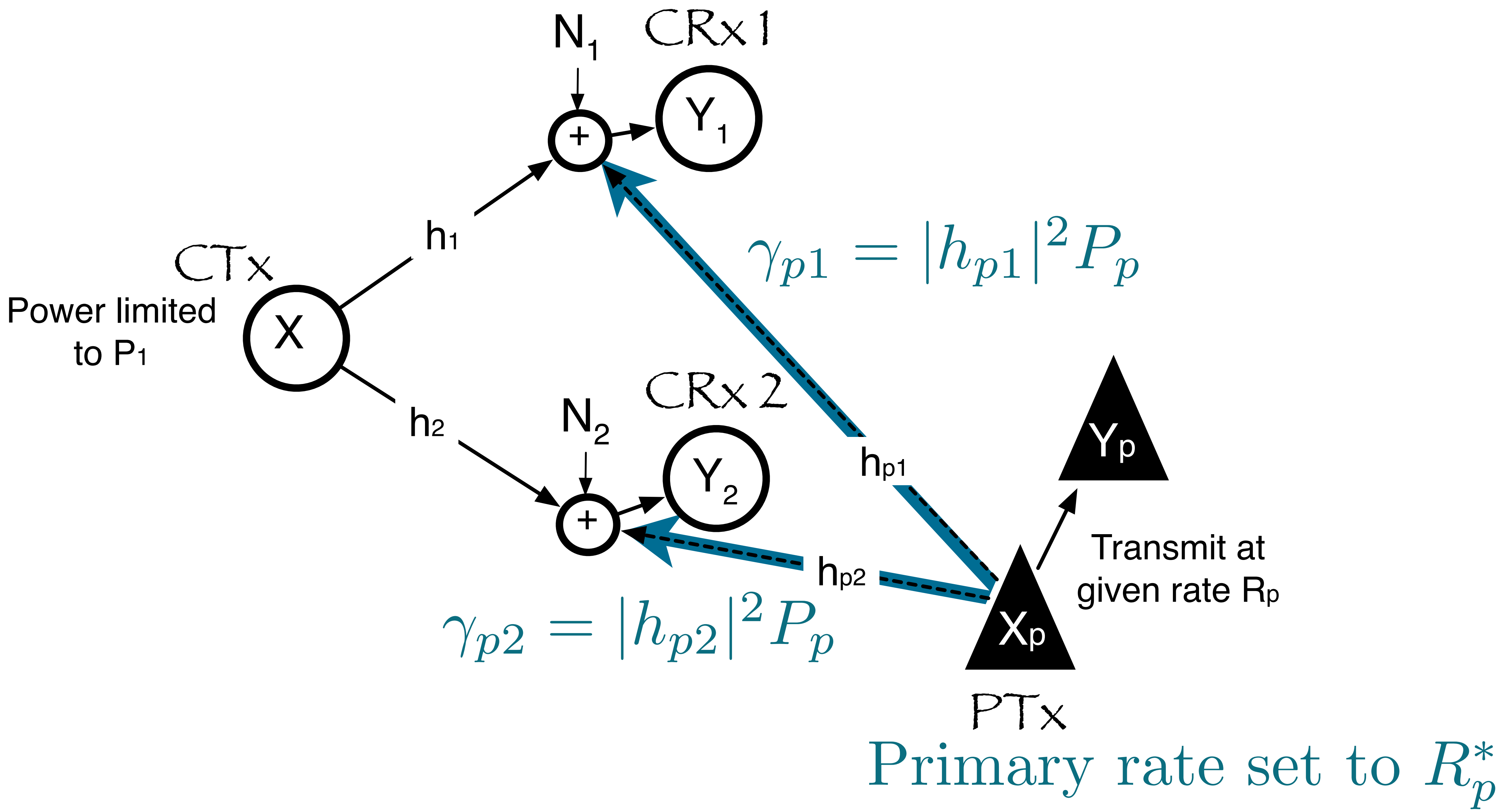
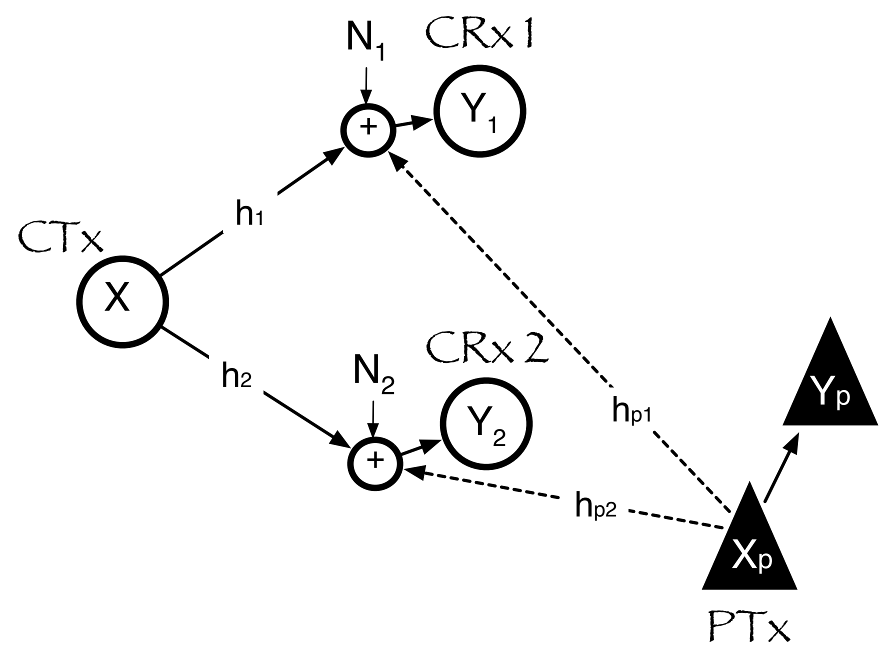


Relative values of $\gamma_{p1}, \gamma_{p2}, R_p^*$ will allow/prevent OIC

Broadcast channel with OIC



- divide into cases: decode PTx message at one, both or neither CRx
- for each case, obtain region as known achievable rate region (adjusted Marton's region) with FIXED R_p^*

For a given primary rate $R_p = R_p^*$, and given γ_{p1} and γ_{p2}, an achievable rate region $\mathcal{R}_{BC}$ is given by the convex hull of the union over all distributions $p(u,v,x) = p(u,v)p(x|u,v)$ of the regions $\mathcal{R}(\mathbf{P}) = \{(R_1, R_2)\}$ such that:

1. If $R_p^* \geq I(X_p;Y_1|X)$ and $R_p^* \geq I(X_p;Y_2|X)$ then the primary signal is treated as noise at both Rxs:

$$R_1 \leq I(U;Y_1) \qquad R_2 \leq I(V;Y_2)$$
$$R_1 + R_2 \leq I(U;Y_1) + I(V;Y_2) - I(U;V)$$

2. If $I(X_p;Y_2|X) < R_p^* < I(X_p;Y_1|X)$, then CRx 1 can decode the primary, while CRx 2 cannot:

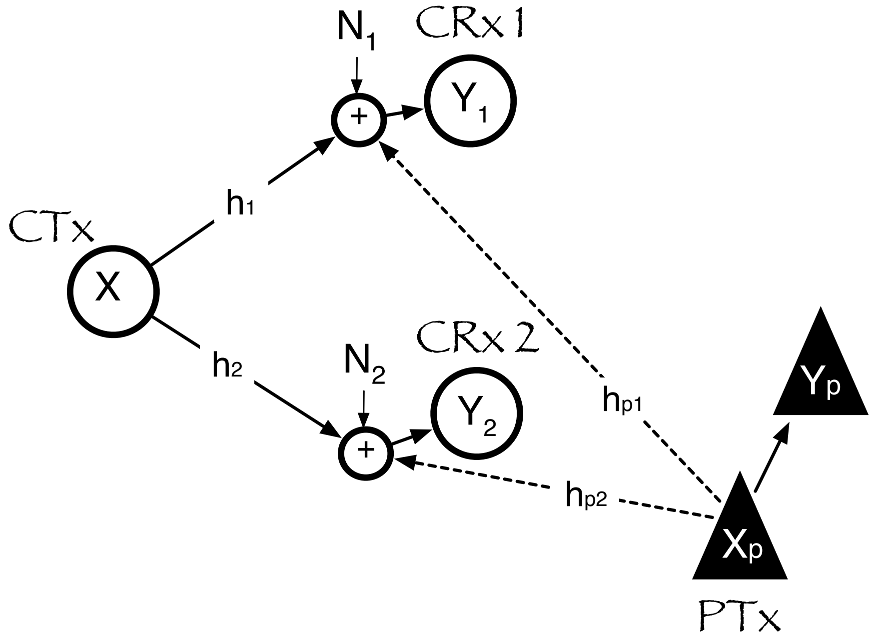
$$\begin{aligned} R_1 &\leq \min(I(U;Y_1|X_p), I(U,X_p;Y_1) - R_p^*) \\ R_2 &\leq I(V;Y_2) \\ R_1 + R_2 &\leq \min(I(U;Y_1|X_p), I(U,X_p;Y_1) - R_p^*) \\ &\quad + I(V;Y_2) - I(U;V) \end{aligned}$$

3. If $I(X_p;Y_1|X) < R_p^* < I(X_p;Y_2|X)$, then CRx 2 can decode the primary, while CRx 1 cannot:

$$\begin{aligned} R_1 &\leq I(U;Y_1) \\ R_2 &\leq \min(I(V;Y_2|X_p), I(V,X_p;Y_2) - R_p^*) \\ R_1 + R_2 &\leq \min(I(V;Y_2|X_p), I(V,X_p;Y_2) - R_p^*) \\ &\quad + I(U;Y_1) - I(U;V) \end{aligned}$$

4. If $R_p^* < I(X_p;Y_1|X)$ and $R_p^* < I(X_p;Y_2|X)$ then both Rxs can decode the primary message:

$$\begin{aligned} R_1 &\leq \min(I(U;Y_1|X_p), I(U,X_p;Y_1) - R_p^*) \\ R_2 &\leq \min(I(V;Y_2|X_p), I(V,X_p;Y_2) - R_p^*) \\ R_1 + R_2 &\leq \min(I(U;Y_1|X_p), I(U,X_p;Y_1) - R_p^*) \\ &+ \min(I(V;Y_2|X_p), I(V,X_p;Y_2) - R_p^*) - I(U;V) \end{aligned}$$



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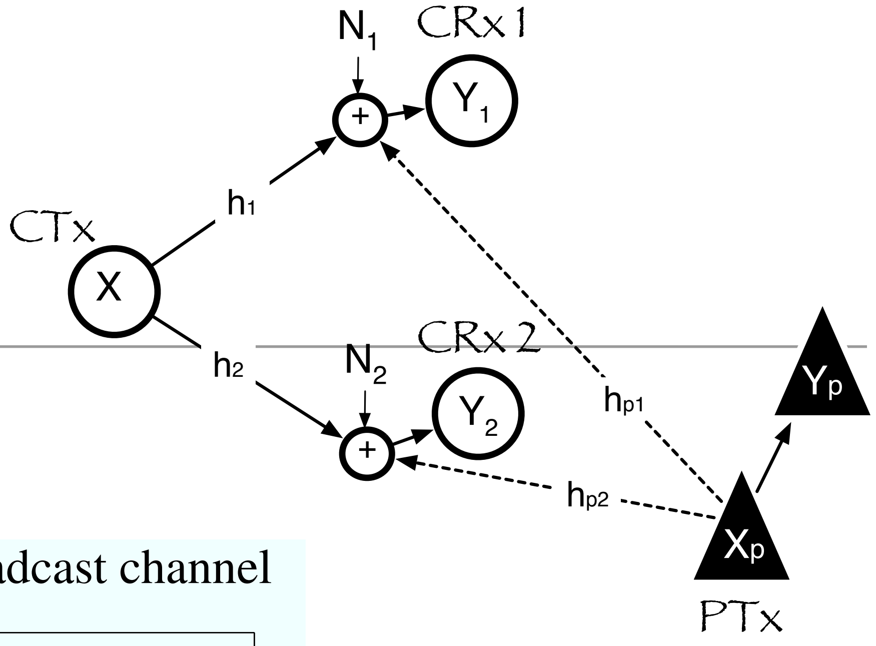
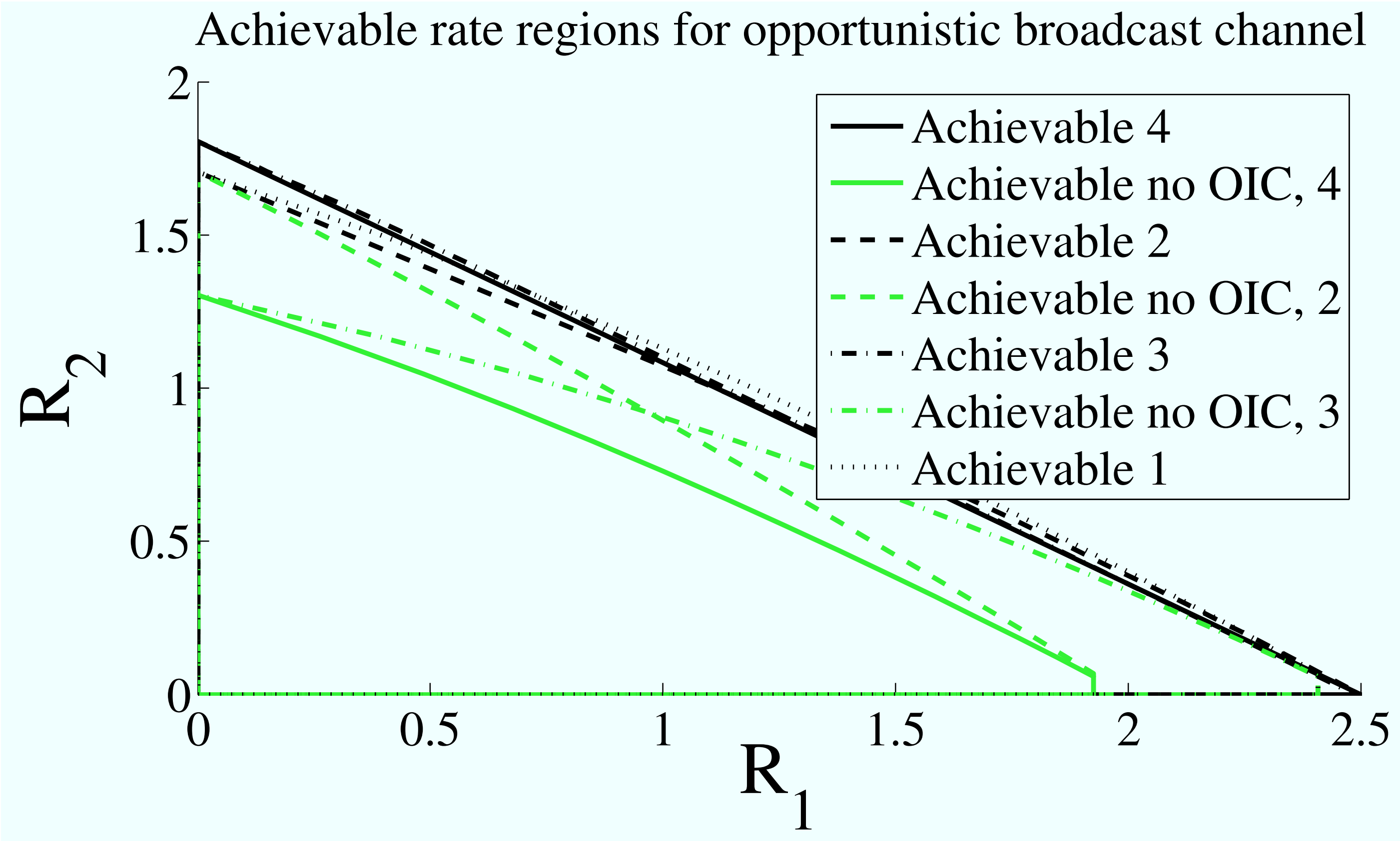
Broadcast Channel with OIC

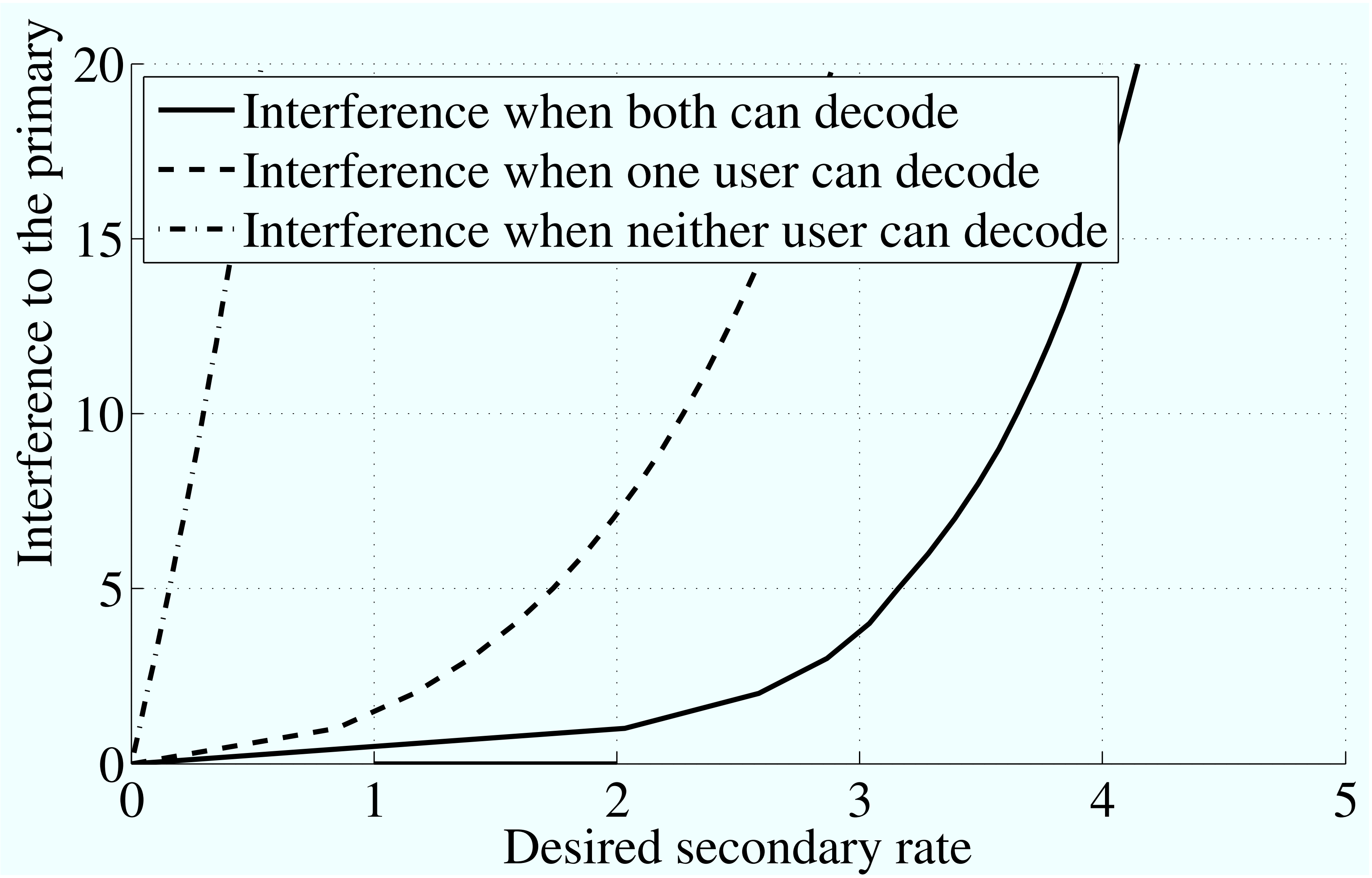




Channel parameters for BC with OIC: For the BC with OIC, we vary the channel to visit the four different OIC scenarios described in Theorem 4. Specifically, let $\gamma_{pi} = |h_{pi}|^2 P_p$ then the parameters used in the four cases of Theorem 4 are: $P = 6$, noise power 1, $R_p = 0.5$, $h_1 = 1, h_2 = 0.7$. Case 1: $\gamma_{p1} = \gamma_{p2} = 0.3$. Case 2: $\gamma_{p1} = 1, \gamma_{p2} = 0.3$. Case 3: $\gamma_{p1} = 0.3, \gamma_{p2} = 1$. Case 4: $\gamma_{p1} = \gamma_{p2} = 1$.

Added benefit of OIC - interference reduction

- for fixed secondary rates, OIC may allow secondary to REDUCE POWER, and thus reduce interference to primary! *(shown for IC with OIC)*



Conclusion

- **Interference margin**
- **Codebook knowledge**
- **Primary remains oblivious to secondary operation**

Cognitive Rxs may **opportunistically decode and cancel primary message**, improving own rates at no cost to primary whatsoever!

Questions?

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