Information-Theoretic Results on D2D Networks

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joint work with S. Bross, G. Kramer, A. Lapidoth, S. Shamai, R. Timo

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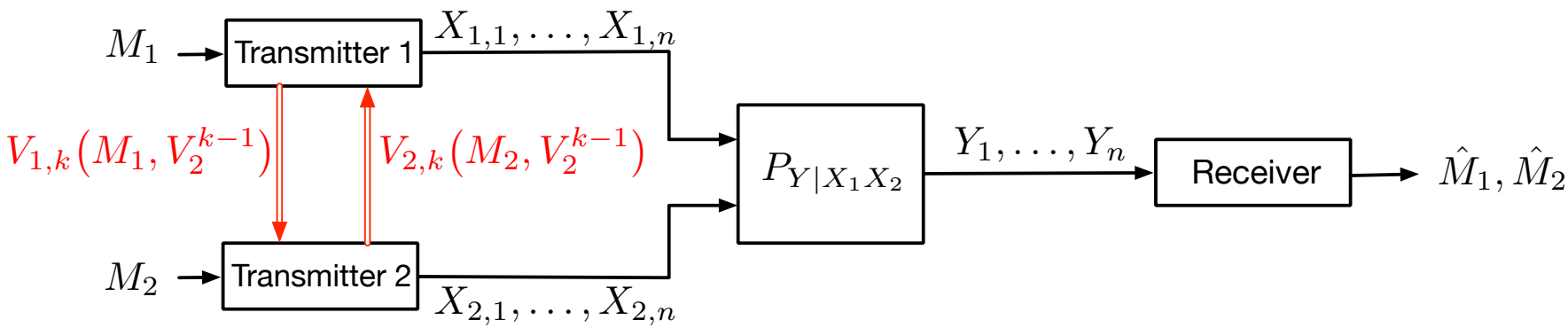
Capacity Region of D2D Networks?

- Block transmission with messages $M_\ell \in \{1, \ldots, 2^{nR_\ell}\}$
- $p(\text{error}) \to 0$ as $n \to \infty$

Which rates $(R_1, \ldots, R_L)$ achievable over a network? Which are not?

- 2 or 3 user multi-access (uplink)
- 2 user broadcast (downlink)
- simple (large) interference networks

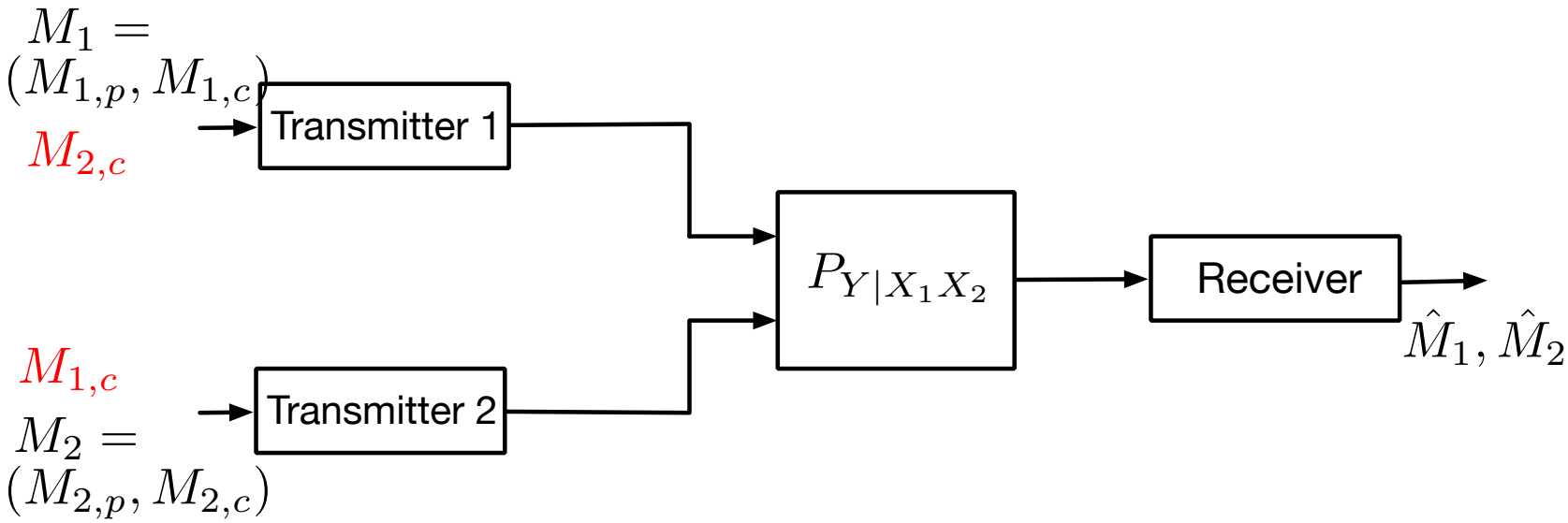
Willems's MAC with D2D Transmitters (Willems'83)



- Interactive communication pipes between transmitters
- Can send $nC_{1,2}$ or $nC_{2,1}$ bits over pipes

Optimal scheme for 2-user MAC with D2D (Willems'83)

- Tx i conveys last $nC_{i,j}$ bits of its message M_i to Tx j



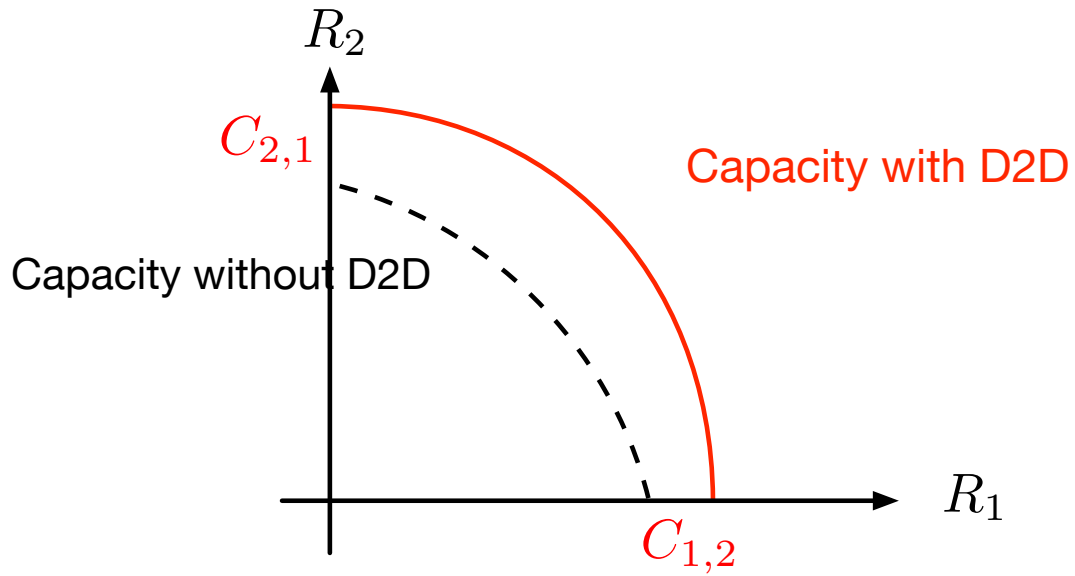
- Send one common message and two individual messages over MAC

- Converse can be established

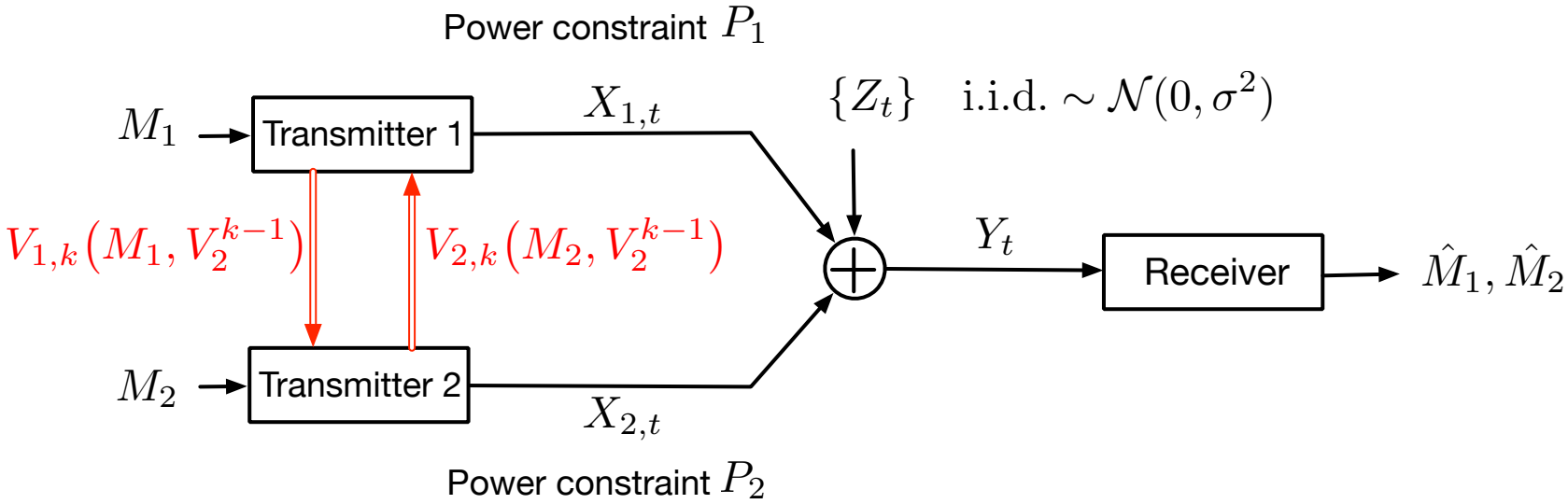
Capacity region for 2-user MAC with D2D (Willems'83)

- Capacity region: all (R_1, R_2) s.t. for some $P_U \cdot P_{X_1|U} \cdot P_{X_2|U} \cdot P_{Y|X_1X_2}$:

$$
\begin{aligned}
R_1 &\leq I(X_1; Y|U, X_2) + C_{1,2} \\
R_2 &\leq I(X_2; Y|U, X_1) + C_{2,1} \\
R_1 + R_1 &\leq I(X_1, X_2; Y|U) + C_{1,2} + C_{2,1} \\
R_1 + R_2 &\leq I(X_1, X_2; Y)
\end{aligned}
$$



Explicit characterization in Gaussian case (Bross,Lapidoth,W'08)



- Capacity region: all (R_1, R_2) s.t. for some $\rho \in [0,1]$:

$$
\begin{aligned}
R_1 &\leq 1/2 \log(1 + P_1(1-\rho)) + C_{1,2} \\
R_2 &\leq 1/2 \log(1 + P_2(1-\rho)) + C_{2,1} + C_{2,1} \\
R_1 + R_1 &\leq 1/2 \log(1 + P_1(1-\rho) + P_2(1-\rho)) C_{1,2} + C_{2,1} \\
R_1 + R_2 &\leq 1/2 \log(1 + P_1 + P_2 + 2\rho\sqrt{P_1 P_2})
\end{aligned}
$$

D2D for 3-user MAC?

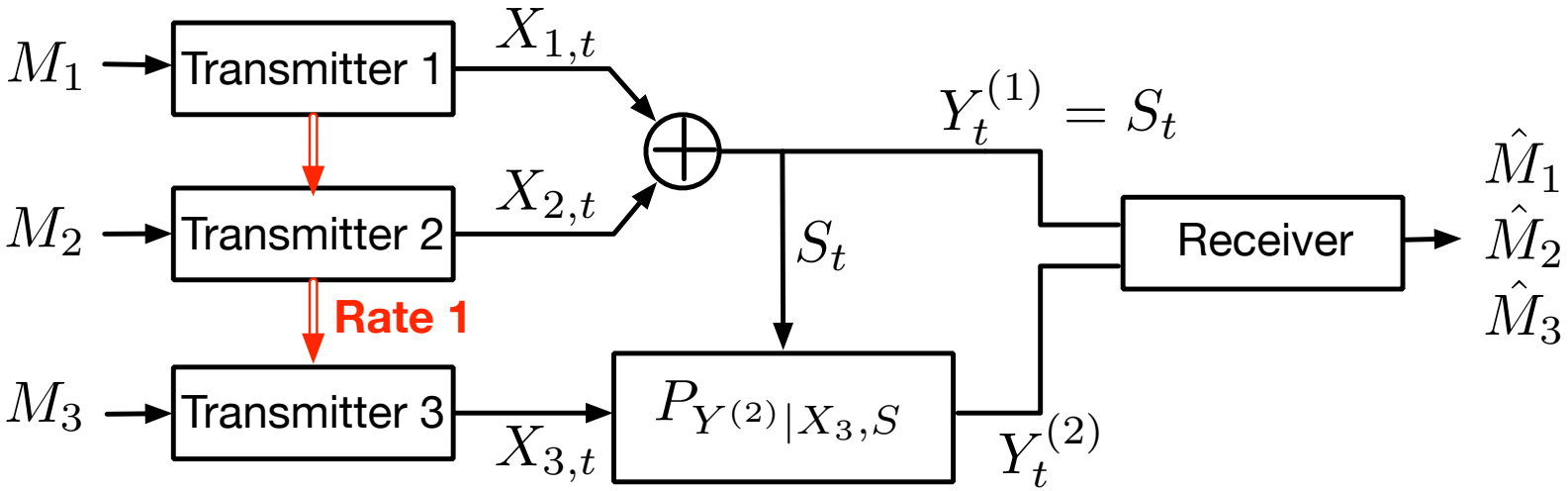
D2D comm. overheard by all txs

- Optimal scheme:
  - share message parts
  - communicate individual and common information
- [Wigger/Kramer'09]

Private D2D comm.

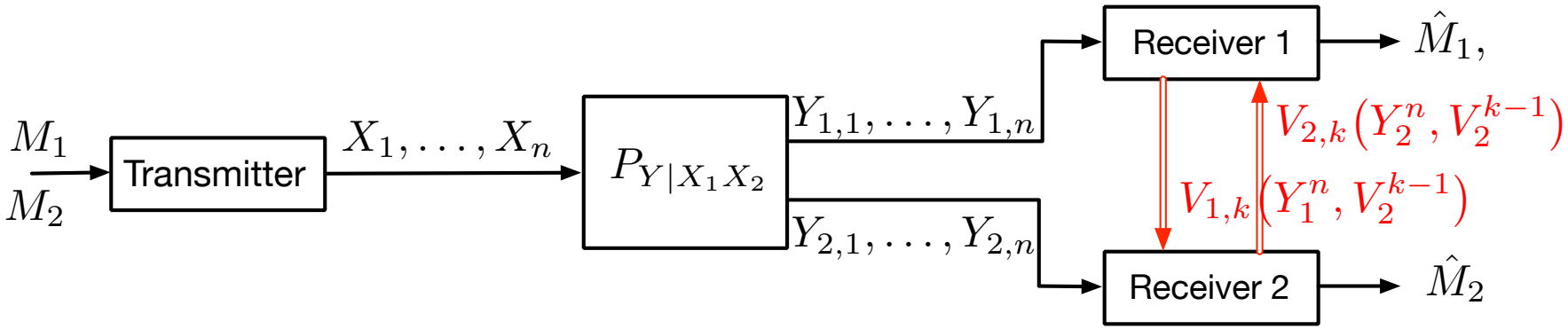
- Previous D2D strategy creates pair-wise and full common messages
- [Simeone/Somekh/Kramer /Poor/Shamai'08]
- Suboptimal!

3-user MAC example: new D2D strategy



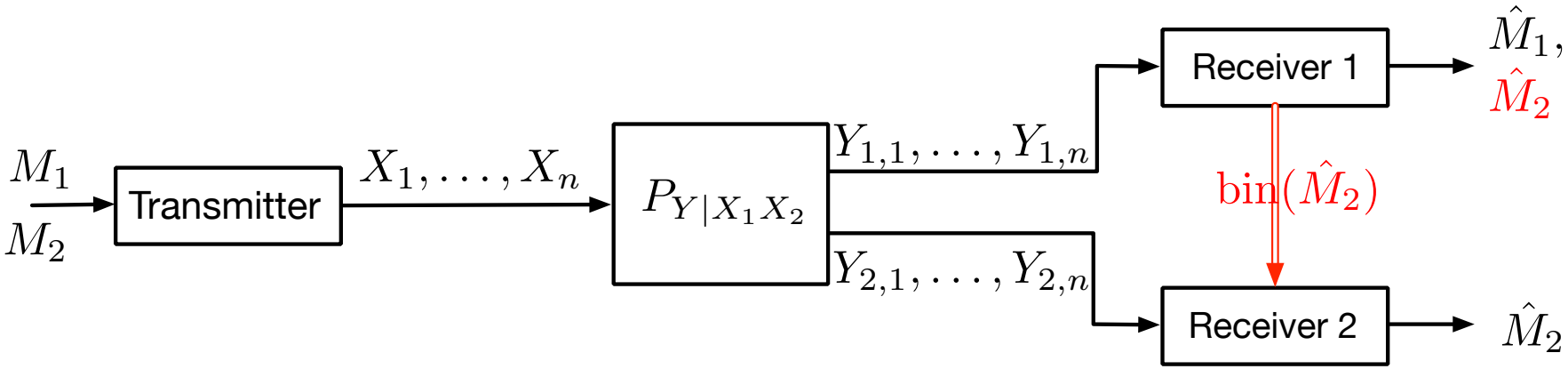
- From Tx2 to Tx 3: say whether S=1 or not!
  $\rightarrow$ Tx 3 can precancel its interference!
- Not possible if Tx2 reroutes messages!

Two-User BC with D2D Receivers (Dabora&Servetto'06)

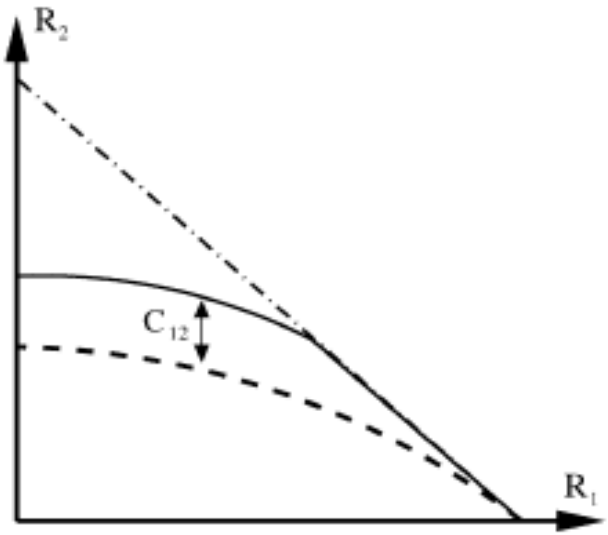


- Interactive communication pipes between receivers
- Can send $nC_{1,2}$ or $nC_{2,1}$ bits over pipes

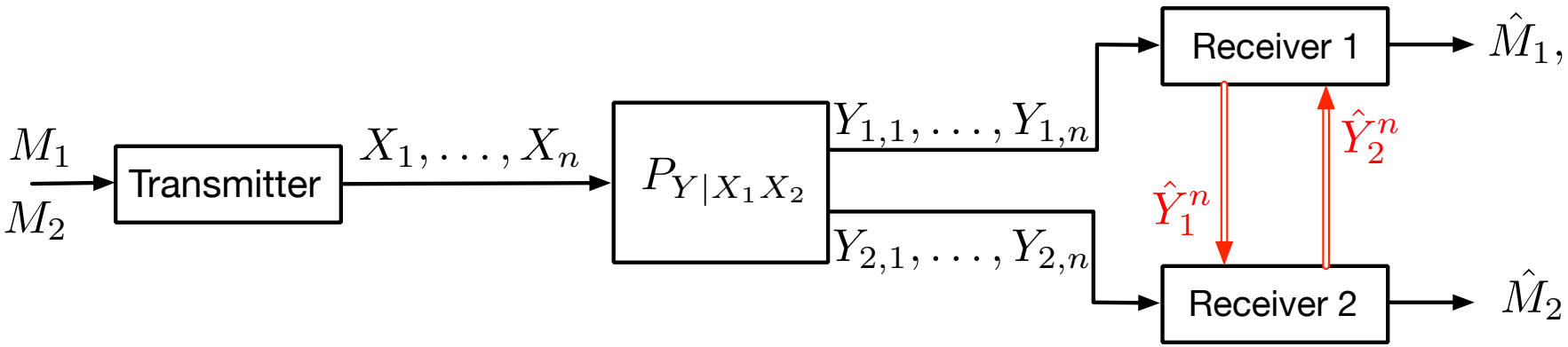
DF-Strategy for BC with D2D Receivers



- Stronger receiver decodes weaker receiver's message and forwards a description of it
- Achieves capacity when BC degraded or semideterministic



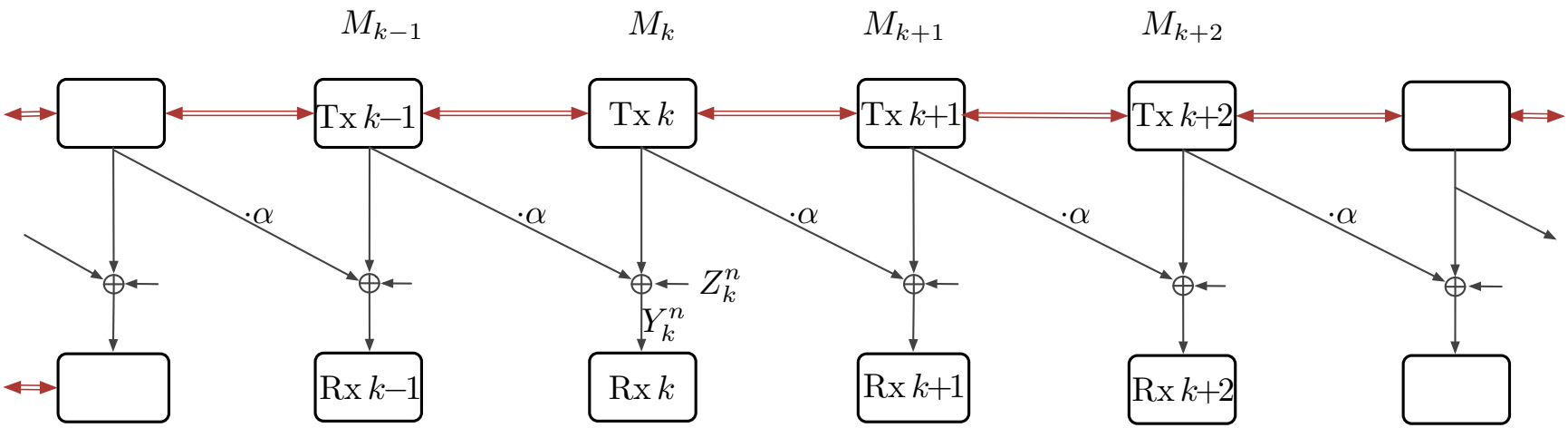
CF-Strategy for BC with D2D Receivers



- Each Rx relays a compressed version of its received signal
- D2D interaction improves performance!
  - Rx 2 decodes M_2 based on $Y_2^n, \hat{Y}_1^n$
  - "cancels effect of M_2 on $Y_2^n \rightarrow$ improved $\hat{Y}_2^{*n}$ more useful for M_1!

D2D communication in large interference networks

- Simplified cellular model (Wyner's soft-handoff model)



- $Y_{k,t} = X_{k,t} + \alpha_k X_{k-1,t} + Z_{k,t}$
- i.i.d Gaussian noises of variance σ^2; equal power constraints P
- D2D between Txs or between Rxs (or both)

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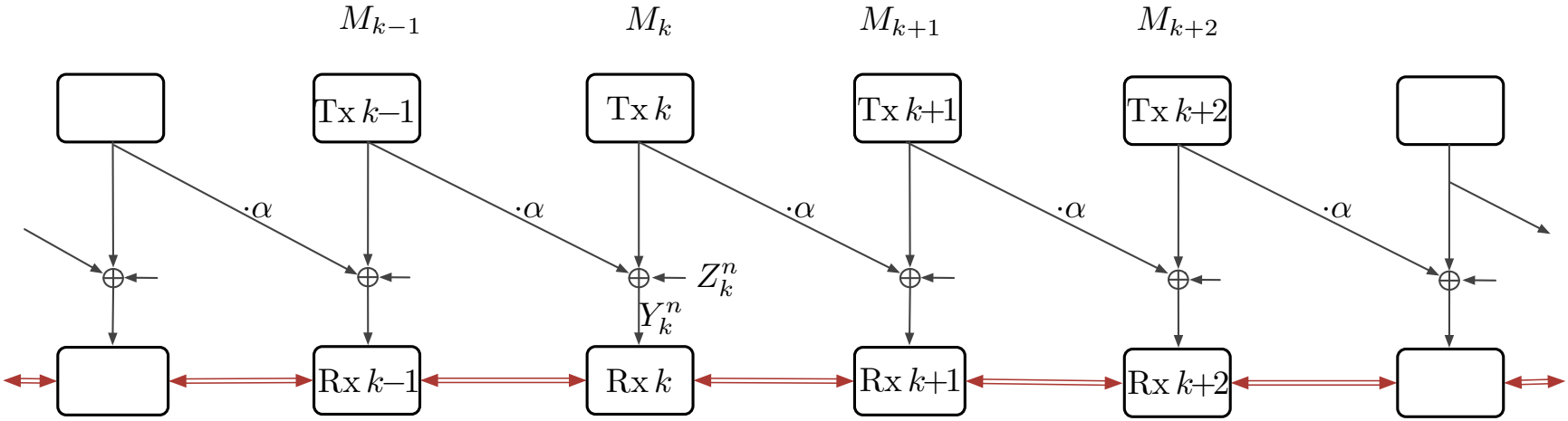

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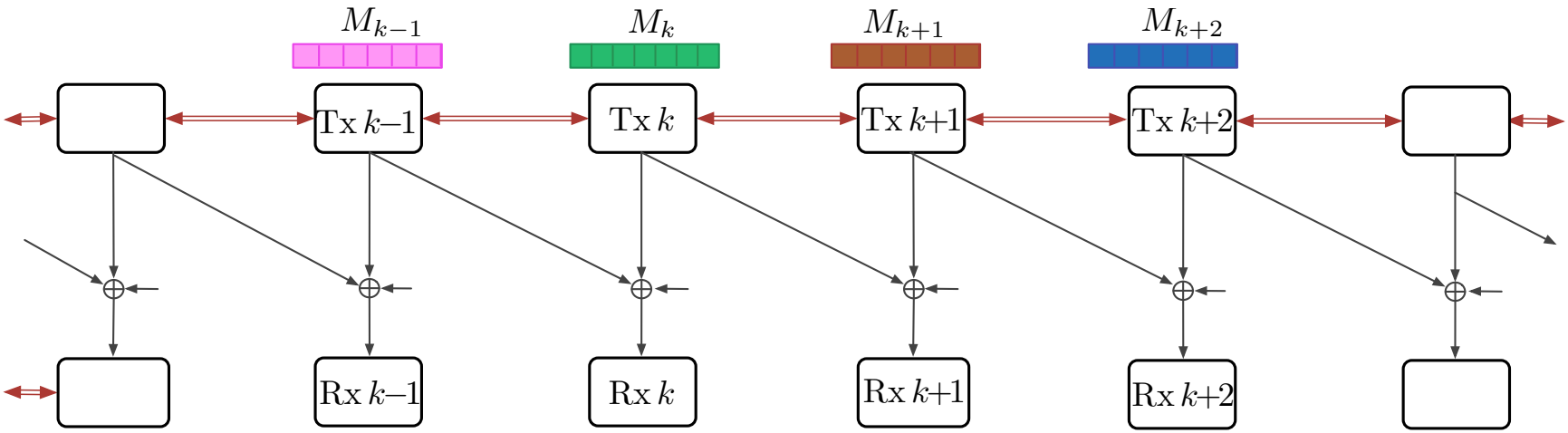
Complexity constraint: max number of D2D rounds κ

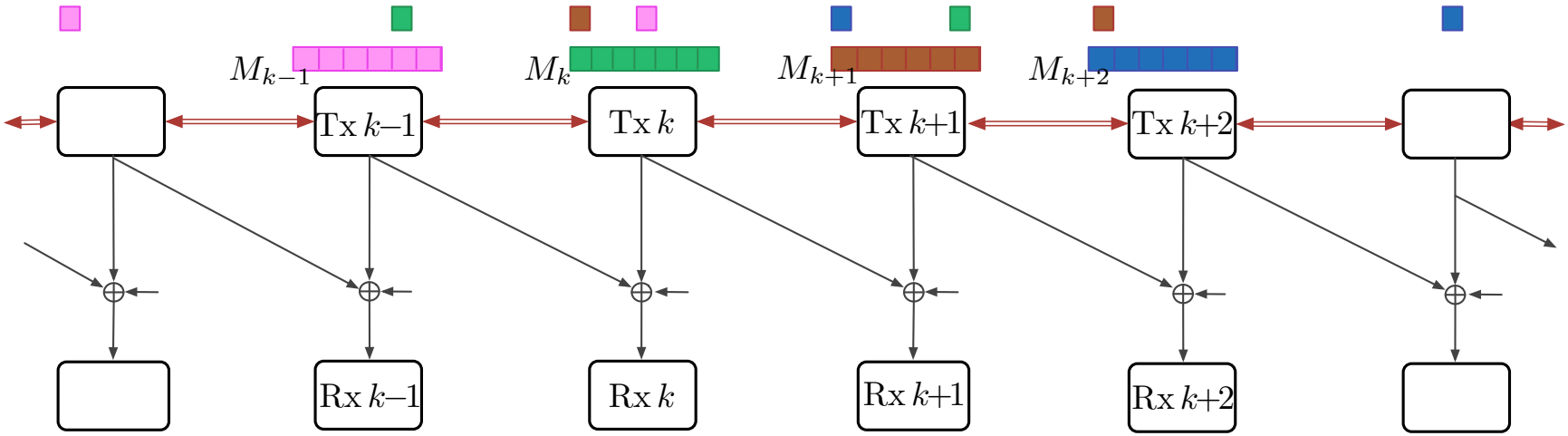


- at most $\kappa > 0$ D2D rounds allowed

Goal

Find sum-capacity in function of D2D rounds κ!

Complexity constraint: max number of D2D rounds κ



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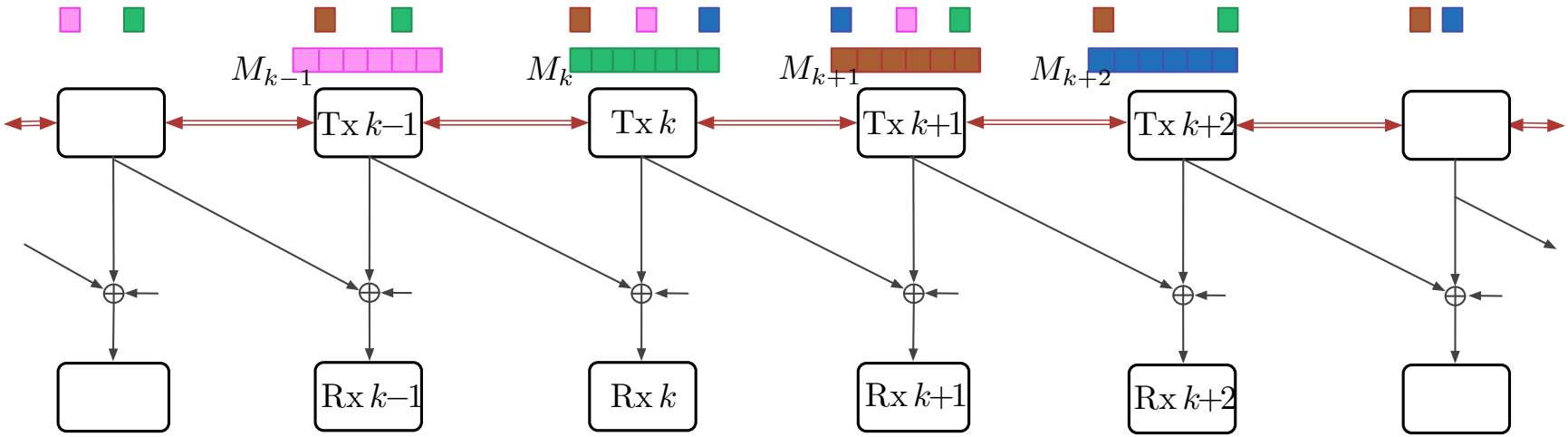


- at most $\kappa > 0$ D2D rounds allowed

Goal

Find sum-capacity in function of D2D rounds κ!

- κ also limits how many hops a message can propagate

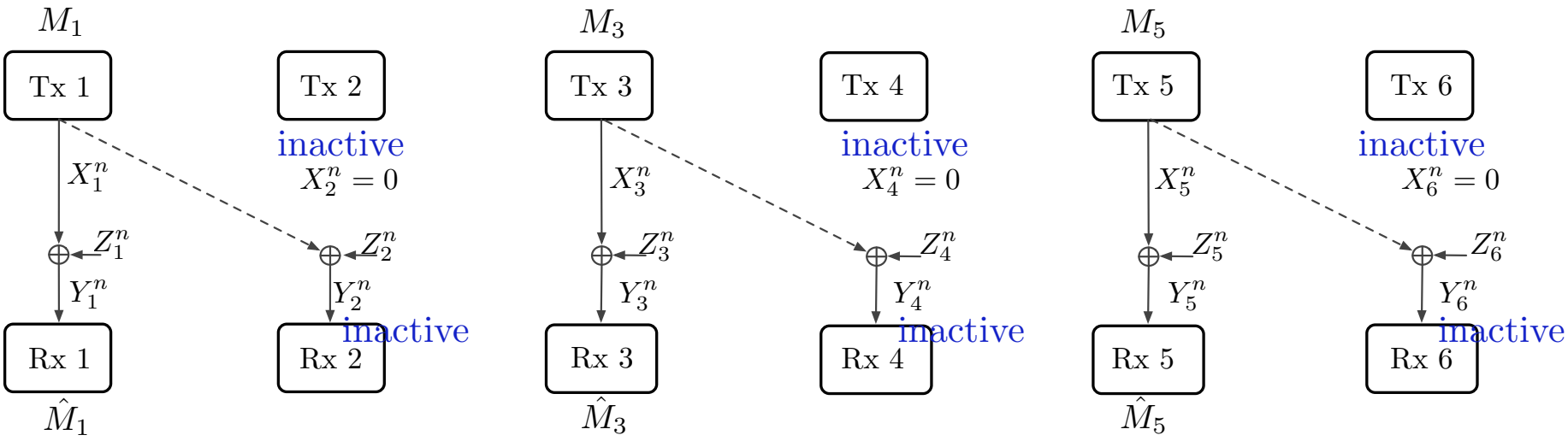
High-SNR performance: per-user Degrees of Freedom

- Sum-capacity: maximum $R_1 + R_2 + \cdots + R_K$ s.t. $p(\text{error}) \to 0$
- Per-user DoF $\mathcal{S}$:

$$\text{Sum-capacity} \approx \mathcal{S} \cdot \frac{K}{2} \log(1 + P/\sigma^2), \qquad P/\sigma^2 \gg 1$$

- Rate-constraint on D2D links: $C_{\text{D2D}} = \mu \cdot \frac{1}{2} \log(1 + P/\sigma^2)$

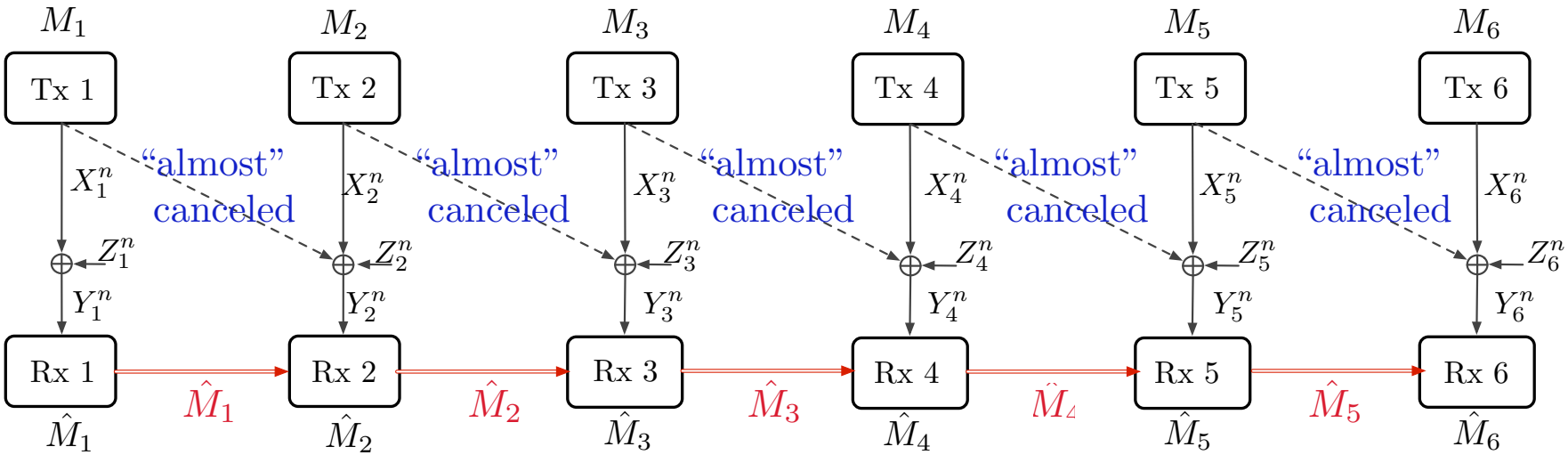
Without D2D, Downlink



- Silence every second Tx $\rightarrow \mathcal{S} = 1/2$

With D2D and $\kappa = \infty$

- Can have $\mathcal{S} = 1$: need $\mu = 1/2$



- Scheme requires $\hat{M}_k = g_k(Y_1^n, \ldots, Y_k^n)$

$\rightarrow$ Interference mitigation propagates interference!

· V. Ntranos, M. A. Maddah-Ali and G. Caire, "Cellular interference alignment," *IEEE Trans. Inform. Theory*, Mar. 2015

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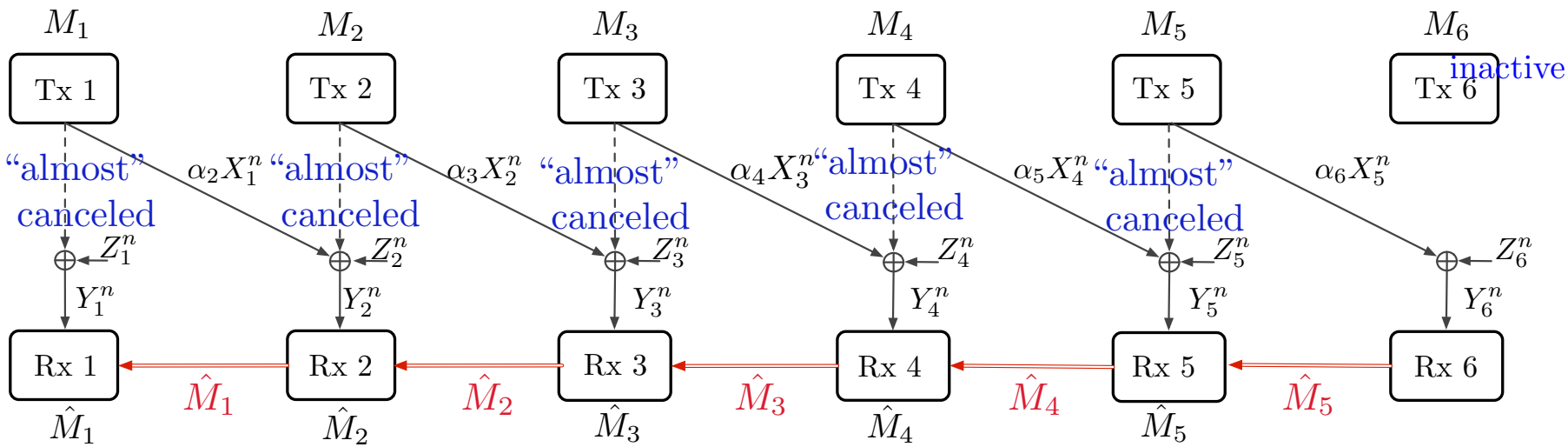

- Scheme requires $\hat{M}_k = g_k(Y_{k+1}^n, \ldots, Y_K^n)$

$\rightarrow$ Interference mitigation propagates interference!

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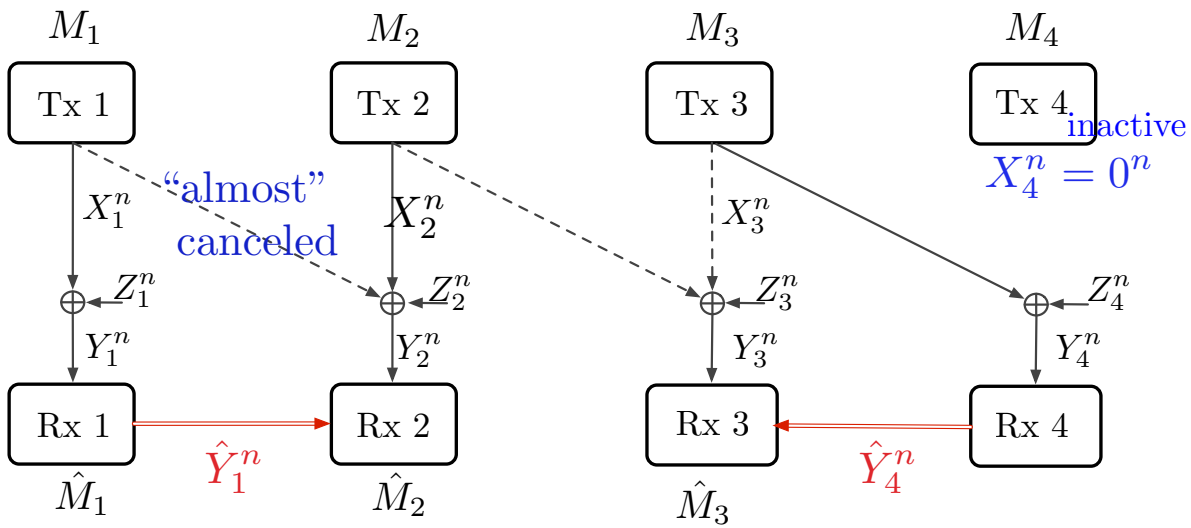
With D2D and $\kappa = 1$

- Stop interference propagation by silencing every 4th Tx
- $\mu = 1/4$: time-share 4 schemes that each can kill 3 interferences out of 4
- $\Longrightarrow \mathcal{S} = 3/4$



- Achievable also when codebooks oblivious during conferencing

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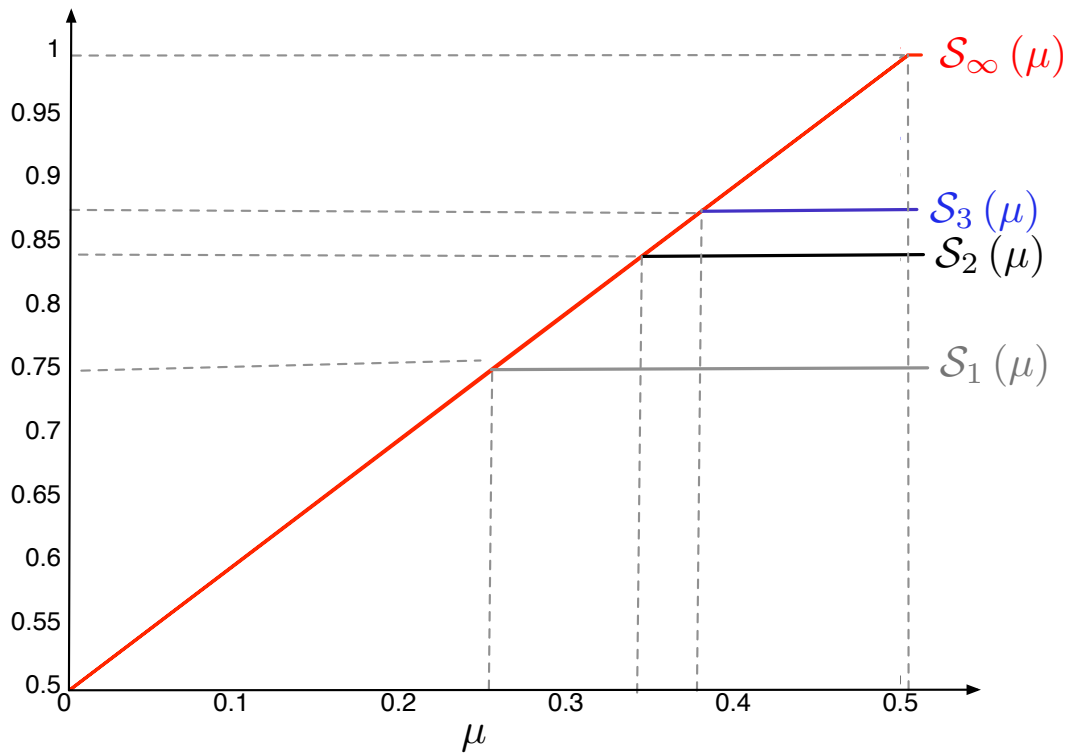
· M. Wigger, R. Timo, S. Shamai, "Conferencing in Wyner's asymmetric interference network: effect of number of rounds," ArXiv: 1603.05540.

Degrees of Freedom $\mathcal{S}$ (Wigger, Timo, Shamai'15)

Theorem For D2D uplink or D2D downlink:

$$\mathcal{S} = \begin{cases} \dfrac{2\mu+1}{2} & \text{if} \quad \mu \leq \frac{\kappa}{2(1+\kappa)} \\ \dfrac{2\kappa+1}{2\kappa+2} & \text{otherwise.} \end{cases}$$



Summary

- Message-sharing or signal sharing on uplink D2D
- Decode-and-forward or compress-and-forward on downlink D2D
- D2D allows to communicate over alternative paths
  $\rightarrow$ interference avoidance (besides diversity)!
- Tradeoff between interference mitigation and complexity of D2D
  (because interference mitigation techniques propagate interference)
- Duality between D2D on uplink and downlink