How Helpful is Algebraic Structure in Network Information Theory?

Sae-Young Chung

Dept. Electrical Engineering, KAIST

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Algebraic Structure in Network Information Theory

Overview

Overview

- Relay networks

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- Relay networks
- Compute-and-forward

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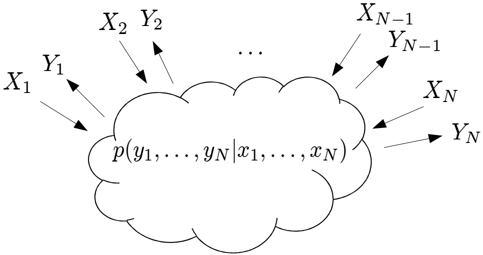
- Compute-and-forward
- Noisy network coding

Network model



- N nodes consisting of sources, relays, and destinations.
- Node k transmits $X_k \in \mathcal{X}_k$ and receives $Y_k \in \mathcal{Y}_k$.
- Channel: $p(y_1, \dots, y_N | x_1, \dots, x_N)$

Encoding, relaying, decoding

- $W_{i,j}$: message from node i to node j, uniformly distributed in $[1, 2^{nR_{i,j}}] \triangleq \{1, \ldots, 2^{nR_{i,j}}\}$. $R_{i,i} = 0$, $\forall i$.
- $X_k^n \triangleq \{X_{k,1}, \ldots, X_{k,n}\}$: transmitted vector at node k over n channel uses
- Y_k^n: received vector at node k
- $X_{k,i} = X_{k,i}(\{W_{k,j} | j \in [1, N]\}, Y_k^{i-1})$
- $\{\hat{W}_{j,k}(Y_k^n, \{W_{k,i} | i \in [1, N]\}) | j \in [1, N]\}$: message estimates at node k
- Discrete memoryless channel

$$p(y_1^n, \ldots, y_N^n | x_1^n, \ldots, x_N^n) = \prod_{i=1}^{n} p(y_{1,i}, \ldots, y_{N,i} | x_{1,i}, \ldots, x_{N,i})$$

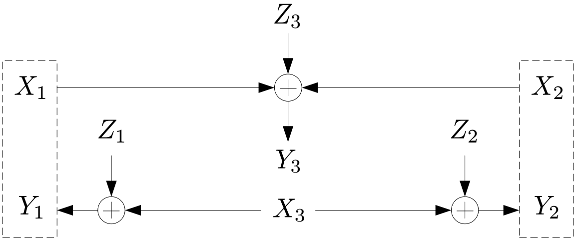
Capacity

- A set of rates $\{R_{i,j} | i, j \in [1, N]\}$ is said to be *achievable* if there exists a sequence of encoding (relaying) and decoding functions such that

$$P_e \triangleq \Pr(W_{i,j} \neq \hat{W}_{i,j} \text{ for some } i, j \in [1, N]) \to 0 \text{ as } n \to \infty$$

- Capacity region: closure of the set of achievable rates

Two-way relay channel



- P_1, P_2: Uplink SNR's of users 1 and 2
- Q_1, Q_2: Downlink SNR's of users 1 and 2

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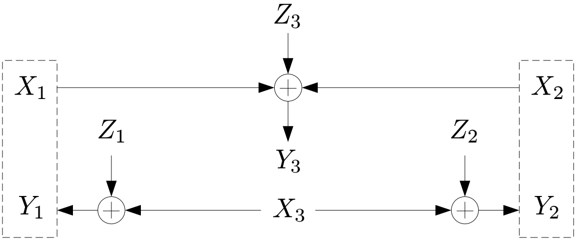

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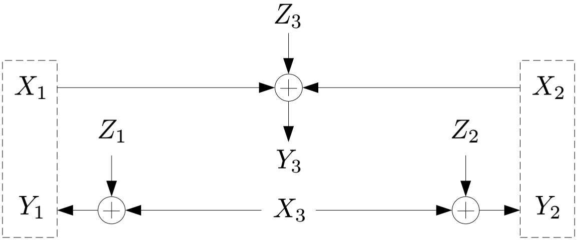

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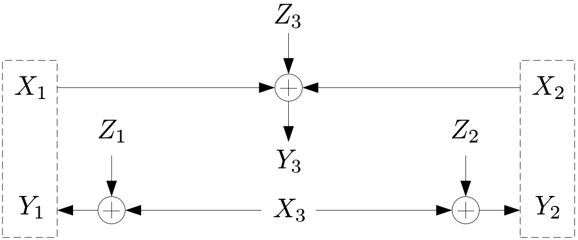

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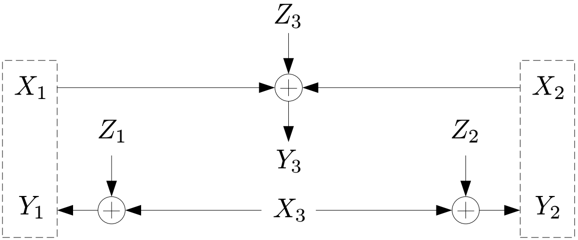

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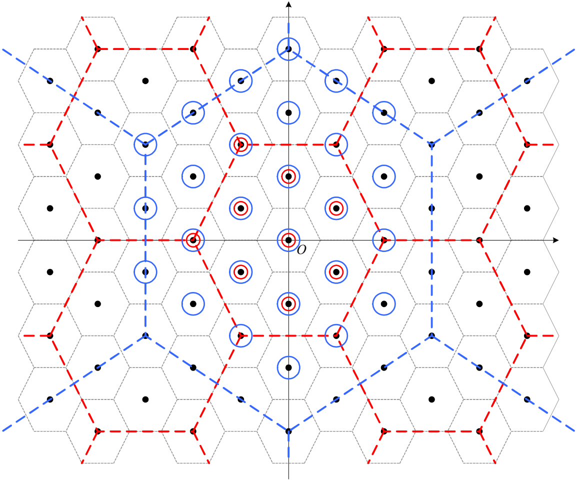
- Unequal power case: Nam, C, Lee, IZS '08, IT '10

Nested lattice code



• Λ_C ○ $\mathcal{C}_2$ ○ $\mathcal{C}_1$ $(\Lambda_1 \subseteq \Lambda_2 \subseteq \Lambda_C)$

Two-way relay channel

Theorem (Nam, C, Lee, IZS '08, IT '10)

For the Gaussian two-way relay channel, the following rate pair is achievable

$$R_1 < \min \left\{ \left[\frac{1}{2} \log \left(\frac{P_1}{P_1 + P_2} + P_1 \right) \right]^+ , C(Q_2) \right\}$$

$$R_2 < \min \left\{ \left[\frac{1}{2} \log \left(\frac{P_2}{P_1 + P_2} + P_2 \right) \right]^+ , C(Q_1) \right\}$$

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- Cut-set bound

$$R_1 \leq \min\{C(P_1), C(Q_2)\}$$
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- Cut-set bound

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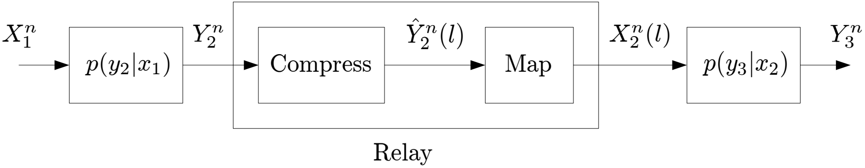
- Gap to capacity: $\frac{1}{2}$ bit per user, $\log\frac{3}{2} \sim 0.58$ bits for the sum rate

Compress-and-forward



- Compress-and-forward for 2-hop noisy RN can achieve

$$\max_{p(x_1)p(x_2)p(\hat{y}_2|y_2):\ I(X_2;Y_3)\geq I(Y_2;\hat{Y}_2)} I(X_1;\hat{Y}_2)$$

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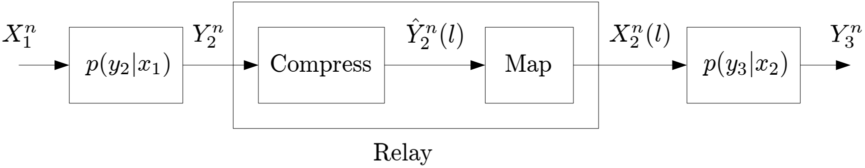

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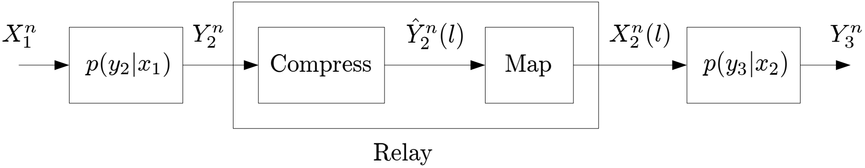

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- $I(X_2;Y_3) > I(Y_2;\hat{Y}_2)$ needed to be able to send the compression index l over the second hop
- Destination decodes l and (roughly speaking) gets an effective channel $X_1 \to \hat{Y}_2$ for X_1 that supports rates up to $I(X_1;\hat{Y}_2)$.

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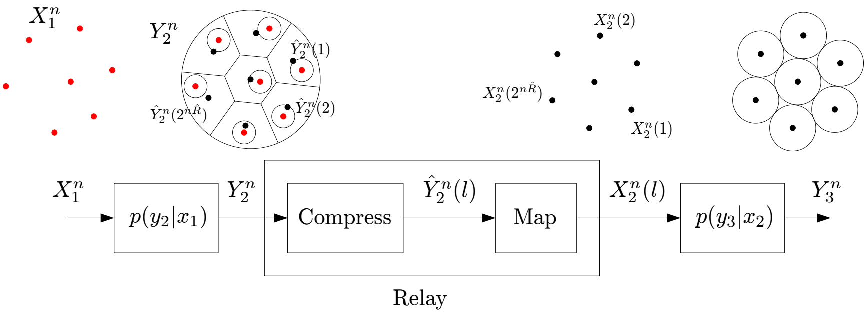

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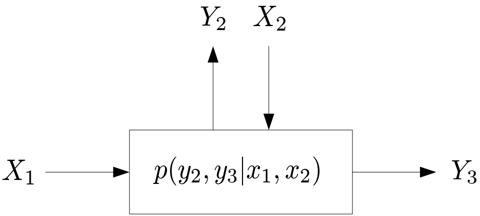

- CF for 3-node relay channel (Cover & El Gamal '79)

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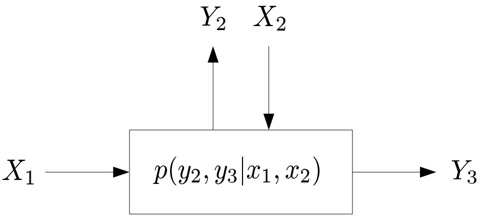

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- Equivalent min-cut-like form (El Gamal, Mohseni, Zahedi '06)

$$\max \min\{I(X_1; \hat{Y}_2, Y_3|X_2), I(X_1, X_2; Y_3) - I(Y_2; \hat{Y}_2|X_1, X_2, Y_3)\}$$

where the maximization is over $p(x_1)p(x_2)p(\hat{y}_2|y_2, x_2)$.

CF for TWRC

- Achievable rate of CF for DM-TWRC, Rankov, Wittneben '06

$$R_1 < I(X_1; Y_2, \hat{Y}_3 | X_2, X_3)$$
$$R_2 < I(X_2; Y_1, \hat{Y}_3 | X_1, X_3)$$

for some $p(x_1)p(x_2)p(x_3)p(\hat{y}_3|x_3, y_3)$ such that $\max_{k=1,2} I(\hat{Y}_3; Y_3|X_3, X_k, Y_k) < \min_{k=1,2} I(X_3; Y_k|X_k)$.

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$$R_1 < C\left(\frac{P_1}{1+\sigma^2}\right)$$
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- $R_1, R_2 \to 0$ if $Q_1 \to 0$. Arbitrarily large gap to capacity.
- Can we do better?

Noisy Network Coding

- Multi-source multicast relay networks
- R_k: rate of node k
- D_k: set of destination nodes receiving message from k

Theorem (Noisy network coding (Lim, Kim, El Gamal, C '10))

For multi-source multicast RN with $D = D_1 = \ldots = D_N$, the following is achievable

$$\sum_{k \in T} R_k < \min_{d \in T^c \cap D} I(X_T; \hat{Y}_{T^c}, Y_d | X_{T^c}, Q) - I(Y_T; \hat{Y}_T | X^N, \hat{Y}_{T^c}, Y_d, Q)$$

for all cuts T s.t. $T^c \cap D \neq \emptyset$ for some $p(q) \prod_{k=1}^N p(x_k|q) p(\hat{y}_k | y_k, x_k, q)$.

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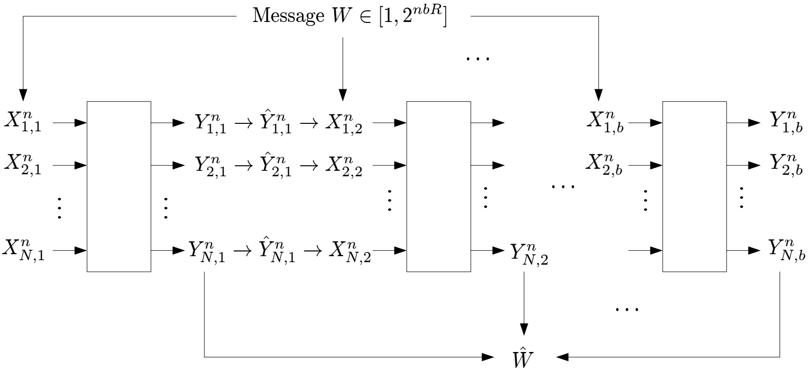
- Non-unique decoding of compression indices and some unwanted messages

Noisy network coding



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for all cuts T s.t. $T^c \cap D \neq \emptyset$ for some $p(q) \prod_{k=1}^{N} p(x_k|q) p(\hat{y}_k | y_k, x_k, q)$.

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Includes the following as special cases:

- Max-flow min-cut theorem (Ford, Fulkerson '56)
- CF for 3-node relay channel (Cover, El Gamal '79)
- Network coding (Ahlswede, Cai, Li, Yeung '00)
- Wireless erasure networks (Dana et al '06)
- Deterministic relay networks (Avestimehr, Diggavi, Tse '07)

Noisy Network Coding

Theorem (Nonunique decoding of unwanted messages)

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Noisy Network Coding

Theorem (Nonunique decoding of unwanted messages)

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for all cuts T s.t. $T^c\cap D_T\neq\emptyset$ for some $p(q)\prod_{k=1}^N p(x_k|q)p(\hat{y}_k|y_k,x_k,q)$, where $D_T=\cup_{k\in T}D_k$.

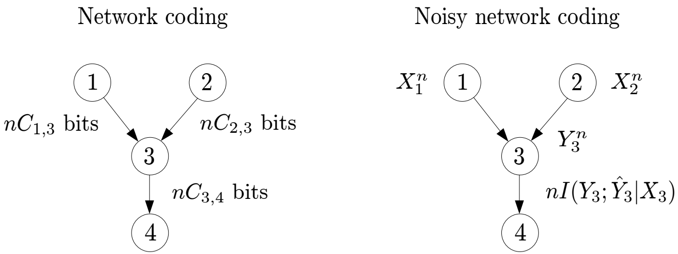
Theorem (Treating interference as noise)

For multi-source multicast RN, the following is achievable

$$\sum_{k\in T} R_k < I(X_T,U_S;\hat{Y}_{S^c},Y_d|X_{T^c},U_{S^c},Q) - I(Y_S;\hat{Y}_S|X_{S_d},U^N,\hat{Y}_{S^c},Y_d,Q)$$

for all cuts S,T and $d\in D_S$ such that $S\cap S_d\subseteq T\subseteq S_d$ and $S^c\cap D_S\neq\emptyset$ for some $p(q)\prod_{k=1}^N p(u_k,x_k|q)p(\hat{y}_k|y_k,u_k,q)$, where $T^c=S_d\setminus T$.

Network coding vs. NNC



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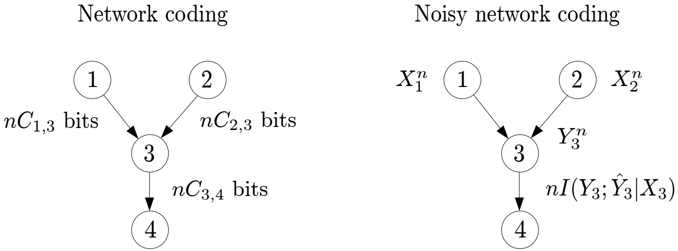

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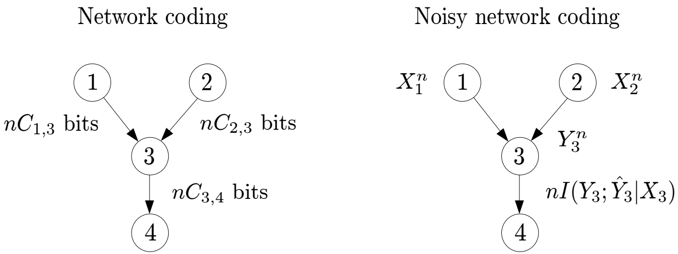

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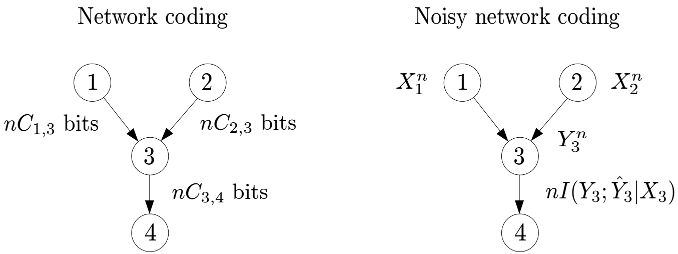

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  - Quantization: Explicit compression

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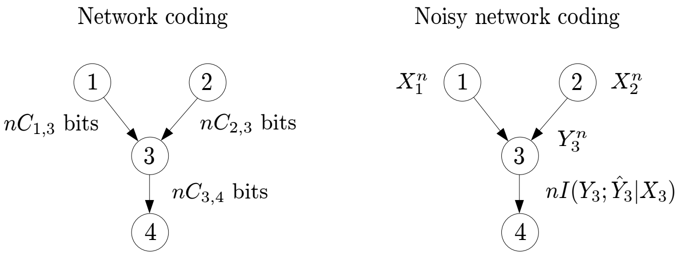

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- Noisy network coding (quantization + network coding)
  - Quantization: Explicit compression
  - Network coding: Additional implicit compression can happen due to bottleneck, i.e., if $I(Y_3; \hat{Y}_3|X_3) > H(X_3)$

Noisy Network Coding for TWRC

- Noisy Network Coding for DM-TWRC, Lim, Kim, El Gamal, C '10

$$R_1 < \min\{I(X_1; Y_2, \hat{Y}_3|X_2, X_3), I(X_1, X_3; Y_2|X_2) - I(Y_3; \hat{Y}_3|X_1, X_2, X_3, Y_2)\}$$

$$R_2 < \min\{I(X_2; Y_1, \hat{Y}_3|X_1, X_3), I(X_2, X_3; Y_1|X_1) - I(Y_3; \hat{Y}_3|X_1, X_2, X_3, Y_1)\}$$

for some $p(x_1)p(x_2)p(x_3)p(\hat{y}_3|x_3, y_3)$.

Noisy Network Coding for TWRC

- Noisy Network Coding for DM-TWRC, Lim, Kim, El Gamal, C '10

$$R_1 < \min\{I(X_1; Y_2, \hat{Y}_3|X_2, X_3), I(X_1, X_3; Y_2|X_2) - I(Y_3; \hat{Y}_3|X_1, X_2, X_3, Y_2)\}$$
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- NNC for Gaussian TWRC w/o direct links

$$R_1 < \min\left\{C\left(\frac{P_1}{1+\sigma^2}\right), C(Q_2) - C\left(\frac{1}{\sigma^2}\right)\right\}$$
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- Gap to capacity: $\frac{1}{2}$ bit per user, 1 bit for the sum rate

Constant gap for Gaussian RN

Theorem (Gaussian RN)

For multi-source multicast Gaussian RN with a single destination set, if $(R_1, \ldots, R_N)$ *is in the cut-set bound, then* $(R_1 - 0.63N, \ldots, R_N - 0.63N)$ *is achievable by NNC.*

- Generalization of constant gap result by ADT

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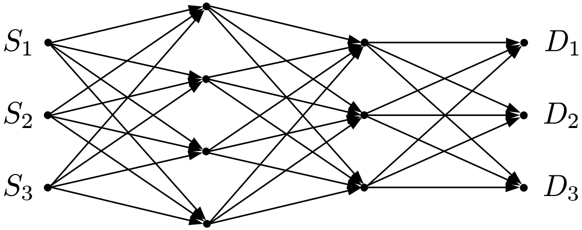
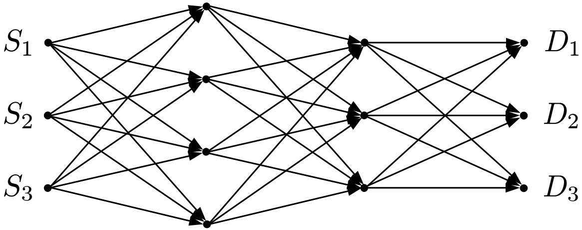
Multiple unicast



Multiple unicast



- New challenges: How to manage inter-user interference?

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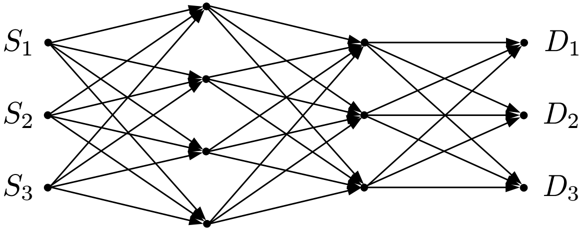

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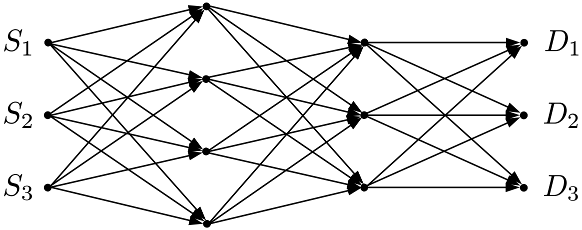

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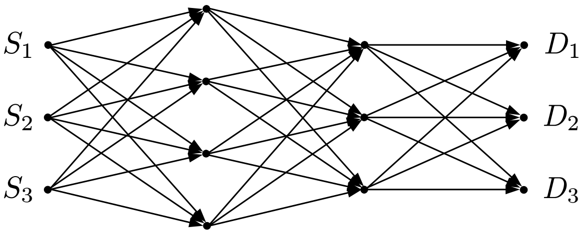

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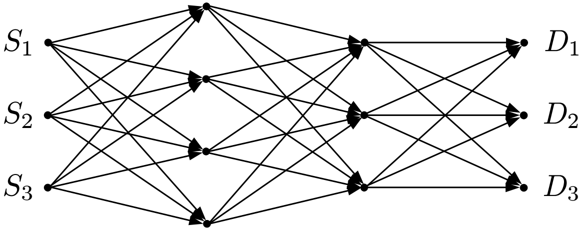

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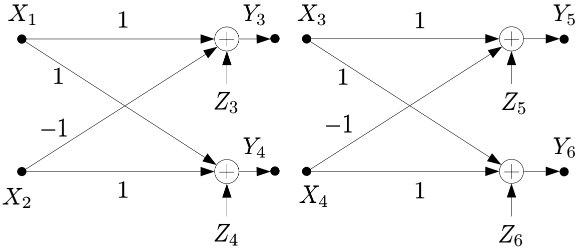
- What do we need?
- Careful control of interference

Interference Neutralization



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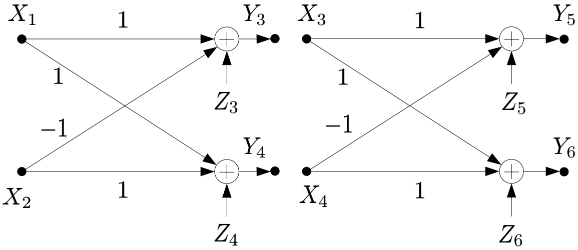

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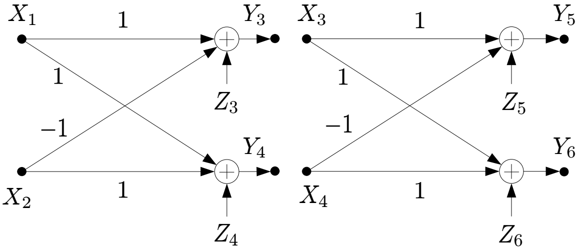

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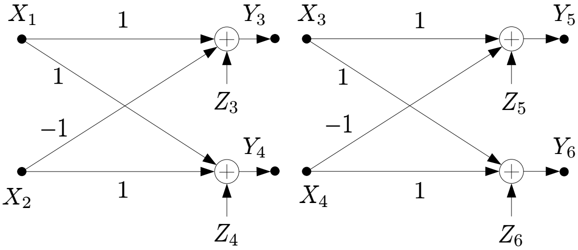

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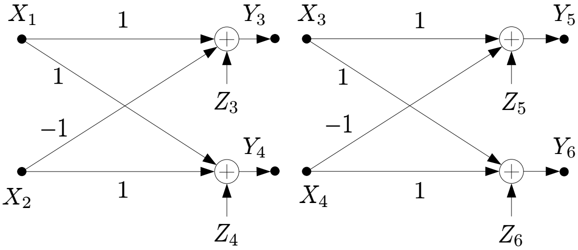

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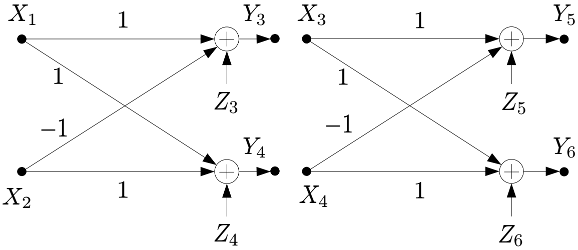

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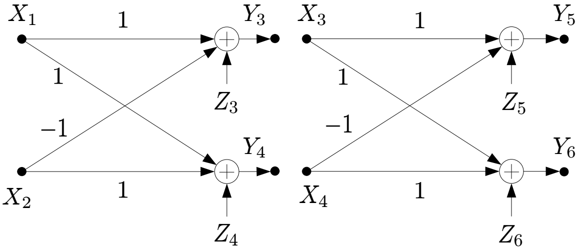

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  - Structured codes can help a lot