From Entropy to Networks

The Future of Communication Engineering Through the Lens of Network Information Theory

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July 19, 2013

Joint work with Fatemeh Arbabjolfaei (UCSD), Bernd Bandemer (UCSD), Sae-Young Chung (KAIST), Abbas El Gamal (Stanford), Sung Hoon Lim (Samsung), Eren Şaşoglu (Berkeley), Lele Wang (UCSD)

Point-to-point communication

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- Source: Voice, video, data, texts, biochemical signals, …

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Information flow questions

Question 1

What is the limit on communication (how much/how fast)?

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Question 2

What are the coding schemes/techniques that achieve this limit?

Answer 1: Channel coding theorem

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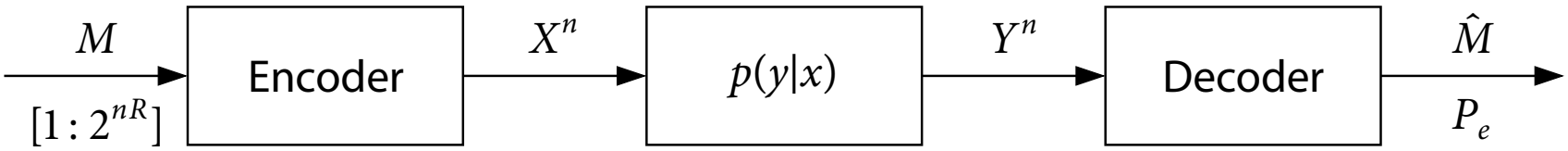

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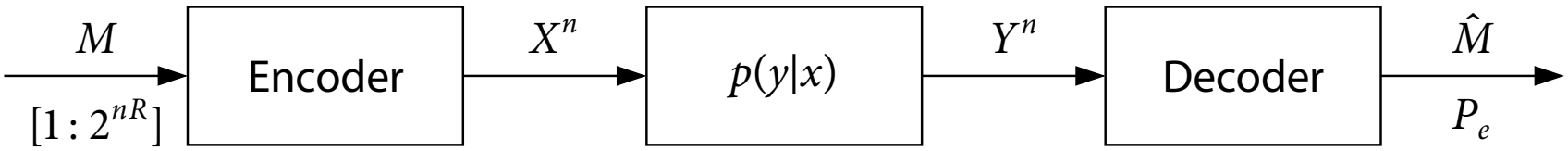

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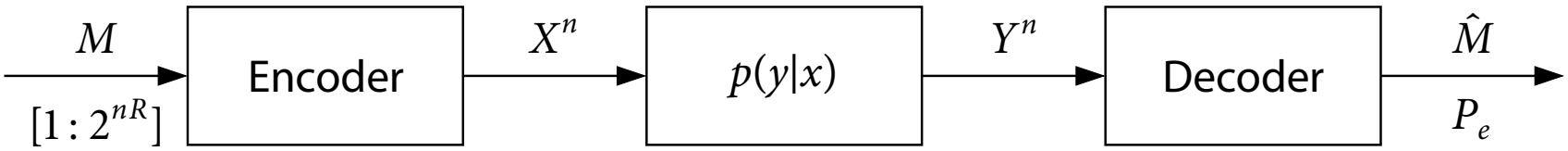

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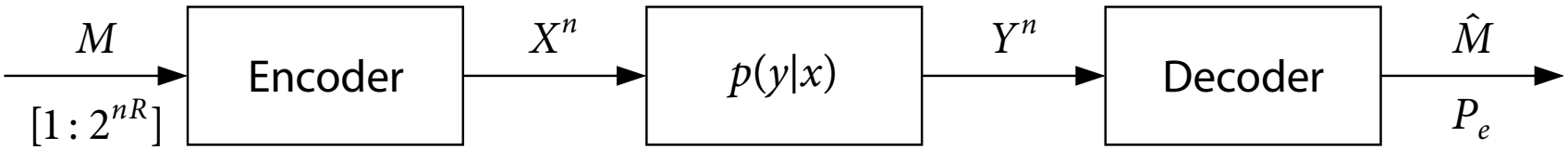

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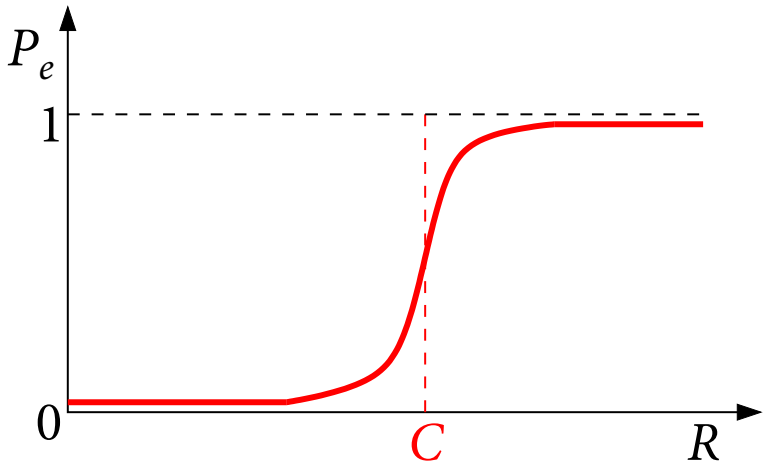

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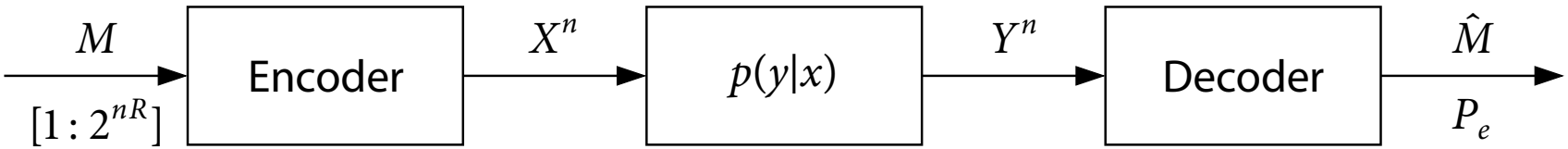

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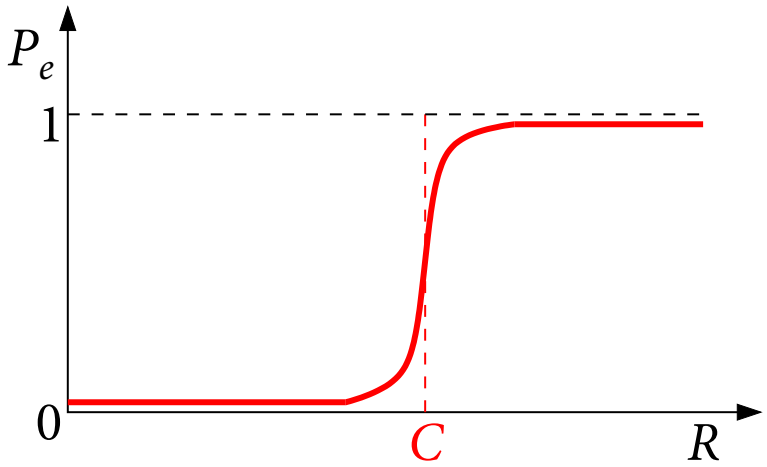

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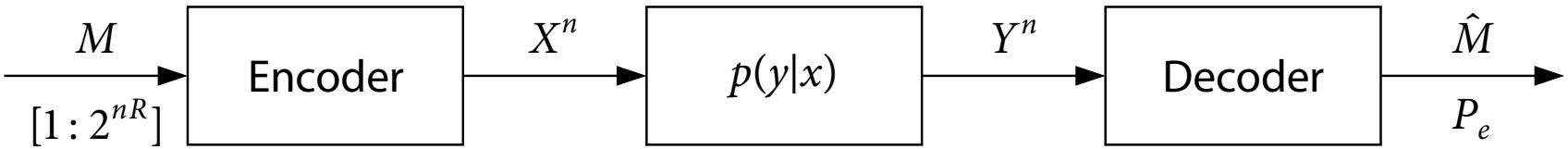

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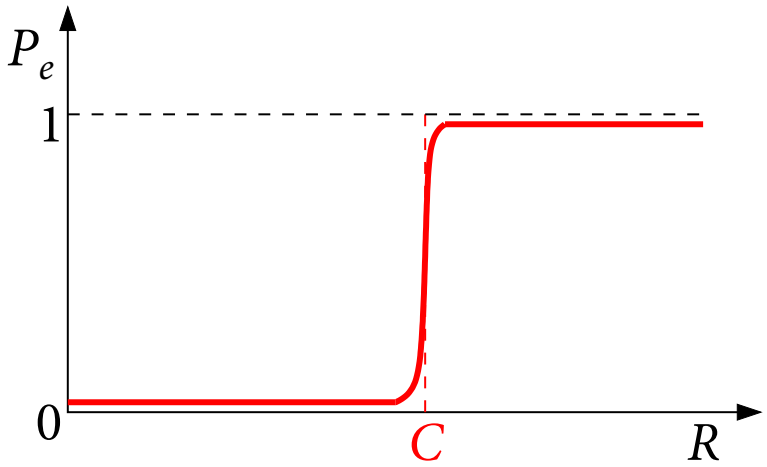

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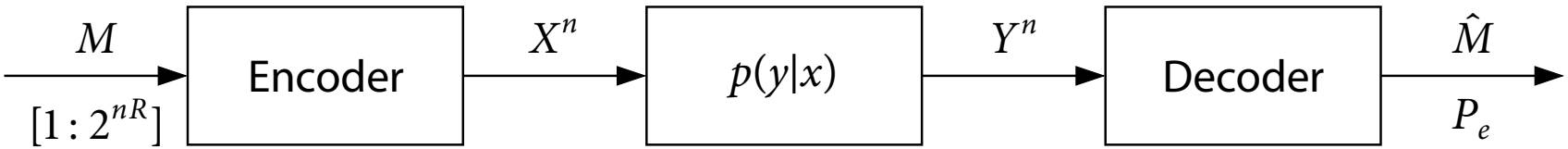

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Shannon (1948)

$$C = \max_{p(x)} I(X;Y)$$

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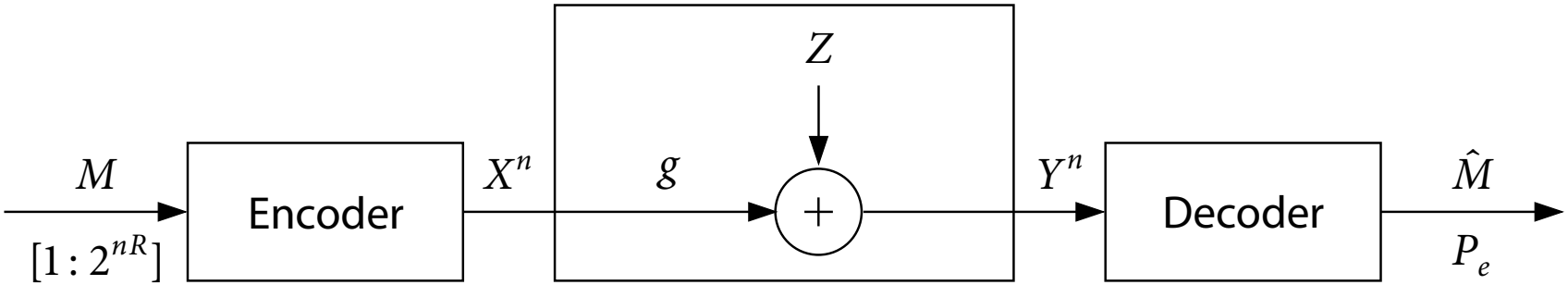

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Shannon (1948)

$$C = \frac{1}{2}\log(1+S) = \mathsf{C}(S)$$

Answer 2: Proof of achievability

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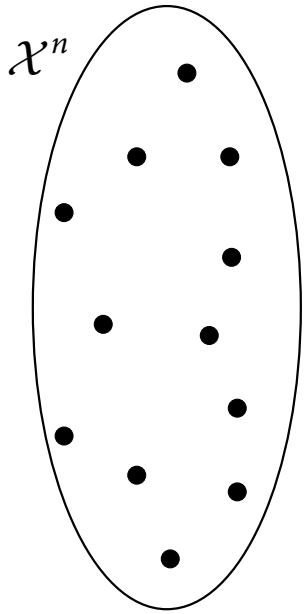

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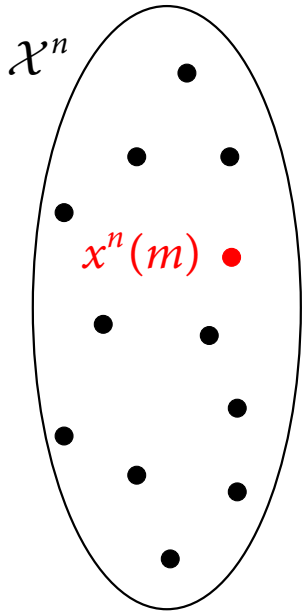

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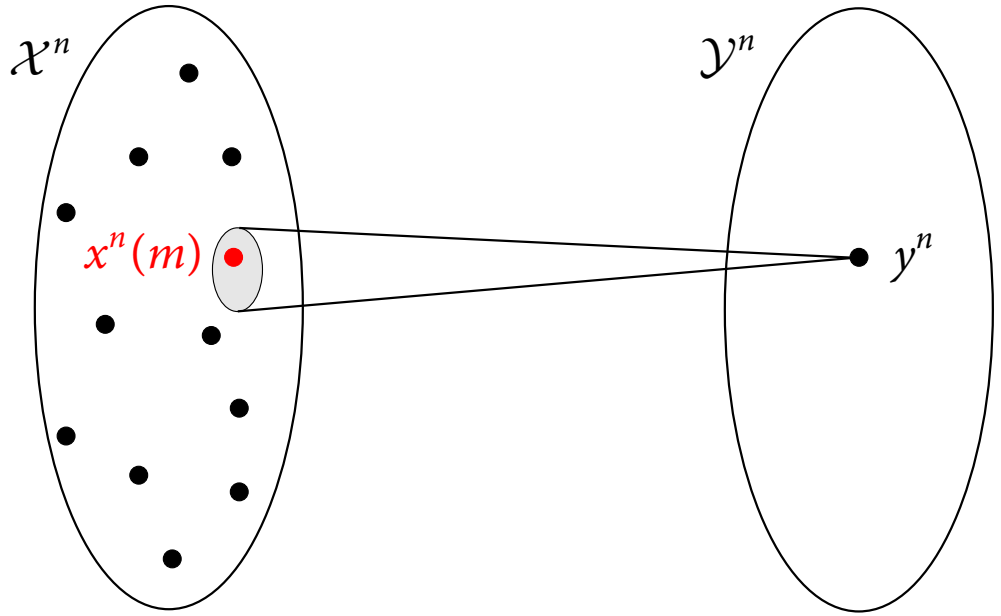

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- Average performance of randomly generate codes is good
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  - 0.0045 dB of the Shannon limit (Chung–Forney–Richardson–Urbanke 2001)

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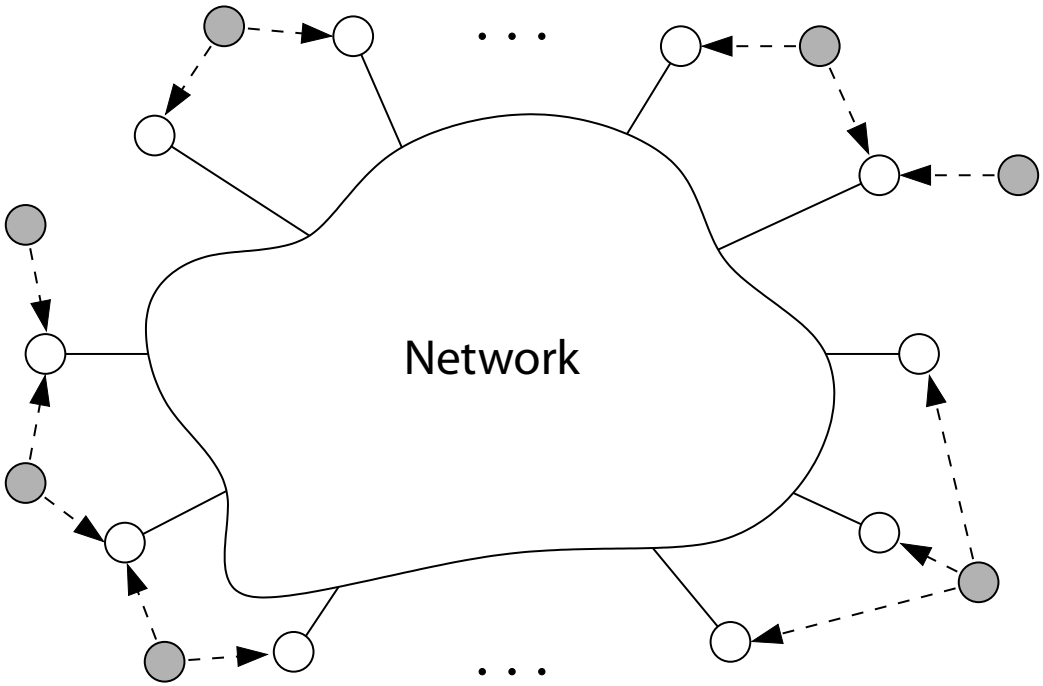
- IEEE CTW 2010 panel discussion: is communication theory dead?

Networked information processing system



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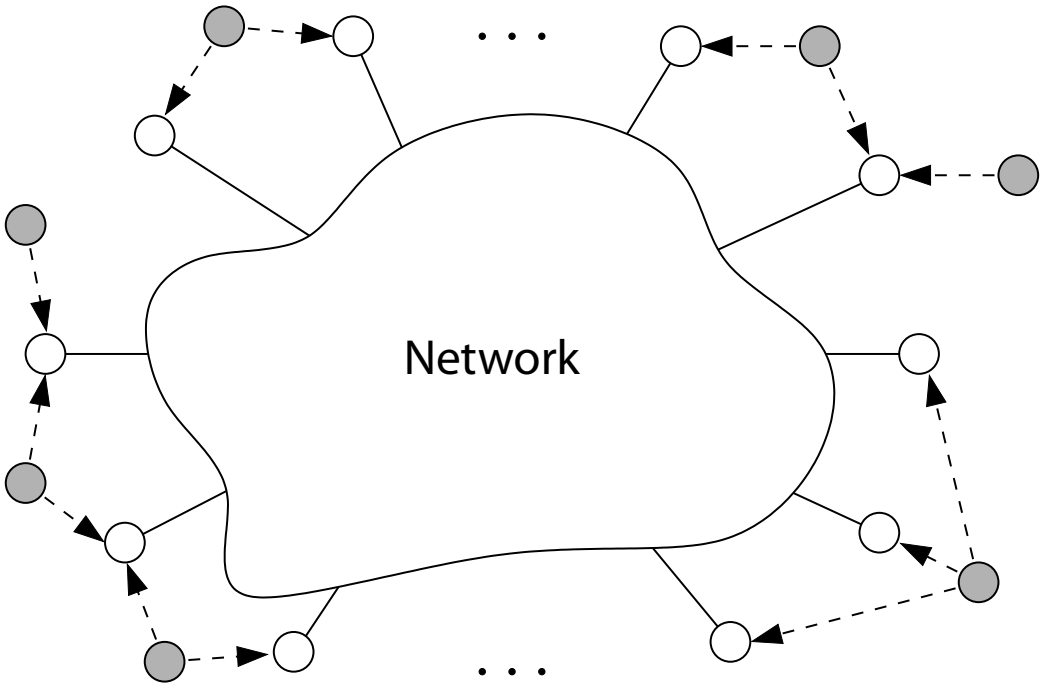
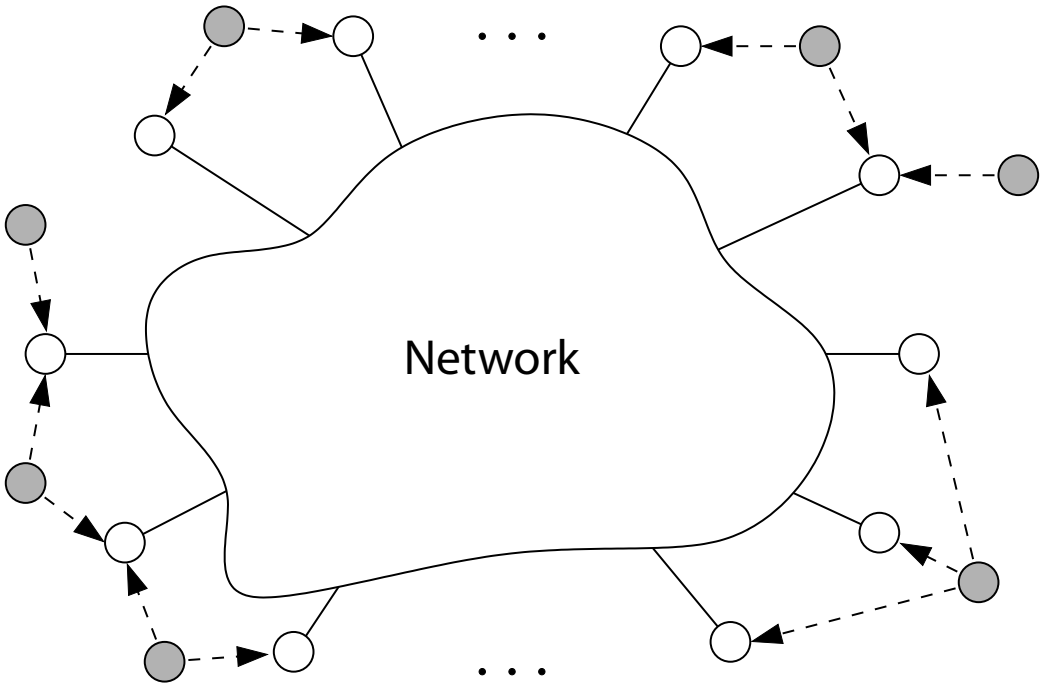


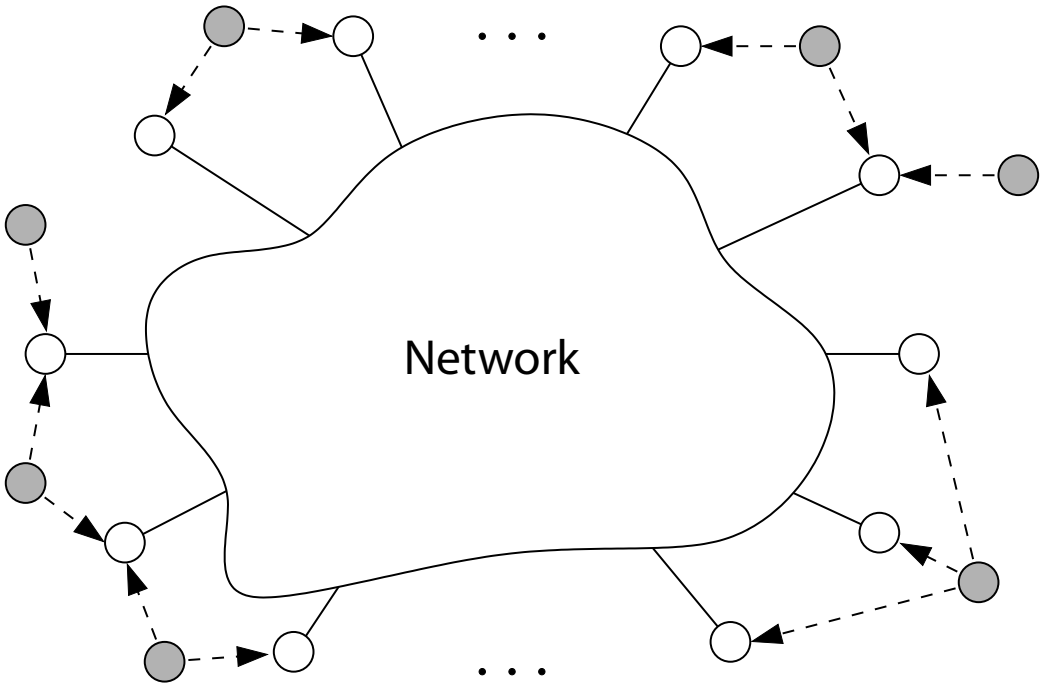
- System: Internet, peer-to-peer network, sensor network, …
- Task: Communicate sources or make decision based on them

Network information flow questions



- What is the limit on communication?

Network information flow questions



- What is the limit on communication?
- What are the coding schemes/protocols/architectures that achieve this limit?

Network information theory

- Multiple sources and destinations

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- Network capacity
- Optimal coding schemes/protocols/architectures

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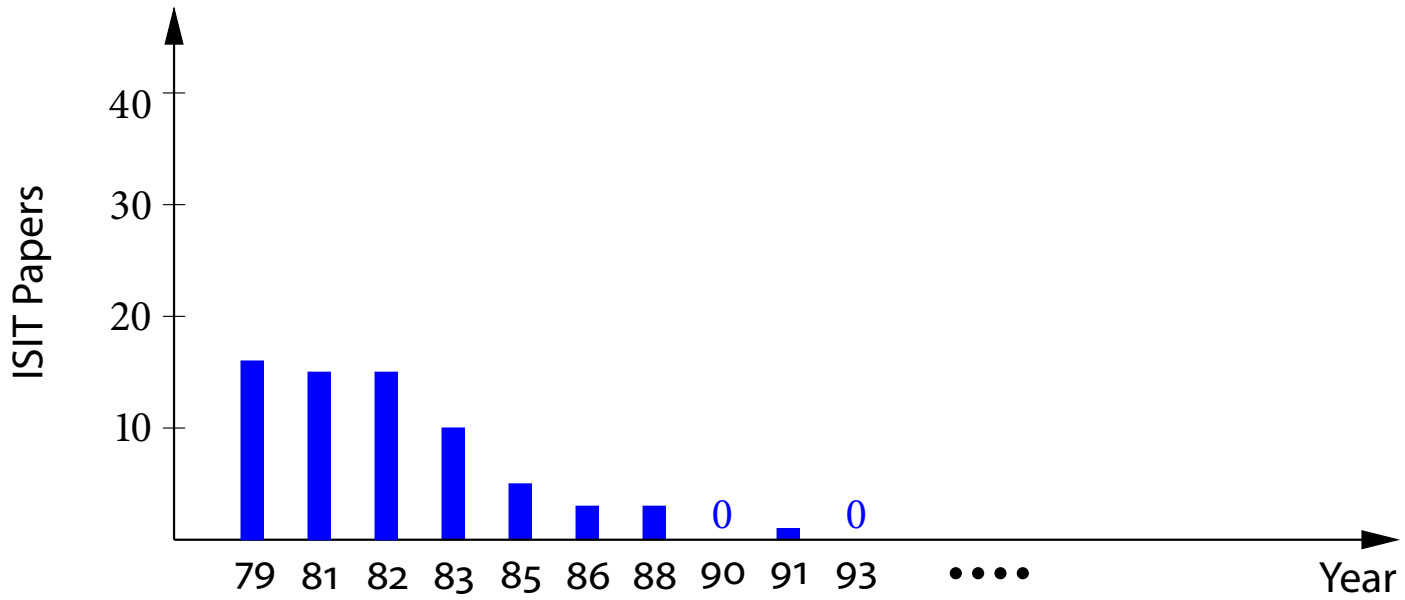
  - ☺ Distributed compression and multiple description coding
  - ☹ Many basic problems open
  - ☹ Little interest from practice



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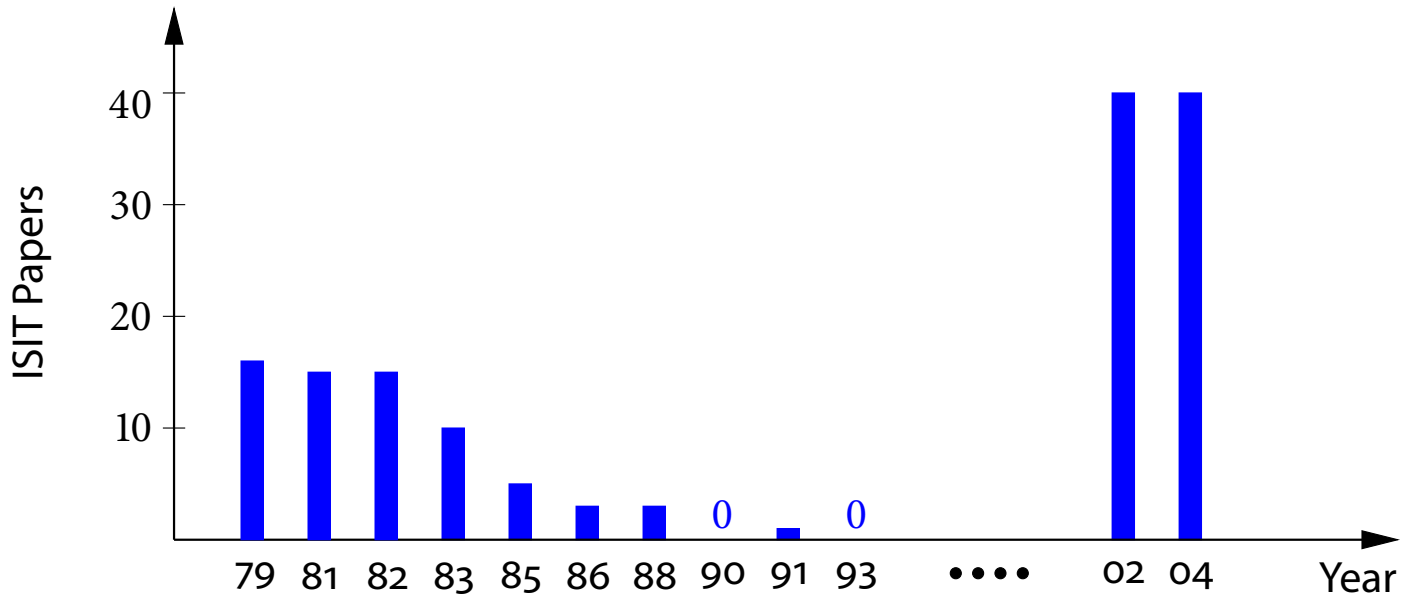
- Significant research activities in 70s and early 80s
- Wireless communications and the Internet revived interest in mid 90s
  - Some progress on old open problems and many new problems
  - Very large number of papers in ISIT, T-IT, T-COM, T-WC, …
  - Results starting to have an impact on real-world networks



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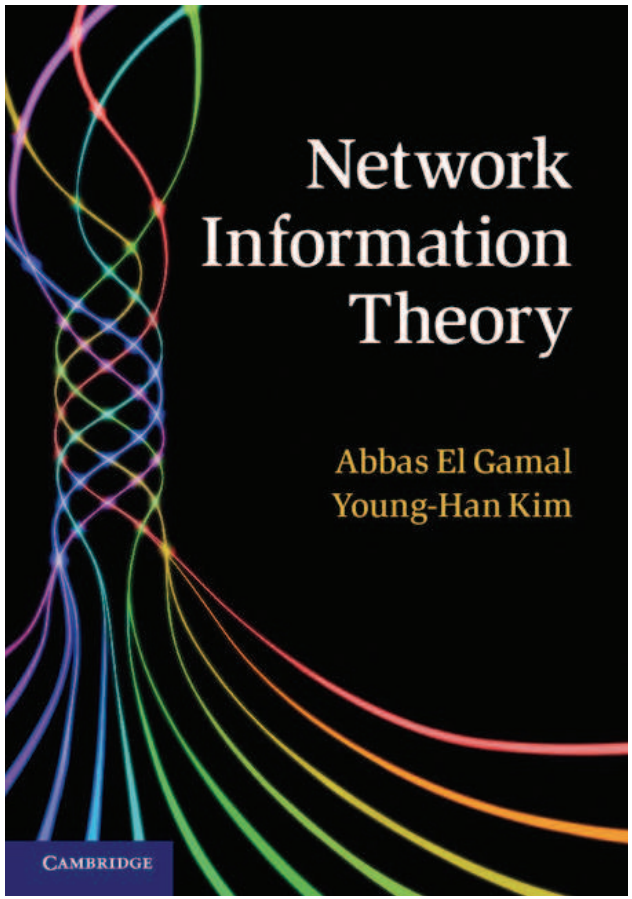
- State of the theory: El Gamal–K (2011)



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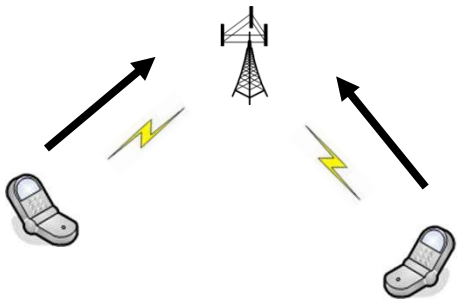

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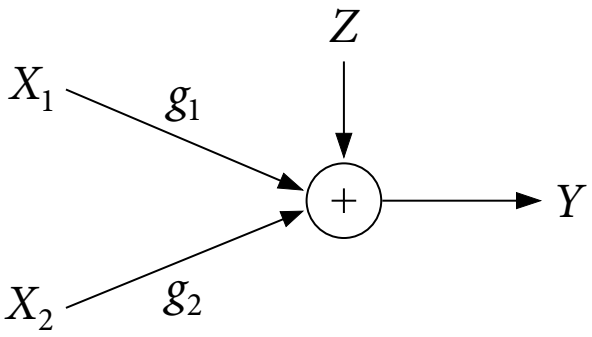

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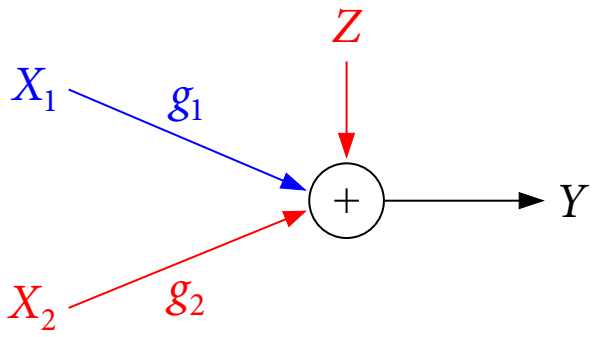

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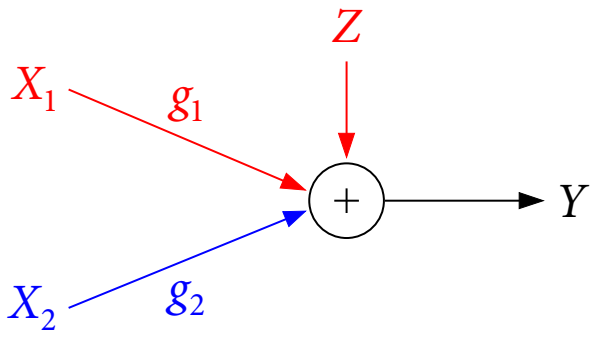

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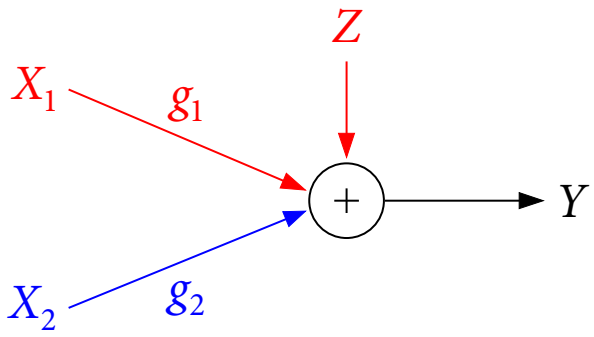

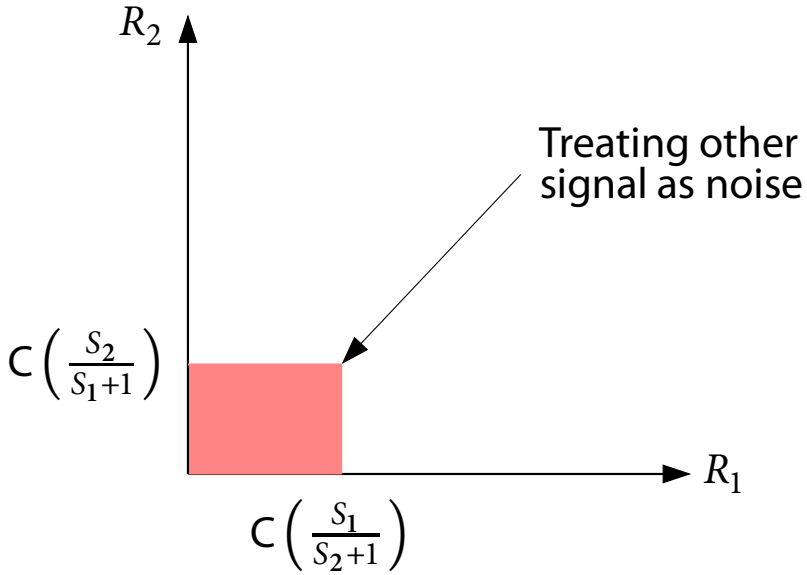

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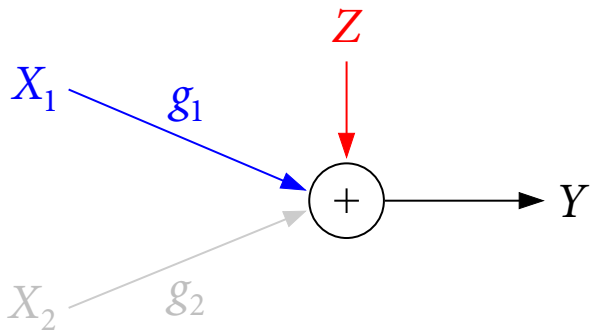

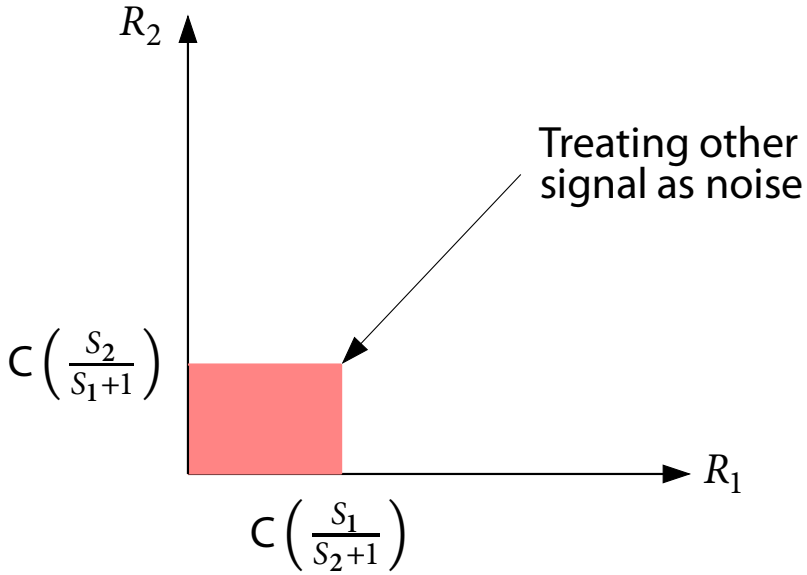

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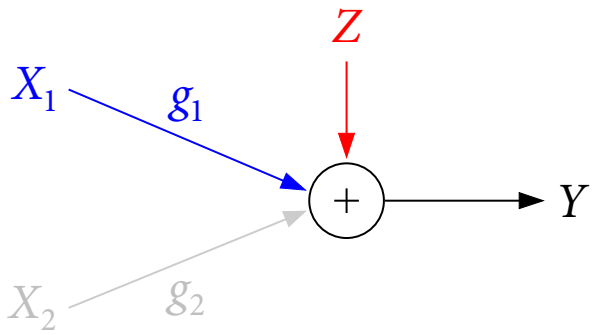

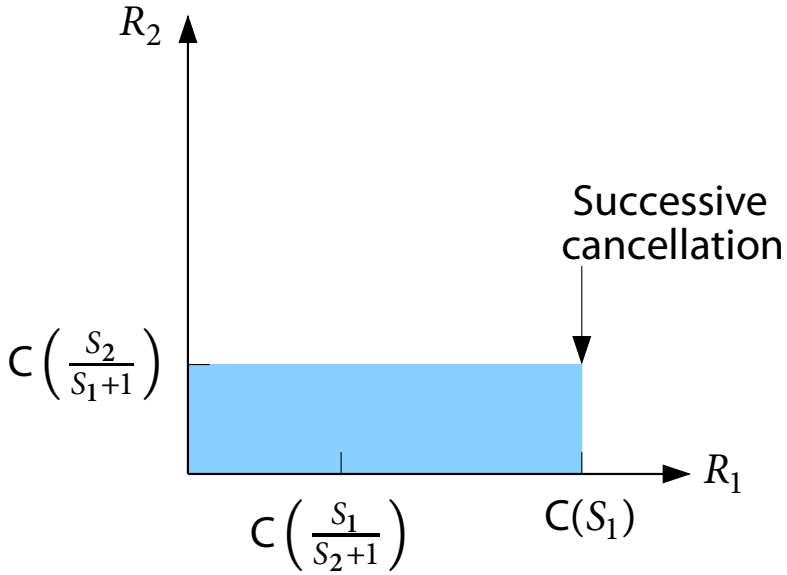

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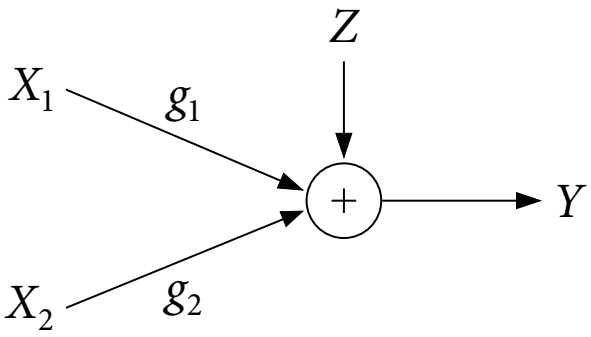

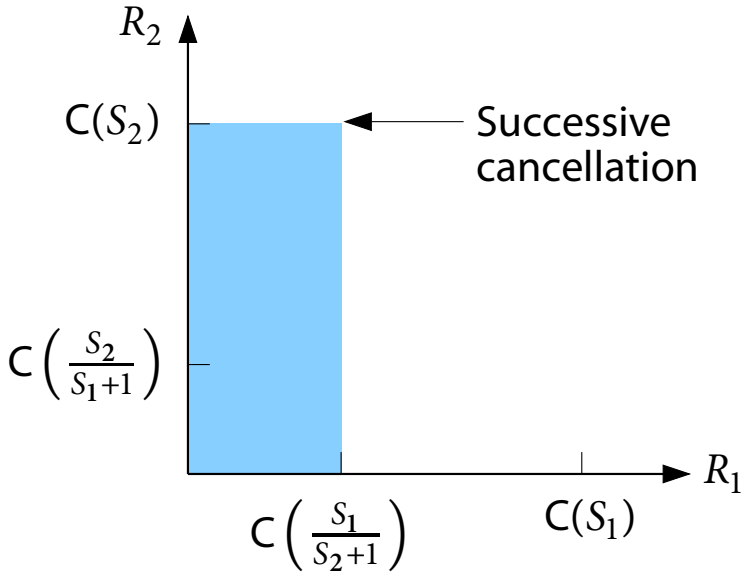

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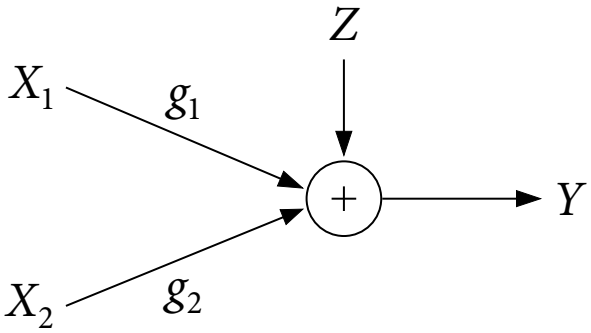

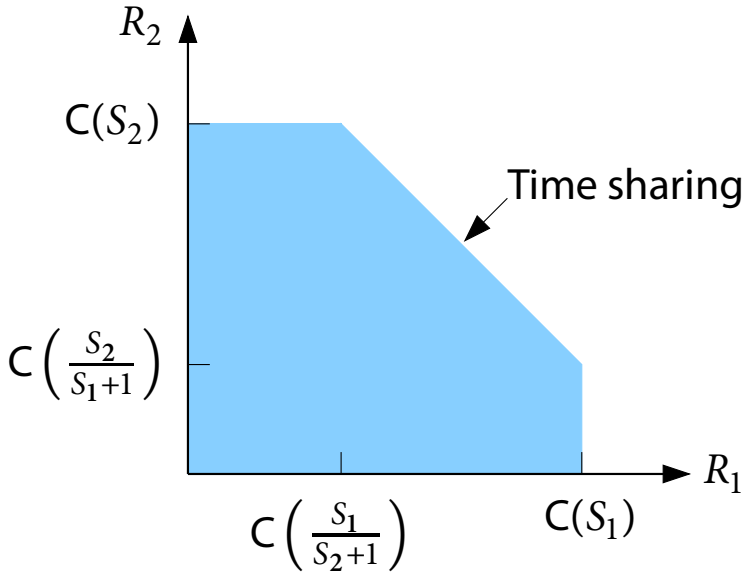

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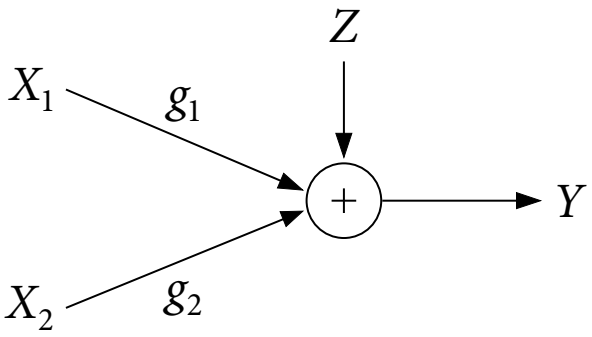

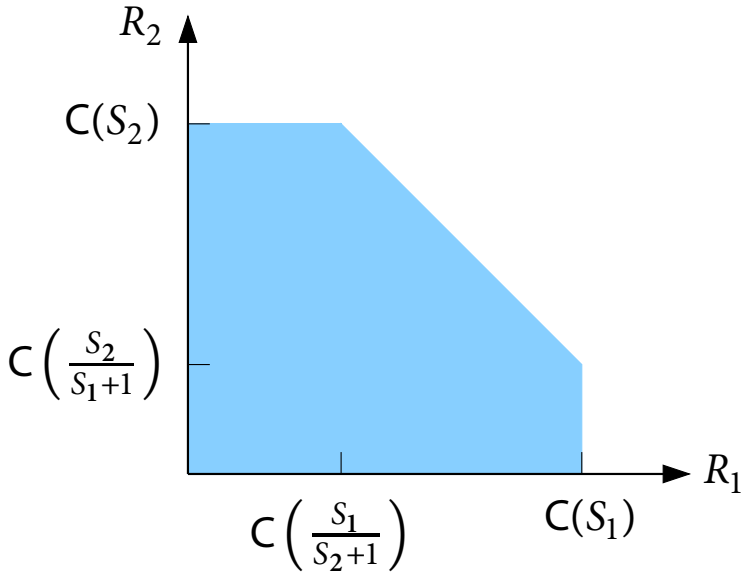

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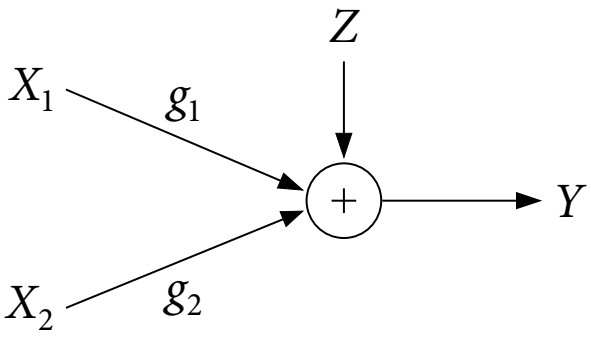

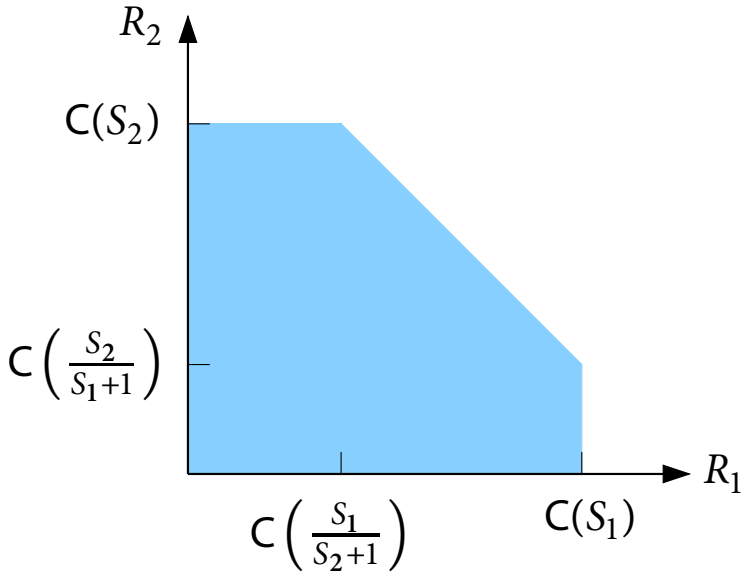

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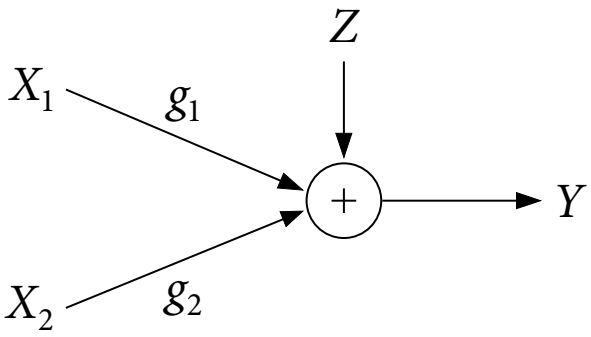

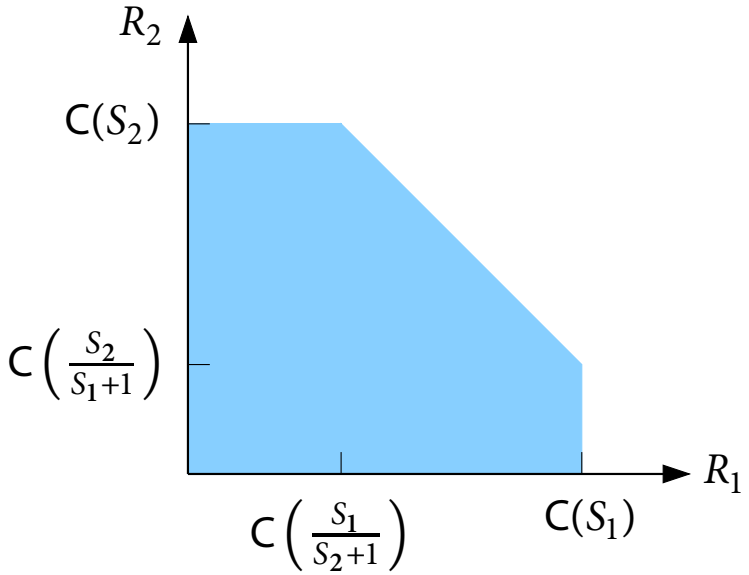

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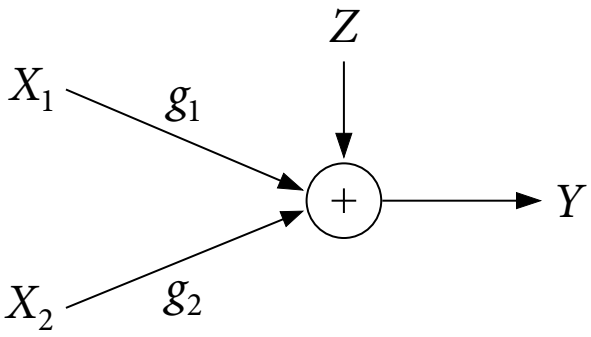
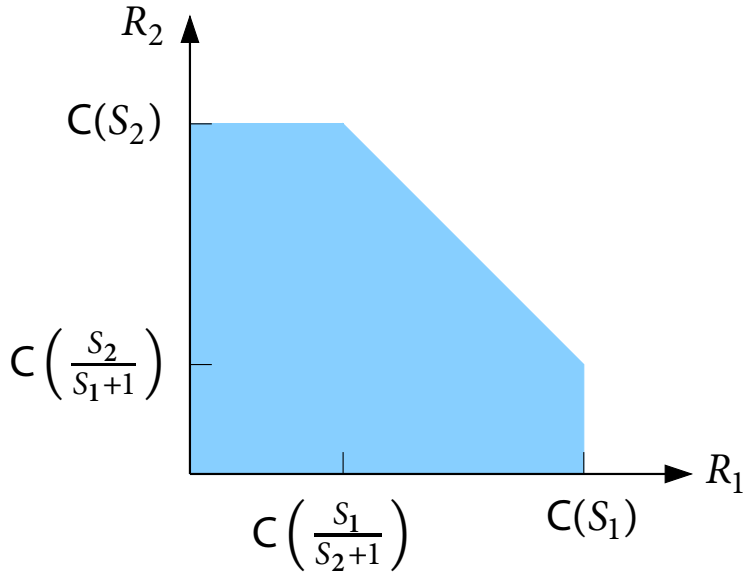
- 3GPP HSPA, EV-DO rev A (Hou–Smee–Pfister–Tomasin 2006)
- Can be generalized to any channel model with any number of senders/antennas

Multiple access (uplink) communication

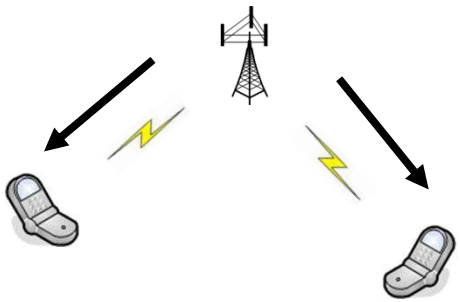




- Optimal (Ahlswede 1971, Liao 1972, Wyner 1974, Cover 1975b)
- 3GPP HSPA, EV-DO rev A (Hou–Smee–Pfister–Tomasin 2006)

- Can be generalized to any channel model with any number of senders/antennas
- Good point-to-point codes + signal processing suffices!

Broadcast (downlink) communication



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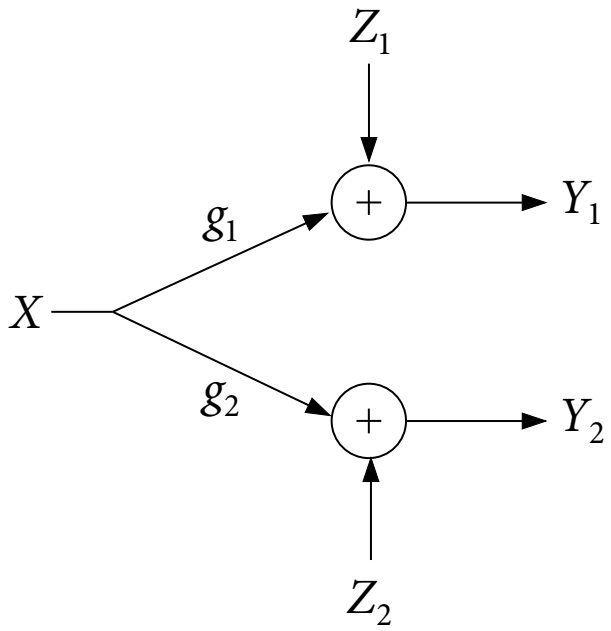
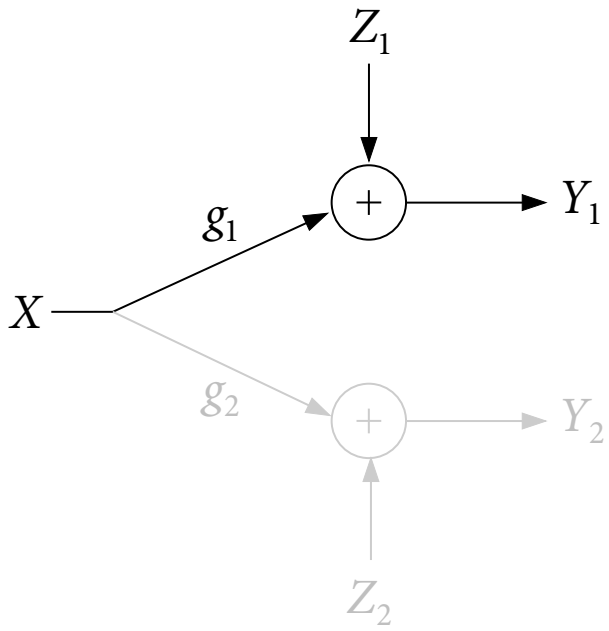


Broadcast (downlink) communication



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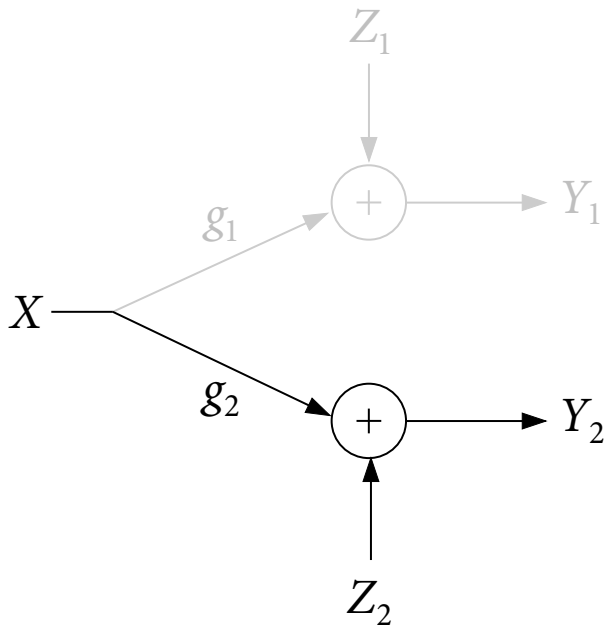

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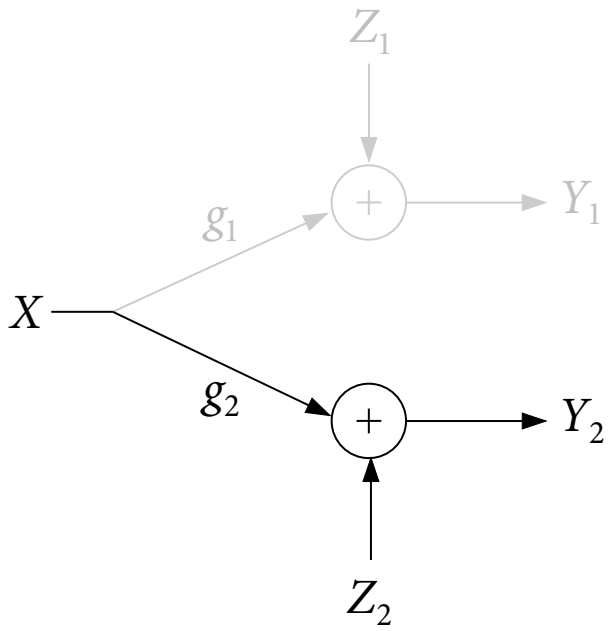

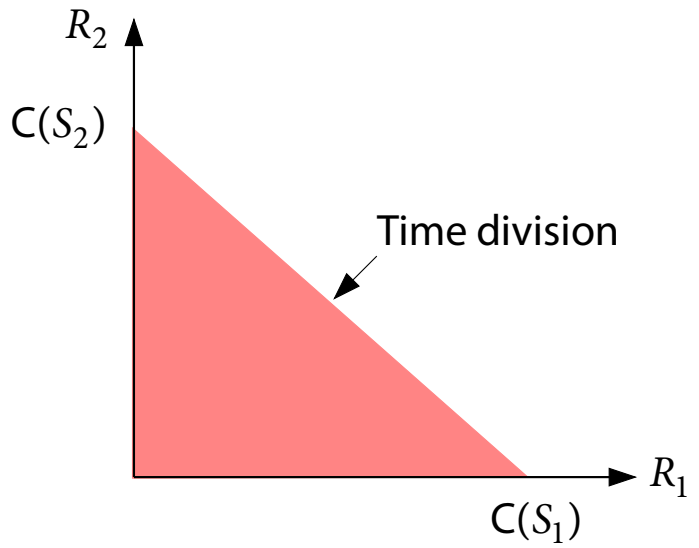

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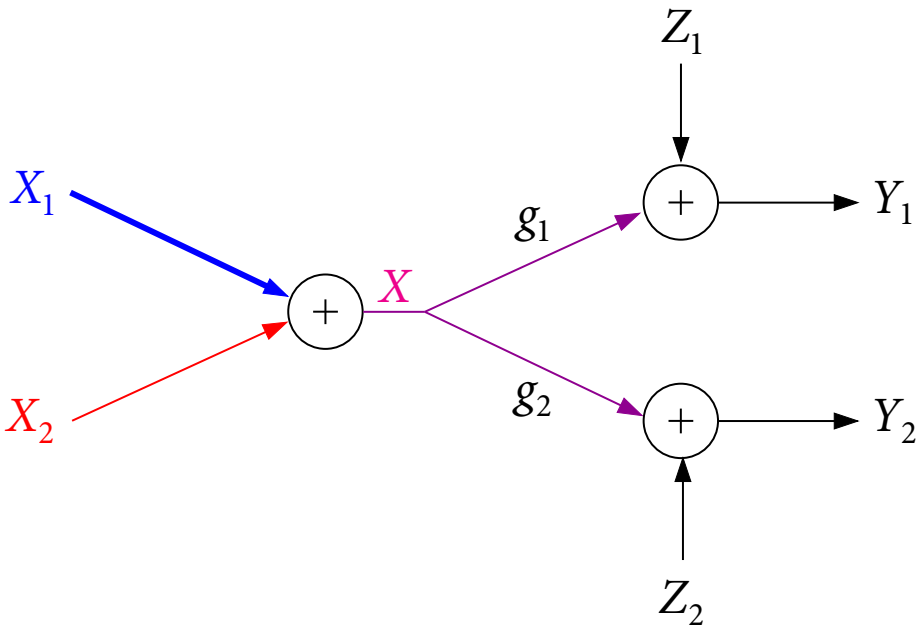

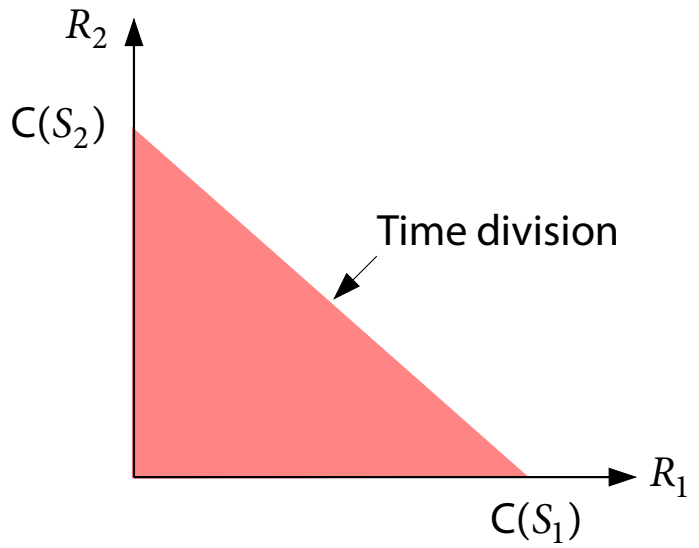

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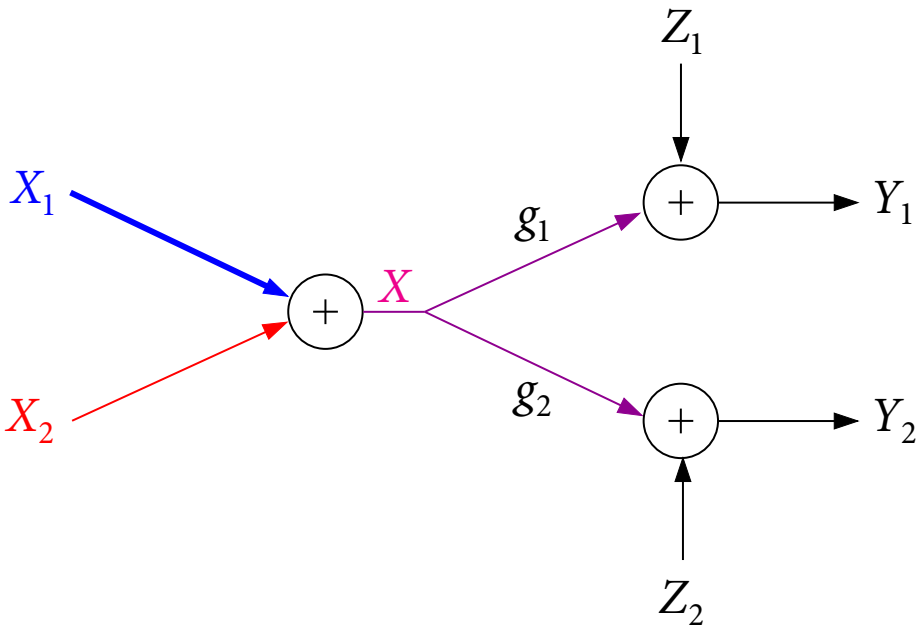

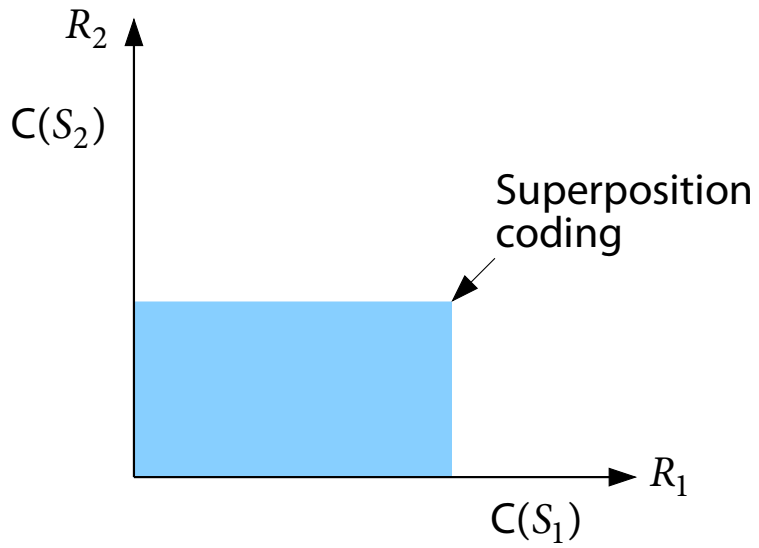

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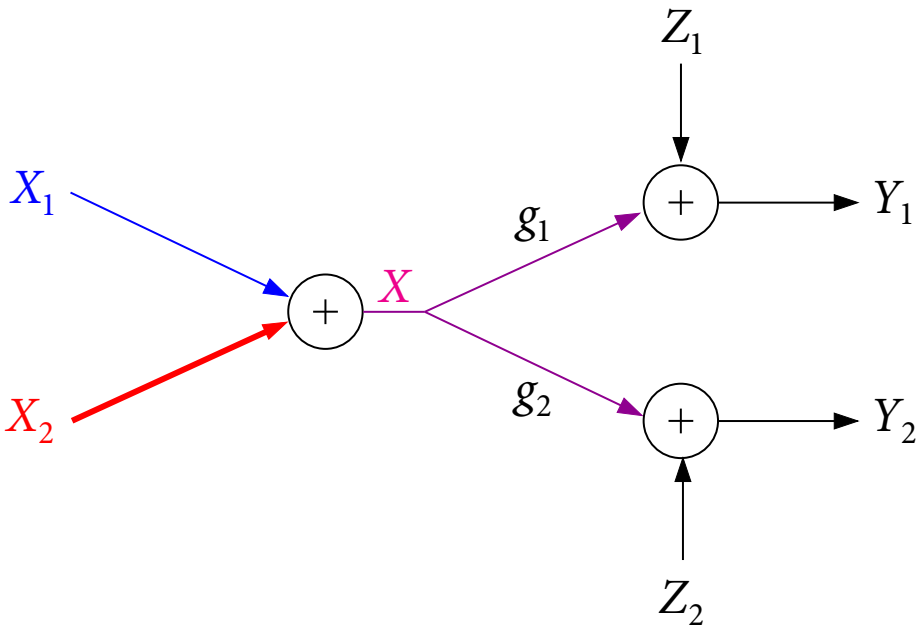

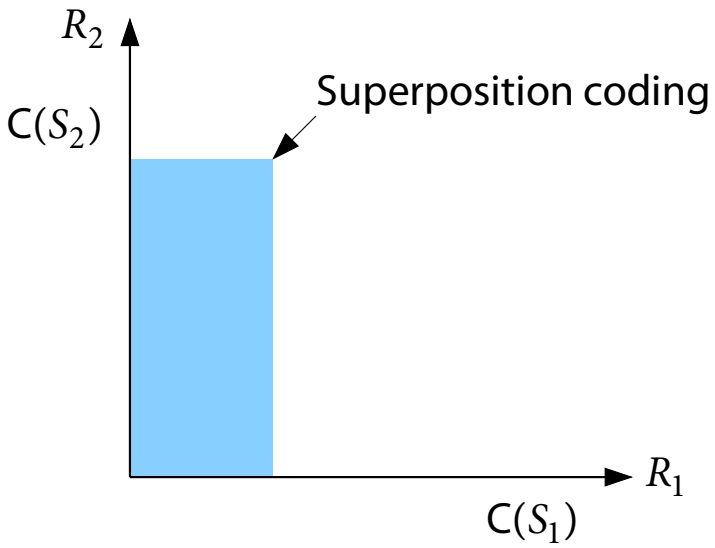

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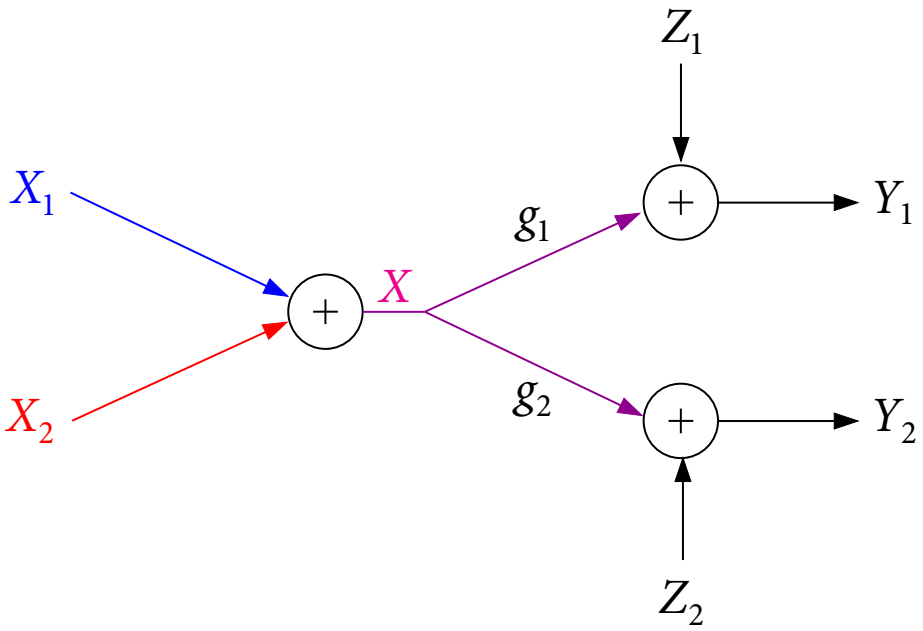

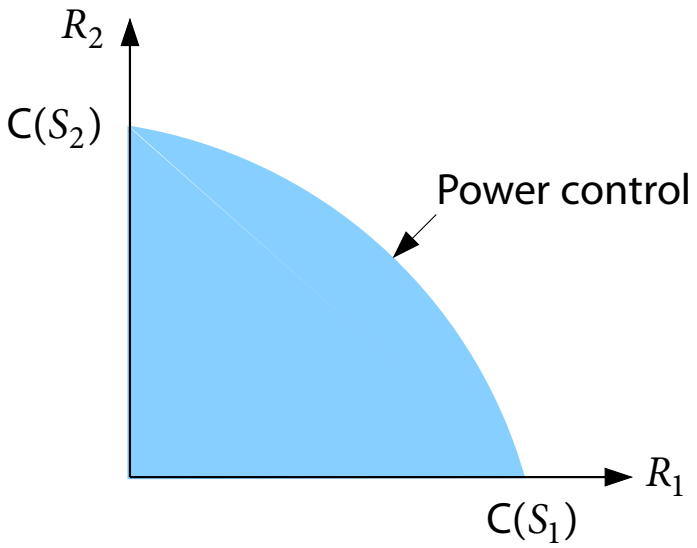

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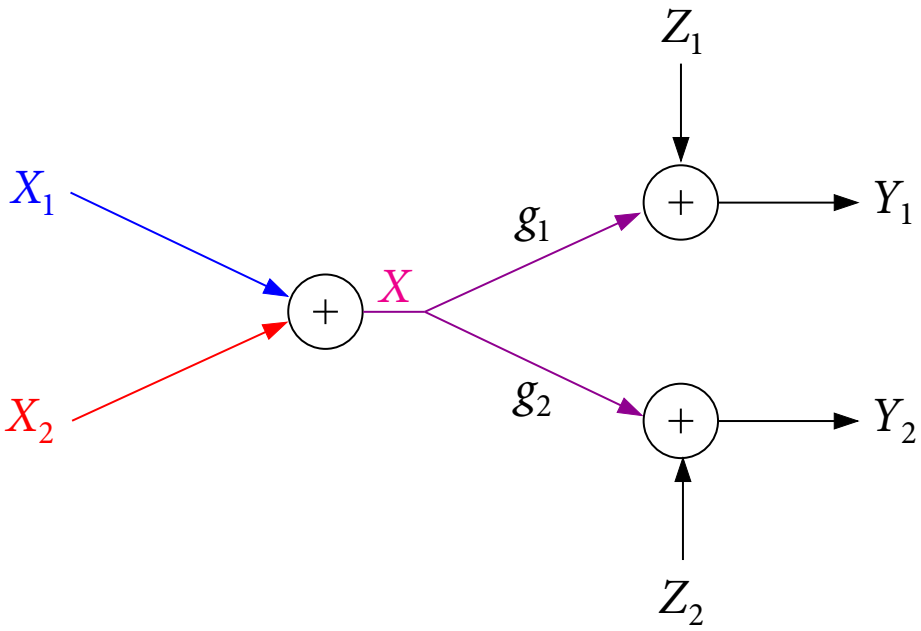

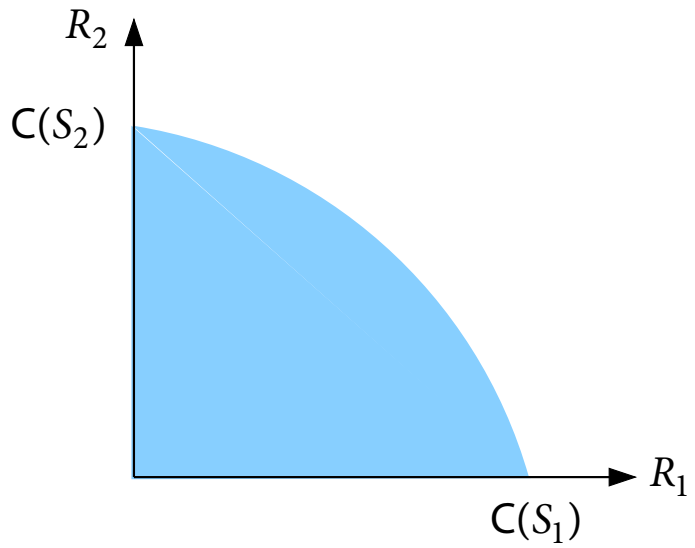

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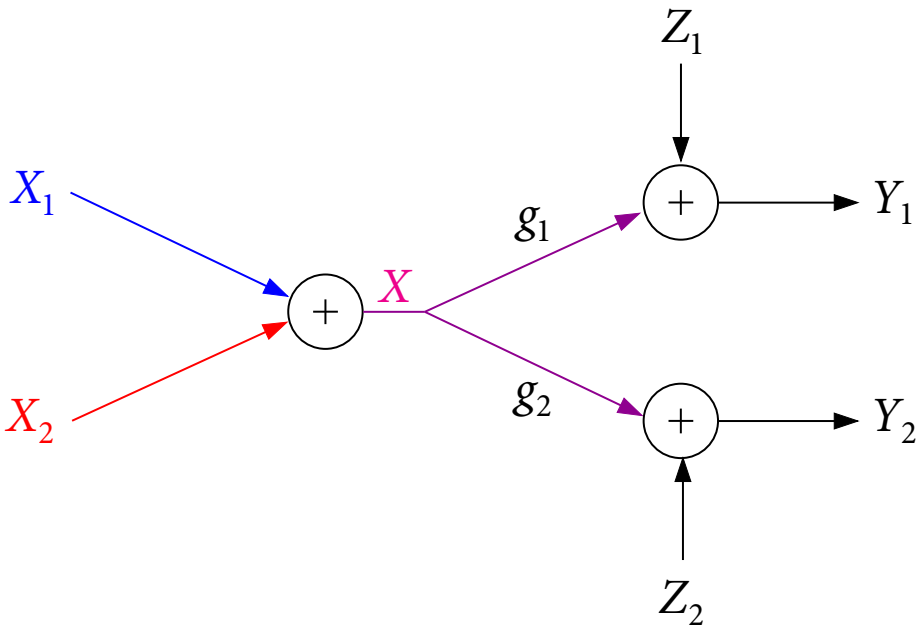
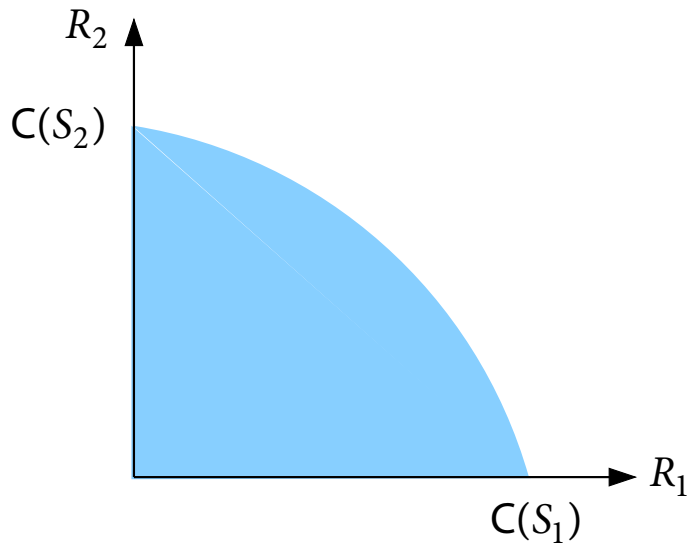
Broadcast (downlink) communication





- Optimal (Cover 1972, Bergmans 1973, 1974, Gallager 1974)
- Hierarchical modulation: DVB-T, 3GPP2 UMB

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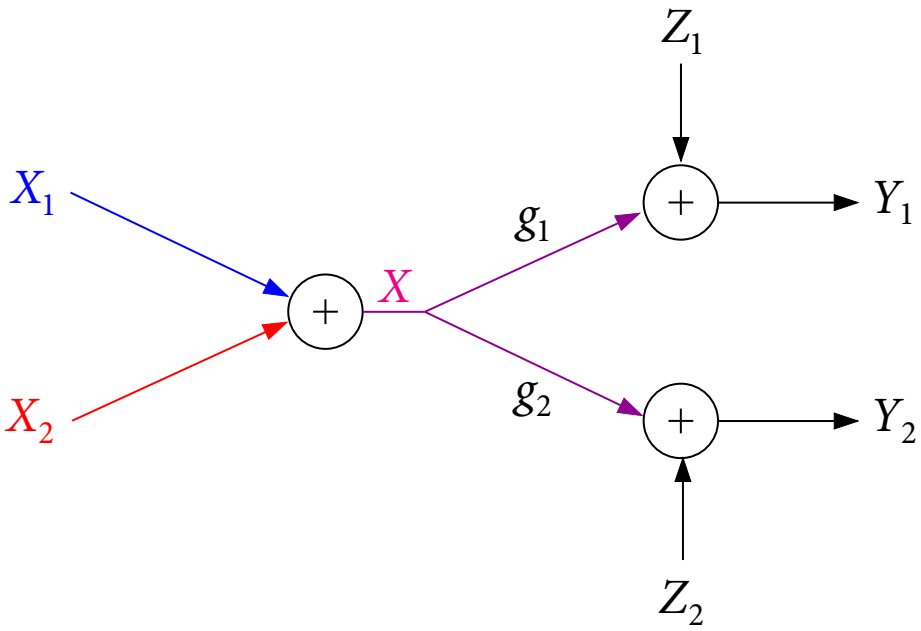

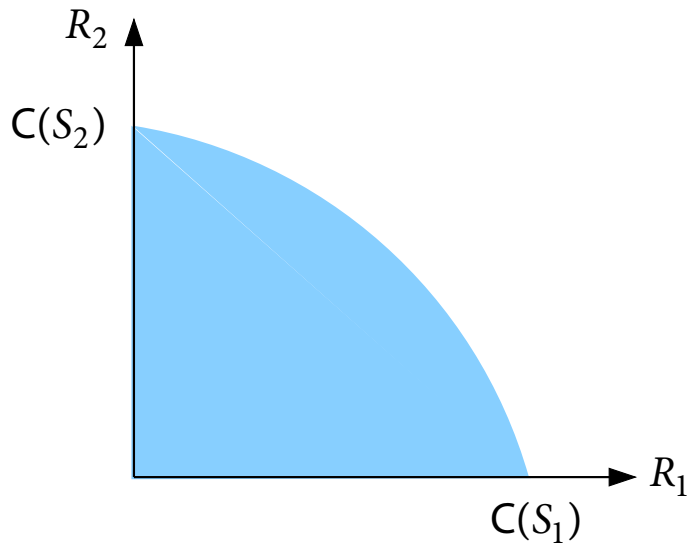

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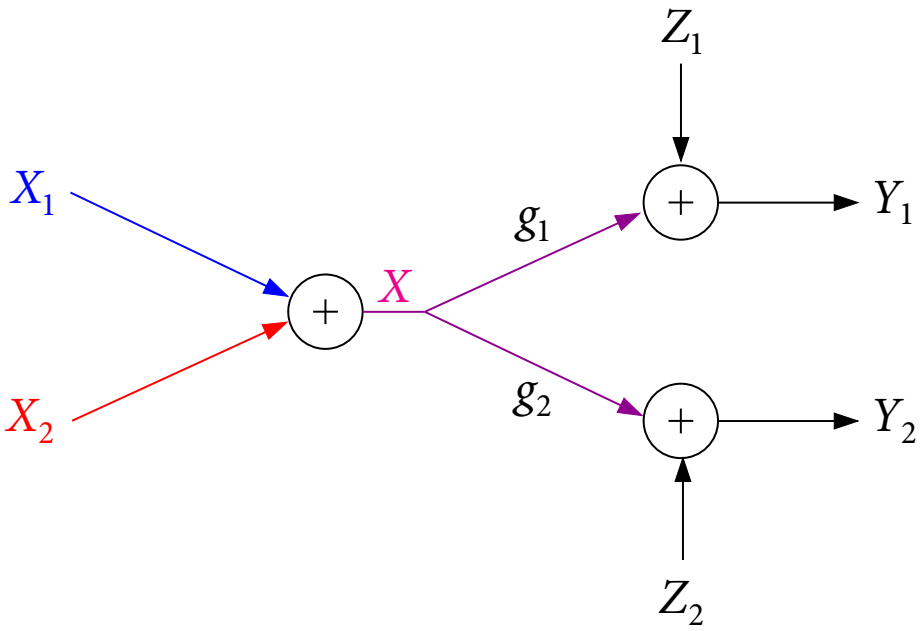
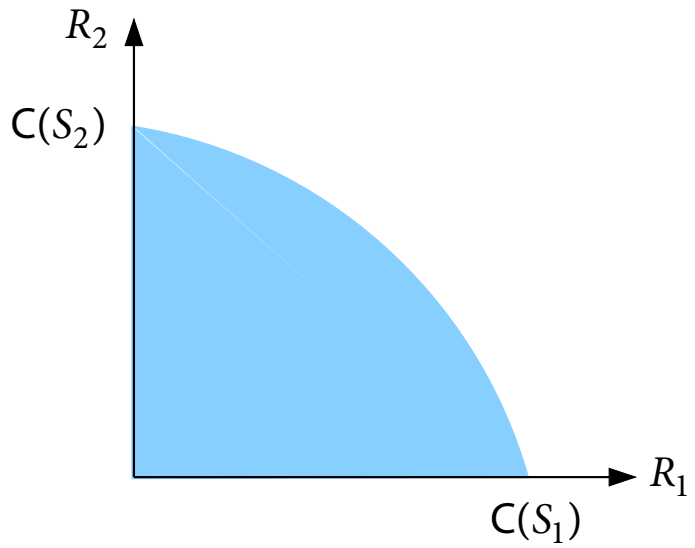
- Can be generalized to any number of single-antenna receivers

Broadcast (downlink) communication





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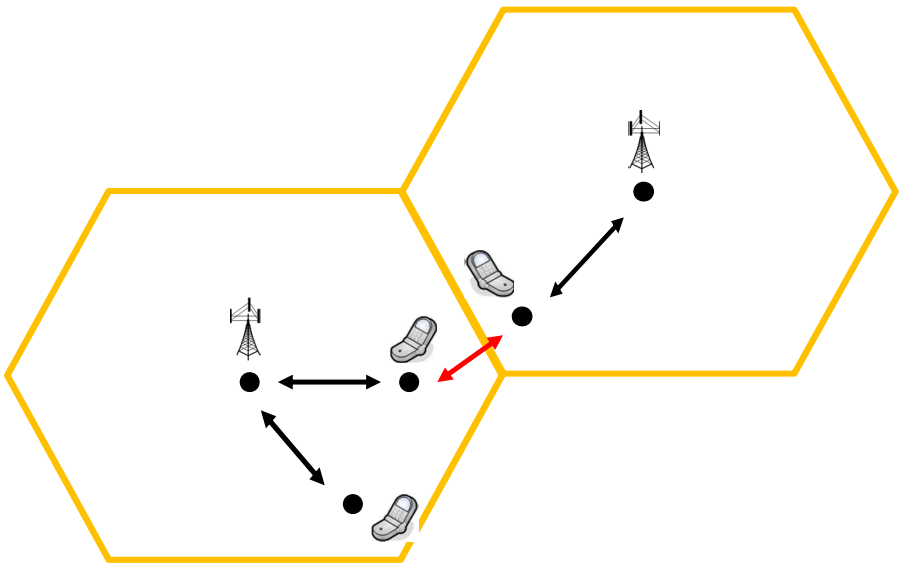
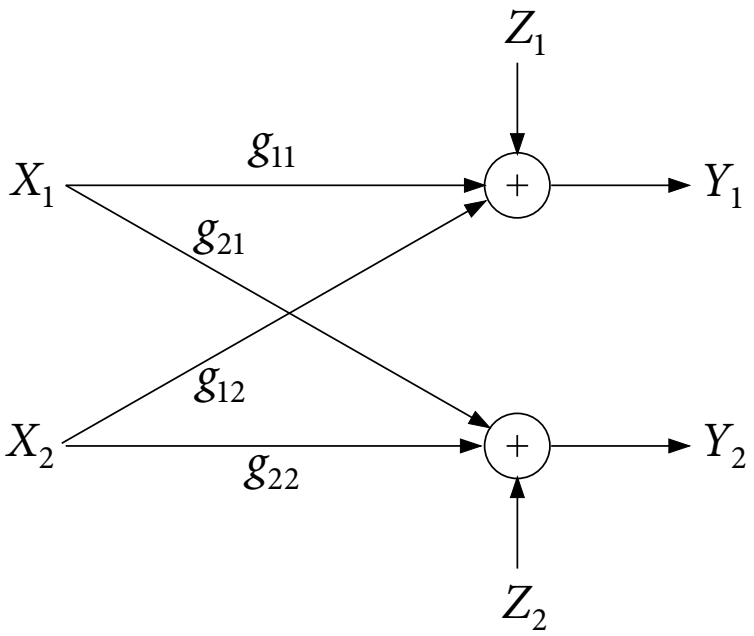
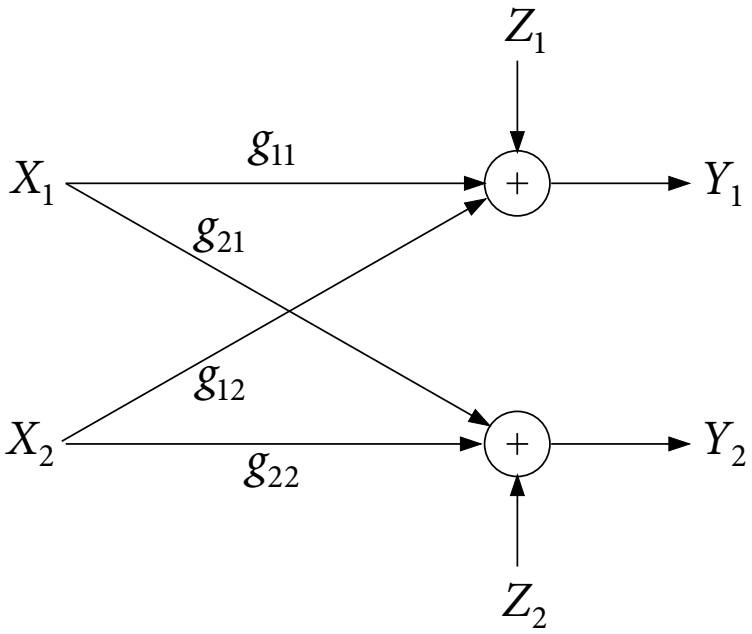
Interference (multicell) communication

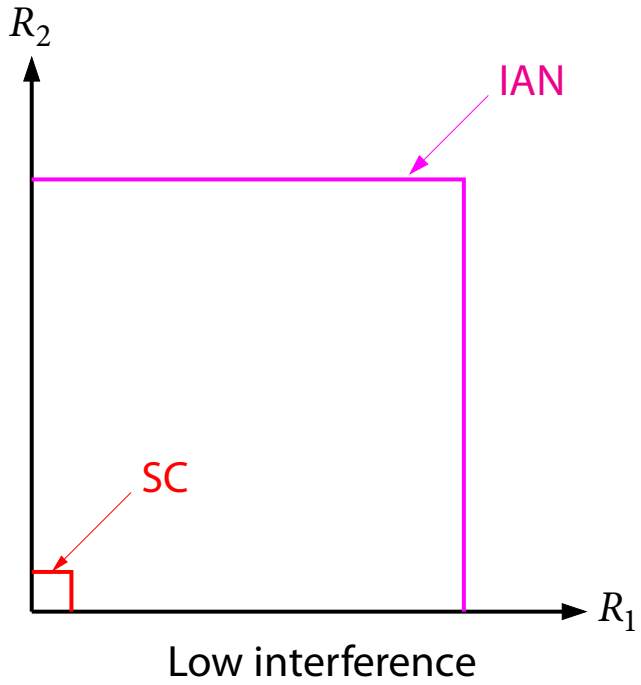


Interference (multicell) communication



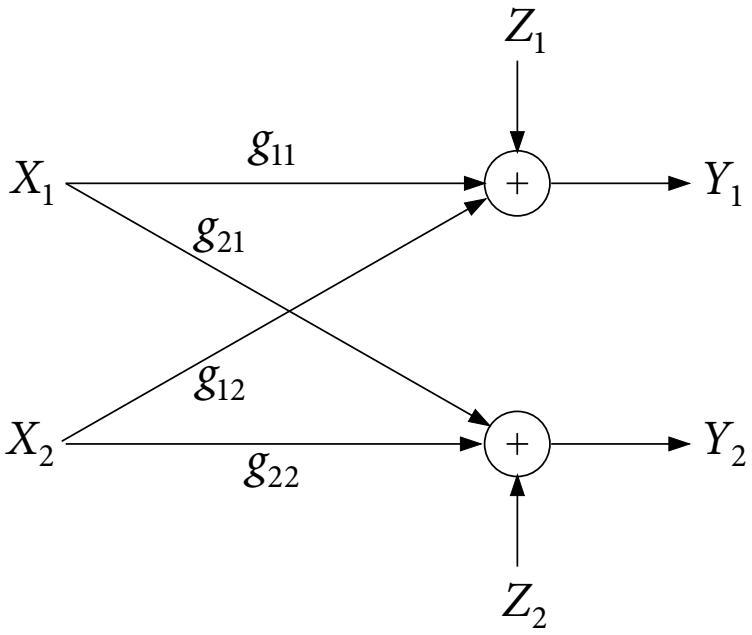
Interference (multicell) communication

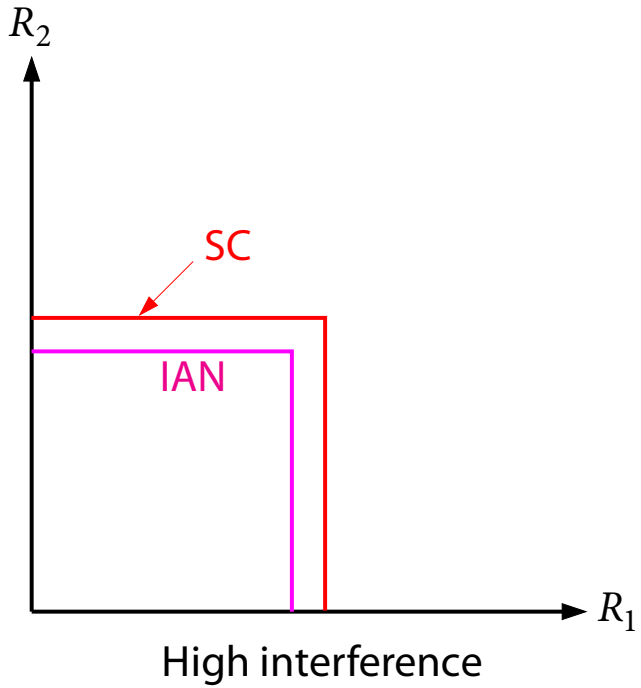




- Low interference: treating interference as noise (IAN) performs well
- High interference: successive cancellation (SC) performs well

Interference (multicell) communication





- Low interference: treating interference as noise (IAN) performs well
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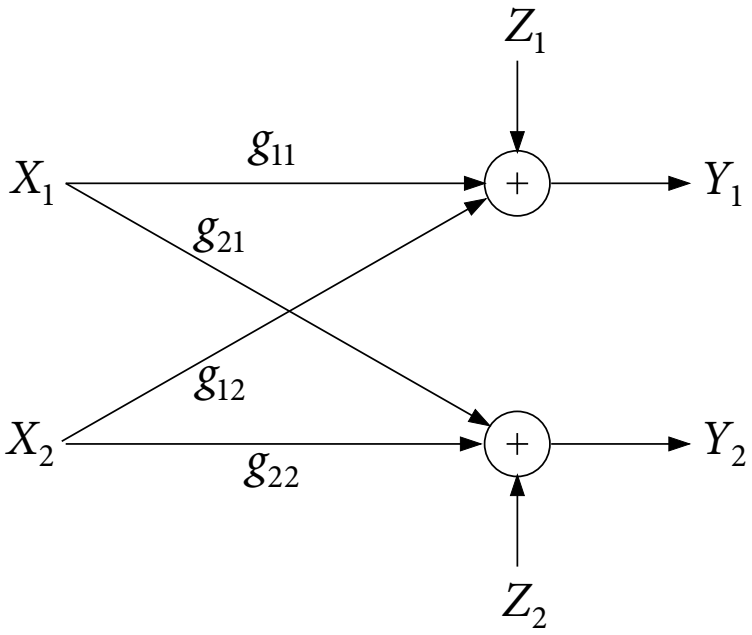
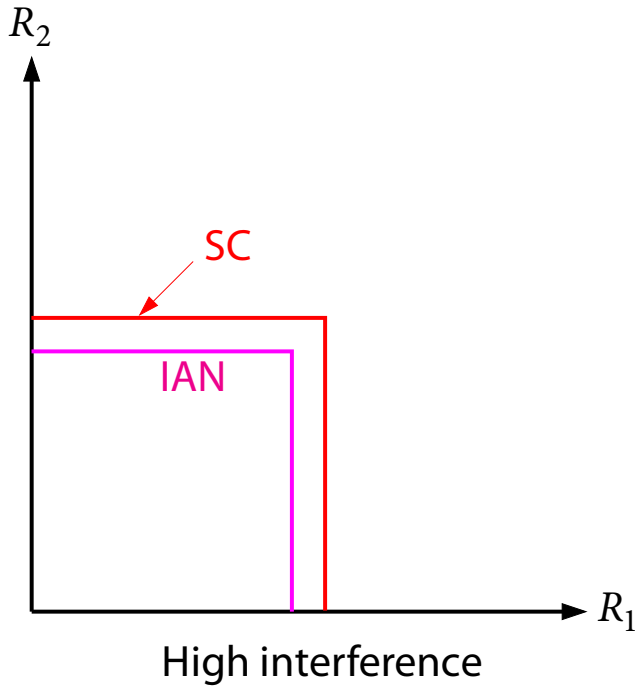
- Neither is optimal in general; nor is time division

Interference (multicell) communication

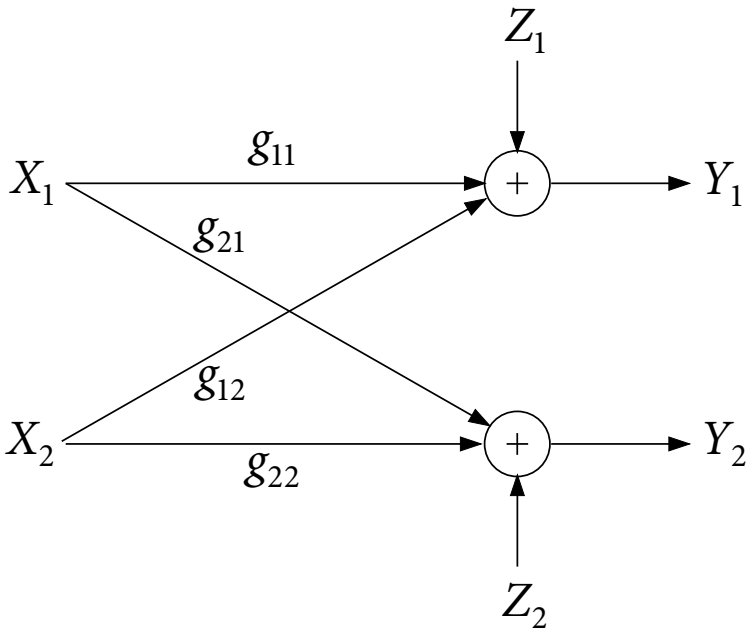


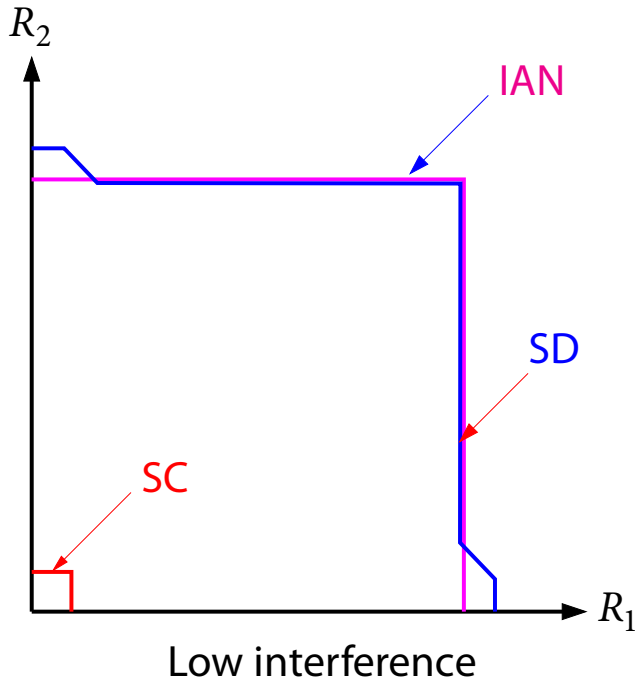


- Low interference: treating interference as noise (IAN) performs well
- High interference: successive cancellation (SC) performs well

- Neither is optimal in general; nor is time division
- In general, we need more than good point-to-point codes + signal processing

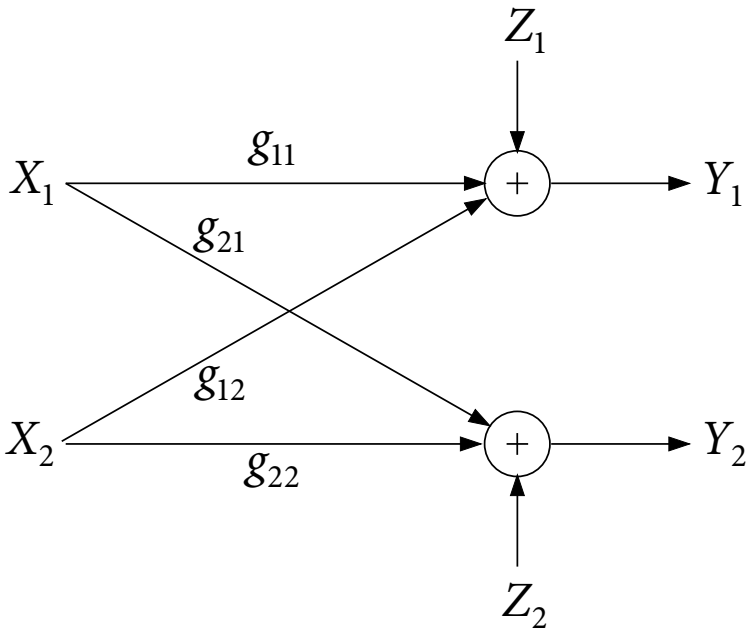
Interference (multicell) communication

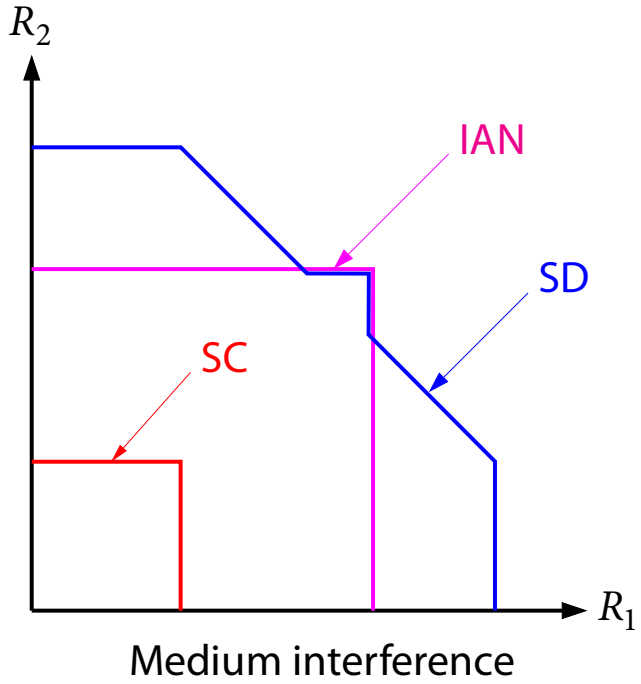




- Simultaneous decoding

Interference (multicell) communication

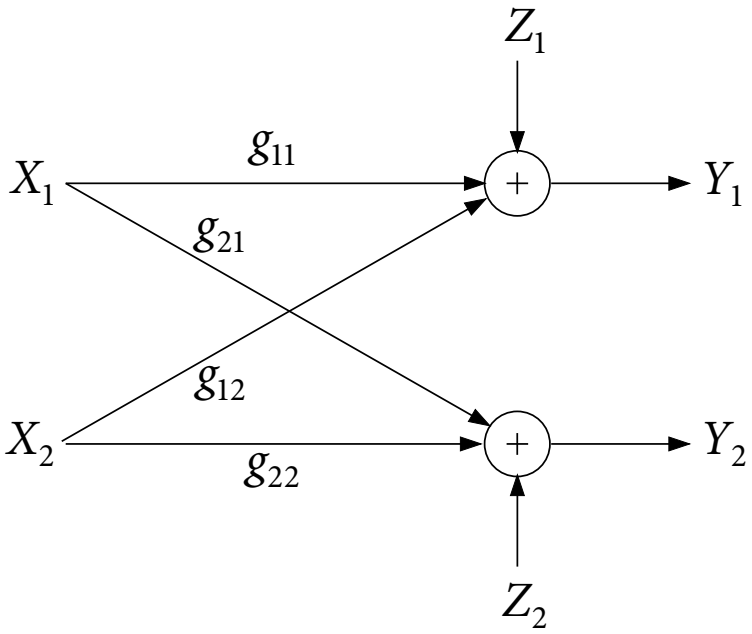


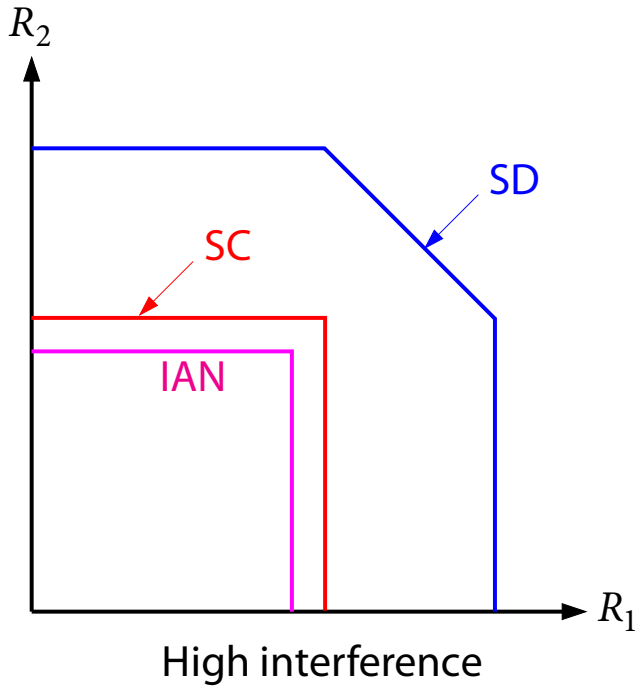


Medium interference

- Simultaneous decoding

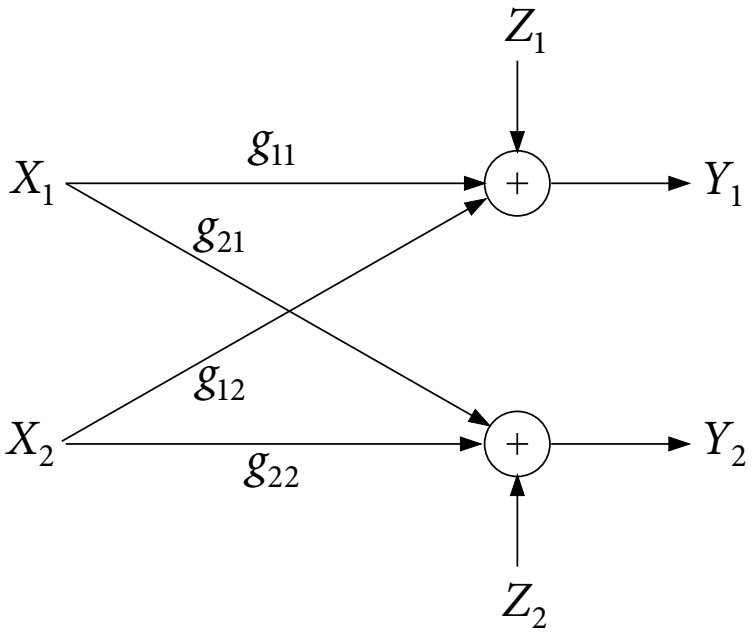
Interference (multicell) communication

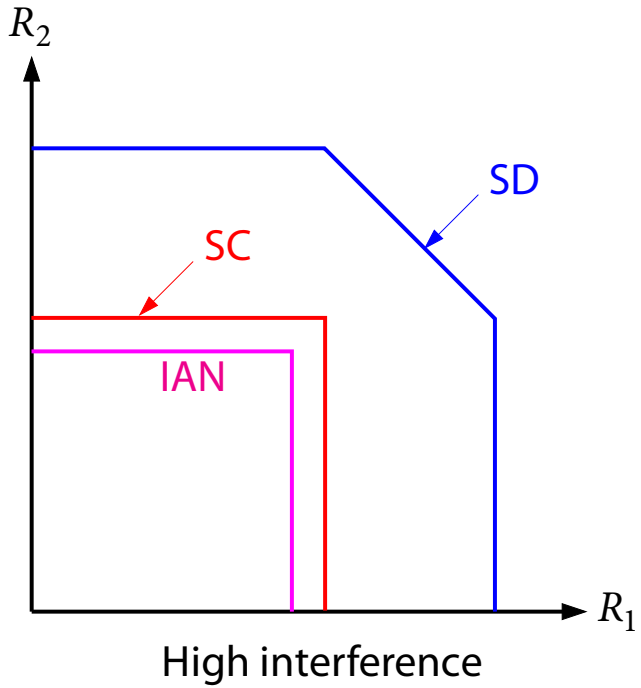




- Simultaneous decoding

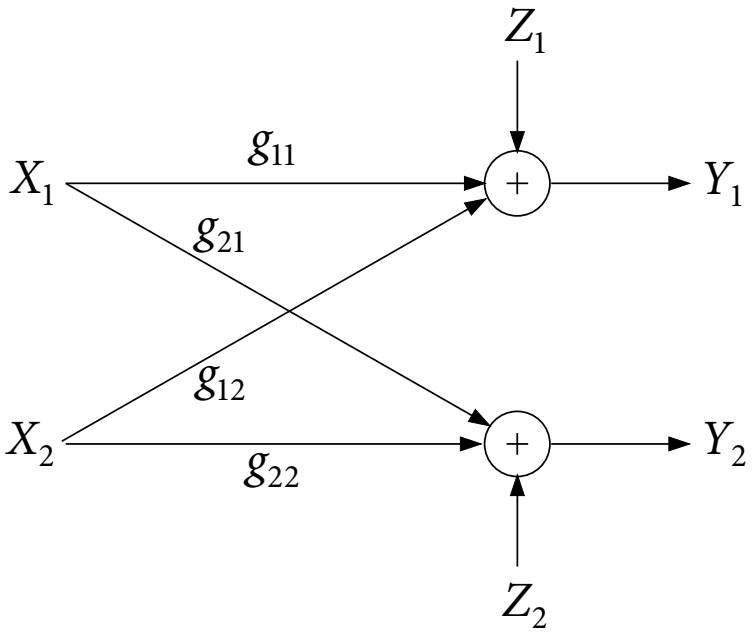
Interference (multicell) communication

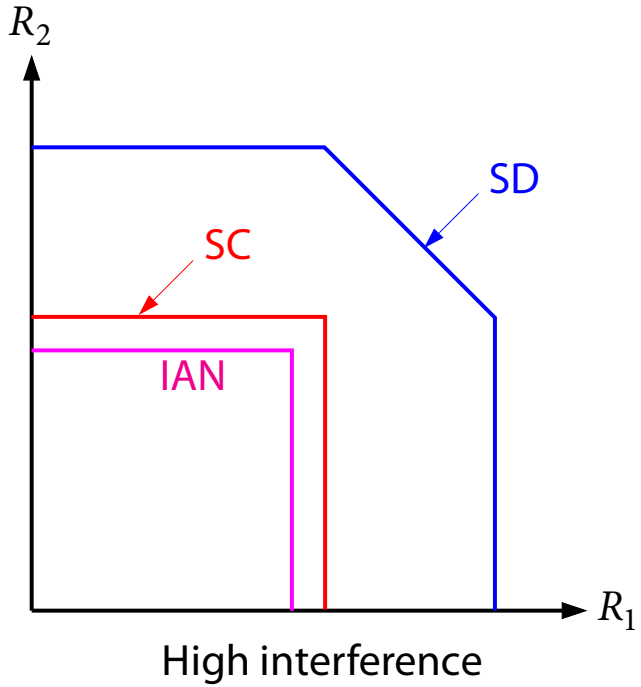




- Simultaneous decoding
  - Always better than treating interference as noise and successive cancellation

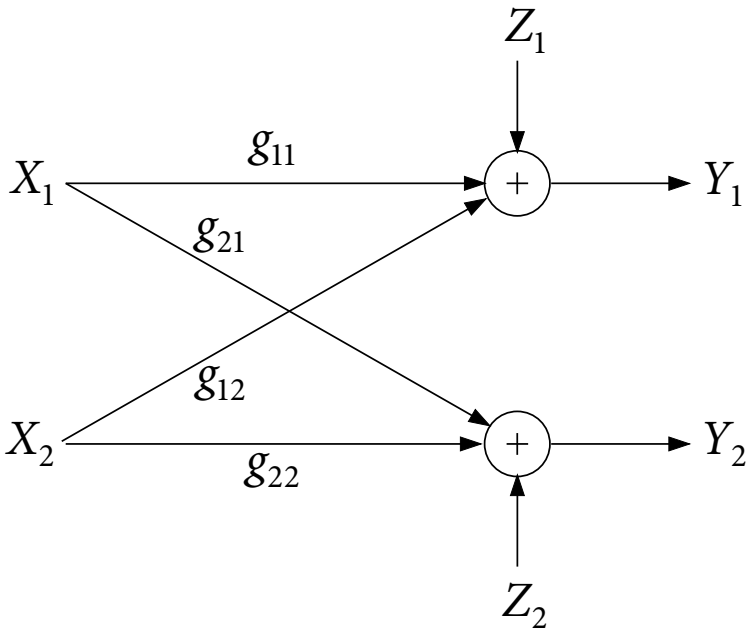
Interference (multicell) communication

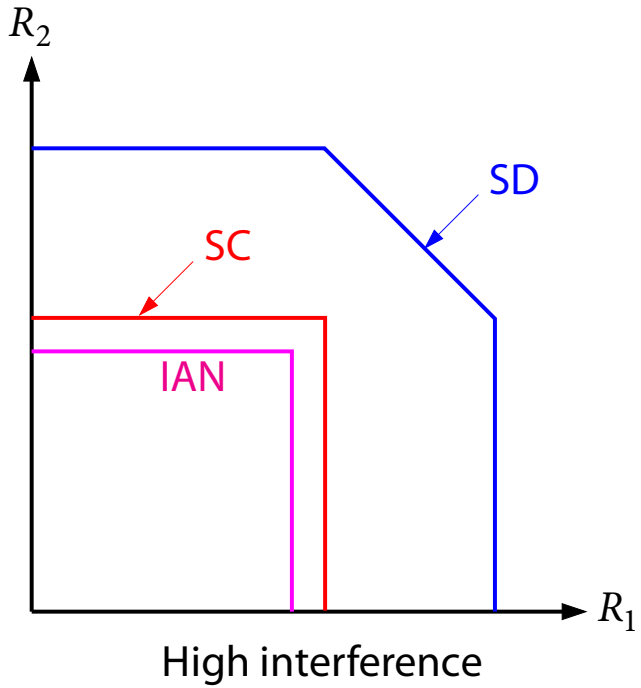




- Simultaneous decoding
  - Always better than treating interference as noise and successive cancellation
  - Optimal under random coding (Bandemer–El Gamal–K 2012)

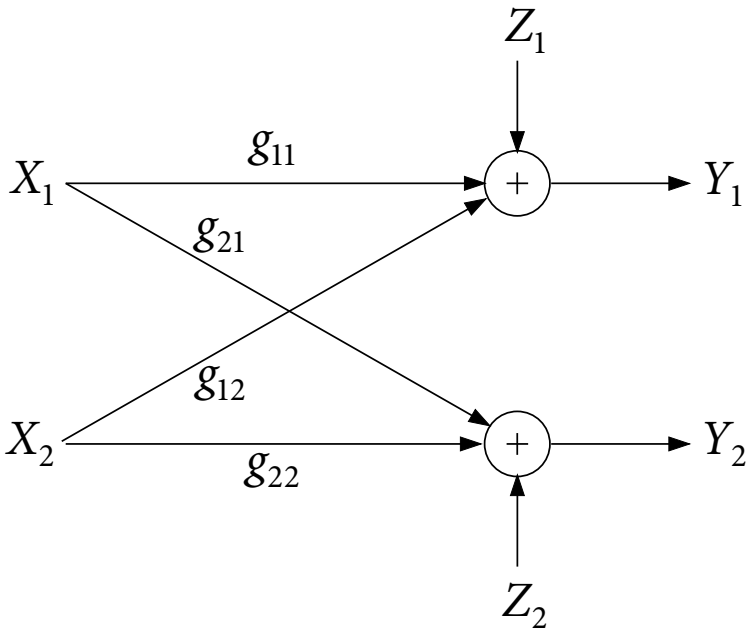
Interference (multicell) communication

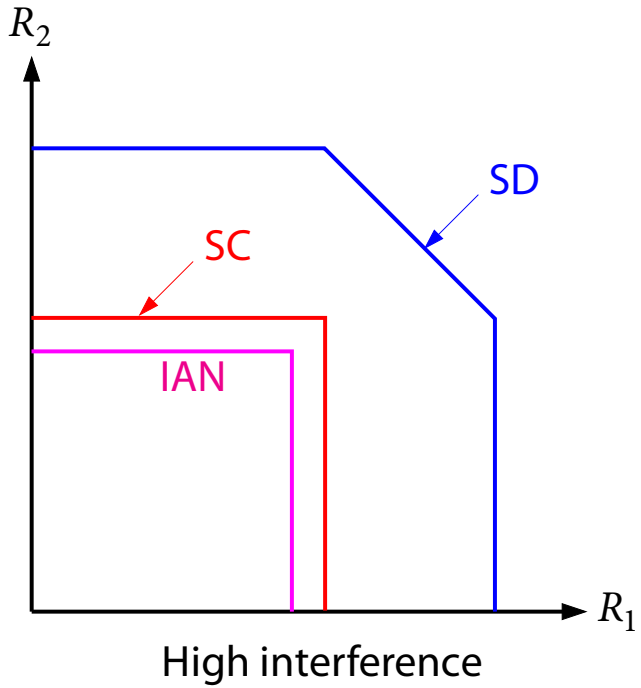




- Simultaneous decoding
  - Always better than treating interference as noise and successive cancellation
  - Optimal under random coding (Bandemer–El Gamal–K 2012)
  - + superposition coding: optimal within $1/2$ bit (Etkin–Tse–Wang 2008)

Interference (multicell) communication

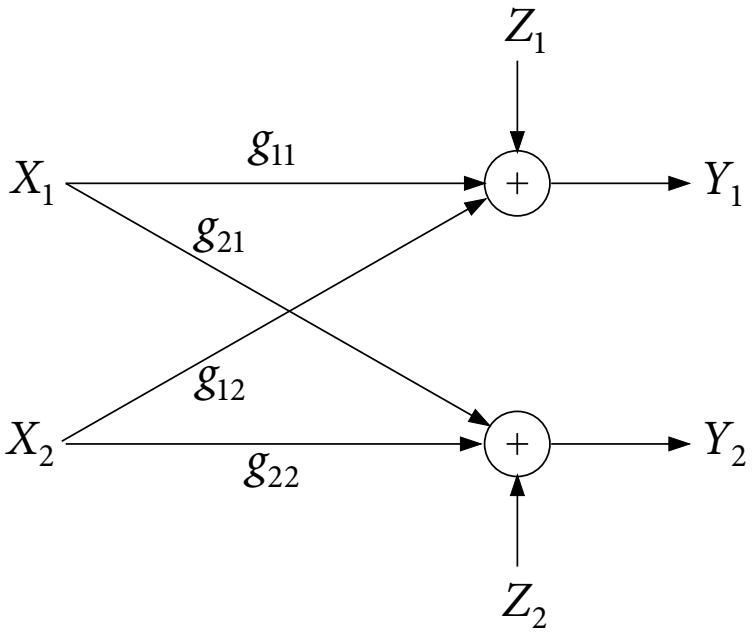


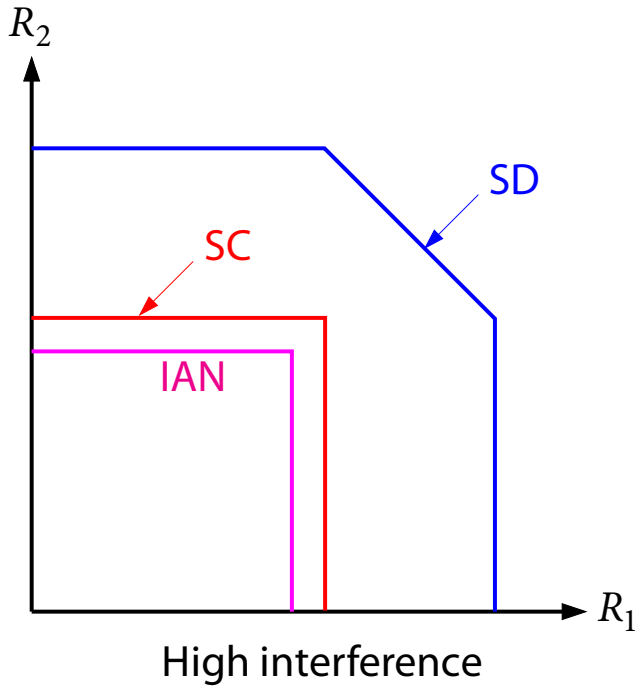


Conclusion 1

Interference-aware coding schemes can boost performance tremendously

Interference (multicell) communication





High interference

Conclusion 1

Interference-aware coding schemes can boost performance tremendously

Challenge 1

Low-complexity implementation of simultaneous decoding

More on simultaneous decoding

- Maximum likelihood decoding (MLD): At receiver 1, find

$$\begin{aligned}
&\arg\max_{\hat{m}_1} f(y_1^n \,|\, x_1^n(\hat{m}_1)) \\
&= \arg\max_{\hat{m}_1} \sum_{m_2} f(y_1^n \,|\, x_1^n(\hat{m}_1), x_2^n(m_2)) \\
&= \arg\max_{\hat{m}_1} \sum_{m_2} \exp(-\|y^n - g_{11}x_1^n(\hat{m}_1) - g_{12}x_2^n(m_2)\|^2/2)
\end{aligned}$$

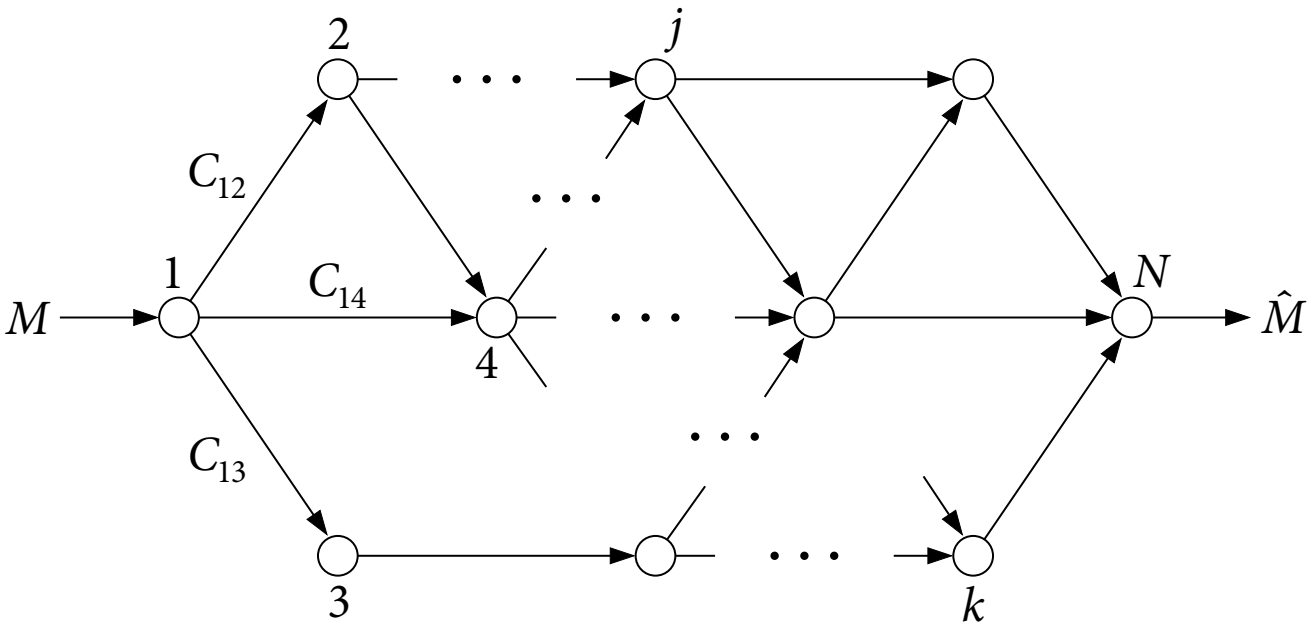
- Simultaneous decoding (Bandemer–El Gamal–K 2012):

$$\begin{aligned}
&\approx \arg\max_{\hat{m}_1} \max_{m_2} \exp(-\|y_1^n - g_{11}x_1^n(\hat{m}_1) - g_{12}x_2^n(m_2)\|^2/2) \\
&= \arg\max_{\hat{m}_1} \max_{m_2} -\|y_1^n - g_{11}x_1^n(\hat{m}_1) - g_{12}x_2^n(m_2)\| \\
&= \arg\min_{\hat{m}_1} \min_{m_2} \|y_1^n - g_{11}x_1^n(\hat{m}_1) - g_{12}x_2^n(m_2)\|
\end{aligned}$$

Outline of the talk

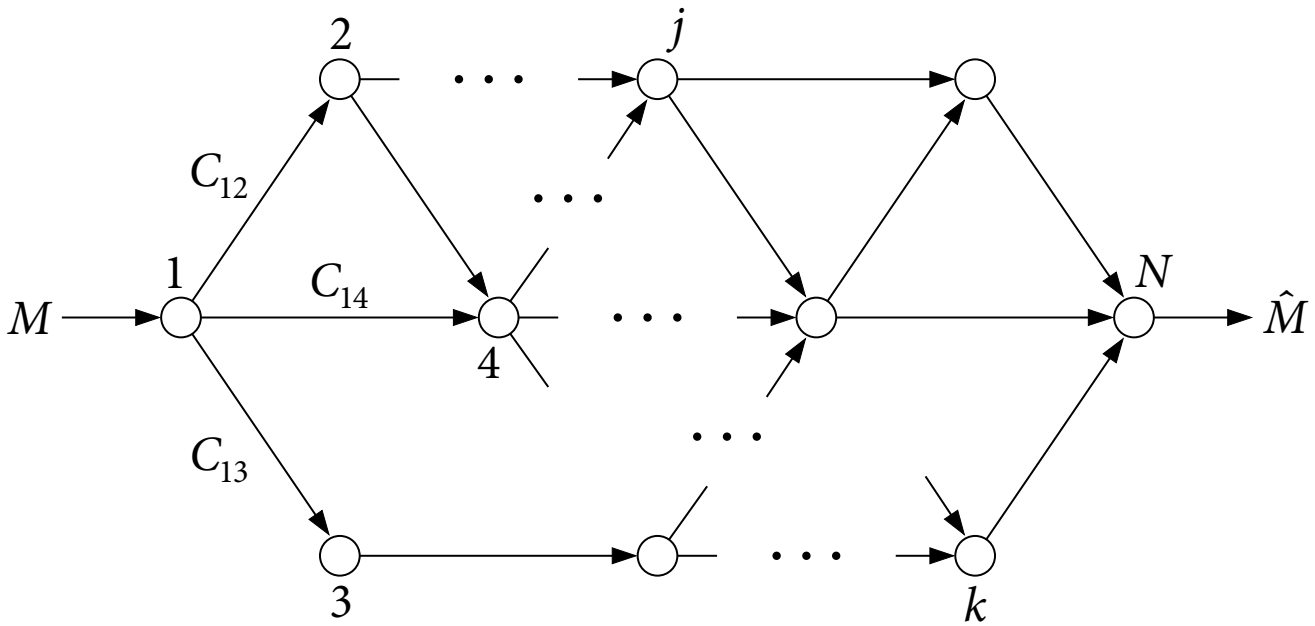
- Canonical problems in network communication
  - Interference management
  - Multiple unicast
  - Wireless relaying
- Solutions from network information theory
- Challenges for the future

Graphical unicast networks



- Model for wired networks (Internet, distributed storage, …)

Graphical unicast networks



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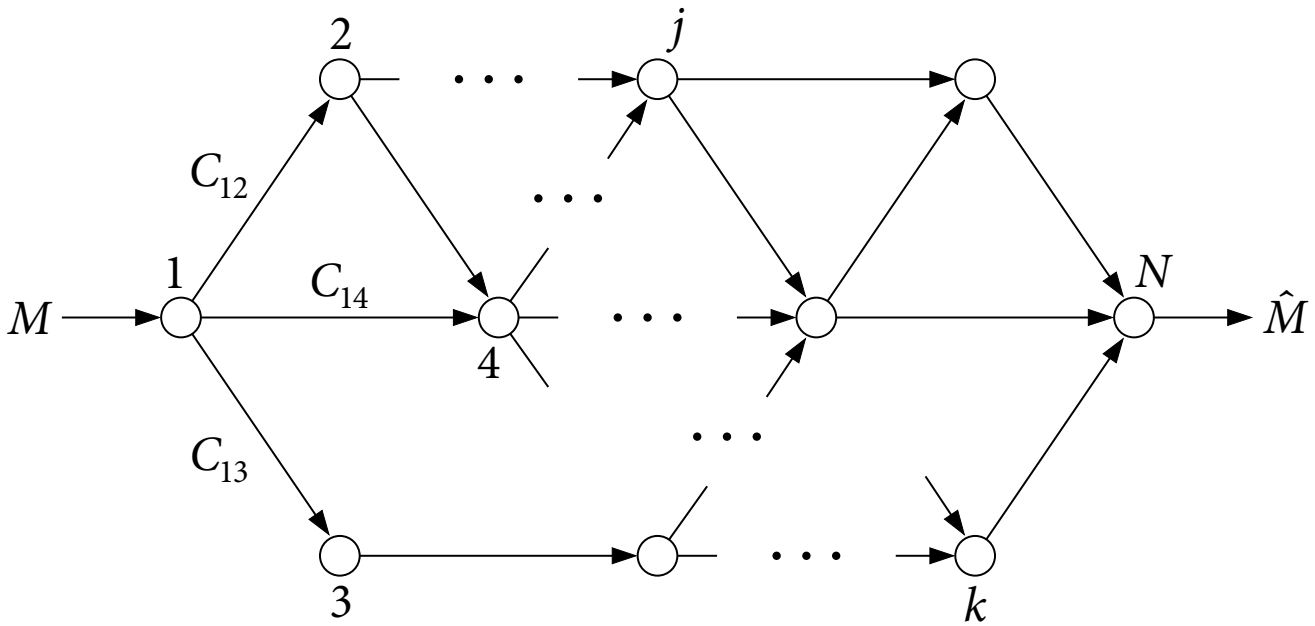
- Directed weighted graph $(\mathcal{N}, \mathcal{E})$ with link capacities C_{jk}

Graphical unicast networks



- Model for wired networks (Internet, distributed storage, …)
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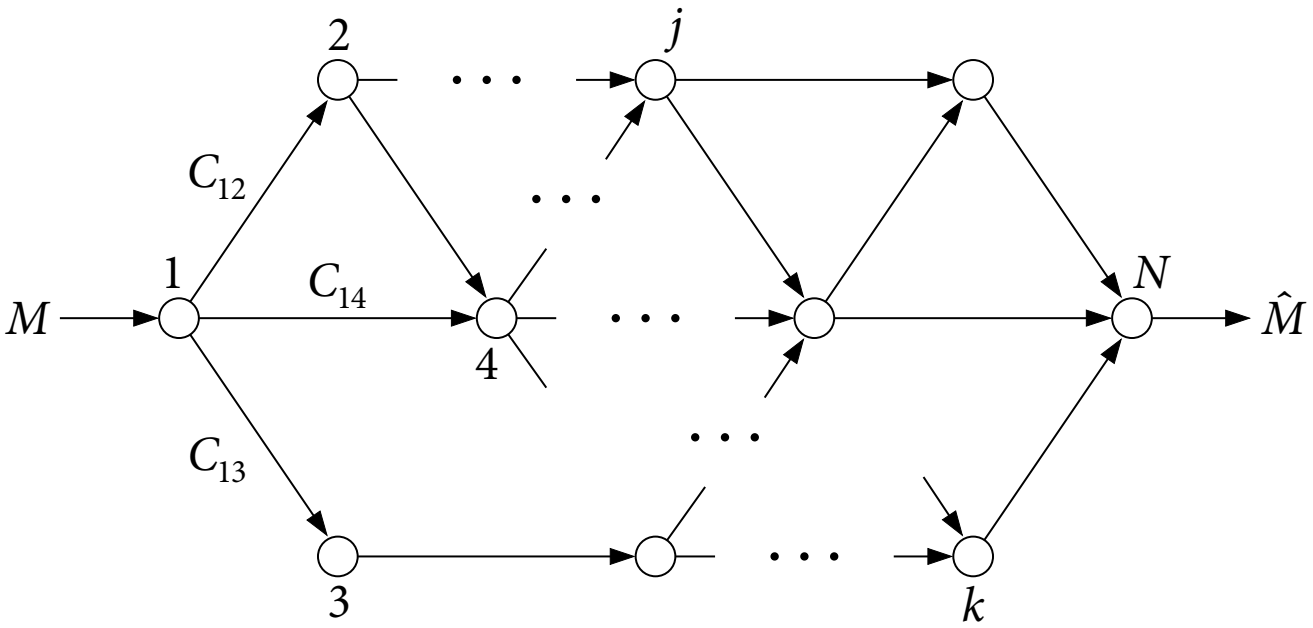
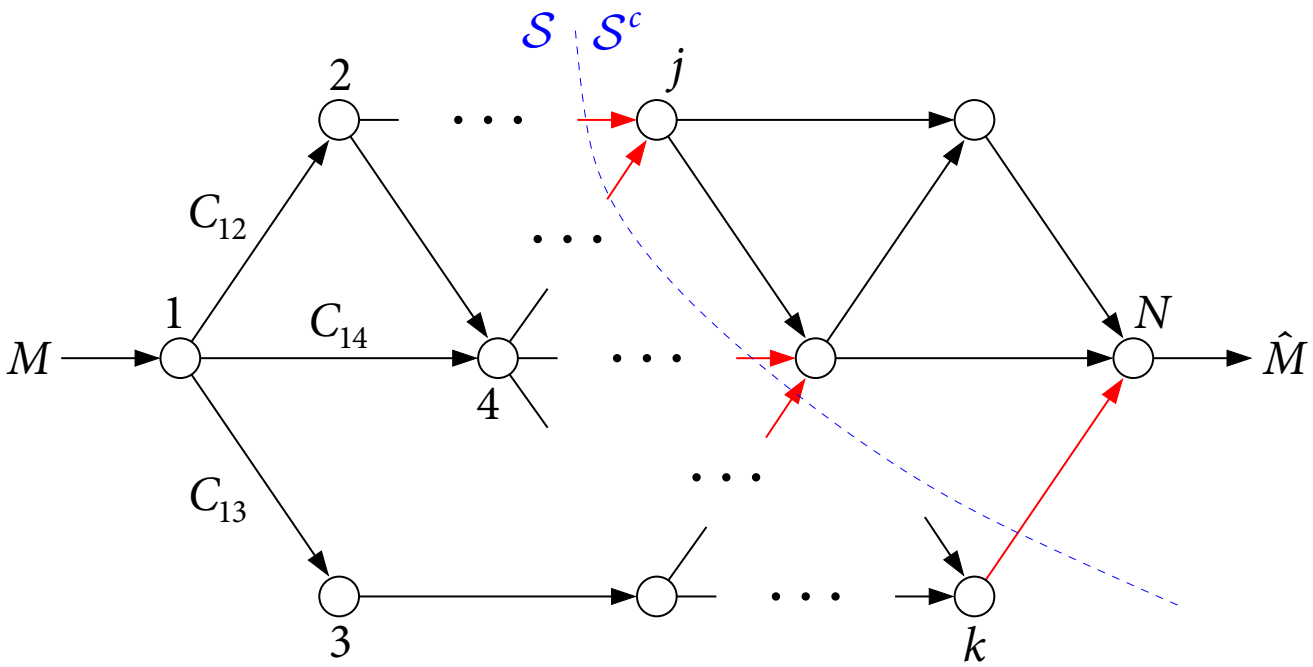
Network information flow questions

- Network capacity
- Optimal coding schemes/protocols/architectures

Max-flow min-cut theorem



Max-flow min-cut theorem



Ford–Fulkerson (1956)

$$C = \min_{\mathcal{S} \subset \mathcal{N} : 1 \in \mathcal{S},\, N \in \mathcal{S}^c} C(\mathcal{S})$$

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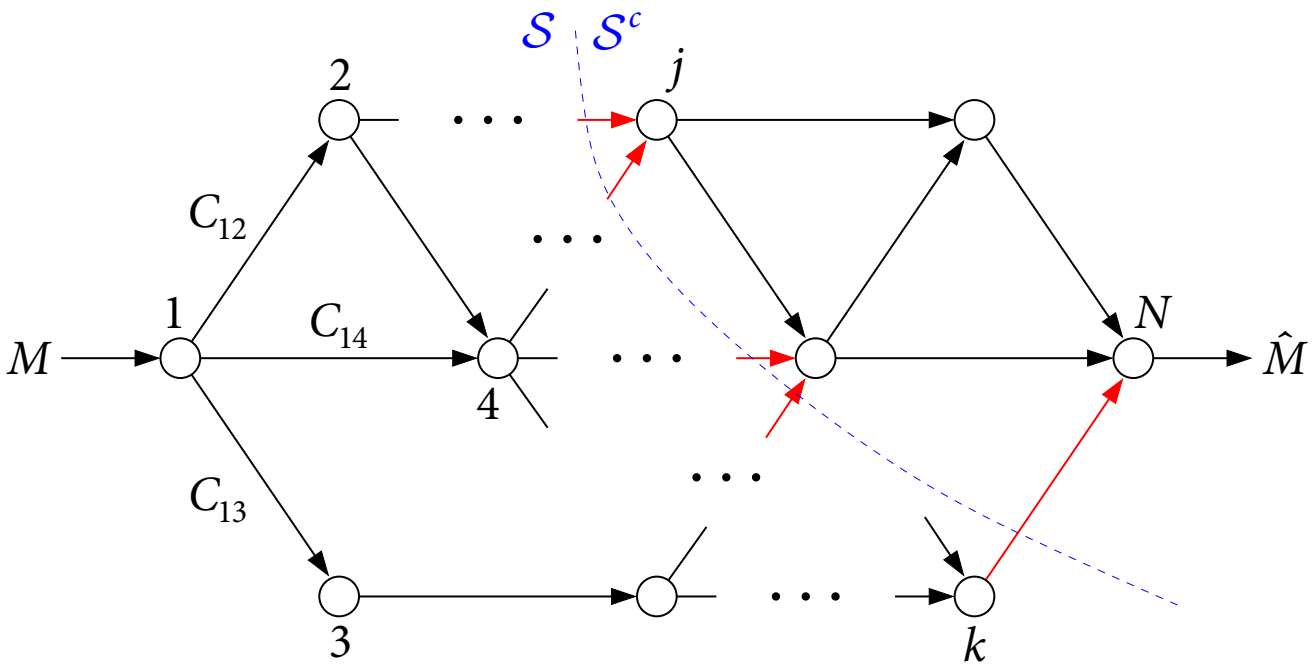

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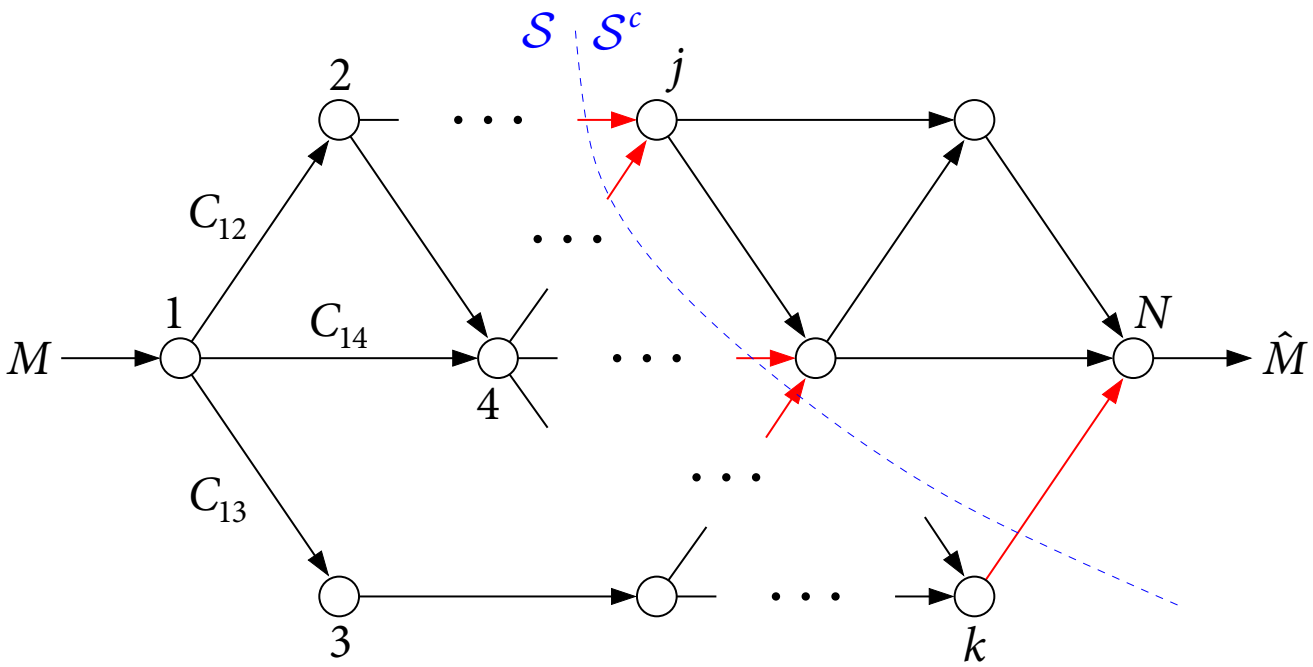

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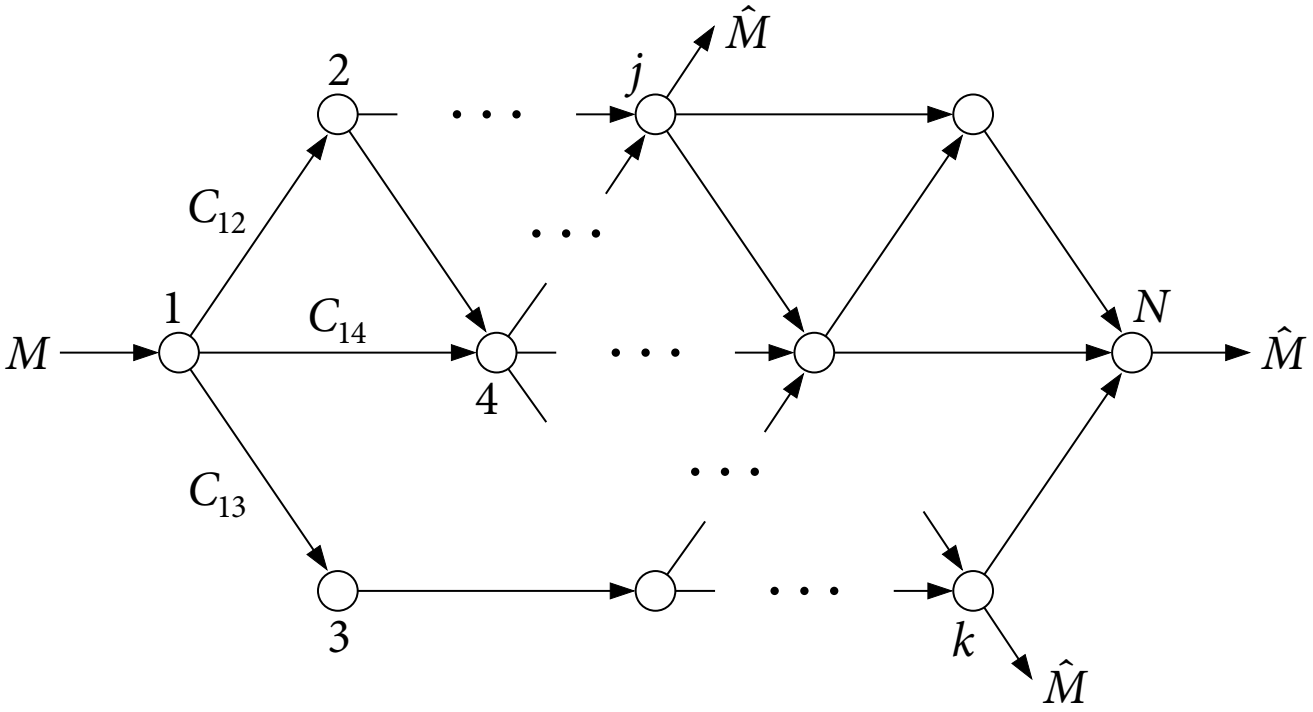
- Achieved error-free using simple routing (Ford–Fulkerson algorithm)
- Information treated as commodity flow

Graphical multicast network



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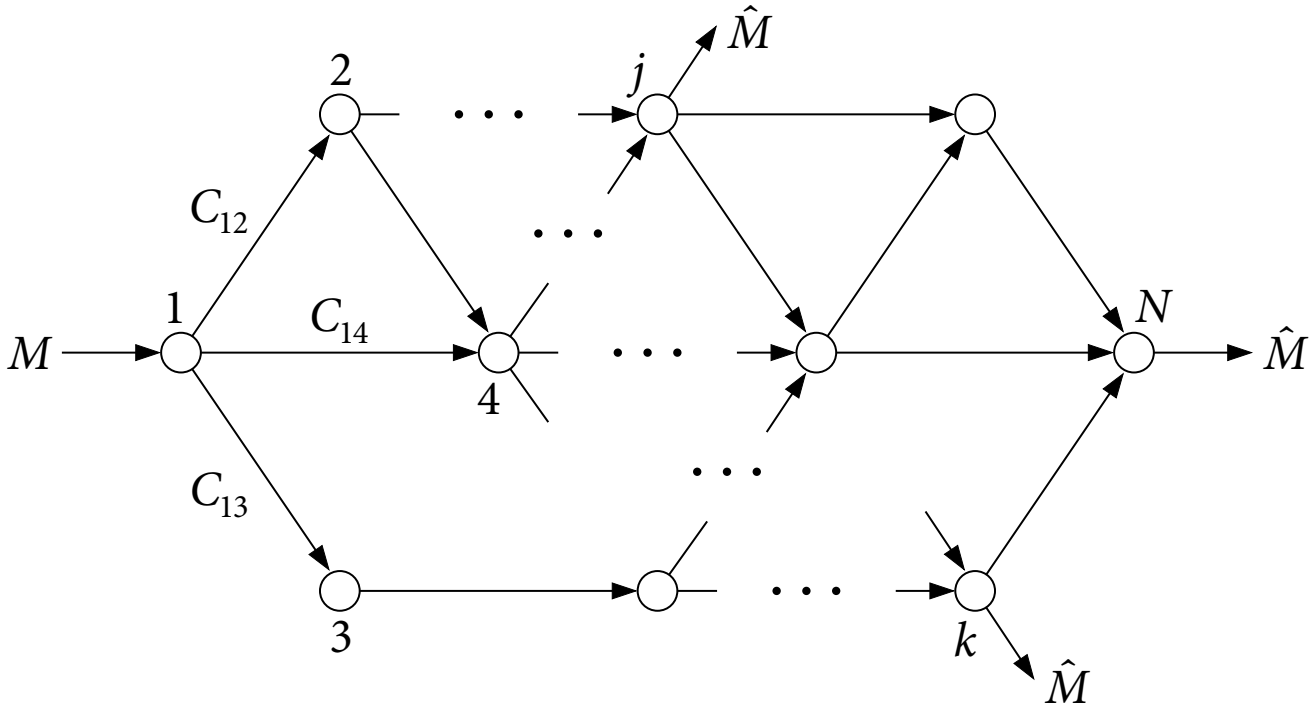
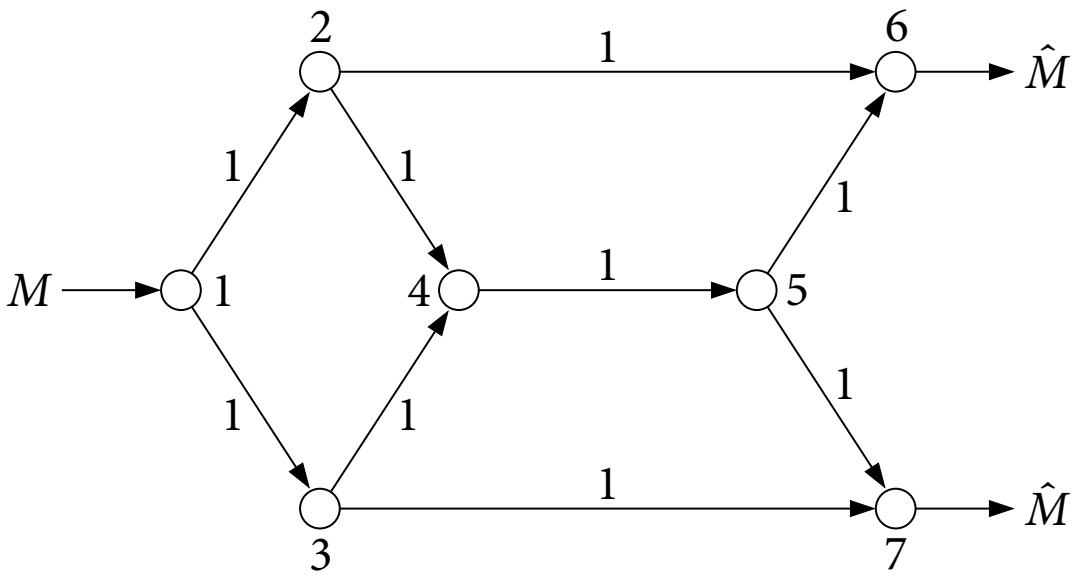


Network information flow questions

- Network capacity?
- Is routing sufficient?

Butterfly network



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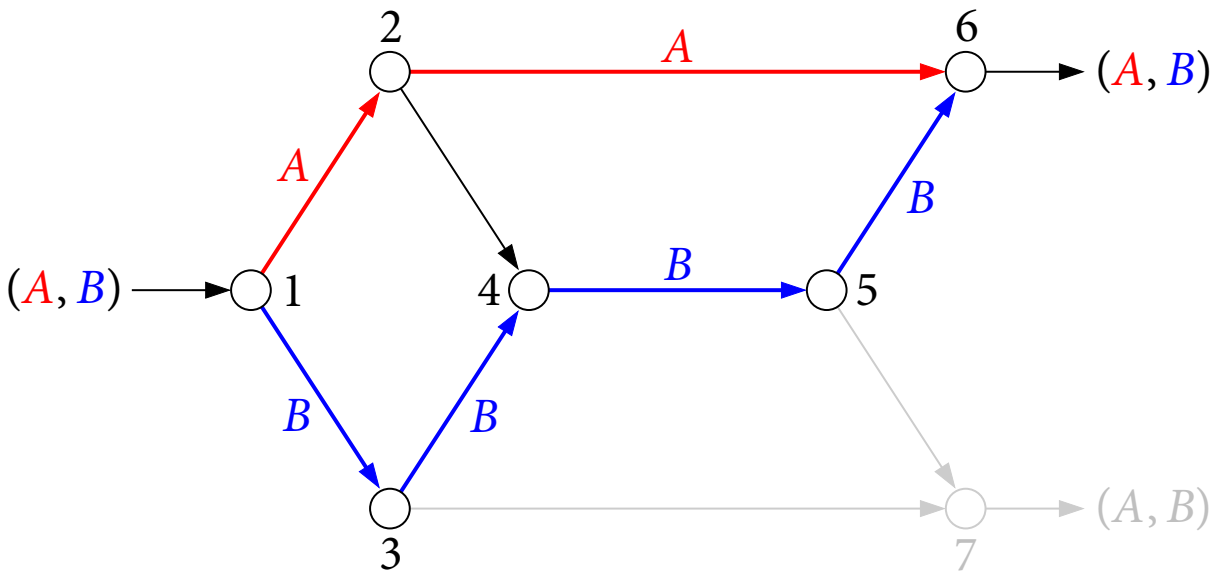

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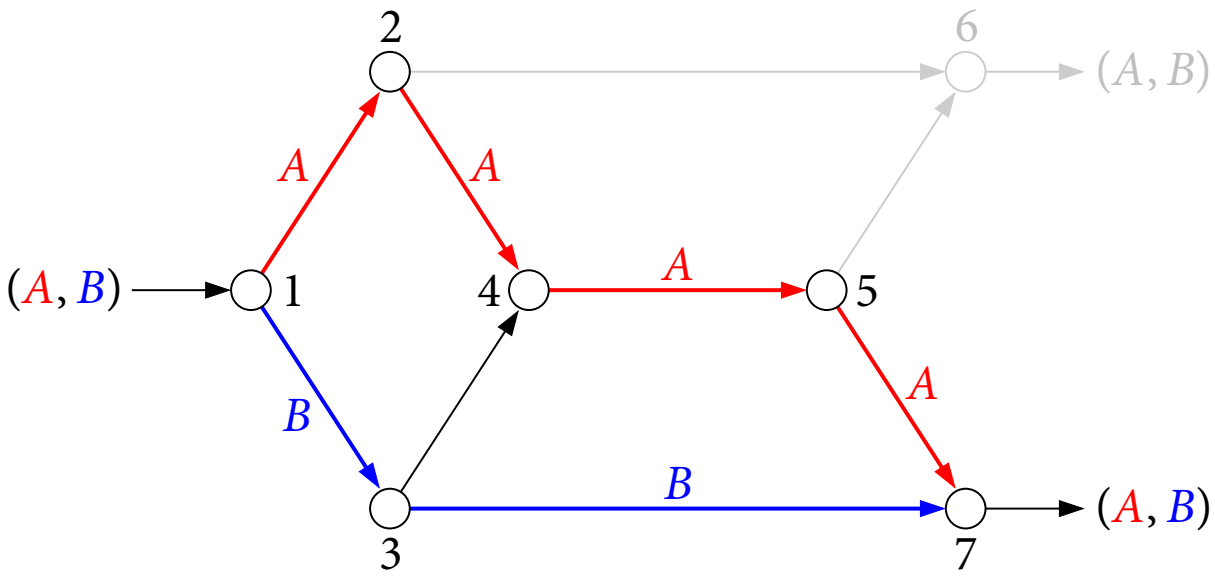

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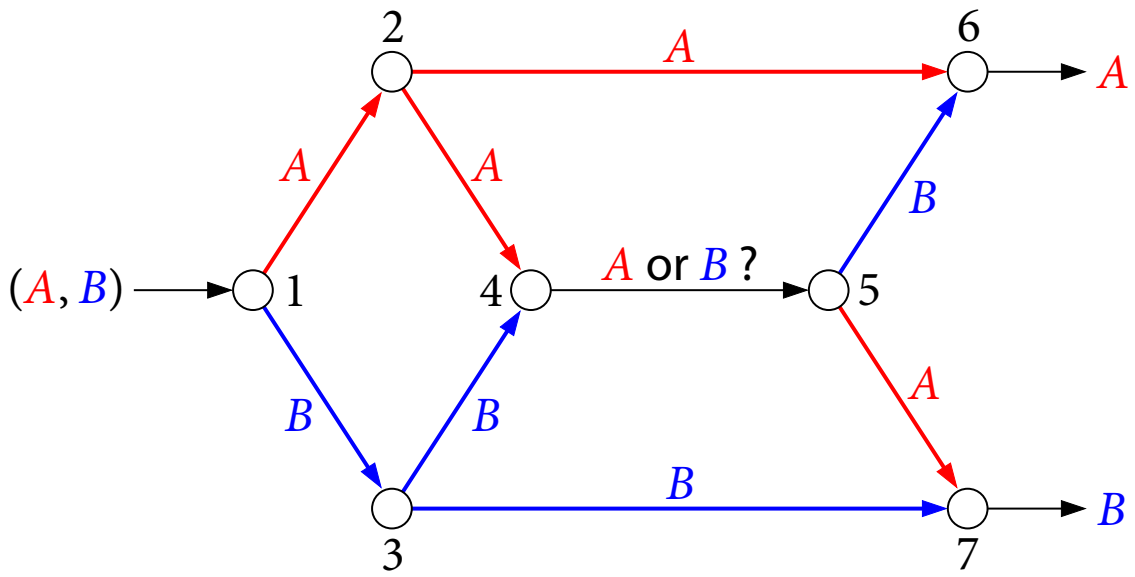

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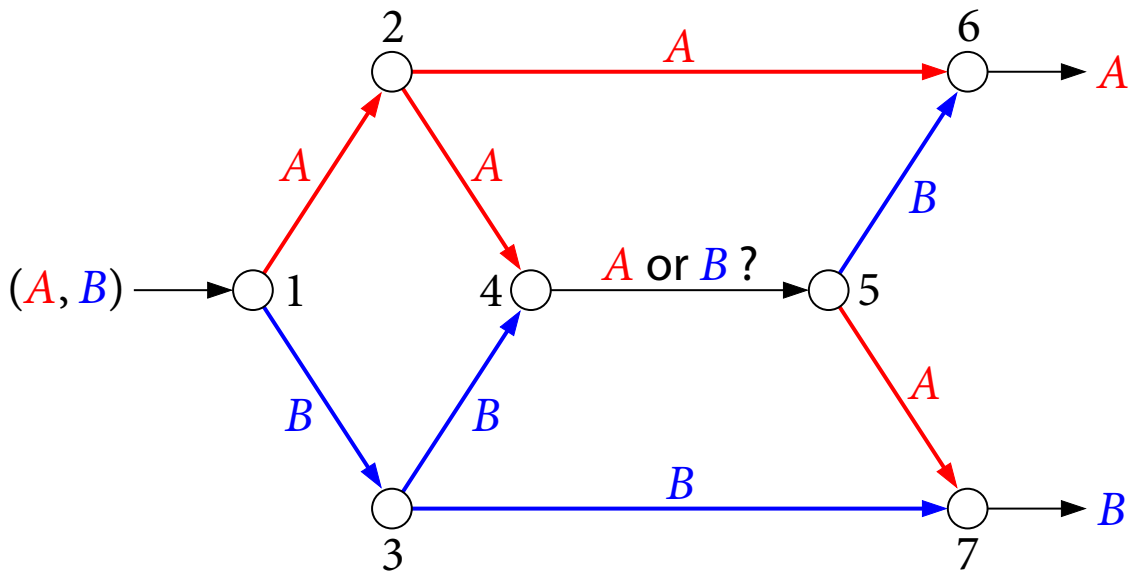
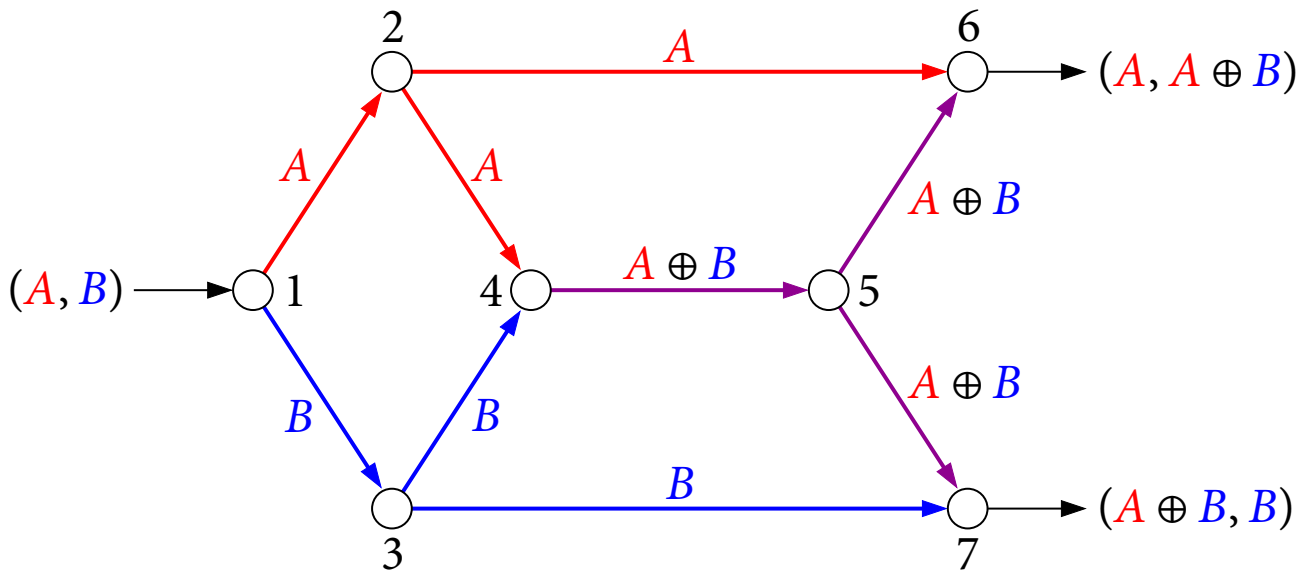


- Routing: $R = 1$

Butterfly network



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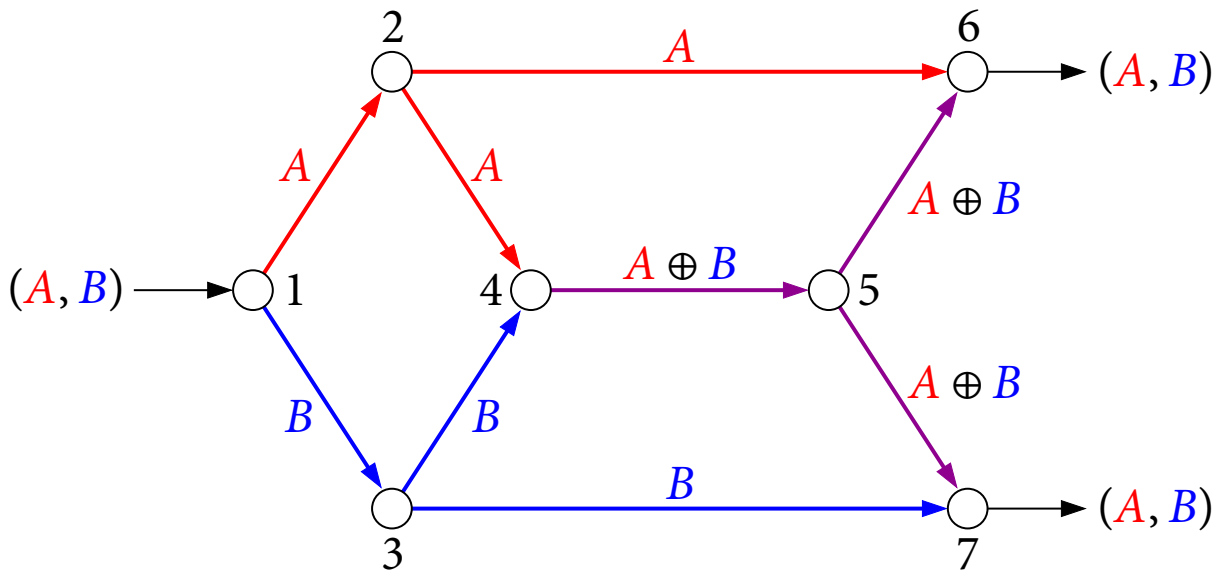
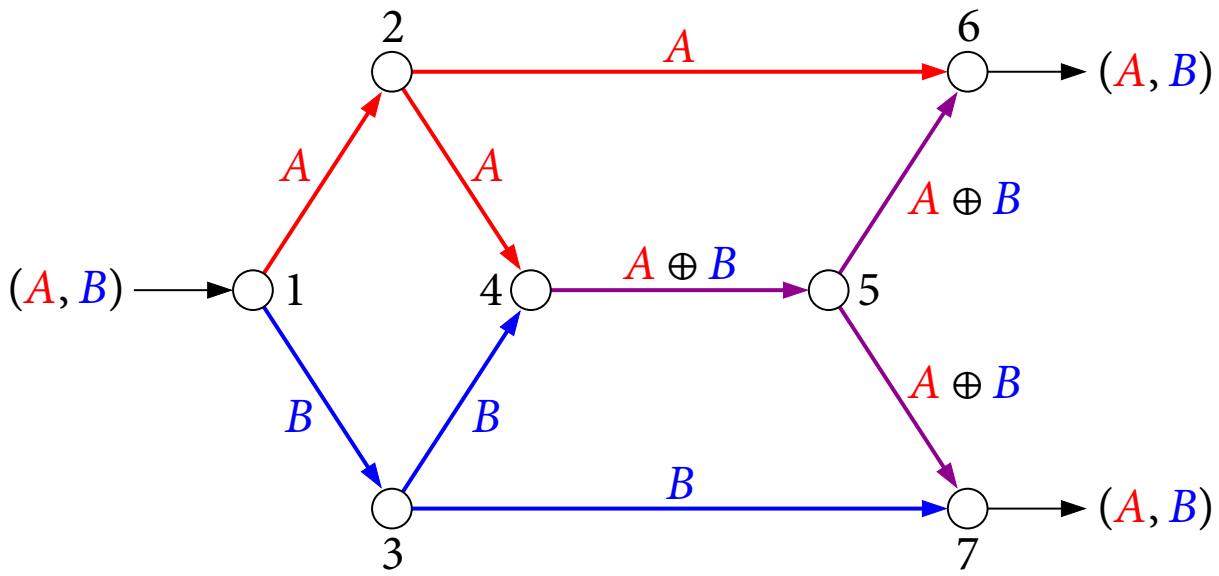


- Routing: $R = 1$
- Coding: $R = 2$ (capacity)

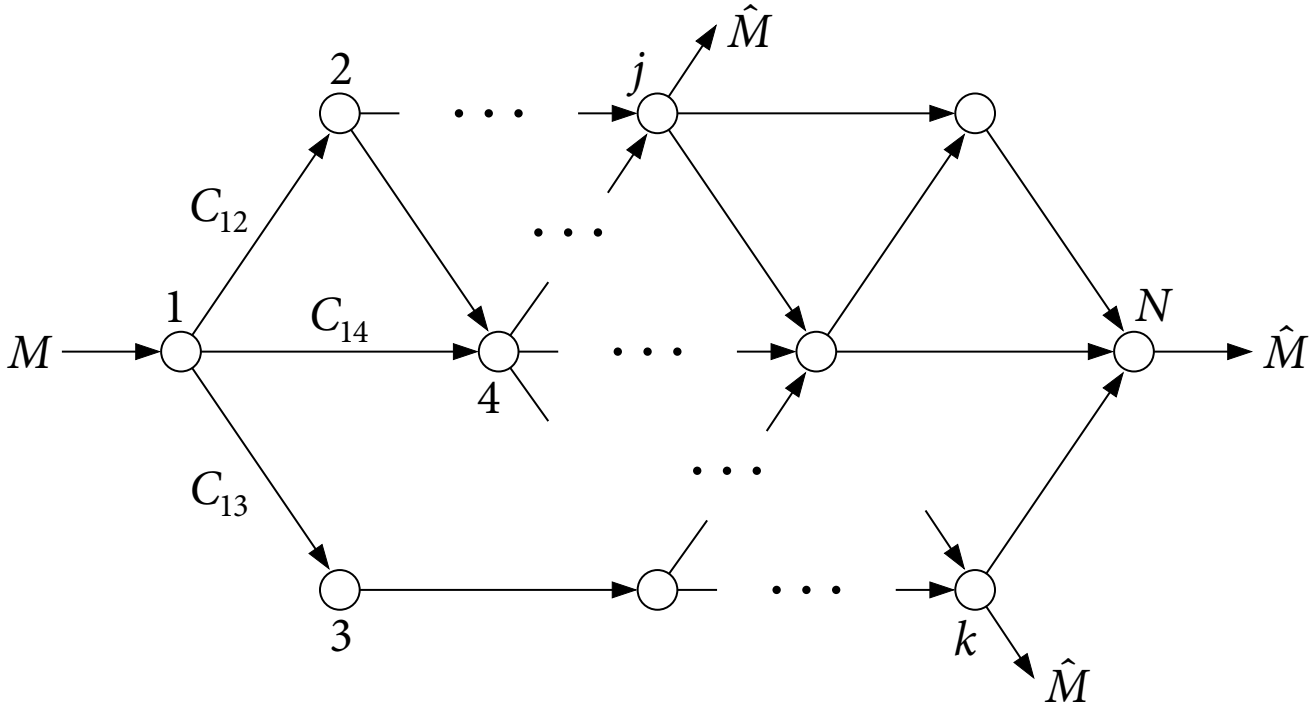
Butterfly network



- Routing: $R = 1$
- Coding: $R = 2$ (capacity)

- Treating information as a commodity is not optimal in general

Network coding theorem



Ahlswede–Cai–Li–Yeung (2000)

$$C = \min_{j \in \mathcal{D}} \min_{\substack{\mathcal{S} \subset \mathcal{N} \\ 1 \in \mathcal{S}, j \in \mathcal{S}^c}} C(\mathcal{S})$$

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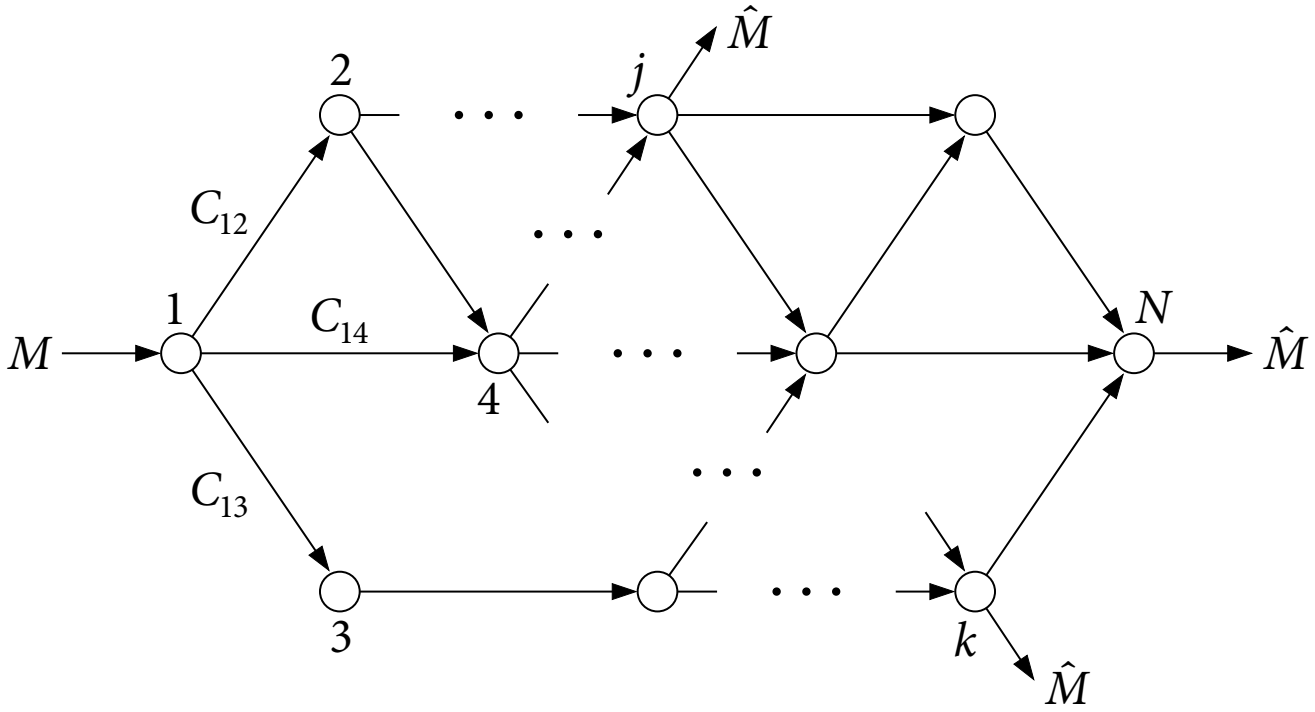

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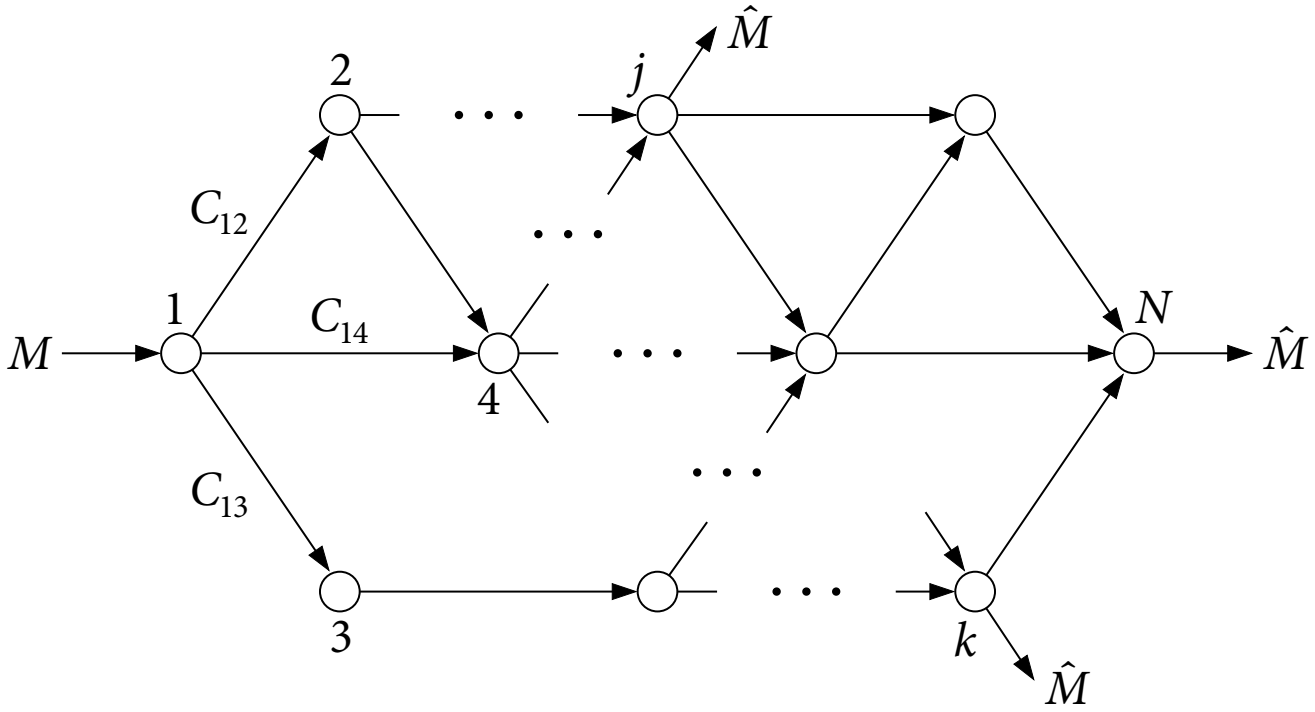

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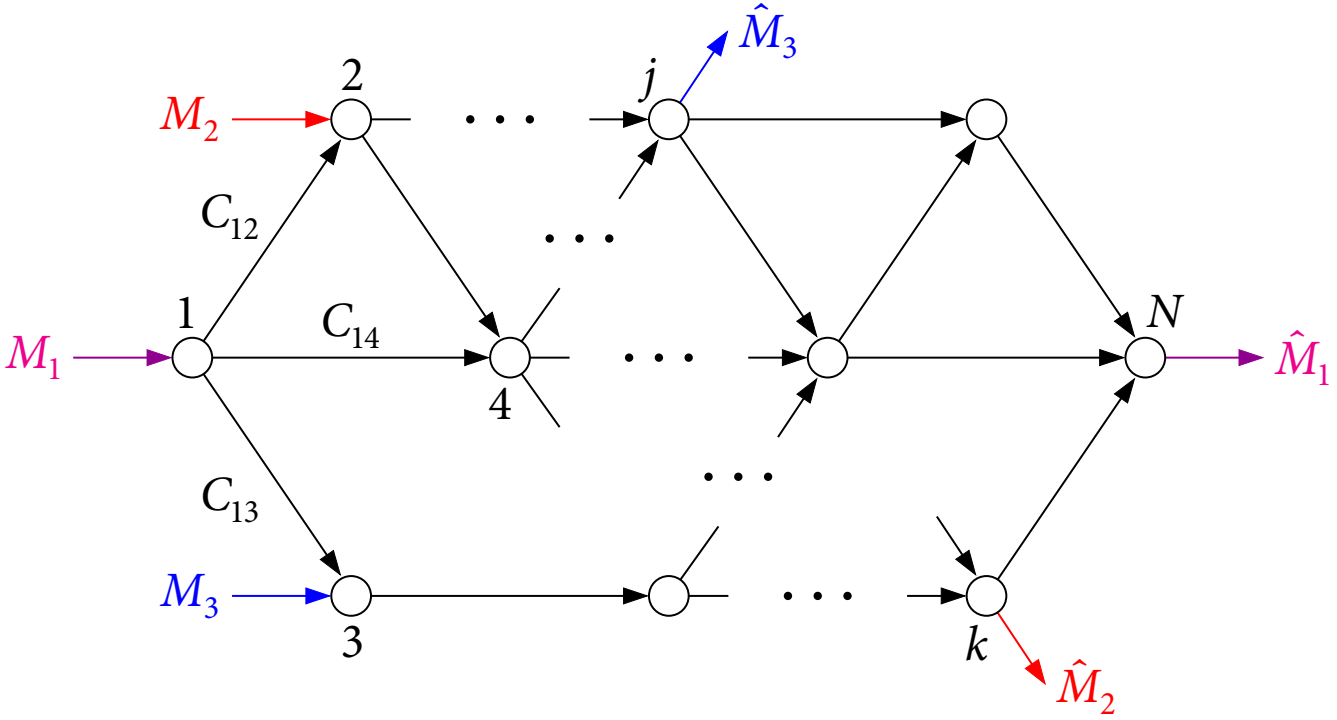
- Coded TCP: performance improvement for wi-fi and cellular networks

Graphical multiple unicast network



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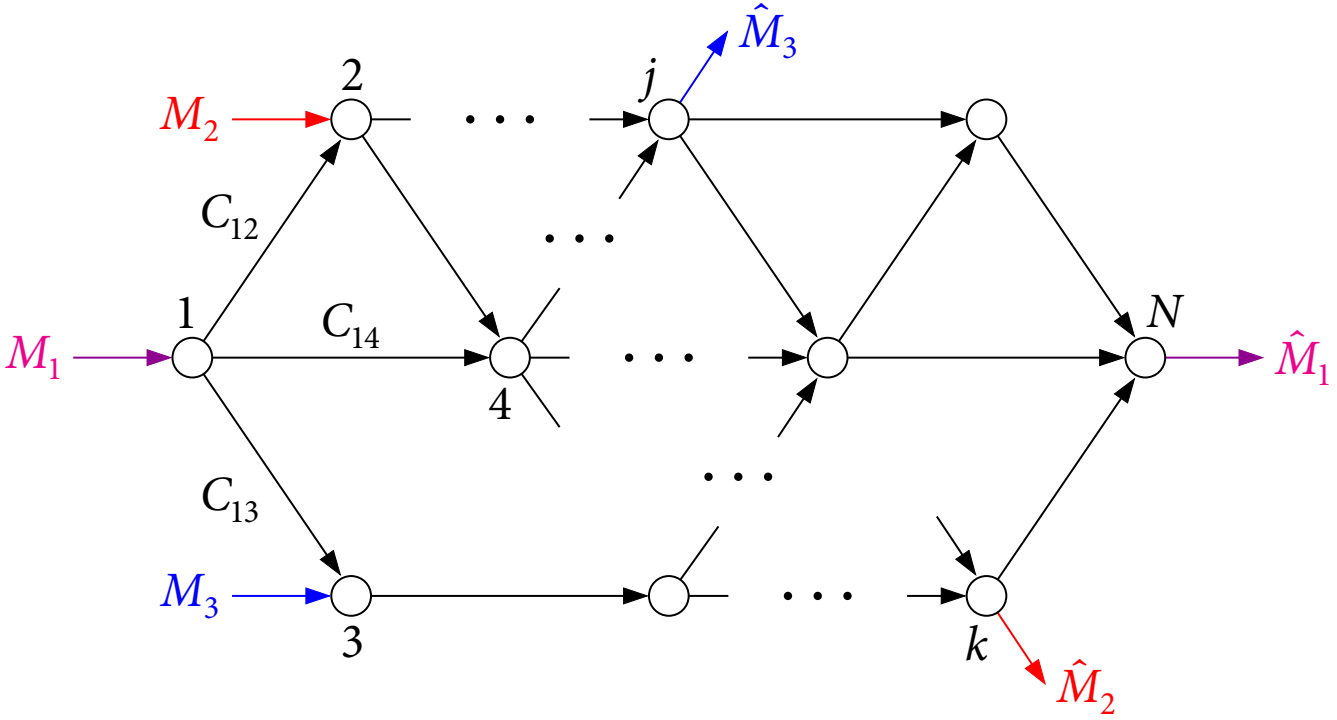

- Capacity not known in general even for two flows

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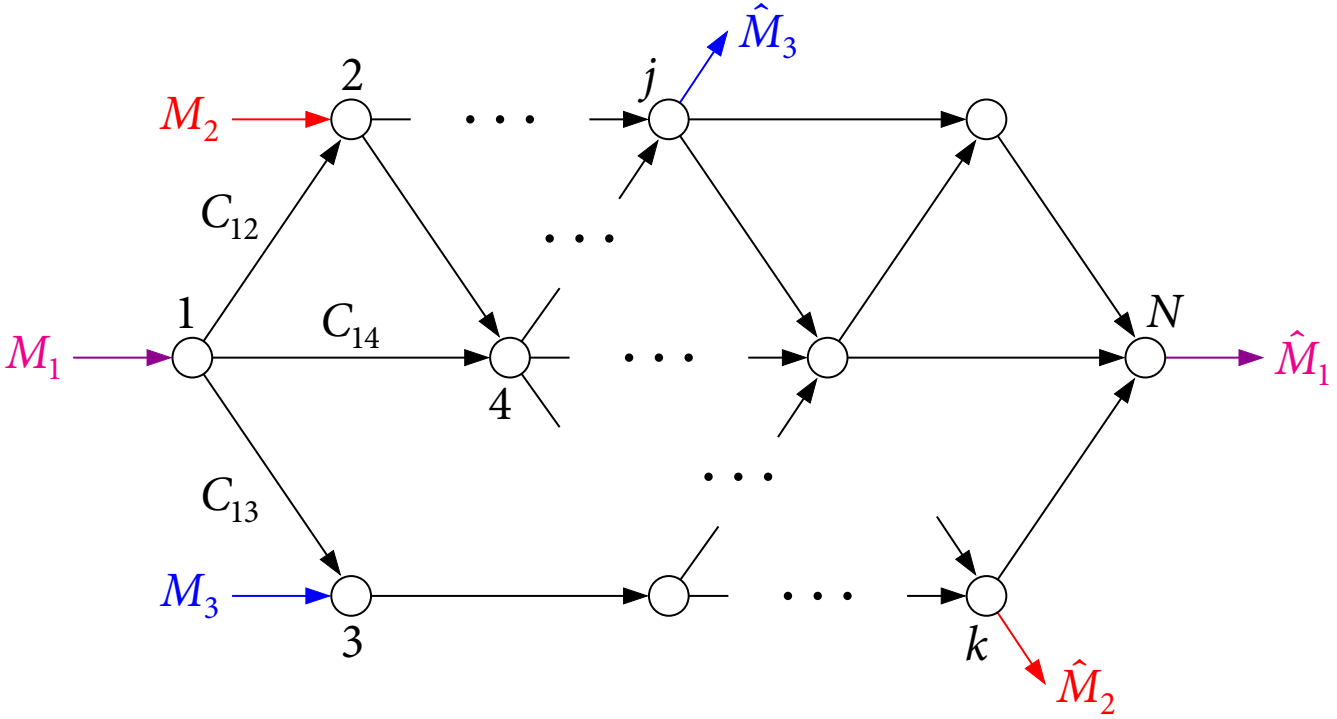
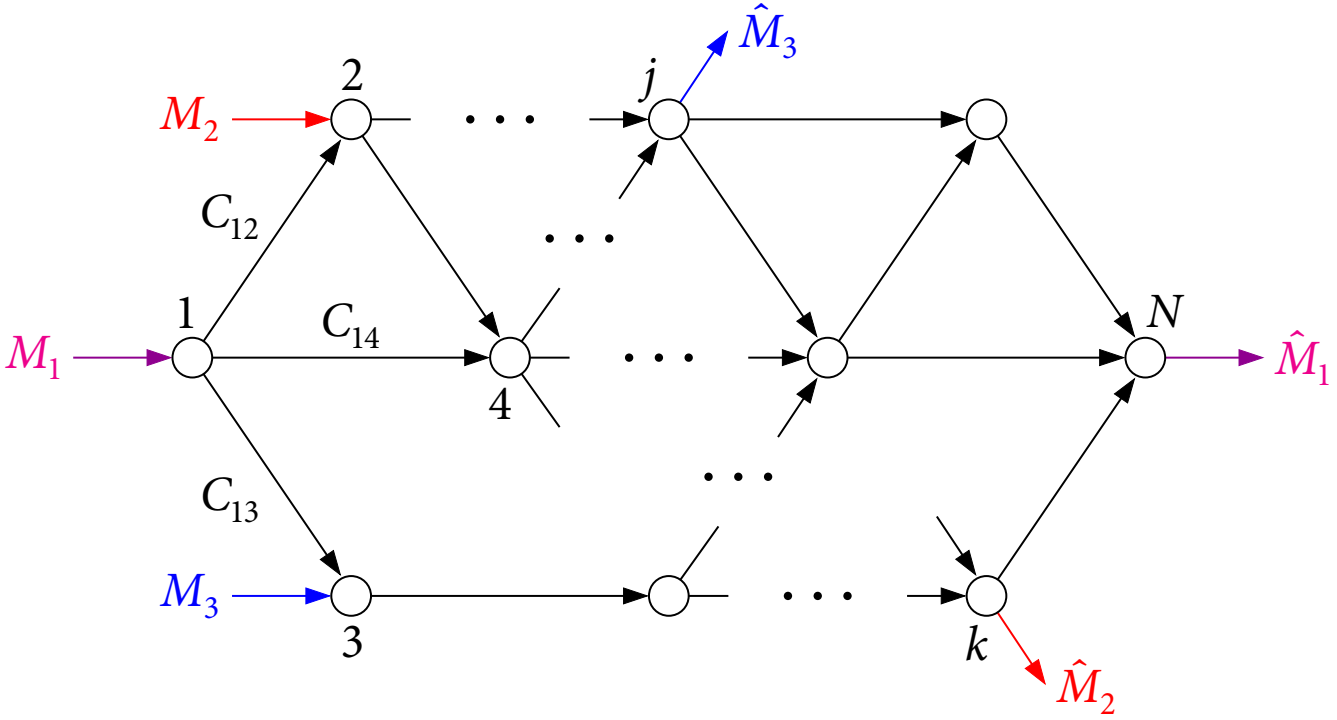


- Capacity not known in general even for two flows
- Nonlinear network coding > linear network coding > routing

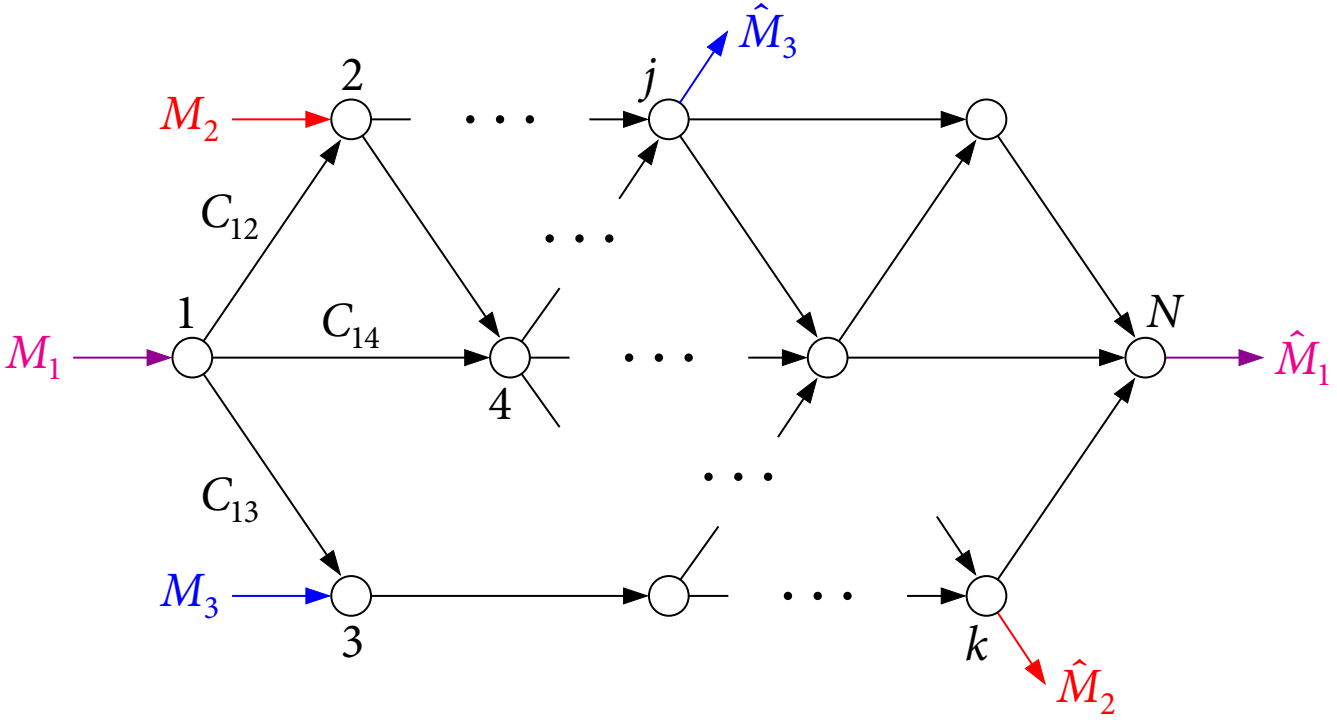
Graphical multiple unicast network



Conclusion 2

Coding brings a new dimension to networking

Graphical multiple unicast network



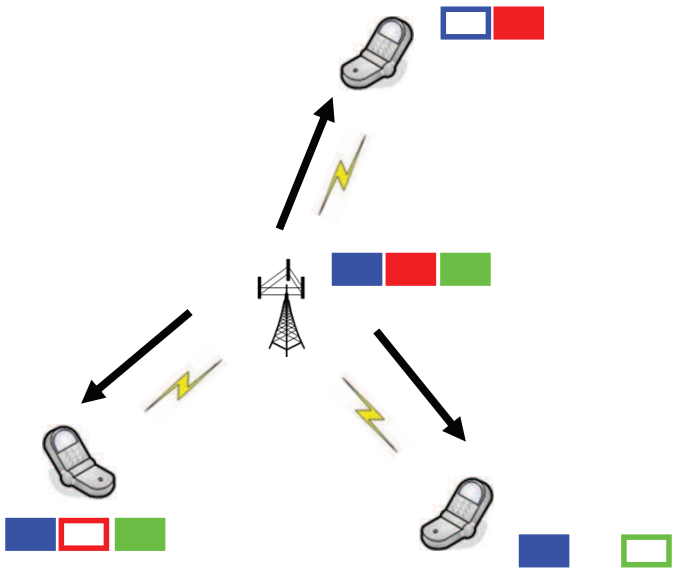
Conclusion 2

Coding brings a new dimension to networking

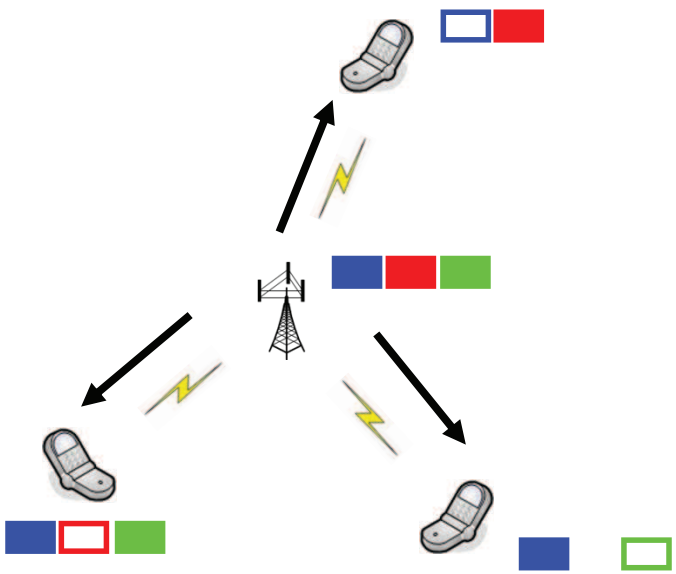
Challenge 2

Network capacity and optimal network coding

Index coding



Index coding



- Content distribution, satellite communication, opportunistic routing, …
- How many transmissions are needed?
- Which coding minimizes the number of transmissions?

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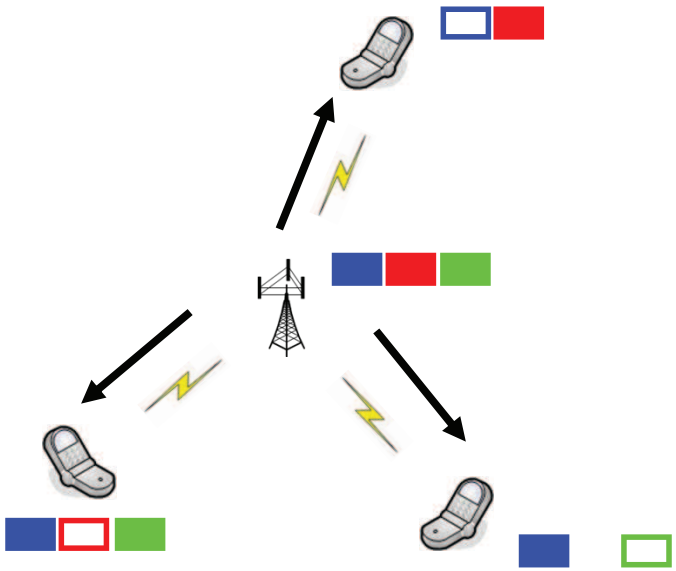
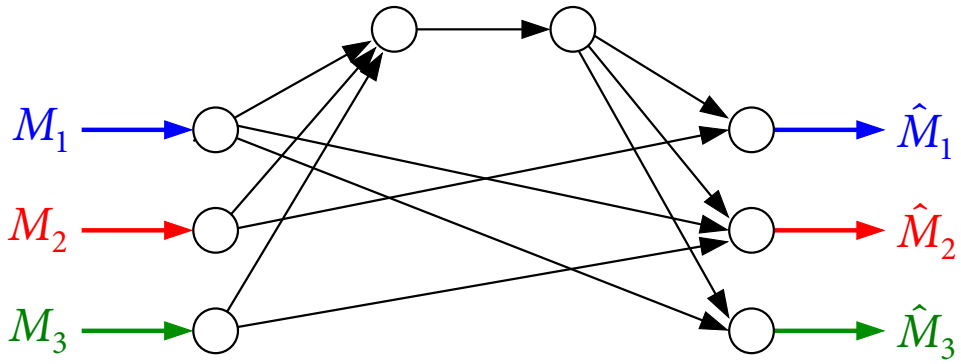
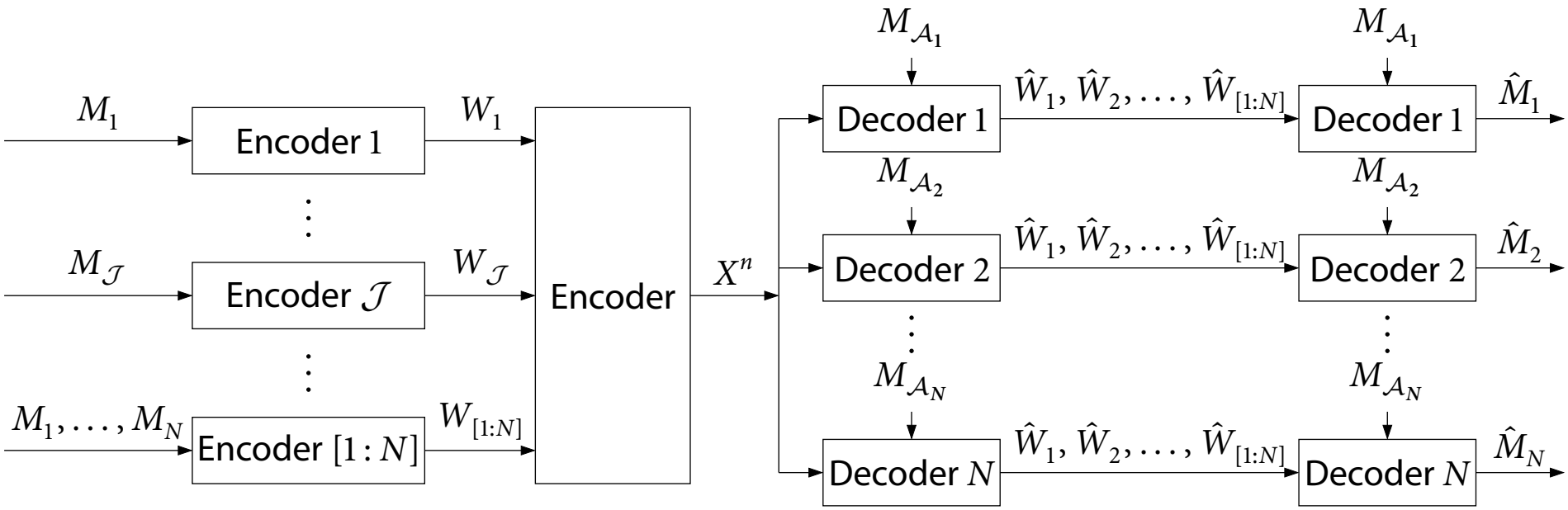




- Content distribution, satellite communication, opportunistic routing, …
- How many transmissions are needed?
- Which coding minimizes the number of transmissions?
- Canonical network coding problem (broadcast and interference)

Composite coding



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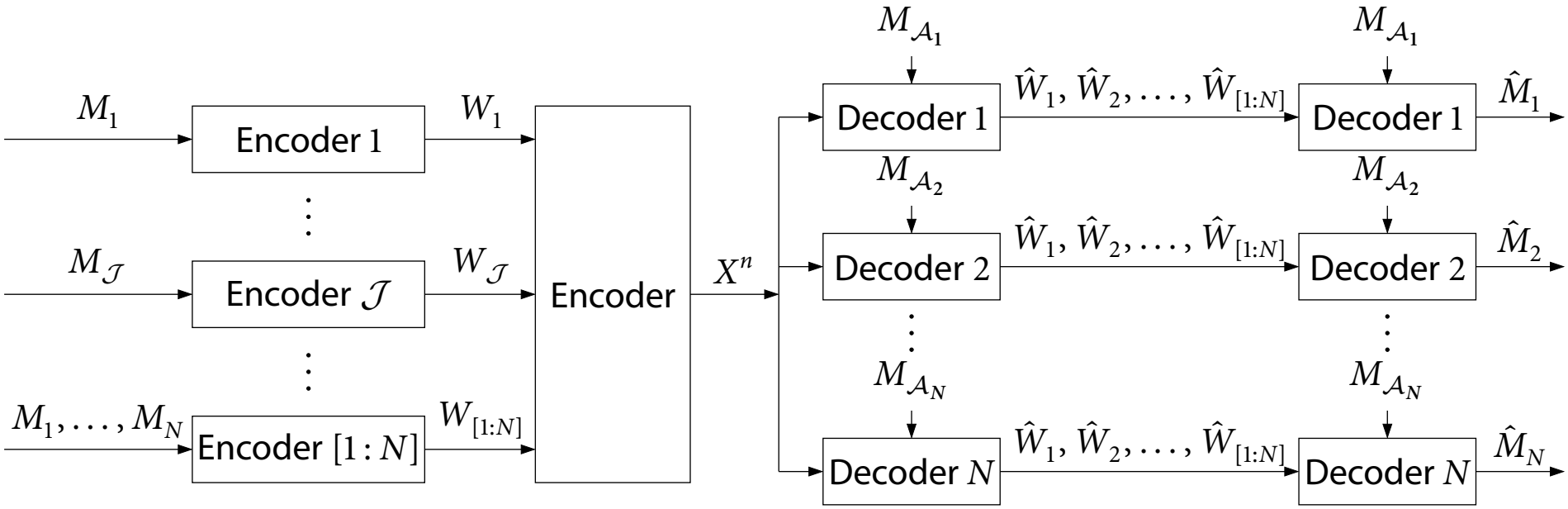

- All 218 index coding problems with $N = 4$

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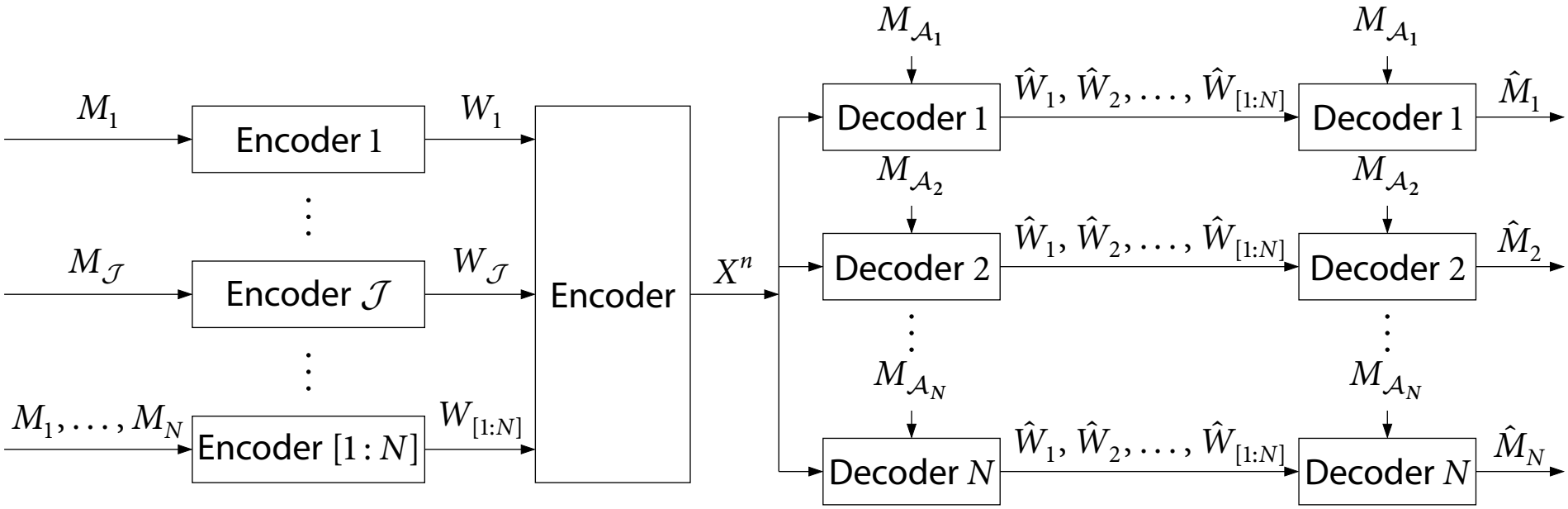

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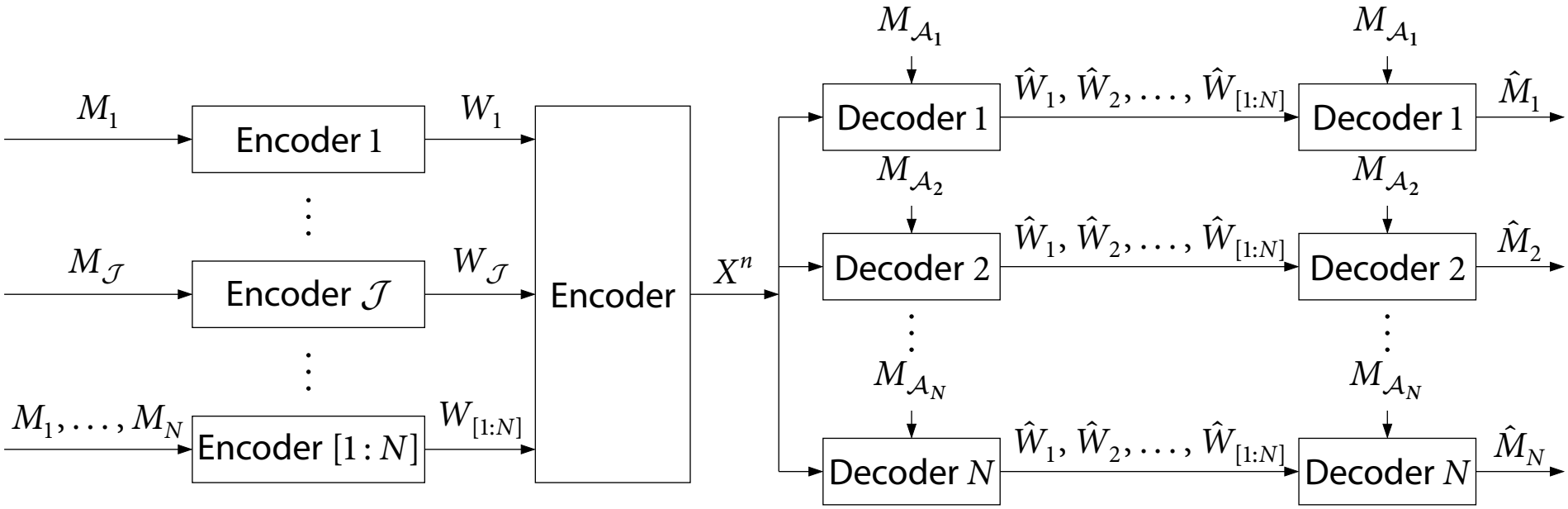

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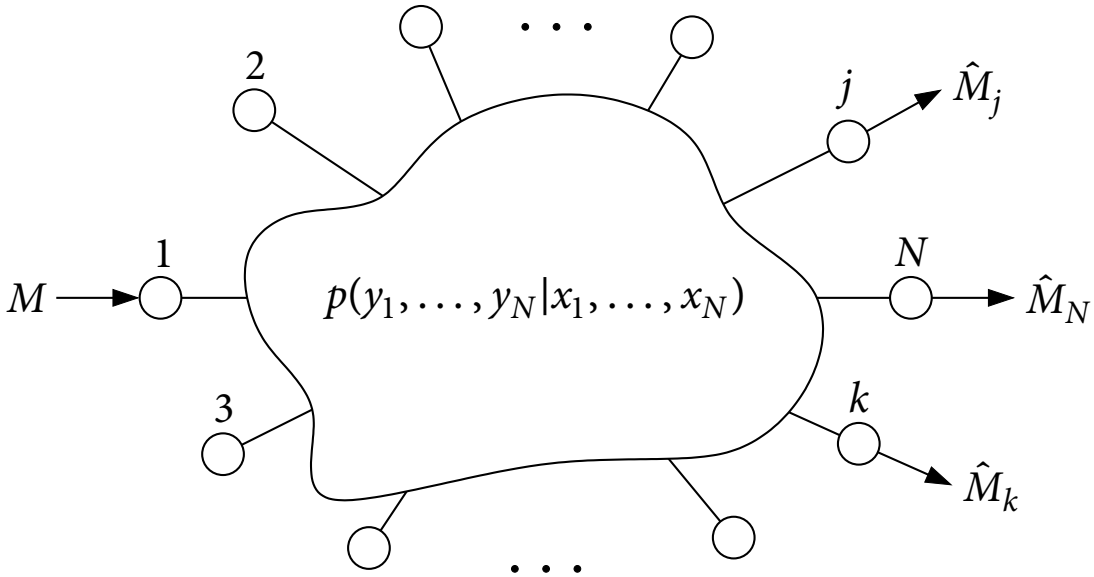
- Problems with circular symmetry (Maleki–Cadambe–Jafar 2012)

Outline of the talk

- Canonical problems in network communication
  - Interference management
  - Multiple unicast
  - Wireless relaying
- Solutions from network information theory
- Challenges for the future

Relay network



- Nodes: $(X_1, Y_1), \ldots, (X_N, Y_N)$
- Network topology/noise: $p(y_1, \ldots, y_N|x_1, \ldots, x_N)$

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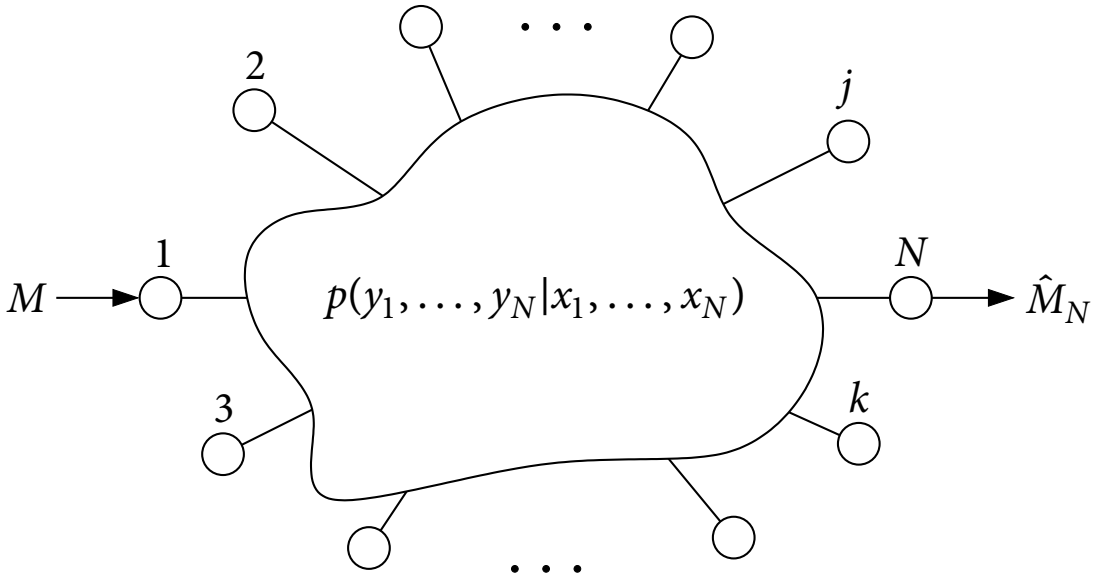

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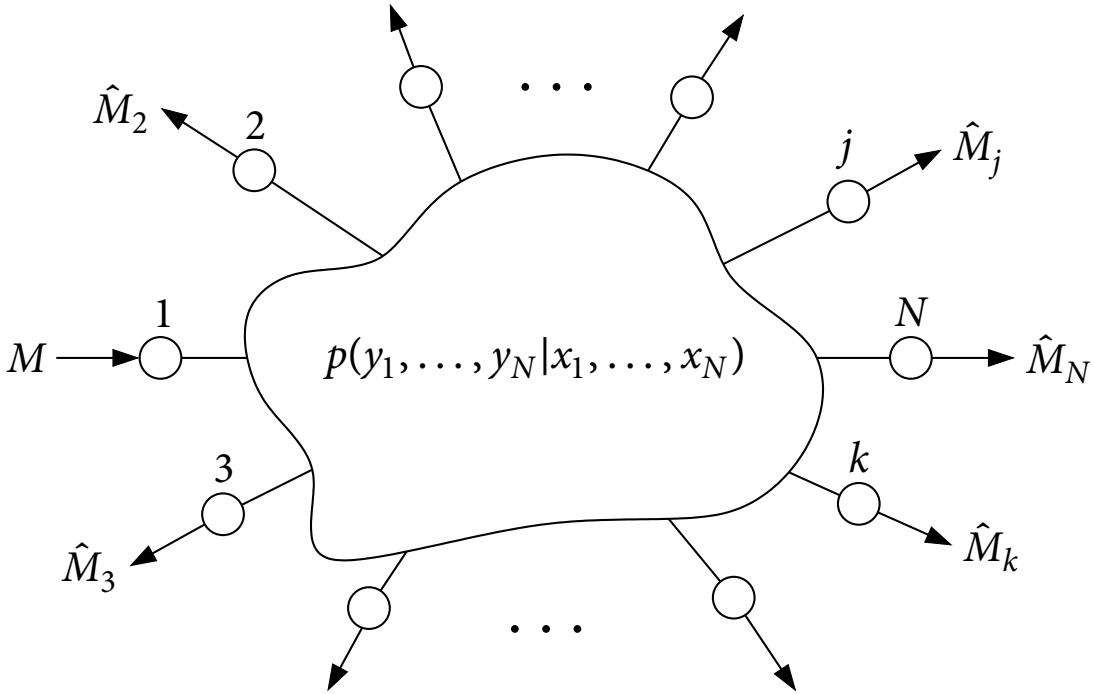

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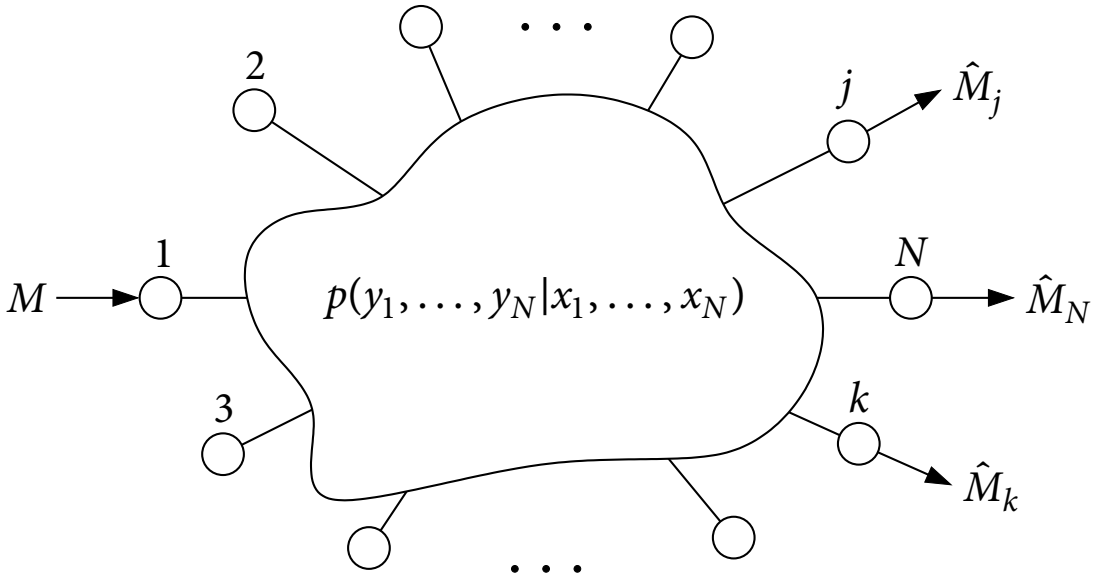

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Dictionary of relaying schemes

- Standard parlance: decode–forward, amplify–forward, compress–forward

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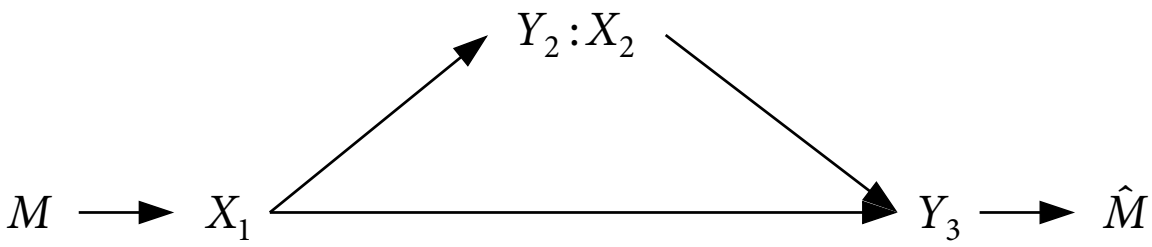
Canonical coding schemes for relay channels



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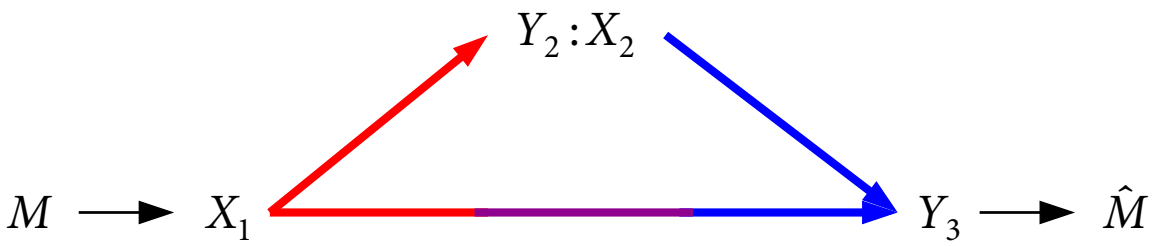

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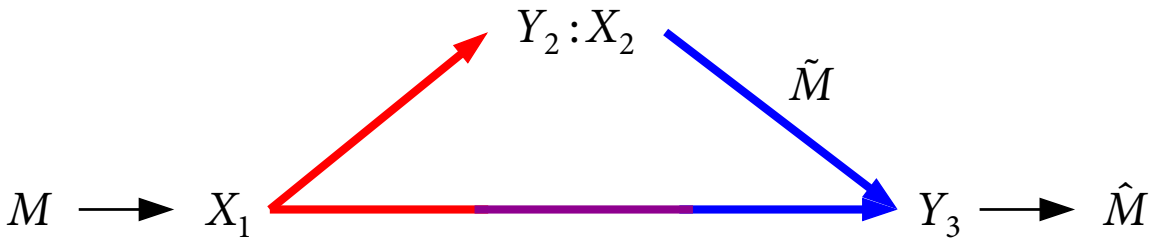

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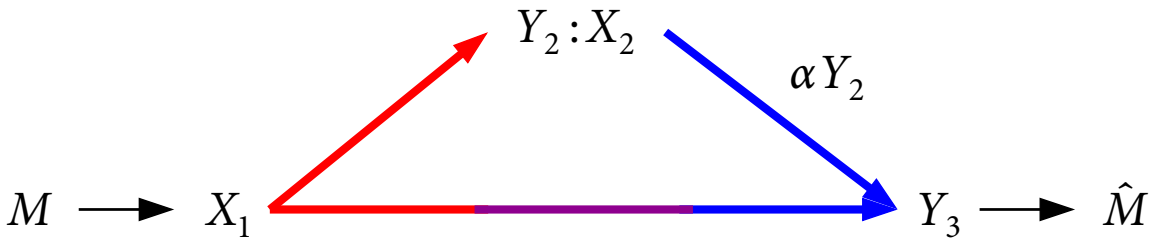

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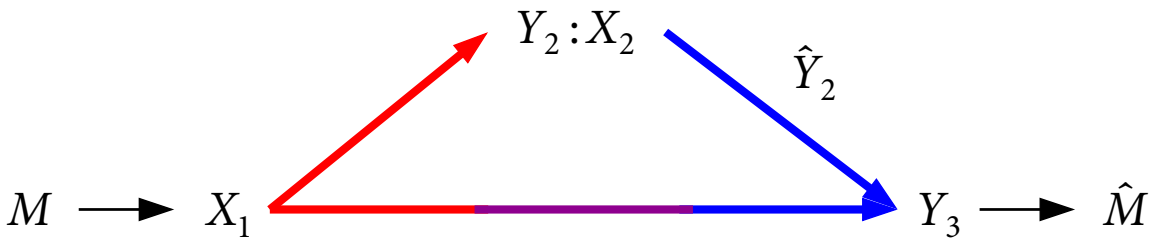

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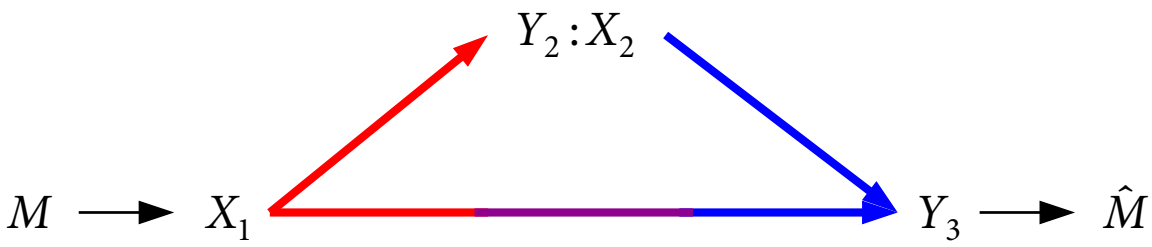

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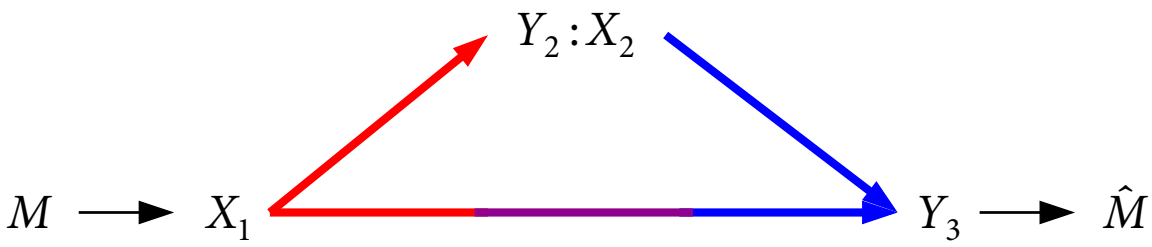

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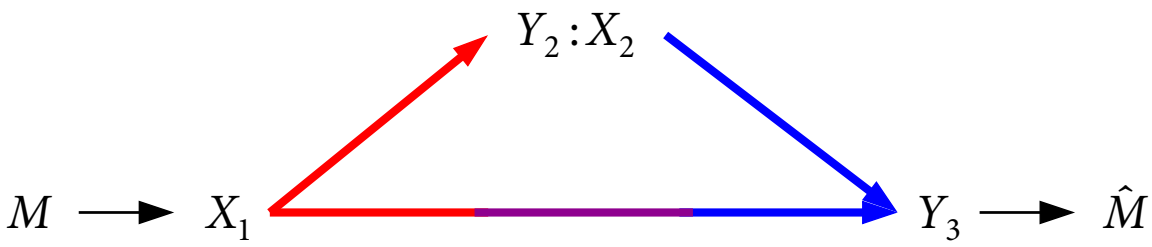

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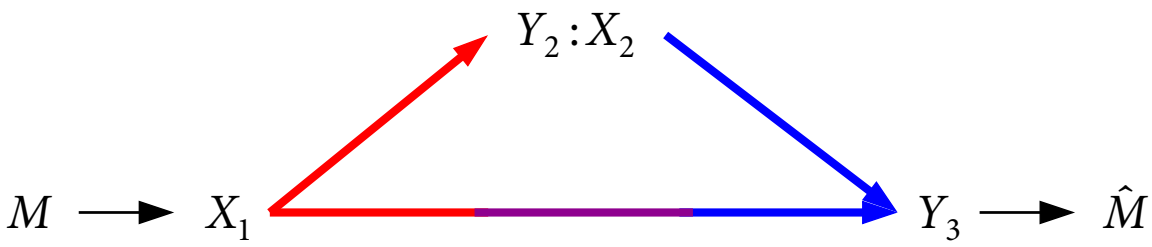

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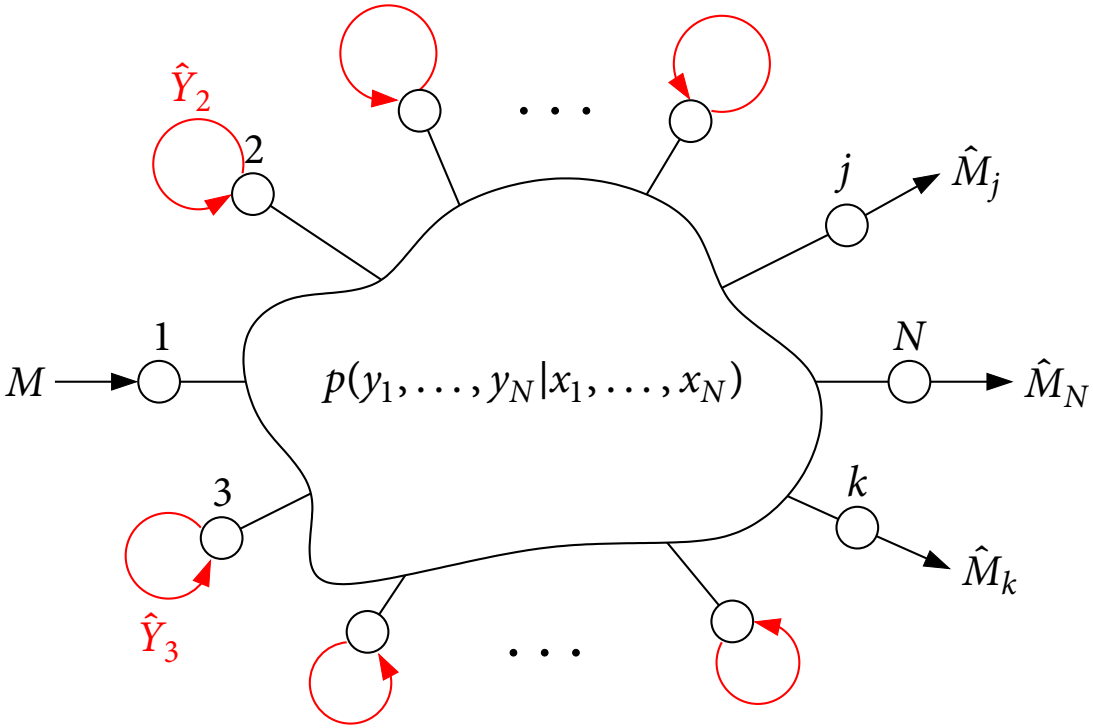
- Compress–forward (Cover–El Gamal 1979): analog-to-digital

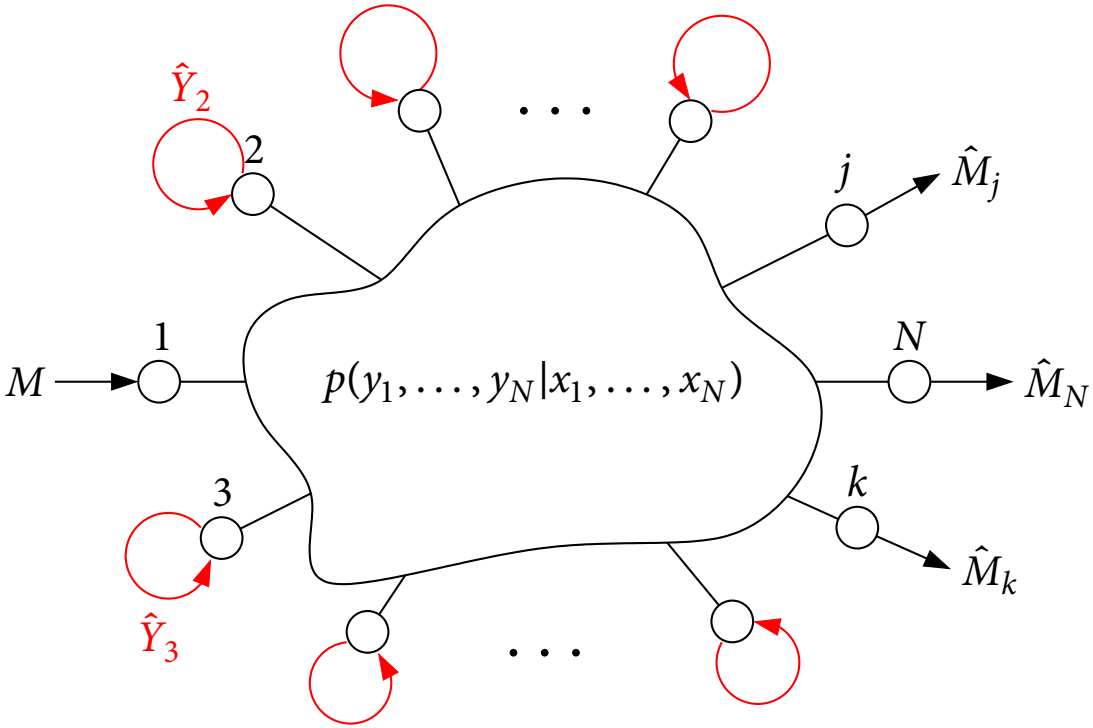
- Extensions to networks
  (Xie–Kumar 2005, Kramer–Gastpar–Gupta 2005, Lim–K–El Gamal–Chung 2011)
- Unification ? (Cover–El Gamal 1979, K–Lim–Minero 2011)
- Beyond $*$–forward (Xiang–Wang–K 2011)

Noisy network coding



- Compress–forward + network coding

Noisy network coding



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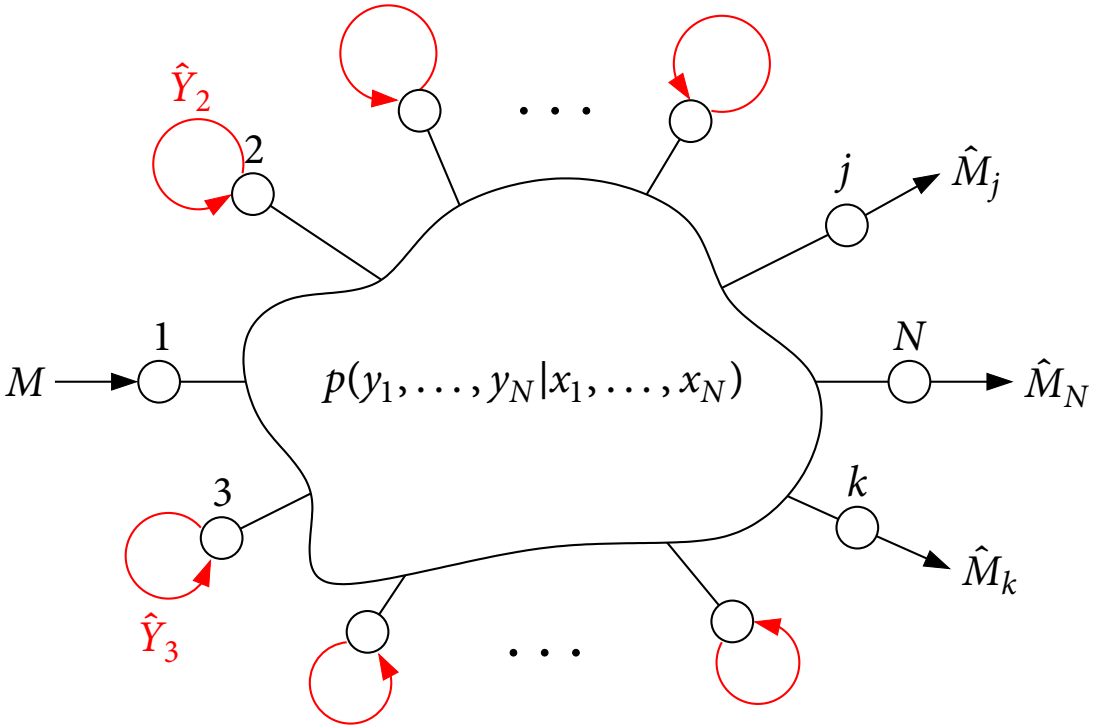

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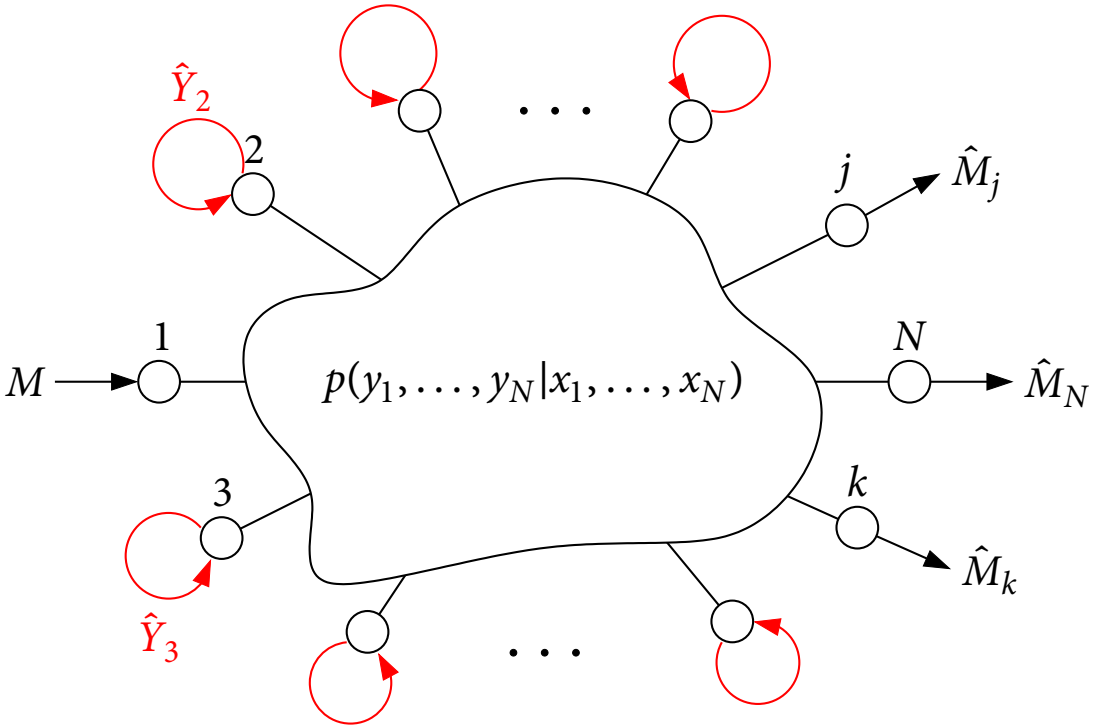

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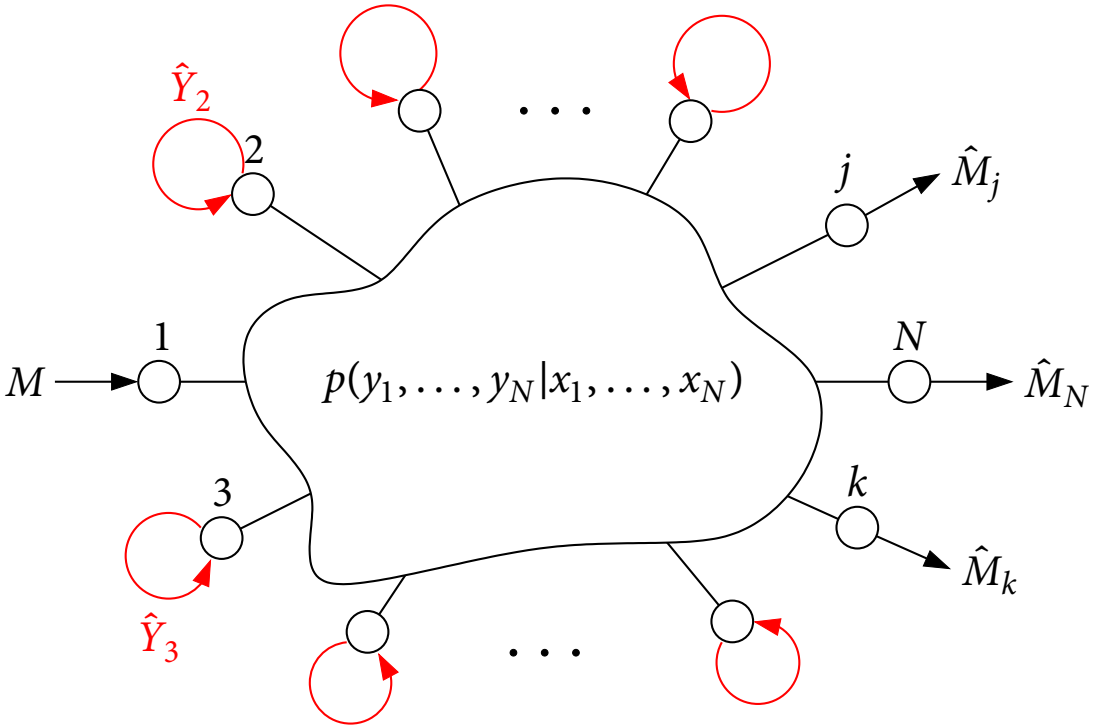

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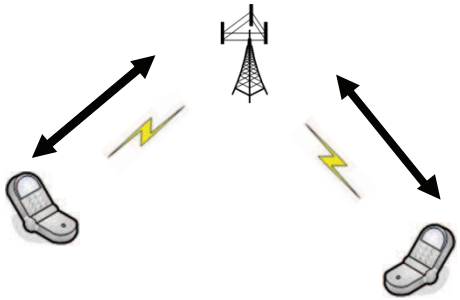
- Hybrid coding: noisy network coding + amplify–forward

Two-way relay communication



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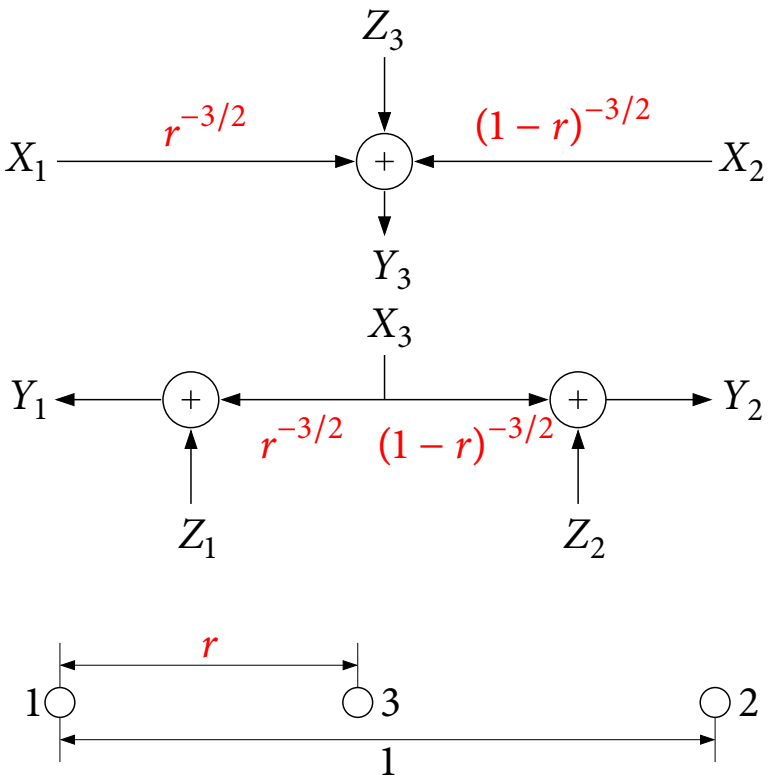

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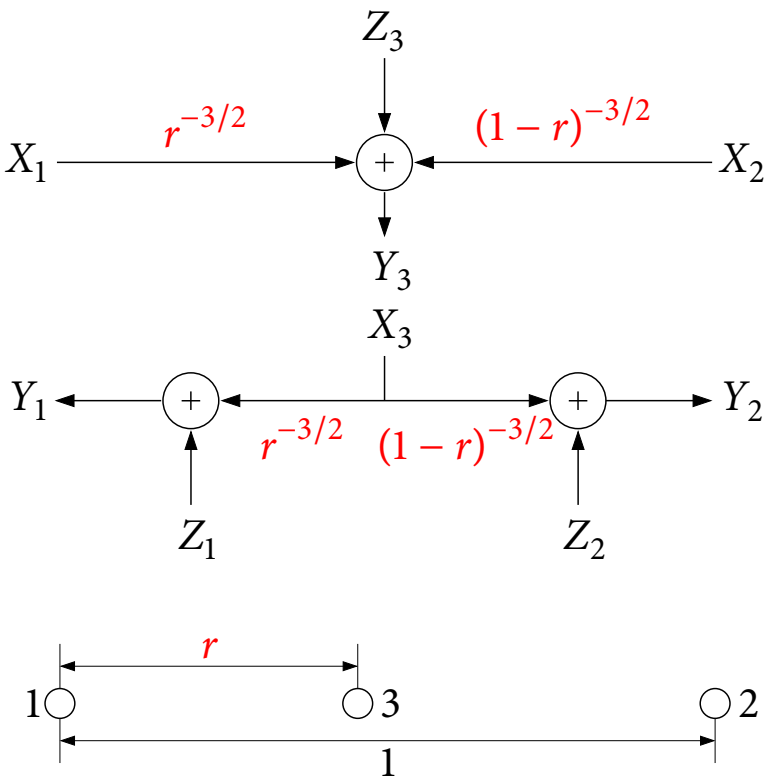

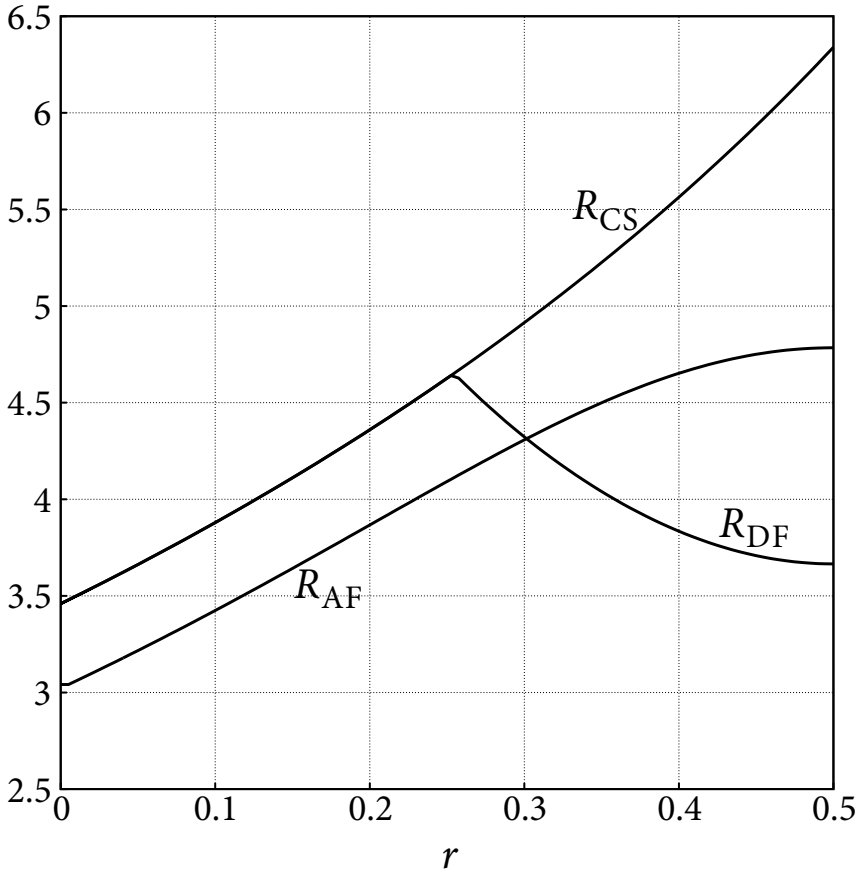

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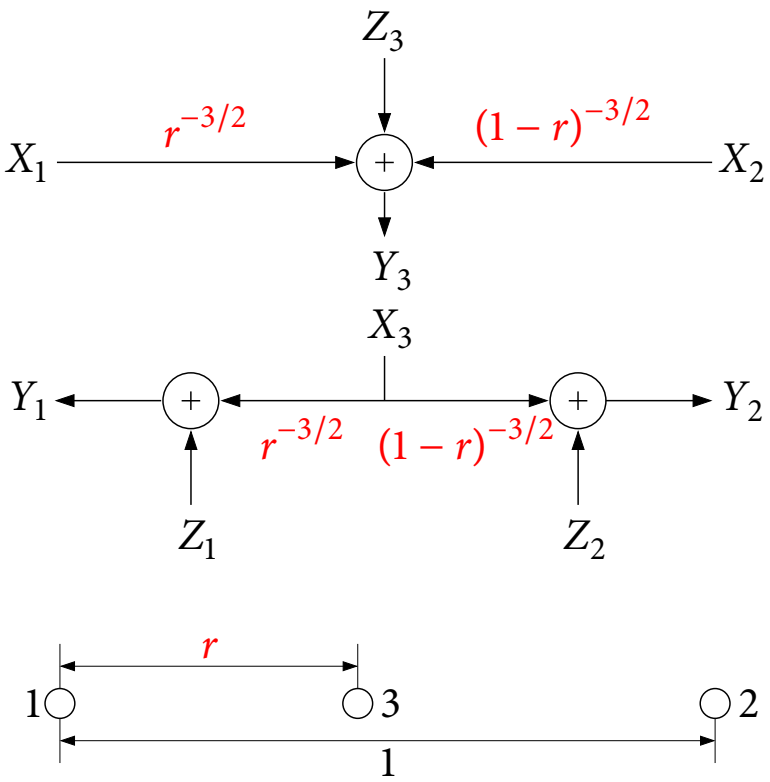

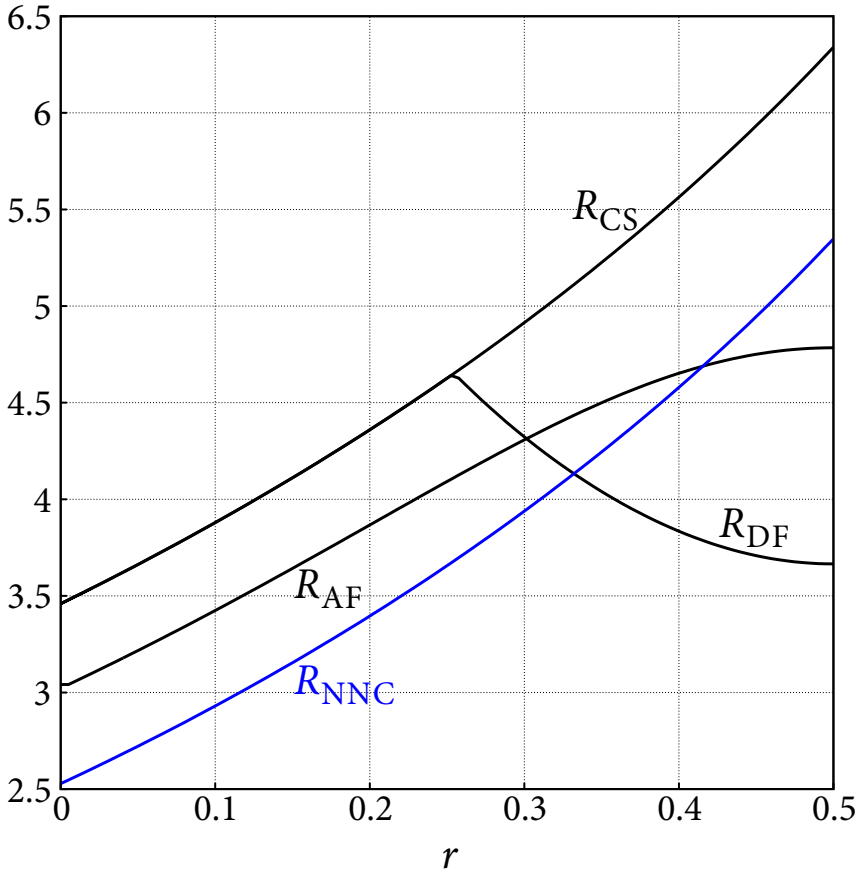

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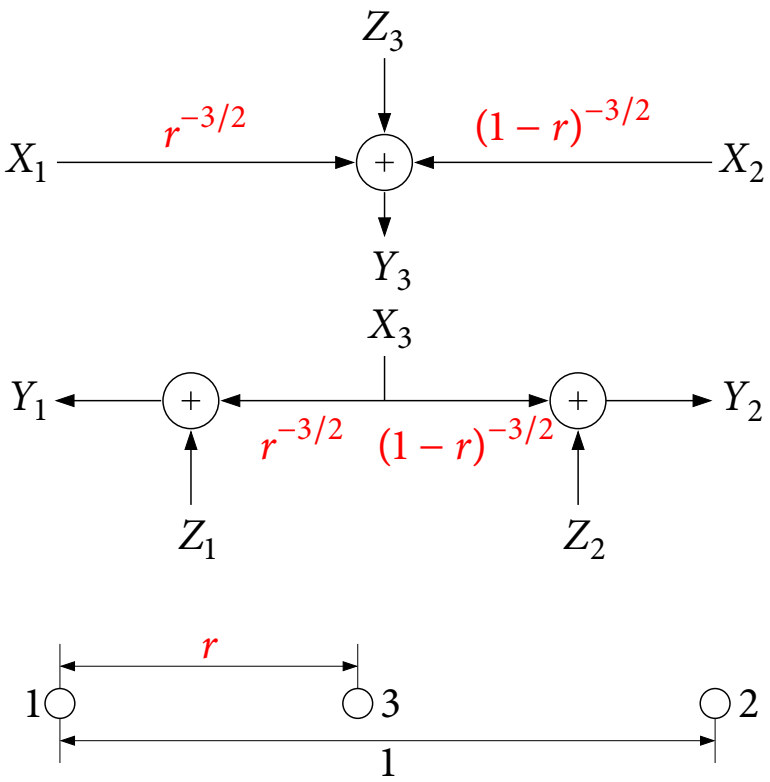
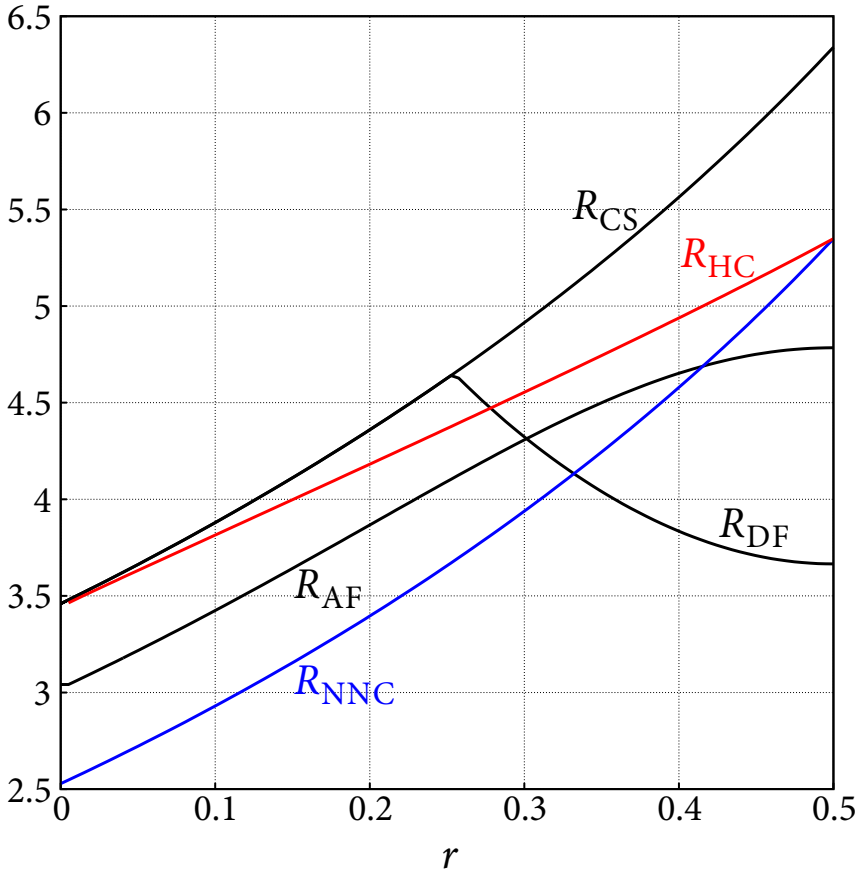
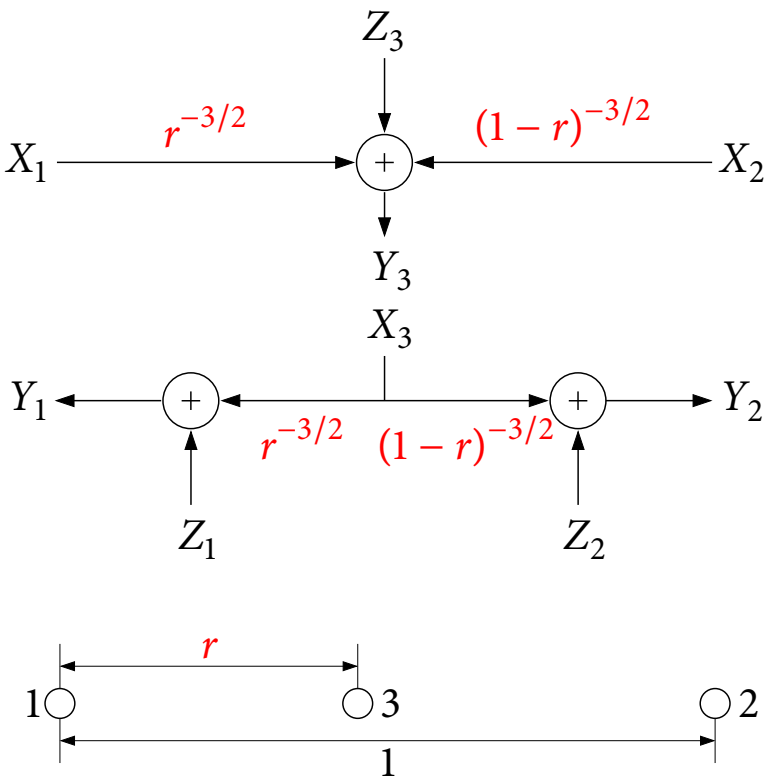
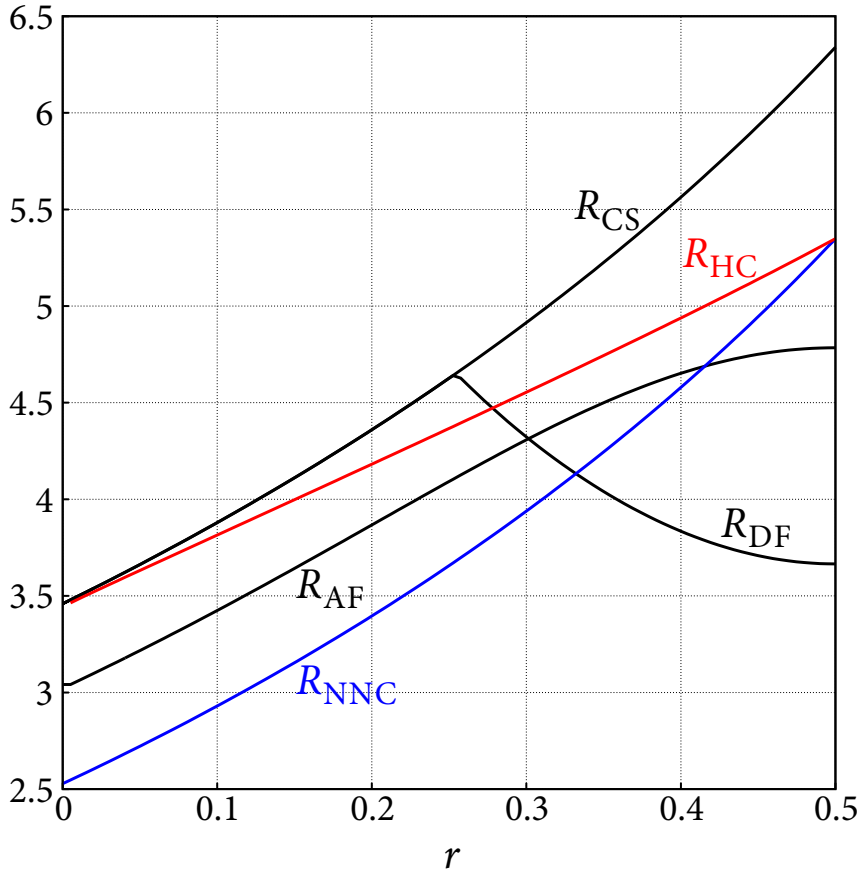




- Decode–forward and amplify–forward: unbounded gap from capacity in general
- Noisy network coding and hybrid coding: within 1 bit gap from capacity

Two-way relay communication

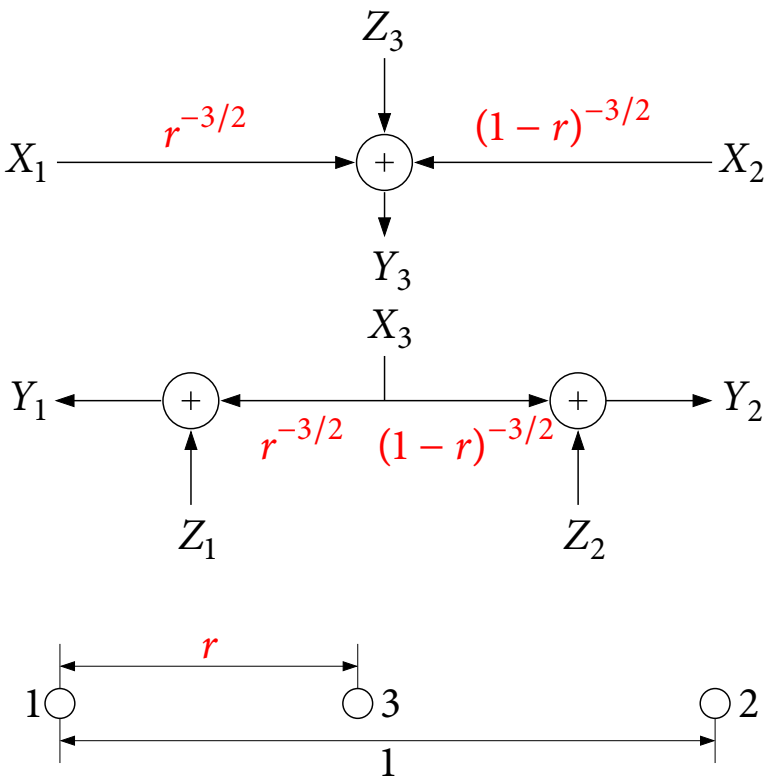


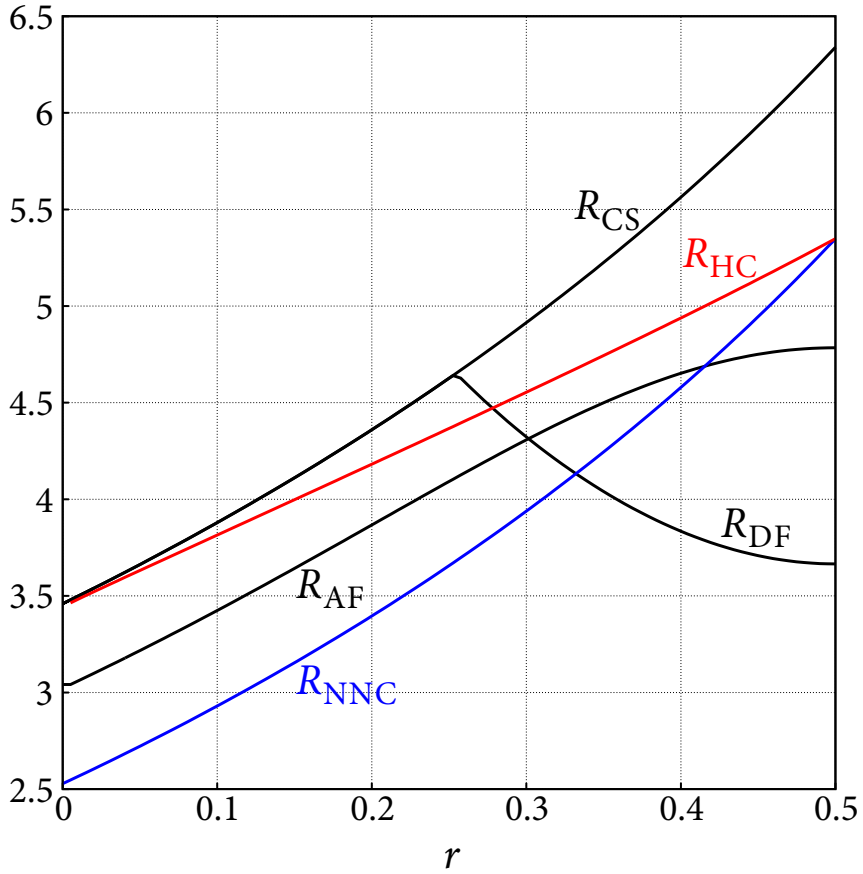


Conclusion 3

Advanced relaying schemes can outperform traditional schemes

Two-way relay communication





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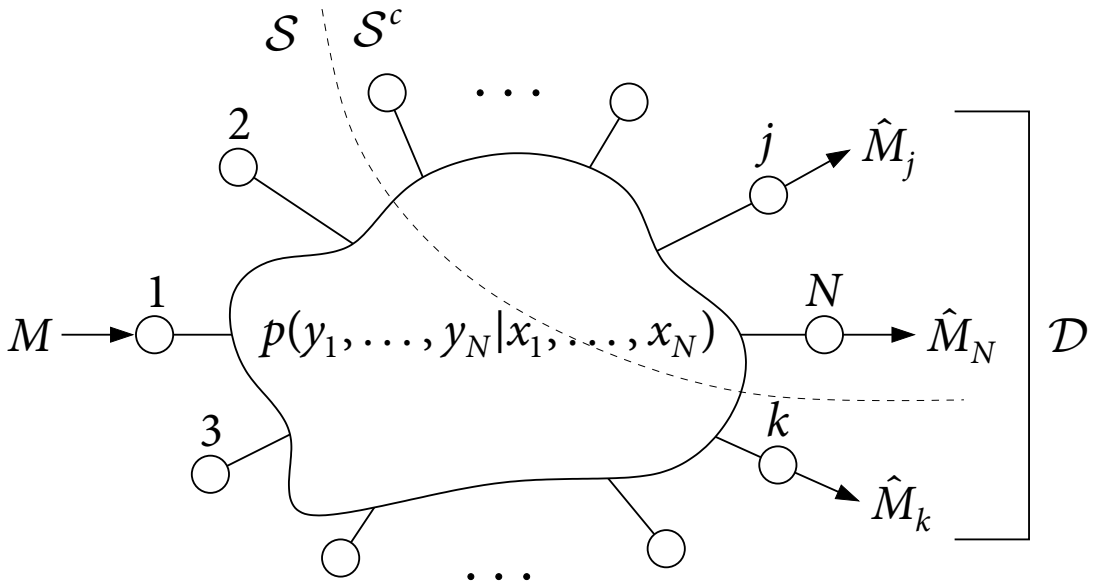
Challenge 3

Practical coding, modulation, and signal processing techniques

More on noisy network coding



Cutset bound (El Gamal 1981)

$$C \leq \min_{\mathcal{S}: 1 \in \mathcal{S},\, k \in \mathcal{S}^c} I(X(\mathcal{S}); Y(\mathcal{S}^c) | X(\mathcal{S}^c))$$

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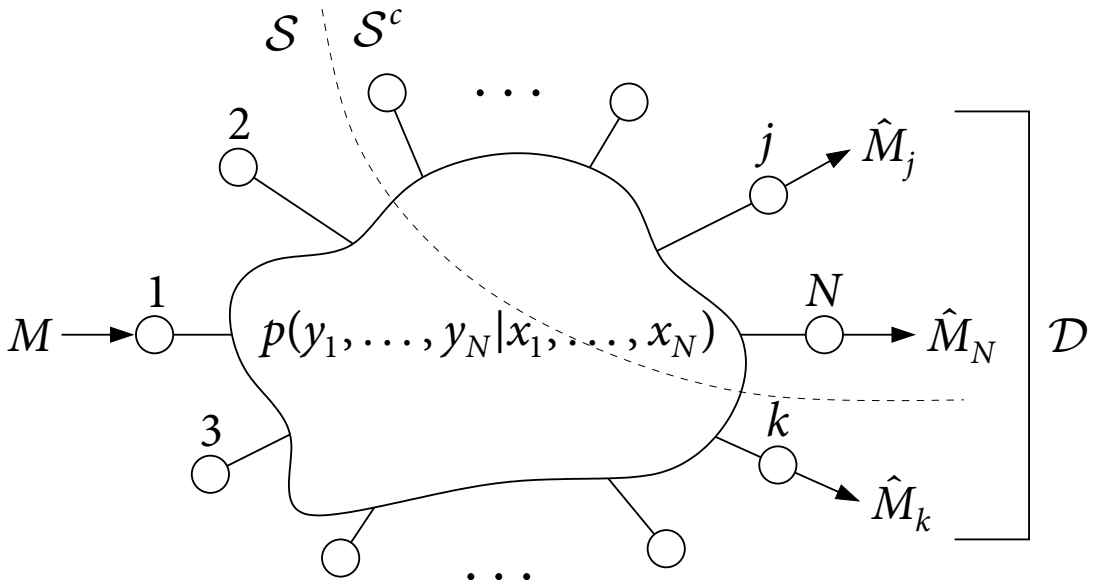

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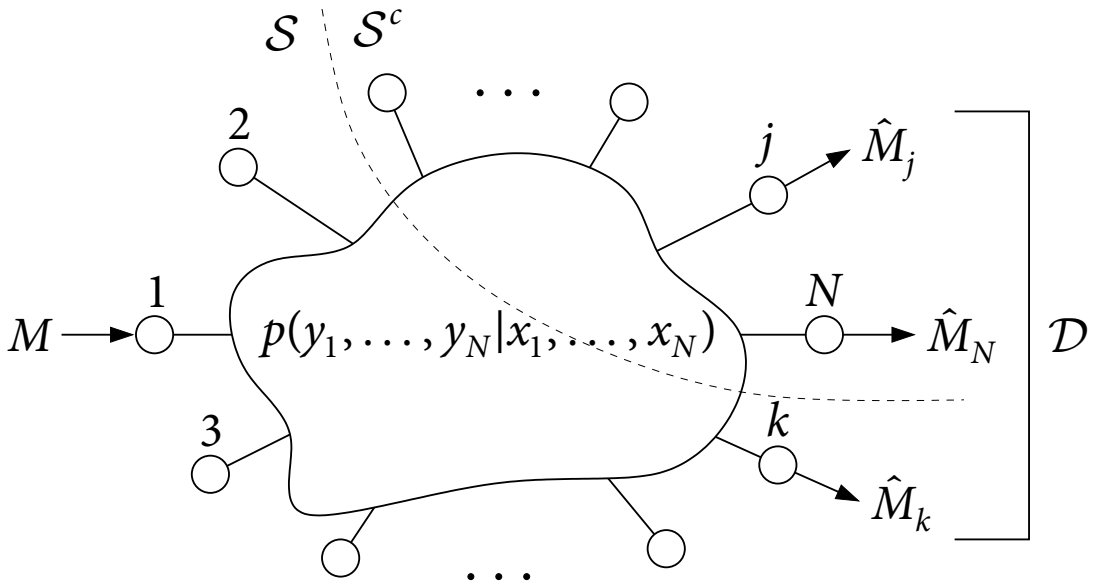

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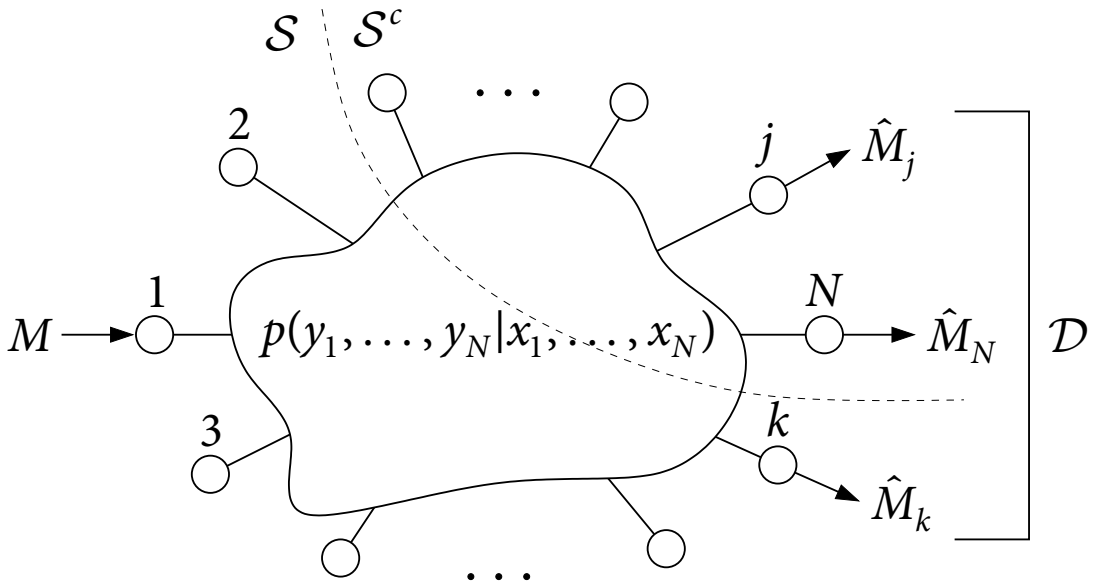

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Noisy network coding bound (Lim–K–El Gamal–Chung 2011)

$$C \ge \max \min_{k \in \mathcal{D}} \min_{\mathcal{S}: 1 \in \mathcal{S}, k \in \mathcal{S}^c} \left(I(X(\mathcal{S}); \hat{Y}(\mathcal{S}^c), Y_k|X(\mathcal{S}^c)) - I(Y(\mathcal{S}); \hat{Y}(\mathcal{S})|X^N, \hat{Y}(\mathcal{S}^c), Y_k)\right),$$

where the maximum is over all $\prod_{k=1}^{N} p(x_k)p(\hat{y}_k|y_k, x_k)$

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