Point-to-point codes for interference channels: A journey toward high performance at low complexity

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Communication Theory Workshop
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Tuesday, May 12, 2015

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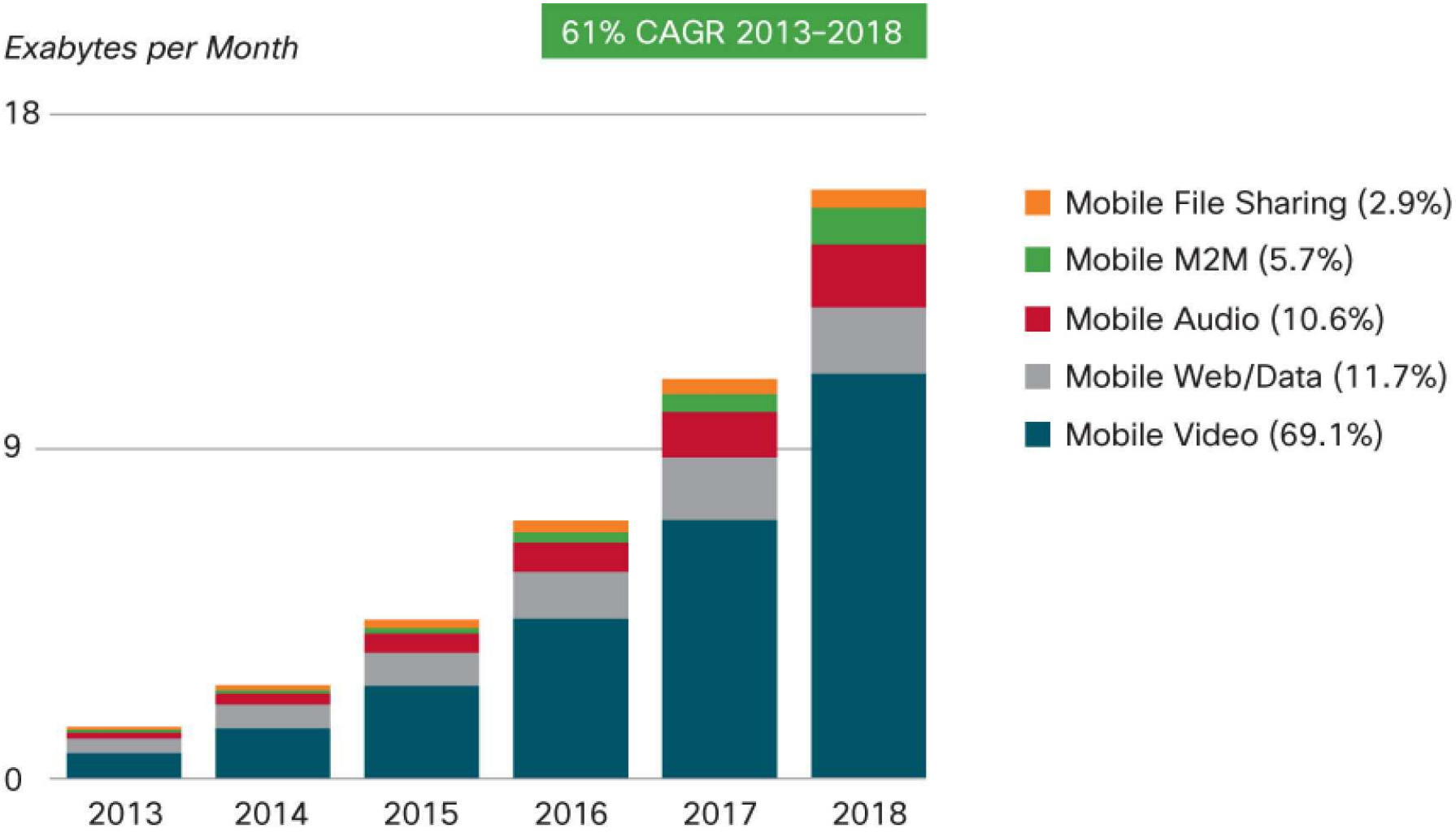
SPECIAL
Report

WORDS **BENNETT RING** ILLUSTRATION **NIGEL BUCHANAN**

CONNECTIVITY
~IS KING~

From smart watches that synchronise with smartphones, to portable high-definition cameras that can be remotely monitored from anywhere on Earth, 2014 has been a year in which to be linked in is everything.

Where is wireless going?



Figures in parentheses refer to traffic share in 2018.

Source: Cisco VNI Mobile, 2014

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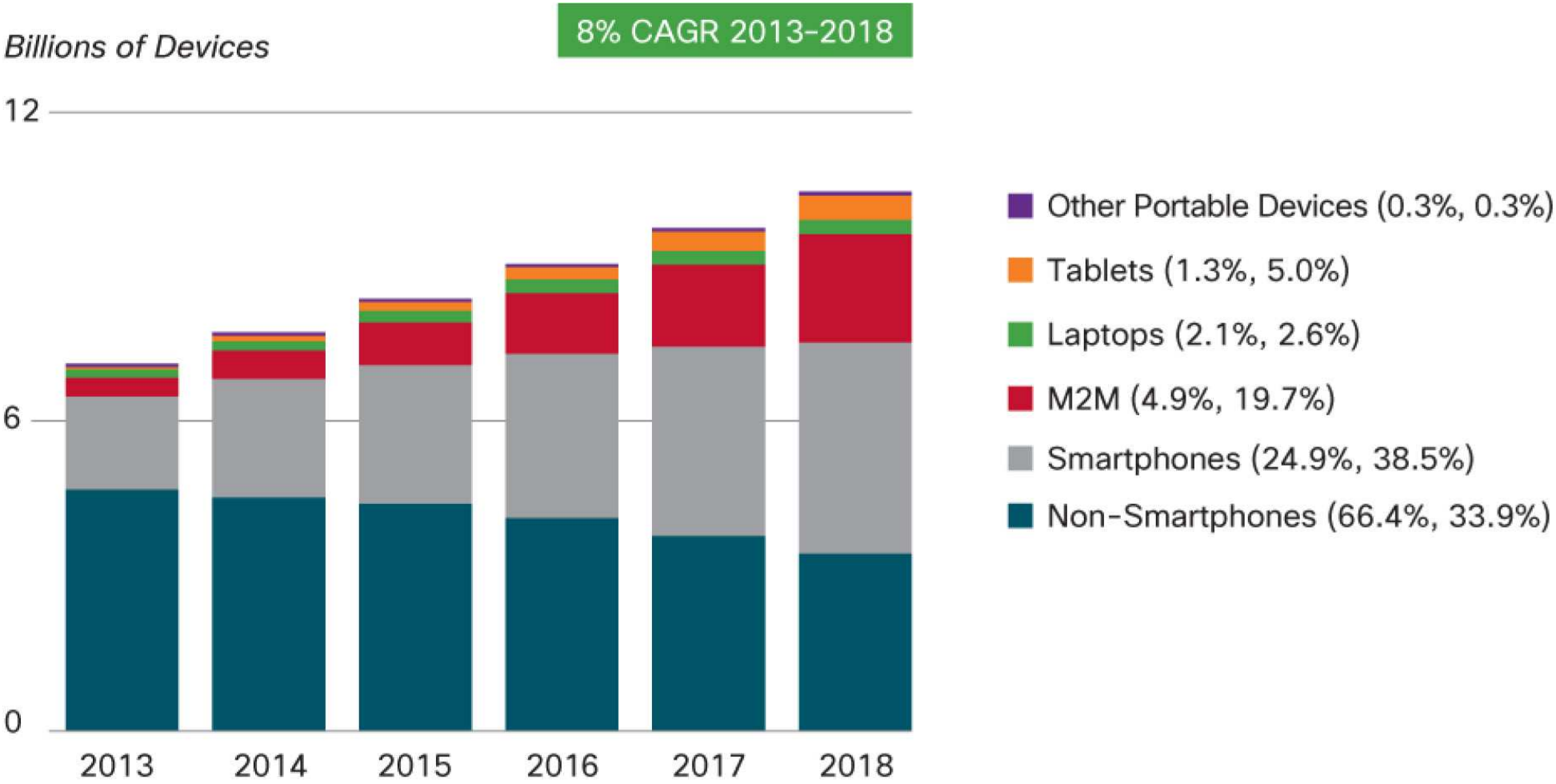

Figures in parentheses refer to device or connections share in 2013, 2018.

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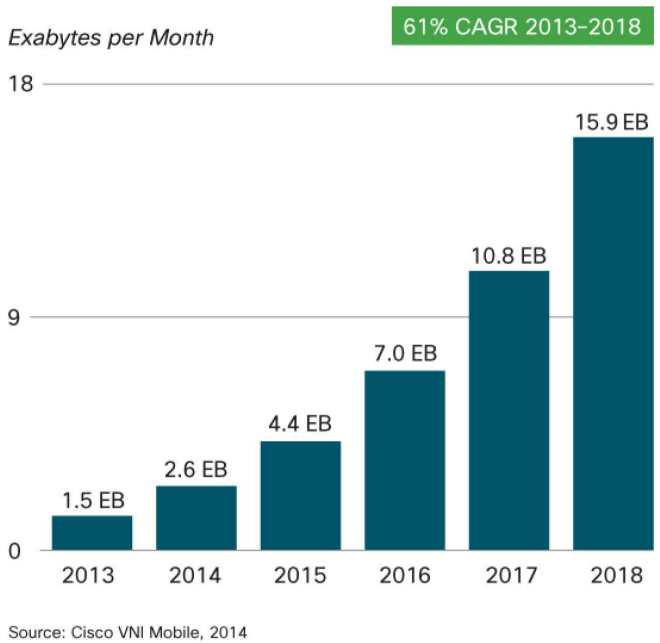
Where is wireless going?

Mobile data per month



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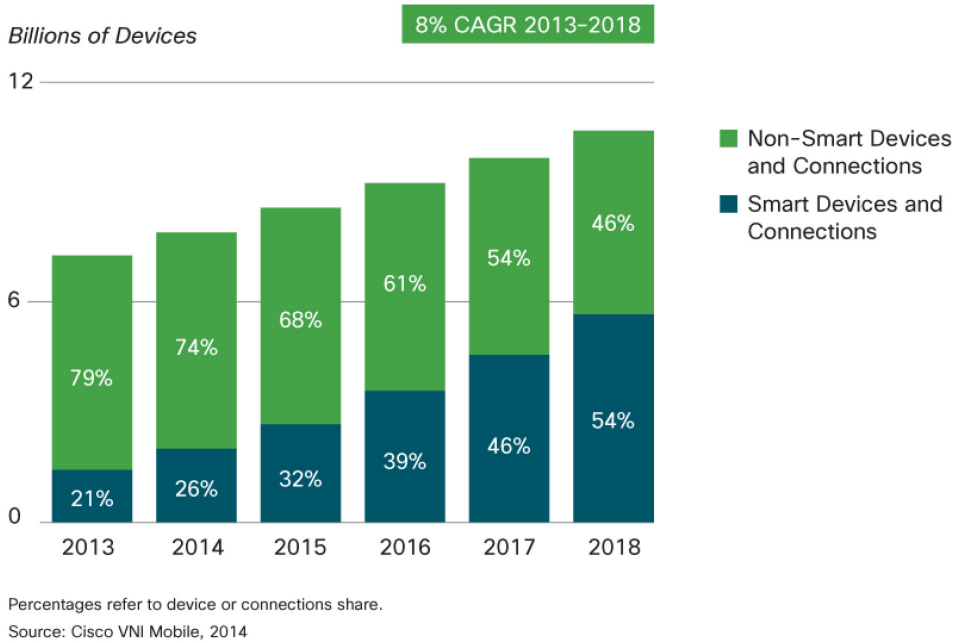
Number of devices



Percentages refer to device or connections share.

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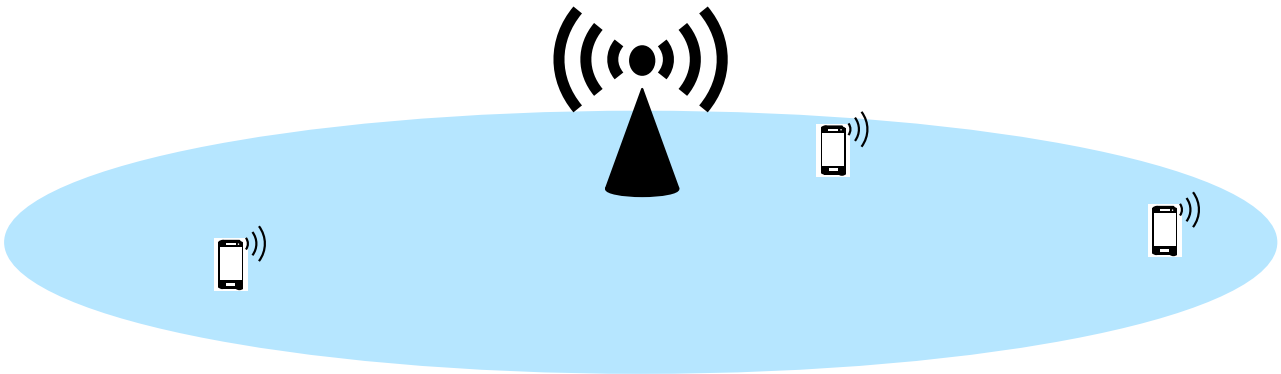

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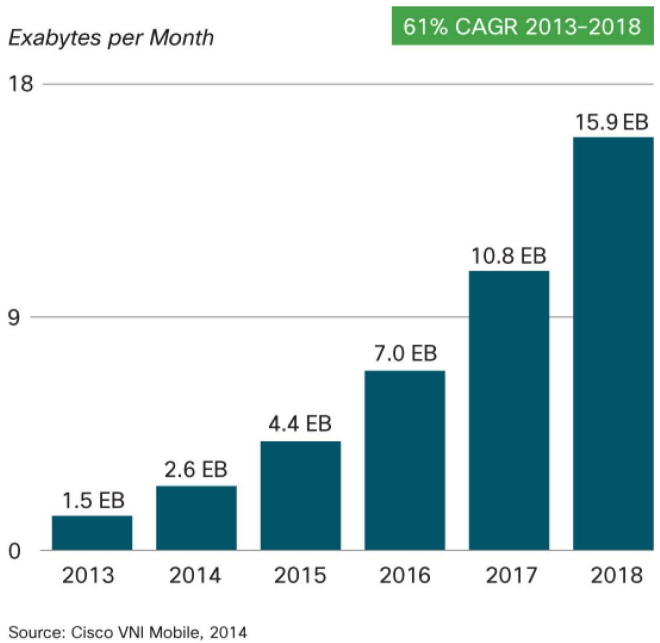

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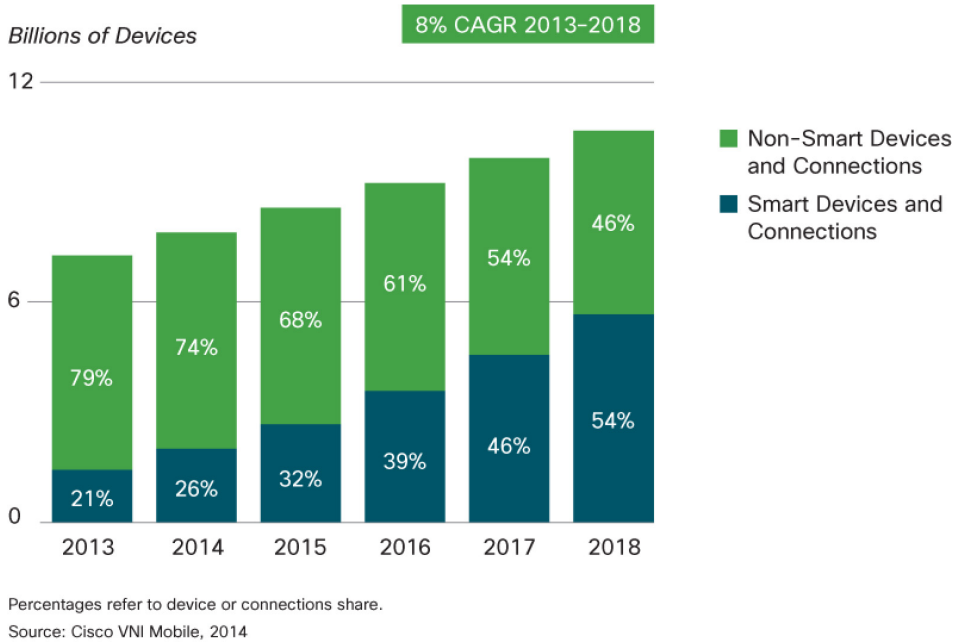

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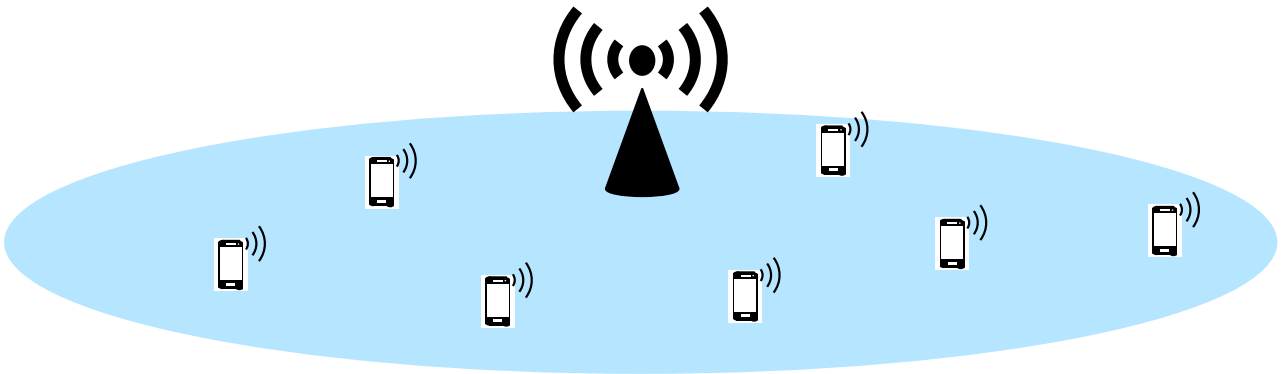

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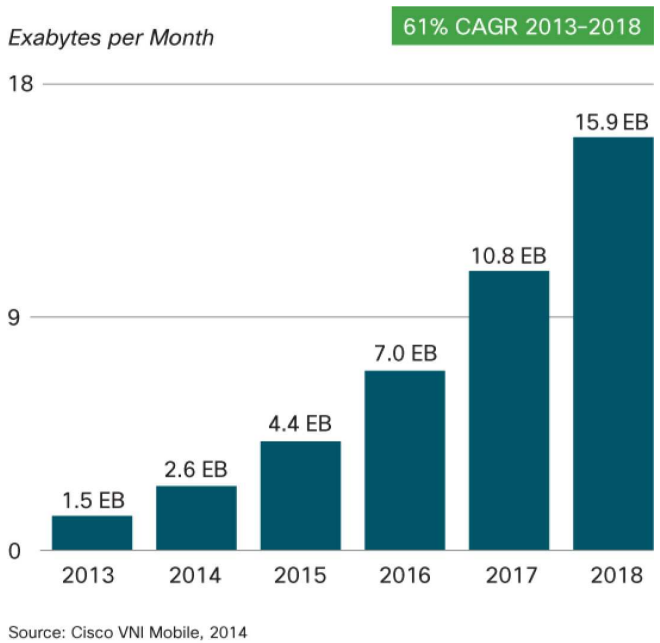

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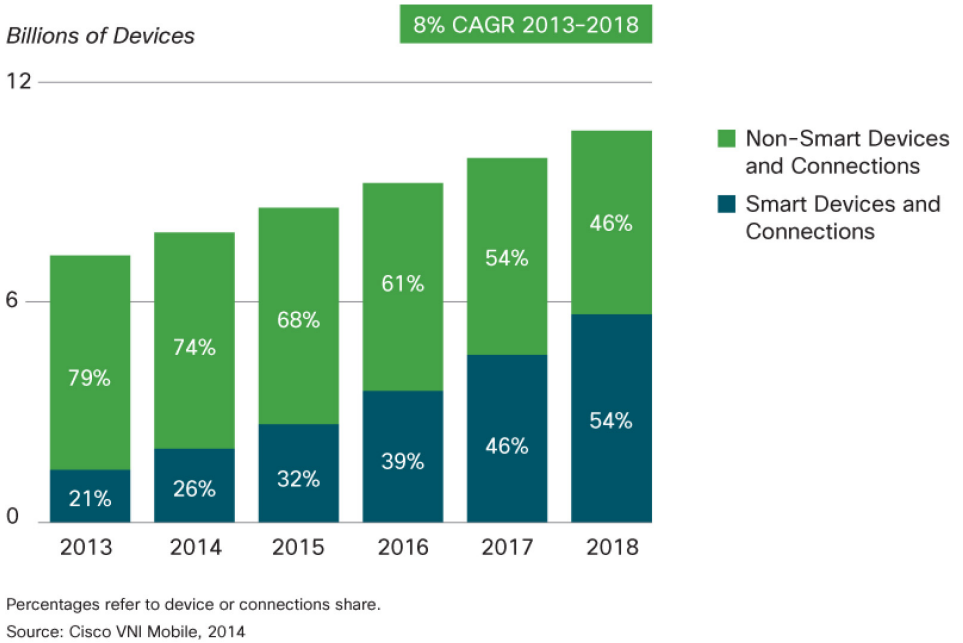

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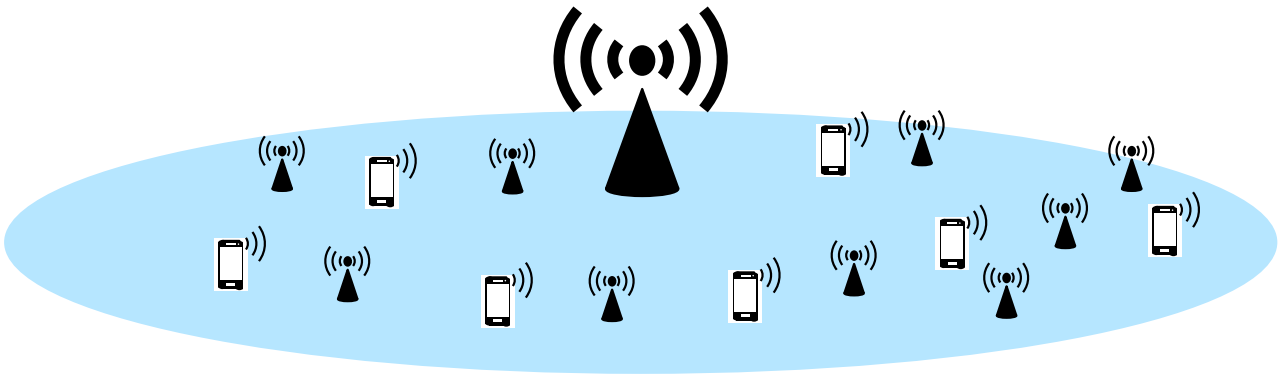
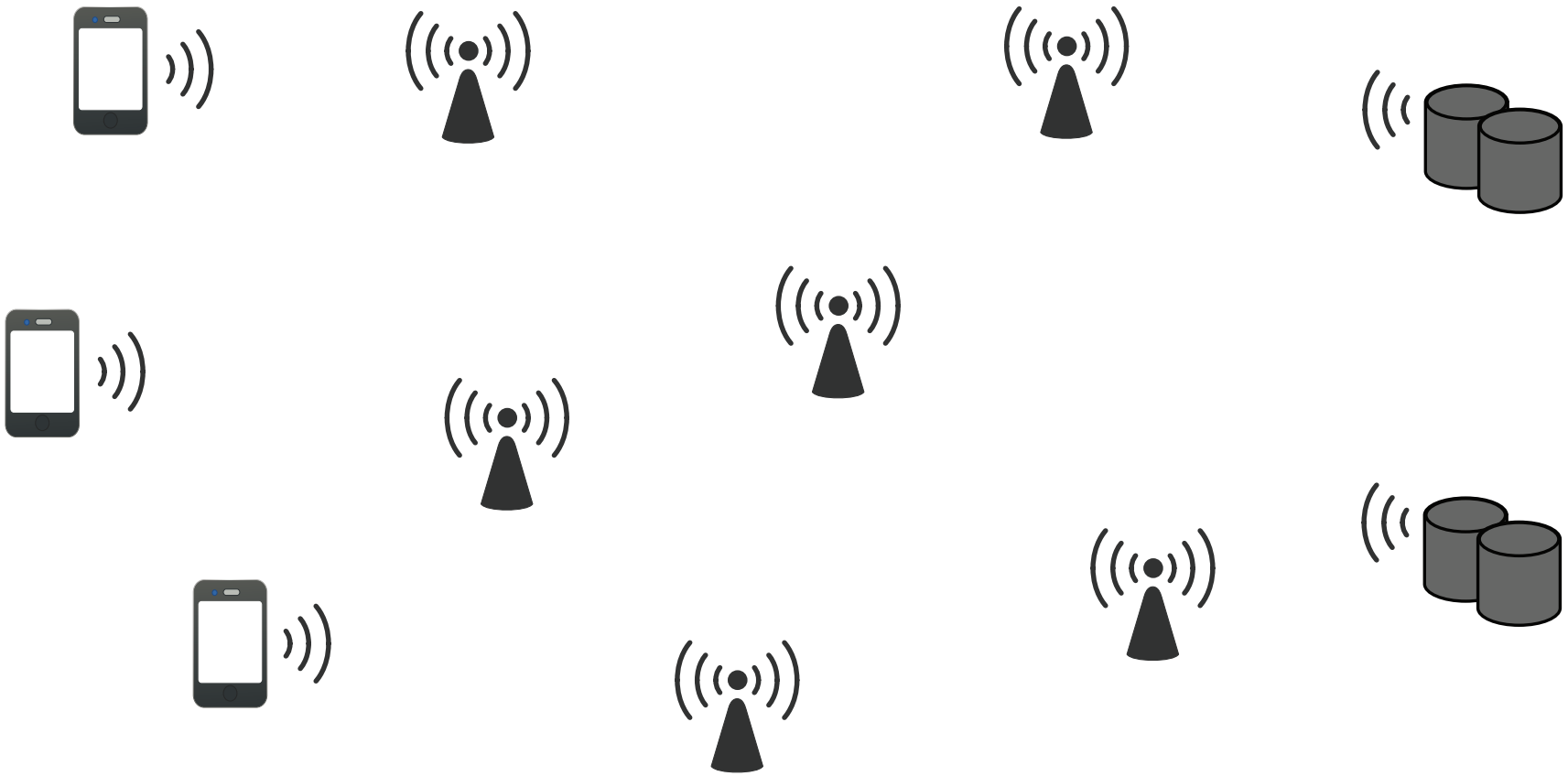



The Internet of THINGS
CONNECTED OBJECTS
CONNECTED PLANT
3km range
4
CONNECT THE WORLD

Interference, interference, interference



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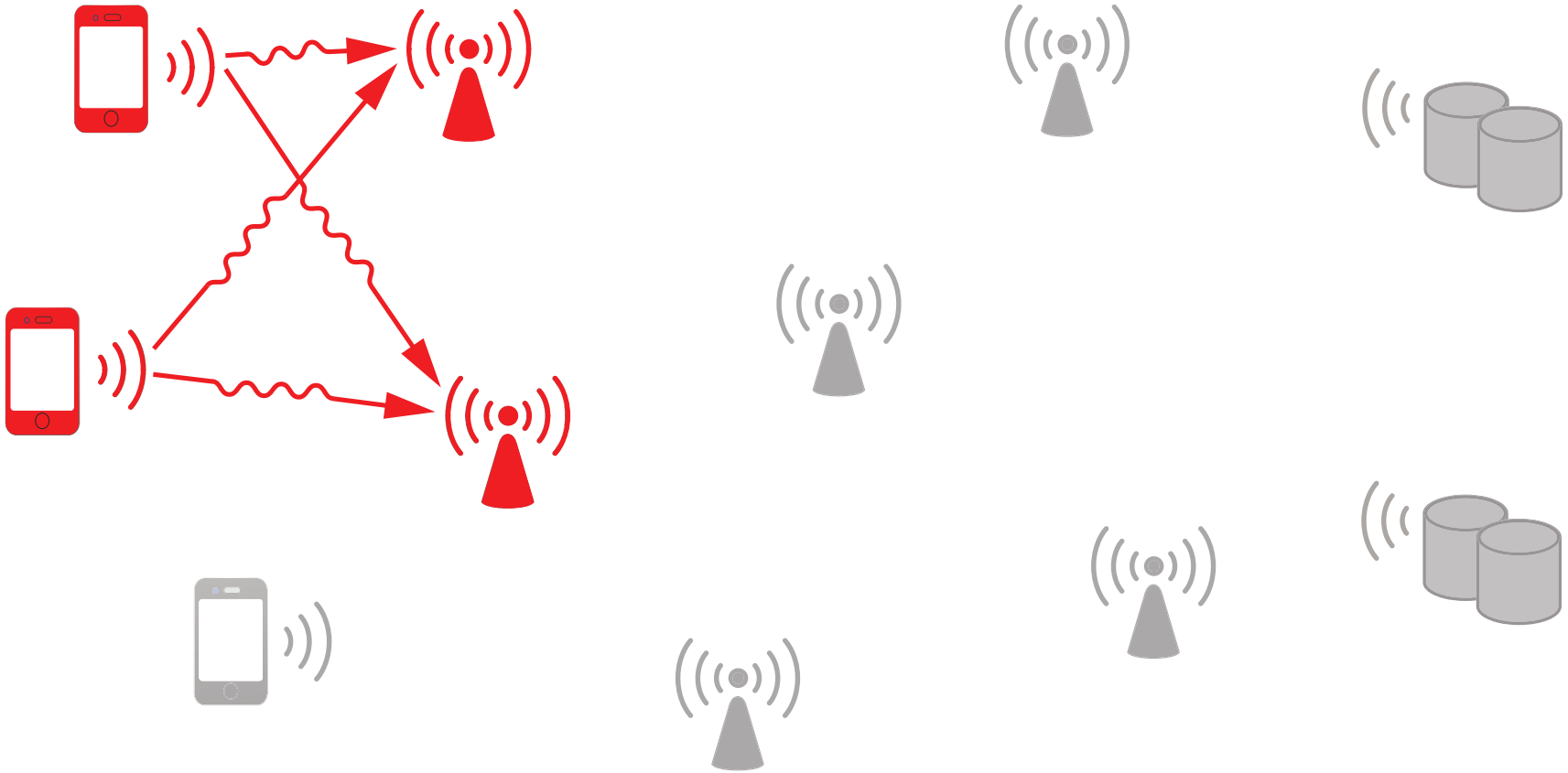

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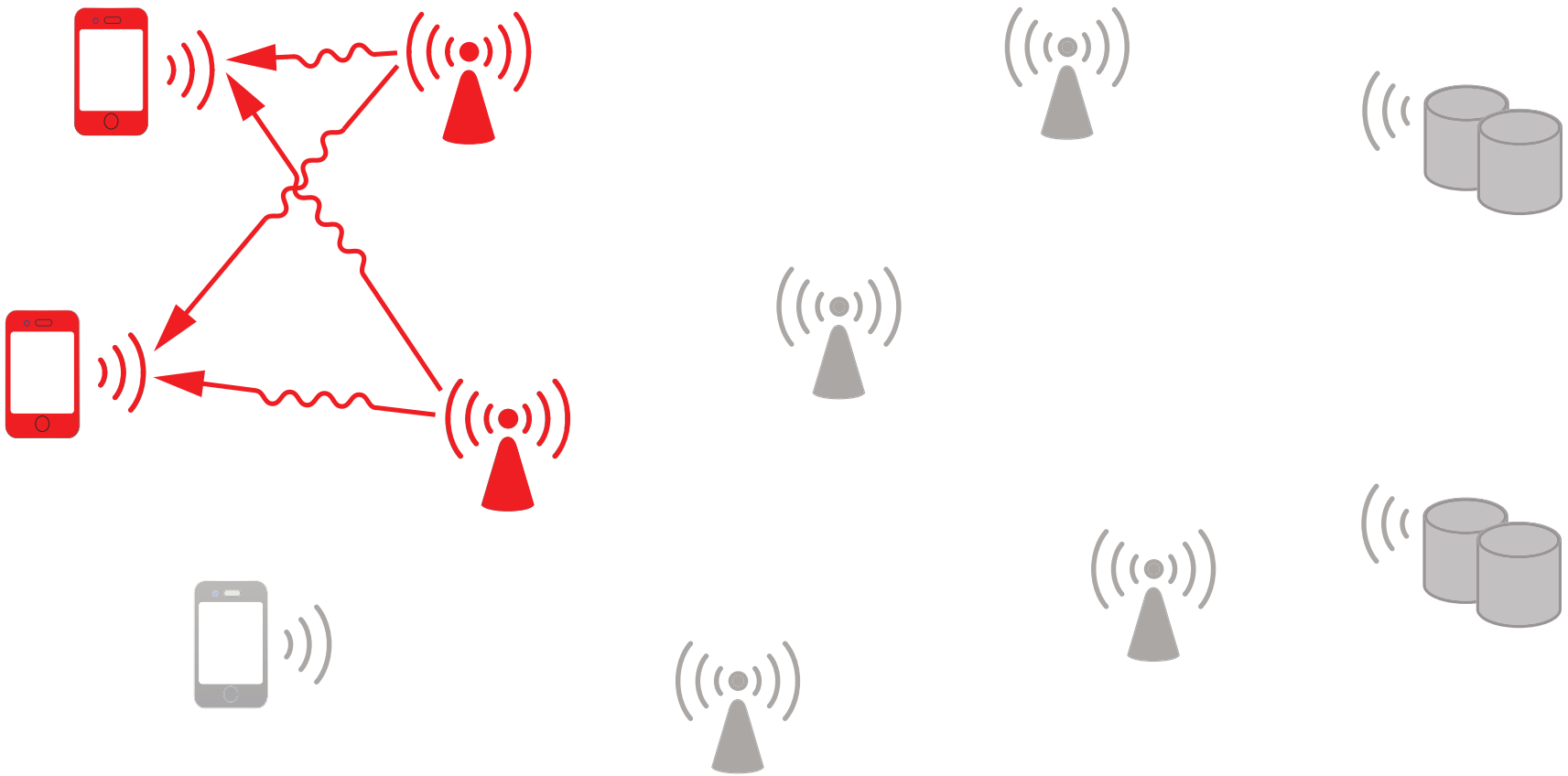
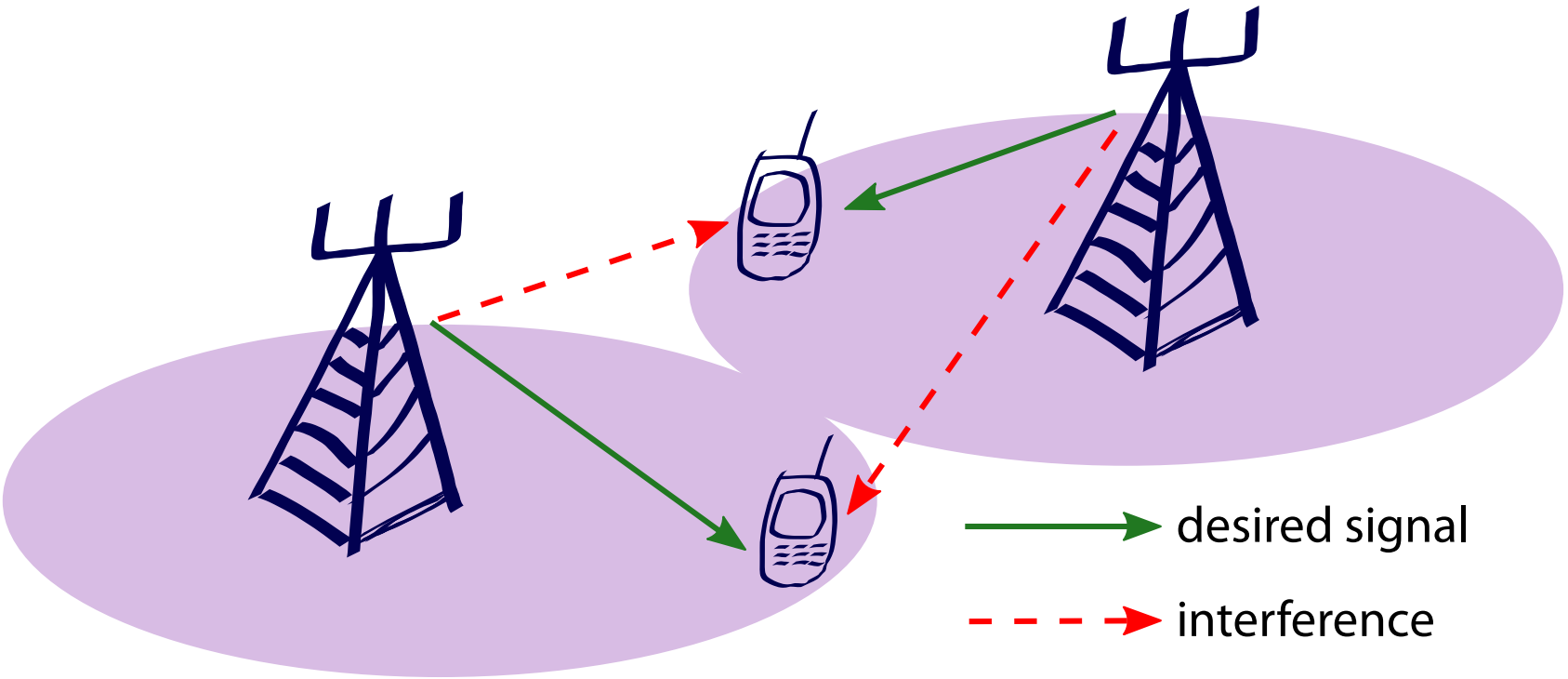


Interference in cellular networks



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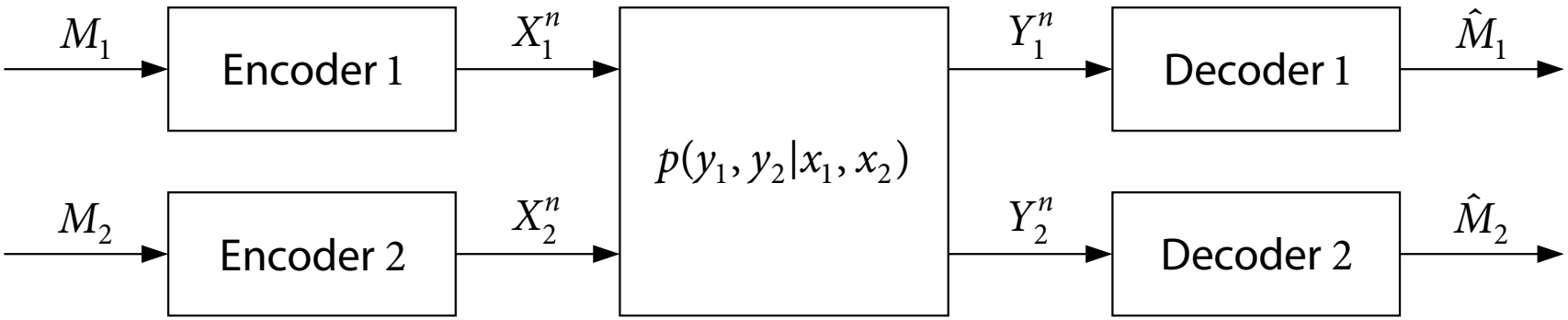

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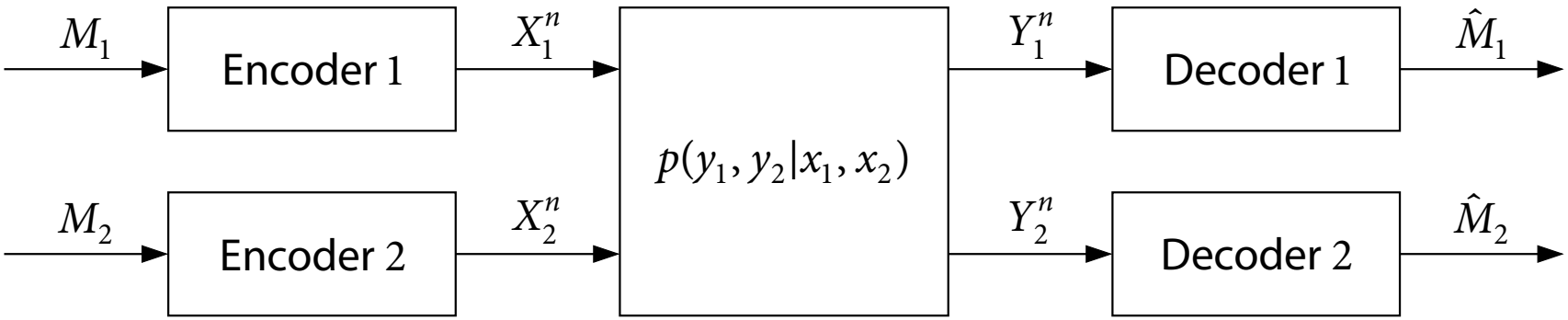

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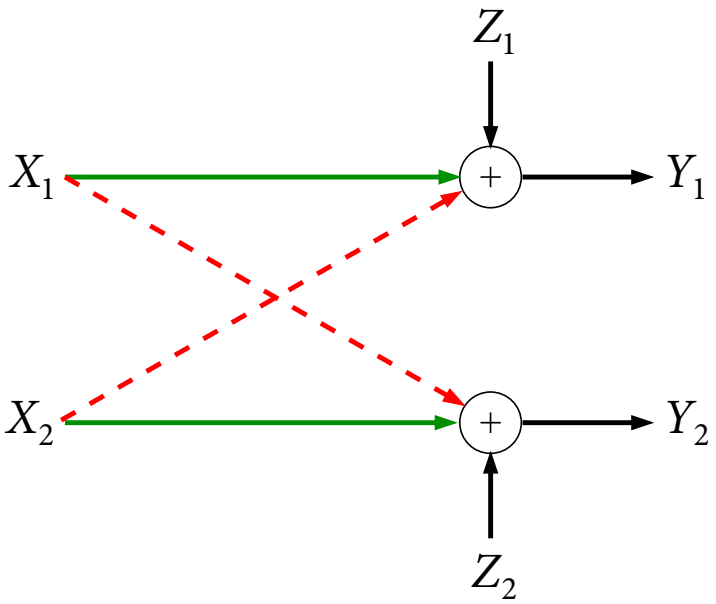

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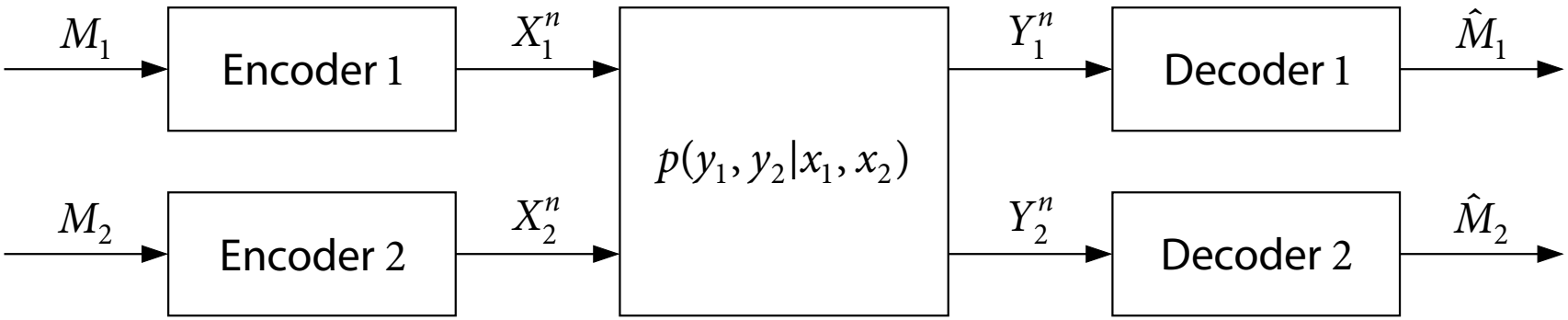

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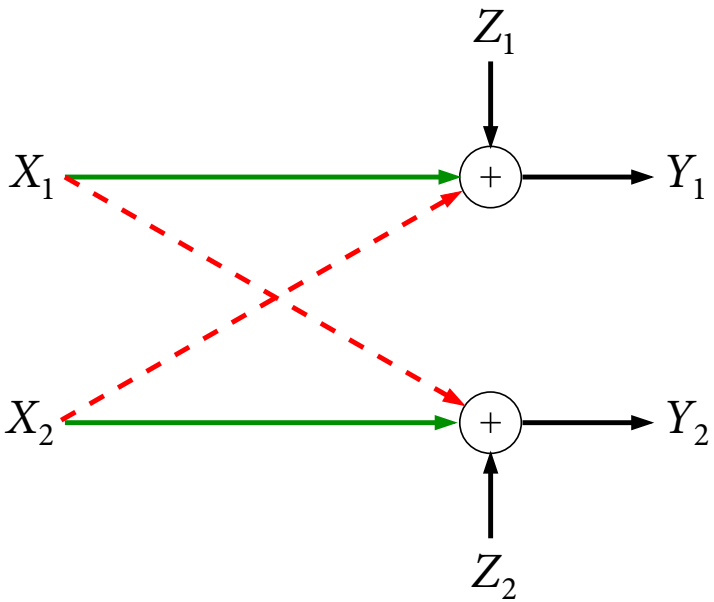
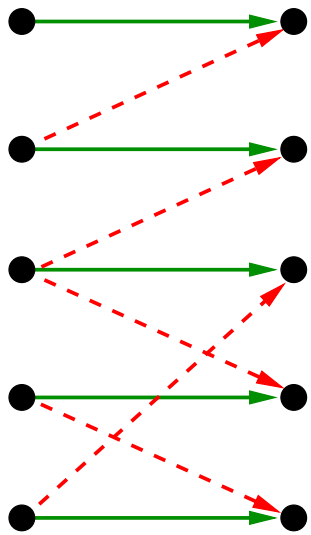


- Network with one dominant interferer



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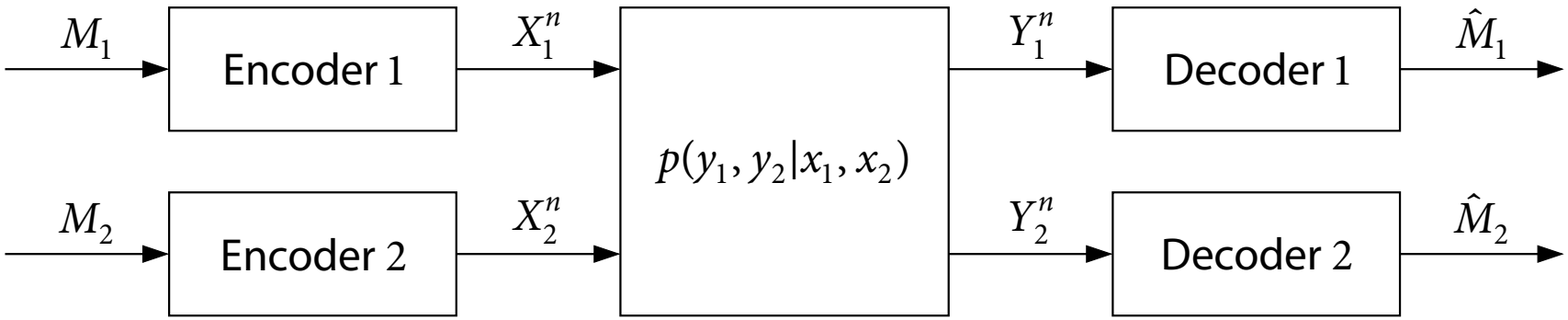

- Capacity region: Optimal tradeoff between the rates

$$R_1 = \frac{1}{n} \log |\text{supp}(M_1)|$$
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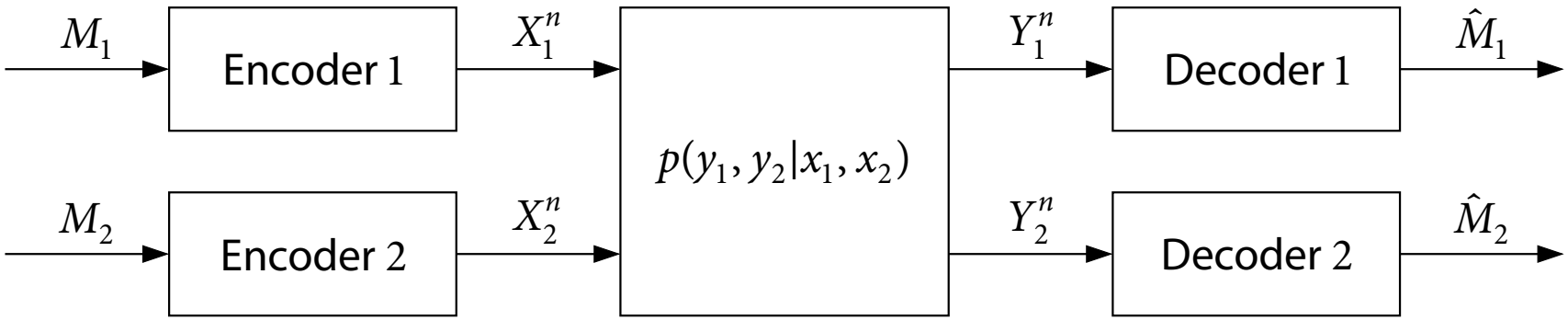

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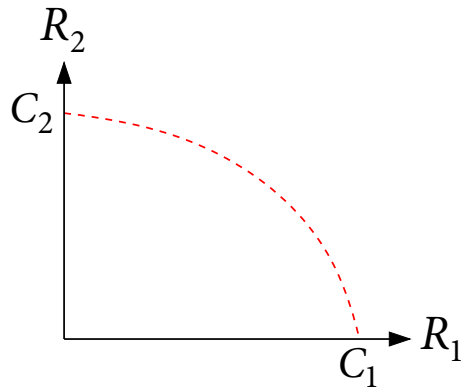

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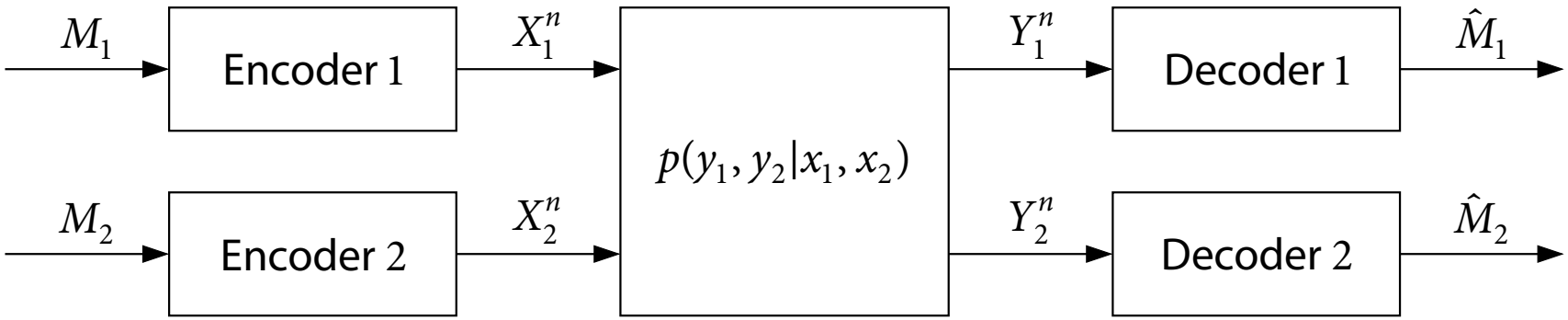

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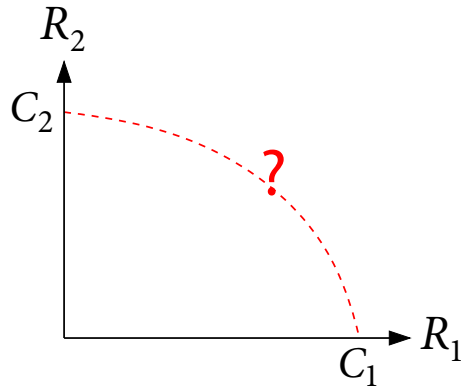

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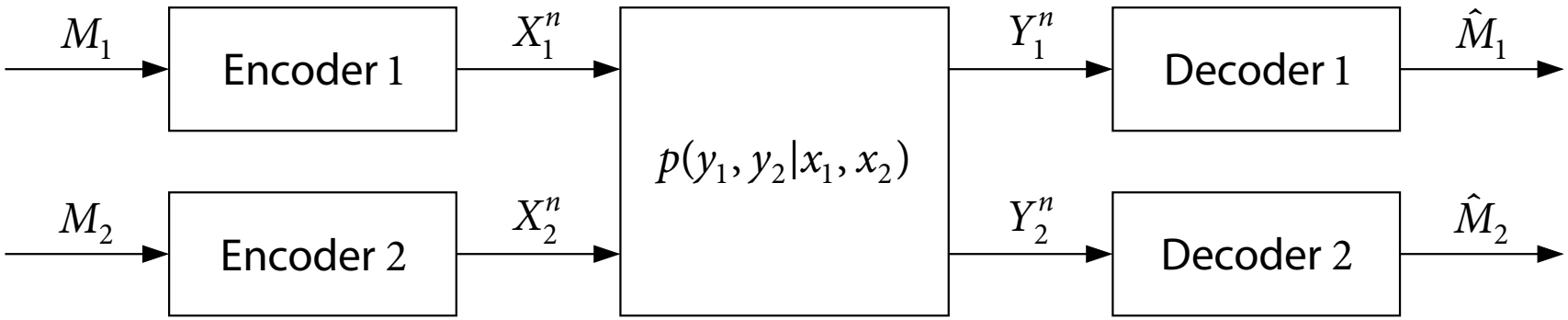

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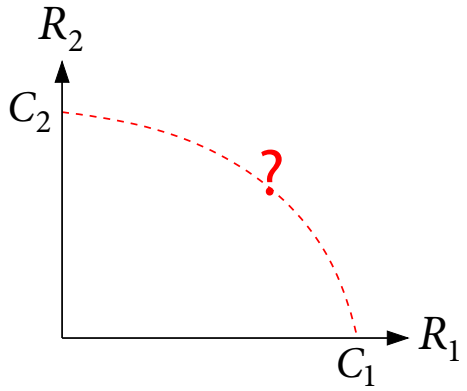

- Best inner bound: Han–Kobayashi (1981) and Nair–Xia–Yazdanpanah (2015)

Performance benchmark

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- Random code ensemble
  - For each $m_1 \in [1 : 2^{nR_1}]$, generate $X_1^n(m_1) \sim \prod_{i=1}^n p_{X_1}(x_{1i})$
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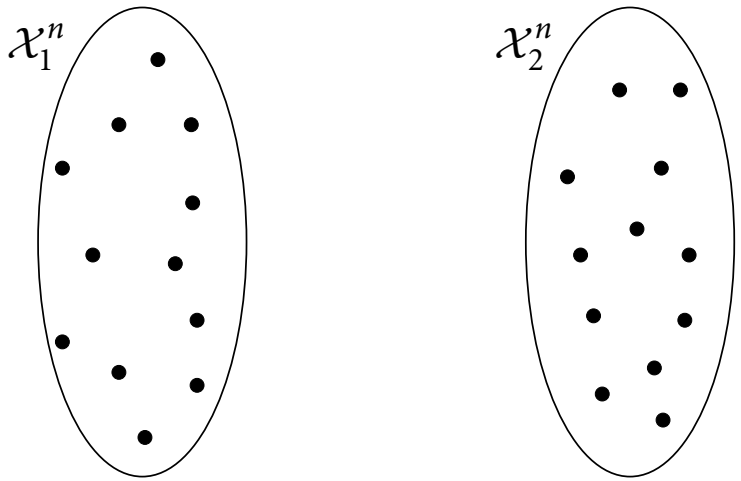

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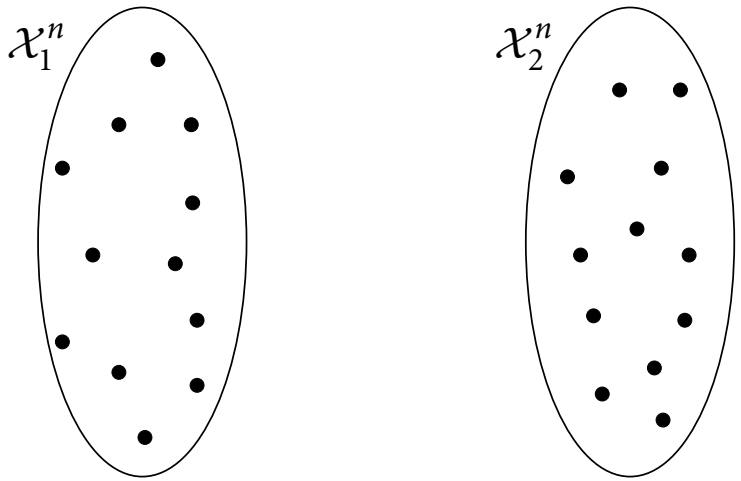

- What is the optimal (MLD) tradeoff between achievable R_1 and R_2?

Why do we care?

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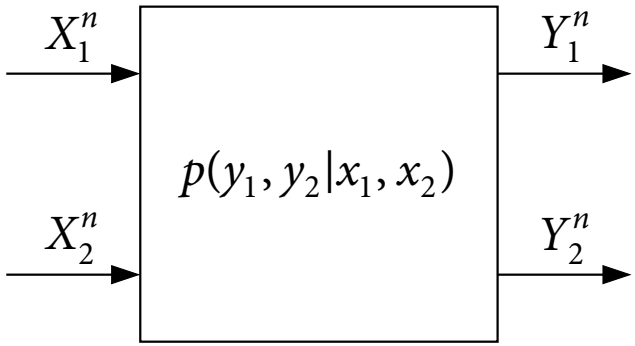

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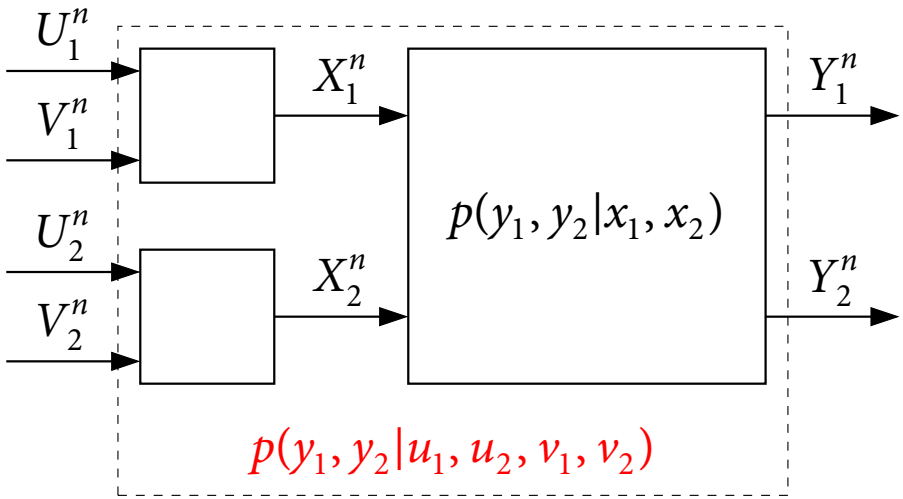

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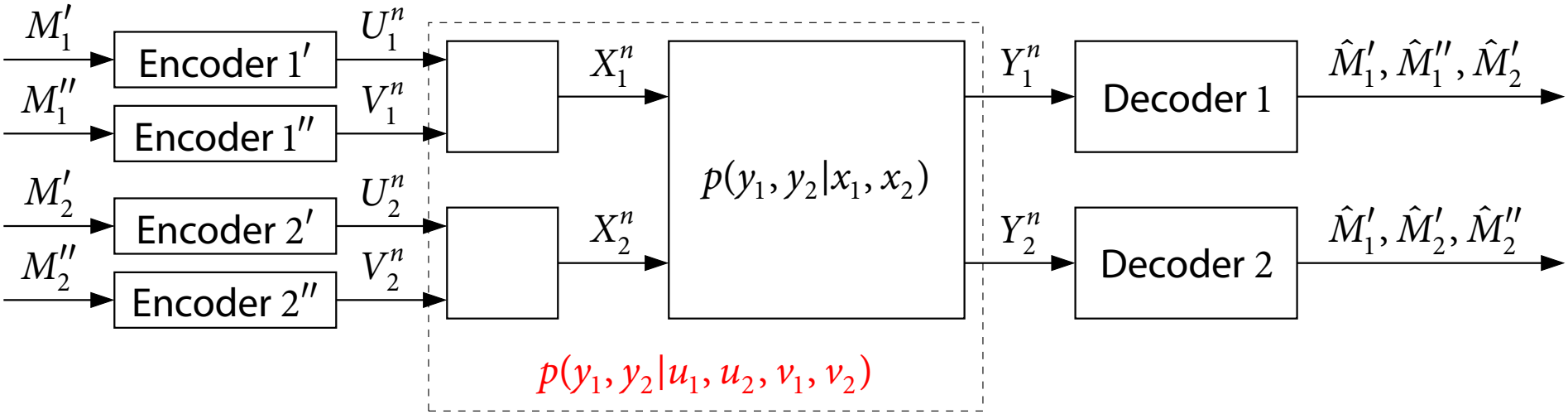

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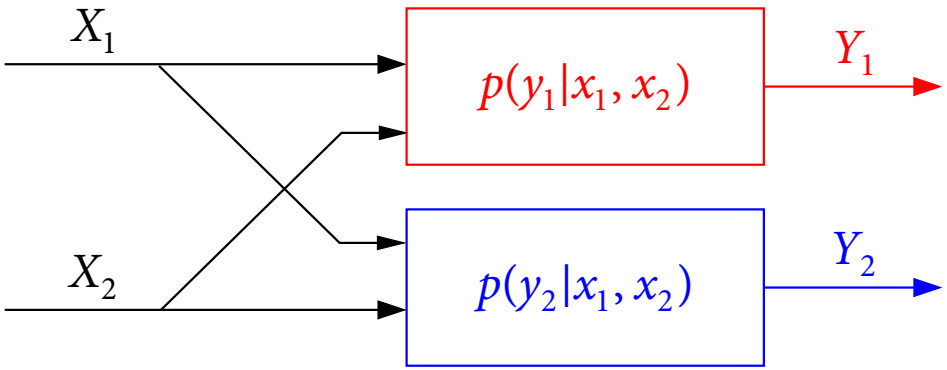

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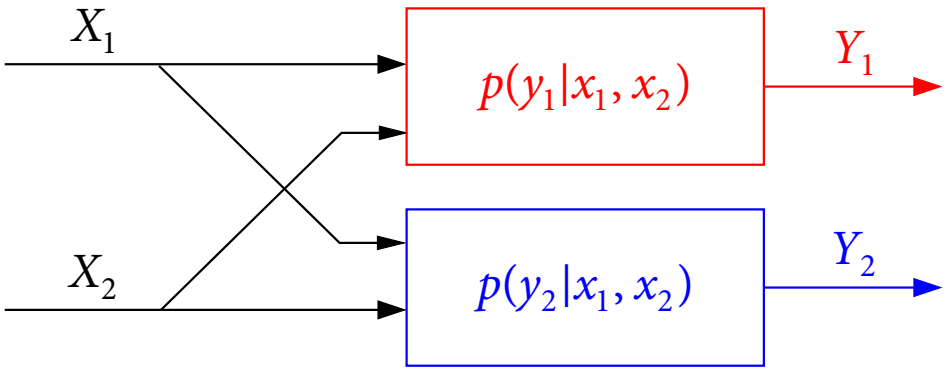

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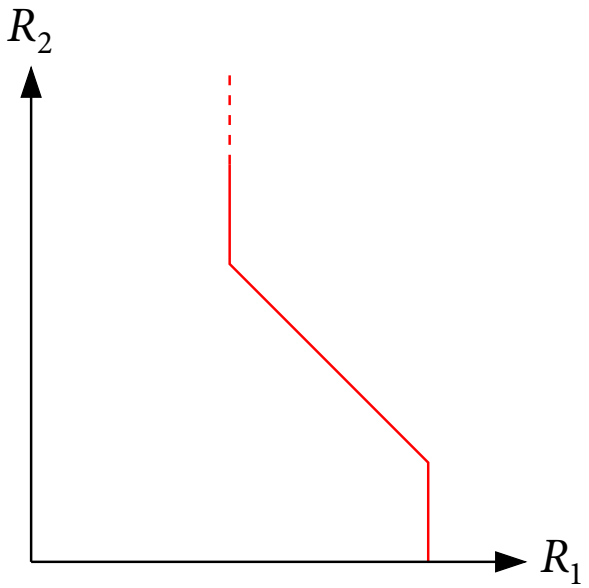

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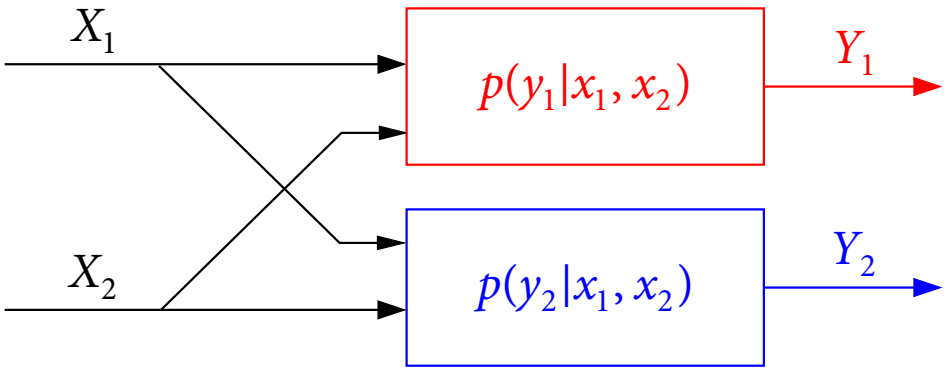

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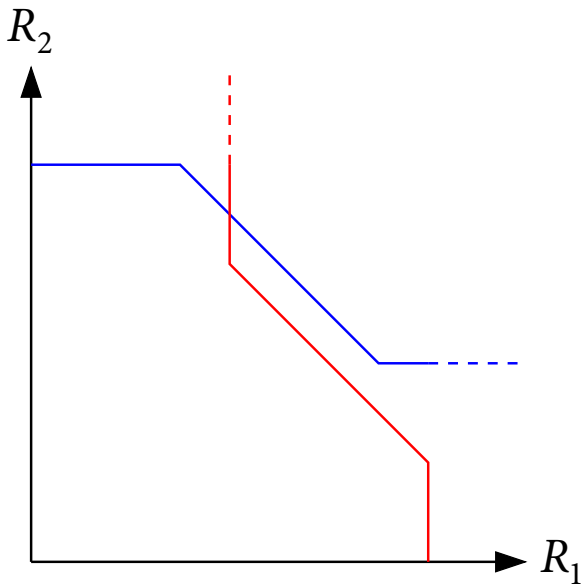

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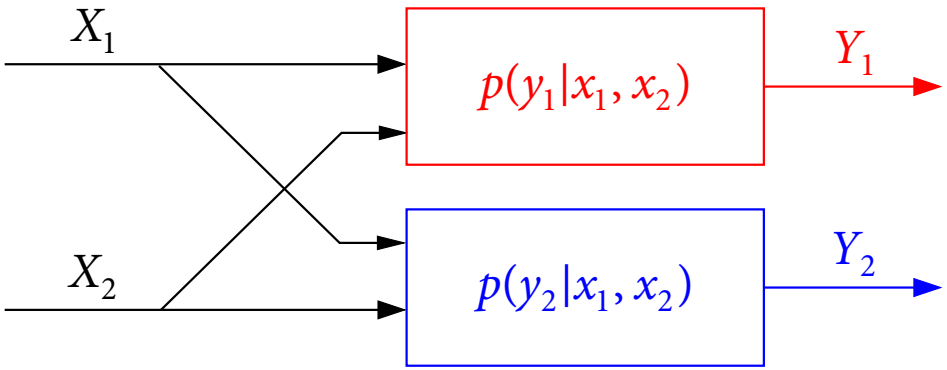

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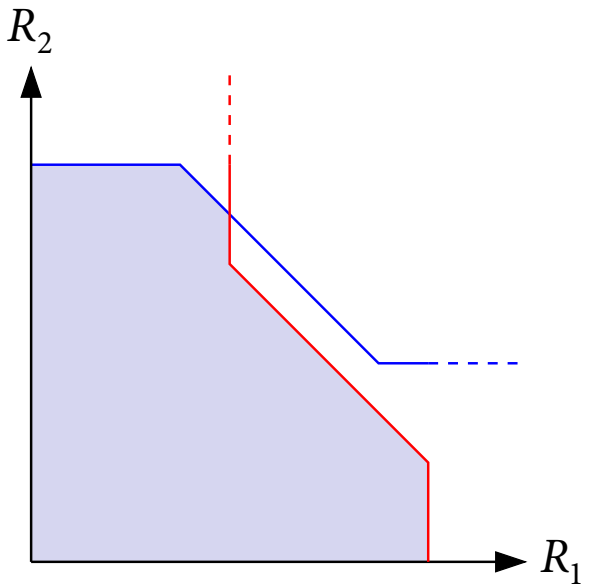

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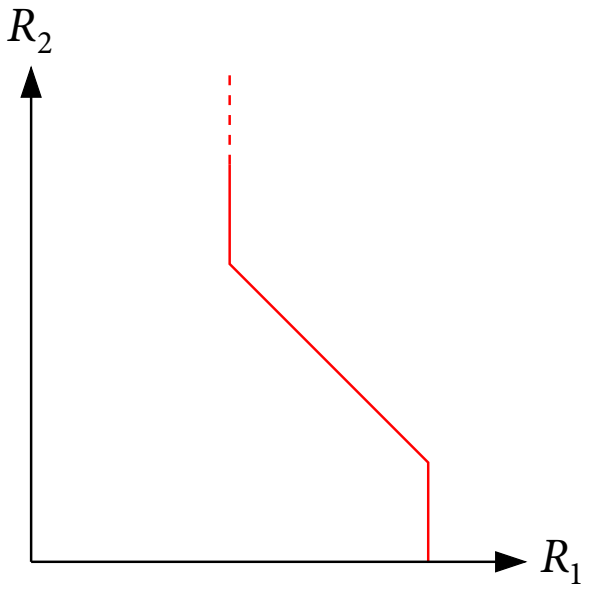

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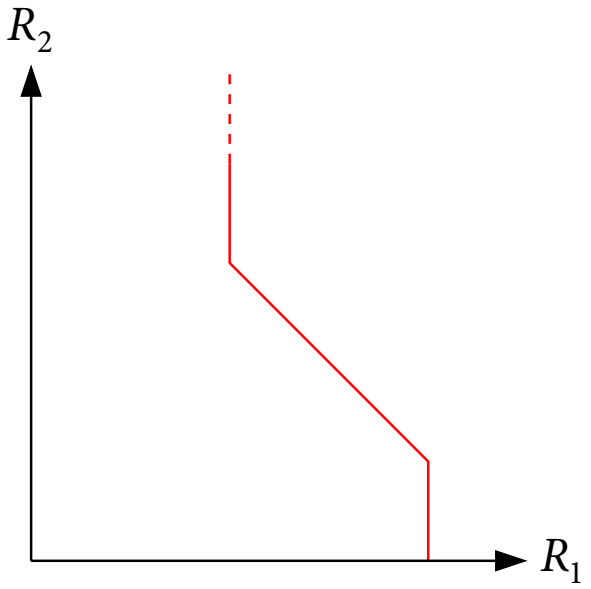

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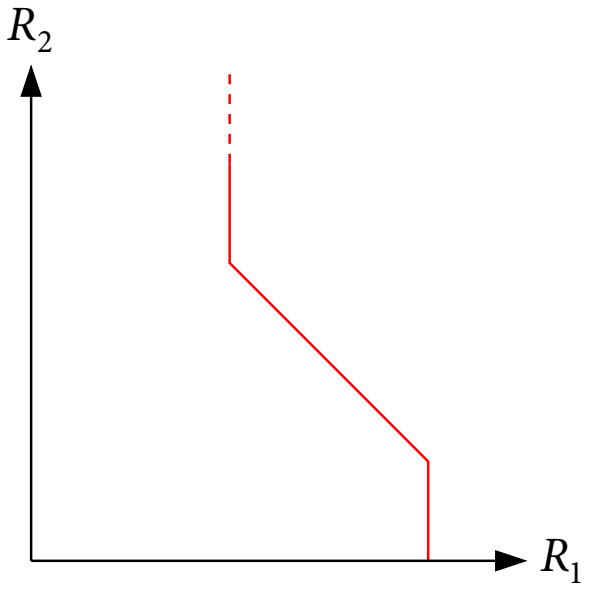

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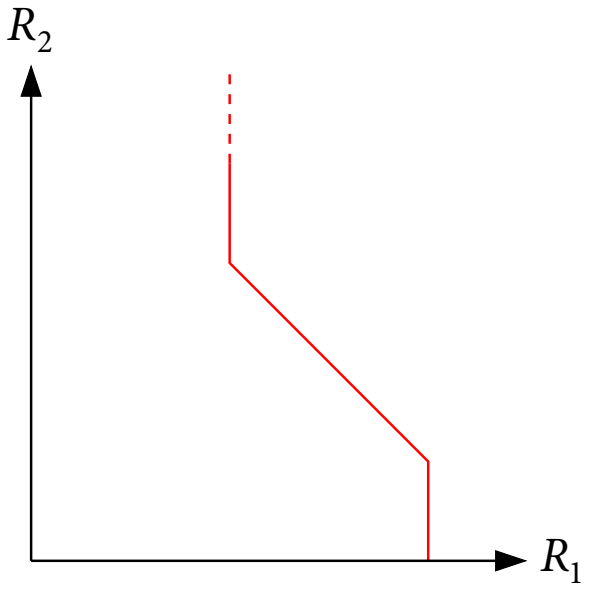

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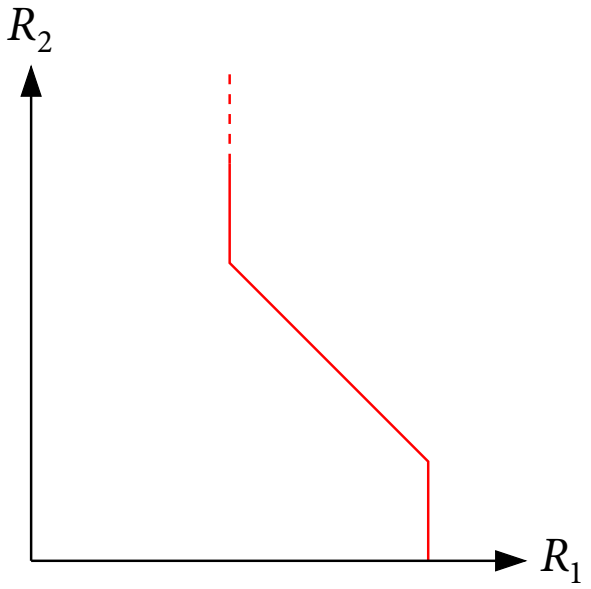
- Simultaneous nonunique decoding (SND): $(x_1^n(\hat{m}_1), x_2^n(m_2), y_1^n) \in \mathcal{T}_\epsilon^{(n)}$ for some m_2

Maximum likelihood decoding ≈ simultaneous decoding

$$R_1 < I(X_1; Y_1|X_2),$$
$$R_1 + R_2 < I(X_1, X_2; Y_1)$$

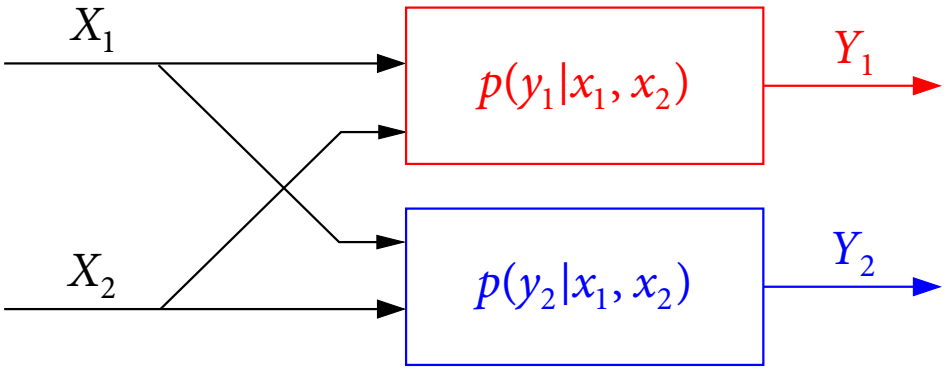
or

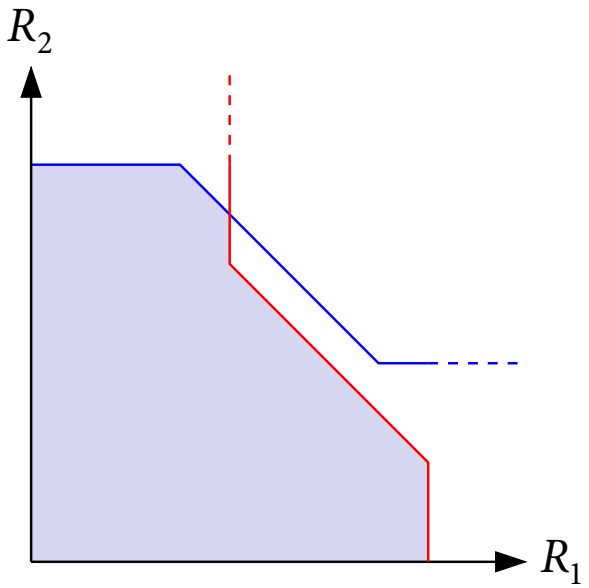
$$R_1 < I(X_1; Y_1)$$



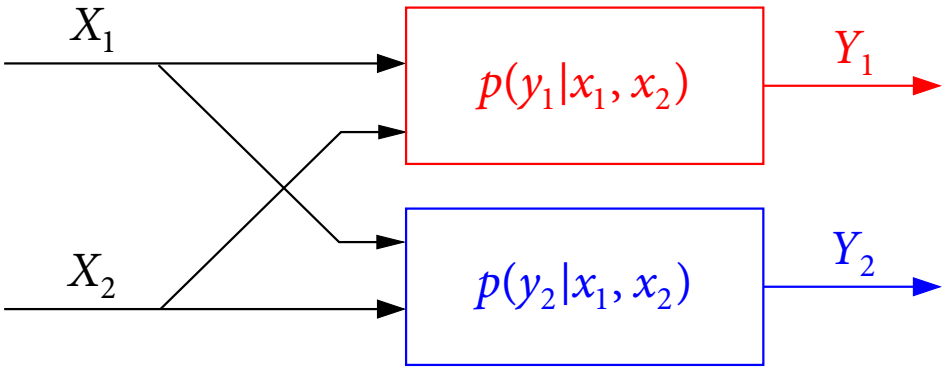
- Maximum likelihood decoding: $\arg\max_{\hat{m}_1} \sum_{m_2} p(y_1^n|\hat{m}_1, m_2)$
- Simultaneous ML decoding: $\arg\max_{\hat{m}_1} \max_{m_2} p(y_1^n|\hat{m}_1, m_2)$
- Simultaneous nonunique decoding (SND): $(x_1^n(\hat{m}_1), x_2^n(m_2), y_1^n) \in \mathcal{T}_\epsilon^{(n)}$ for some m_2
- Multiuser detection: High complexity!

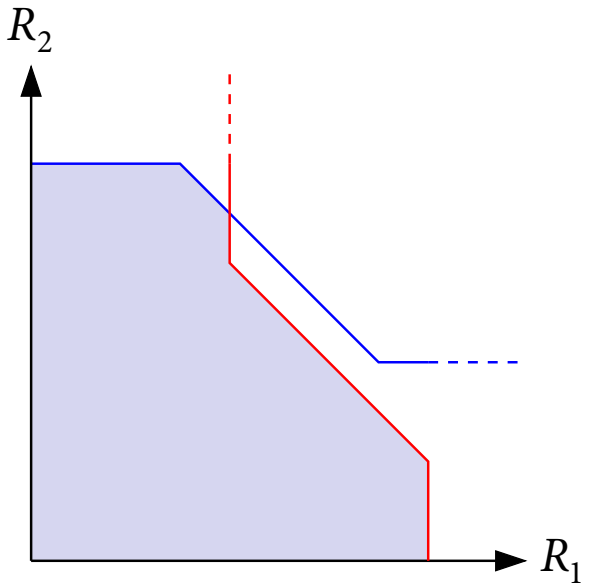
Low-complexity (implementable) alternatives





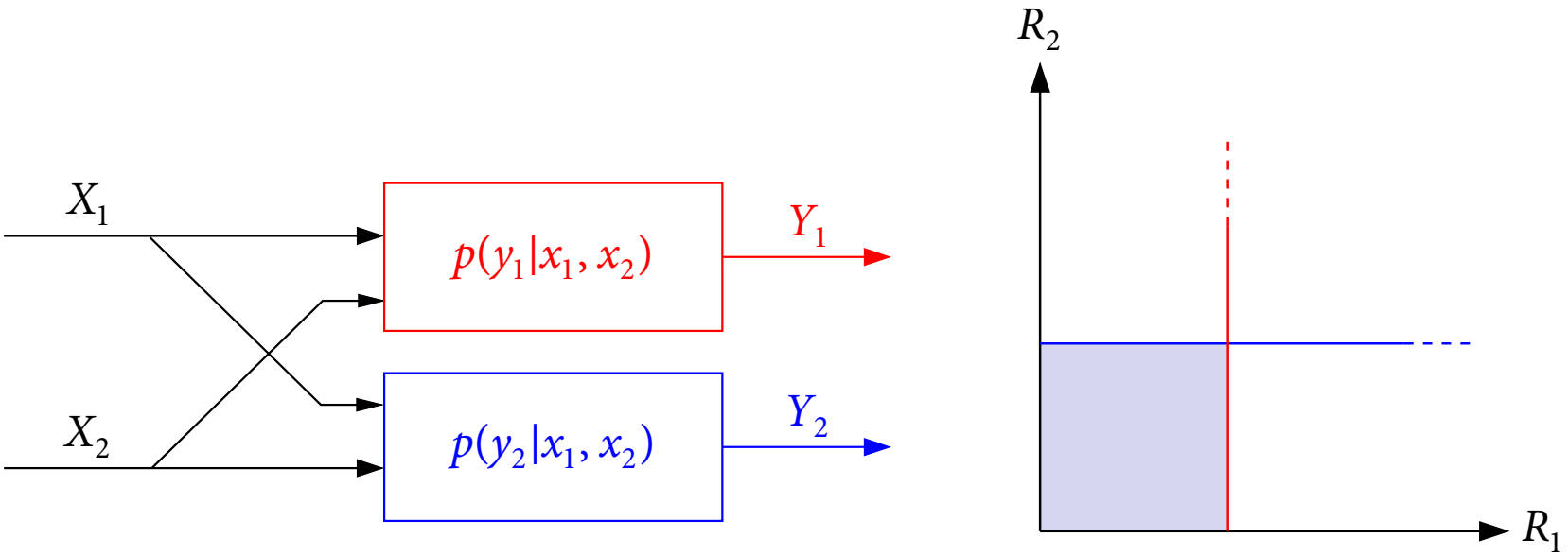
Low-complexity (implementable) alternatives





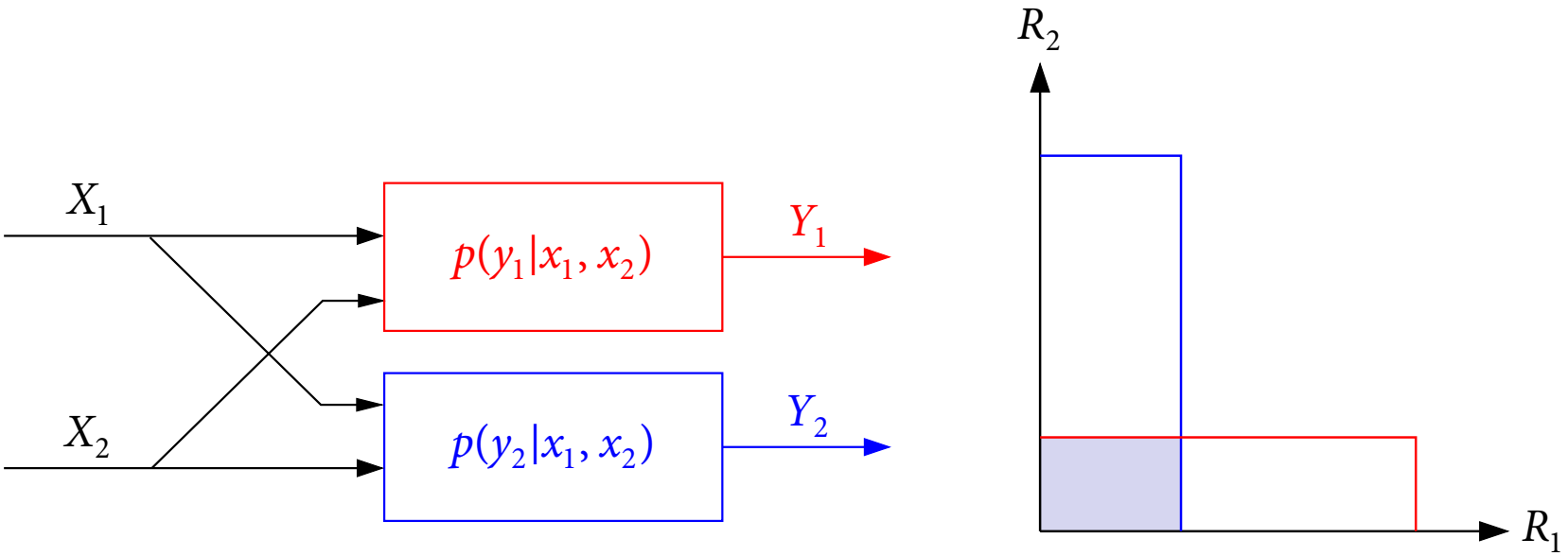
- P2P decoding

Low-complexity (implementable) alternatives



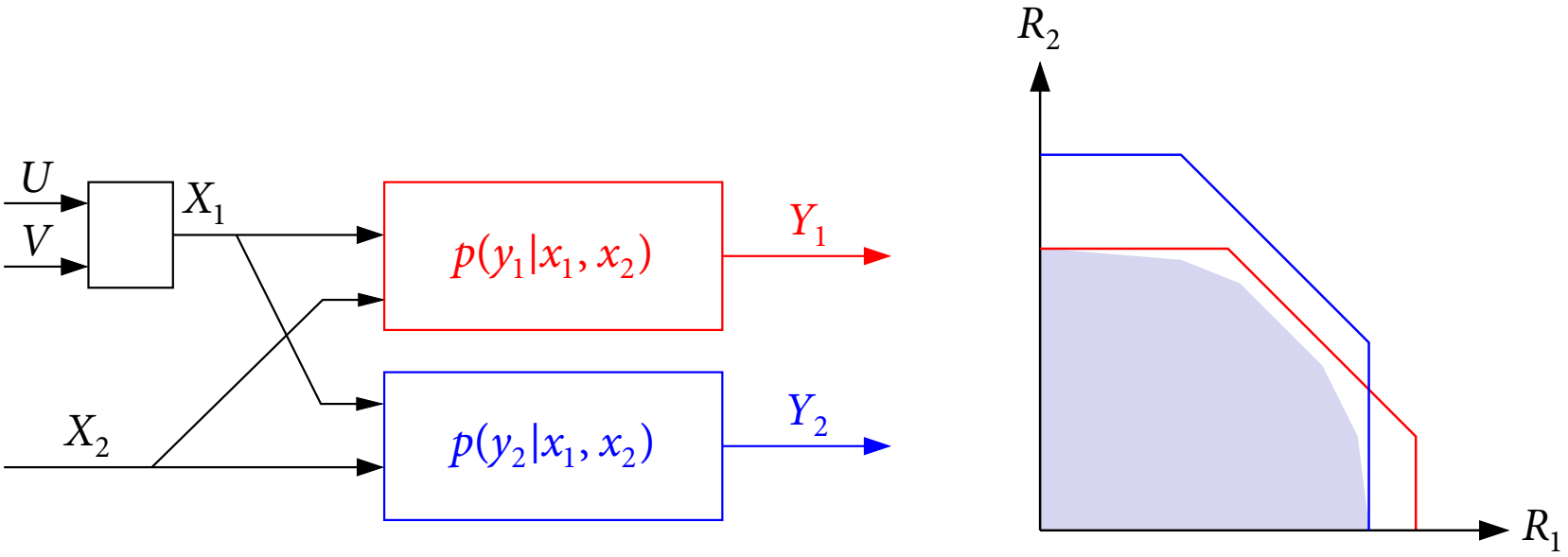
- P2P decoding
  - Treating interference as (Gaussian) noise: $R_1 < I(X_1; Y_1)$

Low-complexity (implementable) alternatives



- P2P decoding
  - Treating interference as (Gaussian) noise: $R_1 < I(X_1; Y_1)$
  - Successive cancellation decoding: $R_2 < I(X_2; Y_1),\ R_1 < I(X_1; Y_1|X_2)$

Low-complexity (implementable) alternatives



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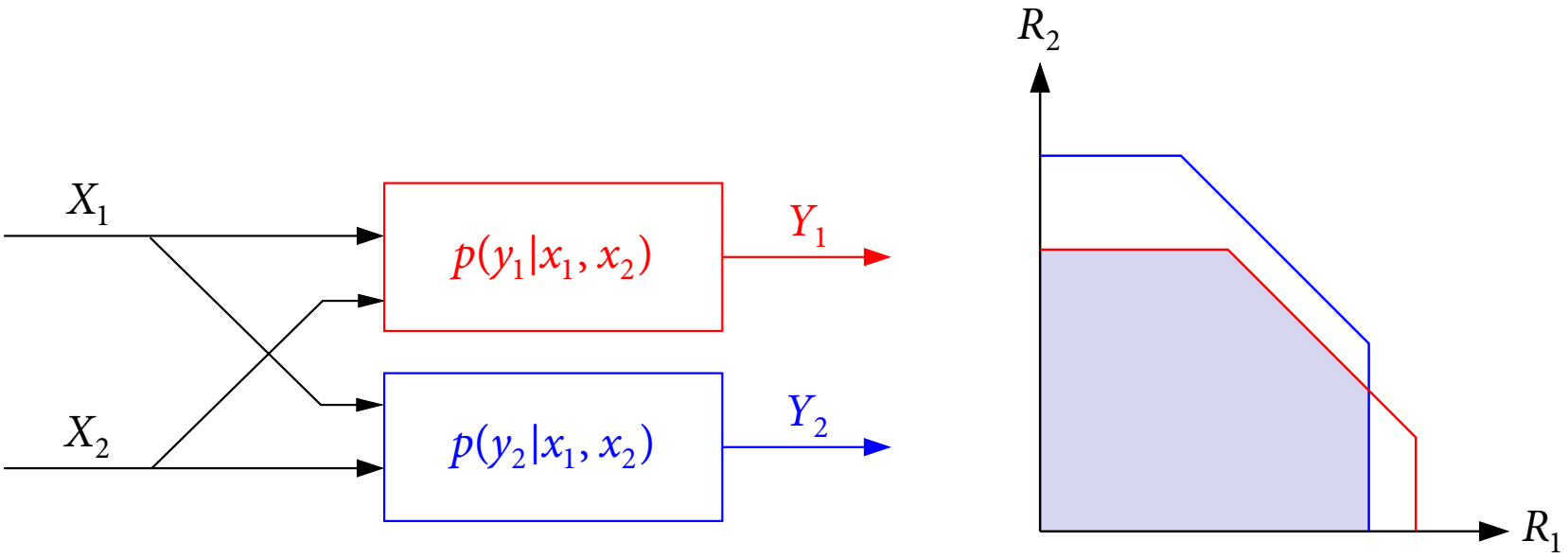
- + rate splitting (Zhao et al. 2011, Wang et al. 2014)

Low-complexity (implementable) alternatives



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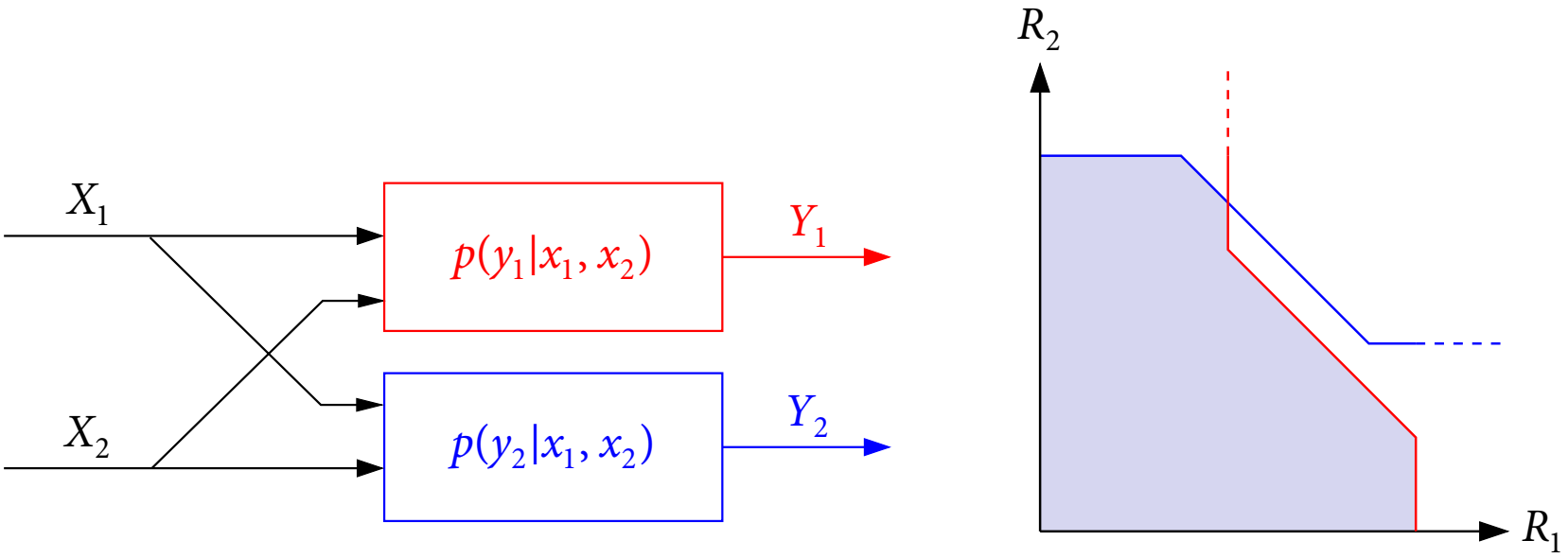
- Novel codes
  - Spatially coupled codes (Yedla, Nguyen, Pfister, and Narayanan 2011)
  - Polar codes (Wang and Şaşoğlu 2014)

Low-complexity (implementable) alternatives



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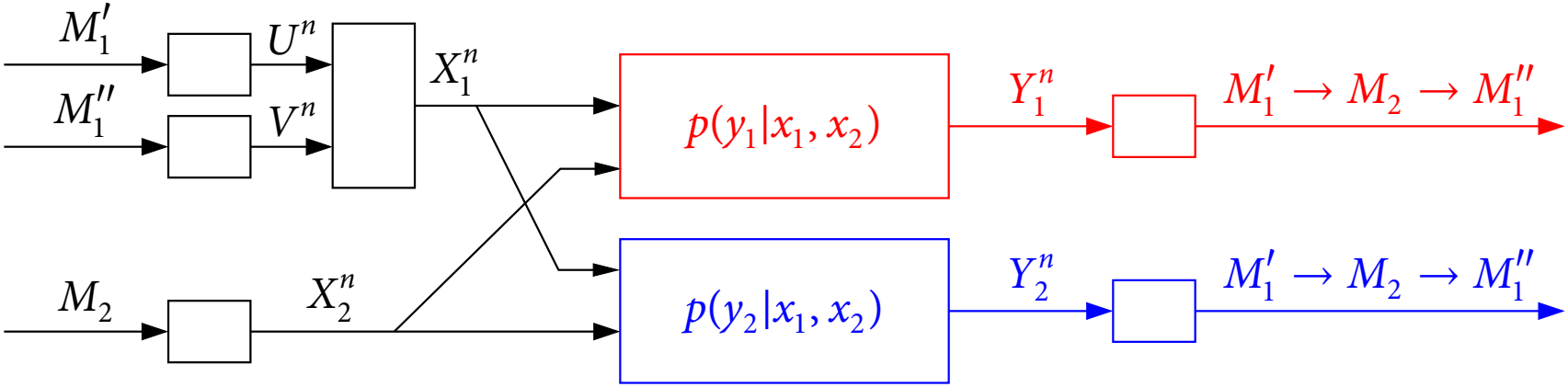
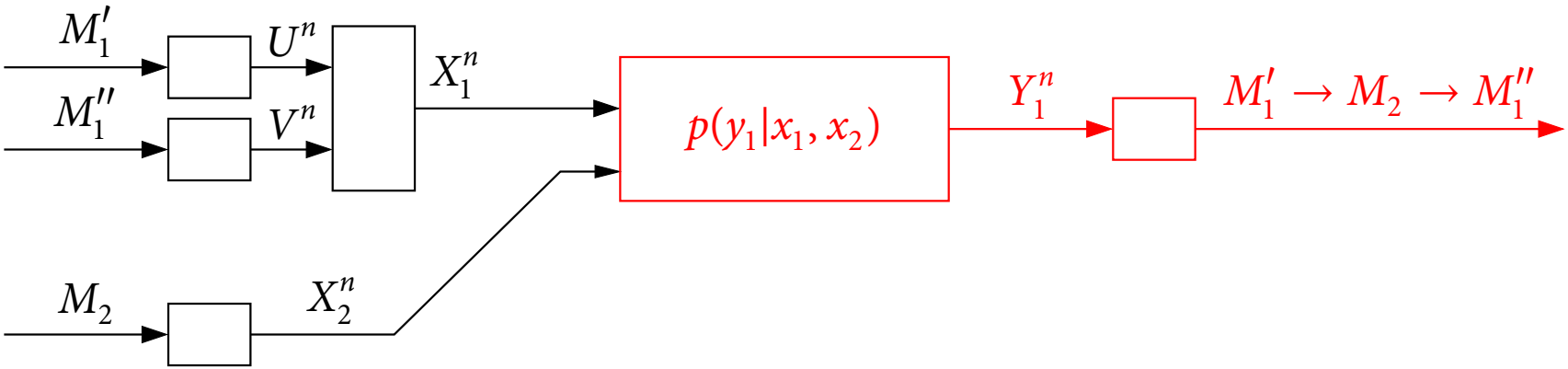
A lesson from rate splitting (Grant et al. 2001)

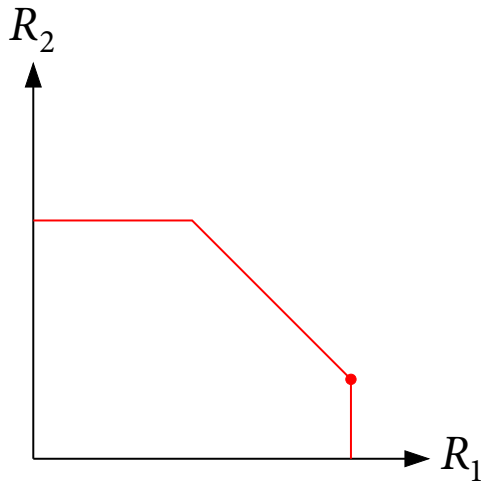


A lesson from rate splitting (Grant et al. 2001)

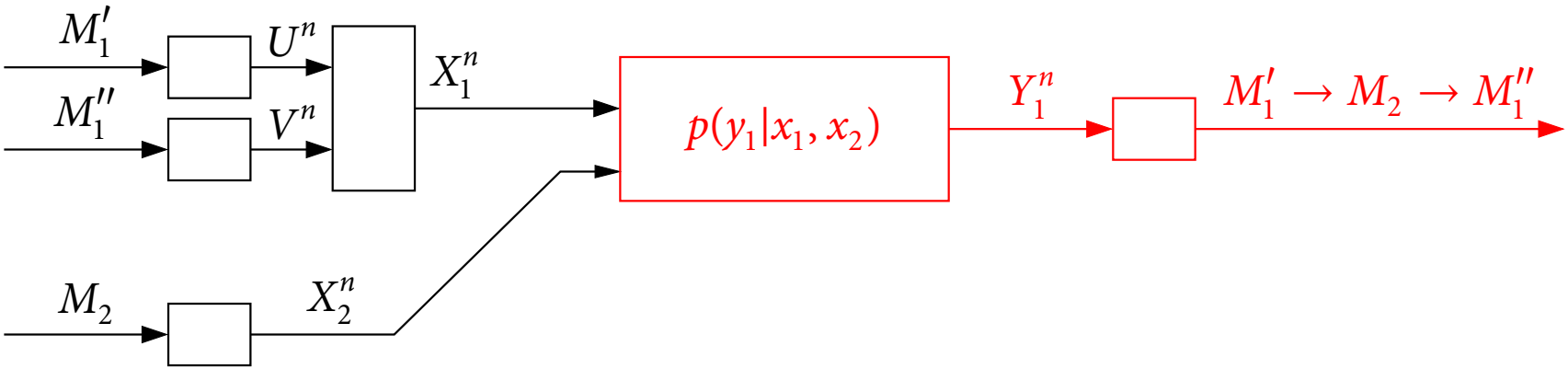


- Decoding at receiver 1:

$$R_1' < I(U; Y_1)$$
$$R_2 < I(X_2; Y_1|U)$$
$$R_1'' < I(V; Y_1|U, X_2)$$



A lesson from rate splitting (Grant et al. 2001)



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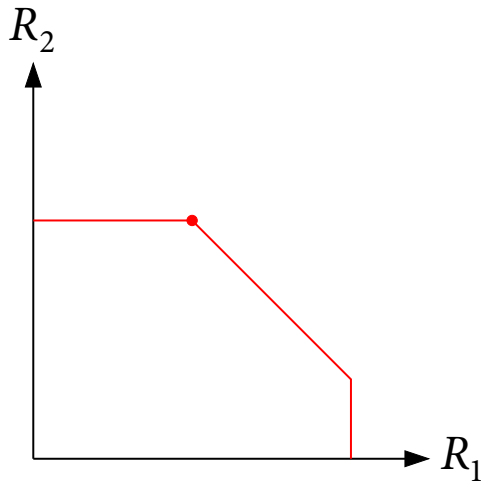
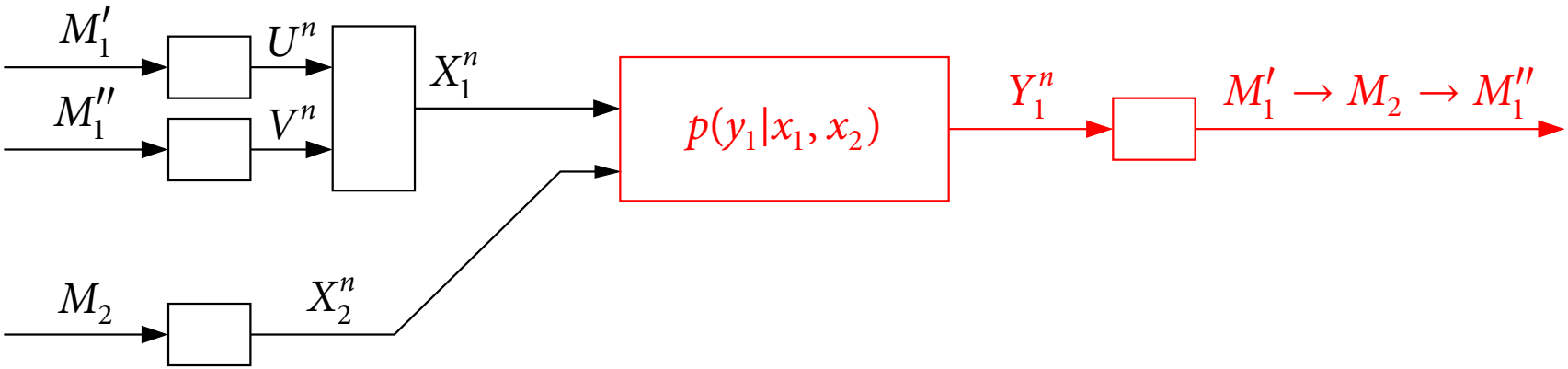


A lesson from rate splitting (Grant et al. 2001)



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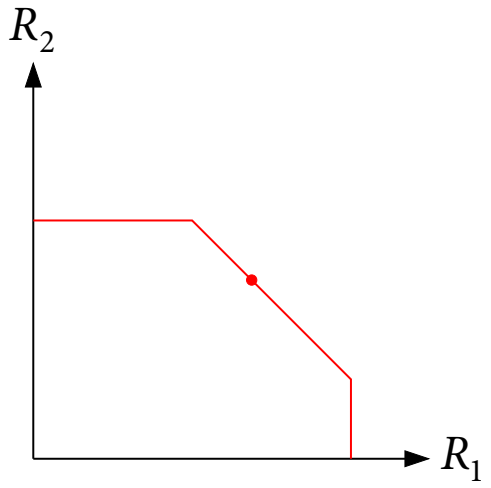
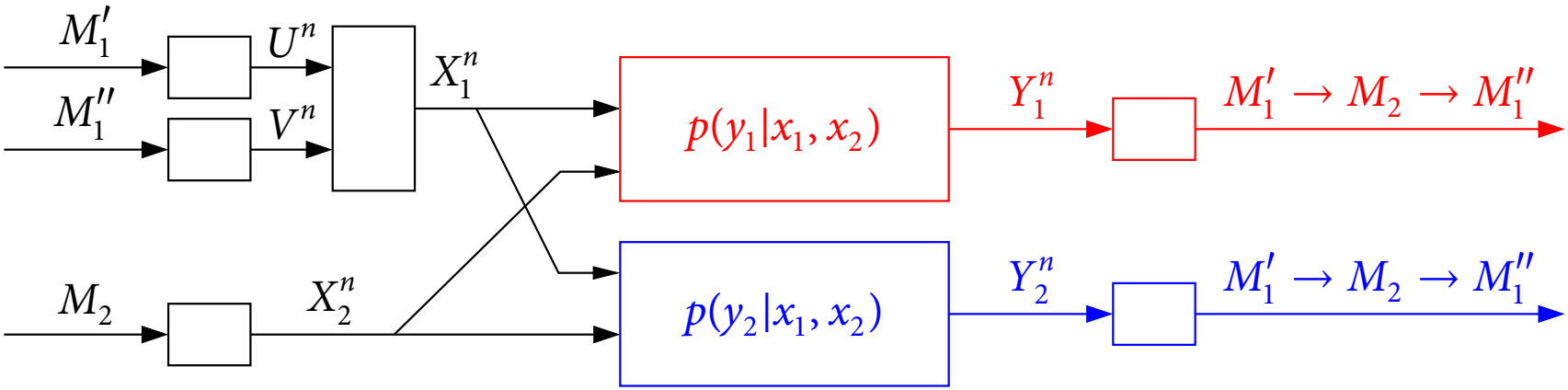


A lesson from rate splitting (Grant et al. 2001)

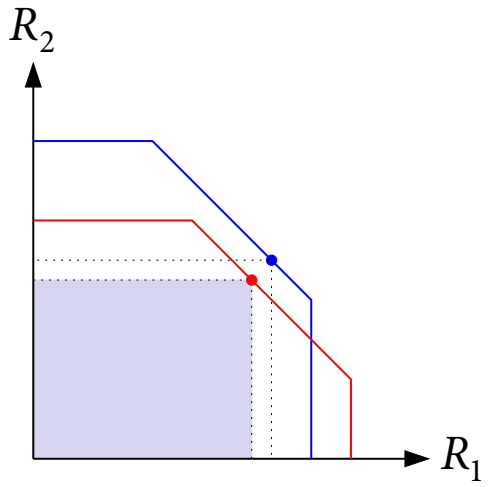


- Decoding at receiver 1:

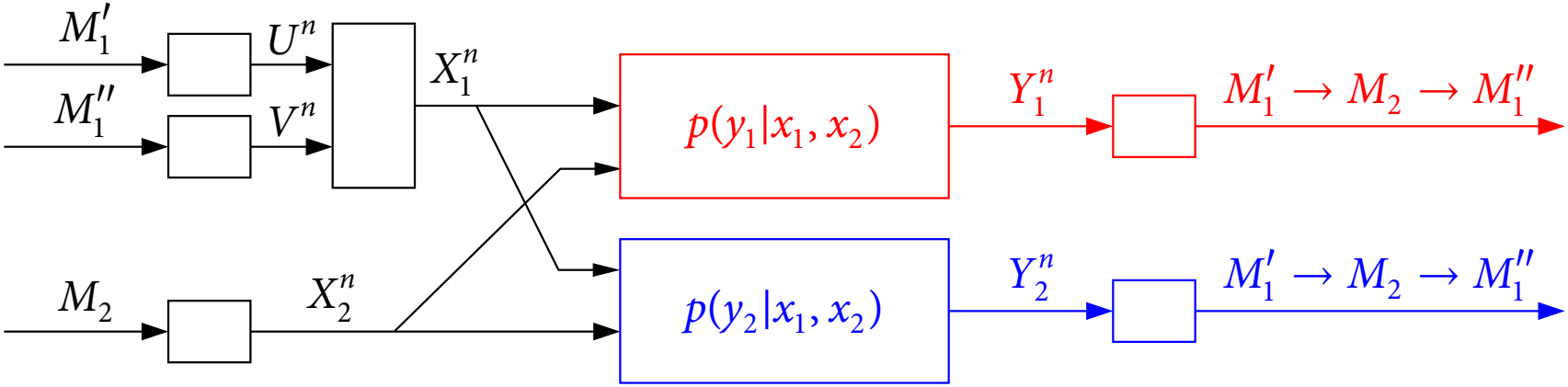
$$R_1' < I(U; Y_1)$$
$$R_2 < I(X_2; Y_1|U)$$
$$R_1'' < I(V; Y_1|U, X_2)$$

- Decoding at receiver 2:

$$R_1' < I(U; Y_2)$$
$$R_2 < I(X_2; Y_2|U)$$
$$R_1'' < I(V; Y_2|U, X_2)$$



A lesson from rate splitting (Grant et al. 2001)

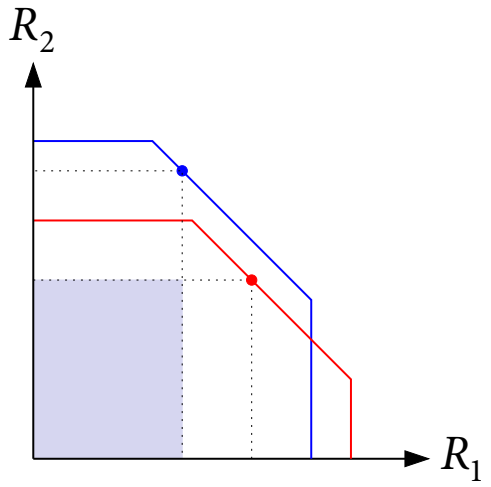


- Decoding at receiver 1:

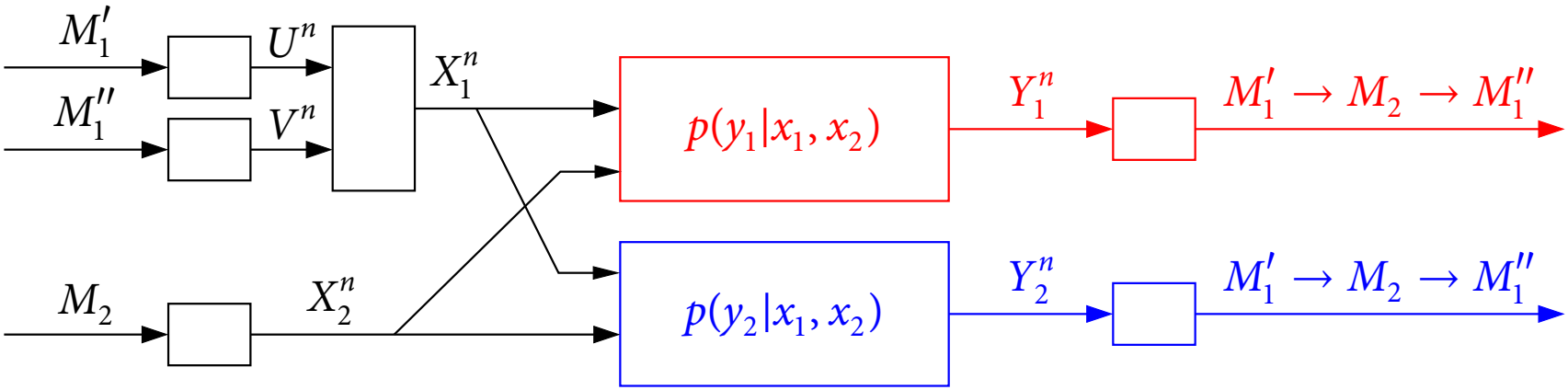
$$R_1' < I(U; Y_1)$$
$$R_2 < I(X_2; Y_1|U)$$
$$R_1'' < I(V; Y_1|U, X_2)$$

- Decoding at receiver 2:

$$R_1' < I(U; Y_2)$$
$$R_2 < I(X_2; Y_2|U)$$
$$R_1'' < I(V; Y_2|U, X_2)$$

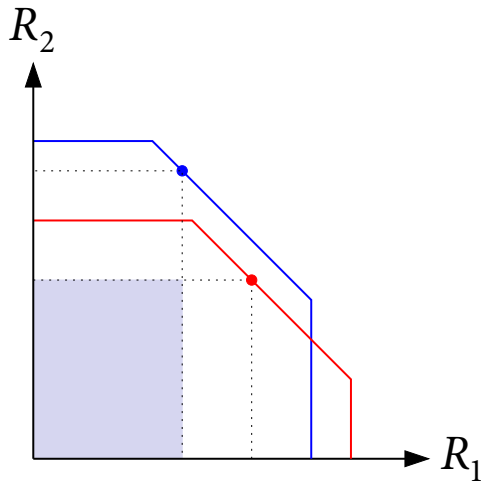


A lesson from rate splitting (Grant et al. 2001)

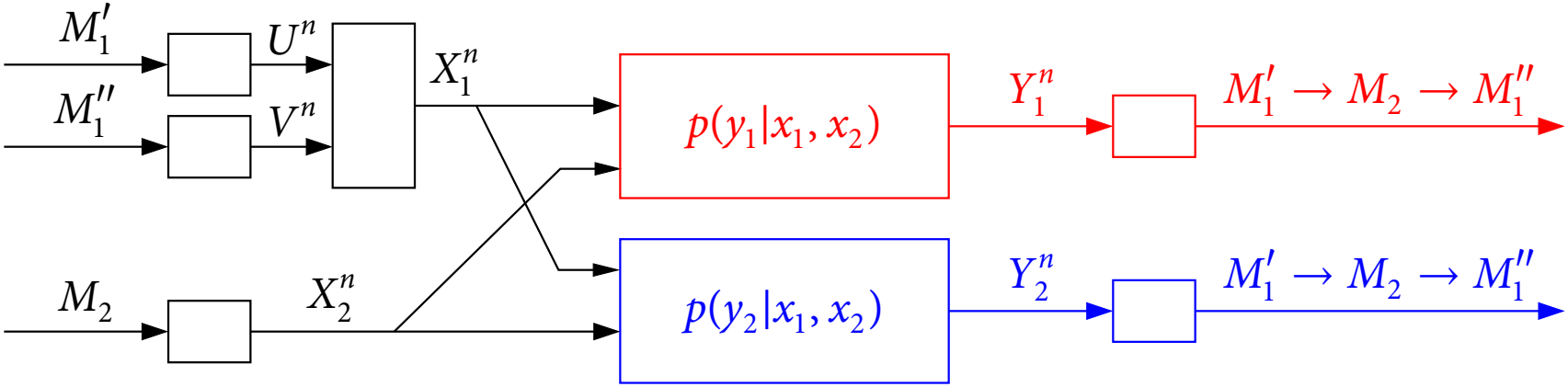


- Decoding at receiver 1: $R_1' < I(U; Y_1),\ R_2 < I(X_2; Y_1|U),\ R_1'' < I(V; Y_1|U, X_2)$
- Decoding at receiver 2: $R_1' < I(U; Y_2),\ R_2 < I(X_2; Y_2|U),\ R_1'' < I(V; Y_2|U, X_2)$
- Combined rate:

$$R_1 < \min_j I(U; Y_j) + \min_j I(V; Y_j|U, X_2)$$



A lesson from rate splitting (Grant et al. 2001)



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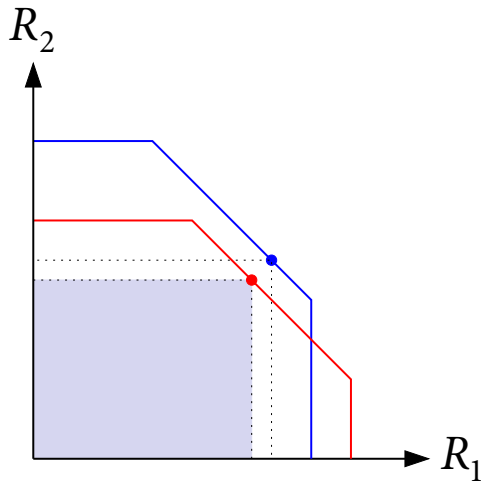
- Decoding at receiver 2: $R_1' < I(U; Y_2),\ R_2 < I(X_2; Y_2|U),\ R_1'' < I(V; Y_2|U, X_2)$
- Combined rate:

$$R_1 < \min_j I(U; Y_j) + \min_j I(V; Y_j|U, X_2)$$
$$< \min_j [I(U; Y_j) + I(V; Y_j|U, X_2)]$$



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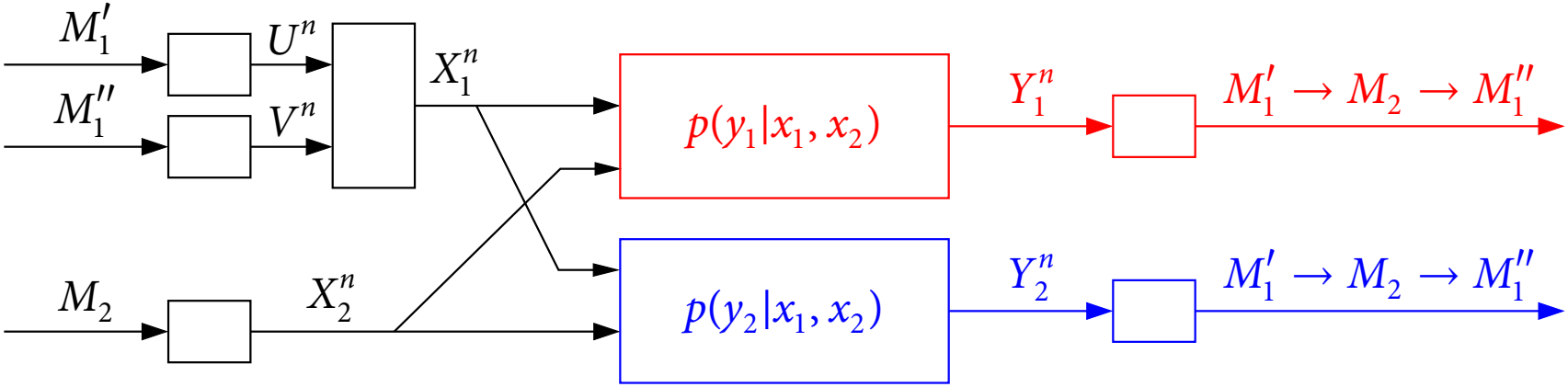
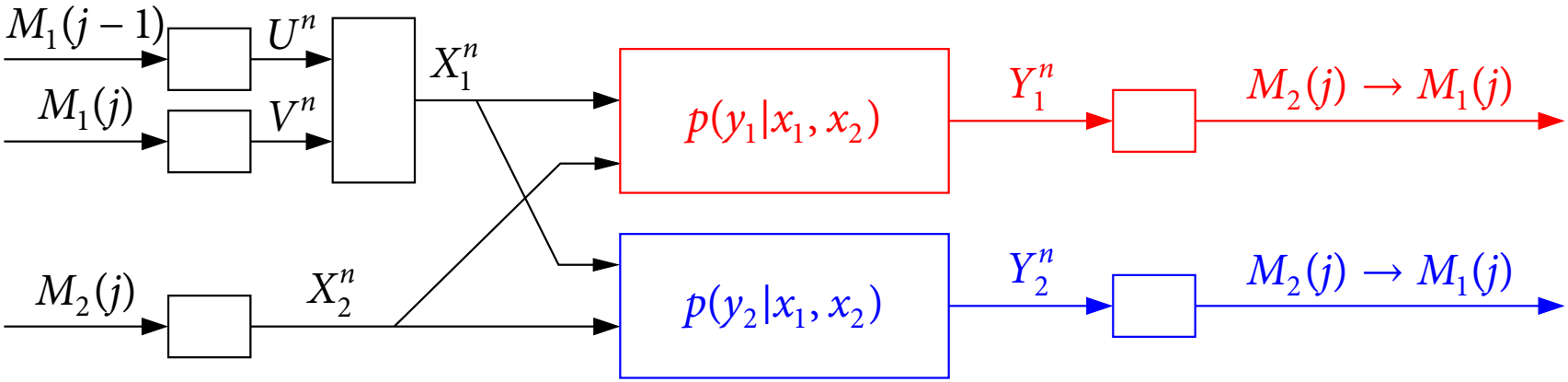


- Decoding at receiver 1: $R_1' < I(U; Y_1),\ R_2 < I(X_2; Y_1|U),\ R_1'' < I(V; Y_1|U, X_2)$
- Decoding at receiver 2: $R_1' < I(U; Y_2),\ R_2 < I(X_2; Y_2|U),\ R_1'' < I(V; Y_2|U, X_2)$
- Combined rate:

$$R_1 < \min_j I(U; Y_j) + \min_j I(V; Y_j|U, X_2)$$
$$< \min_j \left[I(U; Y_j) + I(V; Y_j|U, X_2) \right]$$

- Key to achieving the SD performance: Switch the order of sum and min!

Sliding-window superposition coding (Wang et al. 2014)



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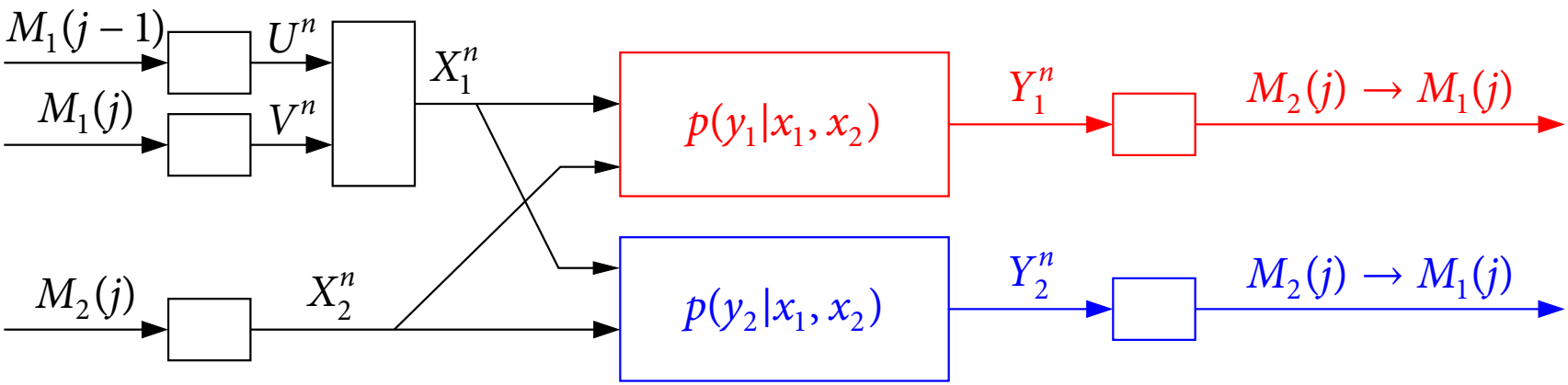
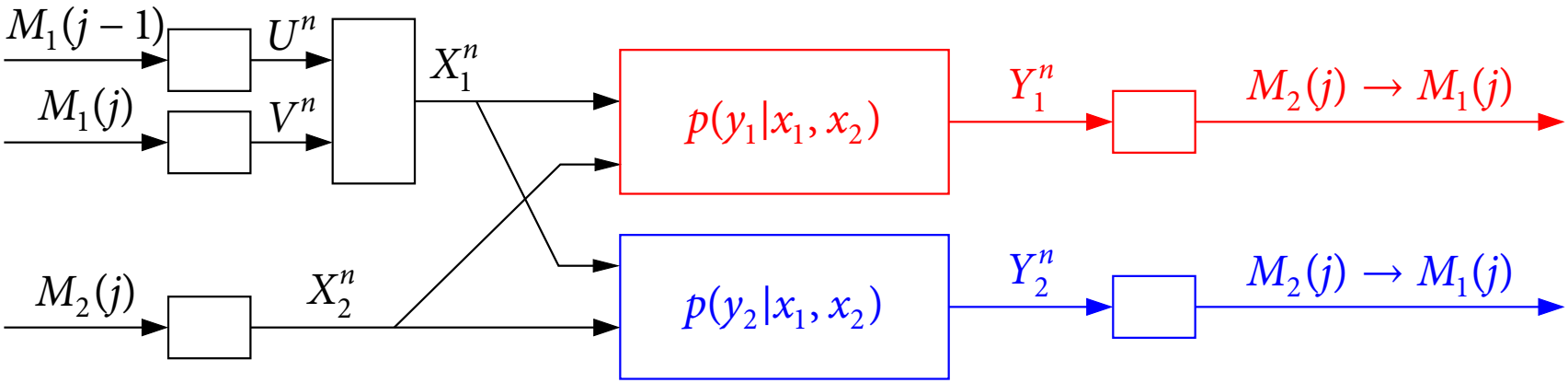


Block	1	2	3	4	5	6	7
U							
V							
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$					
V	$M_1(1)$						
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

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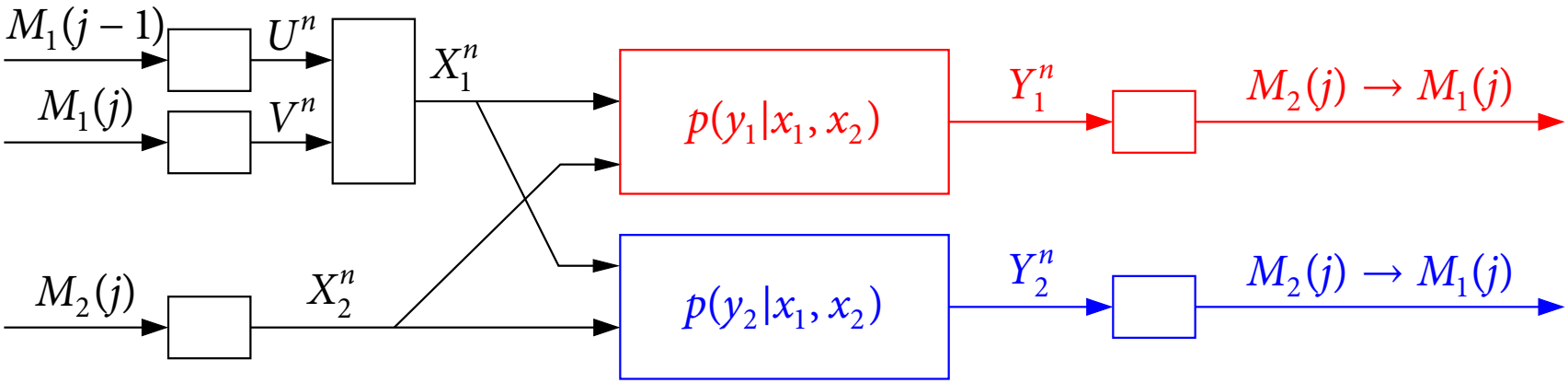

Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$				
V	$M_1(1)$	$M_1(2)$					
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

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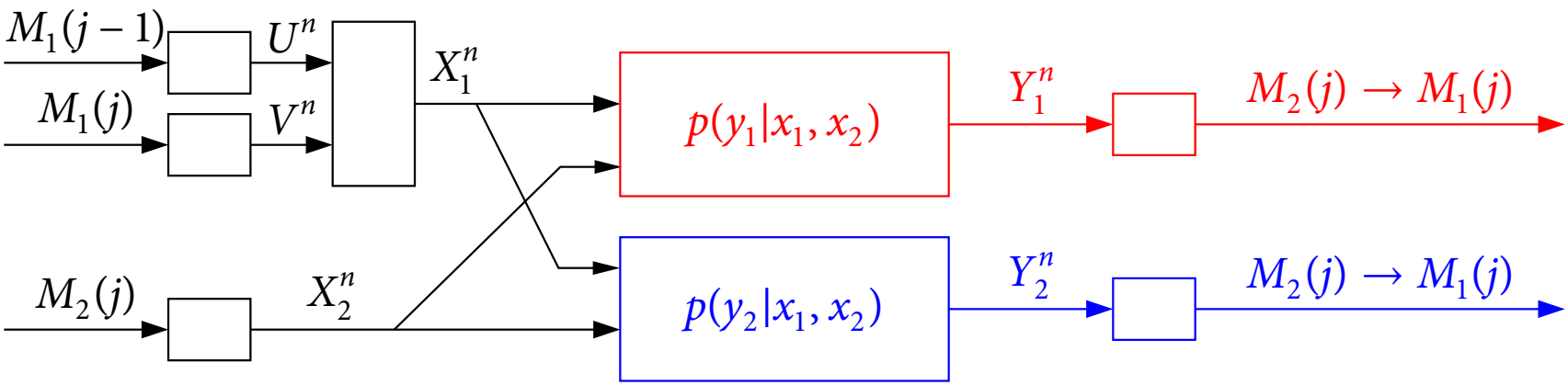

Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$			
V	$M_1(1)$	$M_1(2)$	$M_1(3)$				
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

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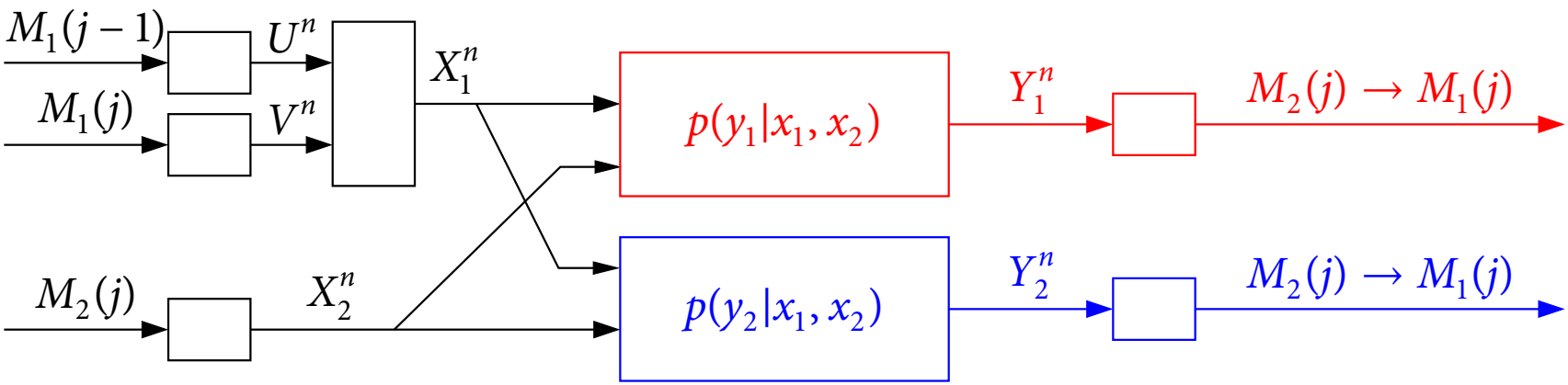
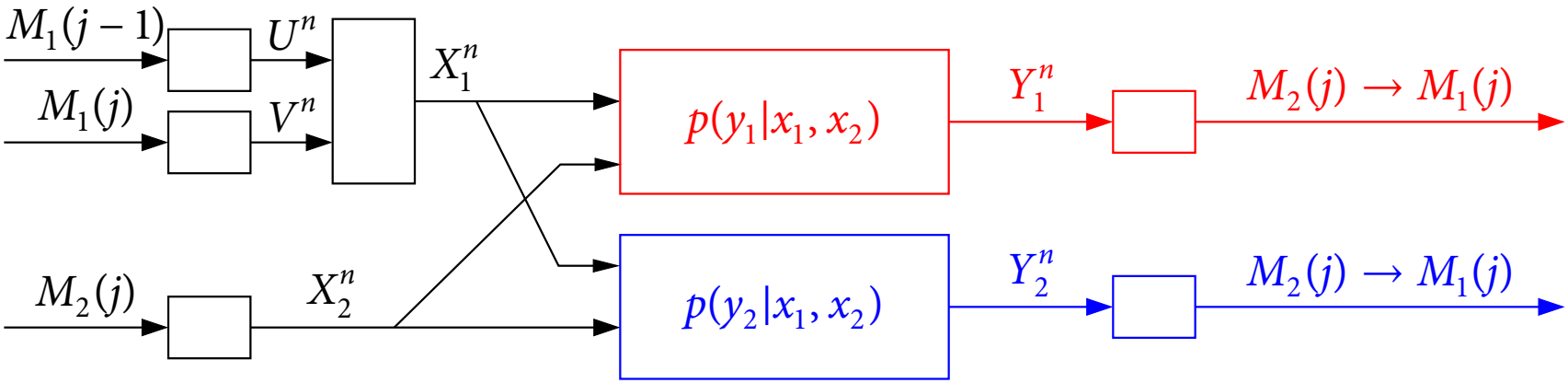


Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$		
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$			
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$		
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

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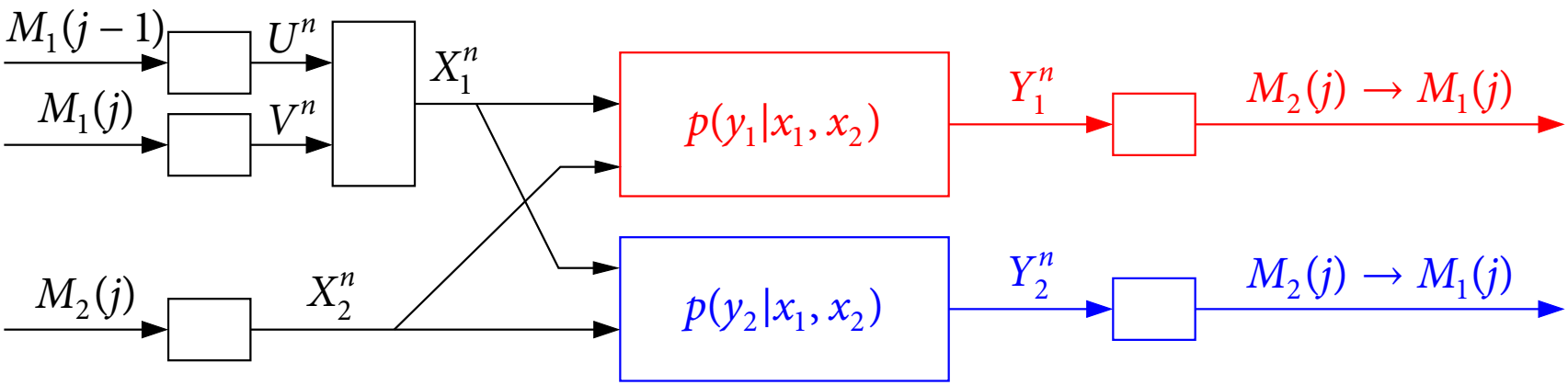
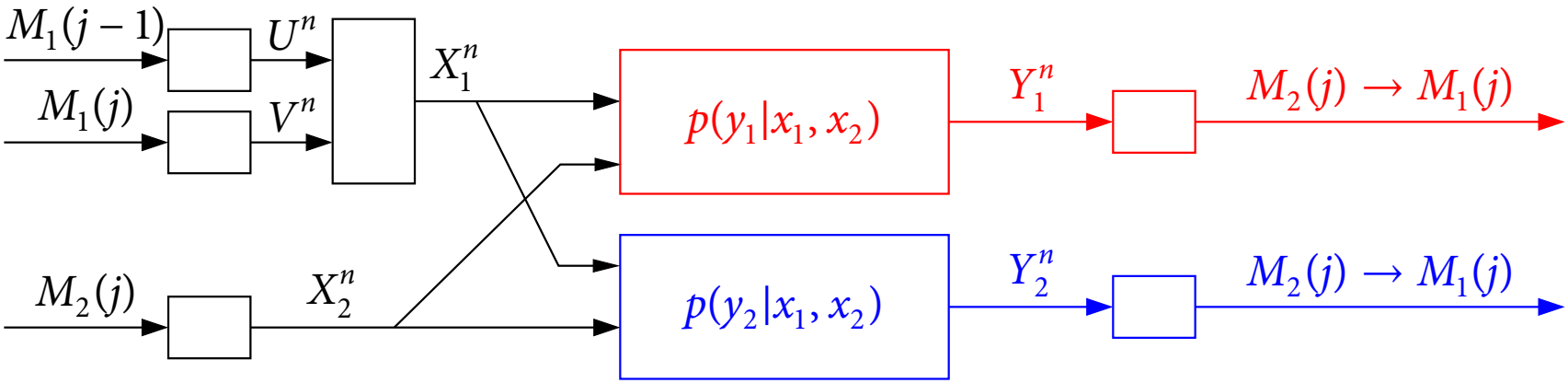


Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

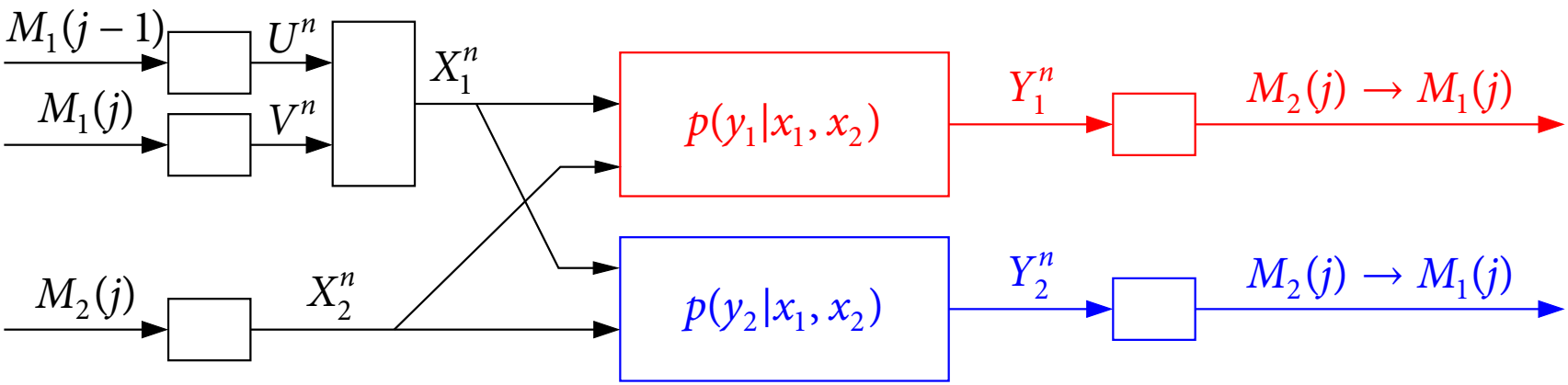
Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Block Markov coding: As in relaying and feedback communication

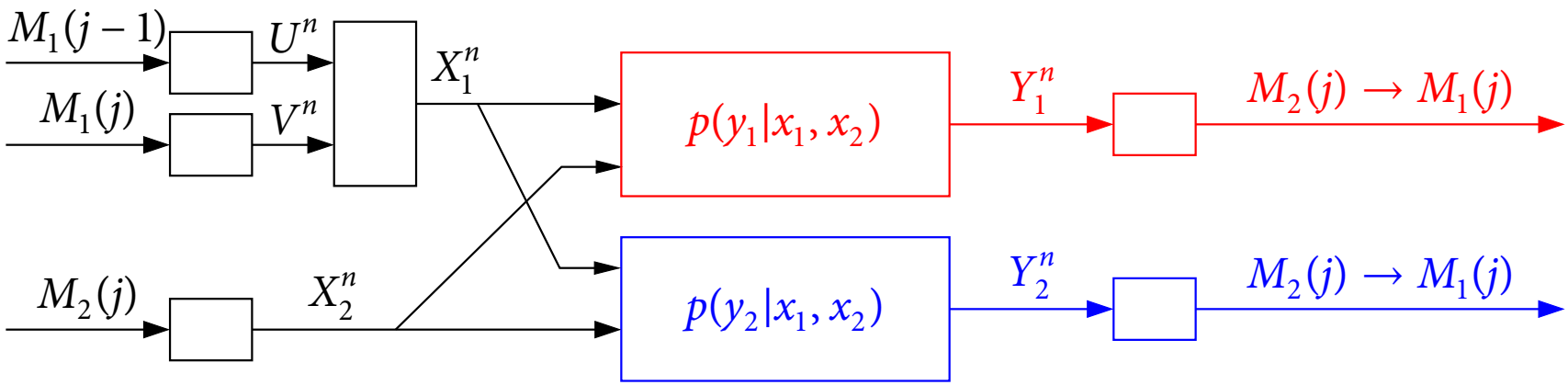
Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Block Markov coding: As in relaying and feedback communication
- Superposition coding: But without rate splitting

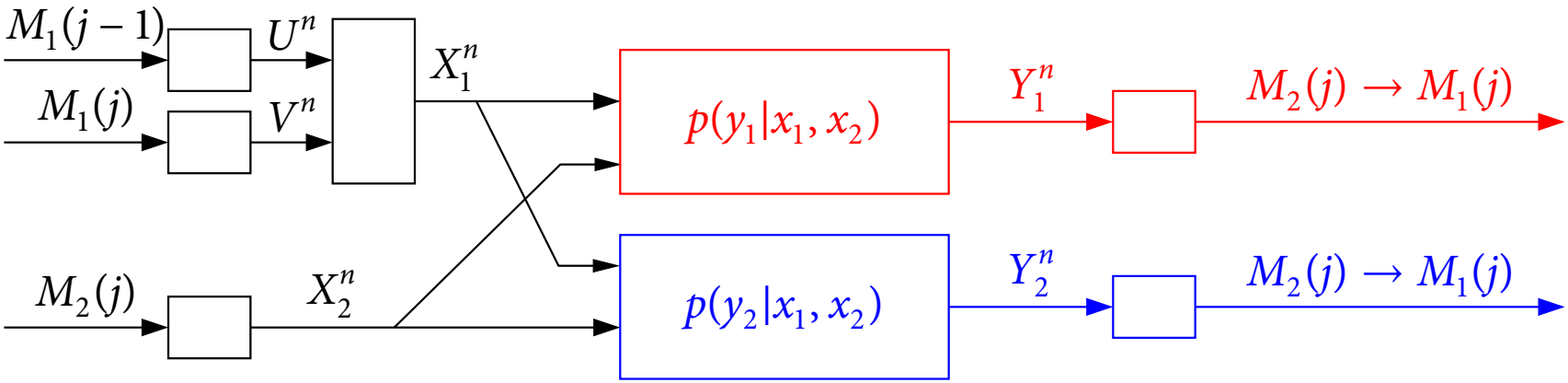
Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Block Markov coding: As in relaying and feedback communication
- Superposition coding: But without rate splitting
- Staggered (asynchronous) transmission: cf. EV-DO rev A, D-BLAST

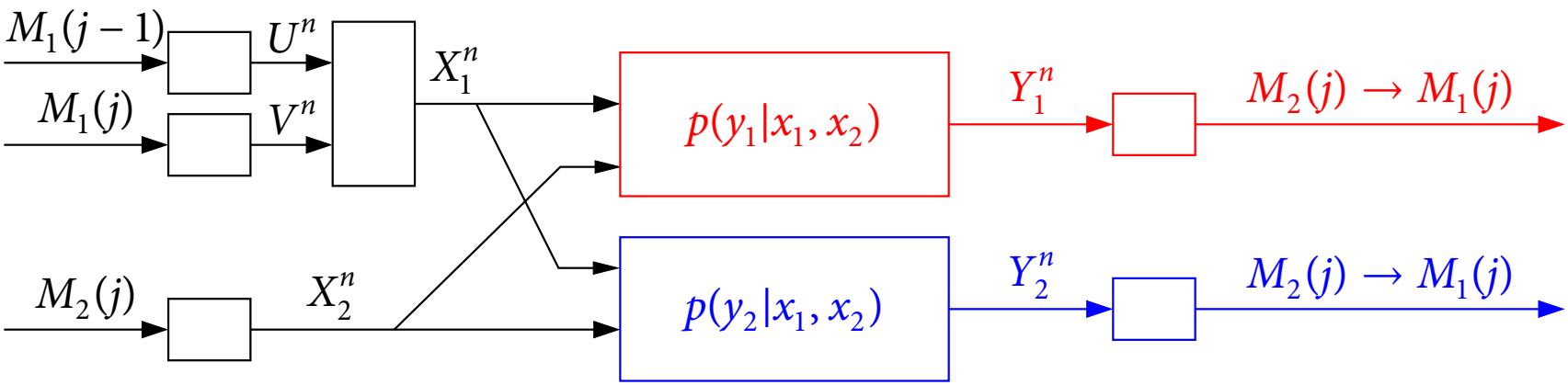
Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U		$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V	$M_1(1)$	$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2	$M_2(1)$	$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Sliding-window decoding

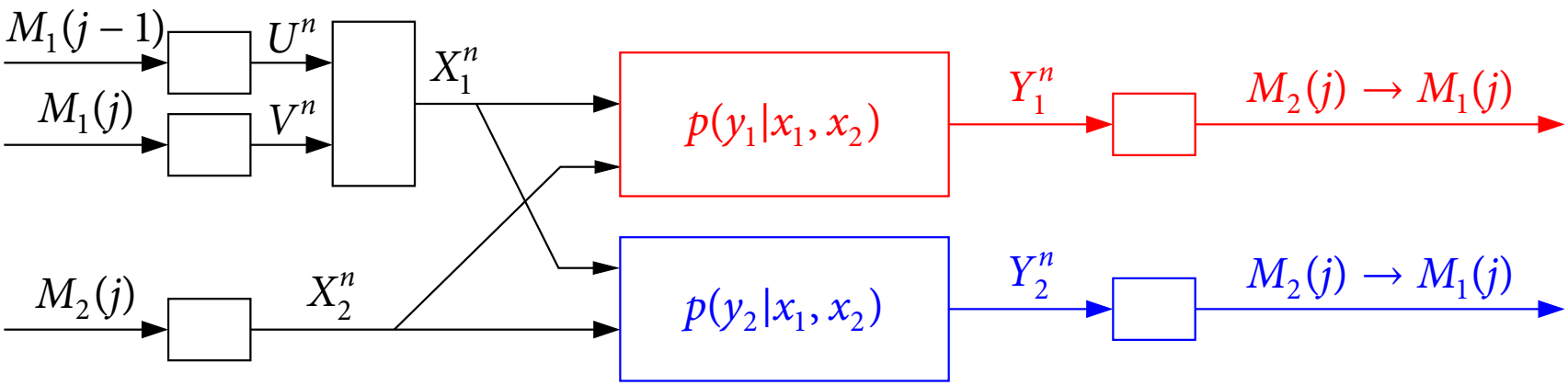
Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U			$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V		$M_1(2)$	$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2		$M_2(2)$	$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Sliding-window decoding
- Successive cancellation decoding

Sliding-window superposition coding (Wang et al. 2014)



Block	1	2	3	4	5	6	7
U				$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V			$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2			$M_2(3)$	$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Sliding-window decoding
- Successive cancellation decoding

$$R_2 < I(X_2; Y_j | U),$$

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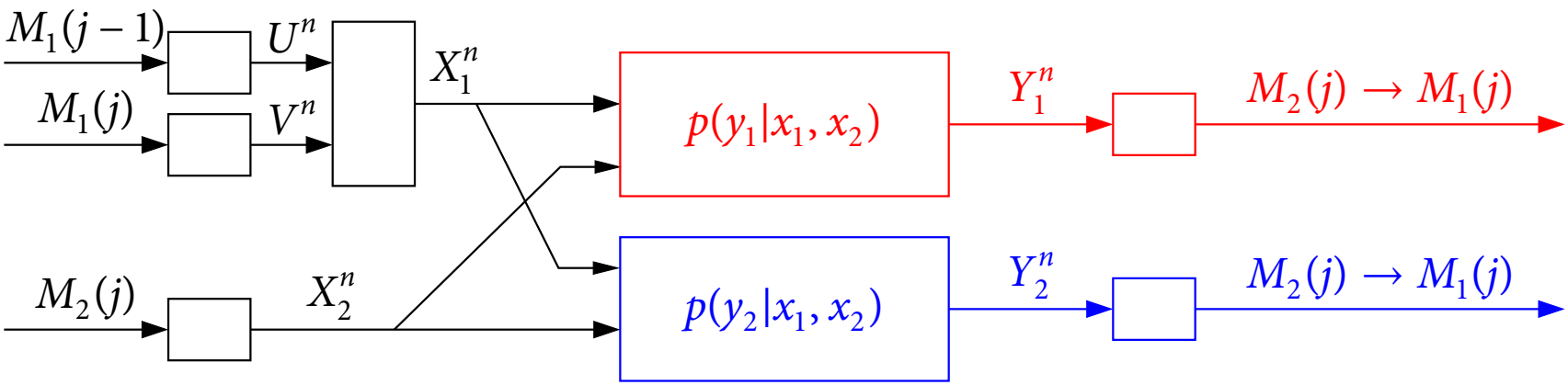
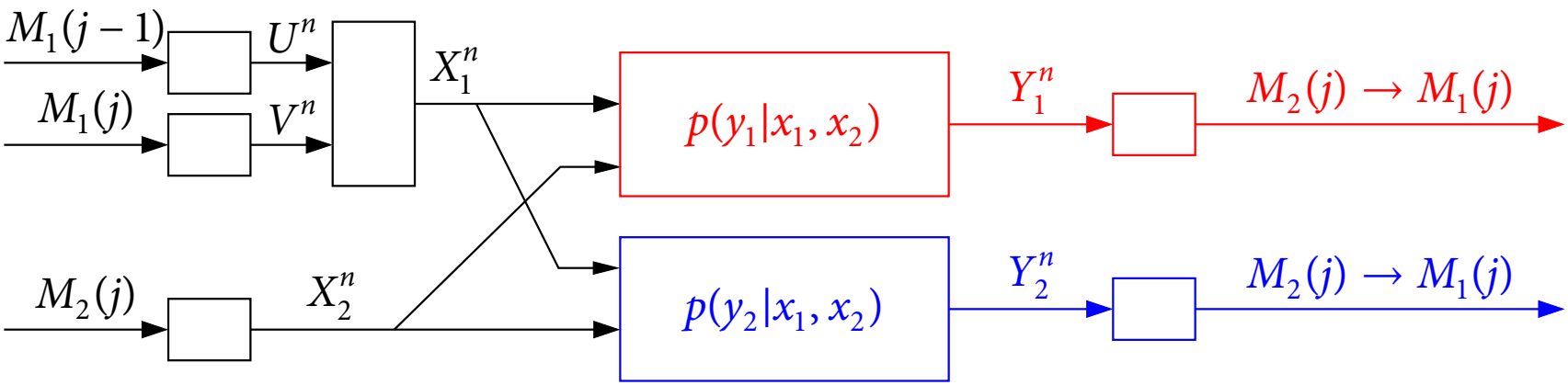


Block	1	2	3	4	5	6	7
U				$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$
V			$M_1(3)$	$M_1(4)$	$M_1(5)$	$M_1(6)$	
X_2				$M_2(4)$	$M_2(5)$	$M_2(6)$	$M_2(7)$

- Sliding-window decoding
- Successive cancellation decoding

$$R_2 < I(X_2; Y_j|U),$$
$$R_1 < I(U; Y_j) + I(V; Y_j|U, X_2)$$

Sliding-window superposition coding (Wang et al. 2014)



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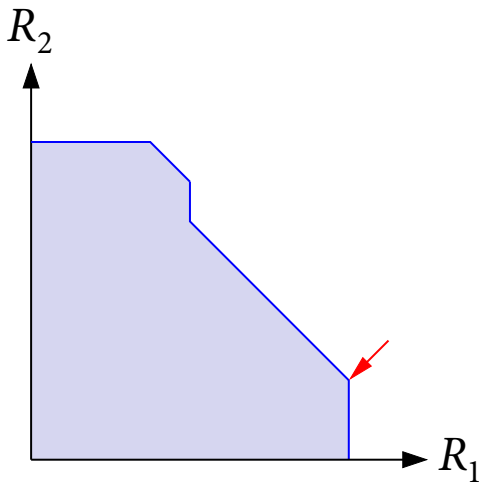
- Every corner point: different decoding orders



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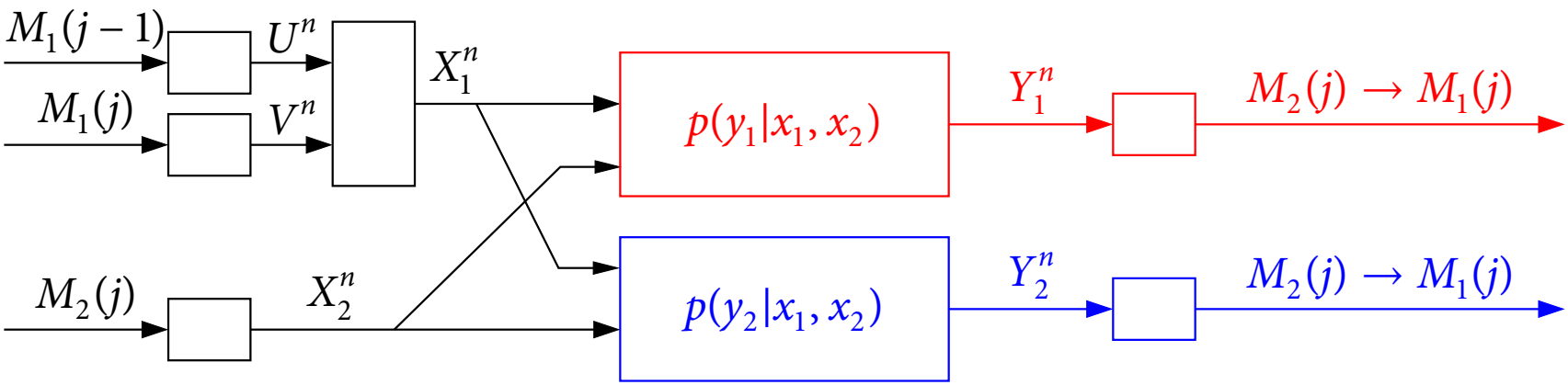

Block	1	2	3	4	5	6	7
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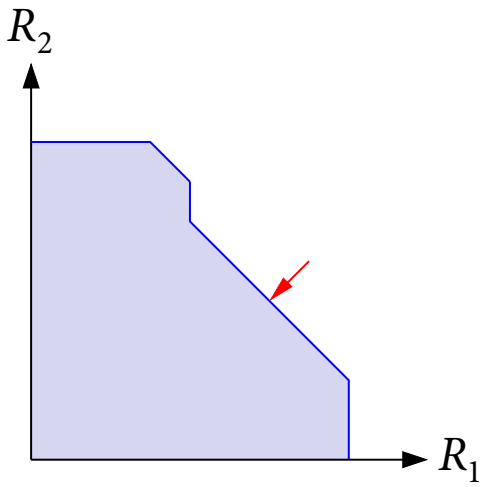
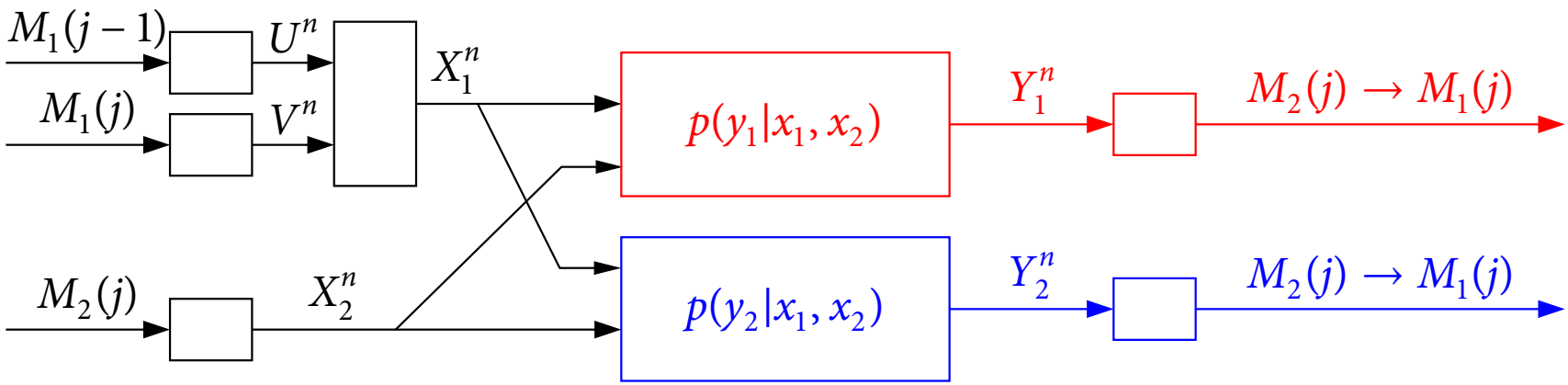
- Every corner point: different decoding orders
- Every point: time sharing or more superposition layers



Sliding-window superposition coding (Wang et al. 2014)



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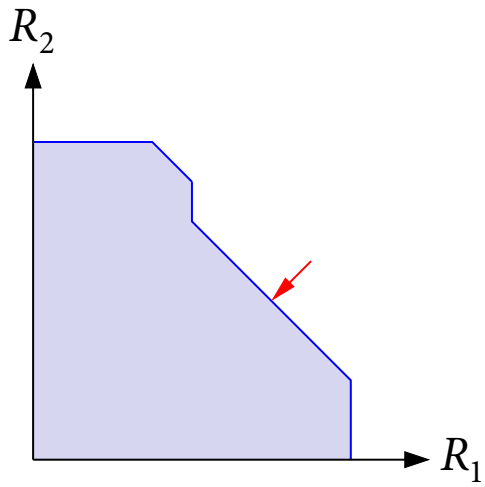
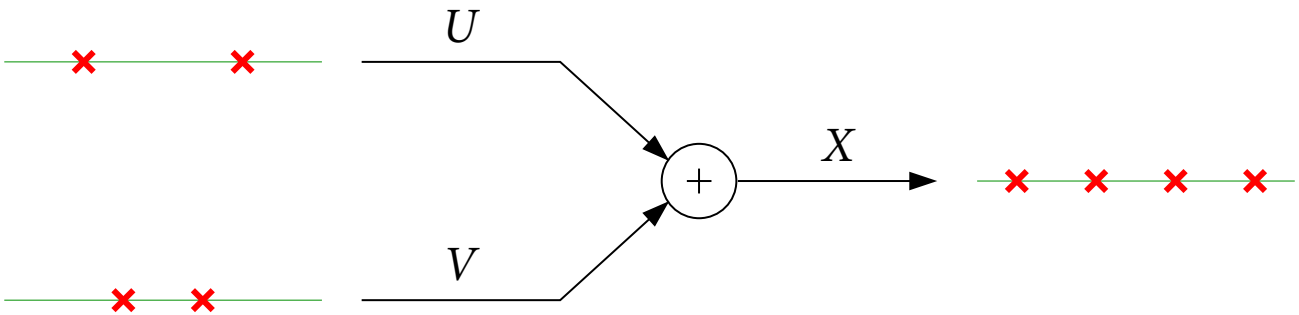
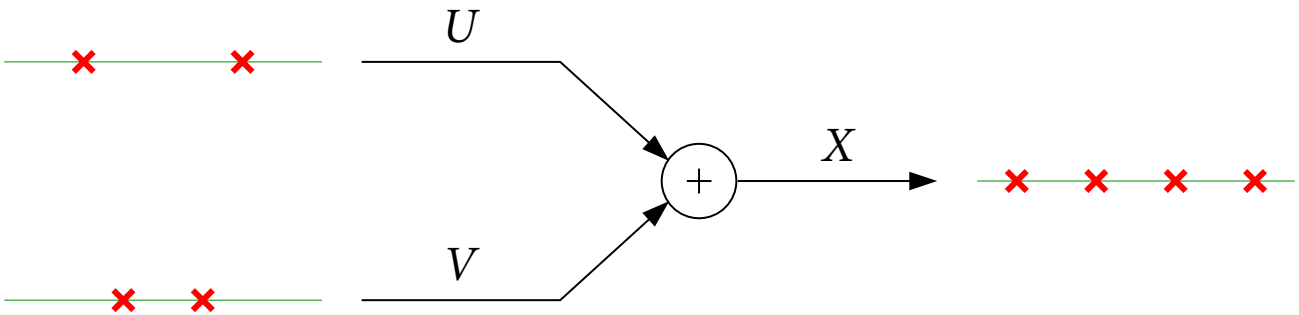
- Every point: time sharing or more superposition layers
- General theory for arbitrary number of users (Wang 2015)

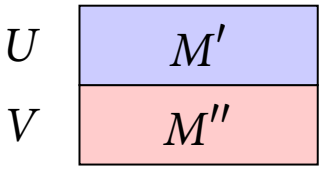


Towards coded modulation



Towards coded modulation



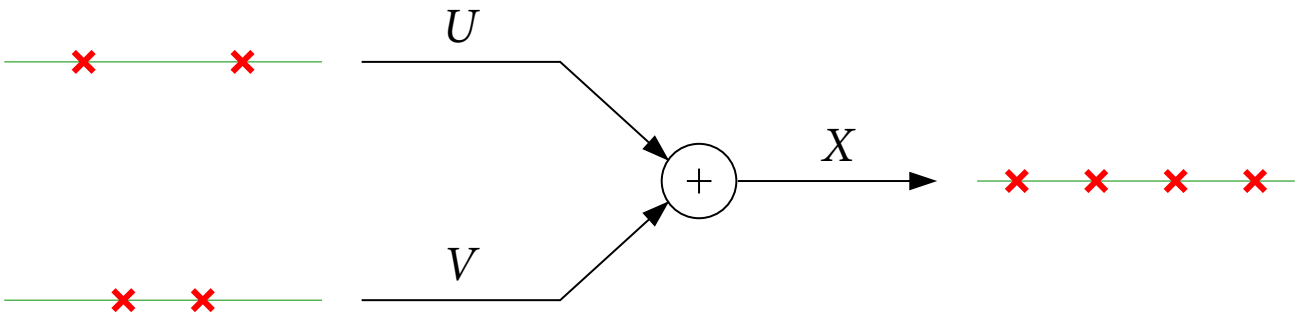


Multilevel coding (MLC)

$$R' < I(U;Y)$$
$$R'' < I(V;Y|U)$$

Short, nonuniversal

Towards coded modulation



Multilevel coding (MLC)

Bit-interleaved coded modulation (BICM)

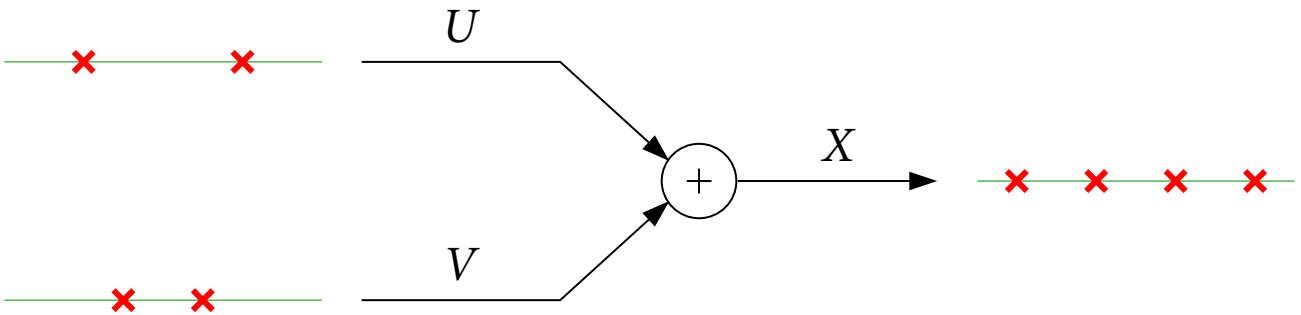
$$R' < I(U;Y)$$
$$R'' < I(V;Y|U)$$

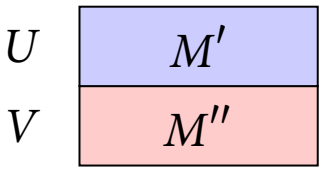
$$R < I(U;Y) + I(V;Y)$$

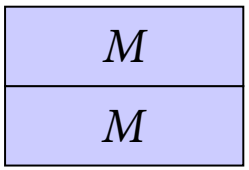
Short, nonuniversal

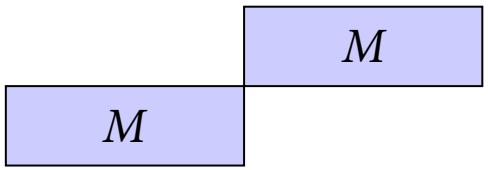
Other layers as noise

Towards coded modulation









Multilevel coding (MLC)

$$R' < I(U;Y)$$
$$R'' < I(V;Y|U)$$

Short, nonuniversal

Bit-interleaved coded modulation (BICM)

$$R < I(U;Y) + I(V;Y)$$

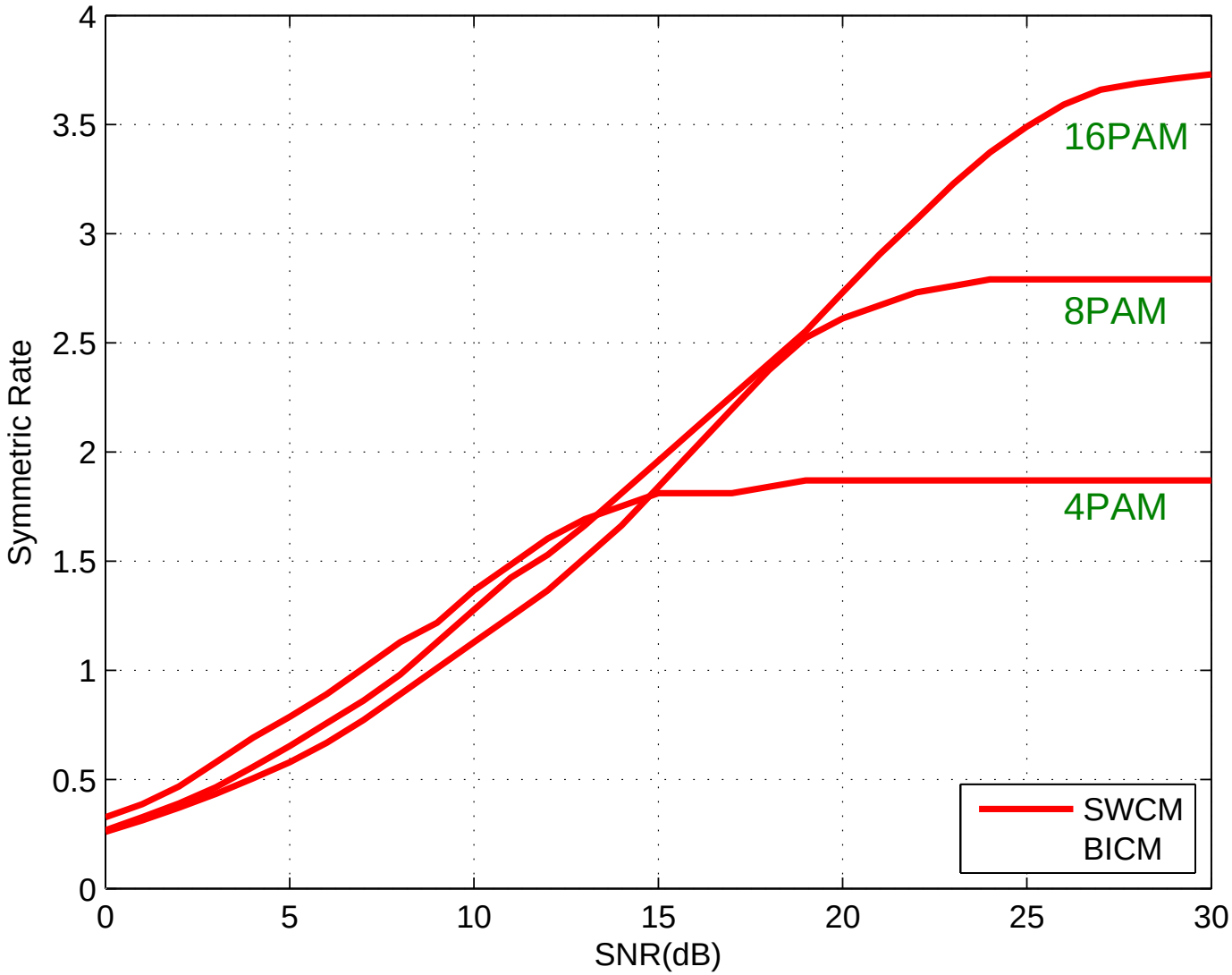
Other layers as noise

Sliding-window coded modulation (SWCM)

$$R < I(U;Y) + I(V;Y|U)$$
$$= I(X;Y)$$

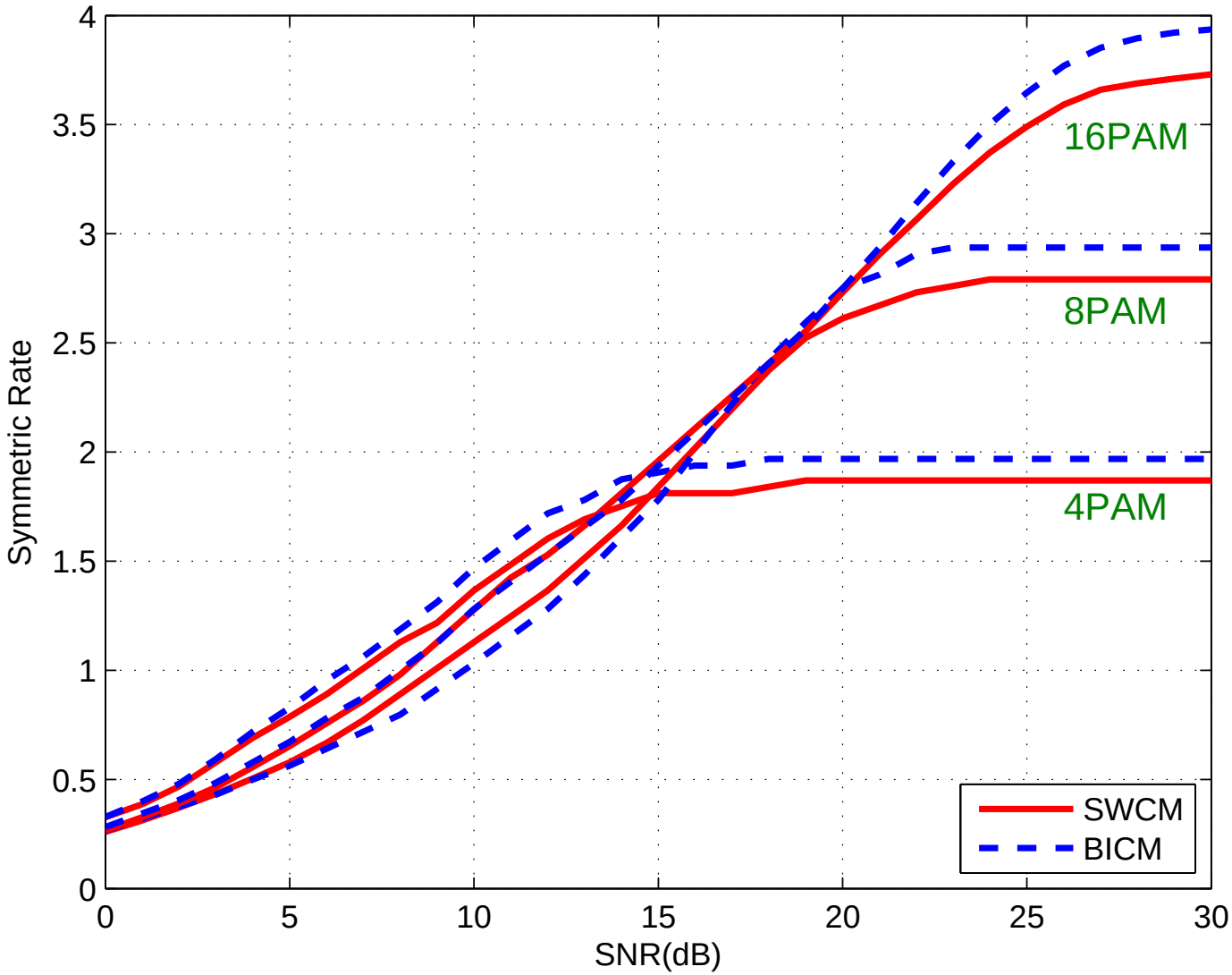
Error prop., rate loss

P2P performance



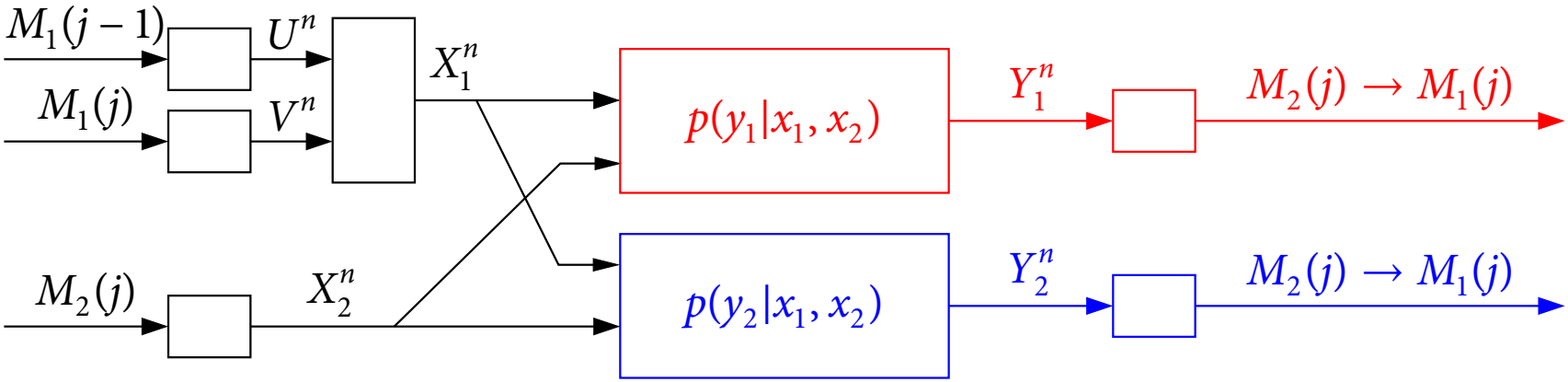
LTE turbo code / ≤ 8-iteration LOG-MAP decoding at $b = 20$, $n = 2048$, BLER $= 0.1$

P2P performance



LTE turbo code / ≤ 8-iteration LOG-MAP decoding at $b = 20$, $n = 2048$, BLER $= 0.1$

Back to interference mitigation



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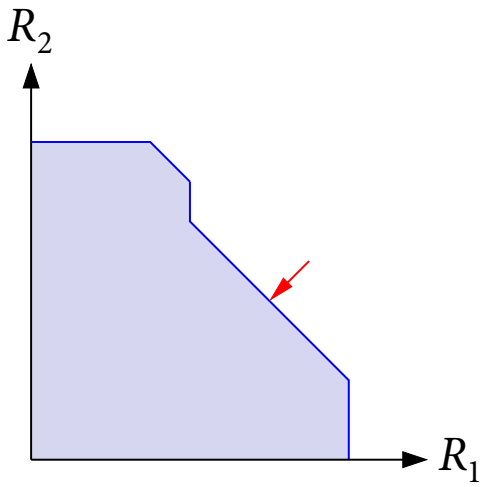
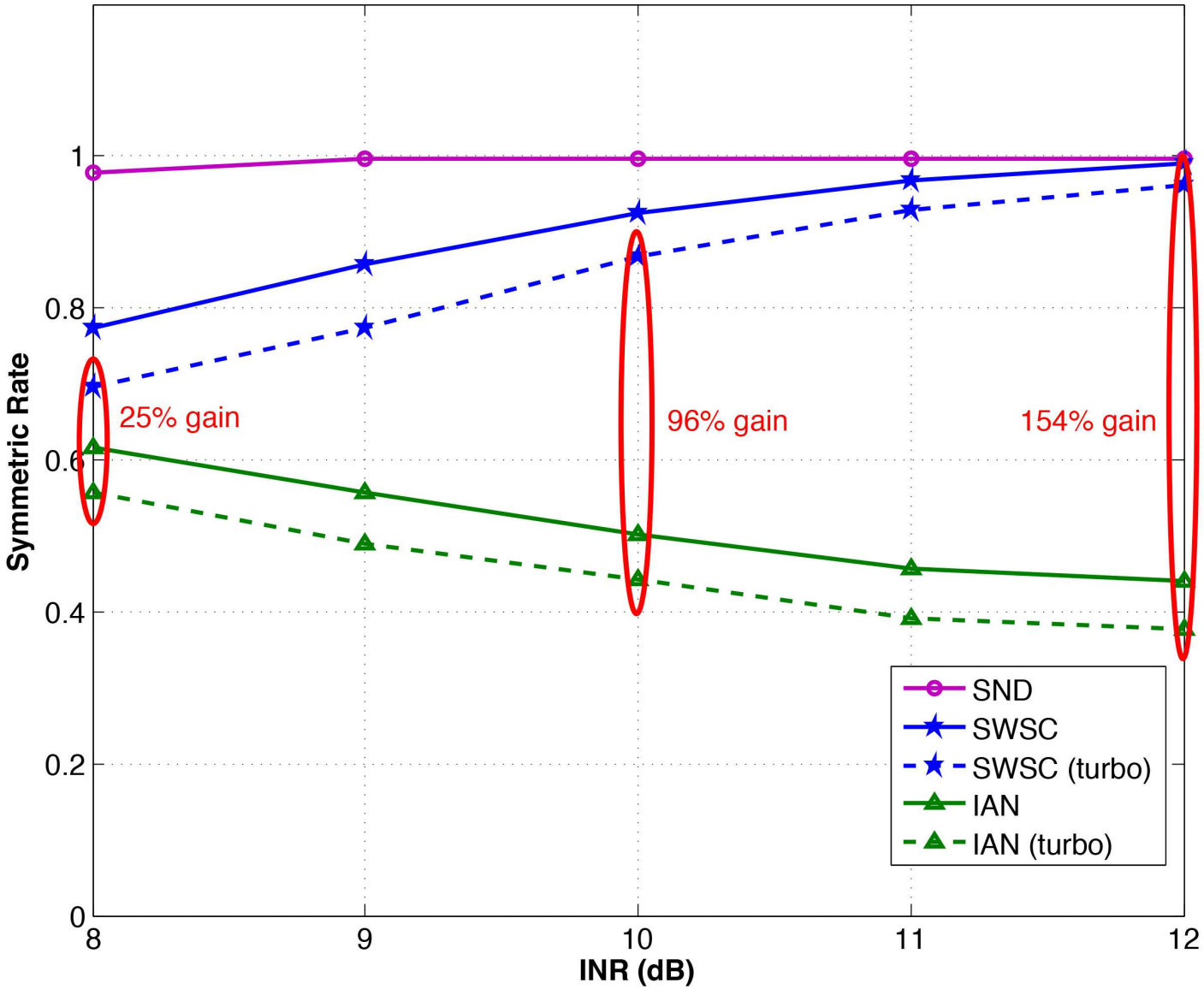
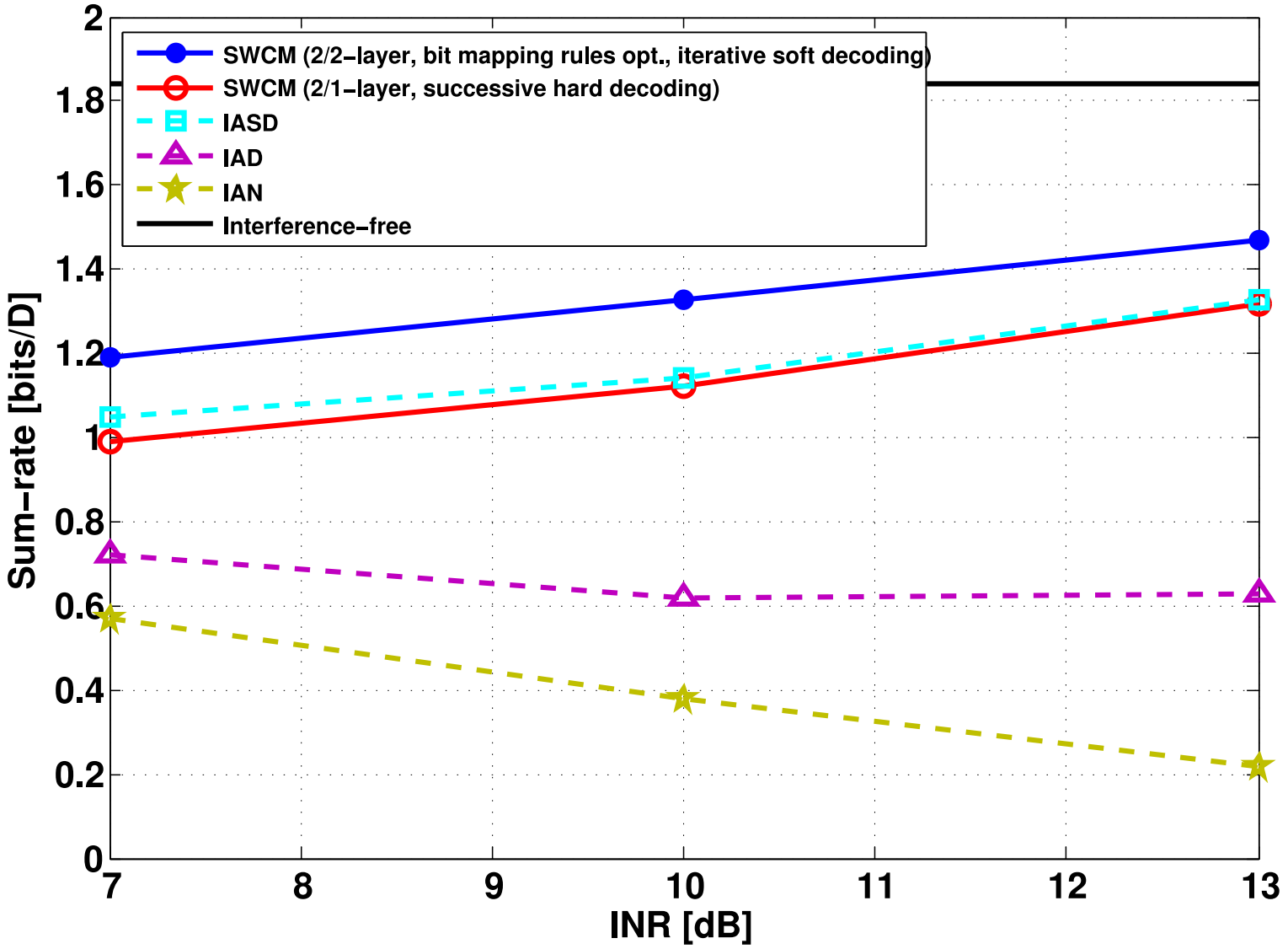


Gaussian channel performance (Park–K–Wang 2014)



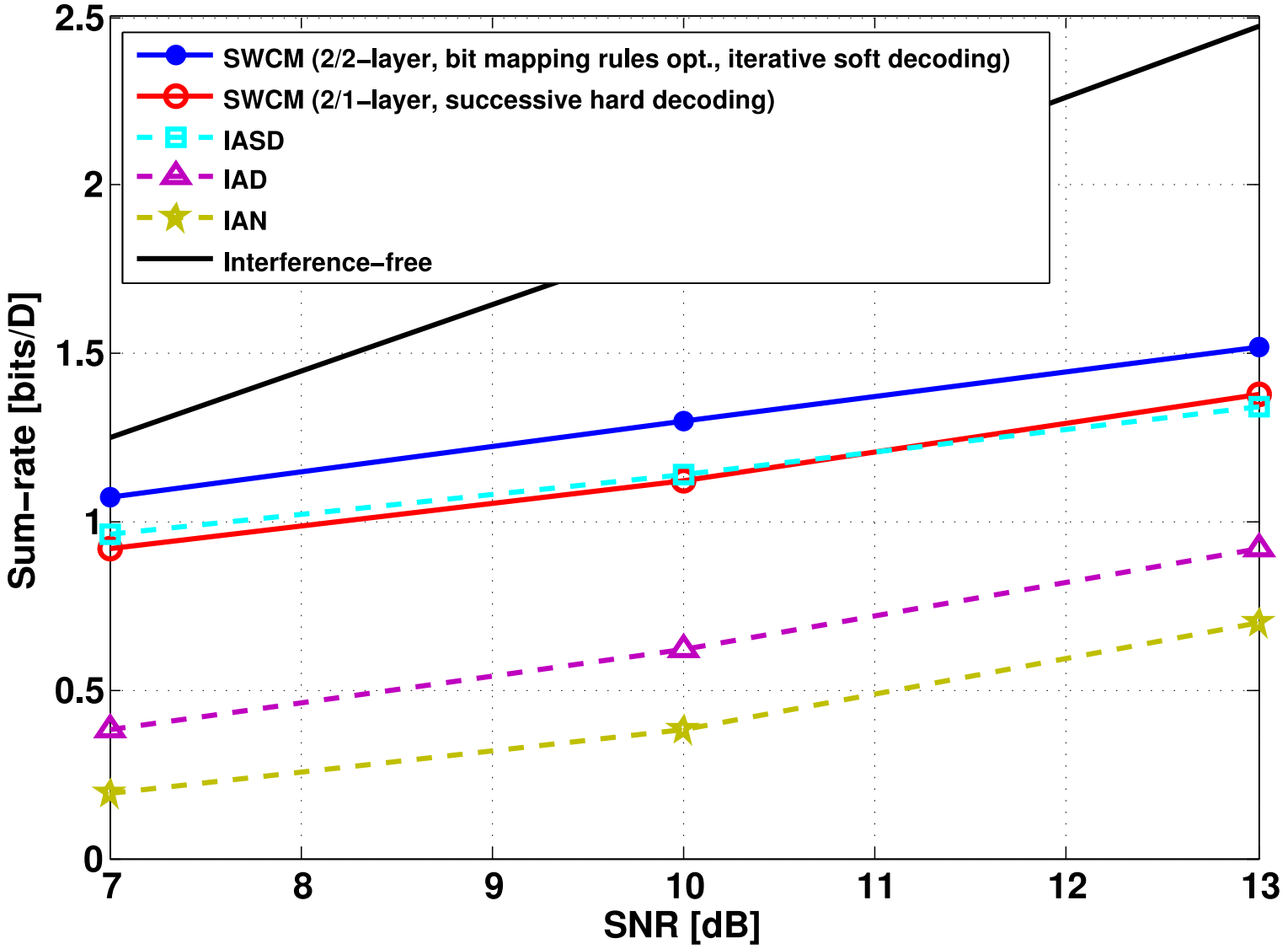
LTE turbo code / ≤ 8-iteration LOG-MAP decoding at $b = 20$, $n = 2048$, BLER $= 0.1$, SNR $= 10$ dB

OFDM/Ped-B channel performance (Kim et al. 2015)



LTE turbo code / ≤ 8-iteration LOG-MAP decoding at $b = 20$, $n = 660$ (13200 REs), BLER $= 0.1$

OFDM/Ped-B channel performance (Kim et al. 2015)



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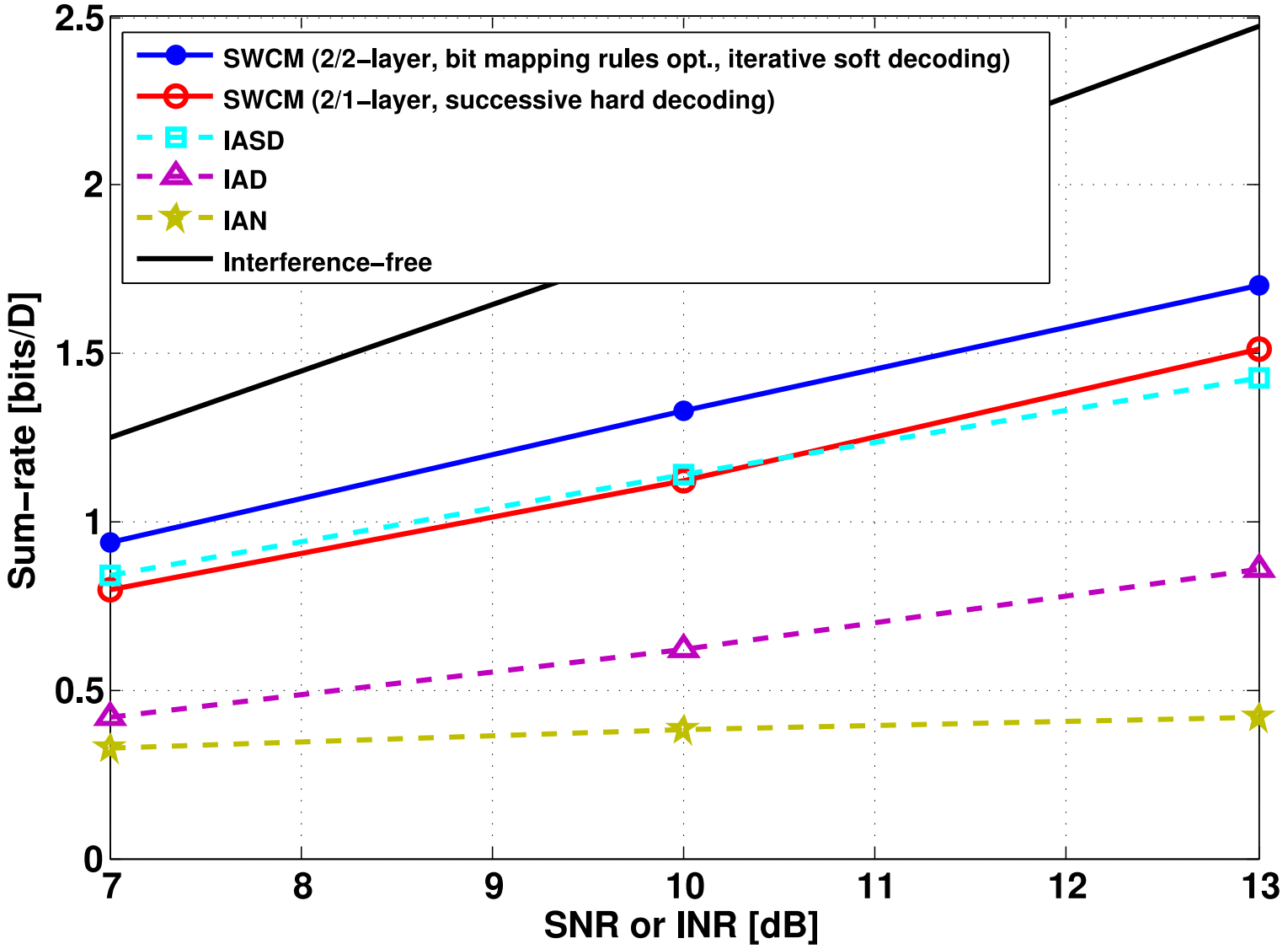

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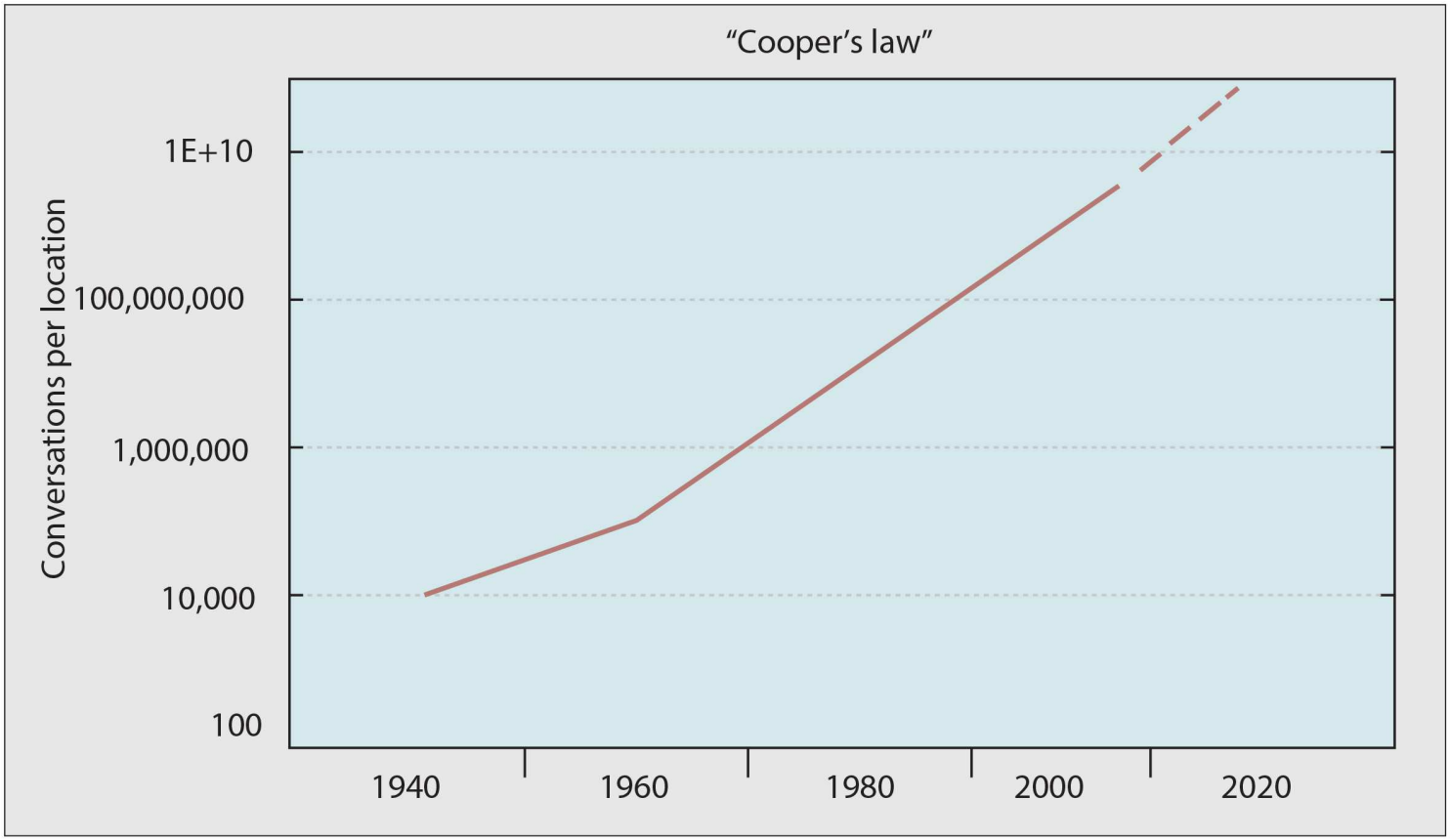
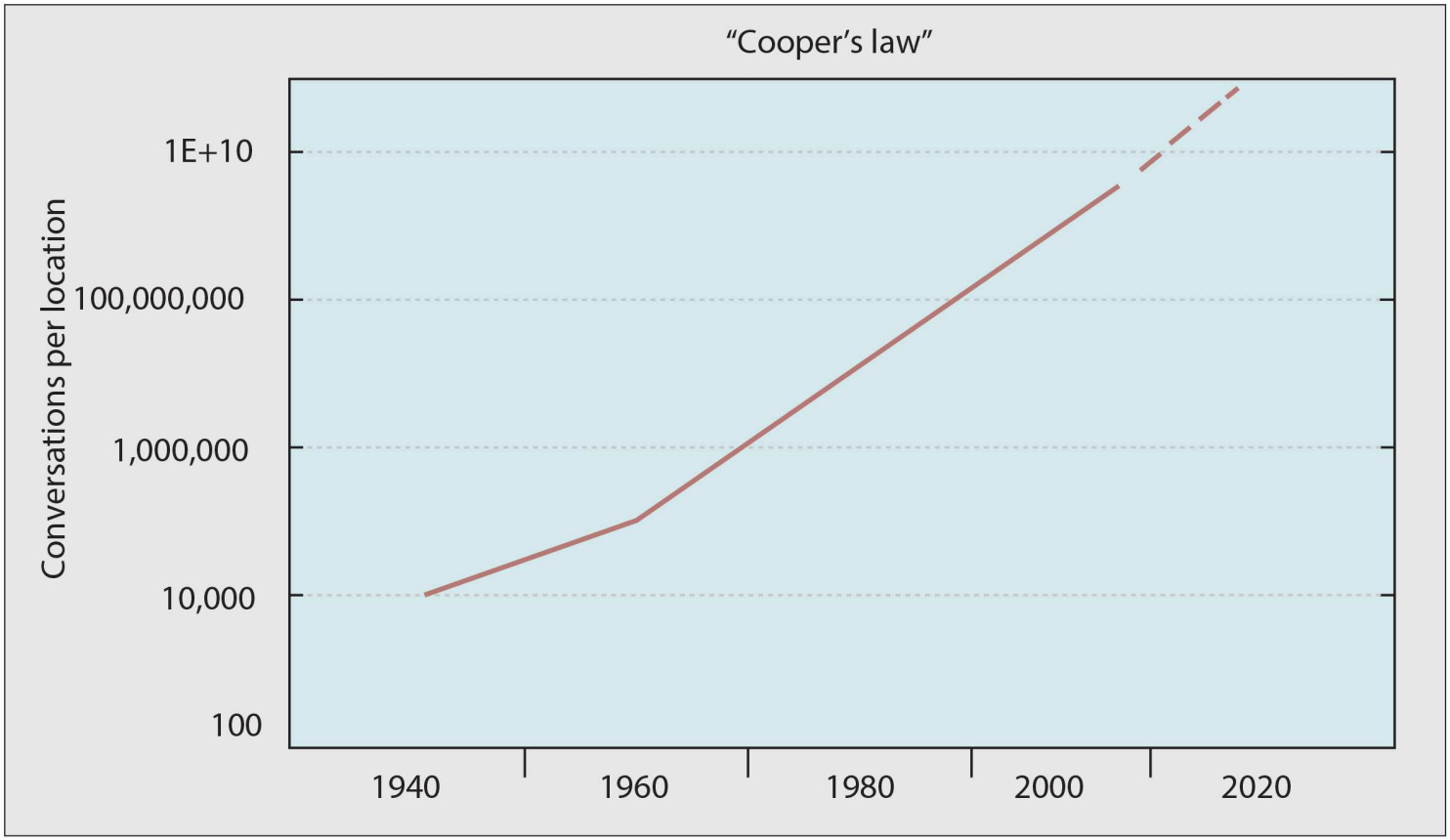
Cooper's Law



Source: Arraycomm, Zander–Mähönen (2013)

Cooper's Law



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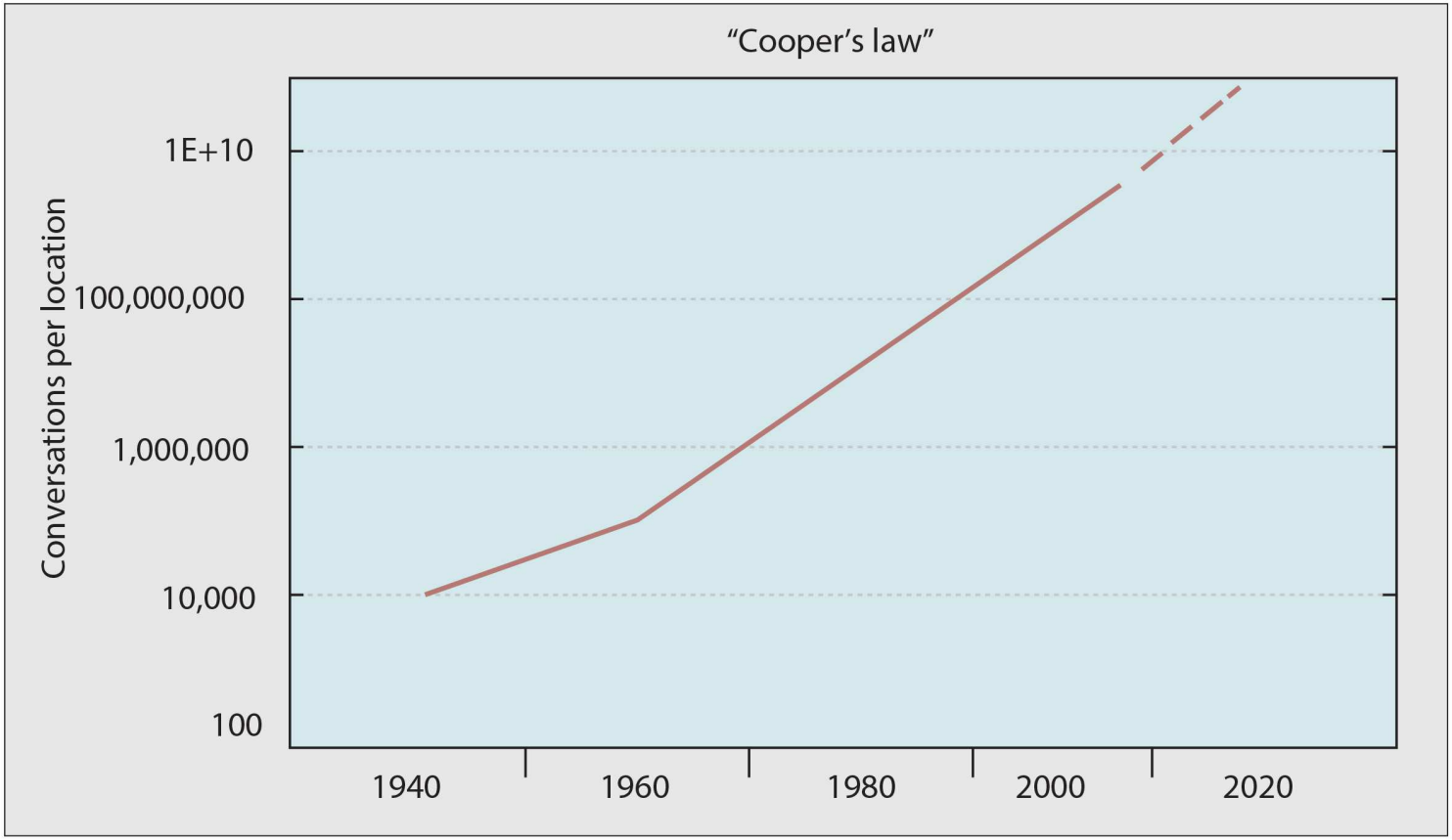
- Gain over the past 45 years = $10^6 \propto \eta W_{\text{sys}} N_{\text{BS}}$

Cooper's Law



Source: Arraycomm, Zander–Mähönen (2013)

- Gain over the past 45 years = $10^6 \propto \eta W_{\text{sys}} N_{\text{BS}}$
  - Spectral efficiency η: x 25

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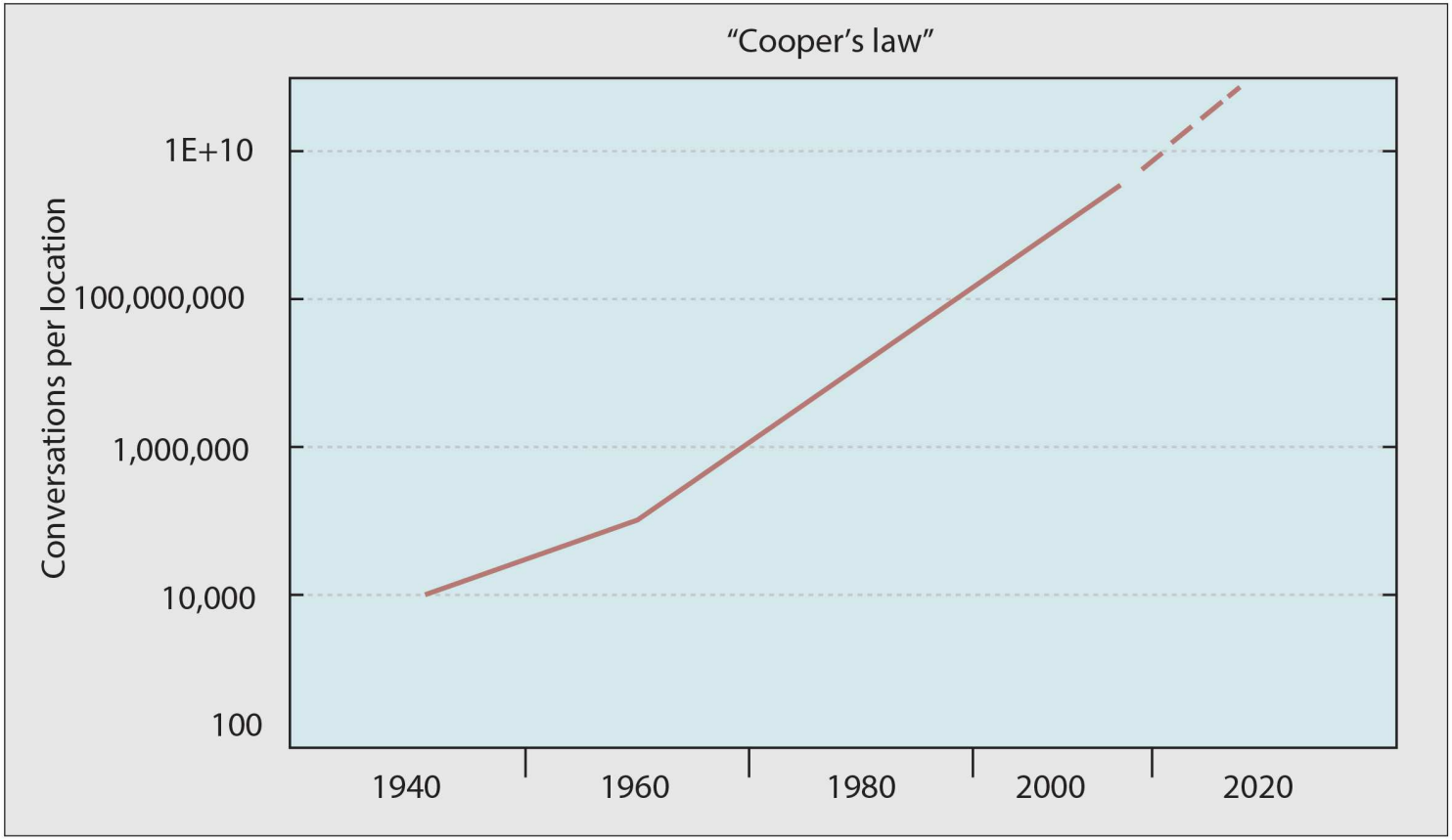

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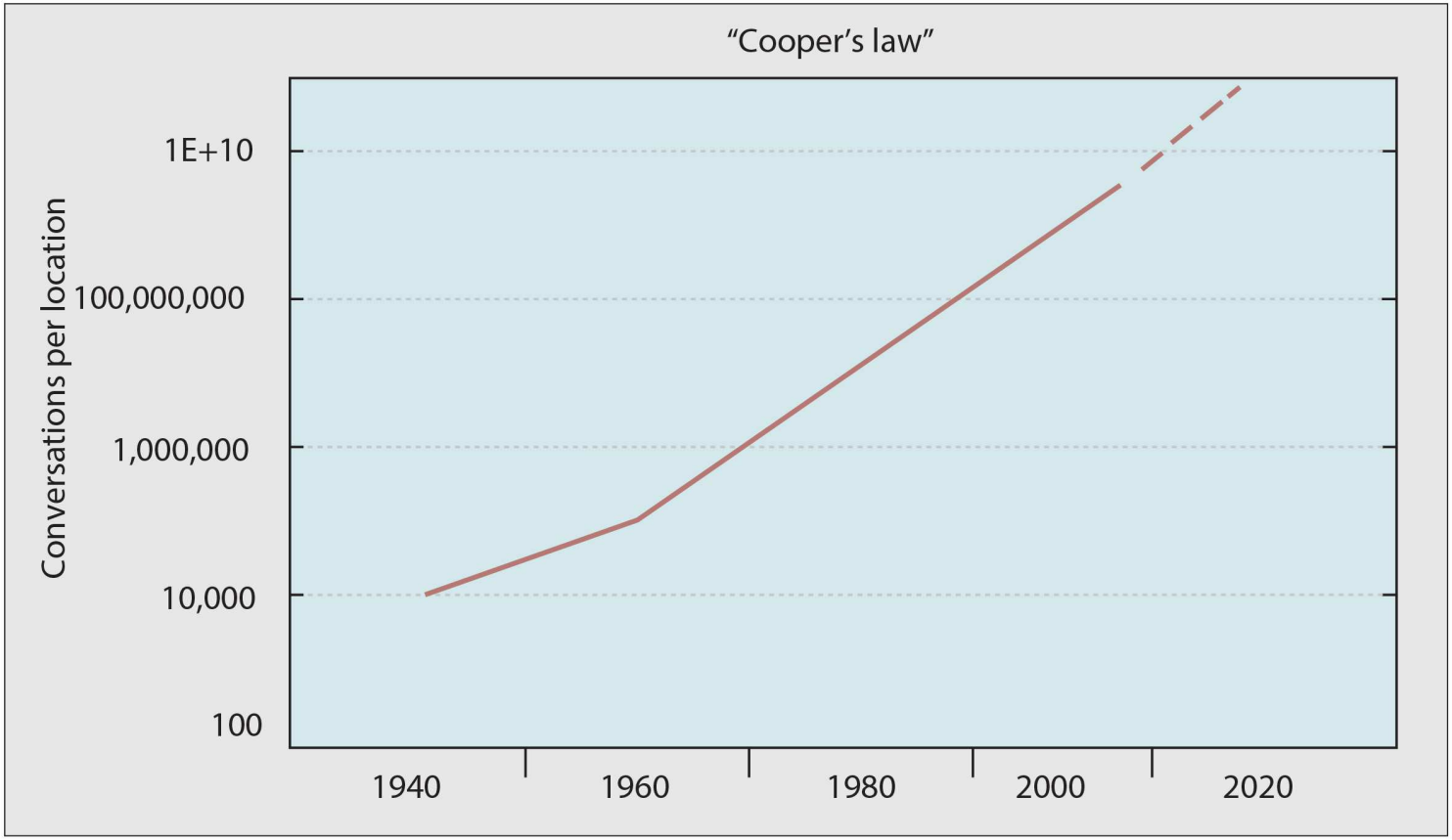
- Gain over the past 45 years $= 10^6 \propto \eta W_{\text{sys}} N_{\text{BS}}$
  - Spectral efficiency η: x 25
  - System bandwidth W_{sys}: x 25

Cooper's Law



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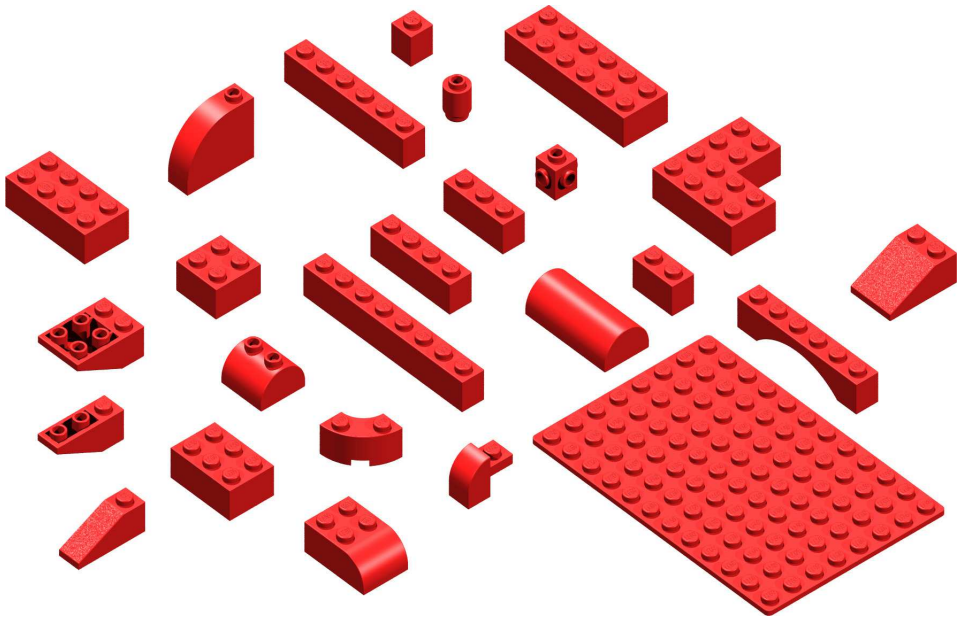
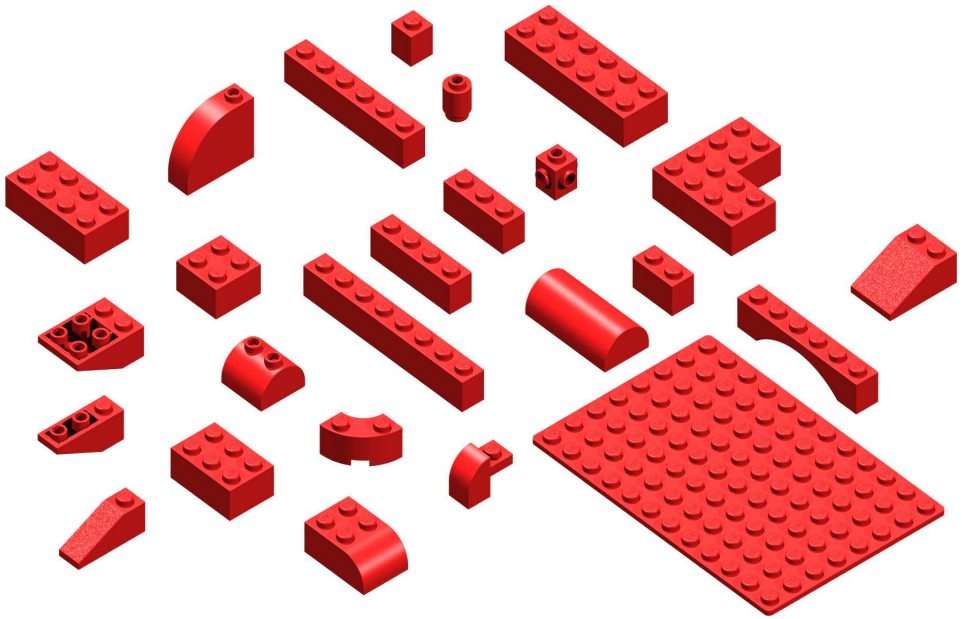
- Gain over the past 45 years $= 10^6 \propto \eta W_{\text{sys}} N_{\text{BS}}$
  - Spectral efficiency η: x 25
  - System bandwidth W_{sys}: x 25
  - # of base stations N_{BS}: x 1600 (spatial reuse of frequency)

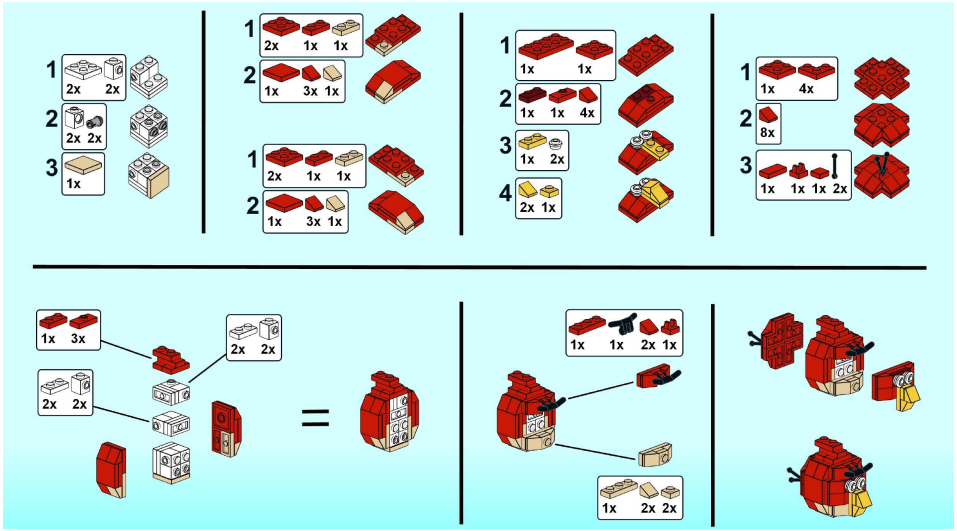
What's next?



- Point-to-point codes (random coding)
- Superposition coding
- Successive cancellation decoding
- Simultaneous decoding
- Multicoding (writing on dirty paper)
- Random binning (Slepian–Wolf)

What's next?





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- Index coding
- Distributed storage coding

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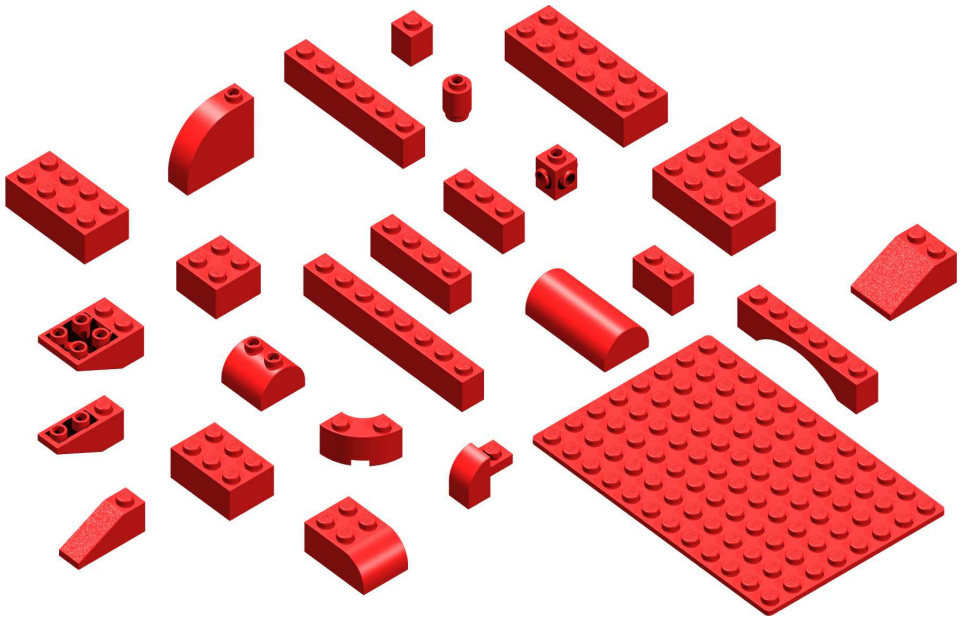

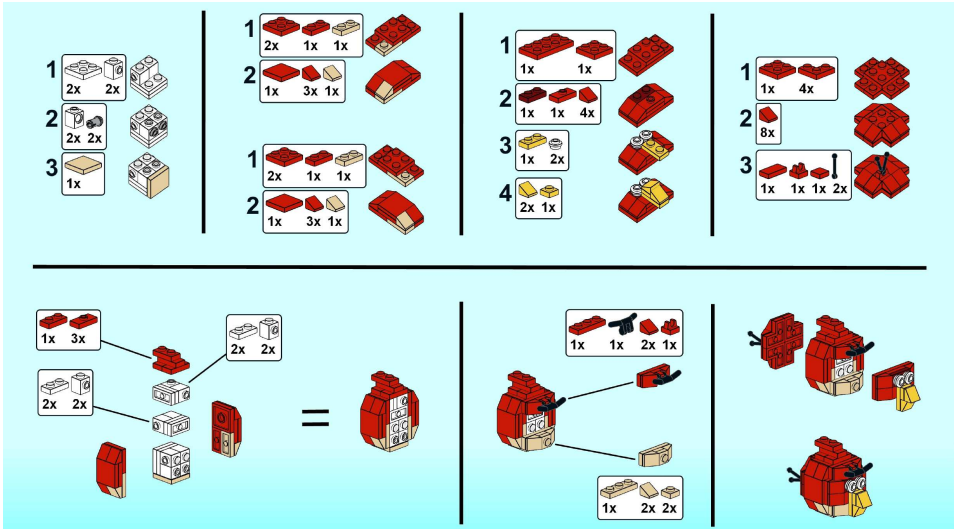

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- Distributed storage coding

What's next?

Let's have fun building better networks!

- Point-to-point codes (random coding)
- Superposition coding
- Successive cancellation decoding
- Simultaneous decoding
- Multicoding (writing on dirty paper)
- Random binning (Slepian–Wolf)
- Network coding
- Noisy network coding
- Distributed decode–forward
- Index coding
- Distributed storage coding