Network-Channel Separation in Adversarial Networks

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Joint work with

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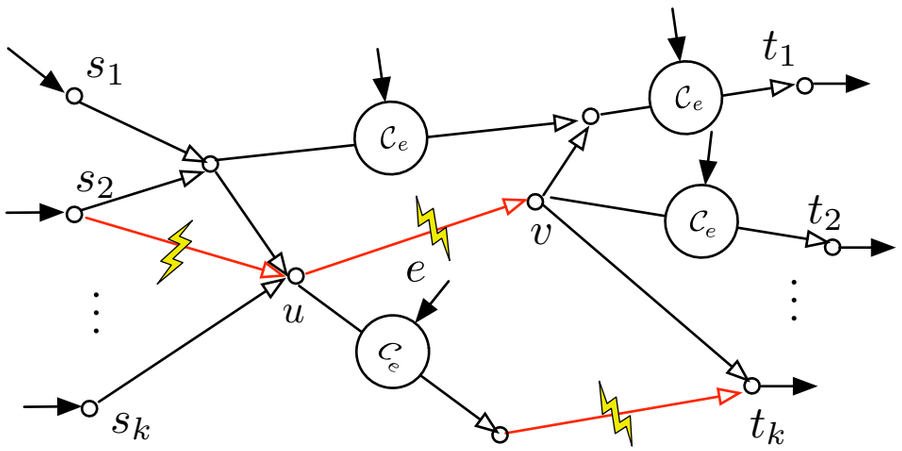
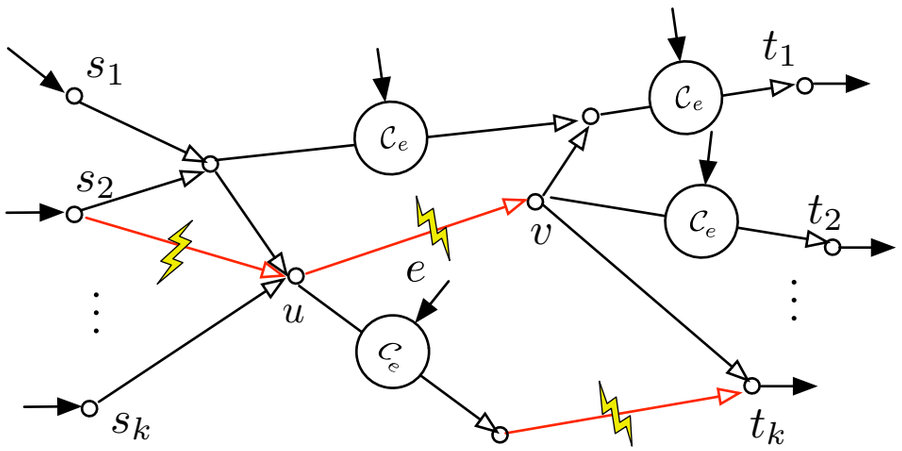
Department of Electrical Engineering, Caltech



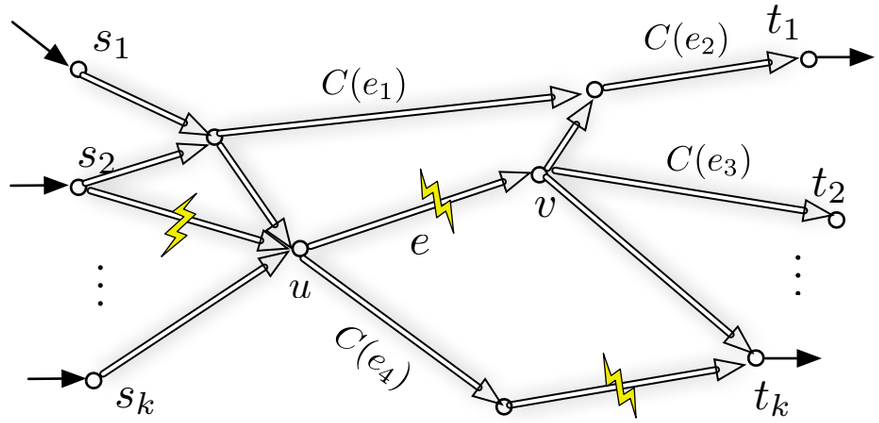
noisy channels + adversary

Q: Can Network Coding and Channel Coding be separated?

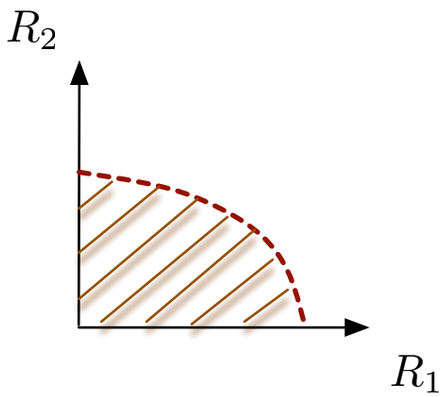


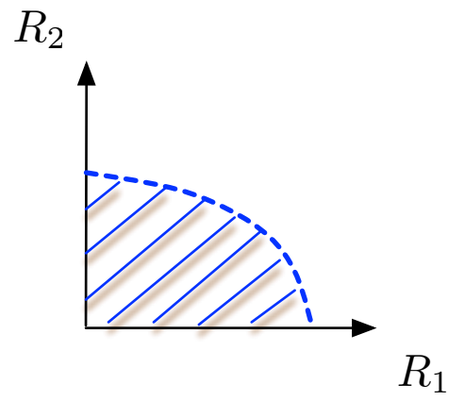
noisy channels + adversary

?



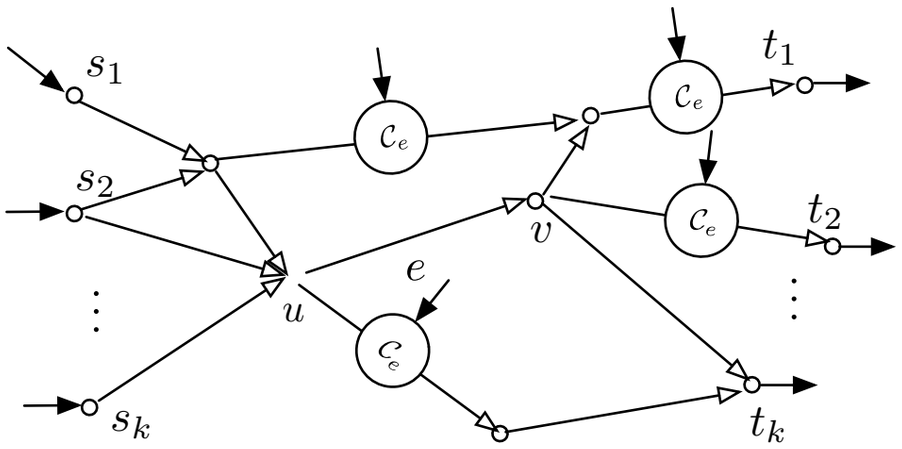
noiseless links + adversary

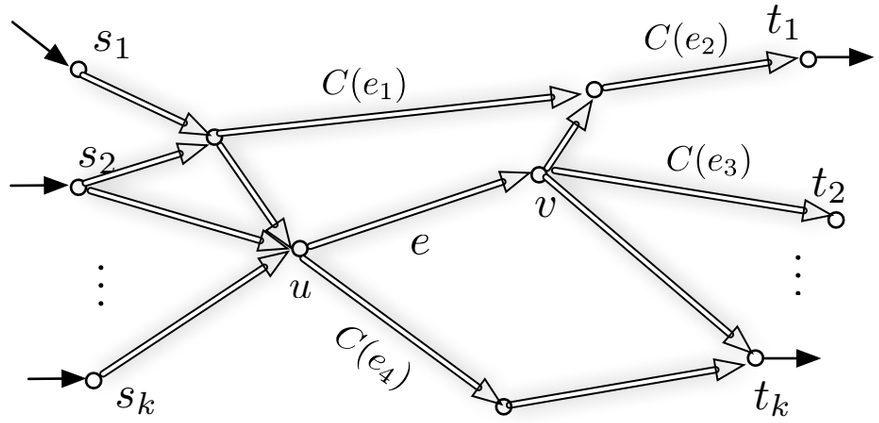




Q: Do the above two networks have same capacity regions?

[Koetter, Effros, Medard ‘2011, Song, Yeung, Cai ‘2006]:

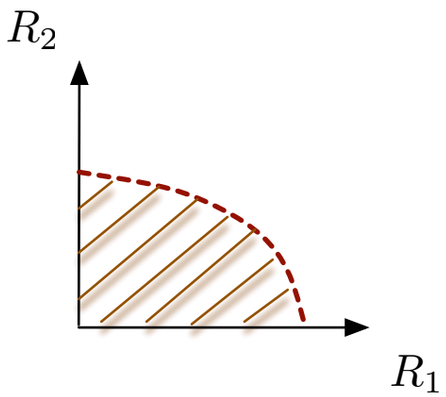


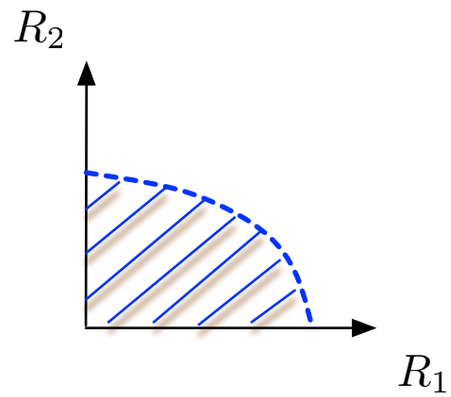


independent noisy channels

$\equiv$

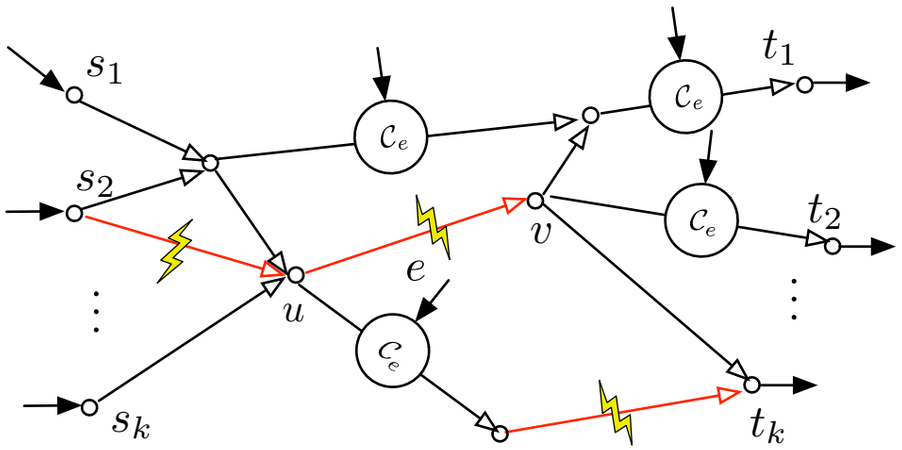
noiseless links





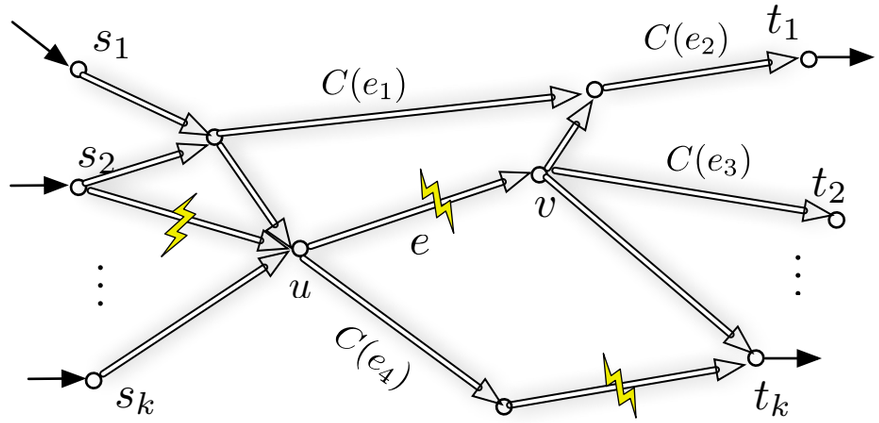
Previous works: Separation holds when there is no adversary

Motivation



noisy channels + adversary

?

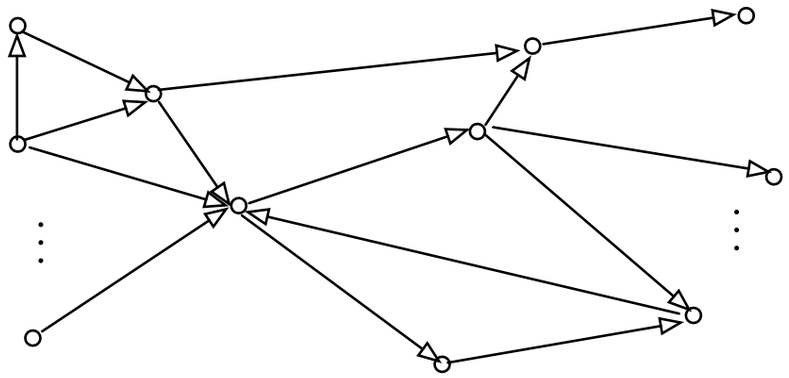


noiseless links + adversary

- Separation based strategies simpler to design and analyze

- Noiseless links + adversary better understood than noisy channels + adversary

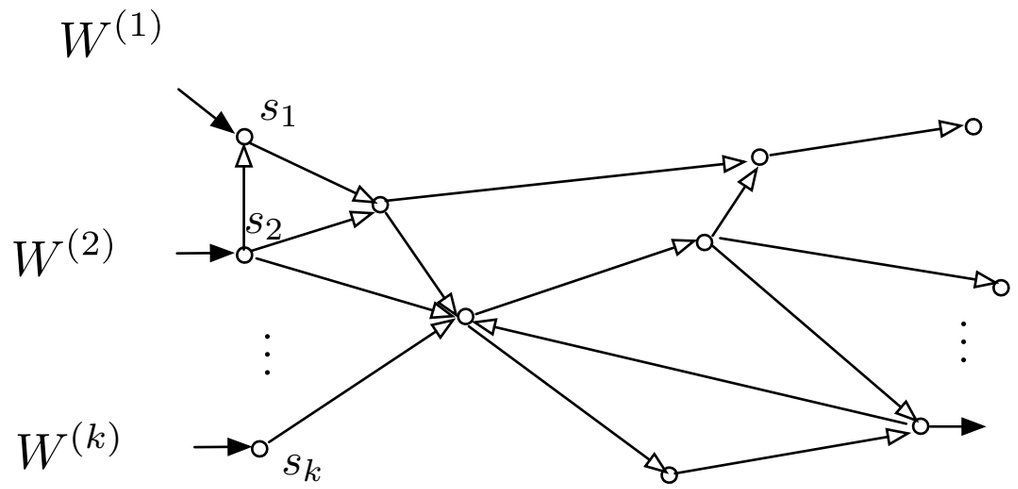
System Model



Network model:

- Directed edges (can be cyclic)

System Model

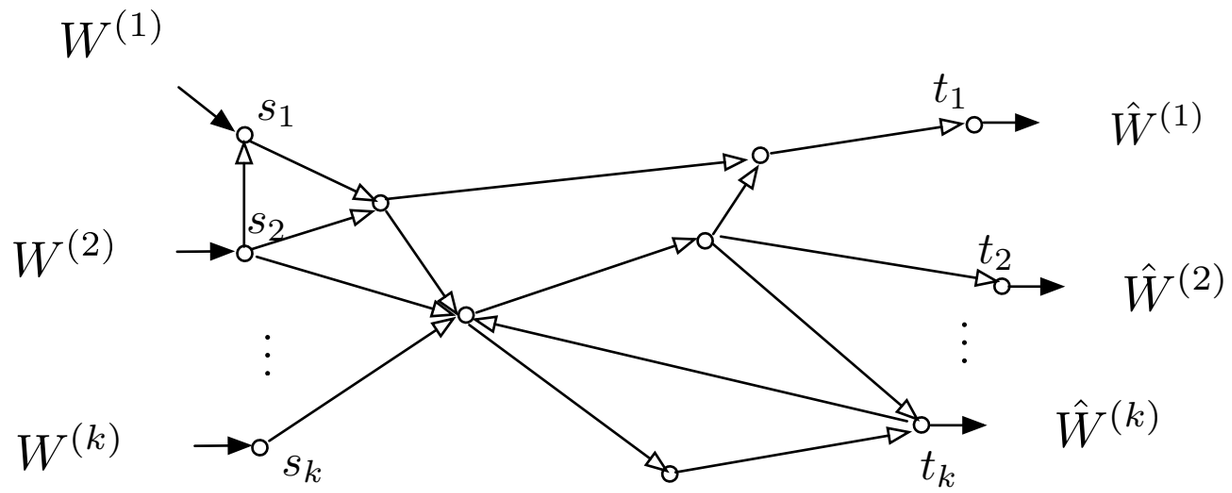


source nodes

Network model:

- Directed edges
- Independent sources

System Model



source nodes

sink nodes

Network model:

- Directed edges
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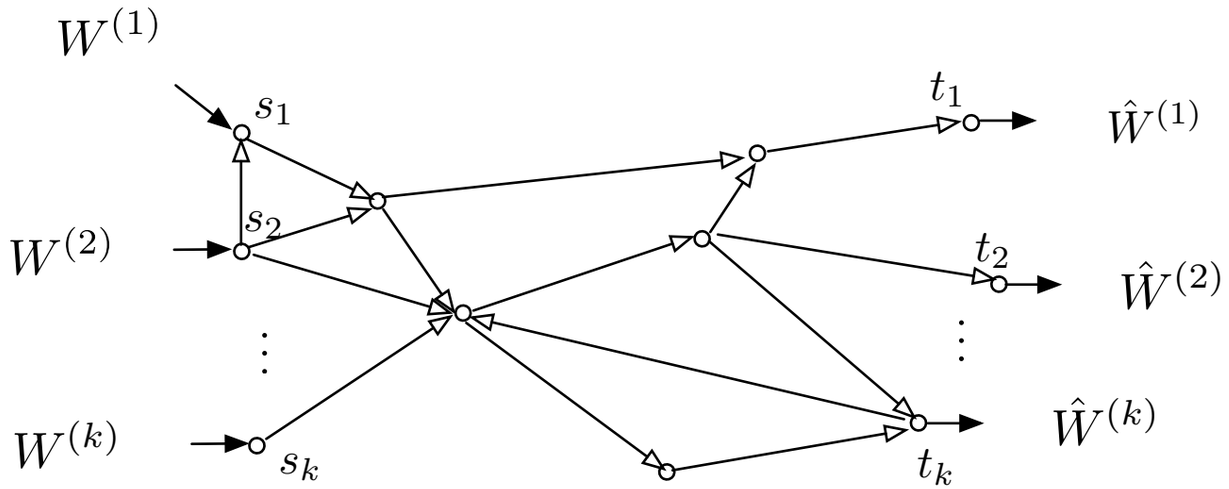
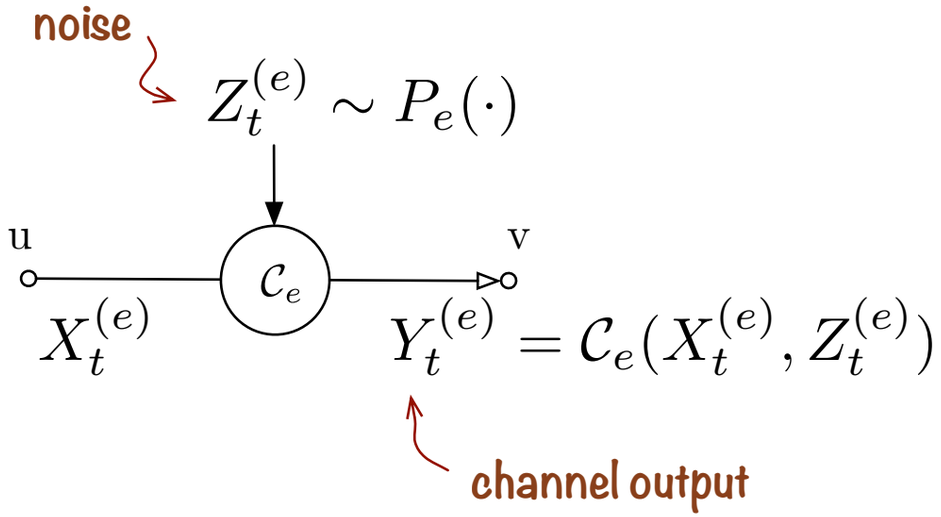
System Model





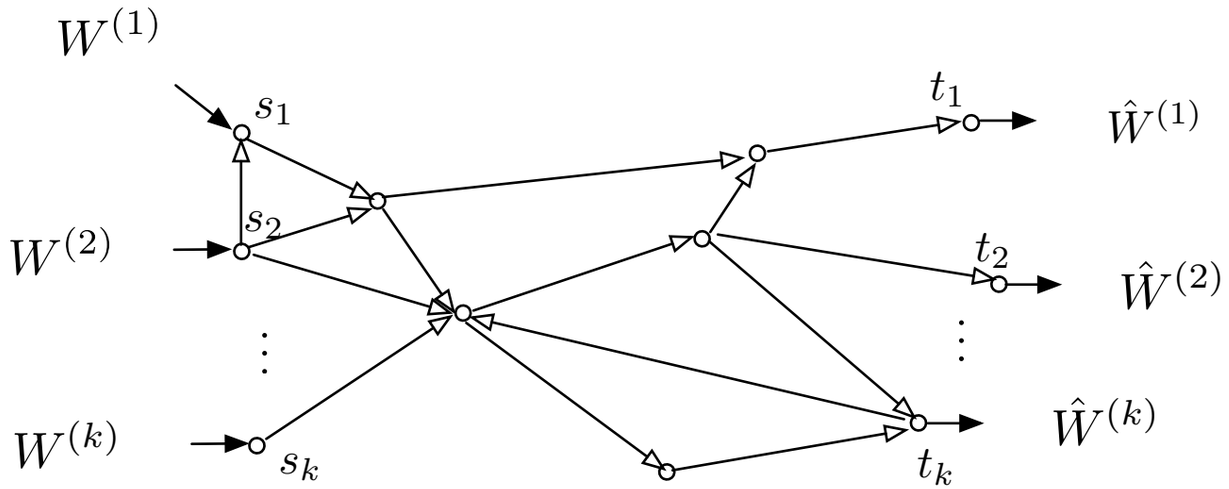
"Noisy Channel"

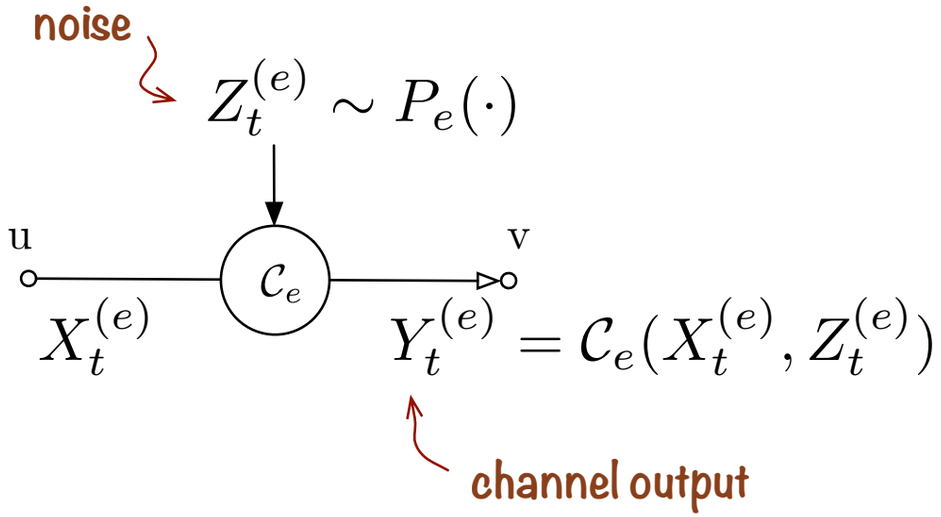
Network model:

- Directed edges
- Independent sources
- Independent, memoryless point-to-point channels

$$P(z_i^{(e)} : e \in E, i = 1, \ldots, n) = \prod_{e \in E} \prod_{i=1}^{n} P_e(z_i^{(e)})$$

System Model





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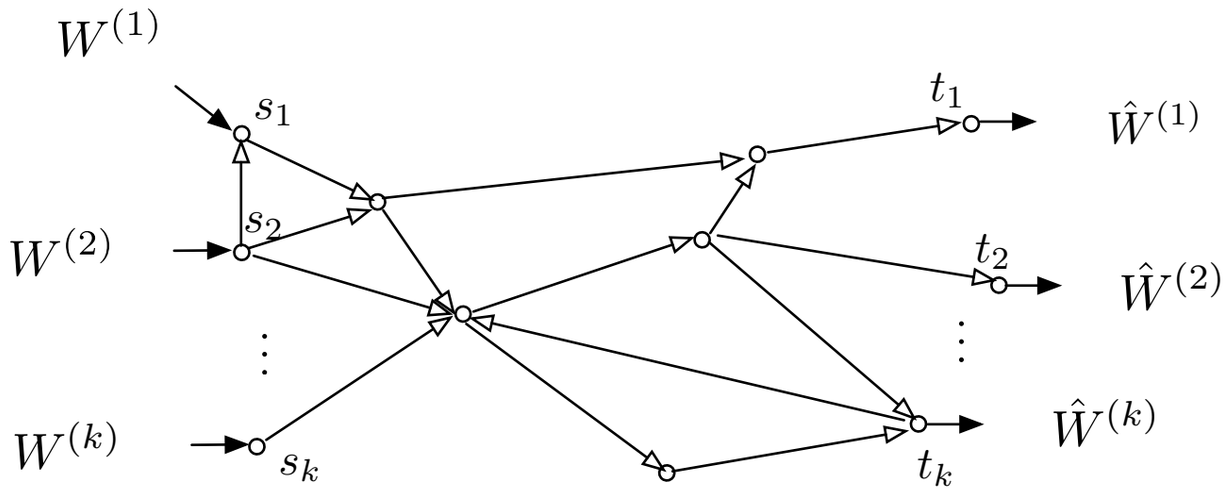
$$P(z_i^{(e)} : e \in E, i = 1, \ldots, n) = \prod_{e \in E} \prod_{i=1}^{n} P_e(z_i^{(e)})$$

Channel capacity:

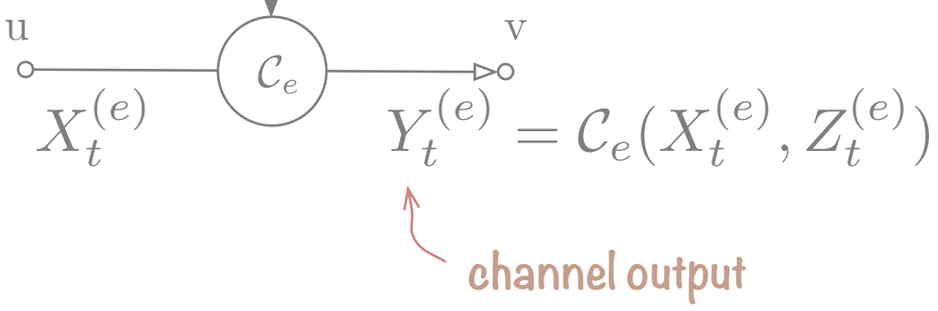
$$C(e) \triangleq \max_{P_{X^{(e)}}(\cdot)} I(X^{(e)}; Y^{(e)})$$

System Model



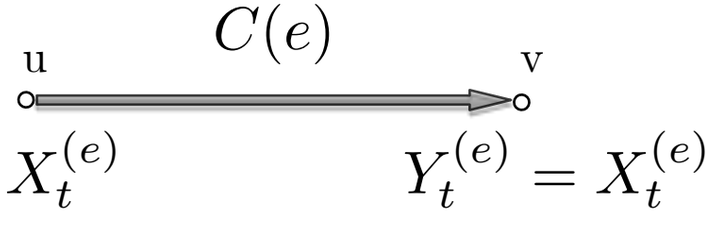
noise

$$Z_t^{(e)} \sim P_e(\cdot)$$



"Noisy Channel"

Special case:



"Noiseless Channel" – $C(e)$ bits/channel use

$$X_t^{(e)}, Y_t^{(e)} \in \{0,1\}^{C(e)} \ \forall\ t$$

Network model:

- Directed edges
- Independent sources
- Independent, memoryless point-to-point channels

$$P(z_i^{(e)} : e \in E, i = 1, \ldots, n) = \prod_{e \in E} \prod_{i=1}^{n} P_e(z_i^{(e)})$$

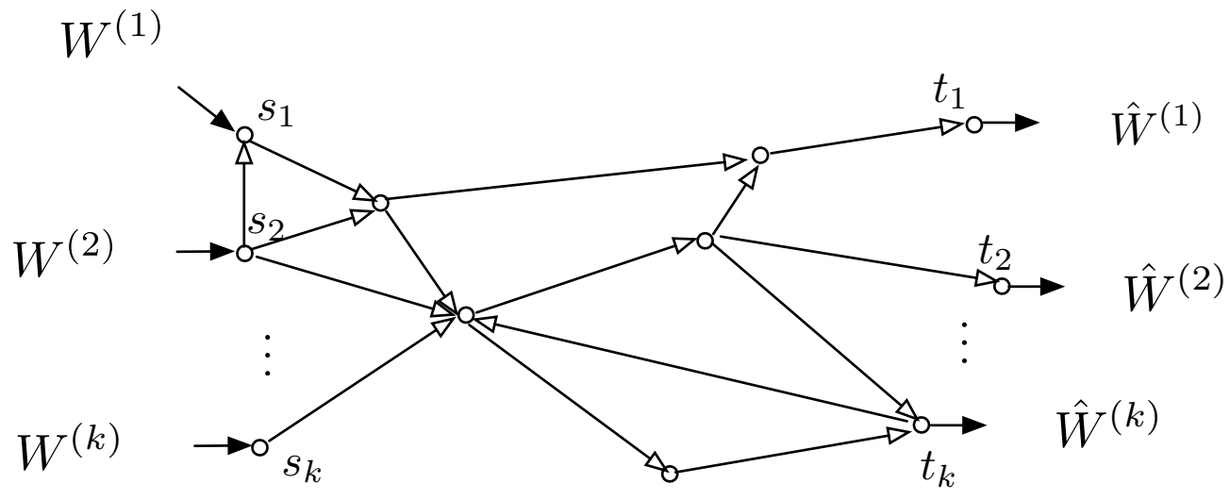
Channel capacity:

$$C(e) \triangleq \max_{P_{X^{(e)}}(\cdot)} I(X^{(e)}; Y^{(e)})$$

Assume (for now):

$$C(e) \in \mathbb{Z}^+ \quad \forall\ e \in E$$

System Model

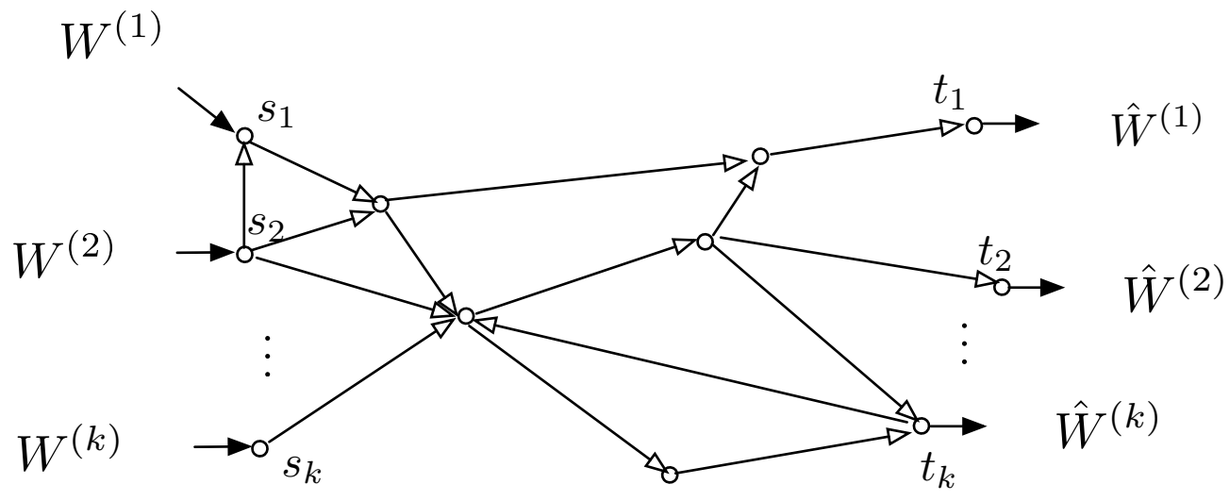


Network Code:

System Model

rate

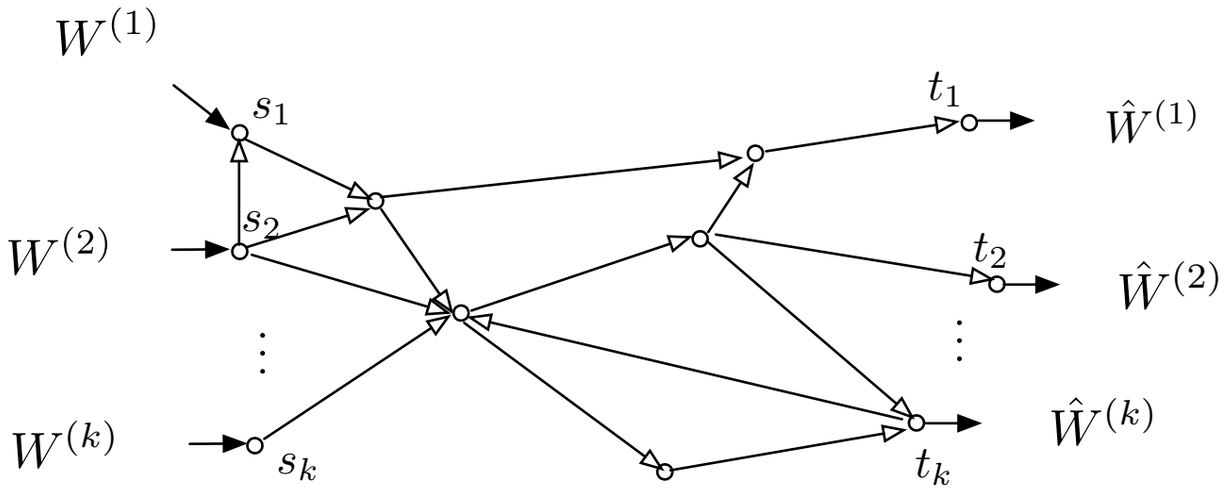
$W^{(i)} \in \{1, 2, \ldots, 2^{nR_i}\}$



Network Code:

- Block network code
  - blocklength $n \in \mathbb{Z}^+$, rate $\mathbf{R} = (R_1, \ldots, R_k)$

System Model



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Network Code:

- Block network code
  - blocklength $n \in \mathbb{Z}^+$, rate $\mathbf{R} = (R_1, \ldots, R_k)$
  - mappings $(f_t^{(e)} : e \in E, t = 1, 2, \ldots, n)$
    $(g^{(i)} : i = 1, 2, \ldots, k)$

System Model

rate

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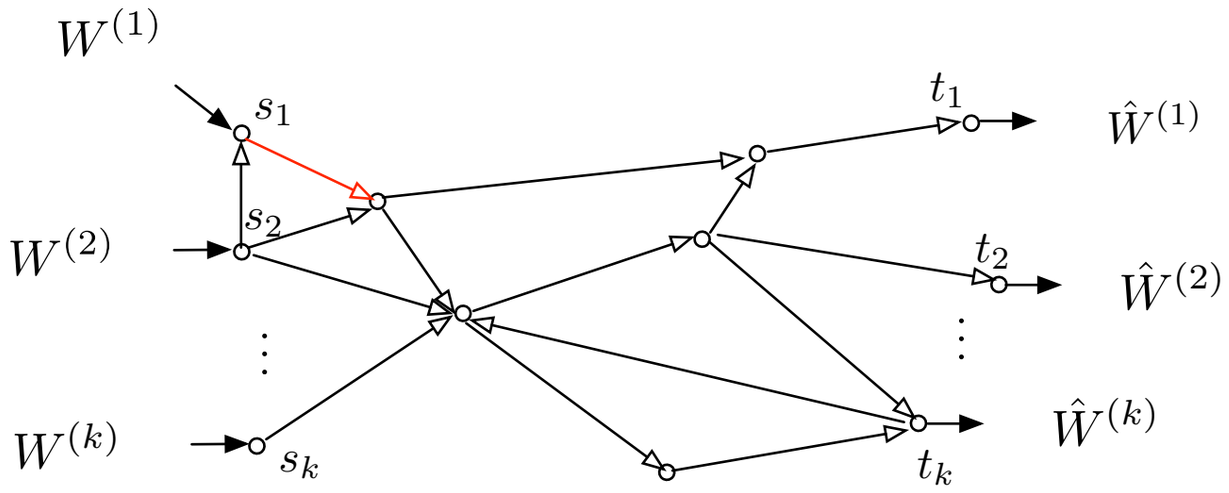

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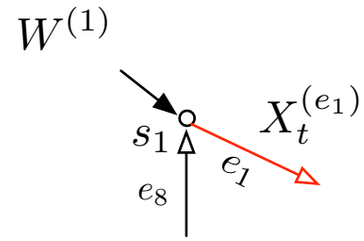
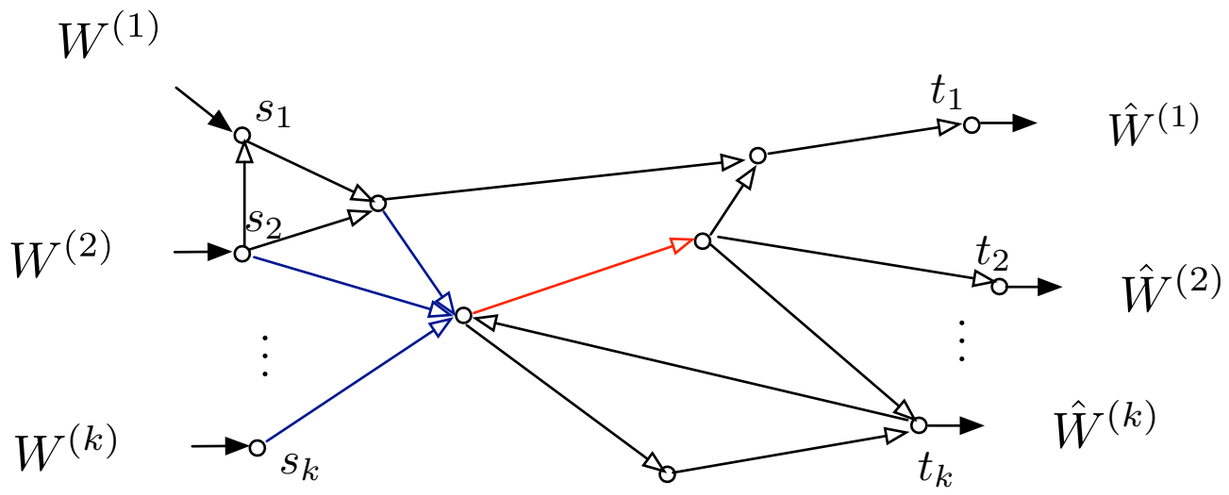


$$X_t^{(e_1)} = f_t^{(e_1)}(W^{(1)}, Y_{1:t-1}^{(e_8)}) \ , \ t = 1, 2, \ldots, n$$

System Model

rate

$W^{(i)} \in \{1, 2, \ldots, 2^{nR_i}\}$



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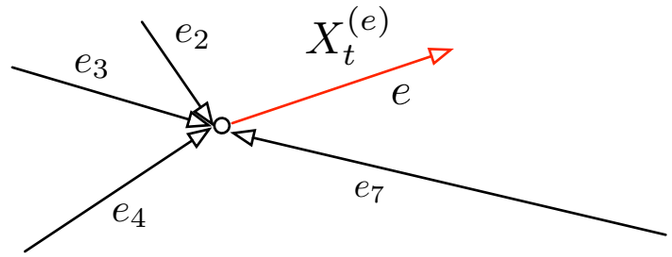

$$X_t^{(e)} = f_t^{(e_1)}(Y_{1:t-1}^{(e_2)}, Y_{1:t-1}^{(e_3)}, Y_{1:t-1}^{(e_4)}, Y_{1:t-1}^{(e_8)})$$

System Model

rate

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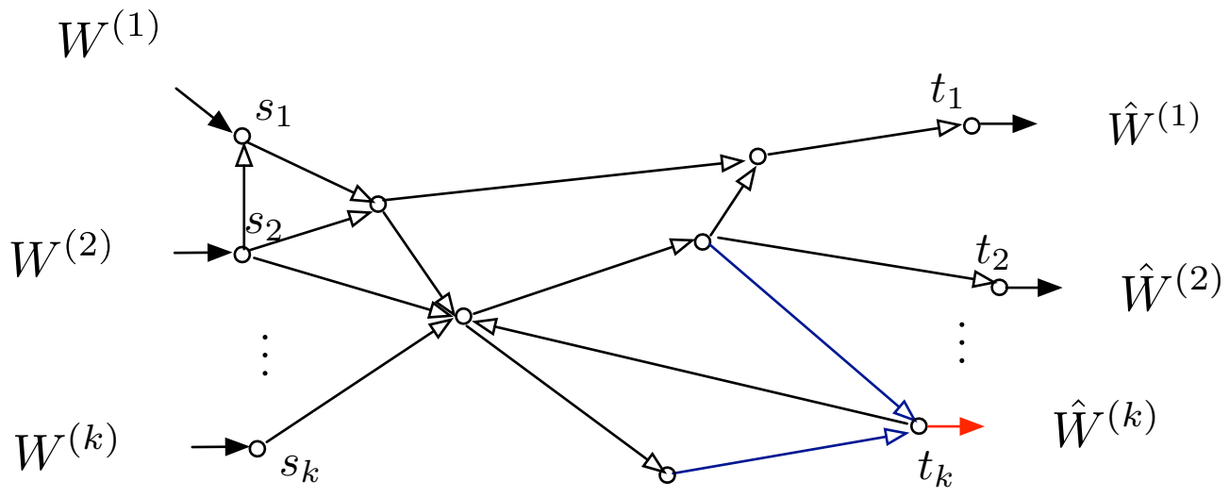

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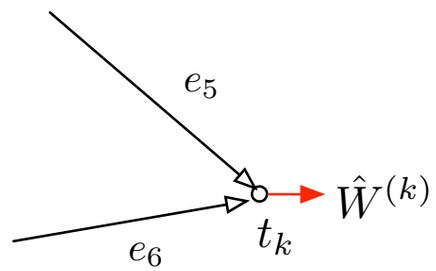
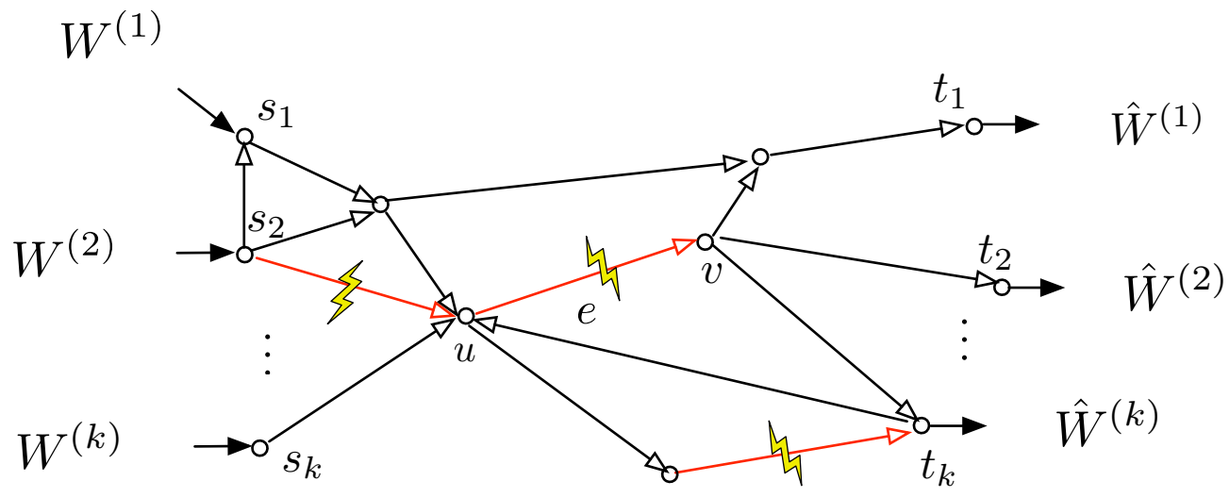


$\hat{W}^{(k)} = g^{(k)}(Y_{1:n}^{(e_5)}, Y_{1:n}^{(e_6)})$

System Model

rate

$W^{(i)} \in \{1, 2, \ldots, 2^{nR_i}\}$



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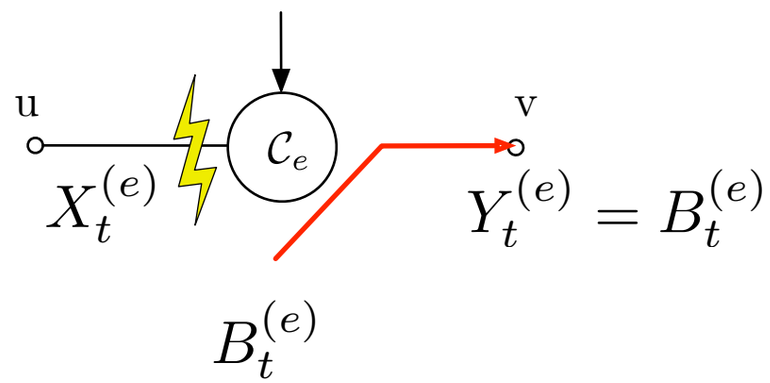
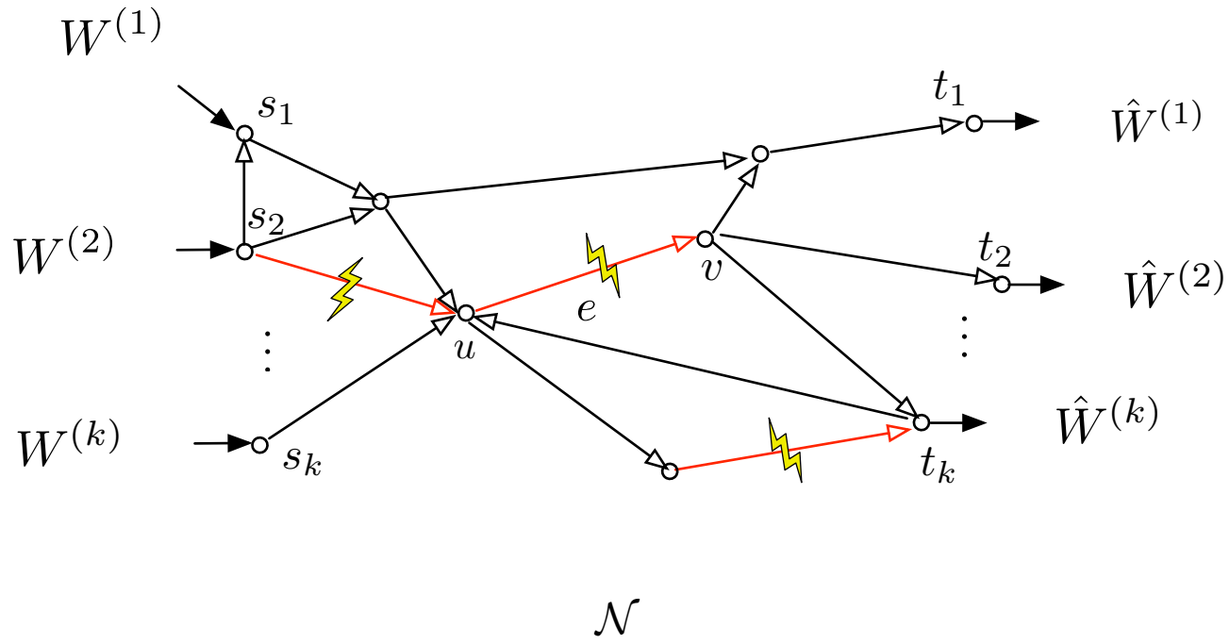
Byzantine Adversary:

- knows all **messages** and **noise values**
- can replace **received** vectors on any K edges



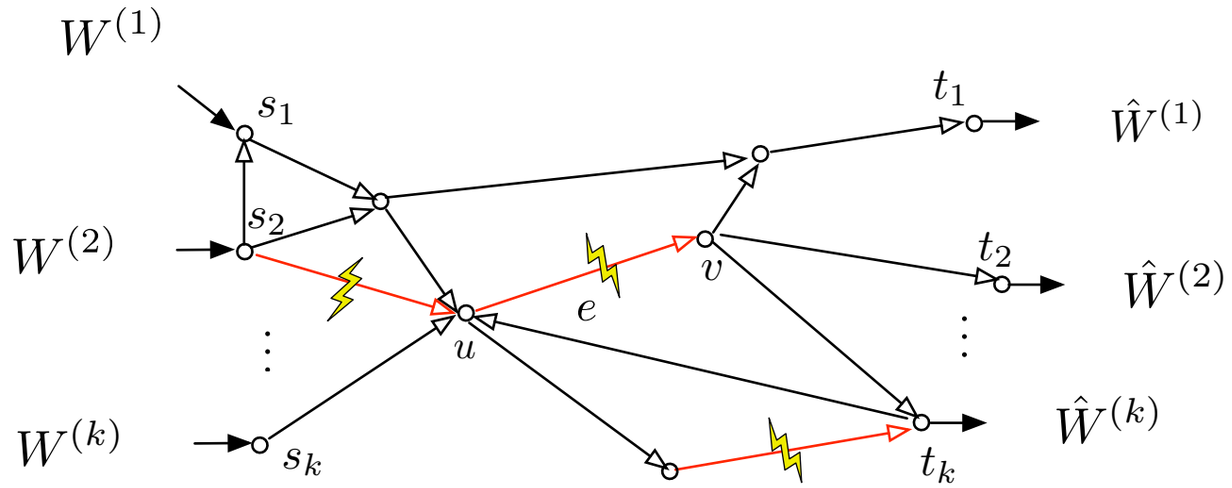
System Model



Communication goal:

"Reliably" communicate $W^{(1)}, W^{(2)}, \ldots, W^{(k)}$ ***irrespective of adversary's attack strategy***

System Model



$\mathcal{N}$

Communication goal:

"Reliably" communicate $W^{(1)}, W^{(2)}, \ldots, W^{(k)}$ ***irrespective of adversary's attack strategy***

Rate vector:

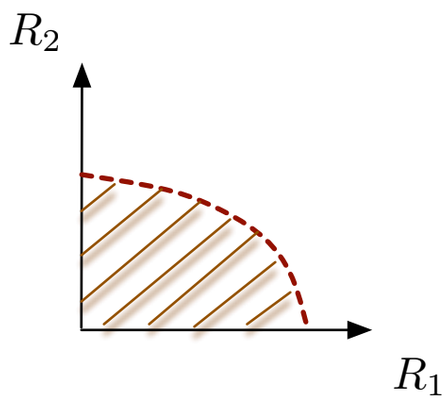
$$\mathbf{R} = (R(1), R(2), \ldots, R(k))$$

Capacity region $\mathcal{R}(\mathcal{N}, K)$

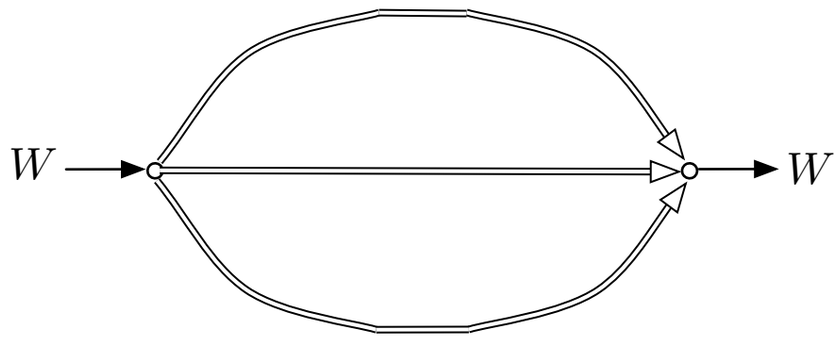
$\mathbf{R} \in \mathcal{R}(\mathcal{N}, K)$ iff there exists a network code for some block-length n such that

$$\Pr(W^{(1)}, W^{(2)}, \ldots \neq \hat{W}^{(1)}, \hat{W}^{(2)}, \ldots) < \lambda$$

for every $\lambda > 0$ ***irrespective of adversary's strategy.***



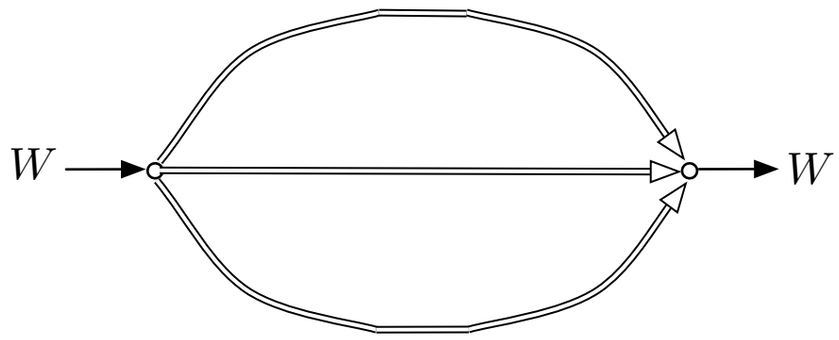
Example



- $C(e) = 1$ for each $e \in E$

- Adversary can attack any one edge

Example



- $C(e) = 1$ for each $e \in E$

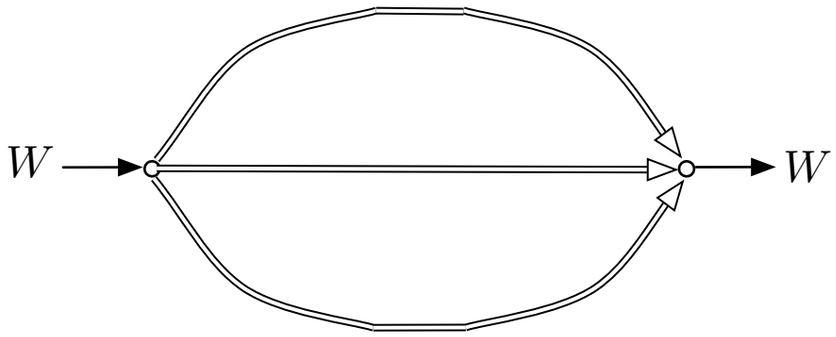
- Adversary can attack any one edge

- Rate 1 is achievable

Example

$W \in \{0, 1\}$

Blocklength =1



- $C(e) = 1$ for each $e \in E$

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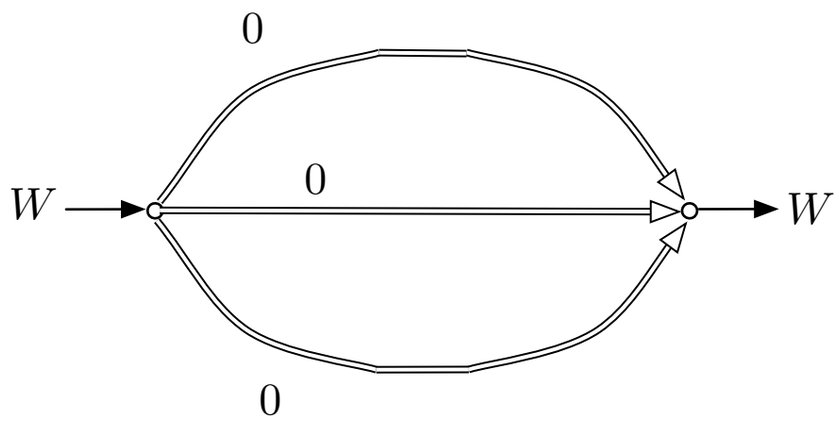
Example

$W = 0$

$W \in \{0, 1\}$

Blocklength =1



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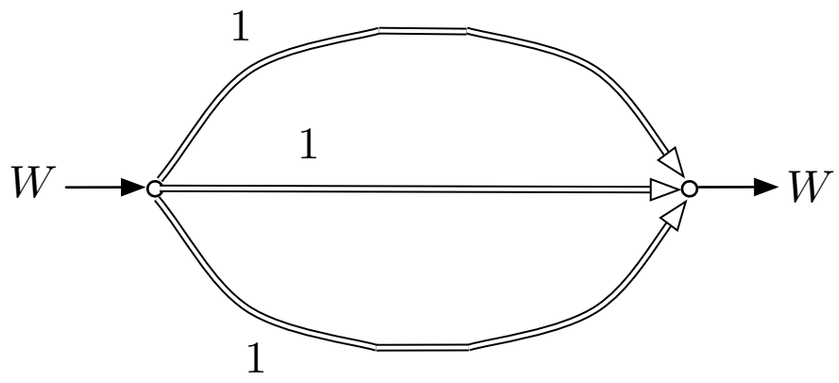

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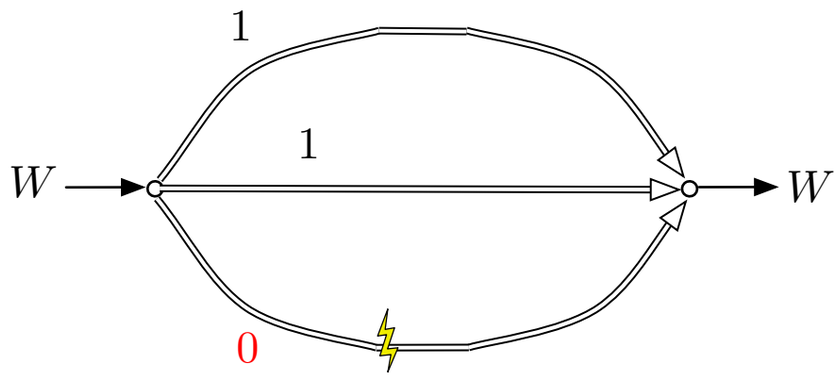

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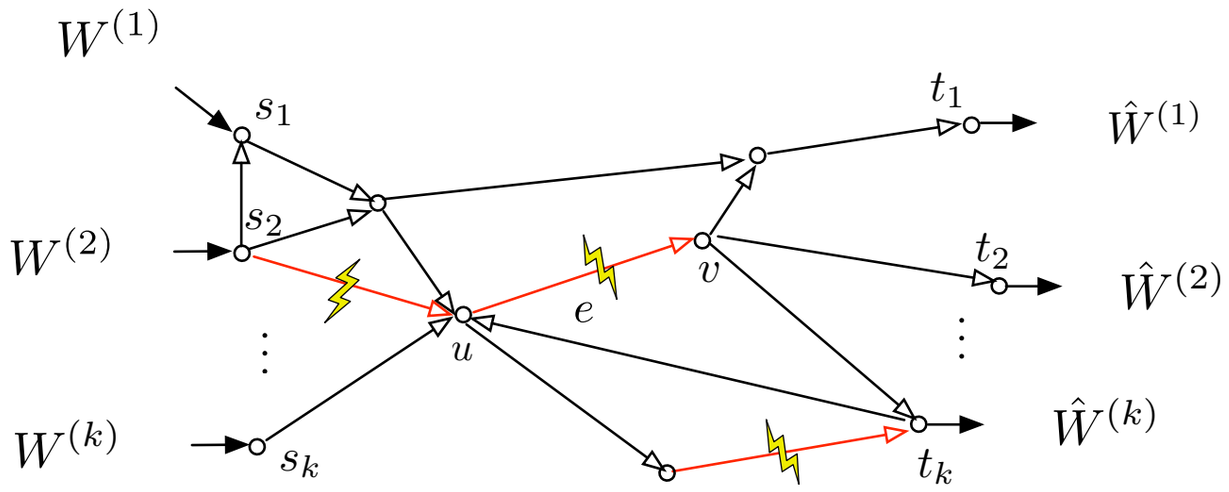
Some known results

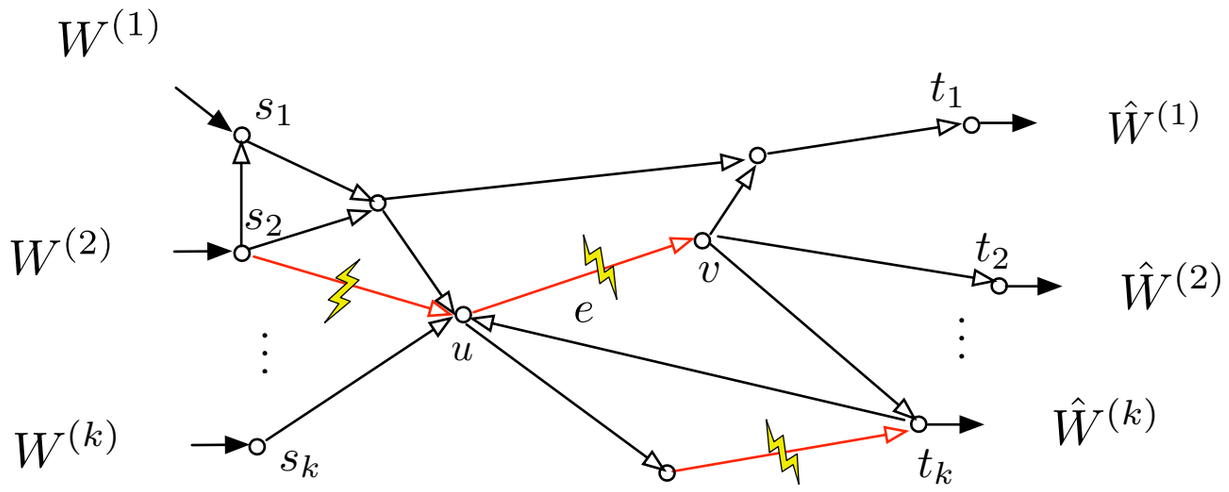


Noiseless networks

- equal link capacities [Yeung et al 2006, Jaggi et al 2007]

  - Capacity = min-cut- $2K$ if each link has capacity 1

Some known results



Noiseless networks

- equal link capacities [Yeung et al 2006, Jaggi et al 2007]

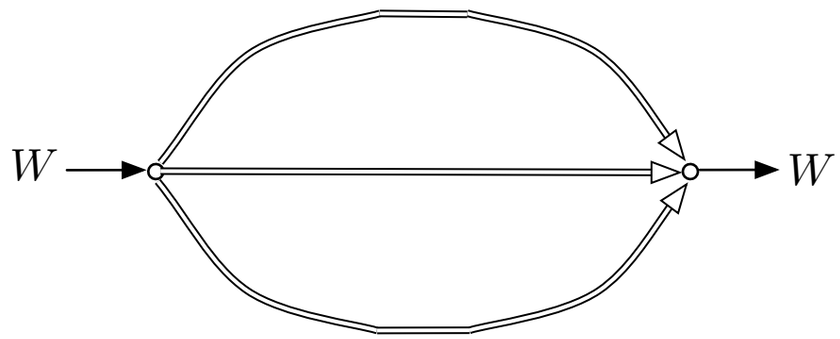
  - Capacity = min-cut- $2K$ if each link has capacity 1

    Previous example:

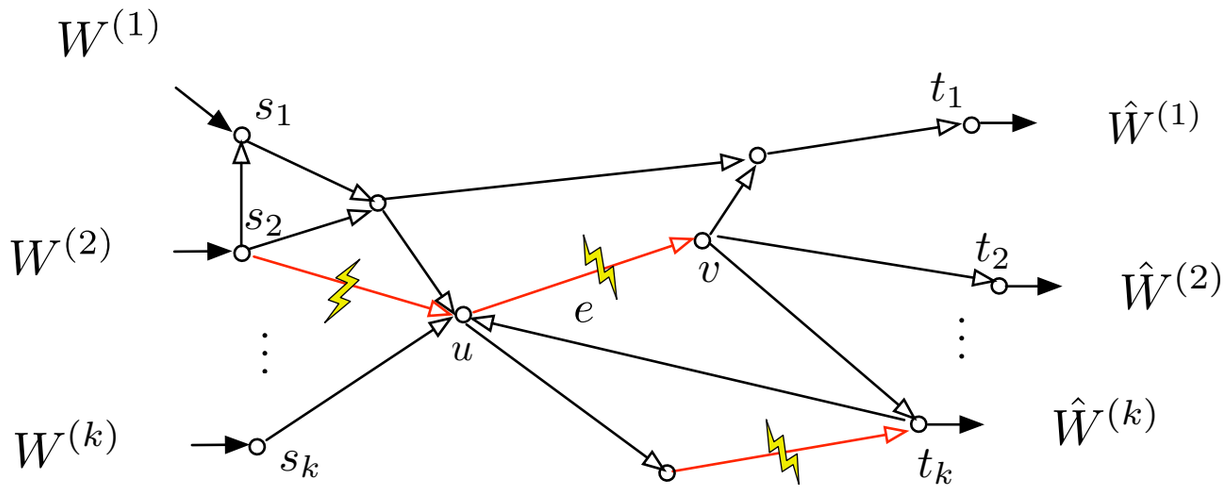
    min-cut = 3

    $K = 1$

    => *Capacity = 1*



Some known results



Noiseless networks

- equal link capacities [Yeung et al 2006, Jaggi et al 2007]

  - Capacity = min-cut- $2K$ if each link has capacity 1

- partial results for unequal link capacities [Kim et al 2009]

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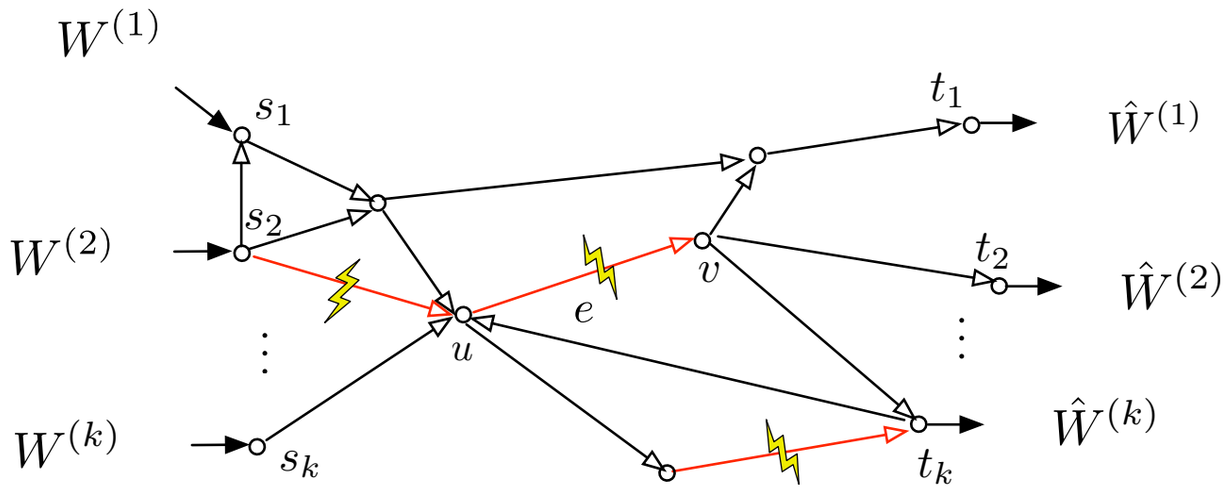

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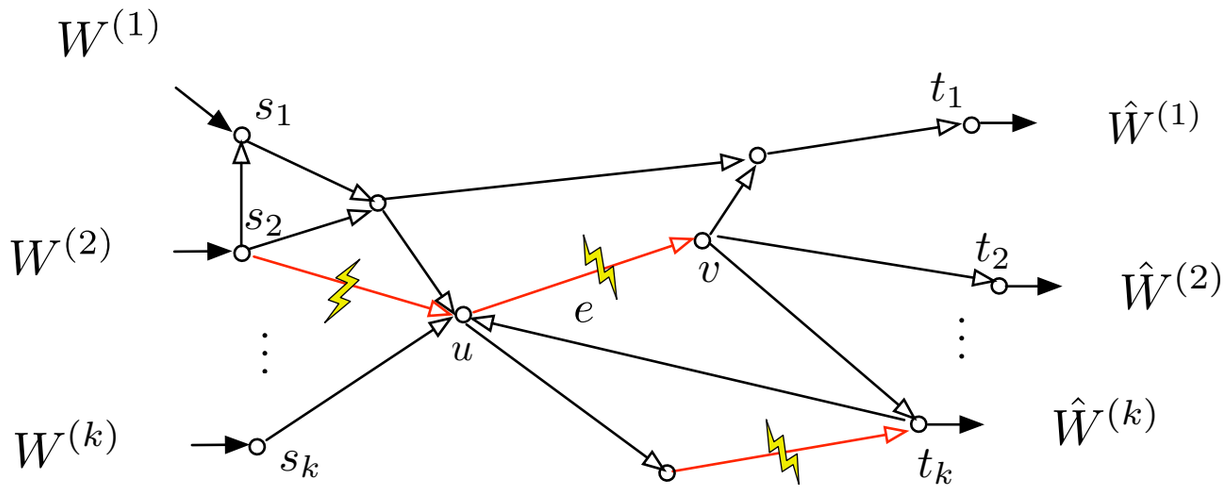
- node based adversaries [Kosut et al 2009]

Some known results



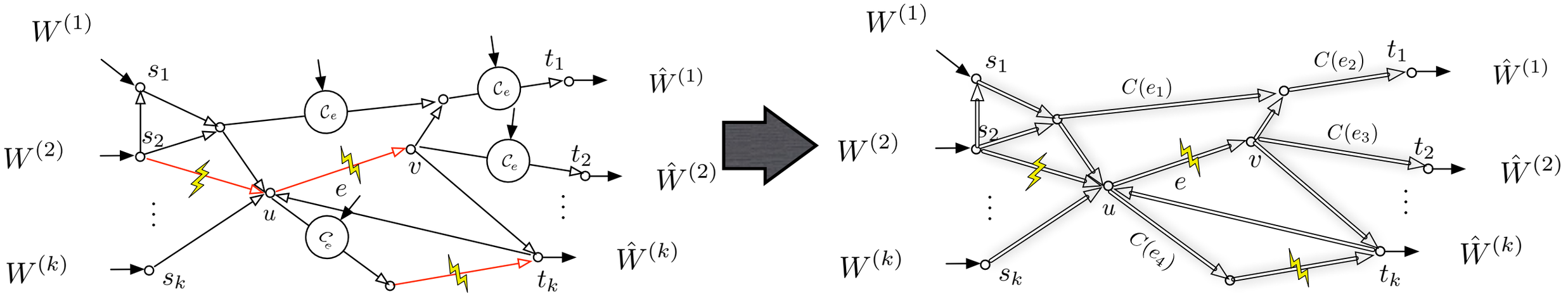
Noisy networks

[Jaggi et al 2007]

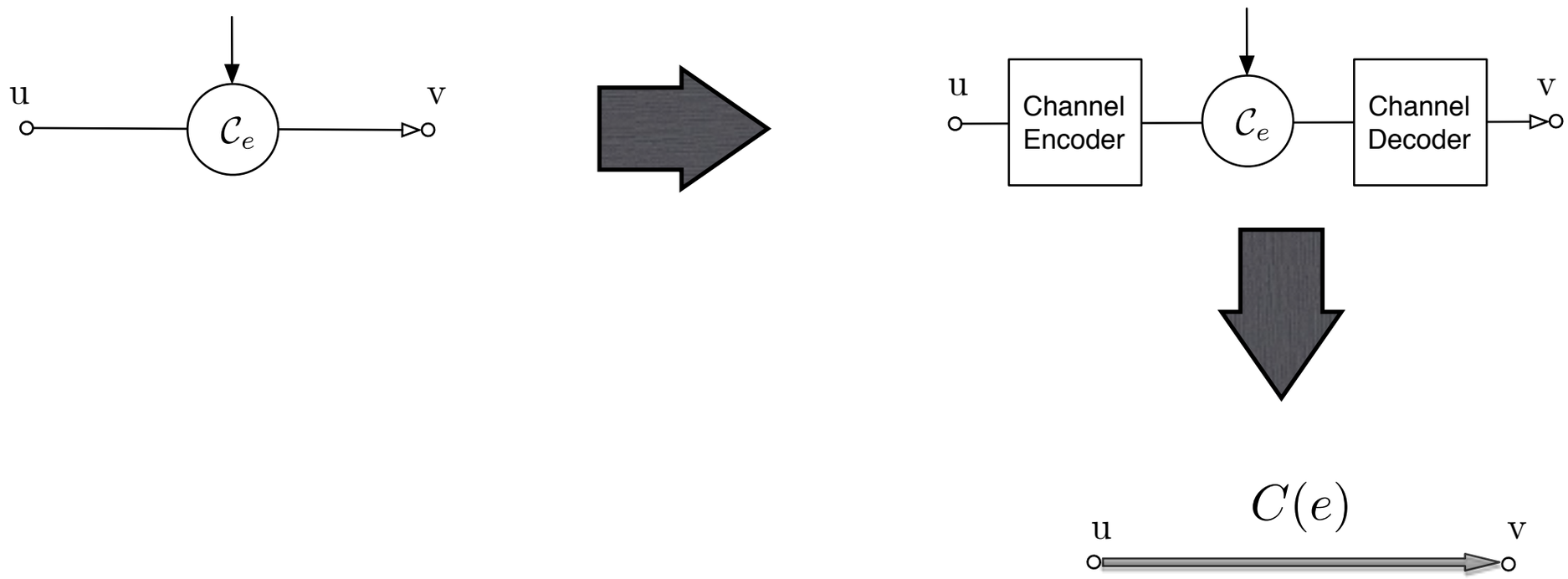
- Noisy problem harder to deal with

- Separating channel coding and network coding gives achievable schemes!

Separating network and channel coding



Step 1: Channel code on each link



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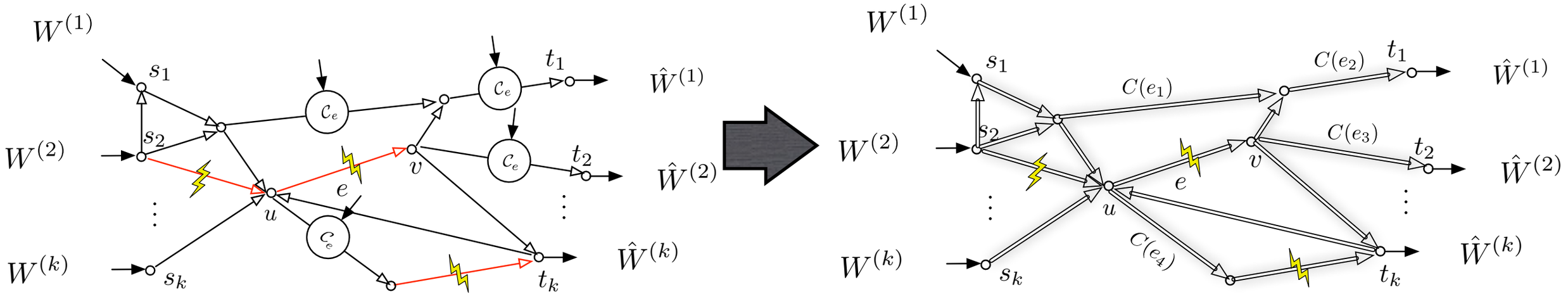
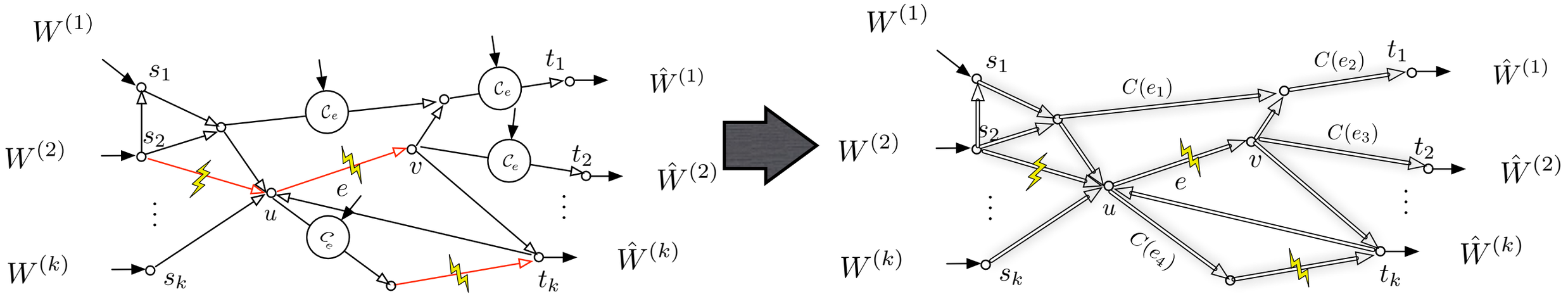


Step 1: Channel code on each link

Step 2: Network code for noiseless network => network code for noisy network

Separating network and channel coding

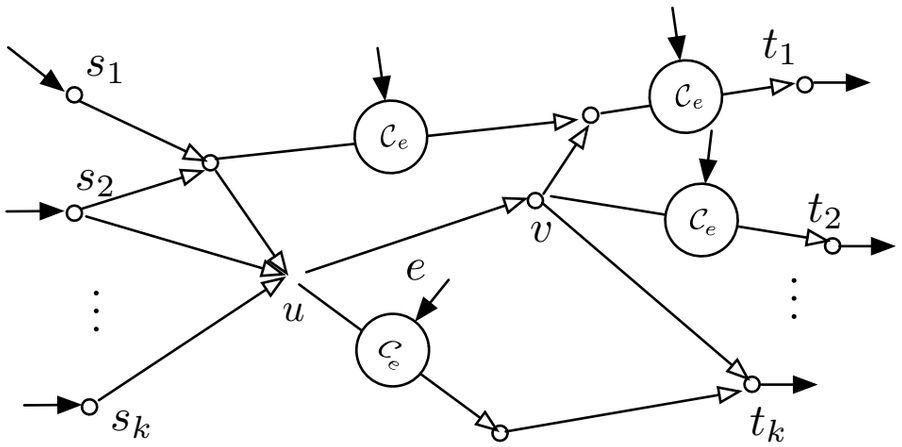


Step 1: Channel code on each link

Step 2: Network code for noiseless network => network code for noisy network

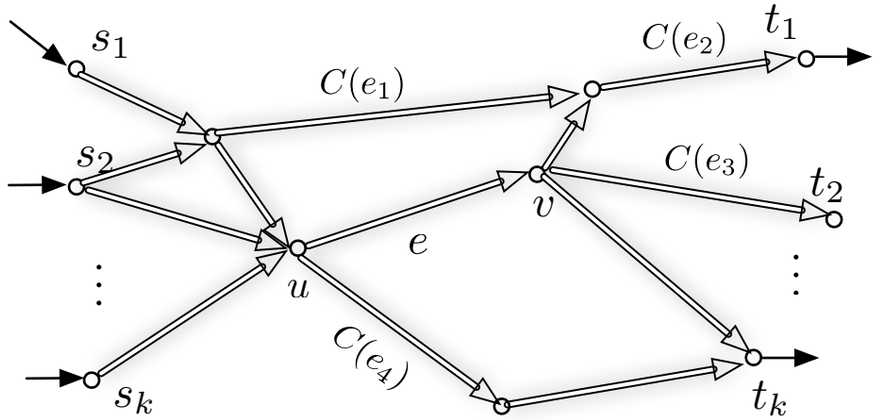
=> Achievable rate vectors for noisy networks

Separating network and channel coding



$\mathcal{N}$

≡



$\hat{\mathcal{N}}$

Noisy network *Noiseless network*

$$\mathcal{R}(\mathcal{N}, 0) = \mathcal{R}(\hat{\mathcal{N}}, 0)$$

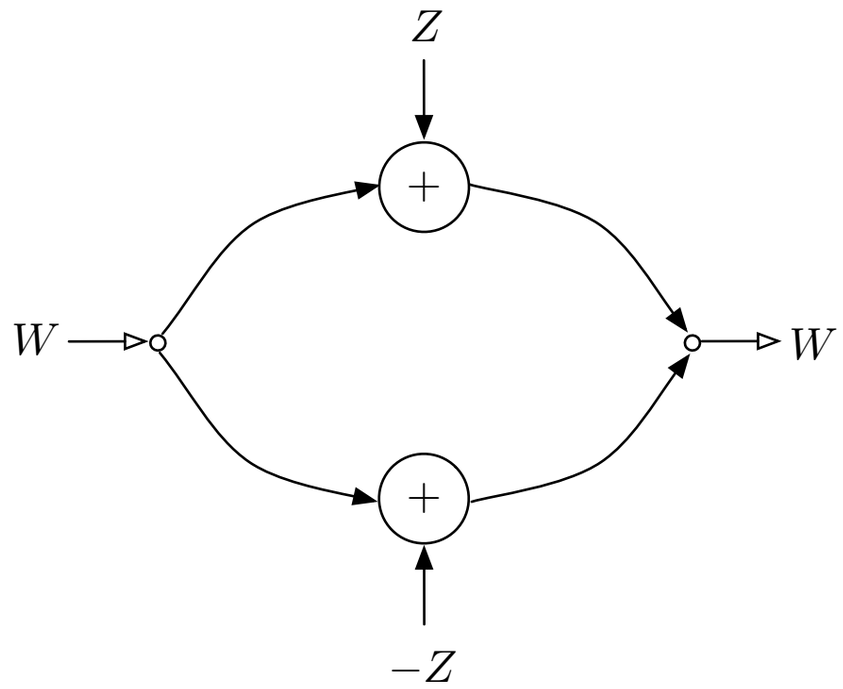
- Separation holds between network coding and channel coding for **independent** channels

- Networks with links of same capacities are "**equivalent**"

[Song, Yeung, Cai ' 2006] for single source multicast
[Koetter, Effros, Medard ' 2011] for general networks

Separation always optimal?

Parallel AWGNs [Koetter et al 2011]



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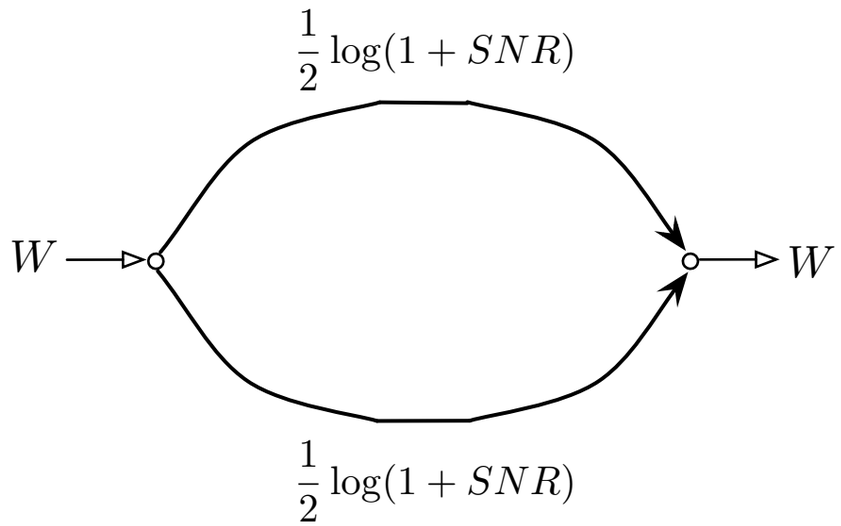

- Separate coding on each link achieves at most $\log(1+SNR)$

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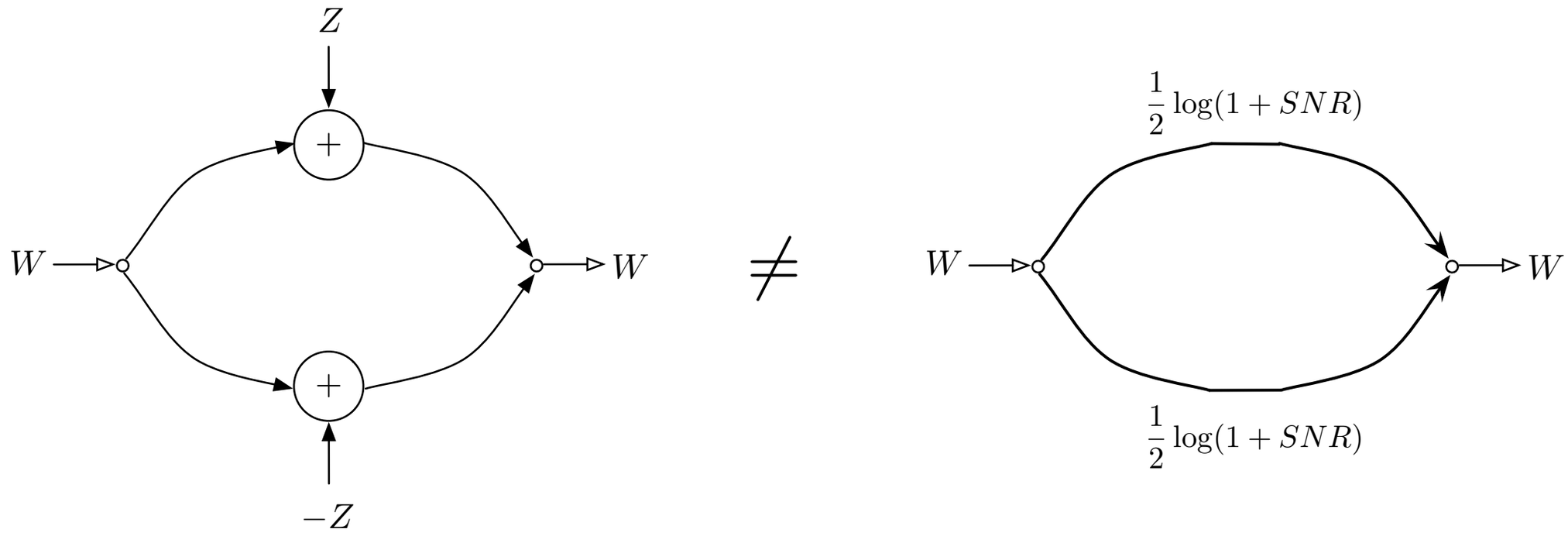


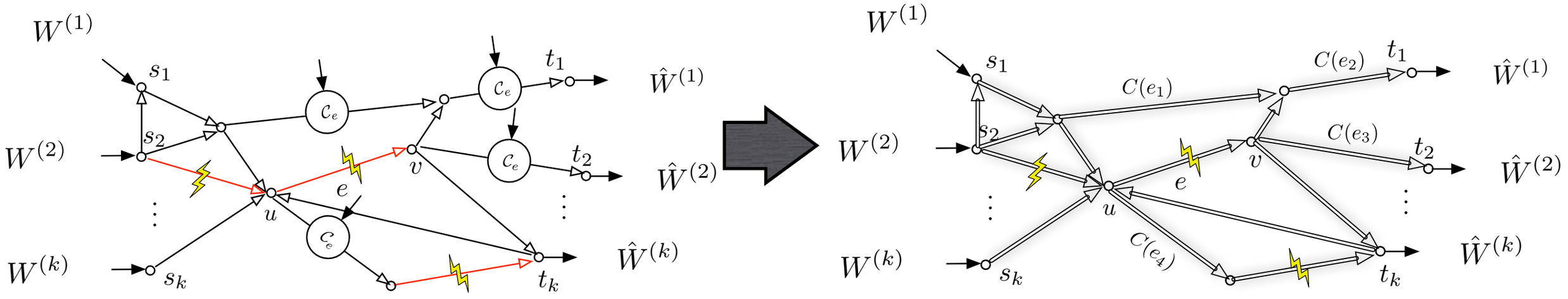
- Separate coding on each link achieves at most $\log(1+SNR)$

- Receiver can “cancel out” noise by adding the two received vectors

- Capacity is infinite

Separation may be **suboptimal** when channels **not independent**!

Separating network and channel coding



Step 1: Channel code on each link

Step 2: Network code for noiseless network => network code for noisy network

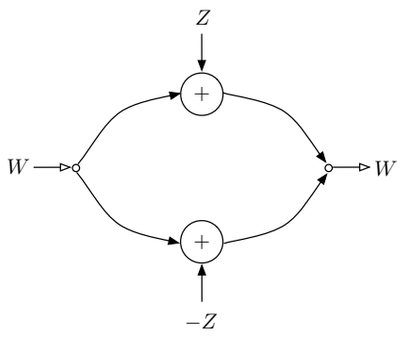
=> Achievable rate vectors for noisy networks

Possible problem: Adversarial noise is not independent on different edges

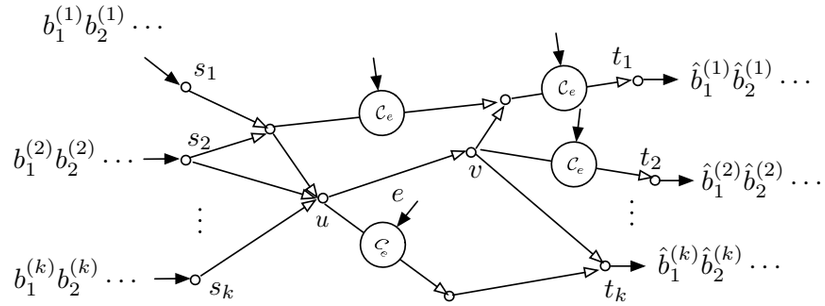
Separation suboptimal

Separation optimal

Networks with jointly distributed noise



Networks of independent channels



Separation suboptimal

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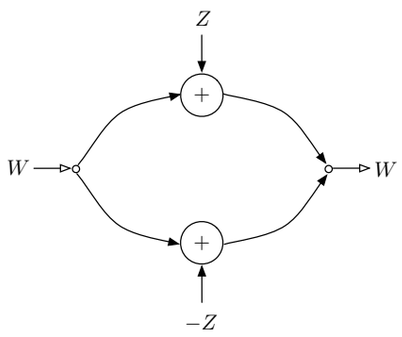
Networks with jointly distributed noise



?

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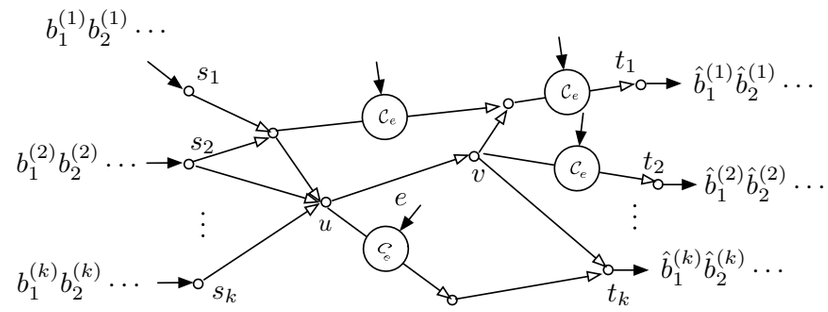
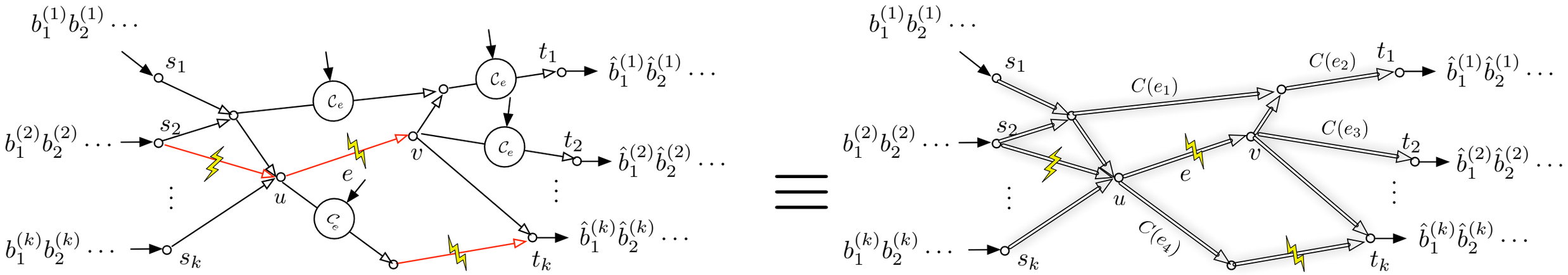


Adversarial Networks?

- independent channels
- adversary may introduce “noise” that is not independent

Our work: Is separation optimal for adversarial networks?

Main Result



$\mathcal{N}$ $\equiv$ $\hat{\mathcal{N}}$

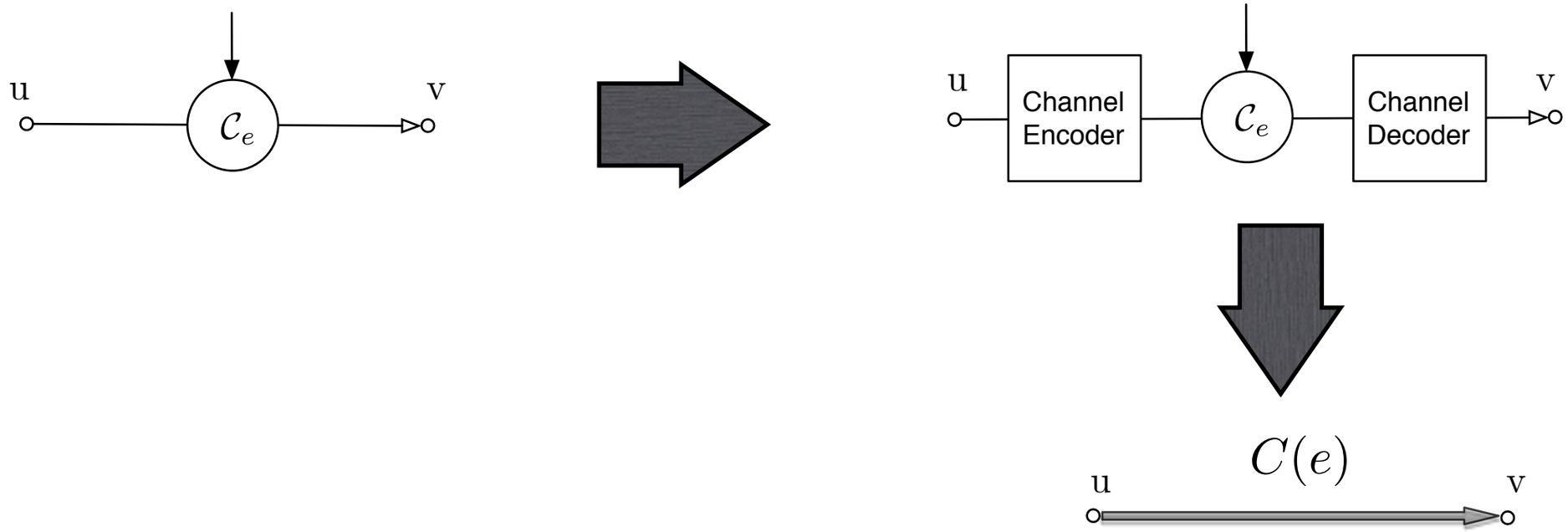
Noisy network *Noiseless network*

Theorem: $\mathcal{R}(\mathcal{N}, K) = \mathcal{R}(\hat{\mathcal{N}}, K)$

Key Ideas

$\mathcal{R}(\mathcal{N}, K) \supseteq \mathcal{R}(\hat{\mathcal{N}}, K)$: separate network coding and channel coding

Step 1: Channel code on each link



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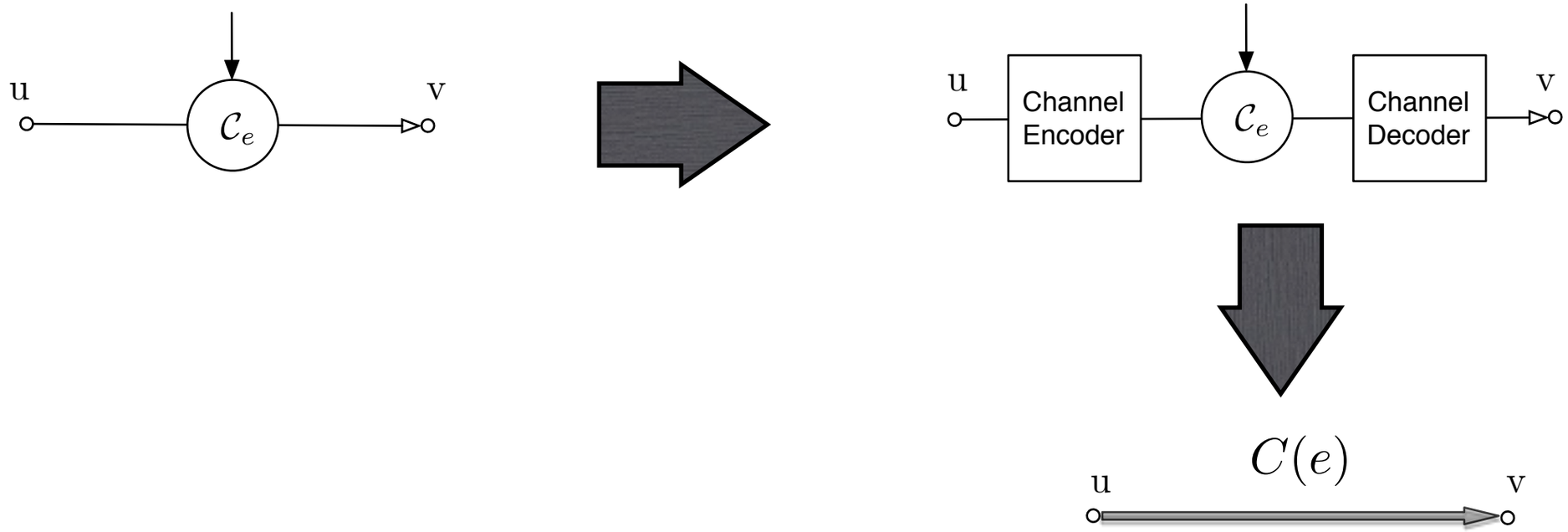

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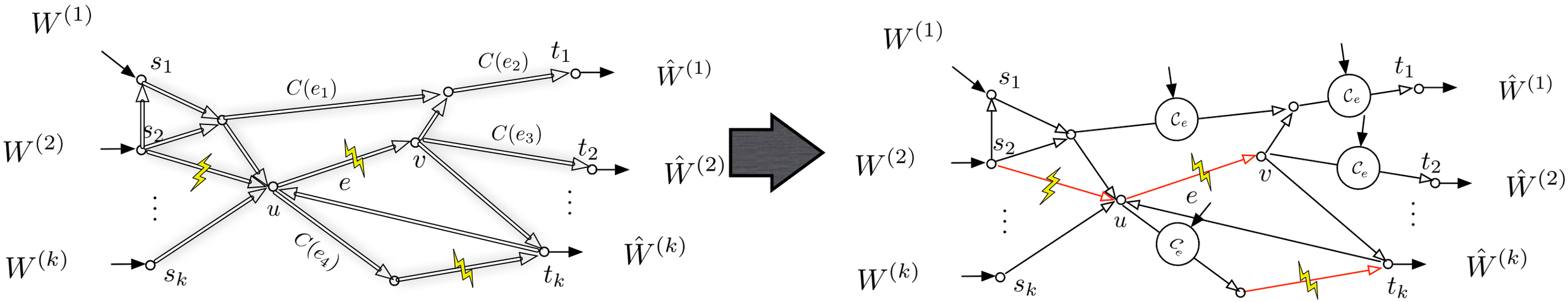

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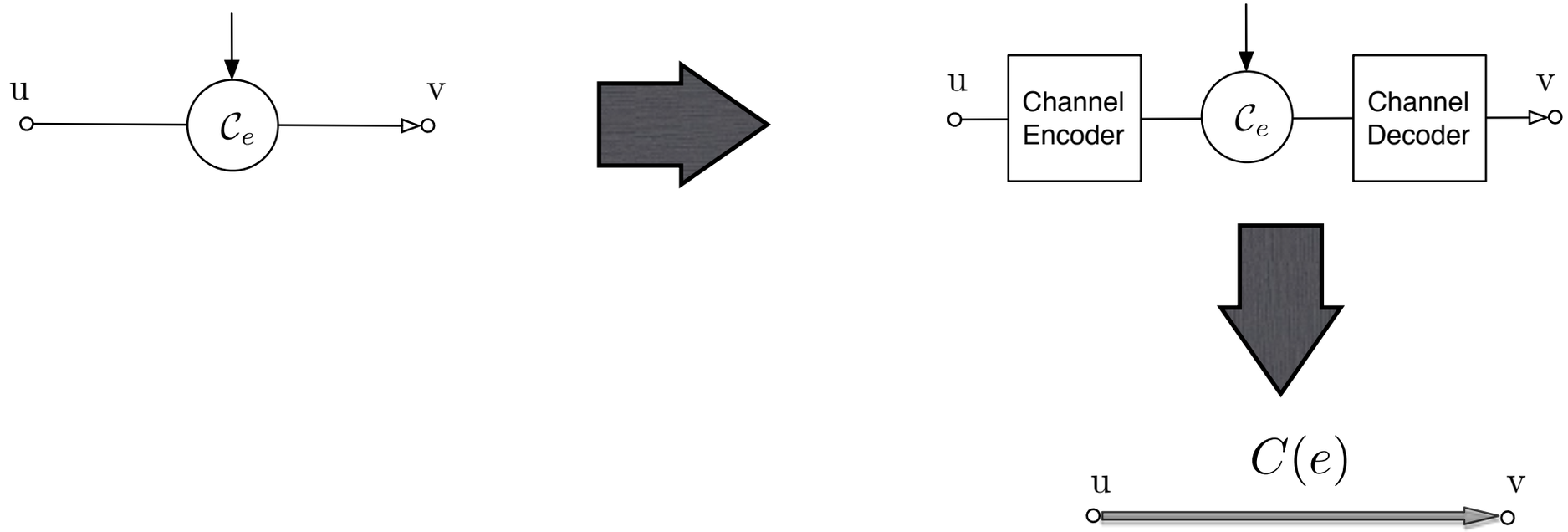

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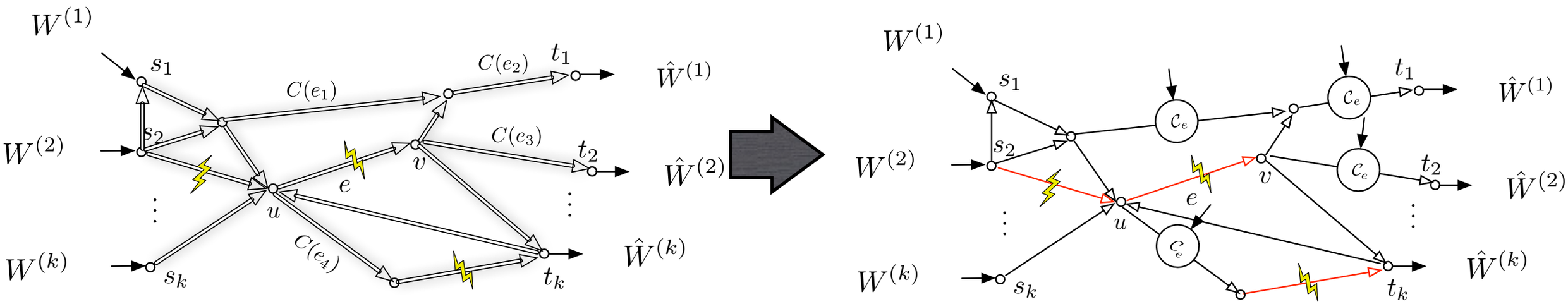


=> $\mathbf{R} \in \mathcal{R}(\hat{\mathcal{N}}, K) \implies \mathbf{R} \in \mathcal{R}(\mathcal{N}, K)$

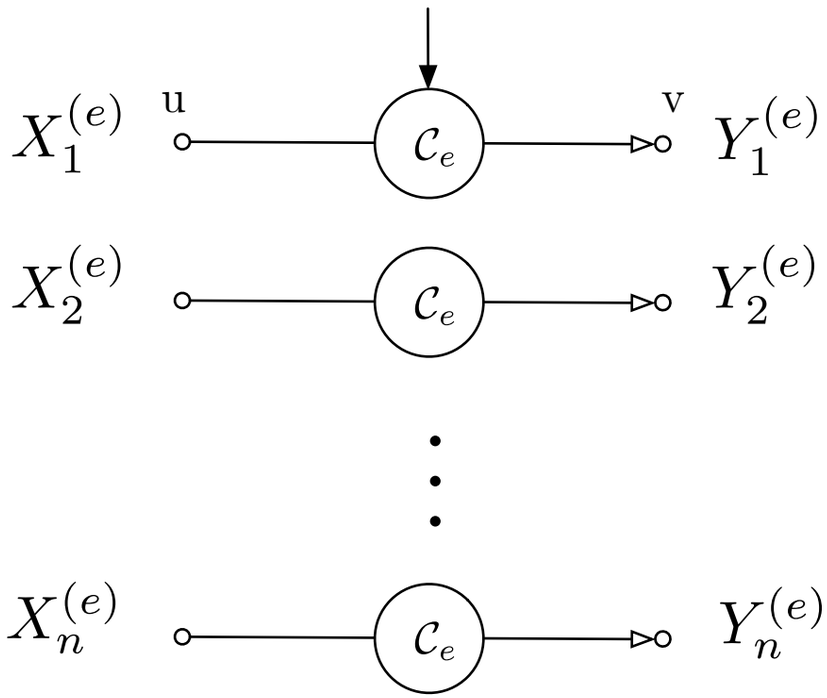
(Same as Koetter et al's proof)

Key Ideas

$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$:

Step 1: "Emulate" channel noise on noiseless links

Channel coding:

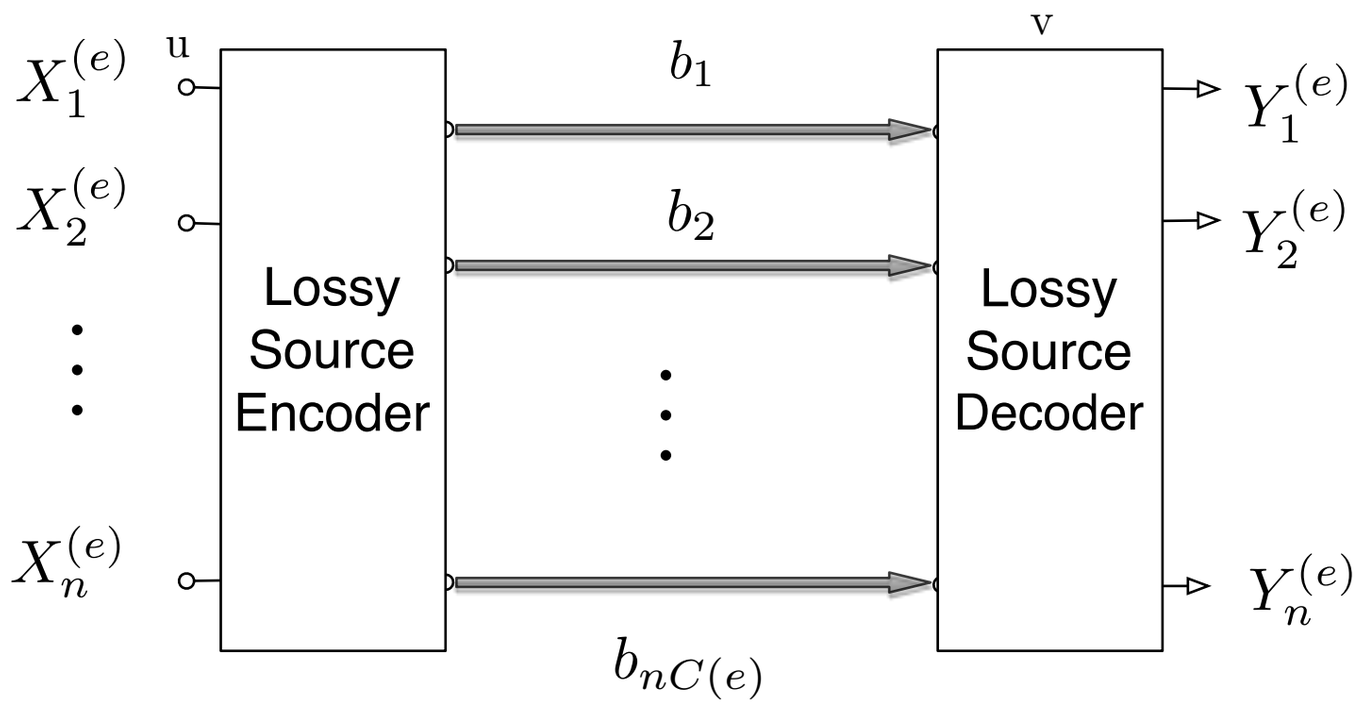


Given: $p(y|x)$

Design: $p(x)$

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

Lossy source coding:



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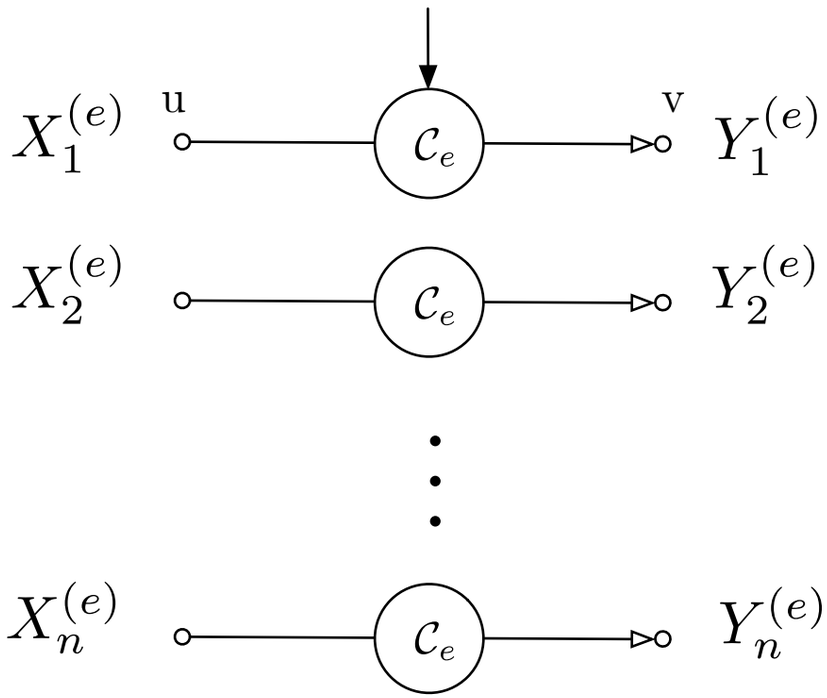

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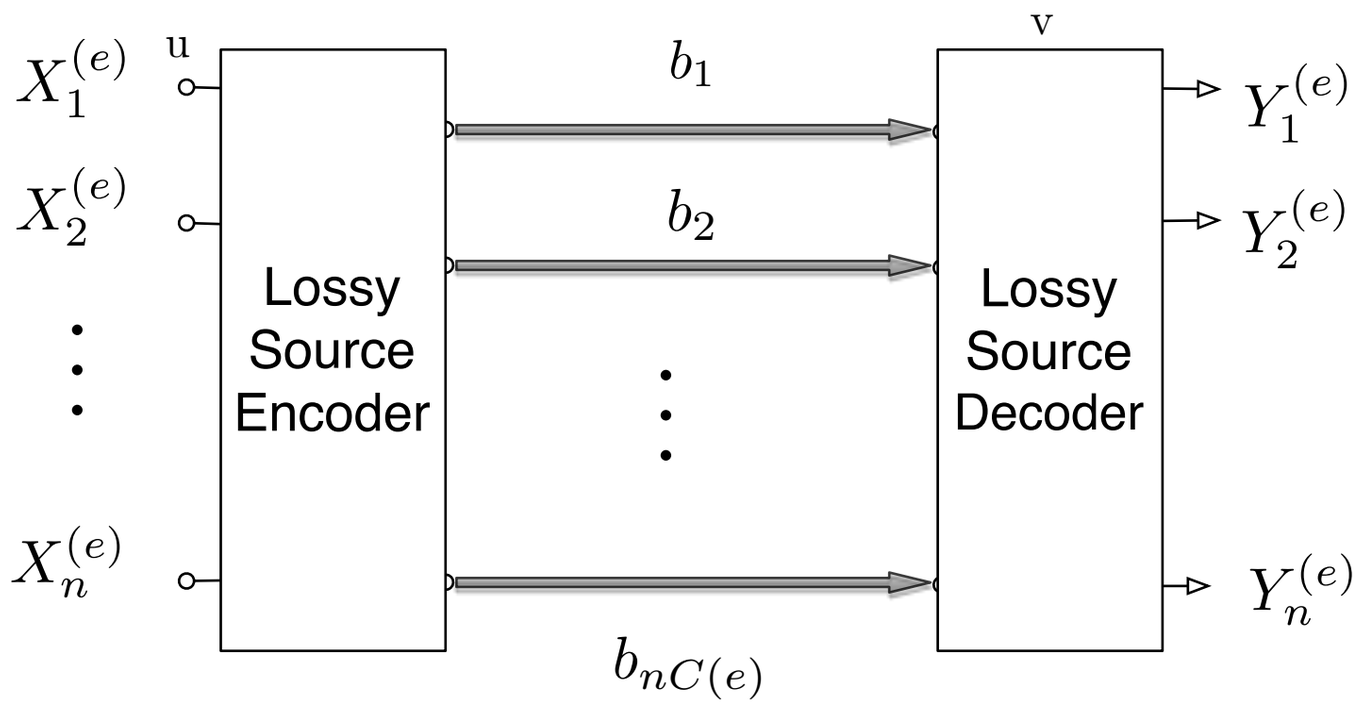

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For a fixed $p(y|x)$, $R = I(X^{(e)}; Y^{(e)})$

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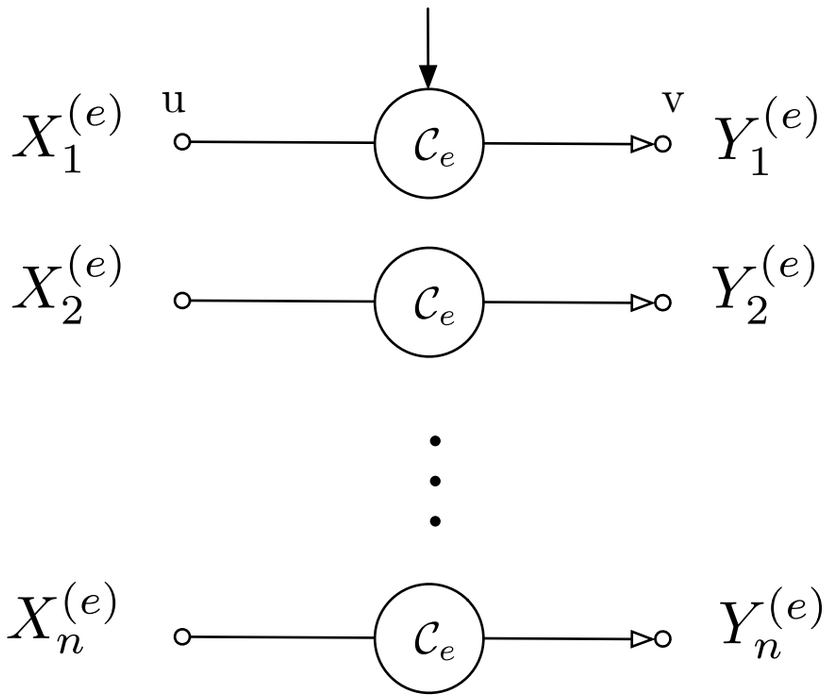

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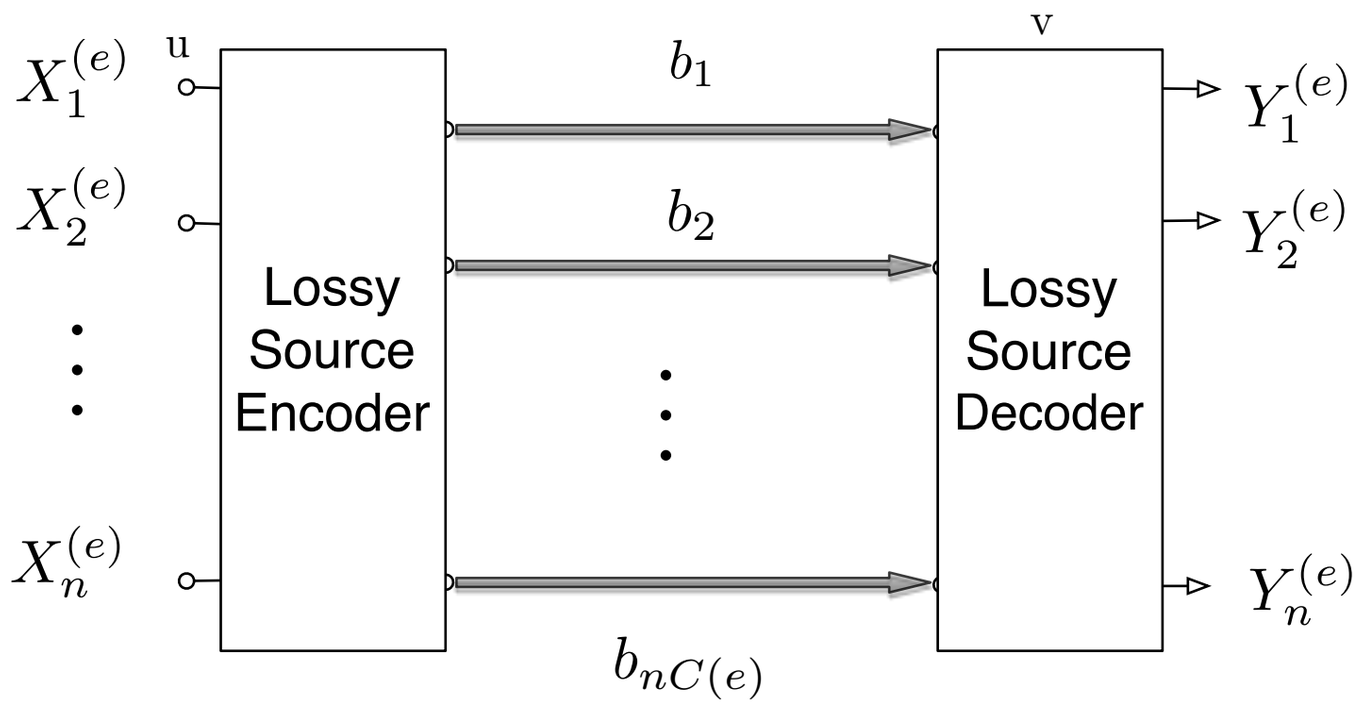

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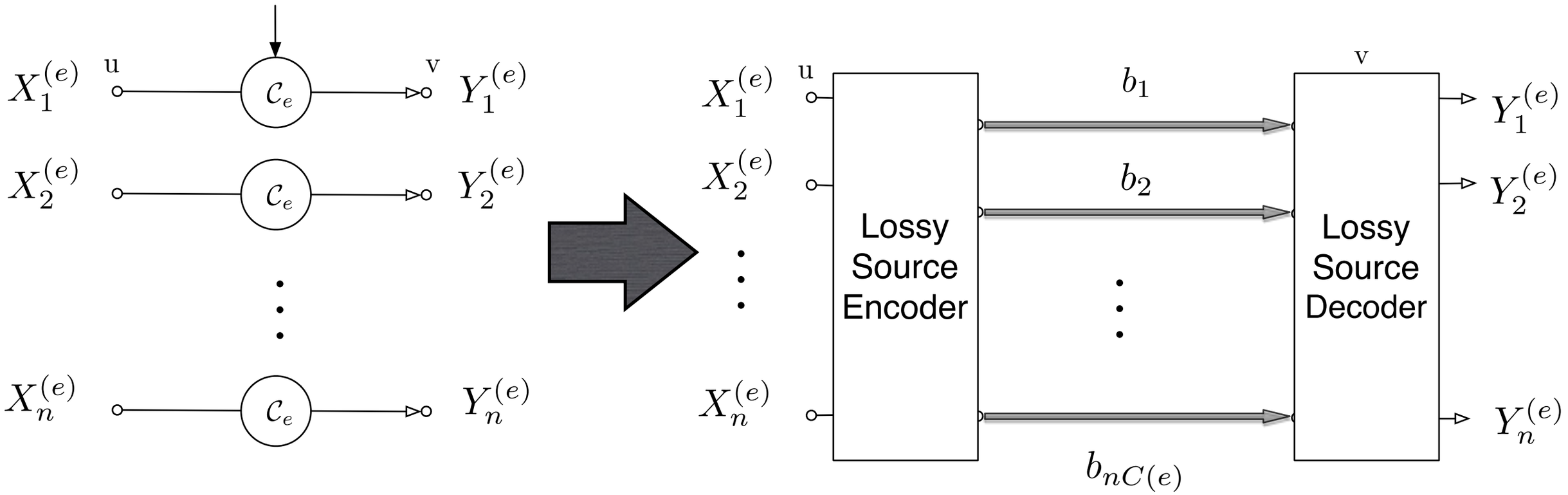
For a fixed $p(y|x)$, $R = I(X^{(e)}; Y^{(e)}) \leq C$

Emulating channel noise



Noisy channel

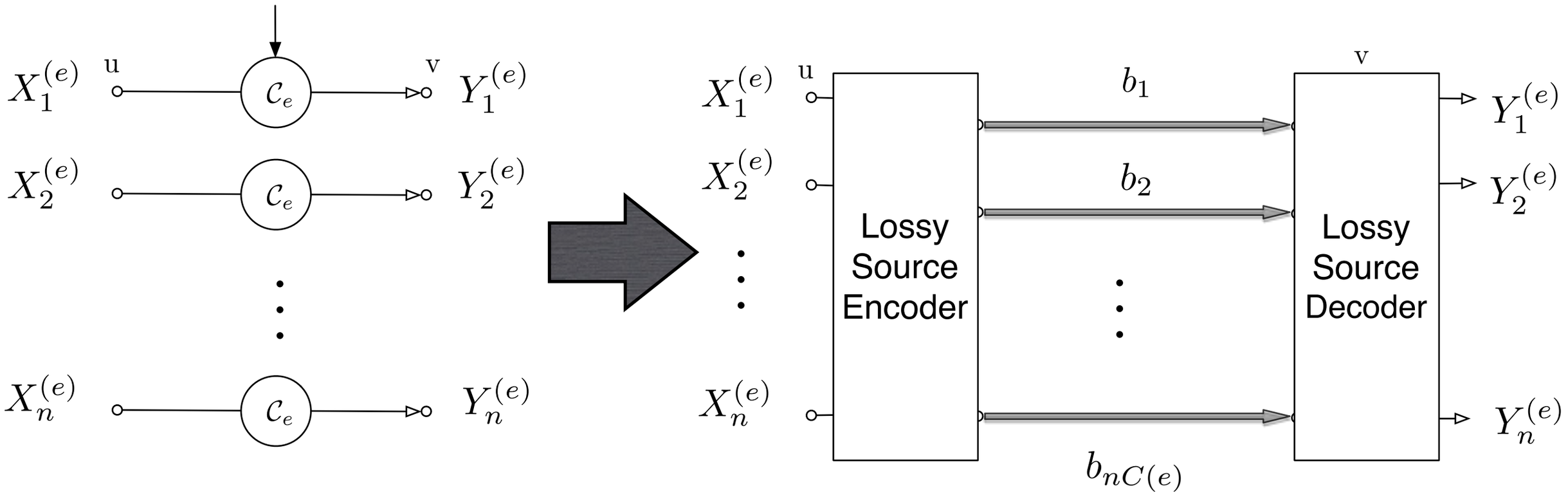
Noiseless channel

- mimic channel transition probability $p_e(y|x)$

- random codebook $p(y) = \sum_x p(x)p(y|x)$

- map input to a typical codeword from the Lossy Source Code according to joint distribution $p(x)p_e(y|x)$

Emulating channel noise



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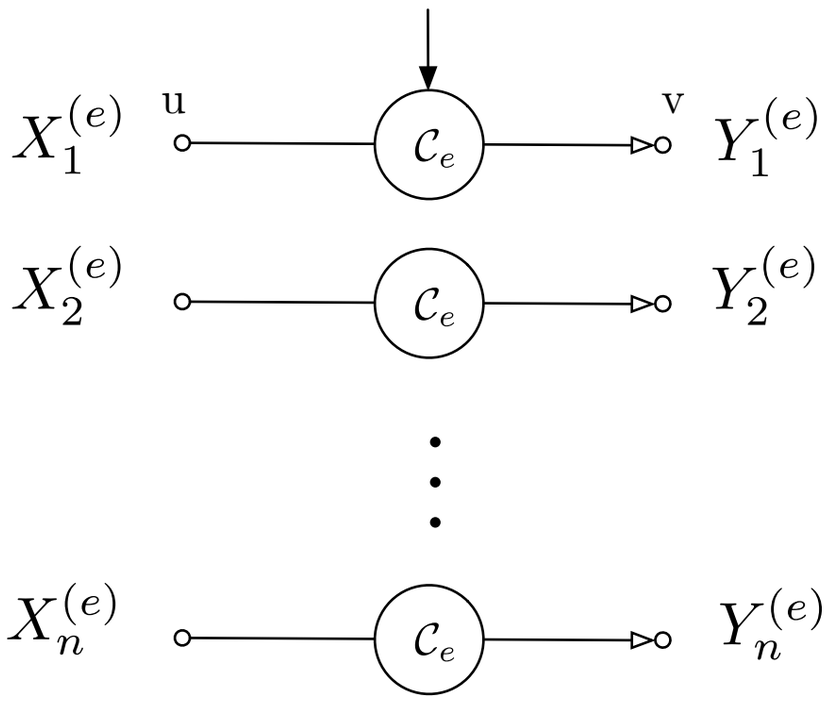
- **Requires input empirical distribution to be close to** $p(x)$

Adversary can control $p(x)$

Emulating channel noise



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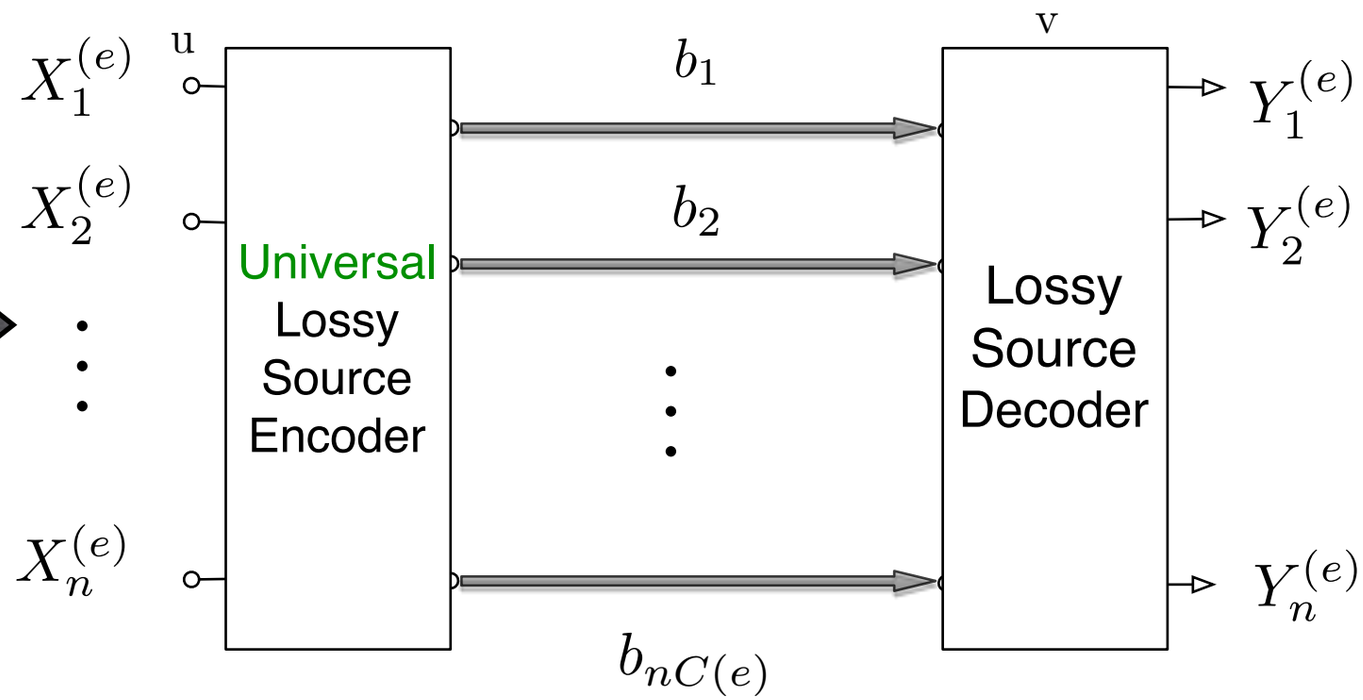
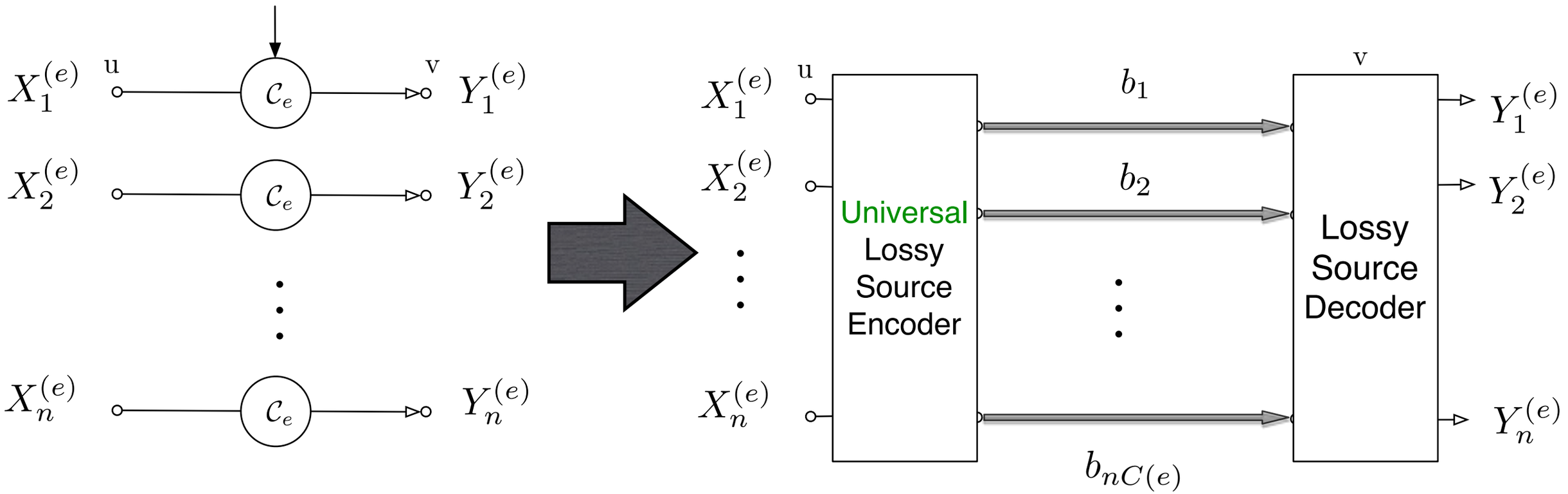


Noiseless channel

- Design different random codebook for each input Type

Emulating channel noise



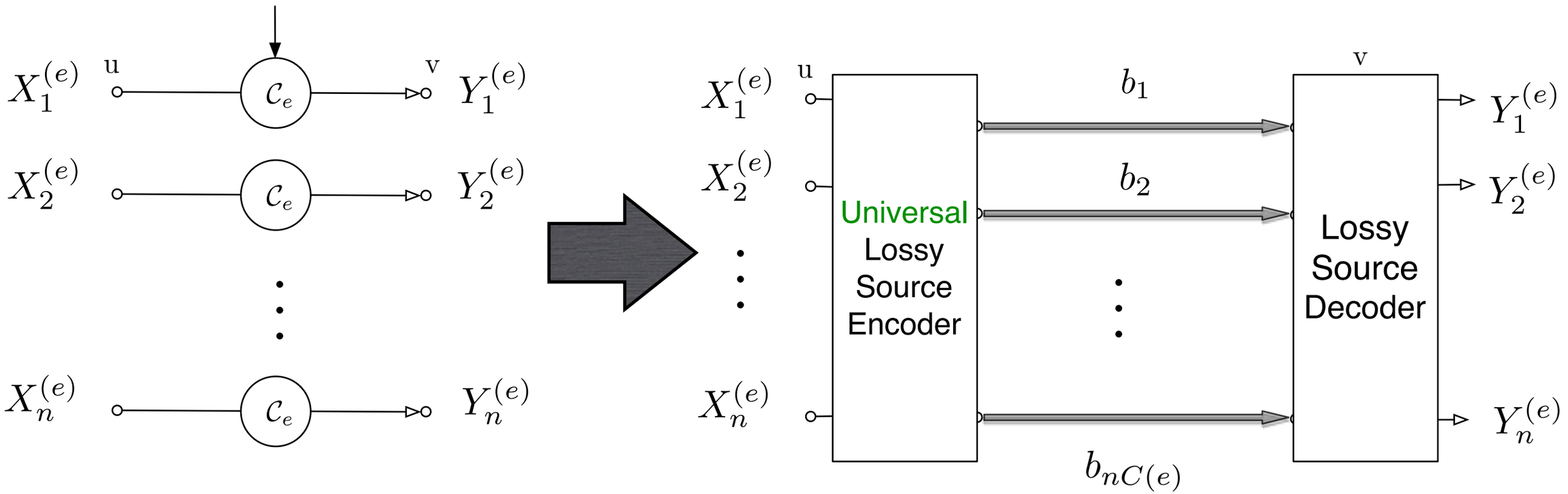
Noisy channel

Noiseless channel

- Design different random codebook for each input Type

Step 1: Describe empirically observed type

Emulating channel noise



Noisy channel

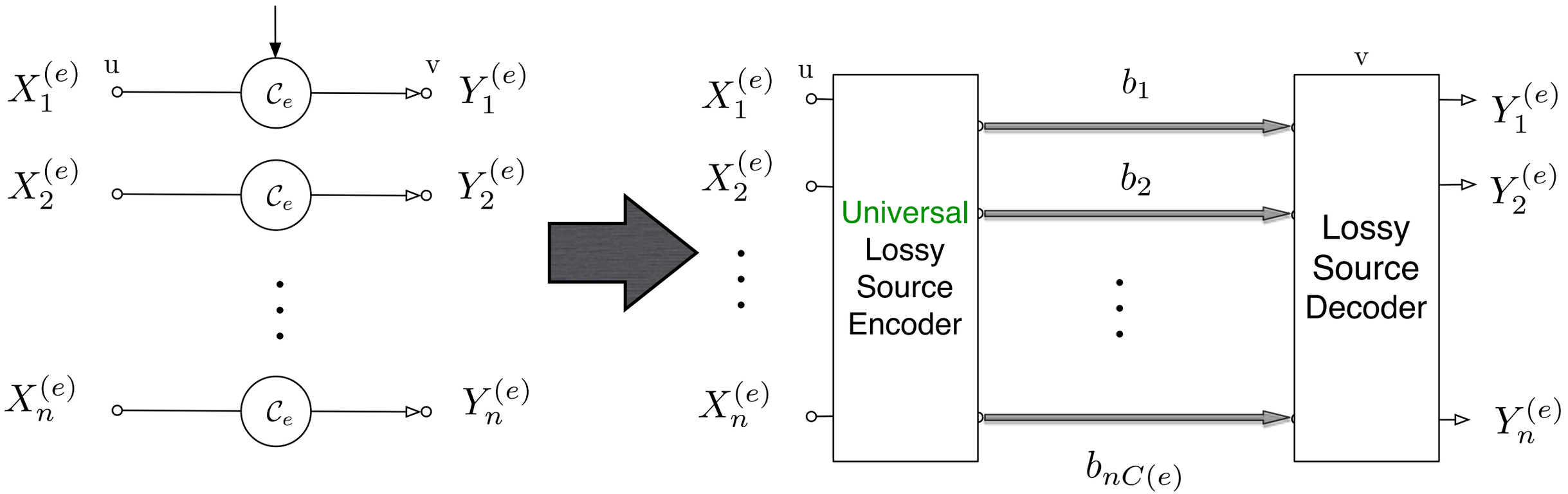
Noiseless channel

- Design different random codebook for each input Type

Step 1: Describe empirically observed type

Step 2: Apply Lossy Source Code designed for the observed type

Emulating channel noise



Noisy channel

Noiseless channel

- Design different random codebook for each input Type

Step 1: Describe empirically observed type

Step 2: Apply Lossy Source Code designed for the observed type

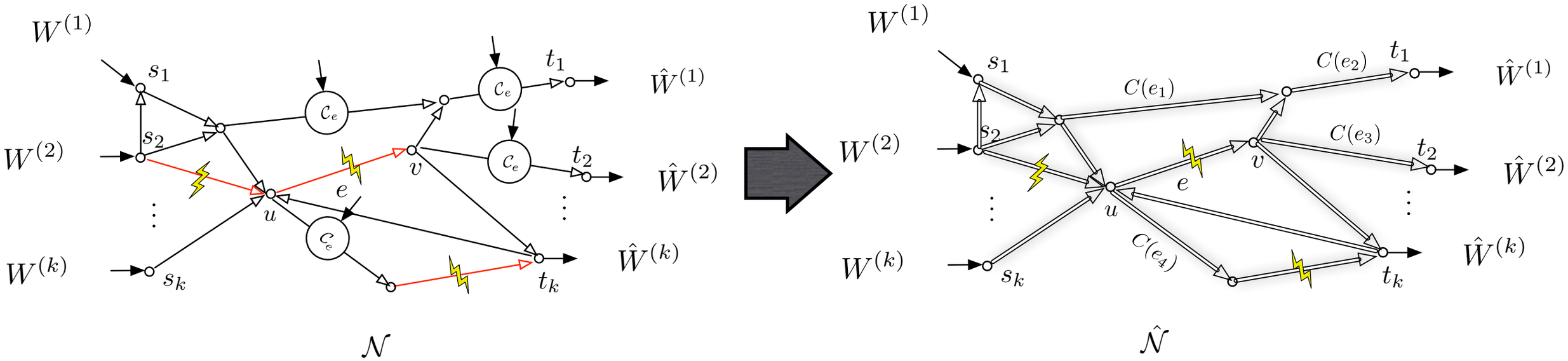
- **Works for all input distributions**

Key Ideas

$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$:

Step 1: "Emulate" channel noise on noiseless links

Step 2: **Operate a code for noisy network on the noiseless network by channel emulation**



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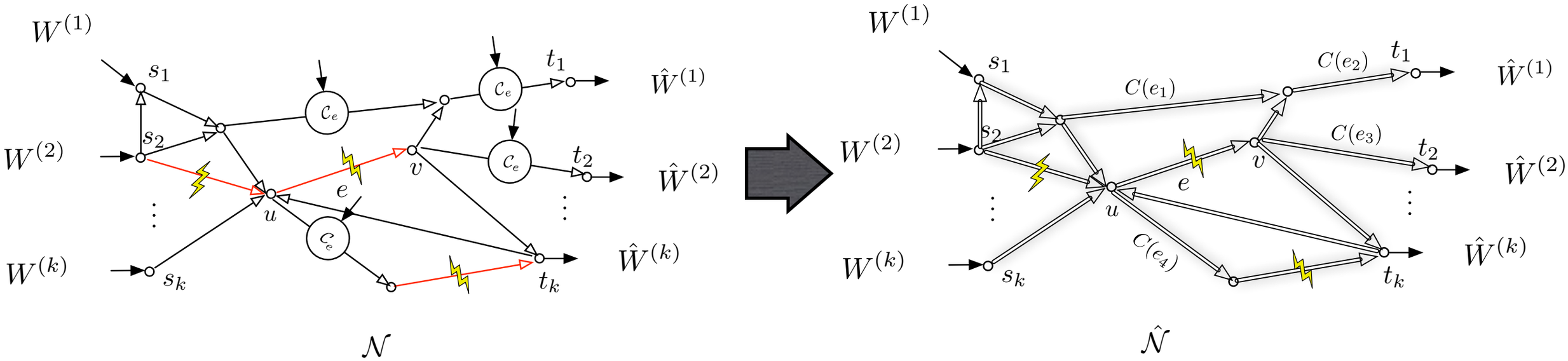

$$\Pr(\text{error}, \hat{\mathcal{N}}) \leq \Pr(\text{error}, \mathcal{N}) \cdot 2^{n\epsilon}$$

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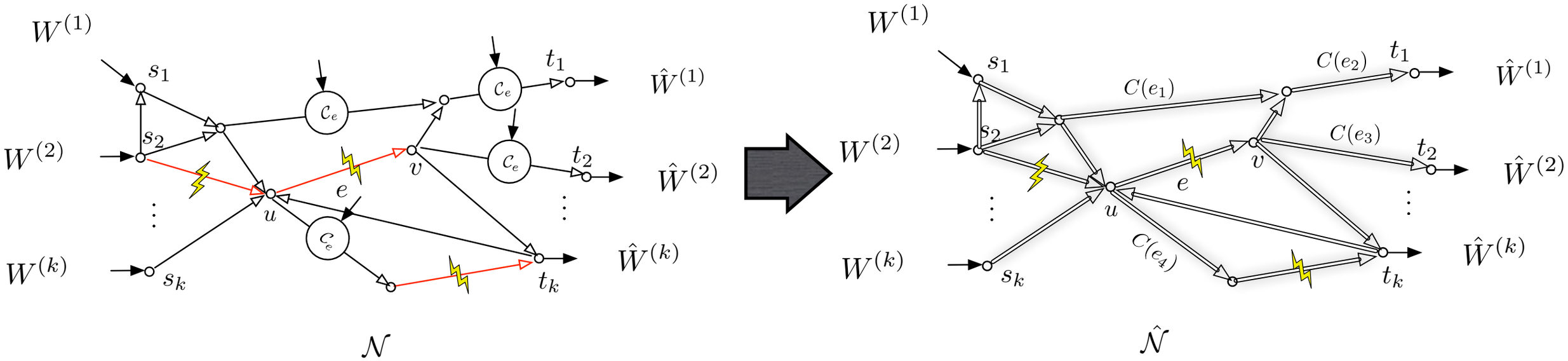
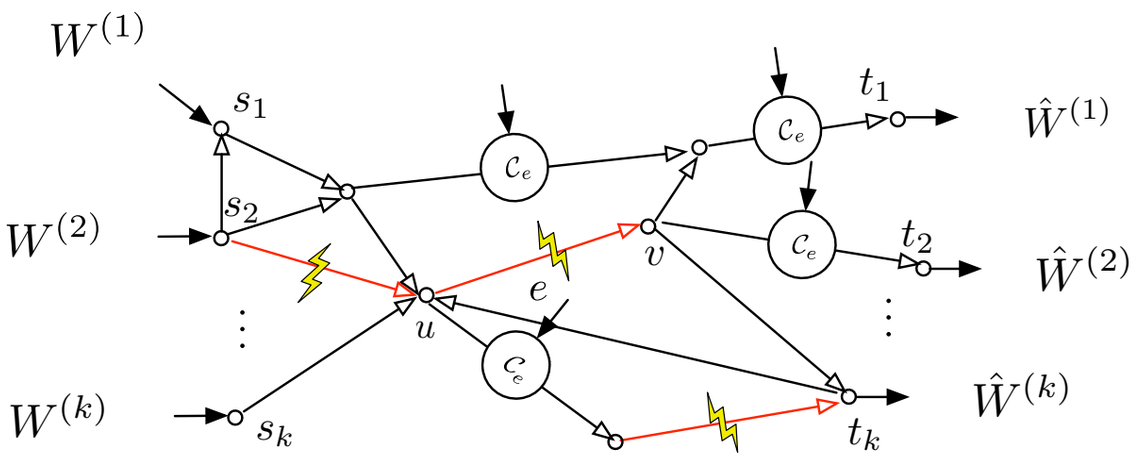


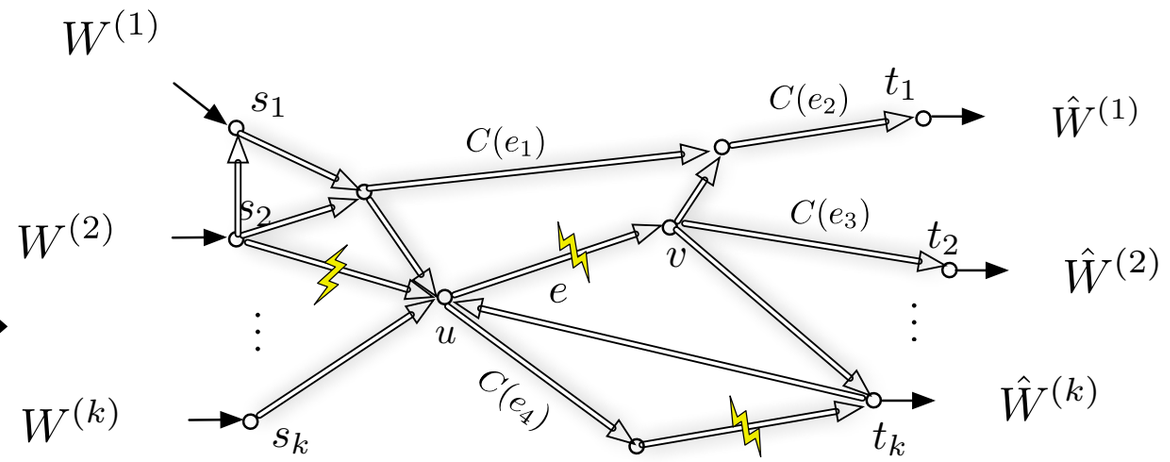
$$\Pr(\text{error}, \hat{\mathcal{N}}) \leq \Pr(\text{error}, \mathcal{N}) \cdot 2^{n\epsilon}$$

- need $\Pr(\text{error}, \mathcal{N}) \leq 2^{-n\delta}$ for some $\delta > \epsilon$

$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$



$\mathcal{N}$



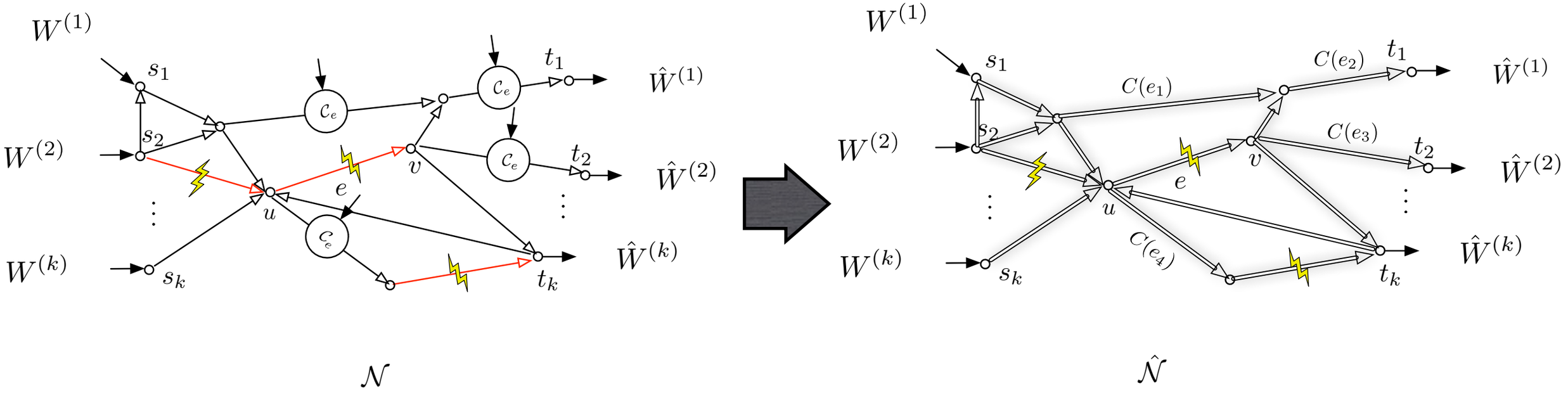
$\hat{\mathcal{N}}$

$$\Pr(\text{error}, \mathcal{N}) \leq 2^{-n\delta}$$

- Given network code of blocklength m s.t. $W^{(i)} \in \{0,1\}^{mR_i}$

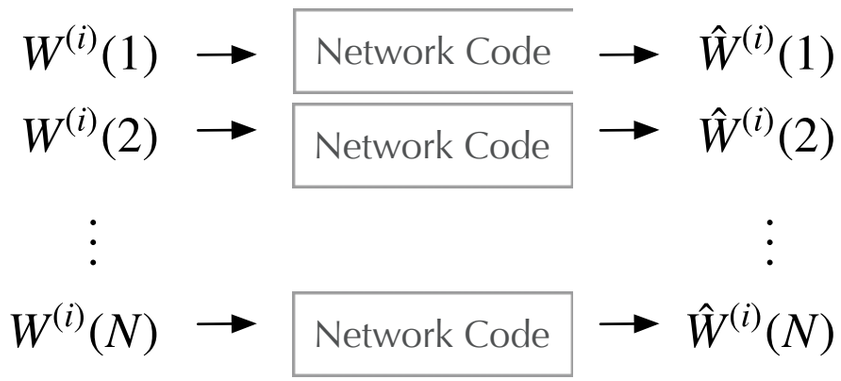
$$W^{(i)} \rightarrow \boxed{\text{Network Code}} \rightarrow \hat{W}^{(i)}$$

$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$

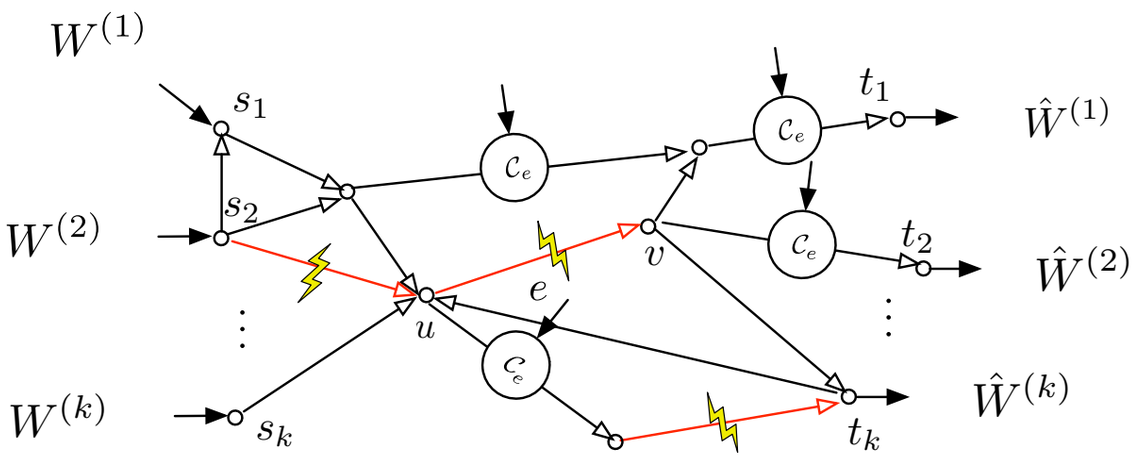


$$\Pr(\text{error}, \mathcal{N}) \leq 2^{-n\delta}$$

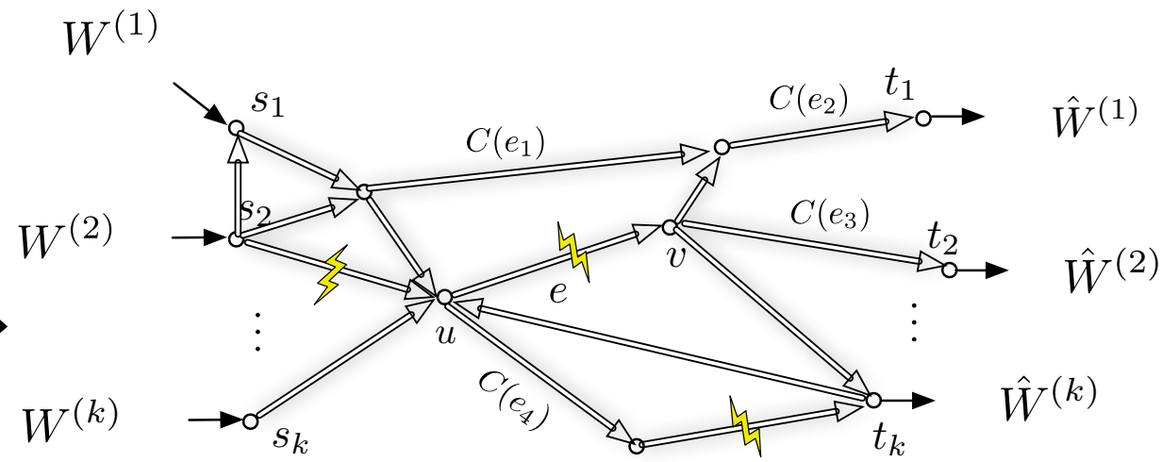
- Given network code of blocklength m s.t. $W^{(i)} \in \{0,1\}^{mR_i}$
- Design code of blocklength mN by concatenation



$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$



$\mathcal{N}$



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$$\Pr(\text{error}, \mathcal{N}) \leq 2^{-n\delta}$$

- Given network code of blocklength m s.t. $W^{(i)} \in \{0,1\}^{mR_i}$
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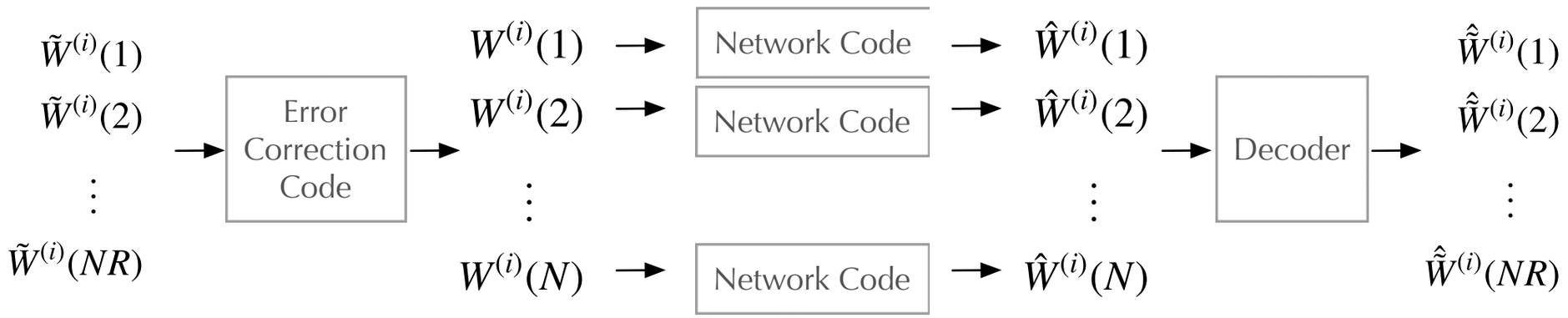
- Add outer code, $R = 1 - \alpha$



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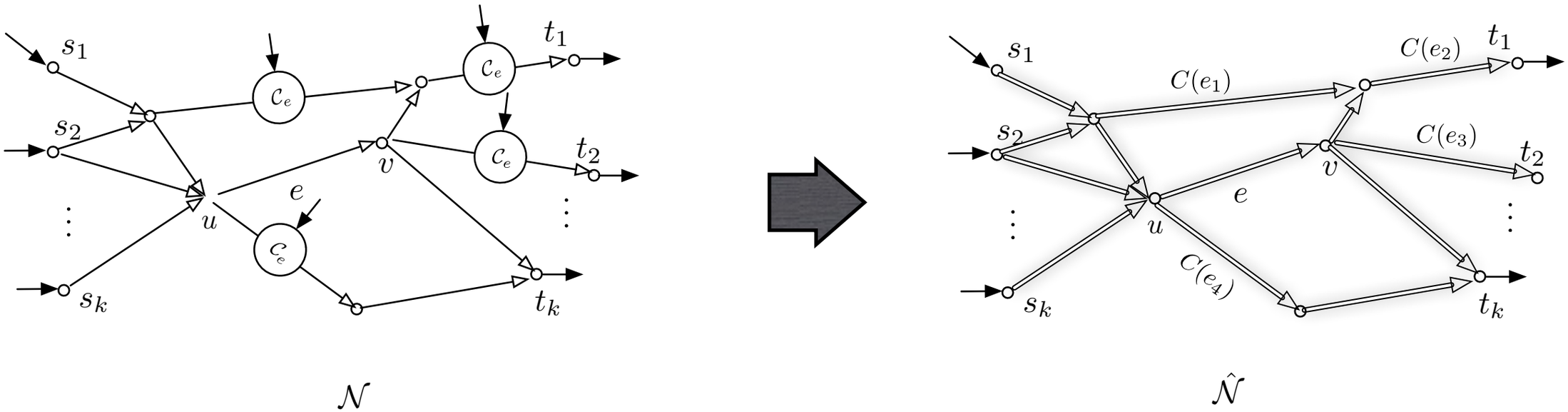

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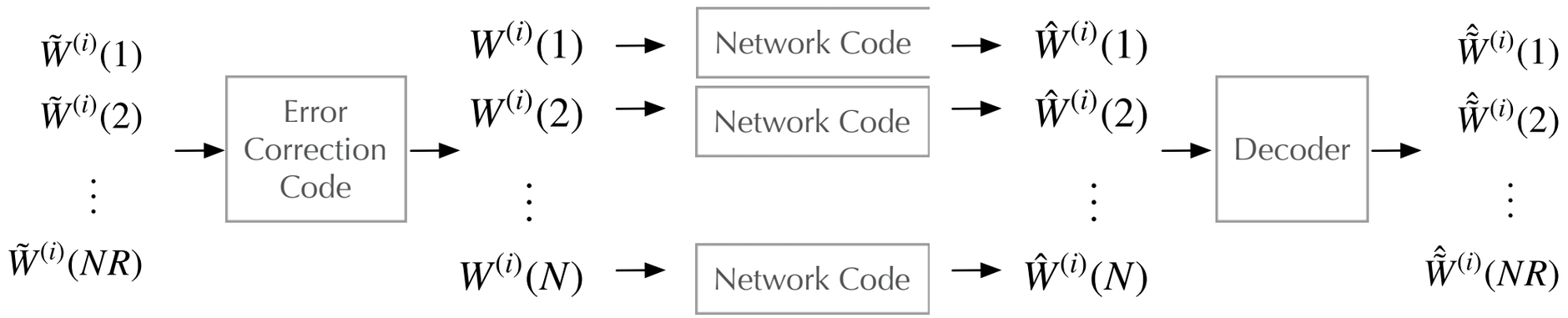

Koetter et al: i.i.d. noise => Gallagher's error exponents/Large Deviations => $\Pr(\text{error}, \mathcal{N}) \leq 2^{-n\delta}$

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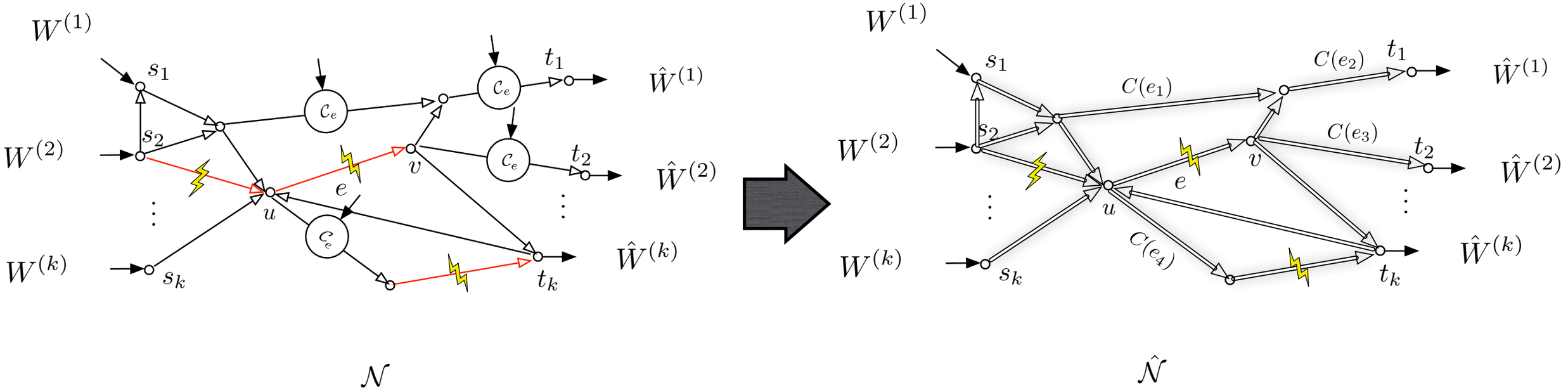

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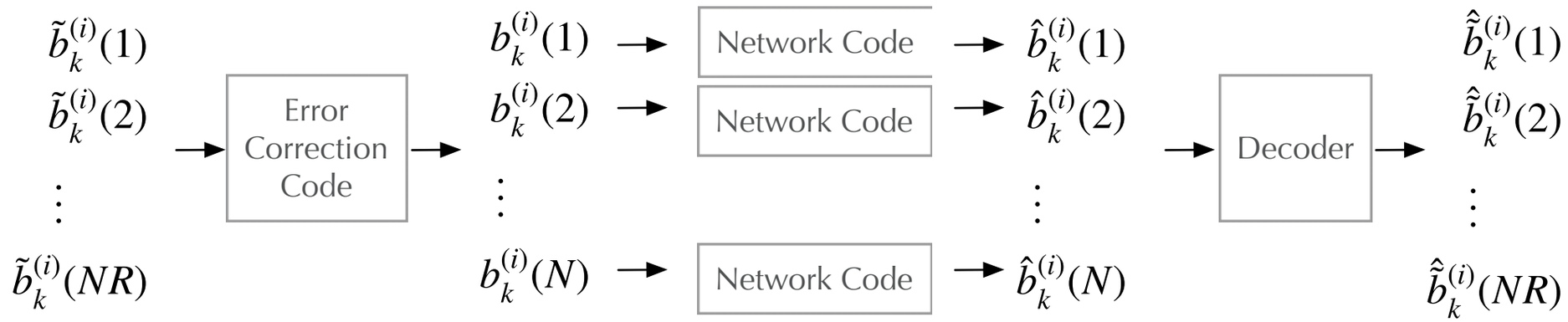

Our proof:

- Each $W^{(i)}(j) = b_1^{(i)}(j), \ldots, b_{mR_i}^{(i)}(j)$

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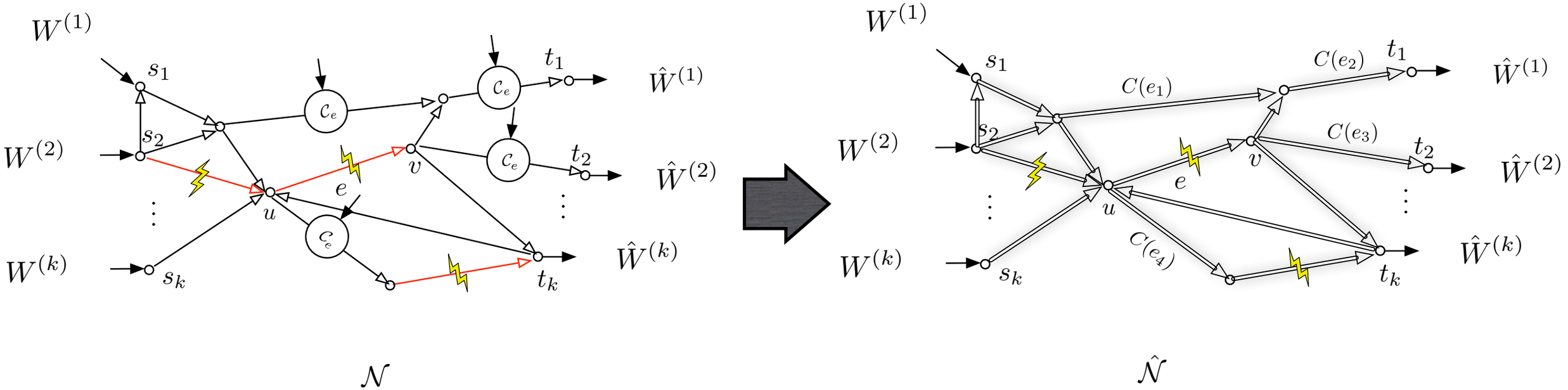

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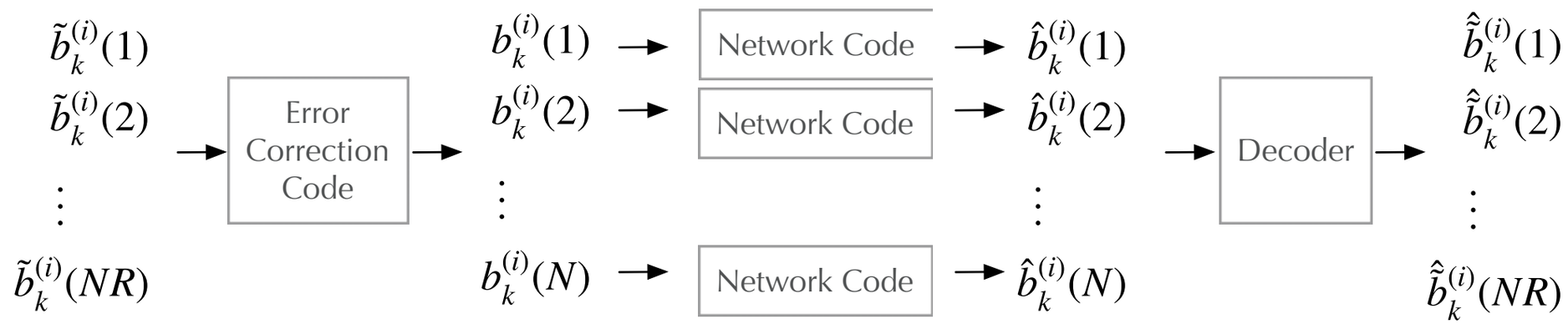

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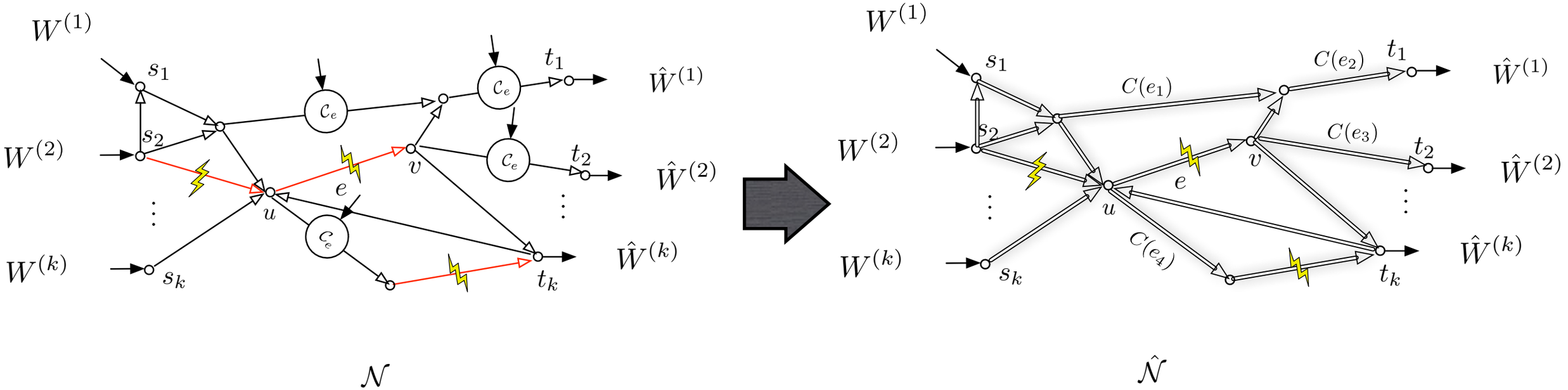

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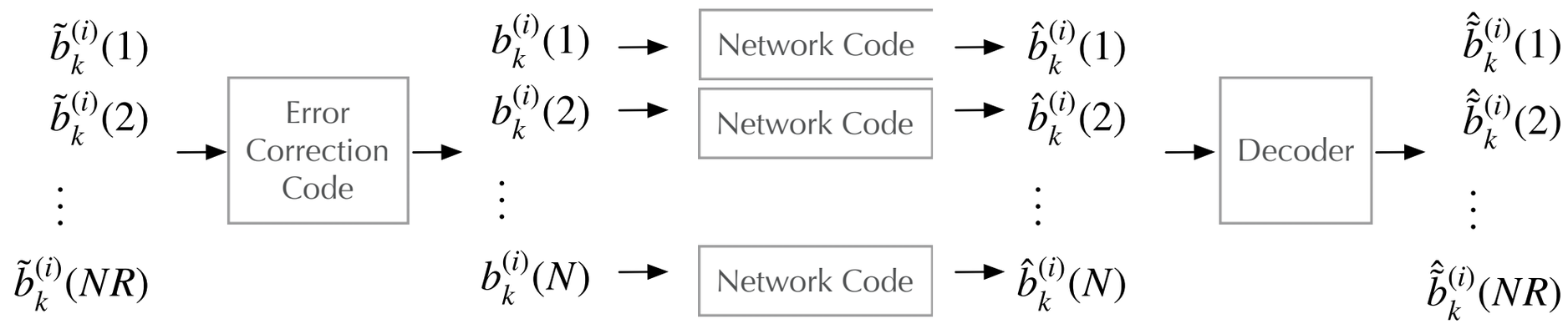

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- Minimum Hamming distance decoding
  - error probability is maximized when adversary acts independently at different time steps
- Upper bound error on probability

in the worst case

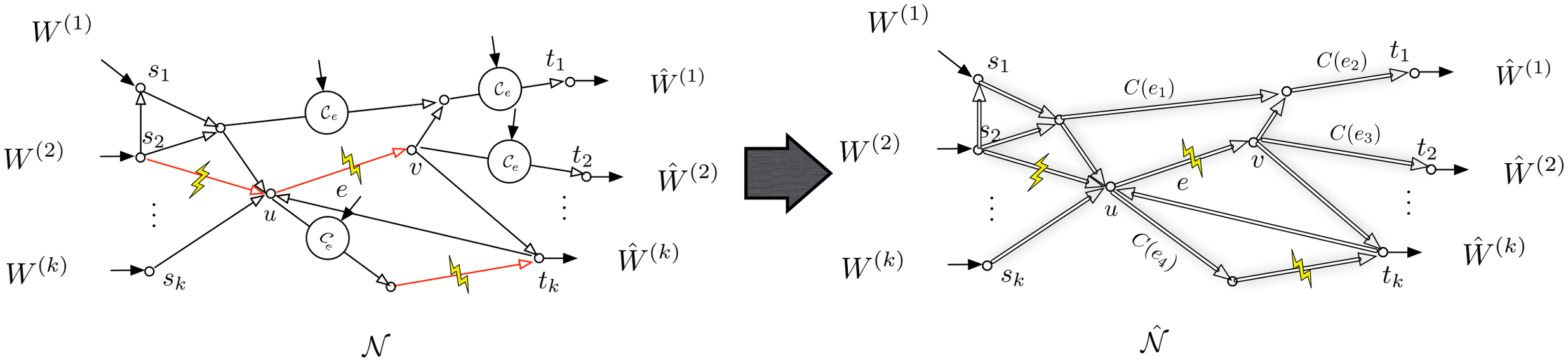
$$P(\underline{W} \neq \underline{\hat{W}}) < 2^{-N\delta}$$

Key Ideas

$\mathcal{R}(\mathcal{N}, K) \subseteq \mathcal{R}(\hat{\mathcal{N}}, K)$:

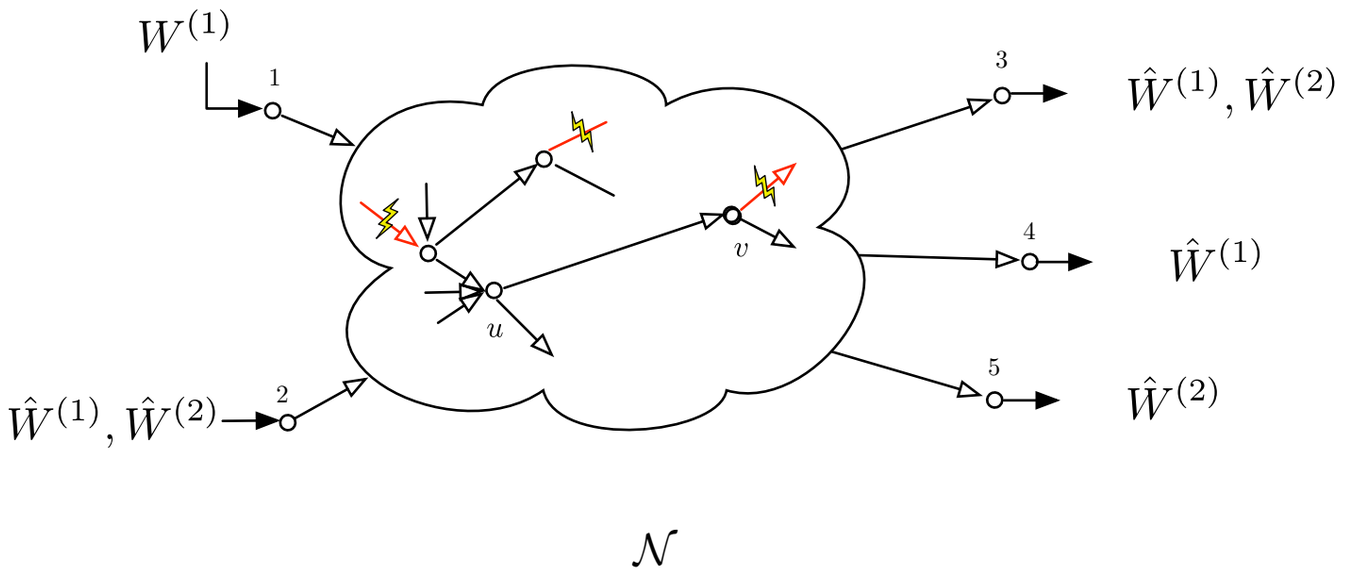
Step 1: "Emulate" channel noise on noiseless links

Step 2: Operate a code for noisy network on the noiseless network by channel emulation



$$\mathbf{R} \in \mathcal{R}(\mathcal{N}, K) \implies \mathbf{R} \in \mathcal{R}(\hat{\mathcal{N}}, K)$$

Generalization



Network:

- Arbitrary demand model (e.g., some unicast, some multicast etc)

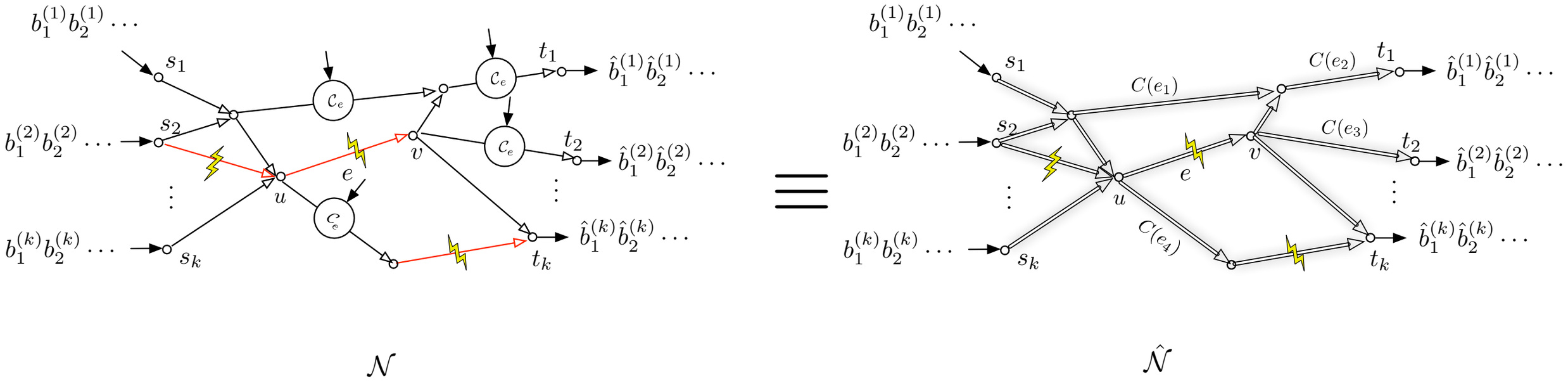
- Channels of arbitrary capacity

Byzantine Adversary:

- can replace received vectors on any edges in any subset σ, where $\sigma \in \mathbf{\Sigma}$, the set of allowed attack sets.

e.g. node-based attacks

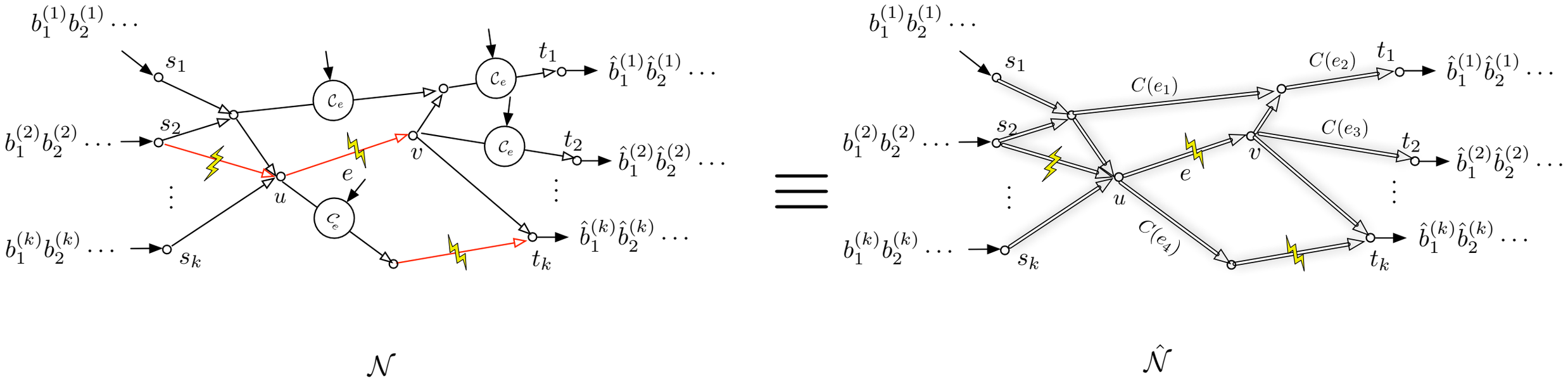
Implications



- Code design: simplifies design of codes

  - channel code for each link
  - network code against adversary

Implications



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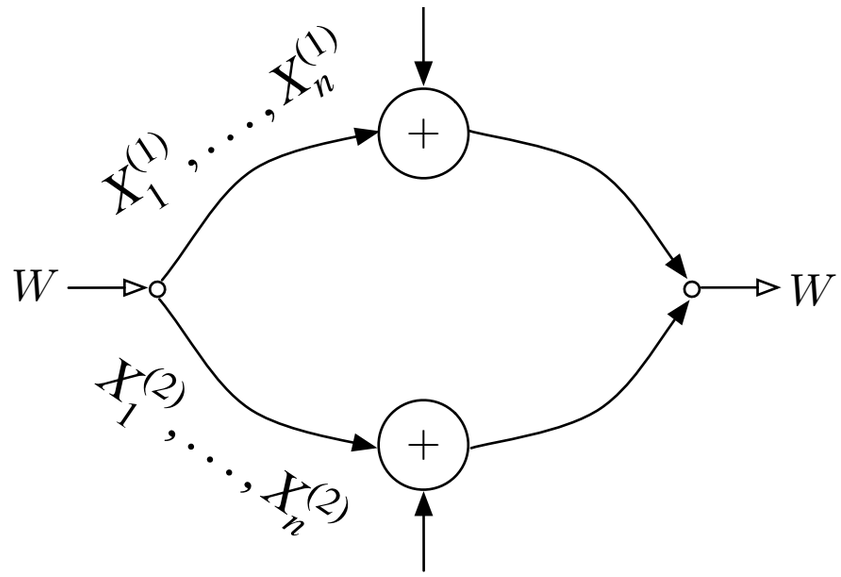
$$W \in \{0,1\}^{nR}$$



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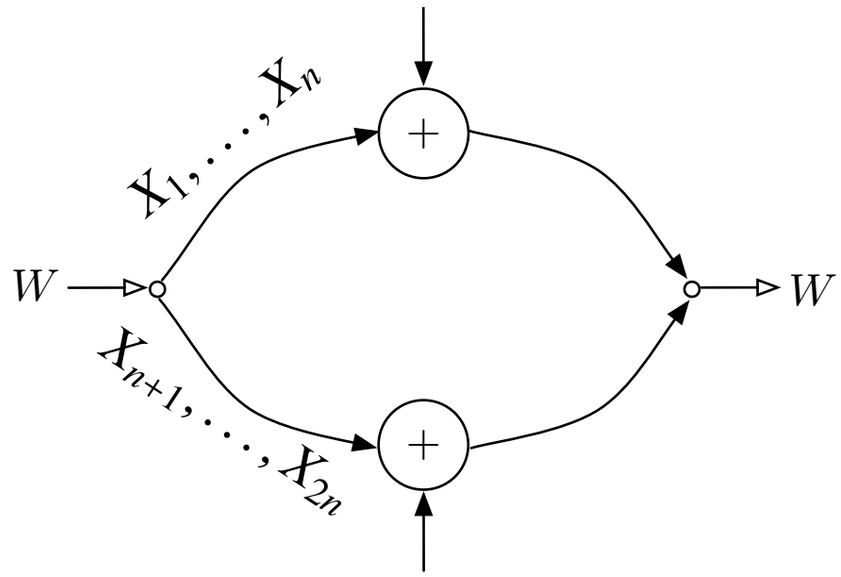

With separation:

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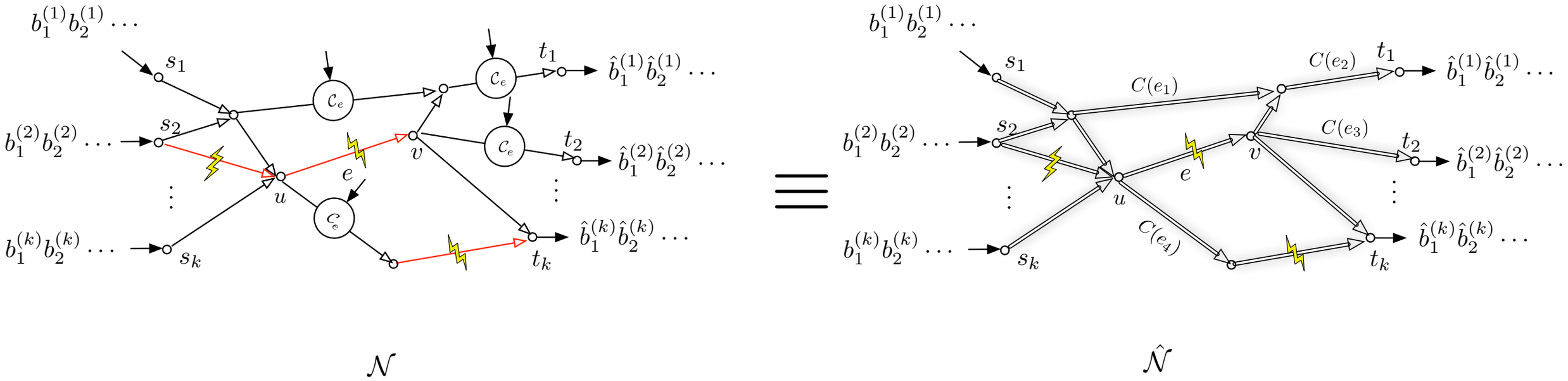
Without separation:

Channel code of length $2n$ can be used

$$\Pr(error) \sim 2^{-2n\delta}$$

Implications



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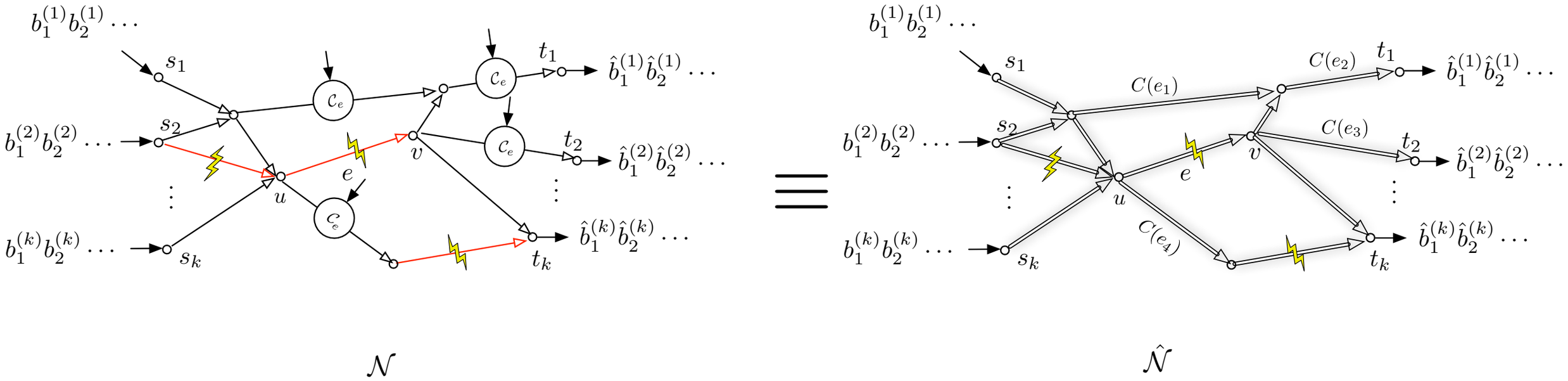

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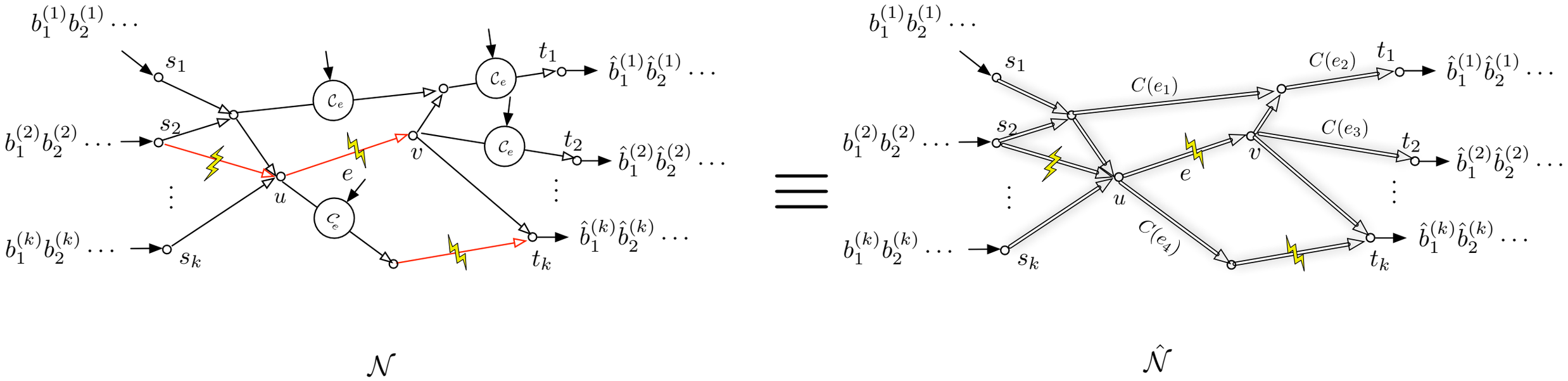
- Capacity calculation: reduces the class of problems

  Noiseless networks <=> Noisy networks

  - equal link capacities [Yeung et al 2006, Jaggi et al 2007]
  - partial results for unequal link capacities [Kim et al 2009]
  - node based adversaries [Kosut et al 2009]

Implications



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- Bounds and techniques for one problem => Bounds and techniques for another problem

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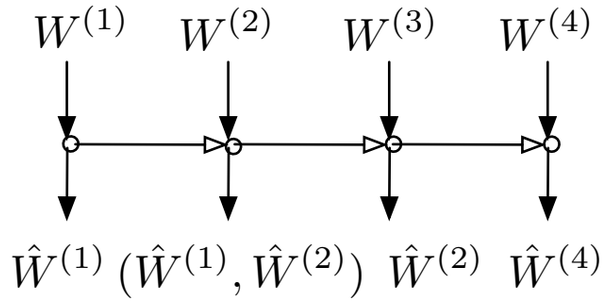

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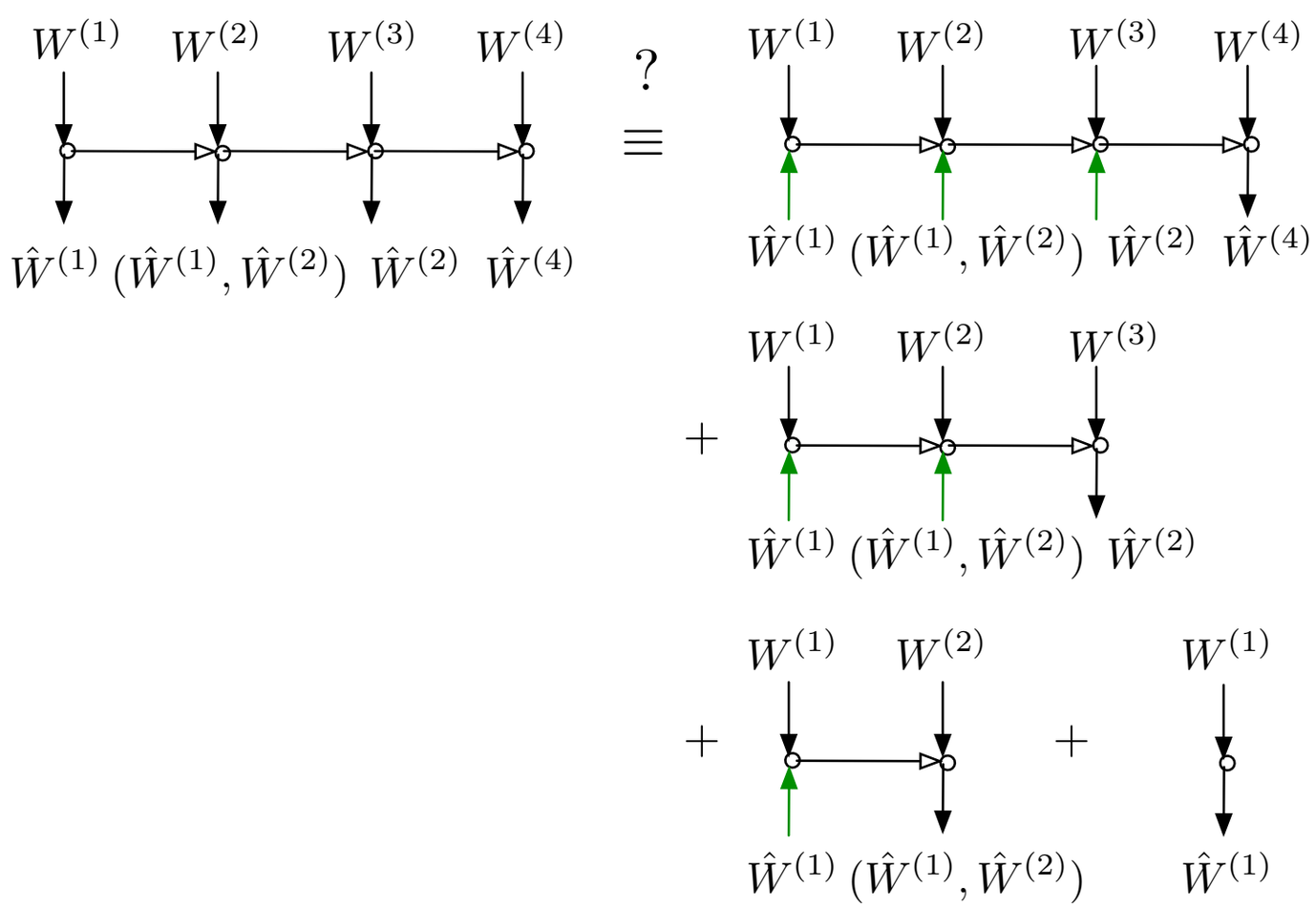

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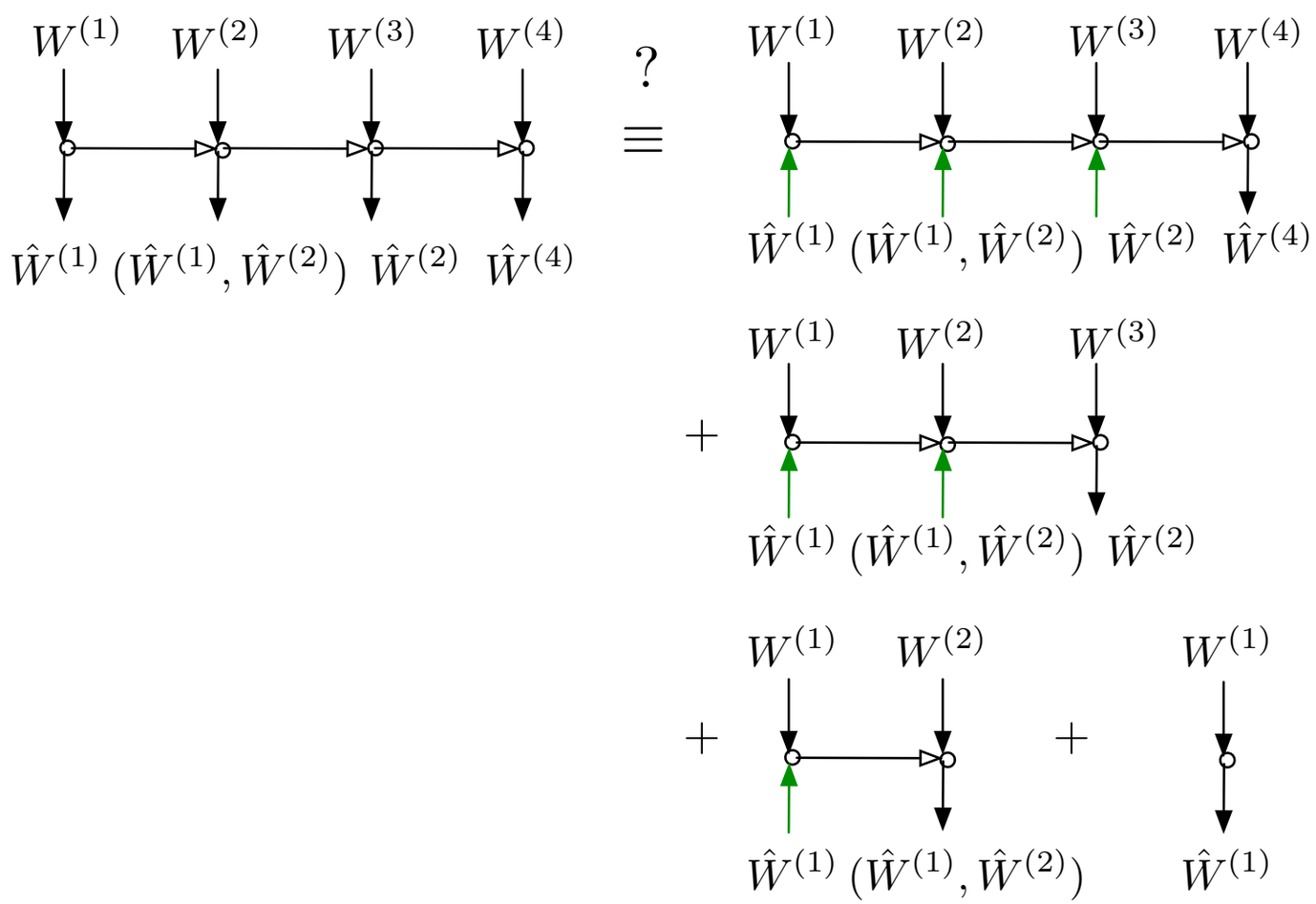

Our results:

- Holds for several classes of demand [BEGK'07]
- Does not hold in general

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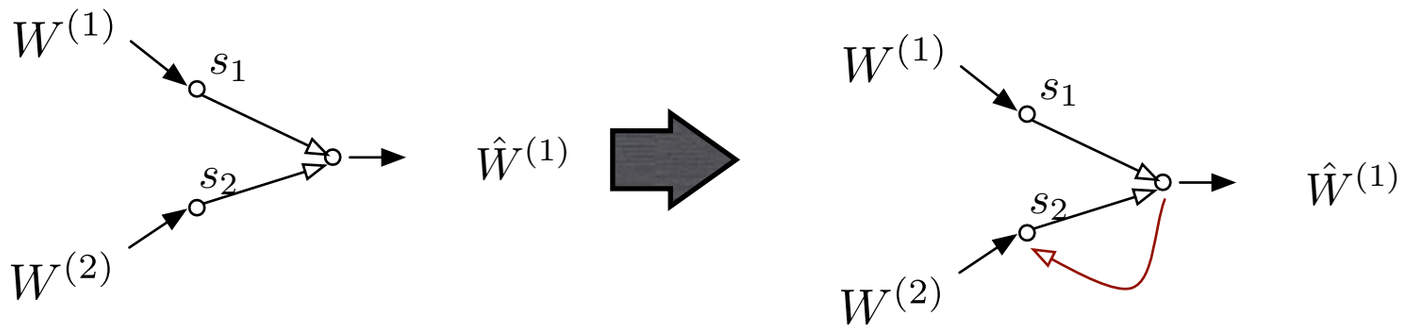

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- Feedback increases capacity [BE'09]
- Exact capacity region for the above network

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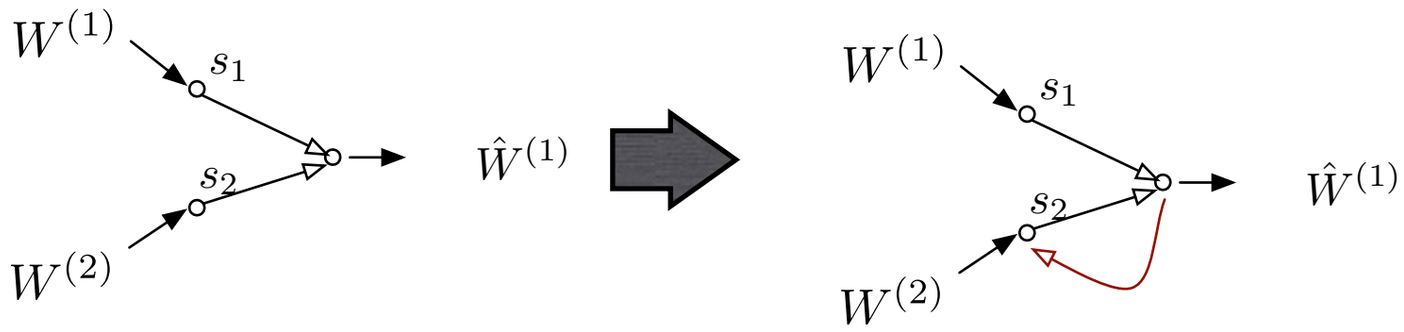

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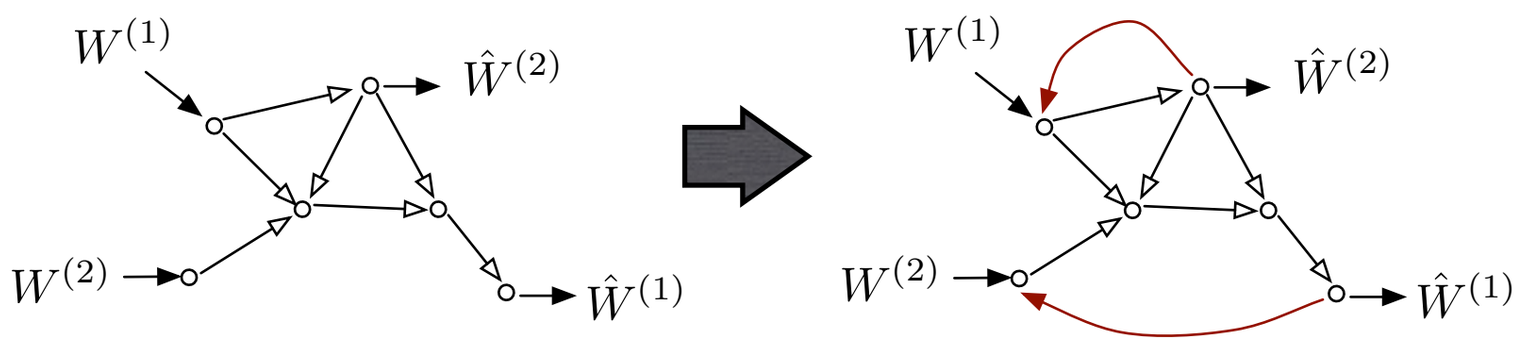
Bounds on capacities for a class of networks with feedback



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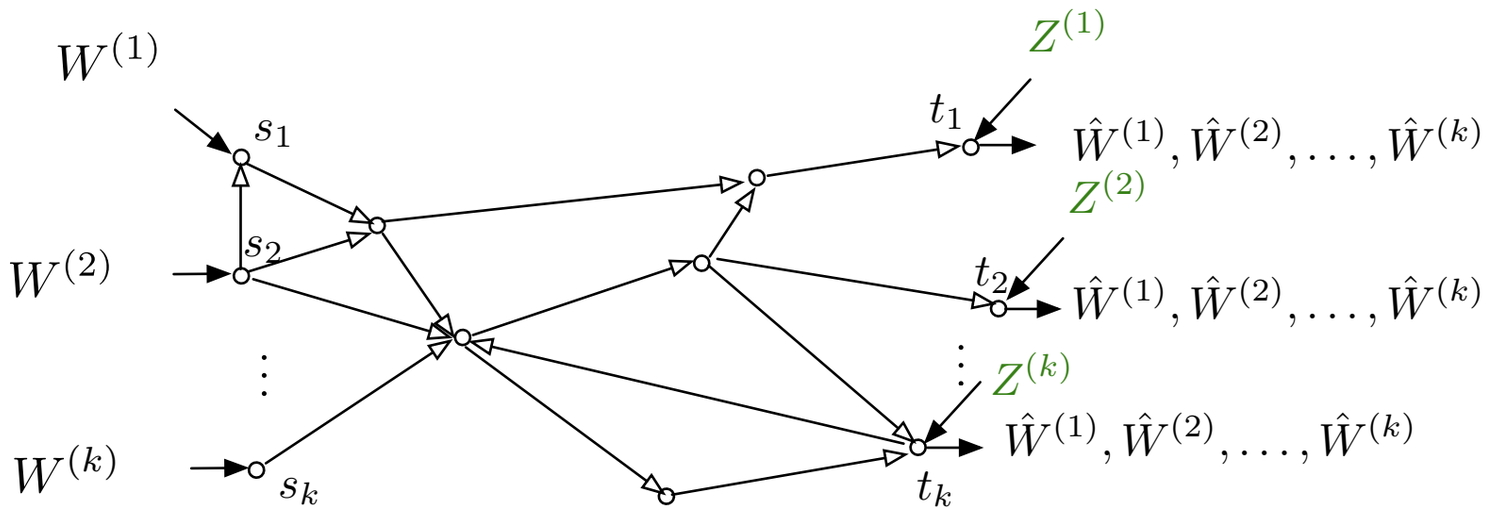

Multicast with side information only at sinks

- Exact capacity region: cut-set bounds [BE'08]

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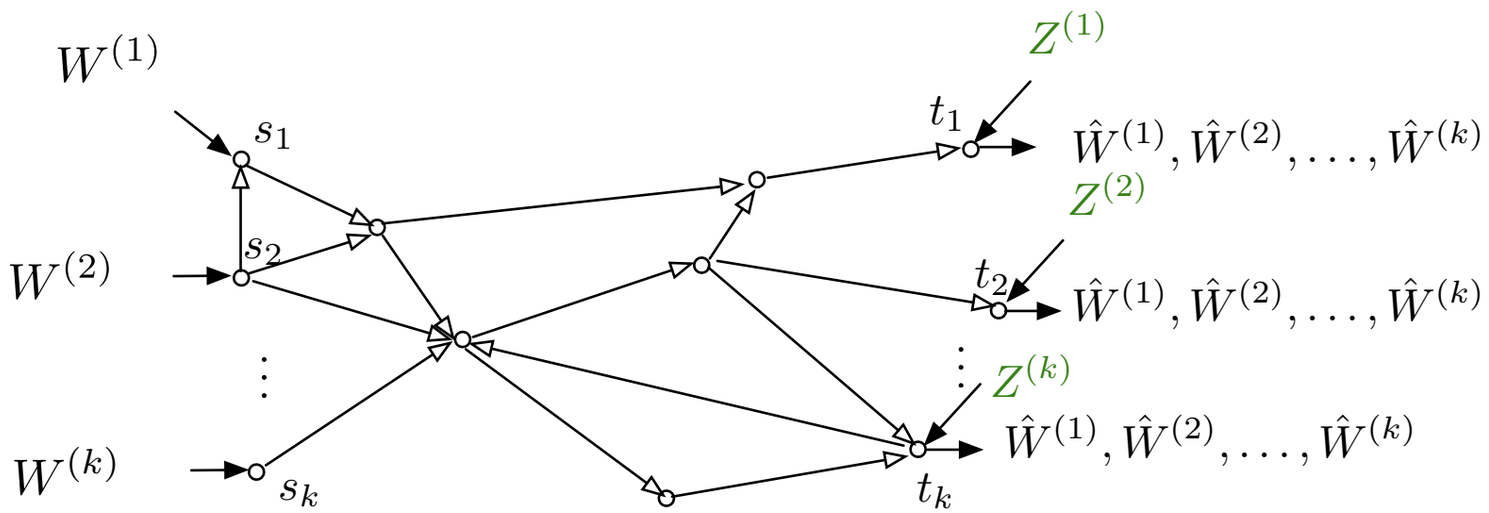

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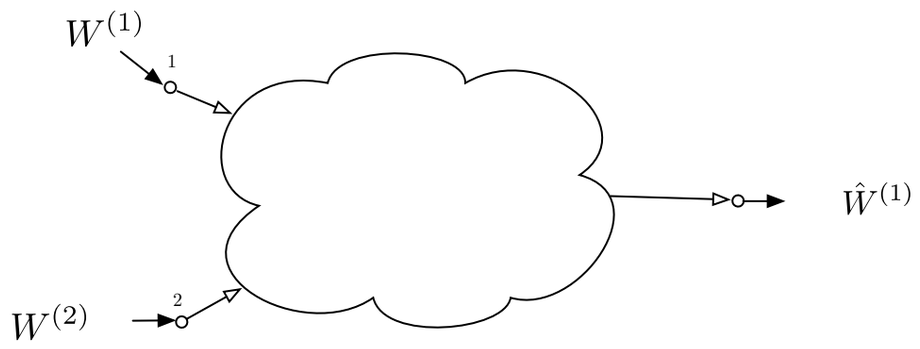
Bounds when side information not at sink



Thank you!