Information Theoretic Concepts of 5G

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Joint work with
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ERICSSON

Outline

- What is new in 5G

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- What is new in 5G
- Multihop Communications for 5G

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- What is new in 5G
- Multihop Communications for 5G
- Channel coding for 5G

5G - What is New?

- Applications

Broadband experience everywhere anytime

Mass market personalized media and gaming

Meters, sensors, “Massive MTC”

Remote controlled machines

Smart transport infrastructure and vehicles

Healthcare

Human–machine interaction

5G - What is New?

- Applications

Broadband experience everywhere anytime | Mass market personalized media and gaming | Meters, sensors, "Massive MTC" | Remote controlled machines | Smart transport infrastructure and vehicles | Healthcare | Human–machine interaction

- Requirements
  - 1000x mobile data, 100x user data rates, 100x connected devices, 10x battery life, 5x lower latency
  - Sustainable, secure

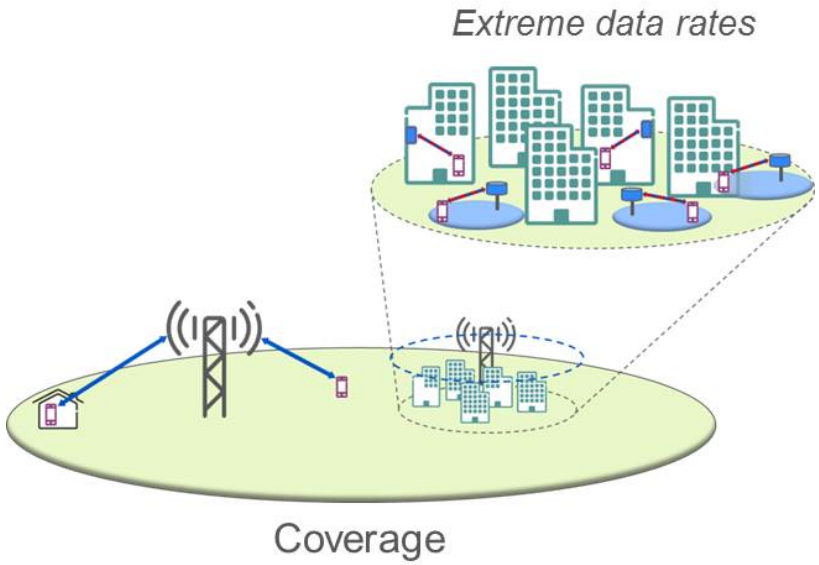
5G - What is New?

- Applications
- Requirements
- Architecture - Common network platform

5G and Spectrum

Design

- Low frequencies: wide coverage
- mmW band: short range, low complexity



Ultra-dense Networks in mmW Bands

Dense deployments

- Due to limited range
- For higher throughput

Ultra-dense Networks in mmW Bands

Backhaul for thousands of access points?

- Backhaul today:
  P2P, line-of-sight
- Tomorrow:
  Wireless multihop backhaul
- Access points relay each other's data

Ultra-dense Networks in mmW Bands

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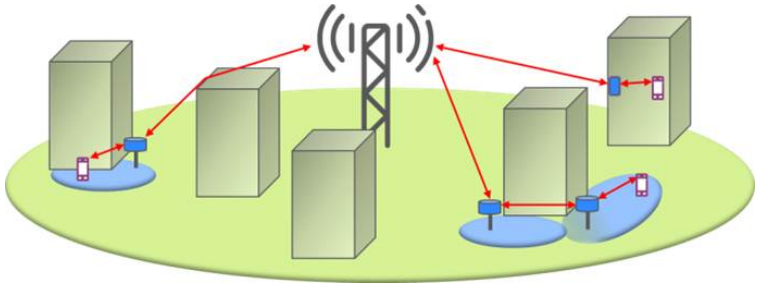
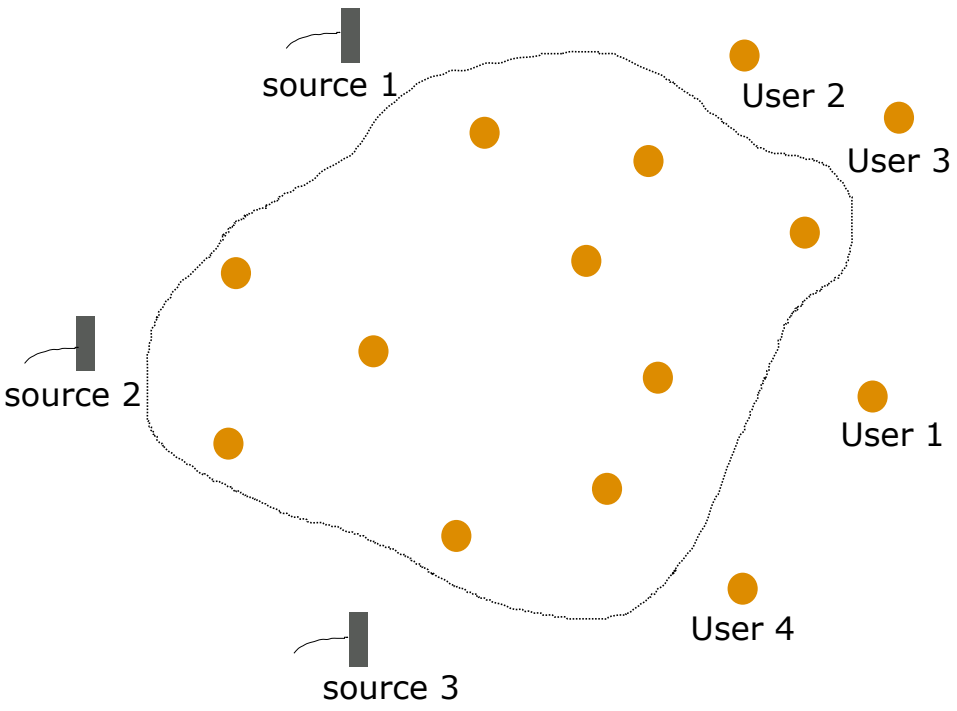


Remove Houses: Mesh Network



Efficient multihop scheme? What should relays do?

Information Theory: Relay Channel is 44 Years Old

Adv. Appl. Prob. **3**, 120–154 (1971)
Printed in Israel

THREE-TERMINAL COMMUNICATION CHANNELS

EDWARD C. VAN DER MEULEN, *University of Rochester*

Summary

The problem of transmitting information in a specified direction over a communication channel with three terminals is considered. Examples are given of the various ways of sending information. Basic inequalities for average mutual information rates are obtained. A coding theorem and weak converse are proved and a necessary and sufficient condition for a positive capacity is derived. Upper and lower bounds on the capacity are obtained, which coincide for channels with symmetric structure.

1. Introduction

In a basic paper Shannon [6] introduced the two-way communication channel and analyzed how to communicate over this channel in two opposite directions as effectively as possible. The present paper considers communication channels which have three different terminals. The problem under investigation is how to send information in one specified direction over such a channel as effectively as possible, assuming that all terminals cooperate so as to optimize the transmission procedure. A three-terminal communication channel is shown schematically in Figure 1. It consists of three terminals, labeled 1, 2, and 3, which are connected to a noisy channel K. At each terminal there is a sender and a receiver who are in direct cross-communication with each other. The sender at one particular terminal can communicate with the receiver at any other terminal only through the noisy channel K. The operation of the channel may be described as follows. Once each second, say, at each terminal $t, t = 1, 2$, or 3, a letter x_t is selected from a finite set A_t (the input alphabet at terminal t) and is presented to the channel for transmission. The channel acts on the input triple (x_1, x_2, x_3) at once and produces an output triple (y_1, y_2, y_3). The letter y_t observed at terminal t belongs to a finite set B_t, the output alphabet at terminal t. The sender at terminal t sees the received letter y_t just before he selects the next input letter to be transmitted at his terminal over the channel. Because of the random nature of the channel, the output (y_1, y_2, y_3) depends statistically on the

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ACKNOWLEDGMENT

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Capacity Theorems for the Relay Channel

THOMAS M. COVER, FELLOW, IEEE, AND ABBAS A. EL GAMAL, MEMBER, IEEE

***Abstract*—A relay channel consists of an input x_1, a relay output y_1, a channel output y, and a relay sender x_2 (whose transmission is allowed to depend on the past symbols y_1). The dependence of the received symbols upon the inputs is given by $p(y, y_1|x_1, x_2)$. The channel is assumed to be memoryless. In this paper the following capacity theorems are proved.**

1) If y is a degraded form of y_1, then
$C = \max_{p(x_1,x_2)} \min\{I(X_1, X_2; Y), I(X_1; Y_1|X_2)\}$.
2) If y_1 is a degraded form of y, then
$C = \max_{p(x_1)} \max_{x_2} I(X_1; Y|x_2)$.
3) If $p(y, y_1|x_1, x_2)$ is an arbitrary relay channel with feedback from (y, y_1) to both x_1 and x_2, then
$C = \max_{p(x_1,x_2)} \min\{I(X_1, X_2; Y), I(X_1; Y, Y_1|X_2)\}$.
4) For a general relay channel,
$C \leq \max_{p(x_1,x_2)} \min\{I(X_1, X_2; Y), I(X_1; Y, Y_1|X_2)\}$.

Superposition block Markov encoding is used to show achievability of C, and converses are established. The capacities of the Gaussian relay channel and certain discrete relay channels are evaluated. Finally, an achievable lower bound to the capacity of the general relay channel is established.

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I. INTRODUCTION

THE DISCRETE memoryless relay channel denoted by $(\mathcal{X}_1 \times \mathcal{X}_2, p(y, y_1|x_1, x_2), \mathcal{Y} \times \mathcal{Y}_1)$ consists of four finite sets: $\mathcal{X}_1$, $\mathcal{X}_2$, $\mathcal{Y}$, $\mathcal{Y}_1$, and a collection of probability distributions $p(\cdot, \cdot|x_1, x_2)$ on $\mathcal{Y} \times \mathcal{Y}_1$, one for each $(x_1, x_2) \in \mathcal{X}_1 \times \mathcal{X}_2$. The interpretation is that x_1 is the input to the channel and y is the output, y_1 is the relay's output and x_2 is the input symbol chosen by the relay as shown in Fig. 1. The problem is to find the capacity of the channel between the sender x_1 and the receiver y.

The relay channel was introduced by van der Meulen [1], [2], [3, p. 7 and pp. 32–34], and has also been studied by Sato [4]. In [1] a timesharing approach was used to find inner bounds for C. Outer bounds were found in [1] and [4]. However, C was established only for relatively degenerate channels.

The model that motivates our investigation of degraded relay channels is perhaps best illustrated in the Gaussian case (see Fig. 3 and the example in Section IV). Suppose the transmitter x_1 has power P_1 and the relay transmitter has power P_2. The relay receiver y_1 sees $x_1 + z_1$, $z_1 \sim N(0, N_1)$. The intended receiver y sees the sum of the relay signal x_2 and a corrupted version of y_1, i.e., $y = x_2 + y_1 + z_2$, $z_2 \sim N(0, N_2)$. How should x_2 use his knowledge of x_1 (obtained through y_1) to help y understand x_1? We shall

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Multihop Schemes in Practice

- Large body of IT results
  - Efficient multihop schemes developed; capacity bounds, scaling laws and capacity in some cases determined

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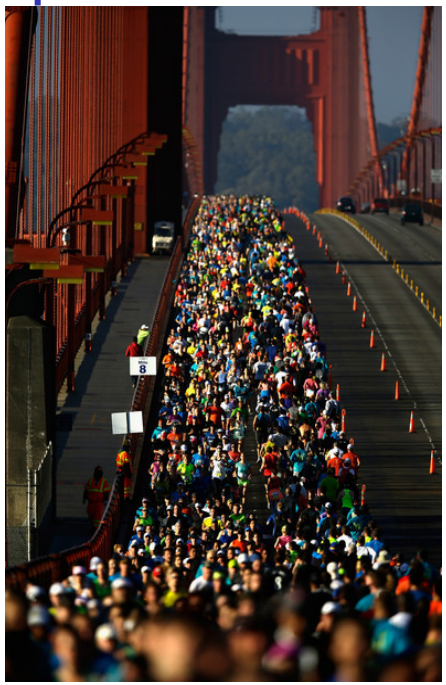
Multihop Schemes in Practice

- Large body of IT results
  - Efficient multihop schemes developed; capacity bounds, scaling laws and capacity in some cases determined
- Not much practical impact
  - Too complex?
  - There was no need?
- 5G will deploy multihop communications

Multihop Communications for 5G

Multihop Backhaul for Ultra-dense Networks

Multihop MTC?

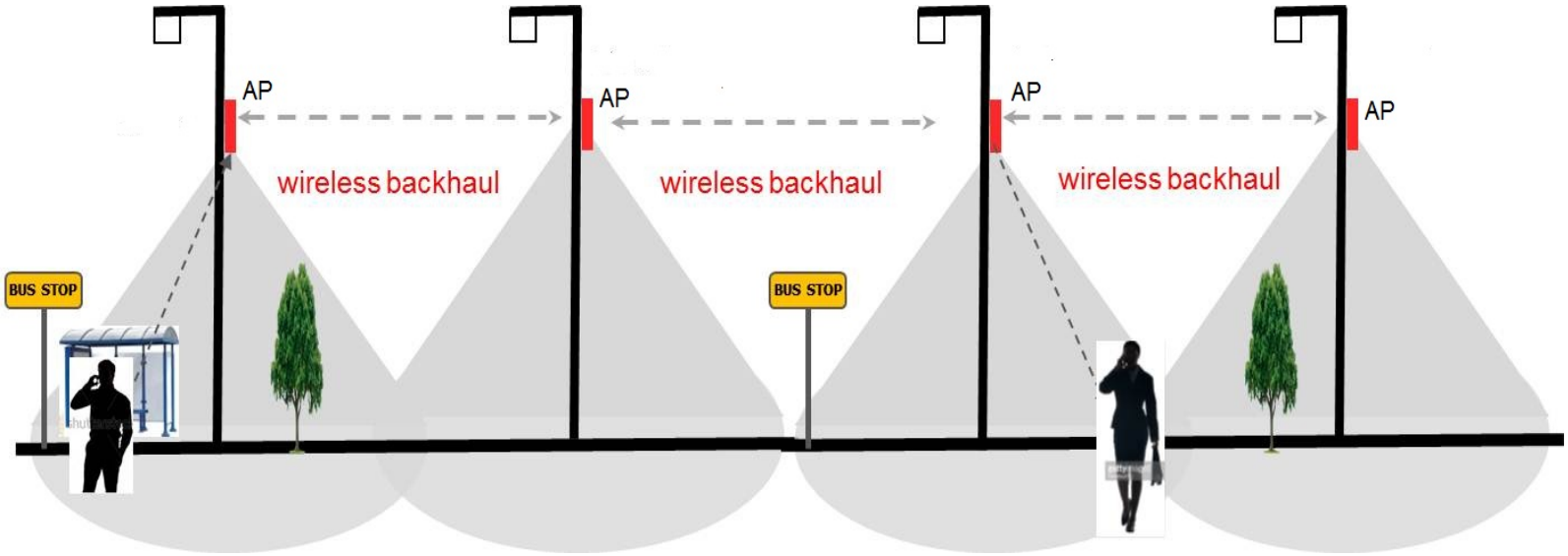


70000 tracking devices

9 Gbyte/user/hour

480 Gbps/km^2

Multihop Backhaul



Current Proposal for 5G

Interference-avoidance routing

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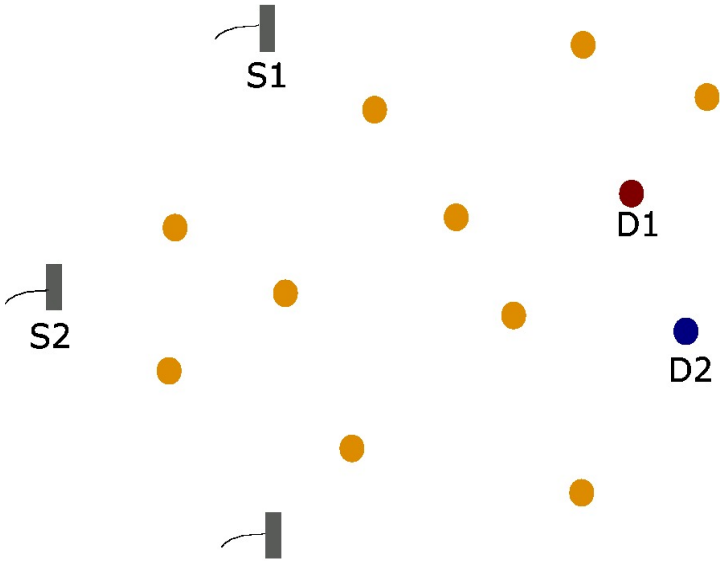

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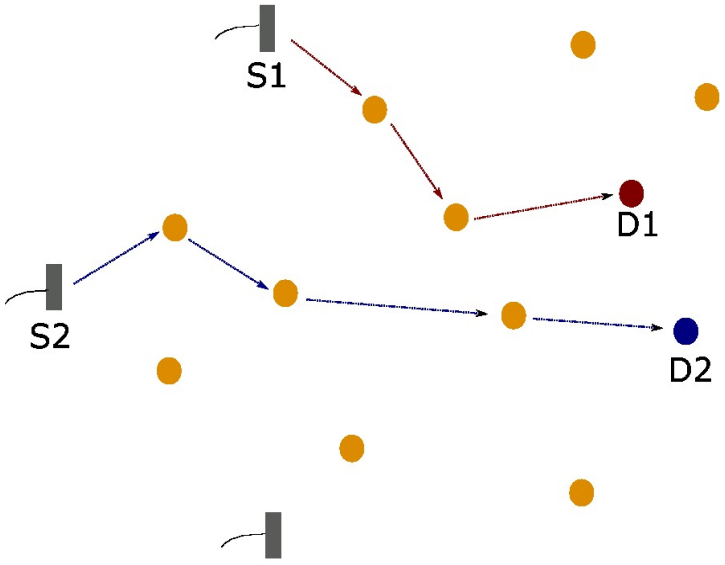
Interference-avoidance routing

- Each relay performs store-and-forward
- Establish routes iteratively



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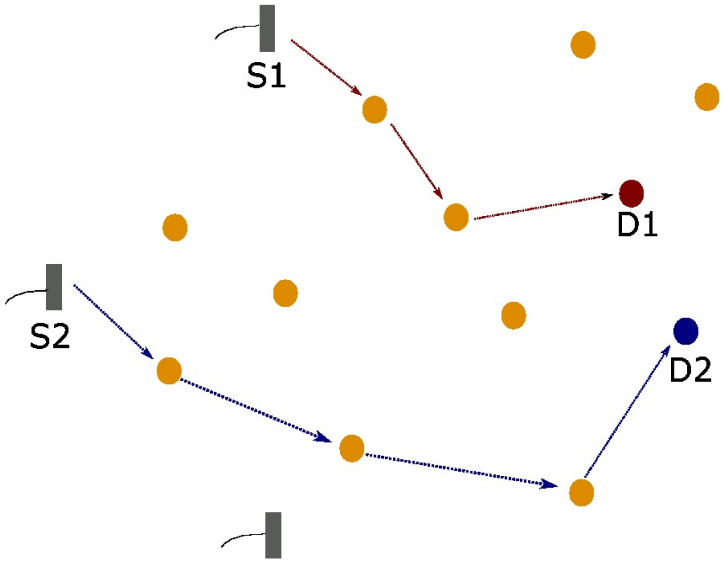

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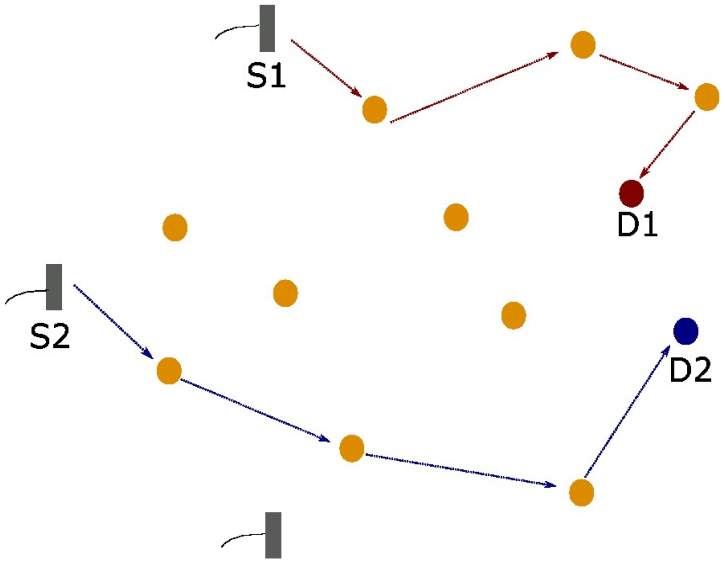

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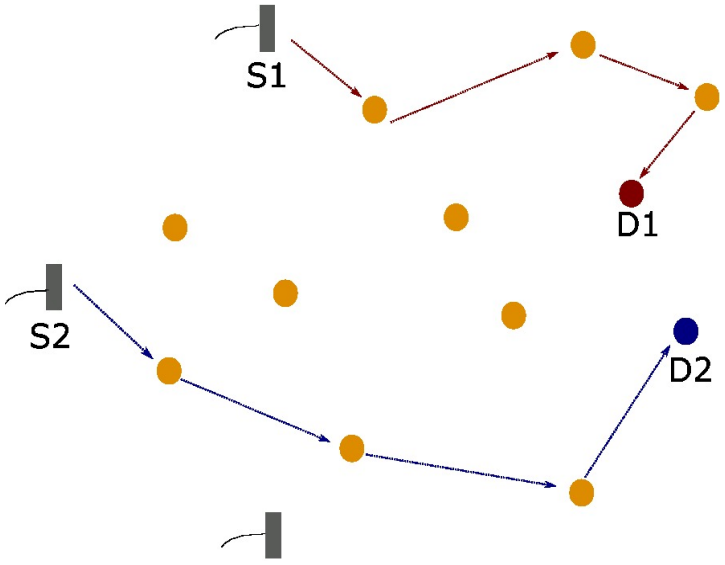
- Each relay performs store-and-forward
- Establish routes iteratively
- Works well in low interference



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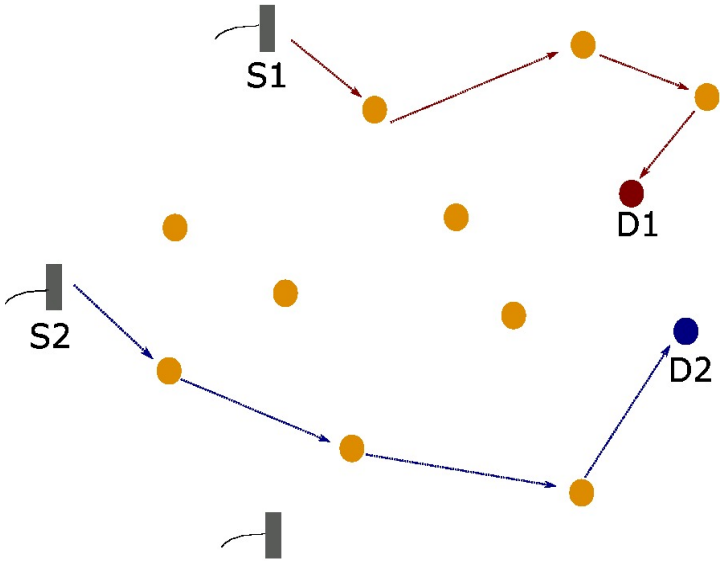
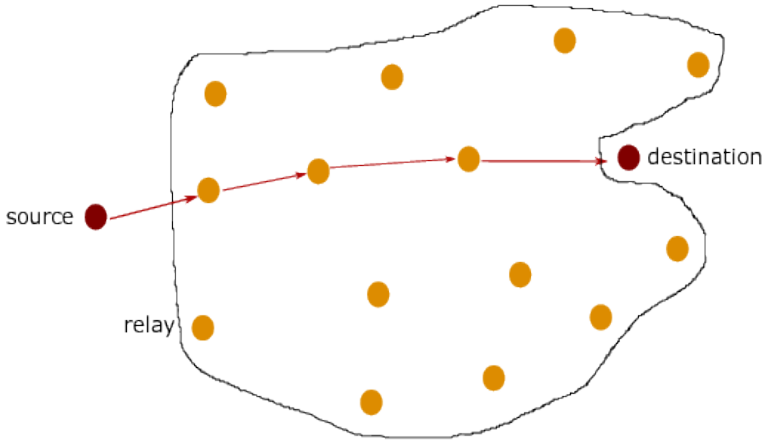


Does not work in high interference

Decode vs. Quantize

Routing

- Each relay has to decode messages
- Worst relay is a bottleneck



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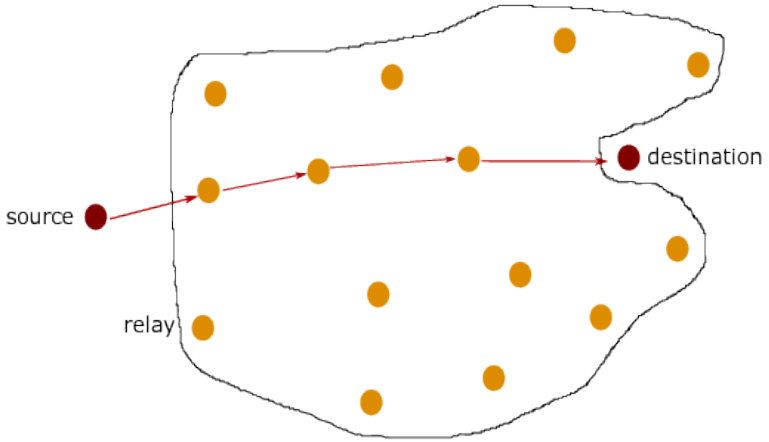
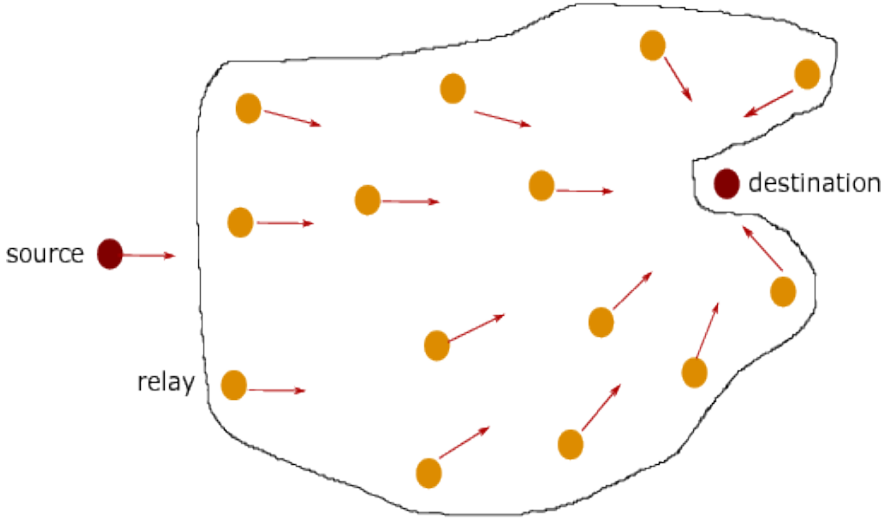


Quantize

- Any relay can quantize source signal



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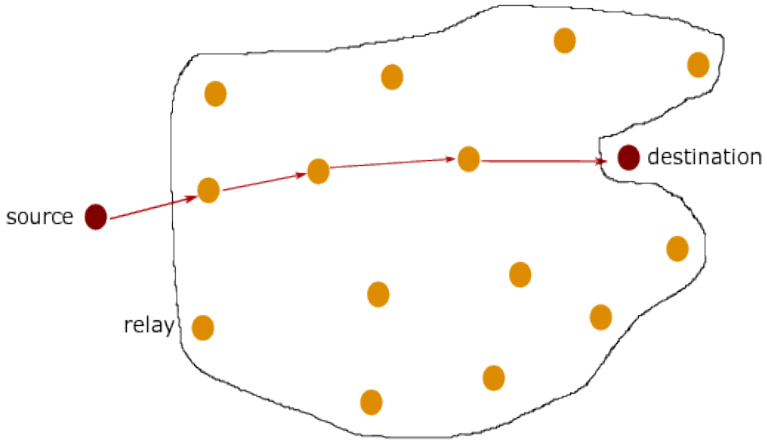
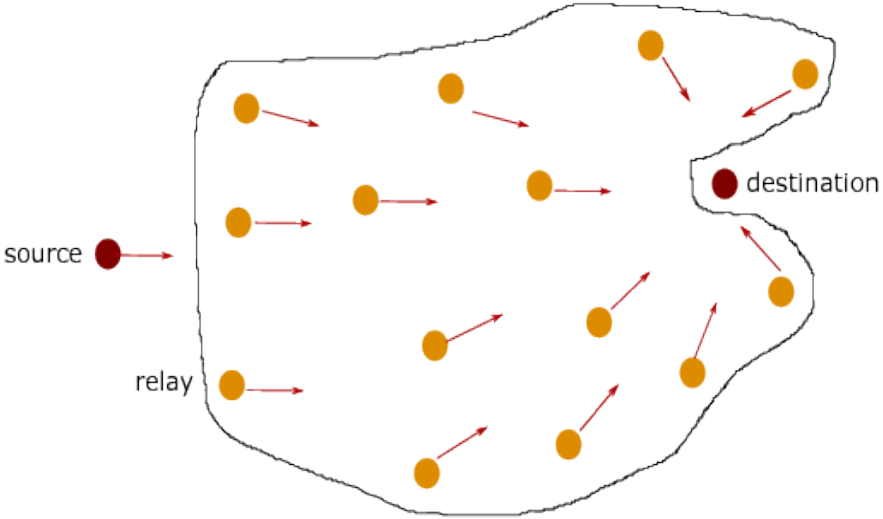


Quantize

- Any relay can quantize source signal
- Noisy network coding (NNC) *[Avestimehr et.al, 2009], [Lim et.al, 2011],[Hou & Kramer, 2013]*

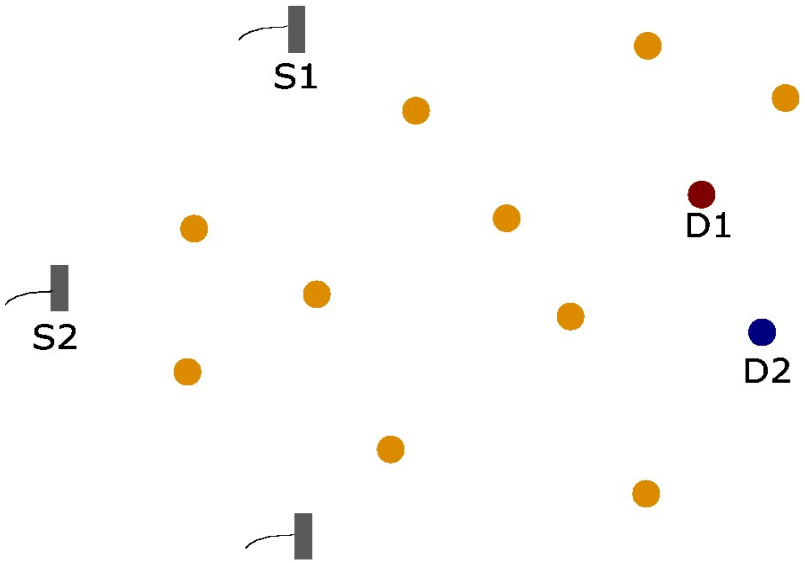


Noisy Network Coding

- No interference at relays: every signal is useful
- A relay sends a mix of data flows
- Can outperform other schemes
- Achieves constant gap to the multicast capacity

Implementation: NNC Challenges

- Full-duplex assumption
- Channel state information
- Relay selection
- Decoder complexity
- Rate calculation



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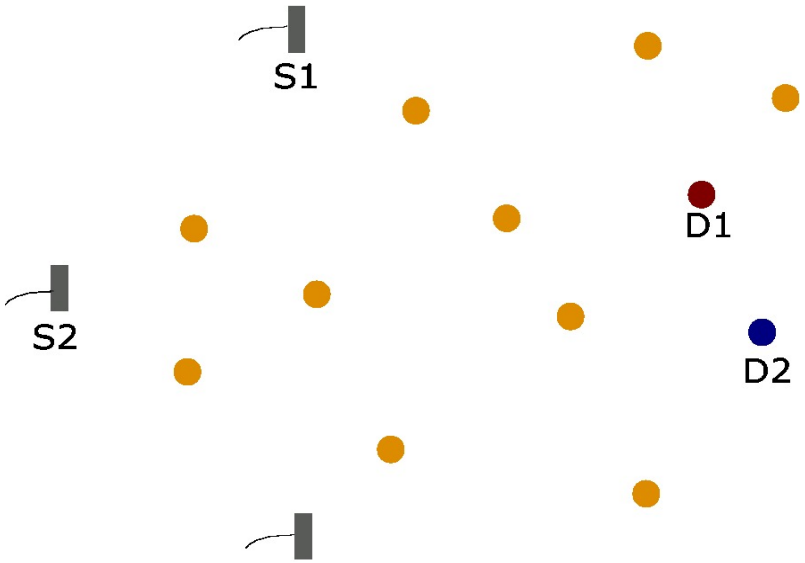

We developed a scheme that has a lower complexity and improved performance *[Hong, Marić, Hui & Caire, ISIT 2015, ITW 2015]*

Relay Selection

Group relaying

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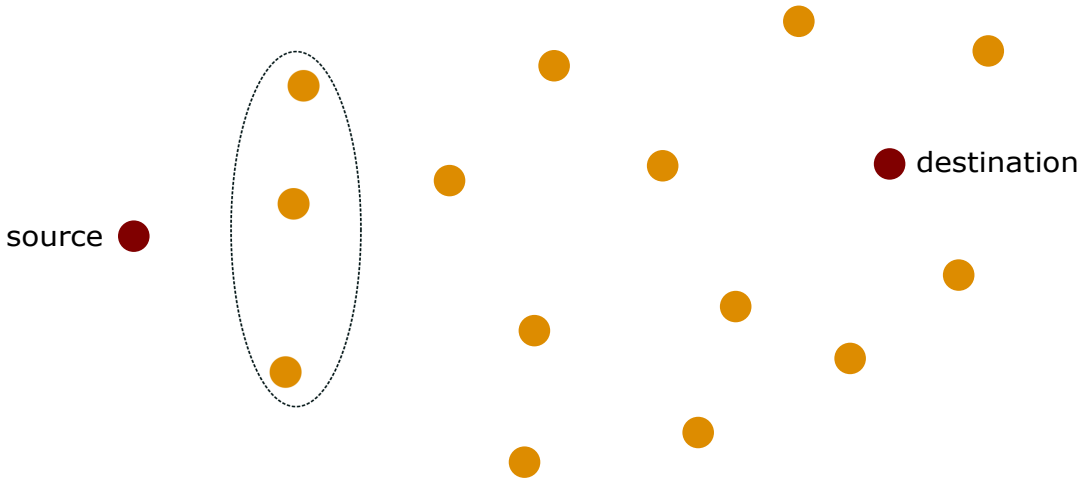

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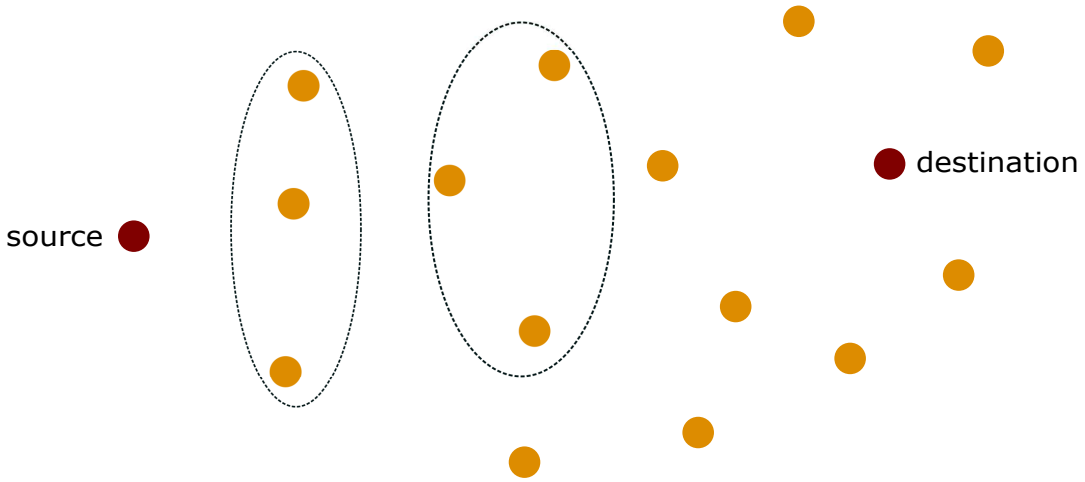

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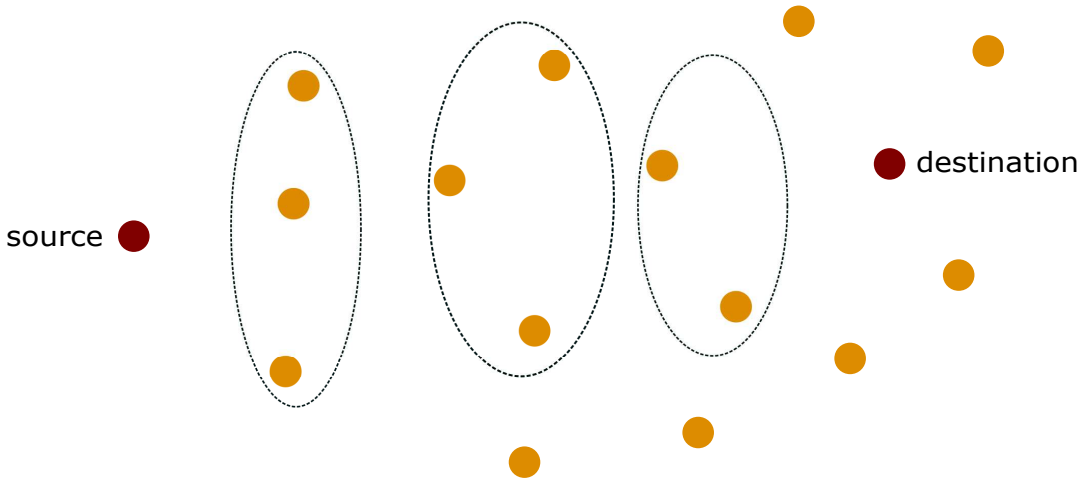
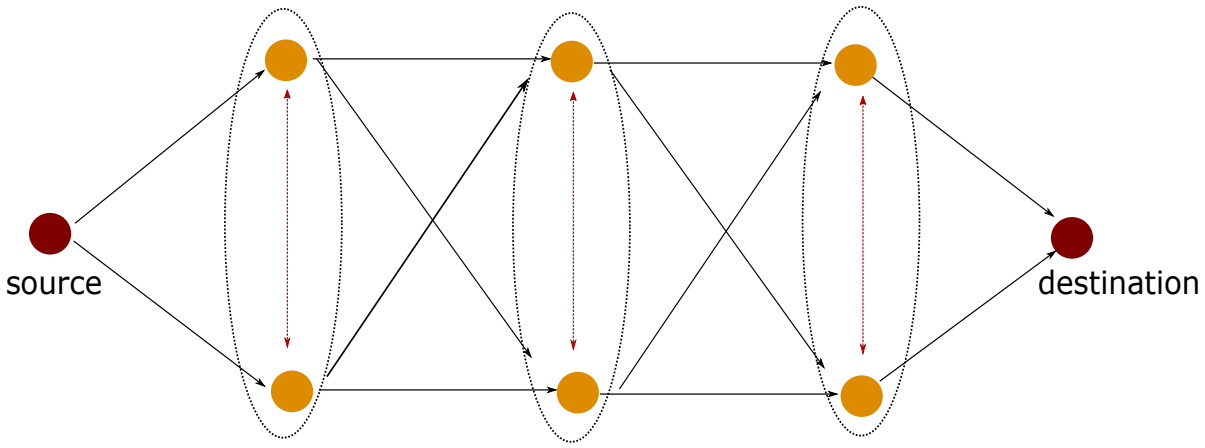


Relay Selection

Layered network



To Improve Performance: Adaptive Scheme

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A relay chooses a forwarding scheme based on SNR

- Relays with good channels decode-and-forward
- The rest of relays quantize

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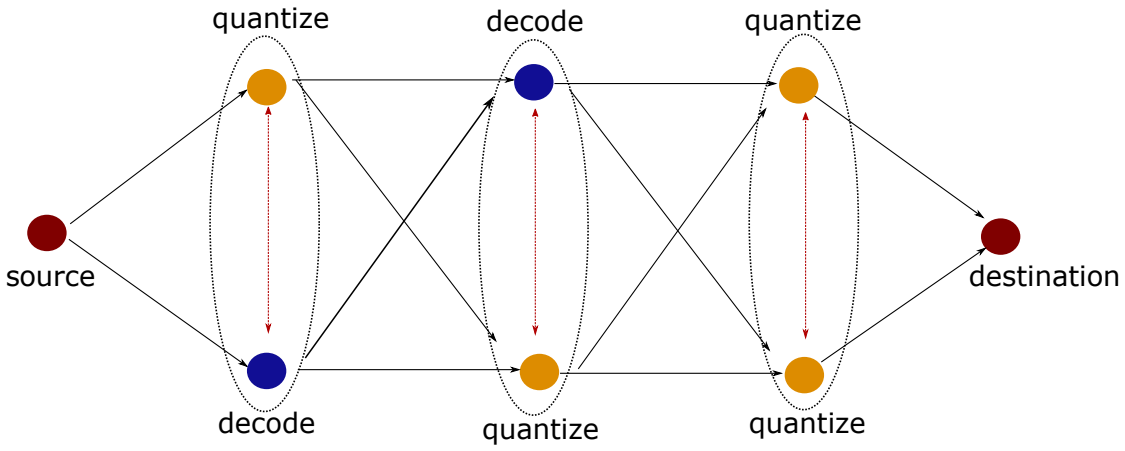

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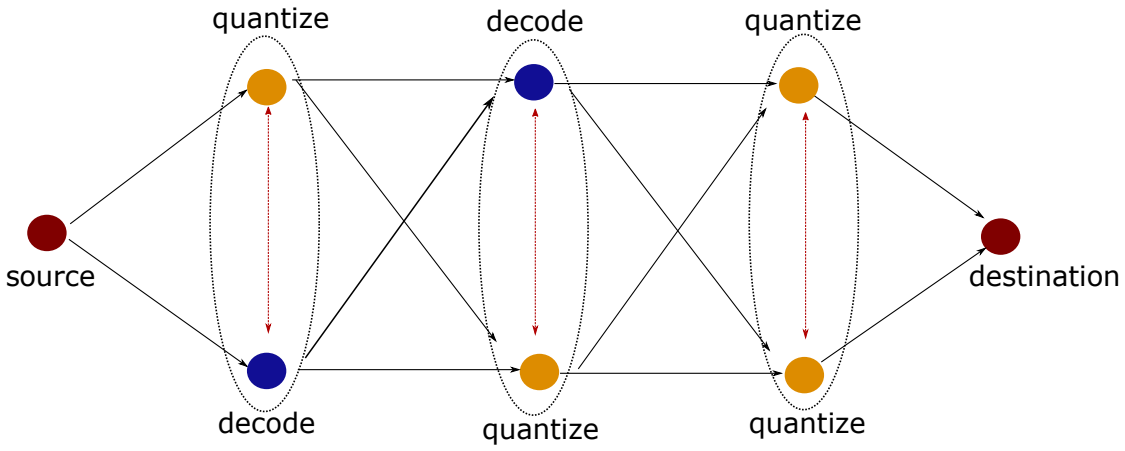


How much to quantize?

To Improve Performance: Optimized Quantization

A relay chooses number of quantization levels based on SNR

- Optimal quantization decreases the gap to capacity from linear to logarithmic

- NNC with noise-level quantization *[Avestimehr et. al., 2009]*

$$R^{(K)} = \log(1 + SNR) - K$$

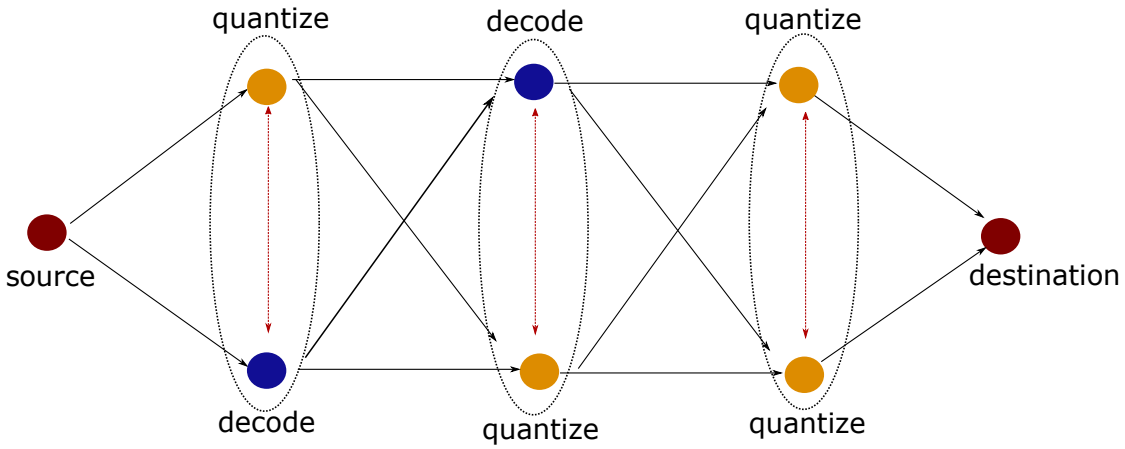
- Optimal quantization *[Hong & Caire, 2013]*

$$R^{(K)} \geq \log(1 + SNR) - \log(K + 1)$$

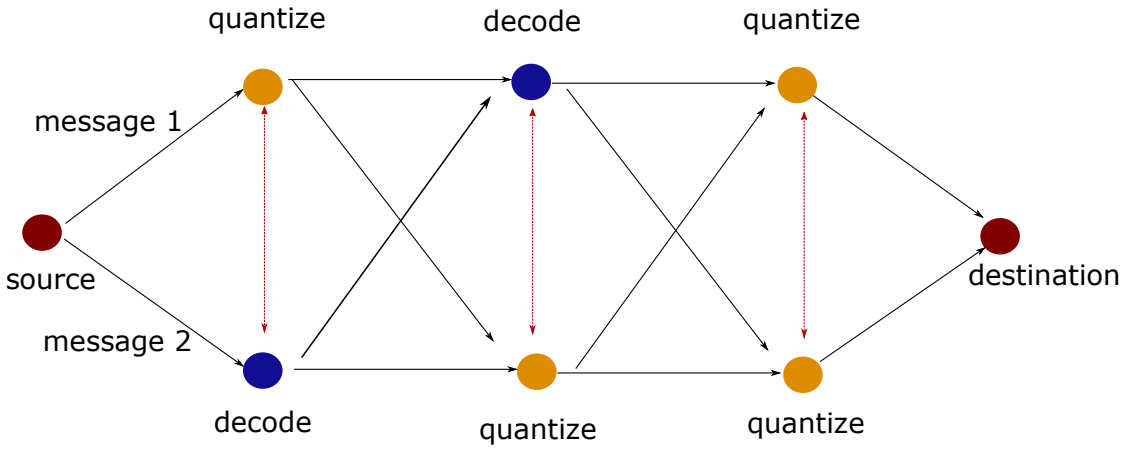
To Reduce Complexity: Successive Decoding

Destination successively decodes messages from different layers

- Does not decrease performance in the considered network *[Hong & Caire, 2013]*



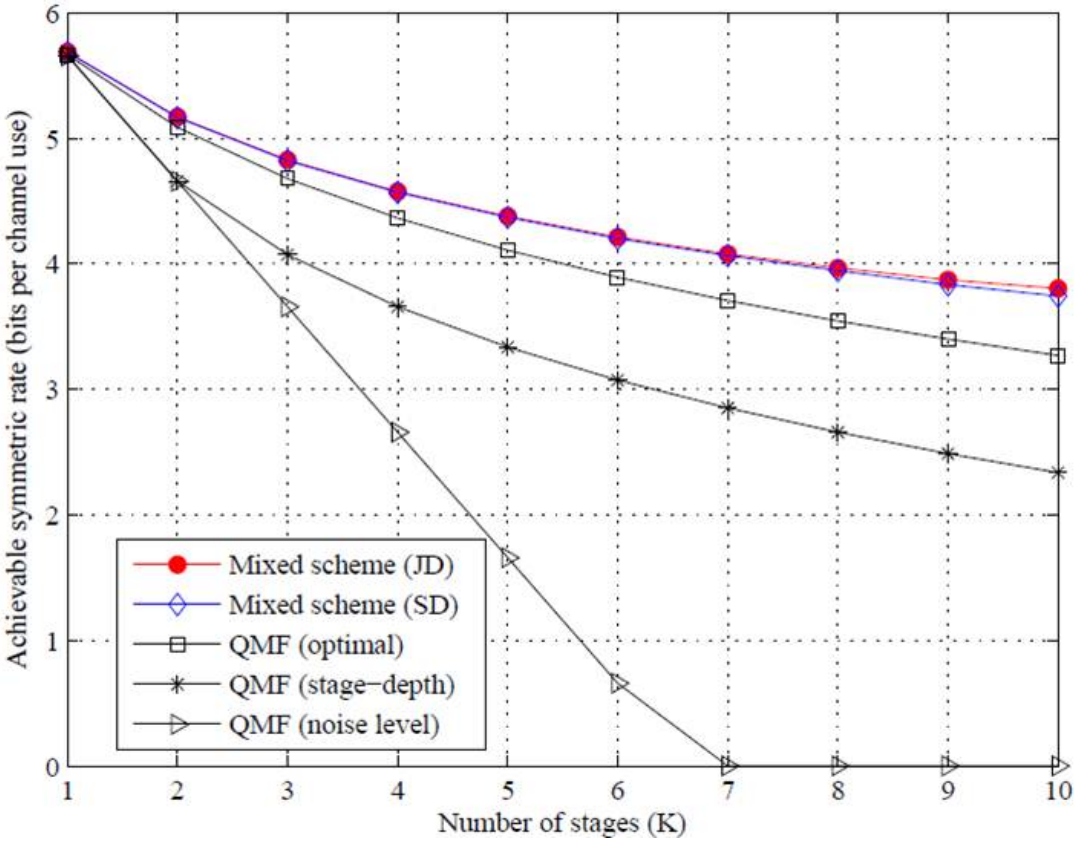
Summary



- Relay selection via interference-harnessing
- Adaptive scheme: each relay chooses to decode or quantize
- Quantization level is optimized
- Destination performs successive decoding
- Successive relaying *[Razaei et.al., 2008]*
- Rate splitting reduces interference at DF relays

Performance Gains

- Derived closed form solution for the rate, for any relay configuration *[Hong, Marić , Hui & Caire, ISIT 2015, ITW 2015]*



Performance Gains

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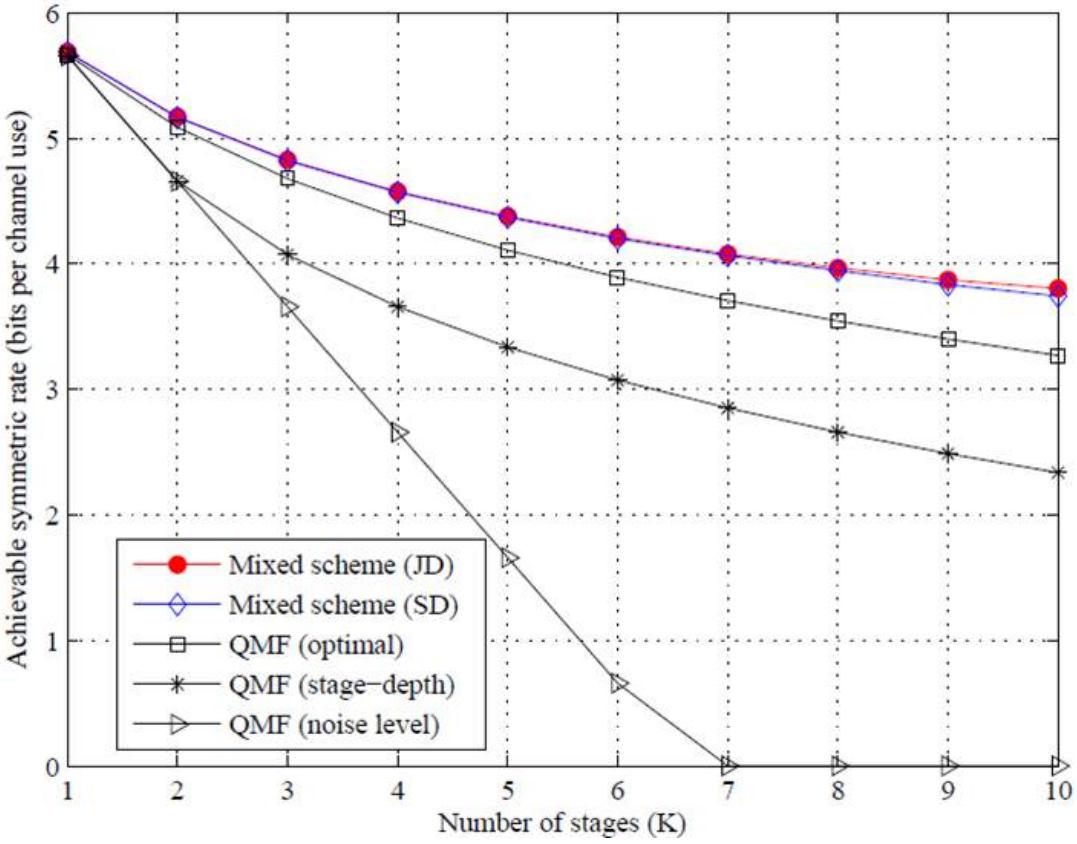
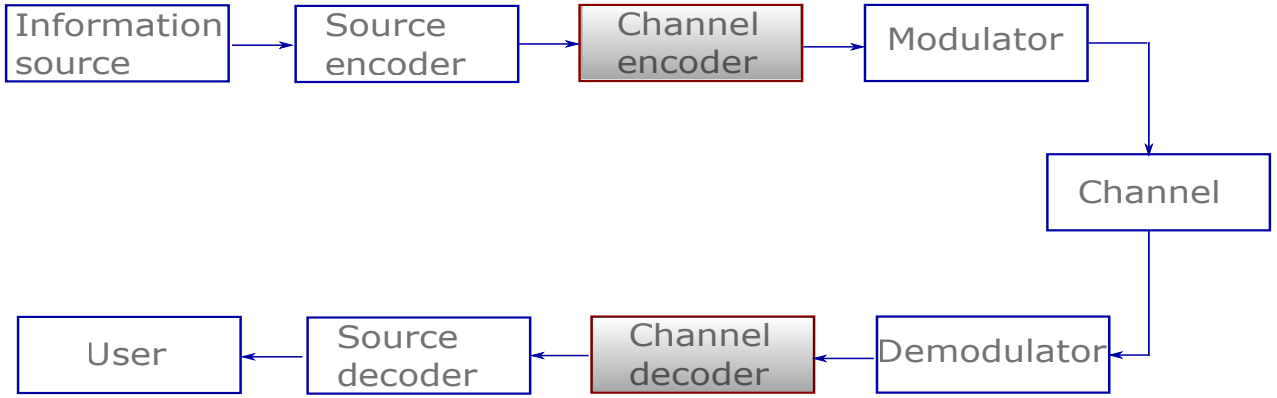
- Better performance with a simpler scheme!



Channel Coding for 5G



Choosing Channel Codes for 5G

- Main considerations
  - Performance, complexity, rate-compatibility

Choosing Channel Codes for 5G

- Main considerations
  - Performance, complexity, rate-compatibility
- LTE deploys turbo codes *[Berrou et. al., 1993]*
  - Perform within a dB fraction from channel capacity

Choosing Channel Codes for 5G

- Main considerations
  - Performance, complexity, rate-compatibility
- LTE deploys turbo codes *[Berrou et. al., 1993]*
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- Why Beyond Turbo Codes?

Choosing Channel Codes for 5G

- Main considerations
  - Performance, complexity, rate-compatibility
- LTE deploys turbo codes *[Berrou et. al., 1993]*
  - Perform within a dB fraction from channel capacity
- Why Beyond Turbo Codes?
- LDPC codes
- New classes of codes that are capacity-achieving with low complexity encoder and decoder

Polar & spatially-coupled LDPC codes

Polar Codes *[Arikan, 2009]*

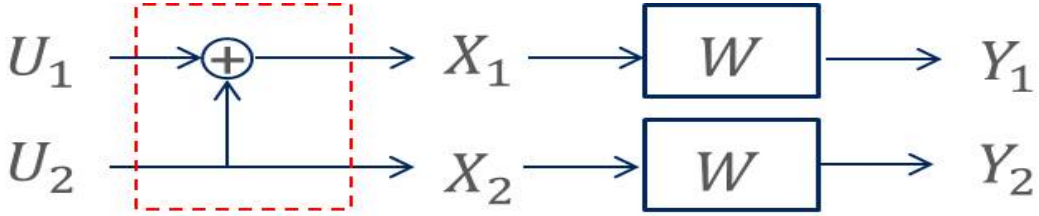
- First provably capacity-achieving codes with low encoding/decoding complexity

Polar Codes *[Arikan, 2009]*

- First provably capacity-achieving codes with low encoding/decoding complexity
- Outperform turbo codes for large block length n
- Best performance for short block length n
- Complexity $O(nlogn)$
- Better energy-efficiency for large n than other codes
- Code construction is deterministic
- No error floor

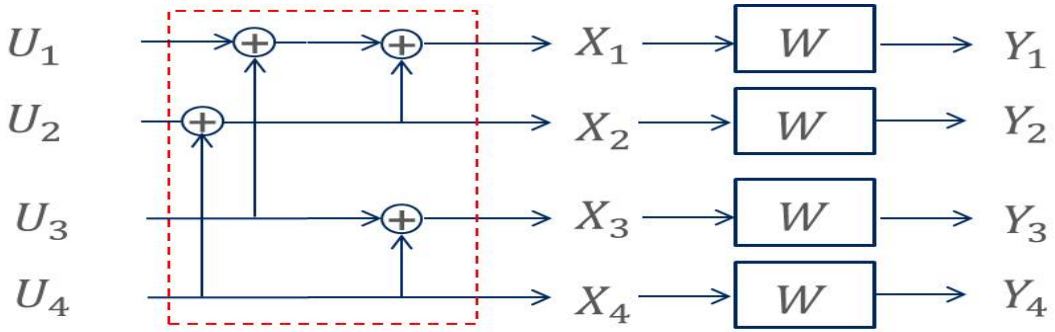
Channel Polarization

Channel Polarization



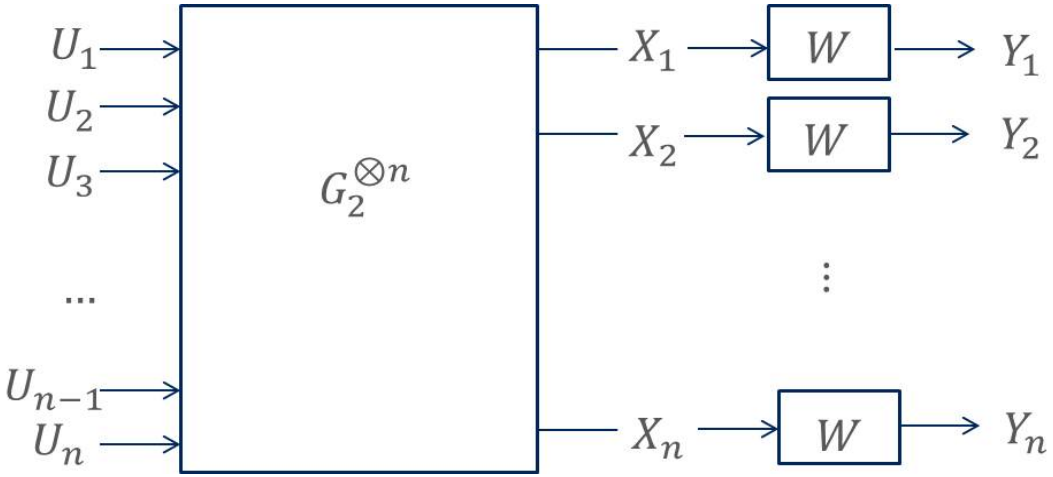
$$G_2 \triangleq \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

Channel Polarization

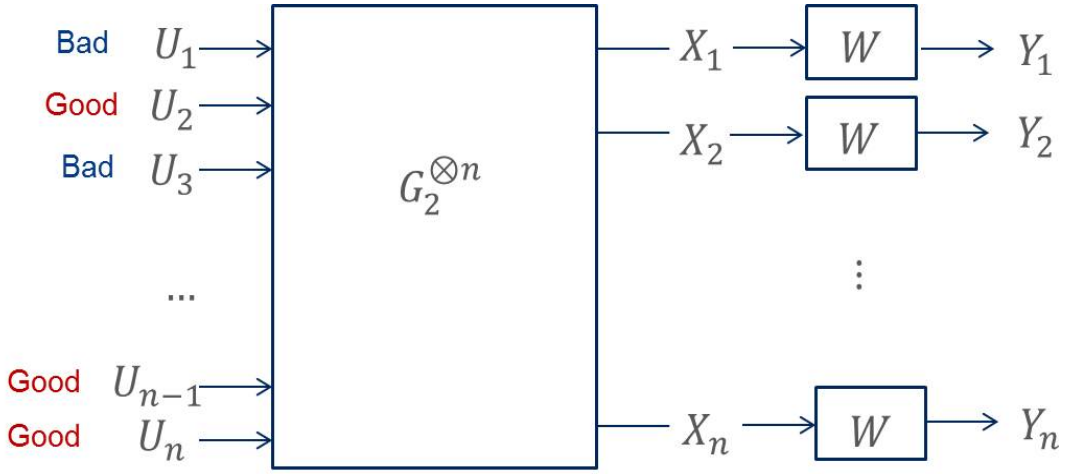


$$G_2^{\otimes 2} \triangleq \begin{bmatrix} G_2 & 0 \\ G_2 & G_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Channel Polarization

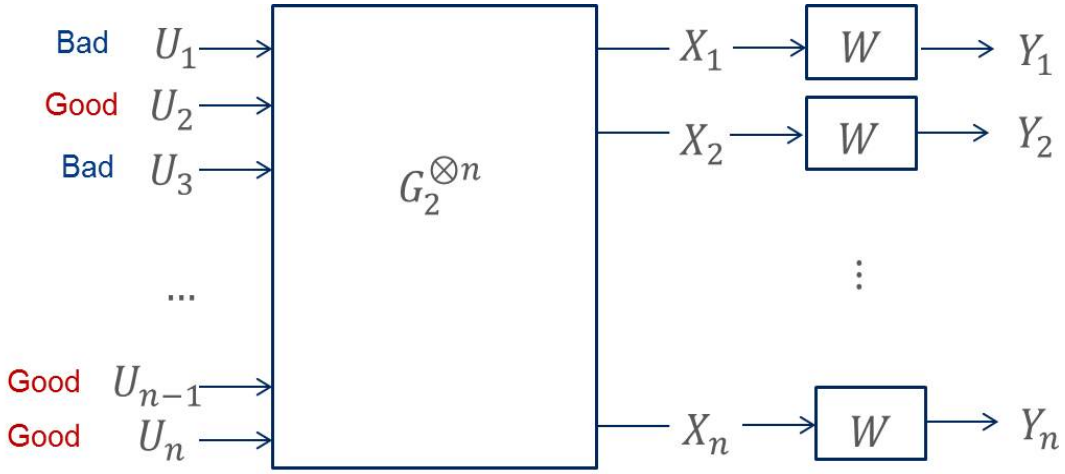


Channel Polarization



- n instances of a channel are transformed into a set of channels that are either noiseless or pure-noise channels

Channel Polarization



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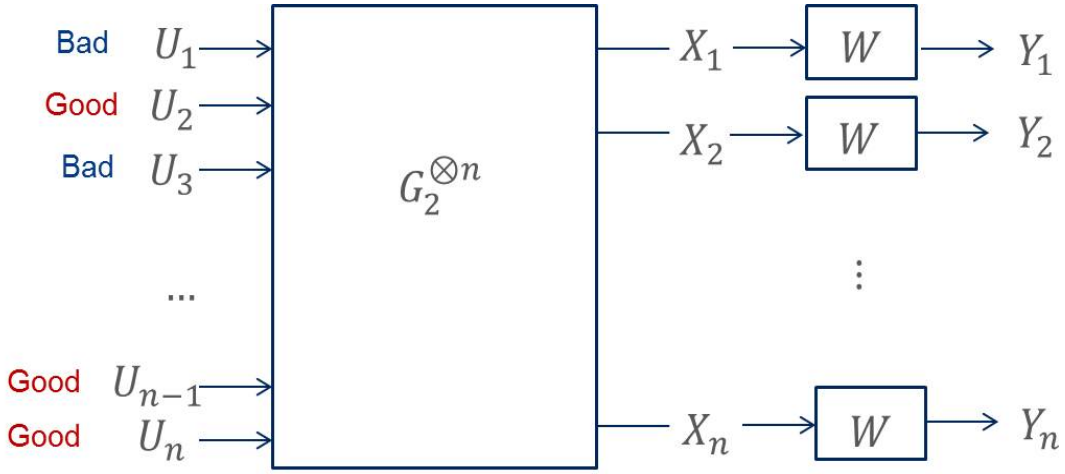
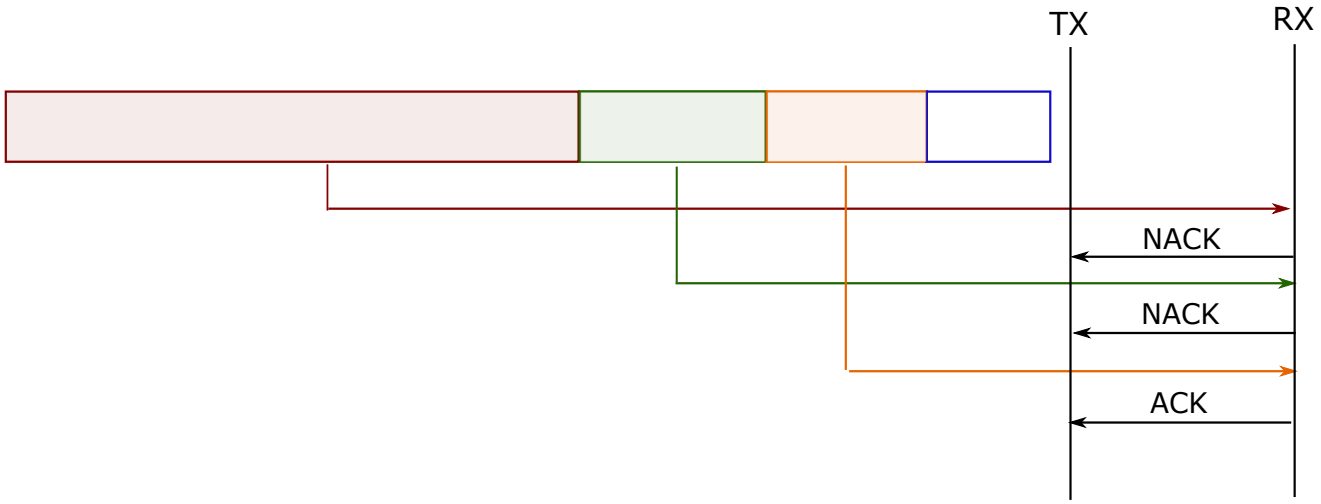


- n instances of a channel are transformed into a set of channels that are either noiseless or pure-noise channels
- Polar code: send information bits over good channels
- Fraction of good channels approaches the capacity of the original channel

Wireless Channel is Time-Varying

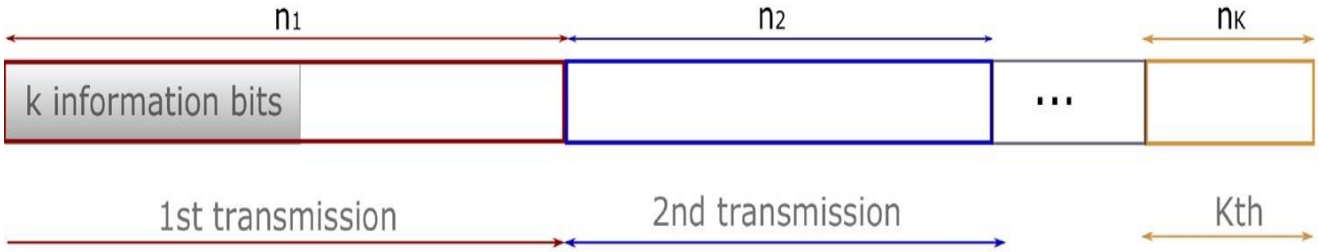
Wireless Channel is Time-Varying

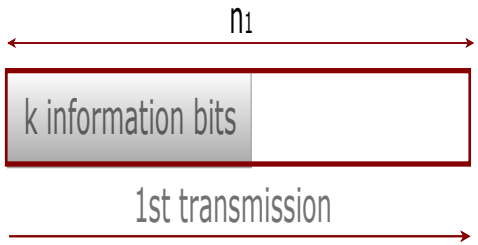
- Hybrid ARQ with Incremental Redundancy (HARQ-IR)
  - Send additional coded bits until decoding is successful



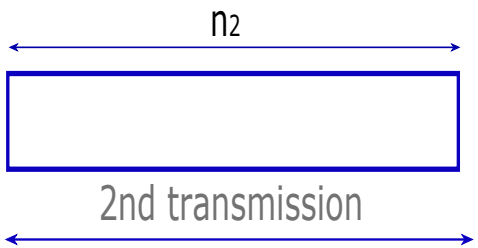
HARQ-IR

- Encode for degraded channels $W_1 \succeq W_2 \succeq \ldots \succeq W_K$ with capacities $C_1 \geq C_2 \geq \ldots \geq C_K$



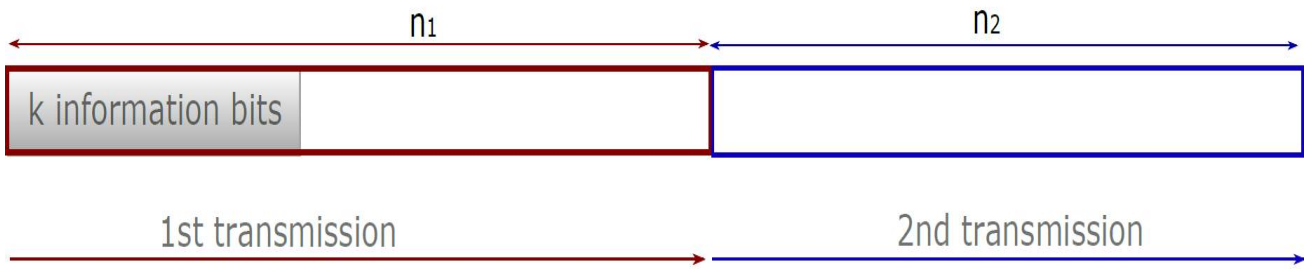


Rate $R_1 = k/n_1$



$R_2 = k/(n_1 + n_2)$

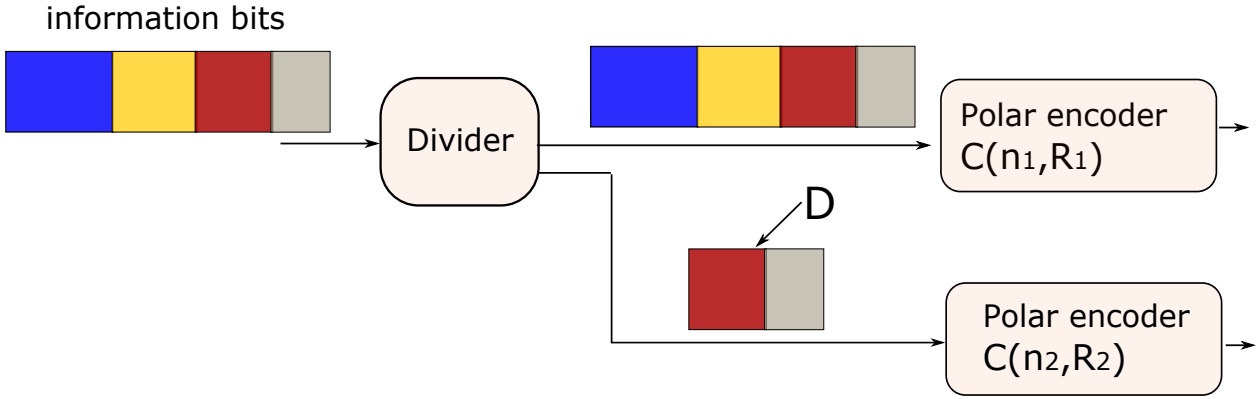
Problem: HARQ-IR with Polar Codes?



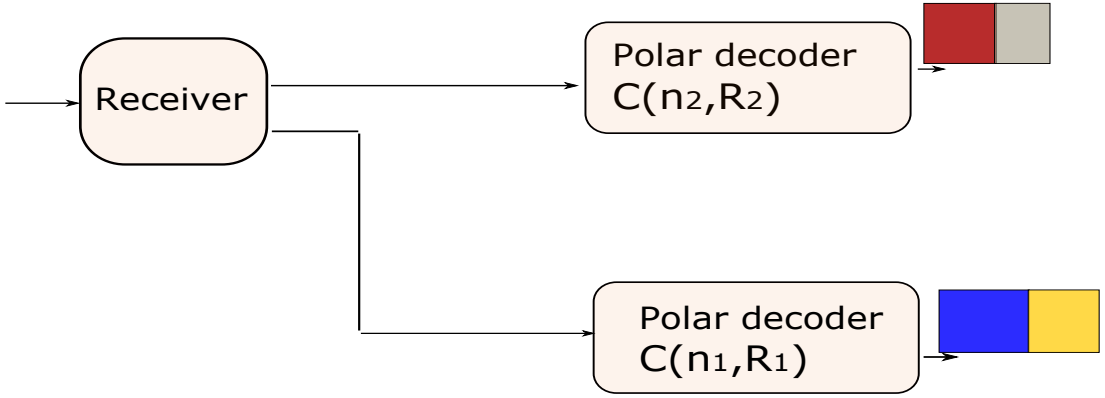
- HARQ-IR requires the same information set for all codes
- Polar code designed for fixed length n
  - Information sets are different for different lengths

Our Solution: Parallel-Concatenated Polar Codes

- Encoder $R_1 > R_2$ (ex. $K = 2$)



- Decoder



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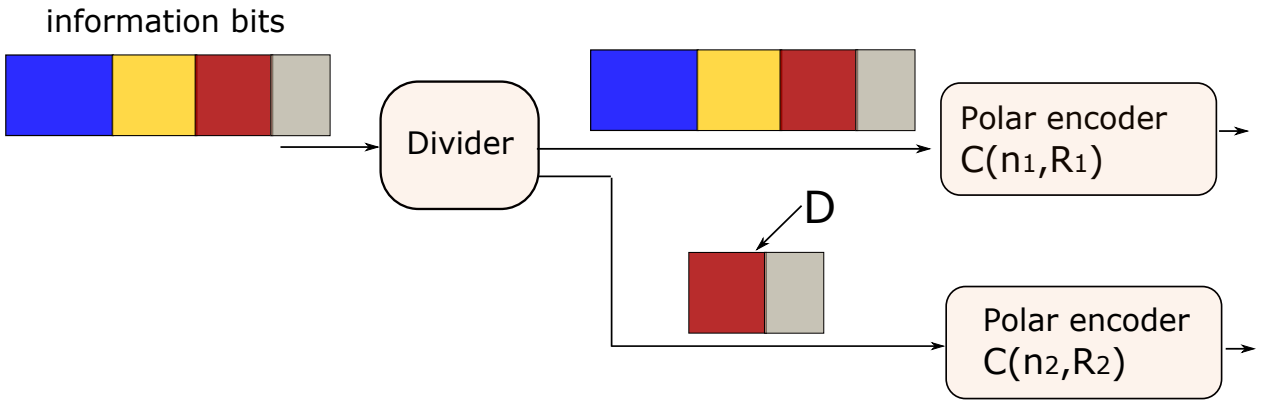
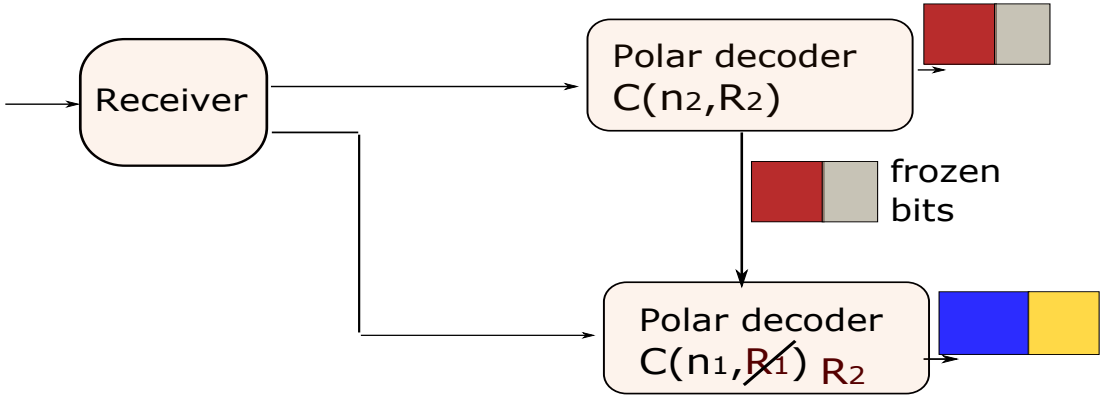


- Decoder



- To choose D, used nested property of polar codes *[Korada, 2009]*

Capacity Result

Theorem *[Hong, Hui & Marić, 2015]*

For any sequence of degraded channels $W_1 \succeq W_2 \succeq \ldots \succeq W_K$ there exists a sequence of rate-compatible punctured polar codes that is capacity-achieving

- Details: arxiv.org/pdf/1510.01776v1.pdf

Summary

Constructed family of rate-compatible polar codes

- Achieves capacity
- Can be used for HARQ-IR

Thank You!