Information Theoretic Concepts of 5G

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IEEE 5G Silicon Valley Summit
November 16, 2015
Outline

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

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  - Remote controlled machines
  - Smart transport infrastructure and vehicles
  - Healthcare
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- 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
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Efficient multihop scheme? What should relays do?
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 channel 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 \( i = 1, 2, \) or 3, a letter \( x_i \) is selected from a finite set \( A_i \) (the input alphabet at terminal \( i \)) 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 \( y_i \) observed at terminal \( i \) belongs to a finite set \( B_i \), the output alphabet at terminal \( i \). The sender at terminal \( i \) sees the letter \( y_i \) 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 input \( (x_1, x_2, x_3) \), but the dependence is re-arranged by the channel and the output becomes a function of the input and the channel. The problem is to determine the capacity of the channel, that is, to find the maximum rate at which information can be sent through the channel if the input and output are constrained to be random variables.

Acknowledgment

In conclusion, the author wishes to express his grateful indebtedness to Professors Solomon Golomb and Albert Whiteman for their guidance and encouragement.

References


IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. 11, NO. 5, SEPTEMBER 1965

Capacity Theorems for the Relay Channel

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

The discrete memoryless relay channel denoted by \( (X_1 \times X_2 \times Y_1 \times Y_2) \) consists of four finite sets: \( X_1, X_2, Y_1, Y_2 \), and a collection of probability distributions \( p (y_1, y_2 | x_1, x_2) \), one for each \( (x_1, x_2) \in X_1 \times X_2 \). The interpretation is that \( y_1 \) is the input to the channel and \( y_2 \) is the output, \( x_1 \) 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 \( y_2 \).

The relay channel was introduced by van der Meulen [1], [2], [3], [7] and has also been studied by others for various channel models. The channel was first studied by van der Meulen [1] and [2]. The channel is a discrete-time communication channel with three users: the sender \( S_1 \) and \( S_2 \) and the receiver \( R \). The sender \( S_1 \) transmits a binary message \( m \) to the relay \( R \). The relay \( R \) transfers the message \( m \) to the receiver \( S_2 \). The problem is to find the capacity of the channel between the sender \( S_1 \) and the receiver \( S_2 \).
Multihop Schemes in Practice

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

- 5G will deploy multihop communications
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- Not much practical impact
  - Too complex?
  - There was no need?

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Multihop Communications for 5G
Multihop Backhaul for Ultra-dense Networks
Multihop MTC?

70000 tracking devices

9 Gbyte/user/hour

480 Gbps/km²
Current Proposal for 5G

Interference-avoidance routing
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Each relay performs store-and-forward

Establish routes iteratively

Works well in low interference

Does not work in high interference
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 ► Establish routes iteratively
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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
Decode vs. Quantize

Routing

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- Worst relay is a bottleneck

Quantize

- Any relay can quantize source signal

References:

- Avestimehr et al., 2009
- Lim et al., 2011
- Hou & Kramer, 2013
Decode vs. Quantize

Routing

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

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

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

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Relay Selection

Group relaying

source

destination
Relay Selection

Group relaying
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source

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Relay Selection

Group relaying
Relay Selection

Layered network
To Improve Performance: Adaptive Scheme

A relay chooses a forwarding scheme based on SNR:
- Relays with good channels decode-and-forward.
- The rest of relays quantize.

How much to quantize?
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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

- Derived closed form solution for the rate, for any relay configuration [Hong, Marić, Hui & Caire, ISIT 2015, ITW 2015]
- Better performance with a simpler scheme!
Channel Coding for 5G

Information source → Source encoder → Channel encoder → Modulator → Channel

User → Source decoder → Channel decoder → Demodulator
Choosing Channel Codes for 5G

- Main considerations
  - Performance, complexity, rate-compatibility
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- LTE deploys turbo codes [Berrou et. al., 1993]
  - Perform within a dB fraction from channel capacity
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- Why Beyond Turbo Codes?
Choosing Channel Codes for 5G

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  - 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 $O(n \log n)$
- Better energy-efficiency for large $n$ than other codes
- Code construction is deterministic
- No error floor
Channel Polarization

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.
Channel Polarization

\[ \begin{align*}
U_1 & \quad \oplus \quad X_1 \quad W \quad Y_1 \\
U_2 & \quad \quad \quad \quad X_2 \quad W \quad Y_2
\end{align*} \]

\[ G_2 \triangleq \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \]
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

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- $n$ instances of a channel are transformed into a set of channels that are either noiseless or pure-noise channels.
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- Polar code: send information bits over good channels.
- Fraction of good channels approaches the capacity of the original channel.
Wireless Channel is Time-Varying
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- Hybrid ARQ with Incremental Redundancy (HARQ-IR)
  - Send additional coded bits until decoding is successful
Encode for degraded channels $W_1 \preceq W_2 \preceq \ldots \preceq W_K$ with capacities $C_1 \geq C_2 \geq \ldots \geq C_K$

1st transmission

2nd transmission

Kth

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
Our Solution: Parallel-Concatenated Polar Codes

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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!