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Cooperative Communications, Distributed Coding and Machine Learning

Presented by

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Outline

- ❑ Background and Motivation
- ❑ Cooperative Communications Models
- ❑ Distributed Coding Schemes
- ❑ Channel Capacity
- ❑ Iterative Learning based Code Design
- ❑ Near-Capacity System Design
- ❑ Applications in UAV Network
- ❑ Conclusions

Background: MIMO

- ❑ Single-Input Single-Output (SISO) channel has limited capacity.
- ❑ Multiple-Input Multiple-Output (MIMO) channel
  - ⇨ Higher capacity than (SISO) channel [1];
  - ⇨ Based on multiple antennas (transmit and/or receive);
  - ⇨ *Small mobile unit: correlation of signals.*
- ❑ Cooperative Communications
  - ⇨ Virtual MIMO;
  - ⇨ Feasible with a single antenna at each User Equipment (UE);
  - ⇨ User cooperation: independent fading [2].

[1] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Transactions on Telecommunication*, vol. 10, pp. 585–595, Nov–Dec 1999.

[2] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity part I: System description," *IEEE Transactions on Communications*, vol. 51(11), pp. 1927–1938, 2003.

Background: Cooperative Communications

- Cooperative communications protocols [3,4]:
  - Decode-and-Forward: *error propagation*
  - Amplify-and-Forward: *noise enhancement*
  - Compress-and-Forward: *error propagation*
  - Coded-Cooperation: *error propagation*

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior", IEEE Transactions on Information Theory, vol. 50, pp. 30623080, Dec. 2004.

[4] A. Host-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels", IEEE Transactions on Information Theory, vol. 51, pp. 20202040, June 2005.

Background: Classical Codes

- Shannon's communication theory [5] (1948) states that reliable communication can be achieved whenever the transmission rate is lower than the channel capacity.
- The quest for near-capacity channel codes has led to various classical codes.
- Block codes: Hamming codes [6] (1950), Reed-Solomon Codes [7] (1960).
- Convolutional codes: encoder [8] (1955), Viterbi decoder [9] (1971).

[5] C. E. Shannon, "A mathematical theory of communication," *Bell System Technical Journal*, pp. 379–427, 1948.

[6] R.W. Hamming, "Error detecting and error correcting codes," *Bell Syst. Tech. Journal*, vol. 29, pp. 41–56, 1950.

[7] I.S. Reed and G. Solomon, "Polynomial codes over certain finite fields," *J. Soc. Ind. Appl. Math.*, vol. 8, pp. 300–304, June 1960.

[8] P. Elias, "Coding for noisy channels," *IRE Conv. Rept.*, pp. 37–47, 1955.

[9] A. Viterbi, "Convolutional codes and their performance in communication systems," *IEEE Transactions on Communications*, vol. 19, pp. 751–772, October 1971.

Background: Concatenated Codes

- Forney proposed concatenated codes in 1966 [10].
- Berrou, Glavieux and Thitimajshima invented Turbo codes in 1993 [11].
- Gallager invented LDPC codes in 1962 [12].
- MacKay and Neal revives LDPC codes in 1995 [13].

[10] G. Forney, *Concatenated codes*. Cambridge: MIT Press, 1966.

[11] C. Berrou and A. Glavieux and P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo codes," in *Proceedings of the International Conference on Communications*, (Geneva, Switzerland), pp. 1064–1070, May 1993.

[12] R. Gallager, "Low-density parity-check codes," *IRE Transactions on Information Theory*, vol. 8, no. 1, pp. 21–28, January 1962.

[13] MacKay and Neal, "Good codes based on very sparse matrices," in *IMA: IMA Conference on Cryptography and Coding, LNCS lately (earlier: Cryptography and Coding II, Edited by Chris Mitchell, Clarendon Press, 1992)*, 1995.

Background: More Codes

- ❏ Robertson and Wörz proposed Turbo Trellis Coded Modulation (TTCM) in 1995 [14].
- ❏ Loeliger proposed Self Concatenated Convolutional Codes in 1997 [15].
- ❏ Tarokh, Seshadri and Calderbank invented Space-Time Trellis Codes in 1997 [16].
- ❏ Arikan proposed Polar Codes in 2009 [17].
- ❏ Distributed coding [18] were proposed for cooperative communications.

[14] P. Robertson and T. Worz, ”Coded modulation scheme employing turbo codes,” in Electronics Letters, 31 Aug. 1995.

[15] H.-A. Loeliger, “New turbo-like codes,” in *IEEE International Symposium on Information Theory*, Ulm, 1997.

[16] V. Tarokh *et. al.*, “Space-Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction,” in *Proceeding of IEEE International Conference on Communications*, Montreal, Canada, June 1997.

[17] E. Arikan, ”Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels”. IEEE Transactions on Information Theory. 55 (7): 3051–73, 2009.

[18] Y. Li, “Distributed coding for cooperative wireless networks: an overview and recent advances,” IEEE Communications Magazine, 2009.

Background: Machine Learning

- Machine Learning (ML): the design and analysis of algorithms, which enable machines/computers to learn and solve problems. ML have been developed over the decades to a state that they are now working really well.
- ML based AlphaGo has beaten human Go champion in 2017 [19].
- ML can be used for assisting the next generation wireless networks [20].
- Research works are continually been done for creating ML based intelligent wireless networks.

[19] "Google AI defeats human Go champion", BBE News 25 May 2017.

[20] C. Jiang, H. Zhang, Y. Ren, Z. Han, K. Chen and L. Hanzo, "Machine Learning Paradigms for Next-Generation Wireless Networks," in IEEE Wireless Communications, April 2017.

Motivation

- Cooperative communications for creating a MIMO channel.
- Distributed coding for achieving the MIMO channel capacity.
- Machine learning for code design and wireless system applications.

Cooperative Communications Models

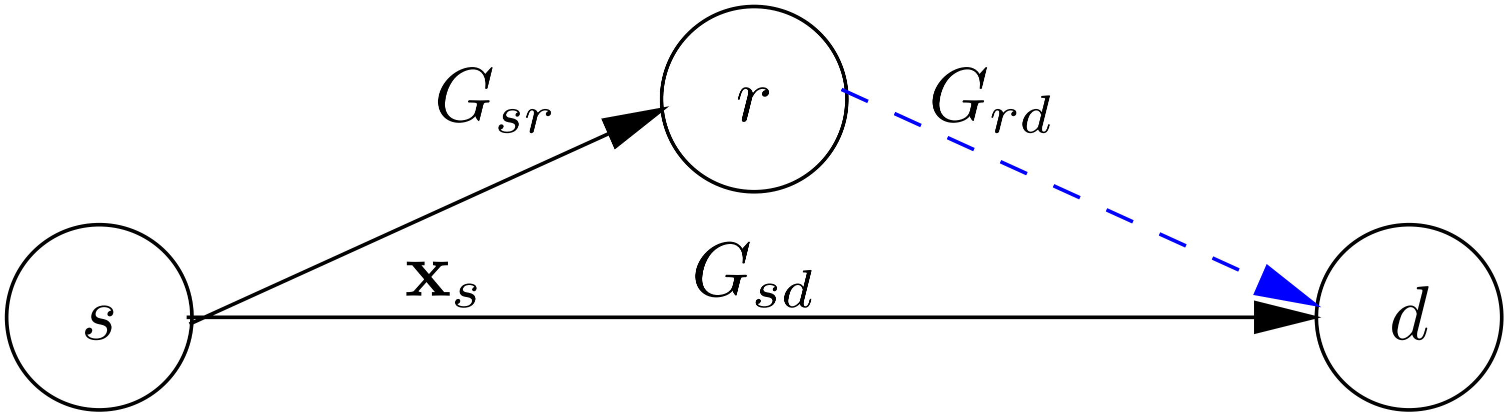

Figure 1: Single relay model. A source (s), a relay (r) and a destination (d). The reduced-distance related path gain between node A and node B is given by $G_{AB} = \left(\frac{d_0}{d_{AB}}\right)^{\Phi}$, where Φ is the pathloss exponent, d_0 is the reference distance and d_{AB} is the distance between node A and node B. $2L$ symbol periods to transmit L source symbols ($\mathbf{x}_s$).

Cooperative Communications Models

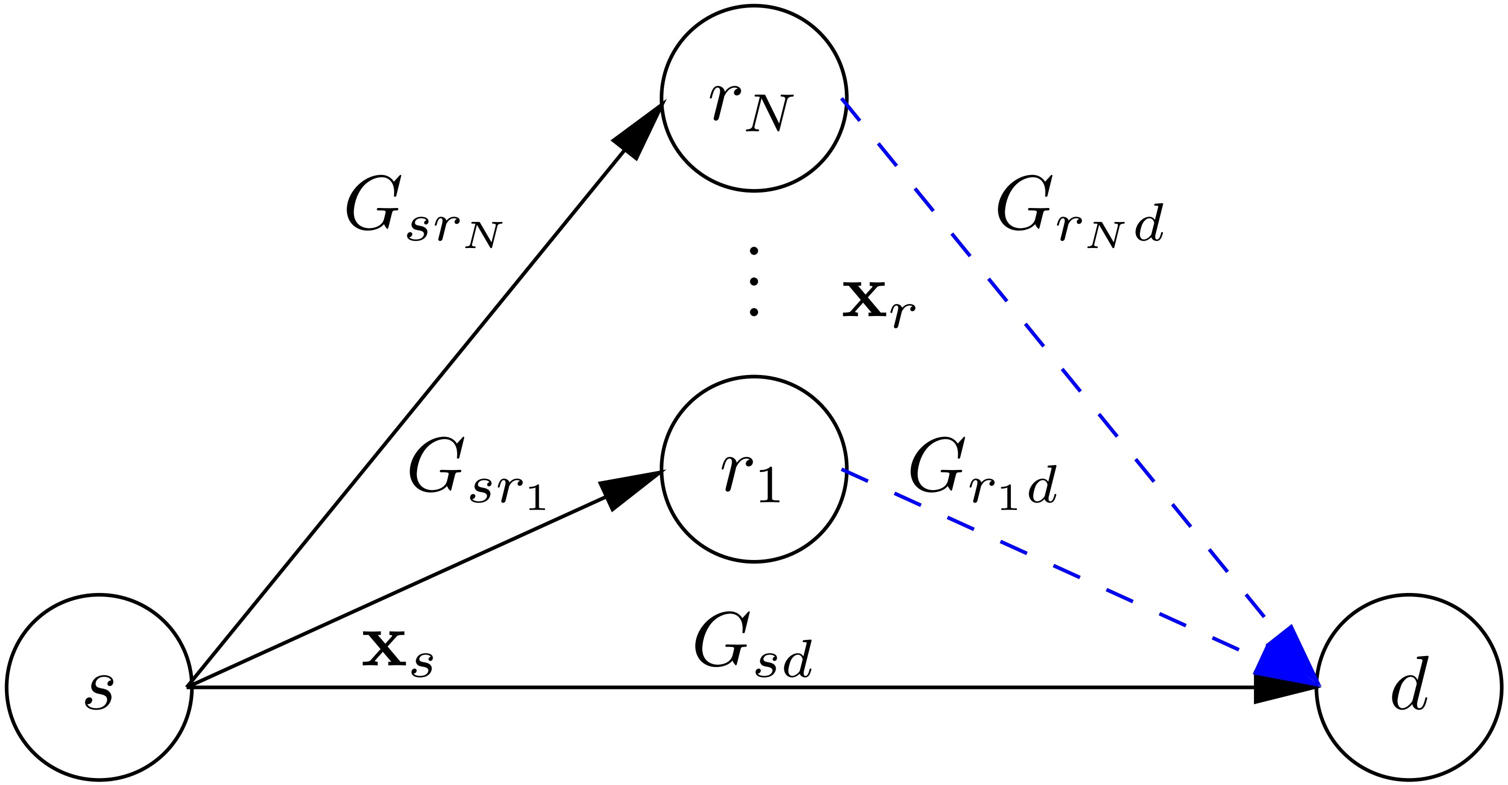

Figure 2: Multiple relays model. $2L$ symbol periods to transmit L source symbols ($\mathbf{x}_s$) and L relay symbols ($\mathbf{x}_r$) to the destination.

Cooperative Communications models

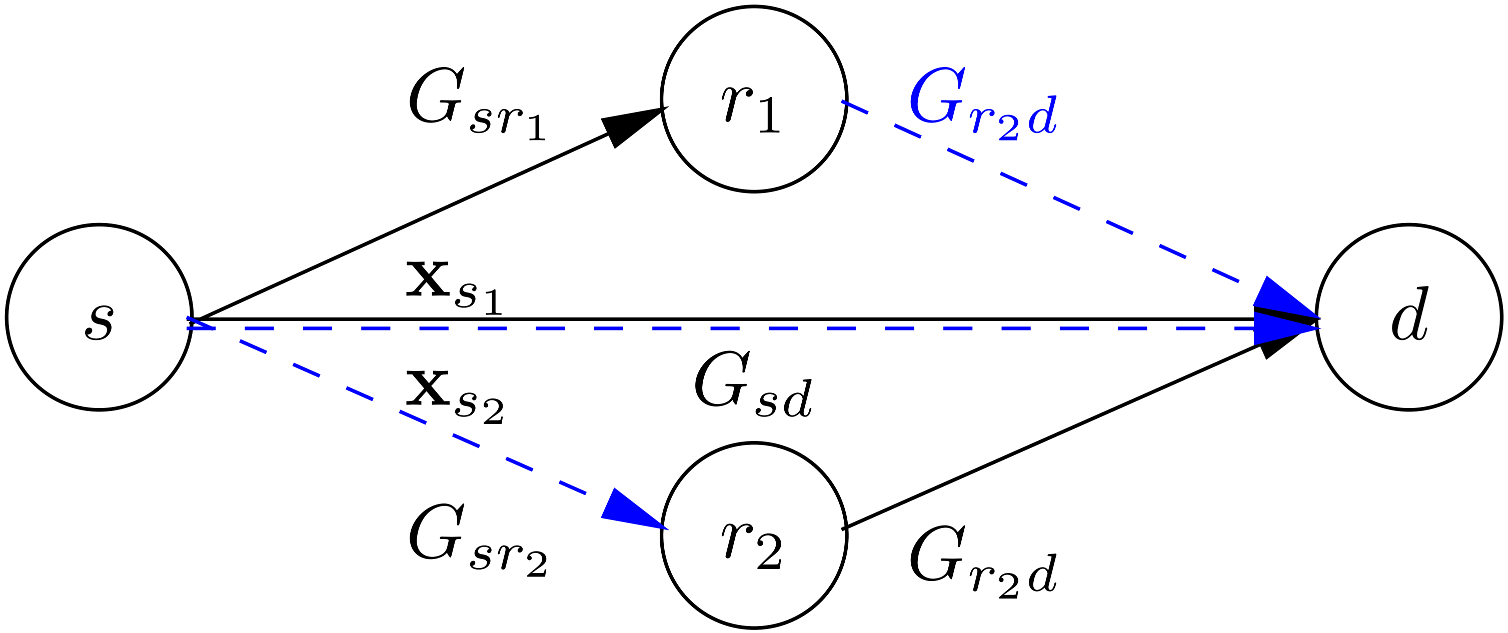

Figure 3: Successive relaying model. $L+2$ (instead of $2L$) symbol periods to transmit L source symbols.

Cooperative Communications Models

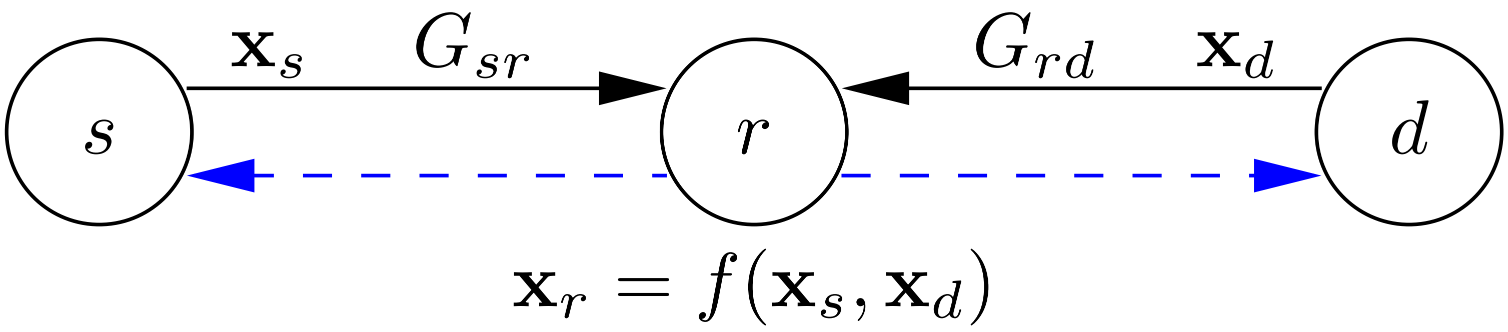

Figure 4: Two ways relaying model. L symbol periods to transmit $L/2$ source symbols ($\mathbf{x}_s$) and $L/2$ destination symbols ($\mathbf{x}_d$). Network coding is used at the relay.

Cooperative Communications Models

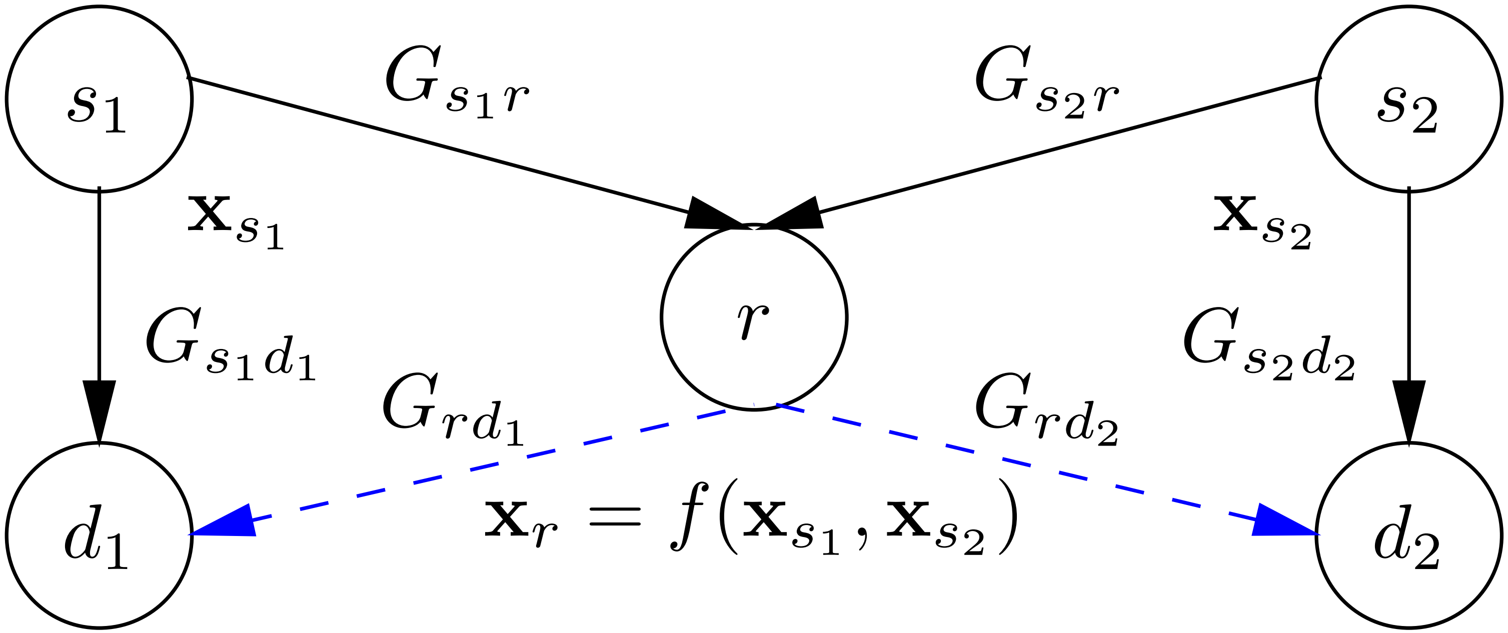

Figure 5: Butterfly relaying model. L symbol periods to transmit $L/2$ source 1 symbols ($\mathbf{x}_{s_1}$) and $L/2$ source 2 symbols ($\mathbf{x}_{s_2}$). Network coding is used at the relay.

Footprint

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- Cooperative Communications Models
- **Distributed Coding Schemes**
- Channel Capacity
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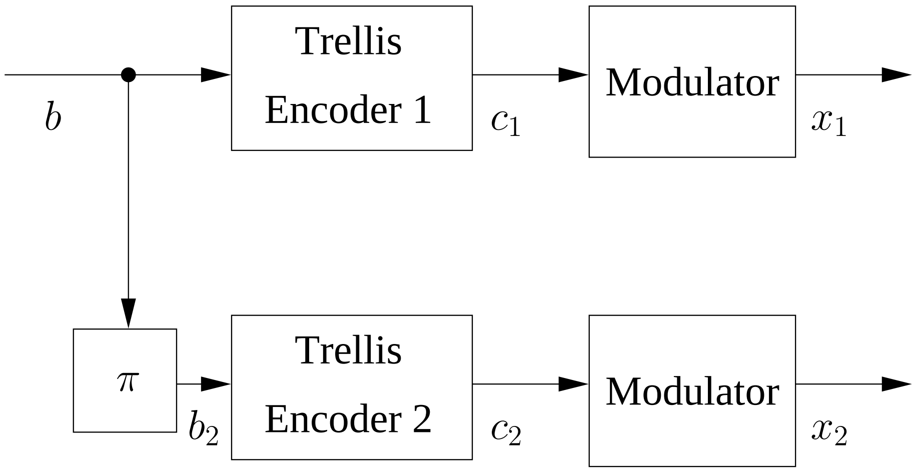
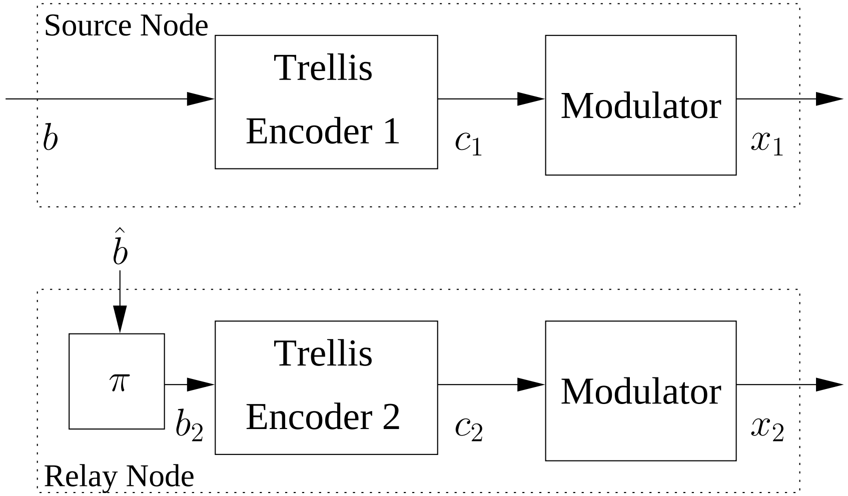
Distributed Coding Schemes

❑ Distributed Turbo Codes (DTCs) have been proposed for cooperative communications [21]:





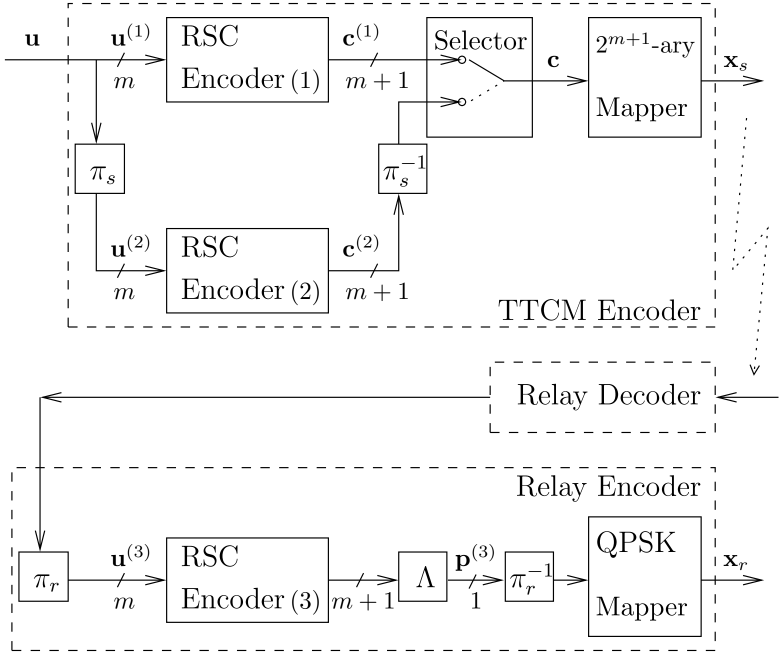
⇨ Benefits from turbo processing gain;

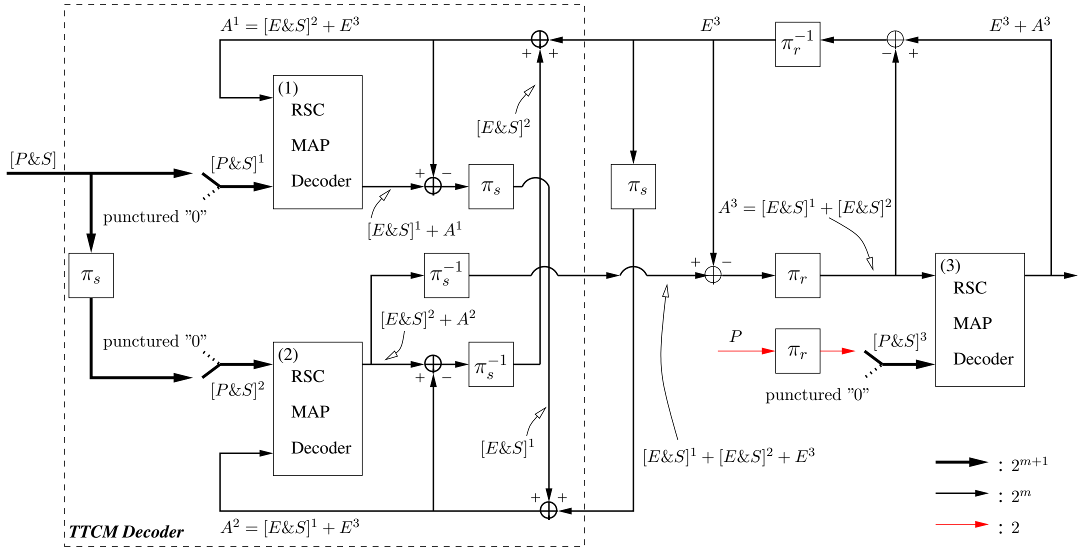
⇨ Assumption: perfect communication link between the source and relay nodes.

[21] B. Zhao and M. Valenti, "Distributed turbo coded diversity for relay channel," *Electronics Letters*, vol. 39, pp. 786–787, May 2003.

Distributed Coding Schemes

❑ A three-component Distributed Turbo Trellis Coded Modulation (DTTCM) scheme was proposed in 2009 [22]:





⇨ Considers an imperfect source-to-relay communication link.

[22] S. X. Ng, Y. Li and L. Hanzo, "Distributed turbo trellis coded modulation for cooperative communications," in *ICC'09*, (Dresden, Germany), 14-18 June 2009.

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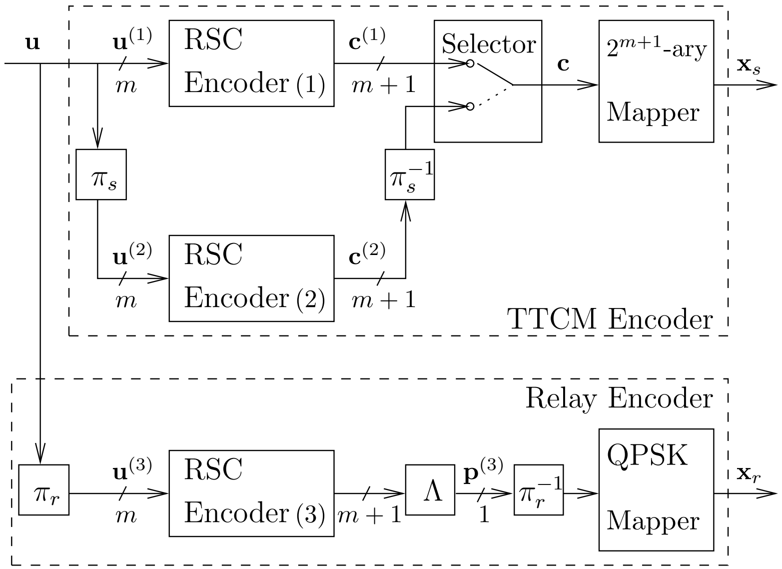

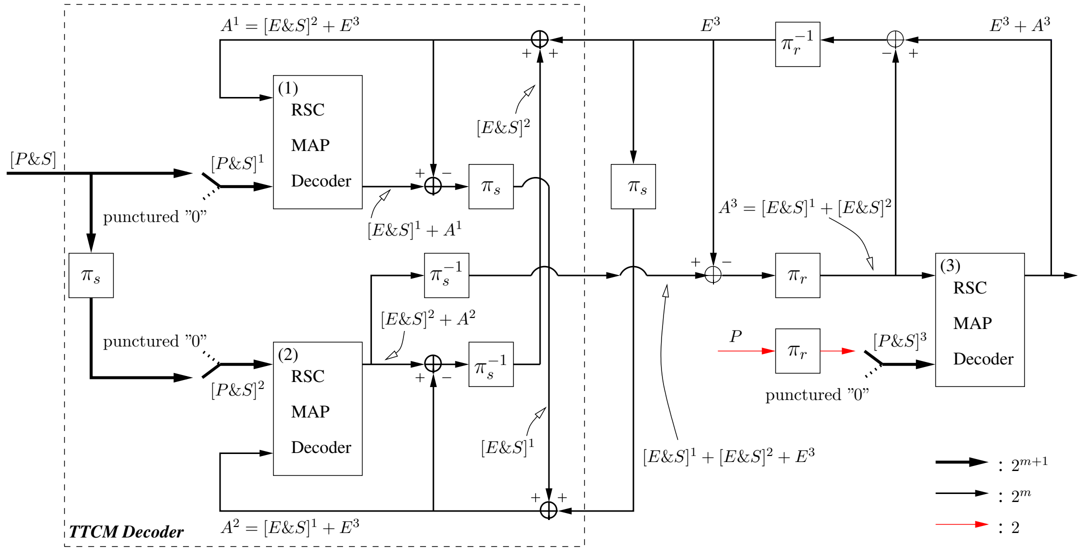

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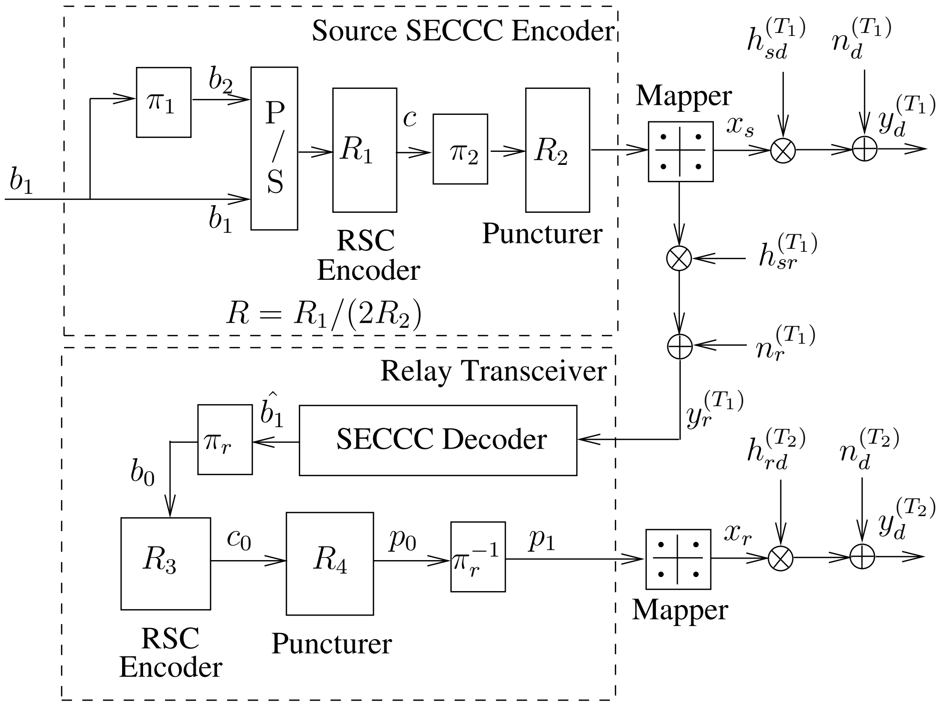
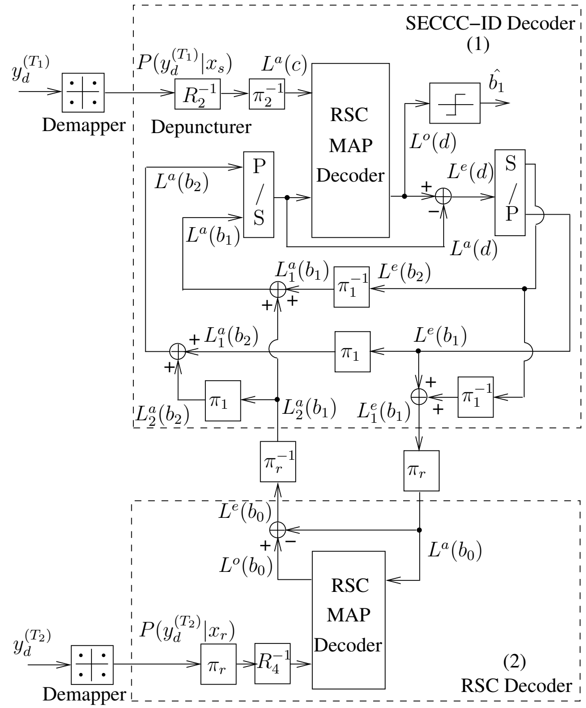
[22] S. X. Ng, Y. Li and L. Hanzo, “Distributed turbo trellis coded modulation for cooperative communications,” in *ICC’09*, (Dresden, Germany), 14-18 June 2009.

Distributed Coding Schemes

❑ A two-component Distributed Self-Concatenated Convolutional Coding (DSECCC) scheme was proposed in 2010 [23]:





[23] M. F. U. Butt, R. A. Riaz, S. X. Ng and L. Hanzo, ”Distributed Self-Concatenated Coding for Cooperative Communication”, IEEE Transactions on Vehicular Technology, vol. 59, no. 6, July 2010.

Distributed Coding Schemes

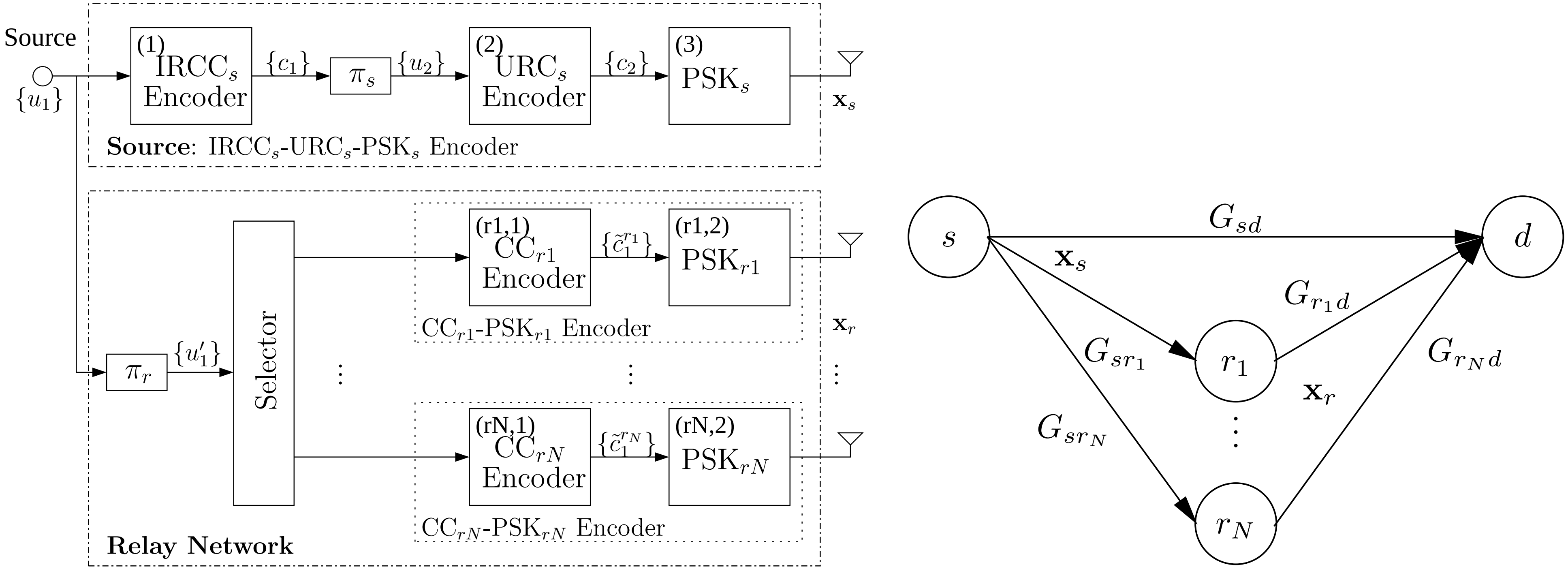
- ❑ Capacity-approaching distributed turbo codes for half-duplex relay system have been proposed in 2007 [24]:
  - ⇨ Specific to a given network topology.
- ❑ Near-capacity Irregular Distributed Space-Time coding scheme for successive relaying was proposed in 2010 [25]:
  - ⇨ Suitable for arbitrary relay network configurations.

[24] Z. Zhang and T. Duman, “Capacity-approaching turbo coding for half-duplex relaying,” *IEEE Transactions on Communications*, vol. 55, pp. 1895–1906, Oct. 2007.

[25] L. Kong, S. X. Ng, R. G. Maunder and L. Hanzo, ”Near-Capacity Cooperative Space-Time Coding Employing Irregular Design and Successive Relaying”, IEEE Transactions on Communications, August 2010.

Distributed Coding Schemes

- Distributed Irregular Convolutional Codes (DIRCCs) was investigated and proposed for cooperative communications in 2014 [26]:



[26] S. X. Ng, Y. Li, B. Vucetic and L. Hanzo, ”Distributed Irregular Codes Relying on Decode-and-Forward Relays as Code Components”, IEEE Transactions on Vehicular Technology, 2014.

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Channel Capacity: Direct Link

- Consider a MIMO scheme modelled as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \,, \tag{1}$$

$\mathbf{y} \in \mathbb{C}^{N_r \times 1}$, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$, $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$, $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$.

- The capacity of the Discrete-input Continuous-output Memoryless Channel (DCMC) for a MIMO system using an M-ary PSK/QAM signal set can be derived as:

$$C = \max_{P(\mathbf{x})} I(\mathbf{x};\mathbf{y}) = \log_2(M) - \frac{1}{M}\sum_{m=1}^{M} \mathsf{E}\left[\log_2 \sum_{n=1}^{M} \exp(\Psi_{m,n}) \,\middle|\, \mathbf{x}^{(m)}\right] , \tag{2}$$

where the exponent $\Psi_{m,n}$ is given by:

$$\Psi_{m,n} = \frac{-\left|\left|\mathbf{H}(\mathbf{x}^{(m)} - \mathbf{x}^{(n)}) + \mathbf{n}\right|\right|^2 + \left|\left|\mathbf{n}\right|\right|^2}{N_0} \,. \tag{3}$$

Relay Channel Capacity

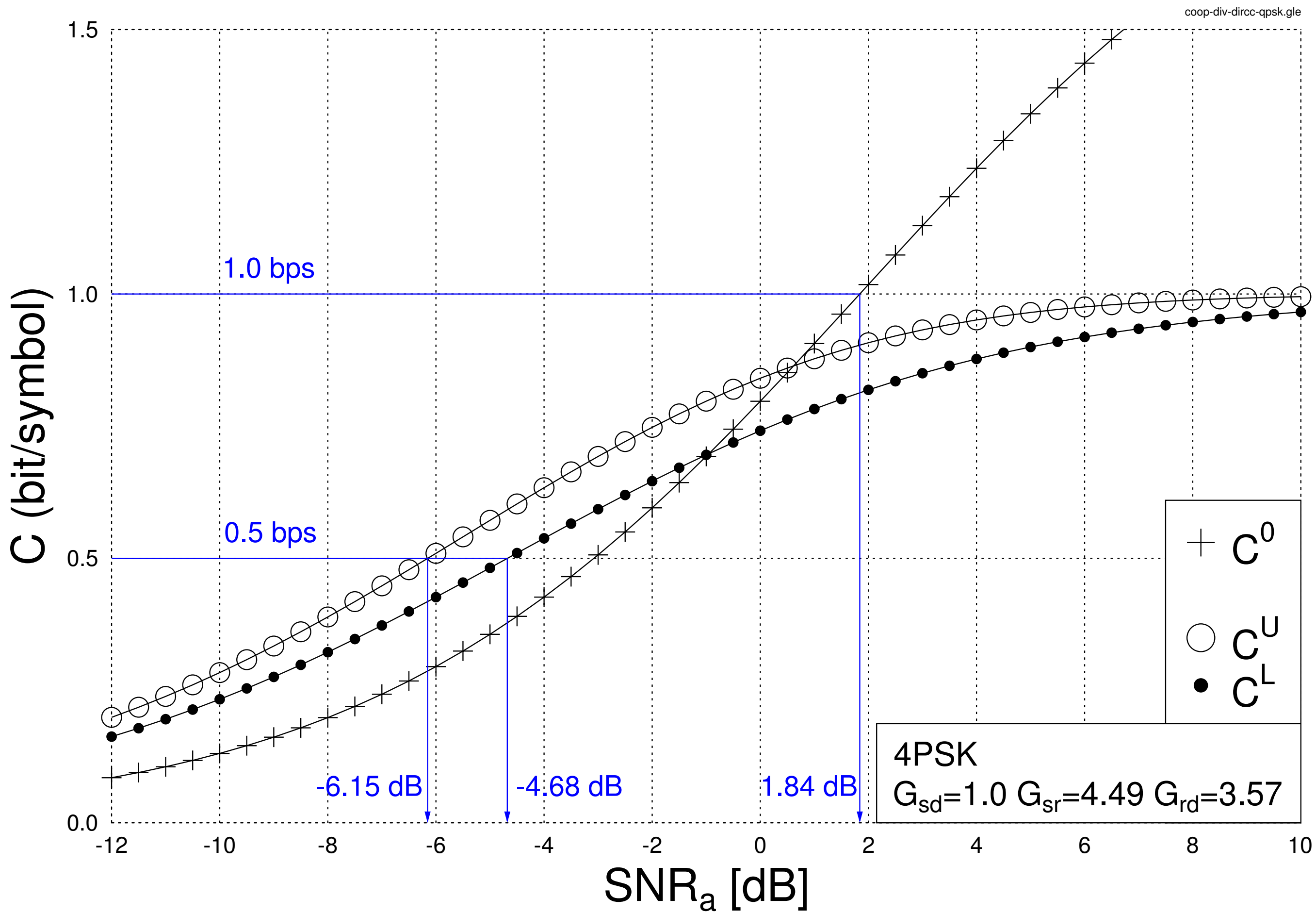
The upper bound C^{U} and lower bound C^{L} of the relay channel capacity of the two-hop half-duplex relay network can be computed as:

$$C^{\mathsf{U}} = \min\left\{\lambda C_{(s\to r,d)}\ ;\ \lambda C_{(s\to d)} + (1-\lambda)C_{(r\to d)}\right\}\ , \tag{4}$$

$$C^{\mathsf{L}} = \min\left\{\lambda C_{(s\to r)}\ ;\ \lambda C_{(s\to d)} + (1-\lambda)C_{(r\to d)}\right\}\ , \tag{5}$$

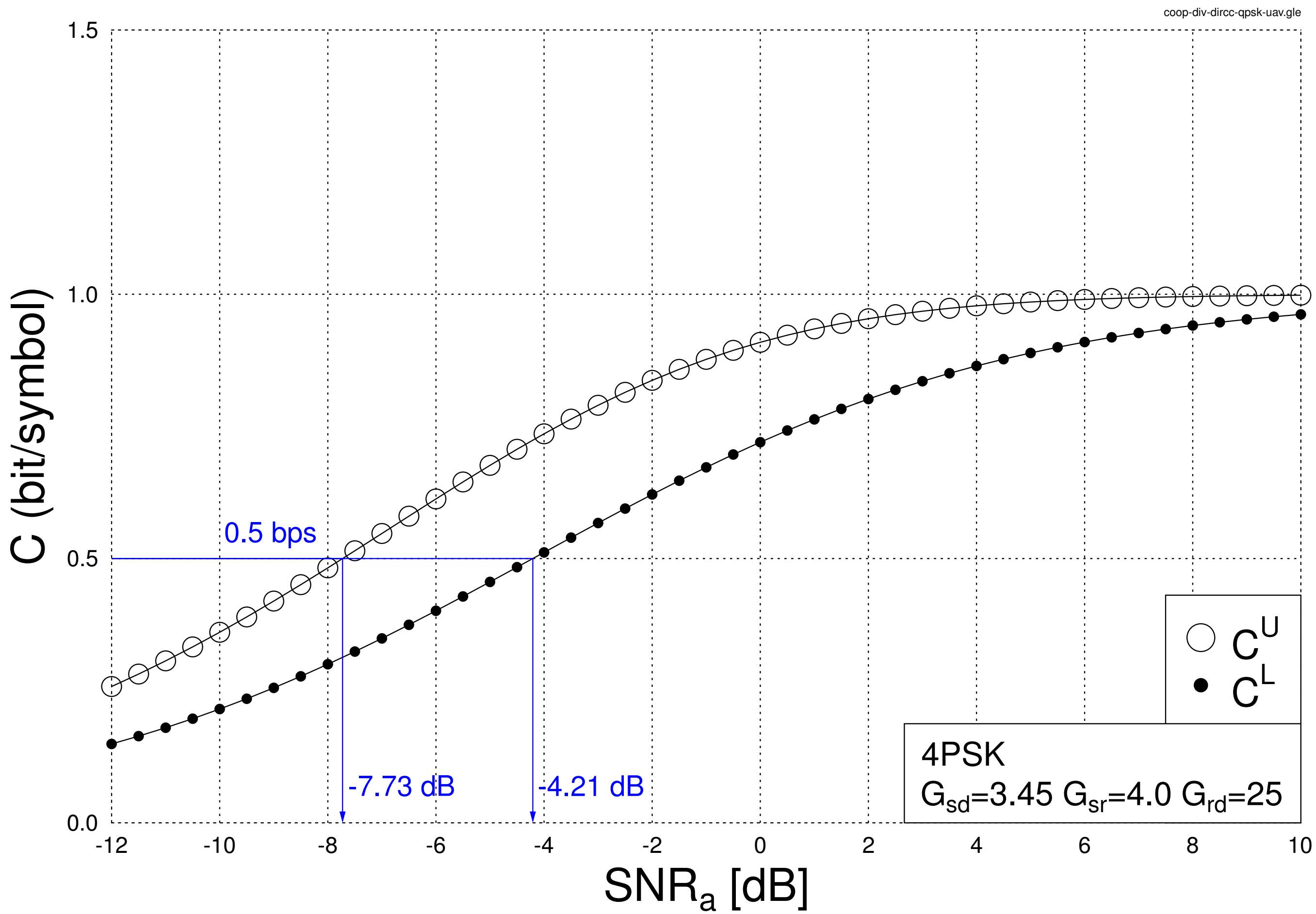
where $C_{(a\to b,c)}$ is the capacity of the channel between the transmitter at node a and the receivers at both node b and node c. The ratio of the first transmission period to the total transmission period is given by $\lambda = N_s/(N_s + N_r)$.

Relay Channel Capacity: Weak R-D Link



- ❑ Discrete-input Continuous-output Memoryless Channel (DCMC): upper bound (C^U) and lower bound (C^L) for $\lambda = 0.5$, as well as the capacity of non-cooperative scheme (C^0).

Relay Channel Capacity: Strong R-D Link



- Discrete-input Continuous-output Memoryless Channel (DCMC): upper bound (C^U) and lower bound (C^L) for $\lambda = 0.5$.

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Conclusions

- Cooperative communications can create a high-capacity virtual MIMO channel.
- Distributed Irregular Convolutional Code (DIRCC) has been introduced and proposed for approaching the virtual MIMO channel capacity.
- EXIT charts based iterative learning algorithm can be invoked for creating near-capacity DIRCC schemes.
- Machine learning can be used for code design and drone location assigmnet for UAV network.
- Cooperative communications, distributed coding and machine learning are the enabling technologies for next generation wireless systems.

Thank you!