Fundamental Bounds for Communications with Reconfigurable Surfaces

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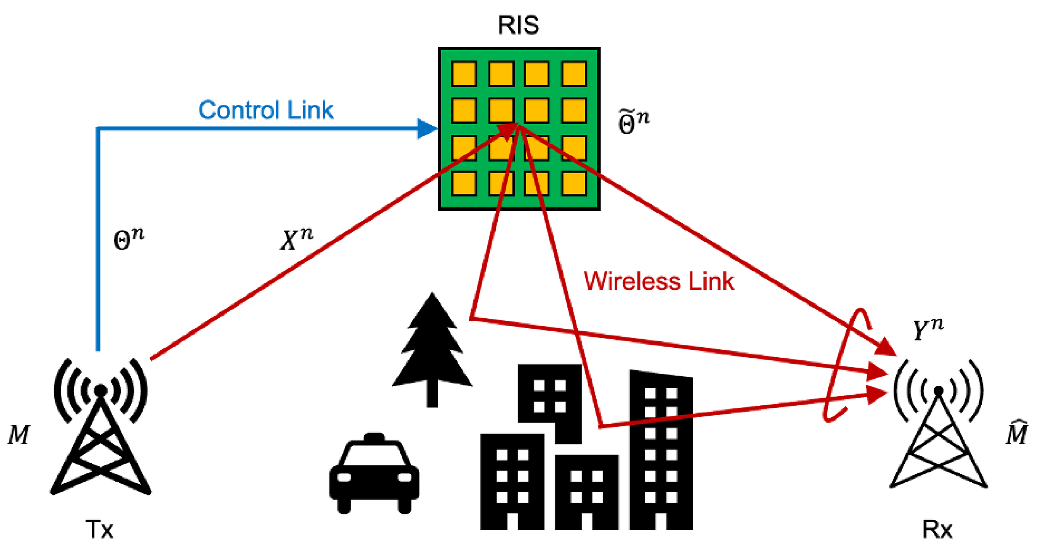
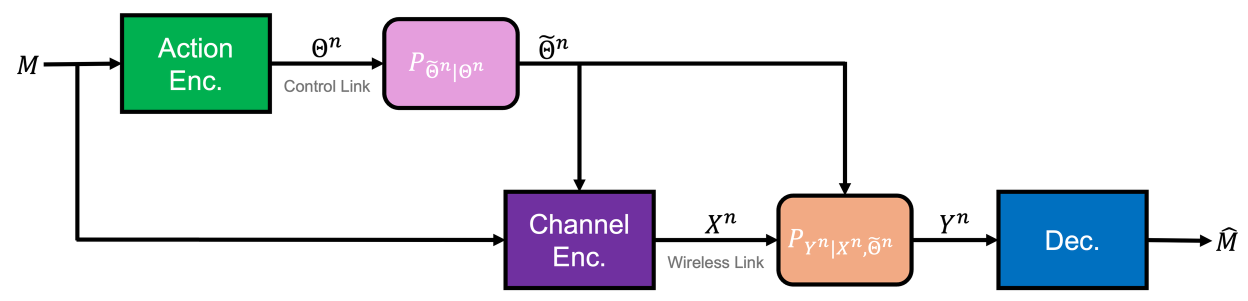
Problem Statement

RIS-assisted Communications



- Shape the wireless propagation environment by adjusting the phase shifts of reconfigurable intelligent surface (RIS) [1].
- **Objective:** Higher data rates, enhanced signal propagation and network coverage, more energy-efficient communication.

Information Theoretic Model

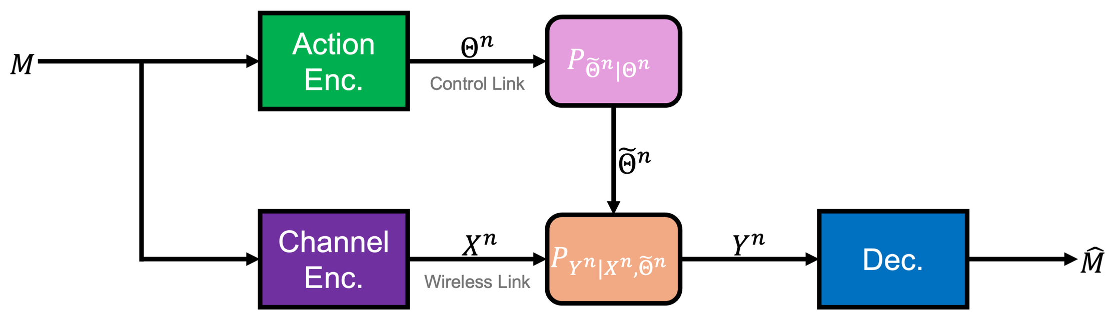


With state information **causally** available at channel encoder [2]:

- Capacity: $C = \max_{P_{U,\Theta,X,\tilde{\Theta},Y}} I(U;Y)$.
- $|\mathcal{U}| \leqslant \{|\Theta|\,|\tilde{\Theta}|\,|\mathcal{X}|+1, |\mathcal{Y}|\}$.

With state information **non-causally** available at channel encoder [2]:

- Capacity: $C = \max_{P_{U,\Theta,X,\tilde{\Theta},Y}} \left[I(U;Y) - I\left(U;\tilde{\Theta}|\Theta\right)\right]$.
- $|\mathcal{U}| \leqslant |\Theta|\,|\tilde{\Theta}|\,|\mathcal{X}|+1$.



Without state information available at channel encoder:

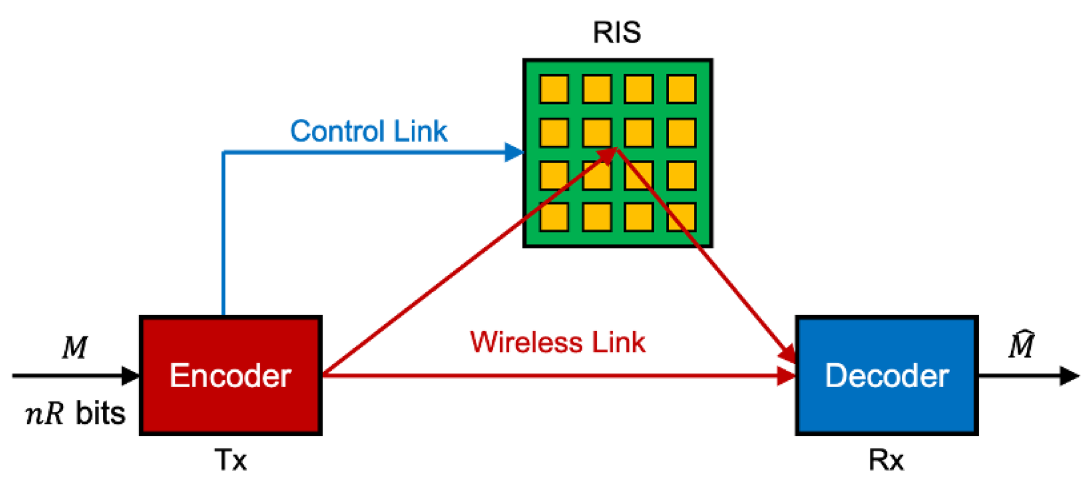
- Capacity: $C = \max_{P_{\Theta,X,Y}} I(\Theta, X; Y)$.
- RIS controls (states) do not work on channel encoder.

State of the Art

Comparison between the max-SNR scheme (beamforming) and modulating information on the RIS phase shifts:

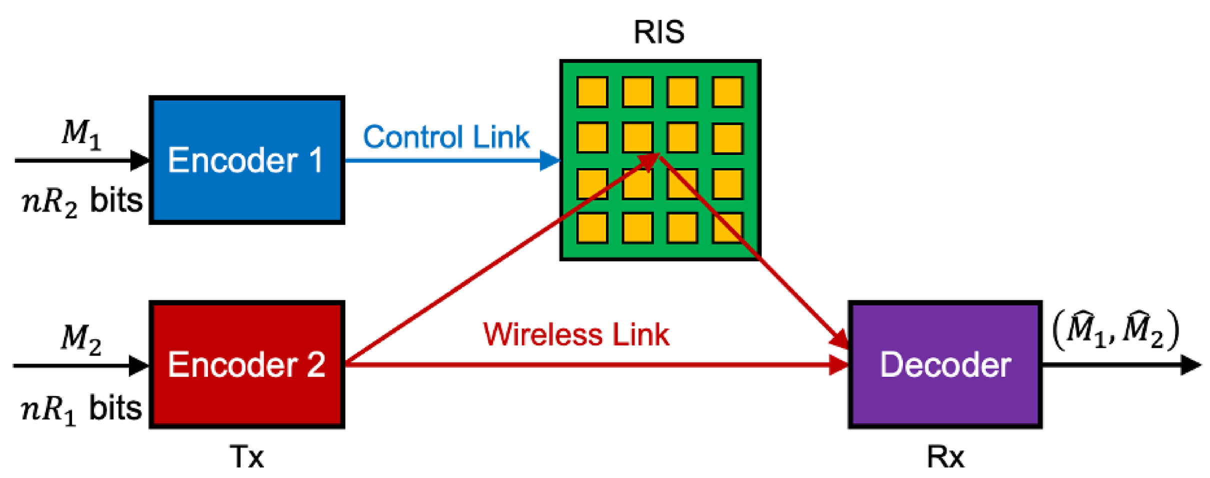
- **Max-SNR scheme**, which aims to maximize the received SNR during each coherence block, does not fully exploit the potential of the RIS: $\max_{P_{X|\hat{h}}(X|\hat{h})} I\left(X;Y|\hat{h},\theta^*\right)$.
- **Modulating information on the RIS phase shifts** is able to significantly enhance the spatial degrees of freedom (DoF) [3]: $\max_{P_{X,\theta|\hat{h}}(X,\theta|\hat{h})} I\left(X,\theta;Y|\hat{h}\right)$.

Joint Encoding [4, 5]



- **Joint encoding:** the transmitter jointly encodes messages onto the transmitted signals and RIS phase shifts, in which the transmitter can control the state of the RIS via a finite-rate control link.
- **Equivalent channel: point-to-point MIMO** channel.
- In the low-SNR regime, or for highly rank-deficient channels or channels with a strong line-of-sight (LOS) link, the optimal RIS configuration reduces to beamforming.

RIS-assisted SR [6, 7]



- **RIS-assisted symbiotic radios (SR):** the active transmitter and the passive RIS are regarded as the primary and secondary transmitters, respectively, each transmitting its own data independently.
- **Equivalent channel:** multiplicative multiple access channel (**M-MAC**).
- Instead of the achievable rate or the channel capacity, the fundamental performance limits of the M-MAC should be characterized by its capacity region.

Reproduced Simulation Results in [4]

Assumptions of system:

- Set of RIS phase shifts $\mathcal{A} = \left\{0, \frac{2\pi}{A}, \dots, \frac{2\pi(A-1)}{A}\right\}$ (uniformly spaced phases).
- 1 transmitter antenna, 2 receiver antennas.
- Direct link between transmitter (Tx) and receiver (Rx) is blocked. Tx-RIS and RIS-Rx links are independent.
- Tx-RIS link: the channel vector is over $\mathcal{CN}(0, \mathbf{I}_K)$.
- RIS-Rx link: the elements of channel matrix are i.i.d. over $\mathcal{CN}(0,1)$.

Simulation parameter setup for Fig. 1:

- 3 RIS elements ($K=3$).
- 2 available phase shifts ($A=2$).
- RIS control rate factor $m=2$.

Simulation parameter setup for Fig. 2:

- 2 RIS elements ($K=2$).
- 2 available phase shifts ($A=2$).
- Average power constraint $P=40$ dB.

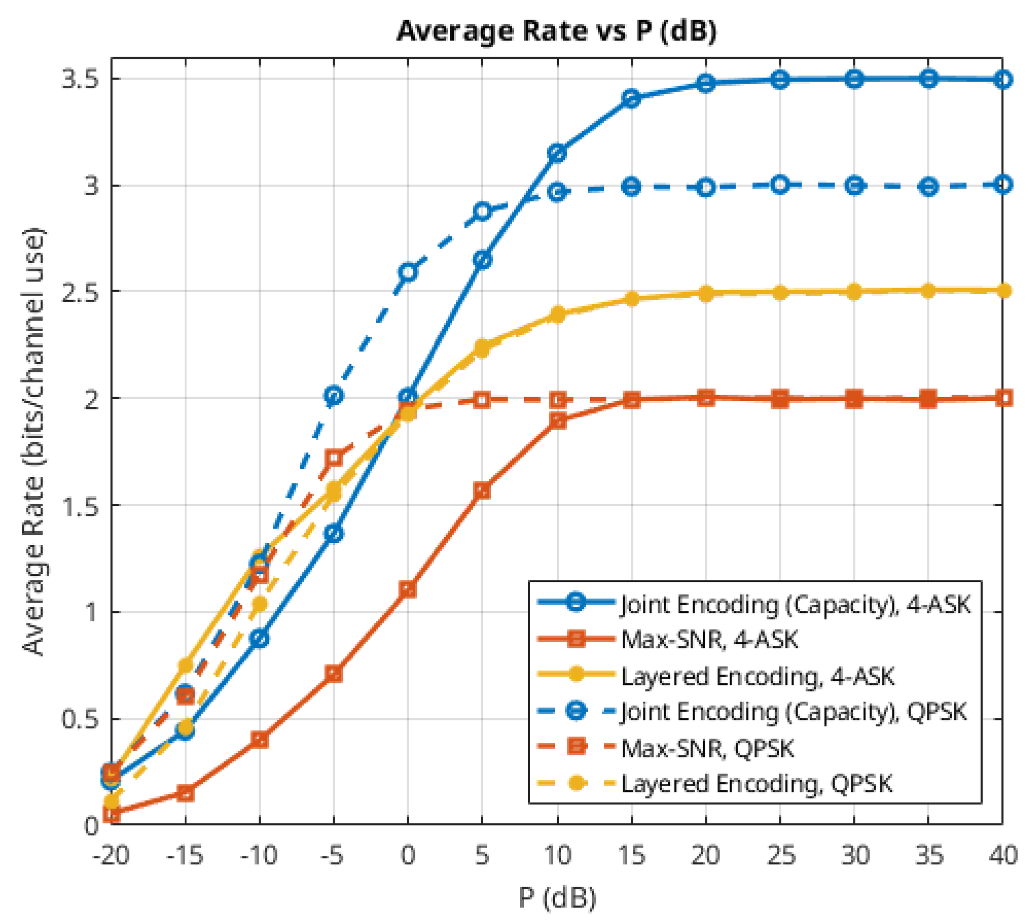


Fig. 1. Average rate vs power constant P for 4-ASK (solid lines) and QPSK (dashed lines) input constellations $\mathcal{B} = \{\pm\sqrt{P}, \pm i\sqrt{P}\}$ and $\mathcal{B} = \{\beta, 3\beta, 5\beta, 7\beta\}$ ($\beta = \sqrt{\frac{P}{21}}$), respectively.

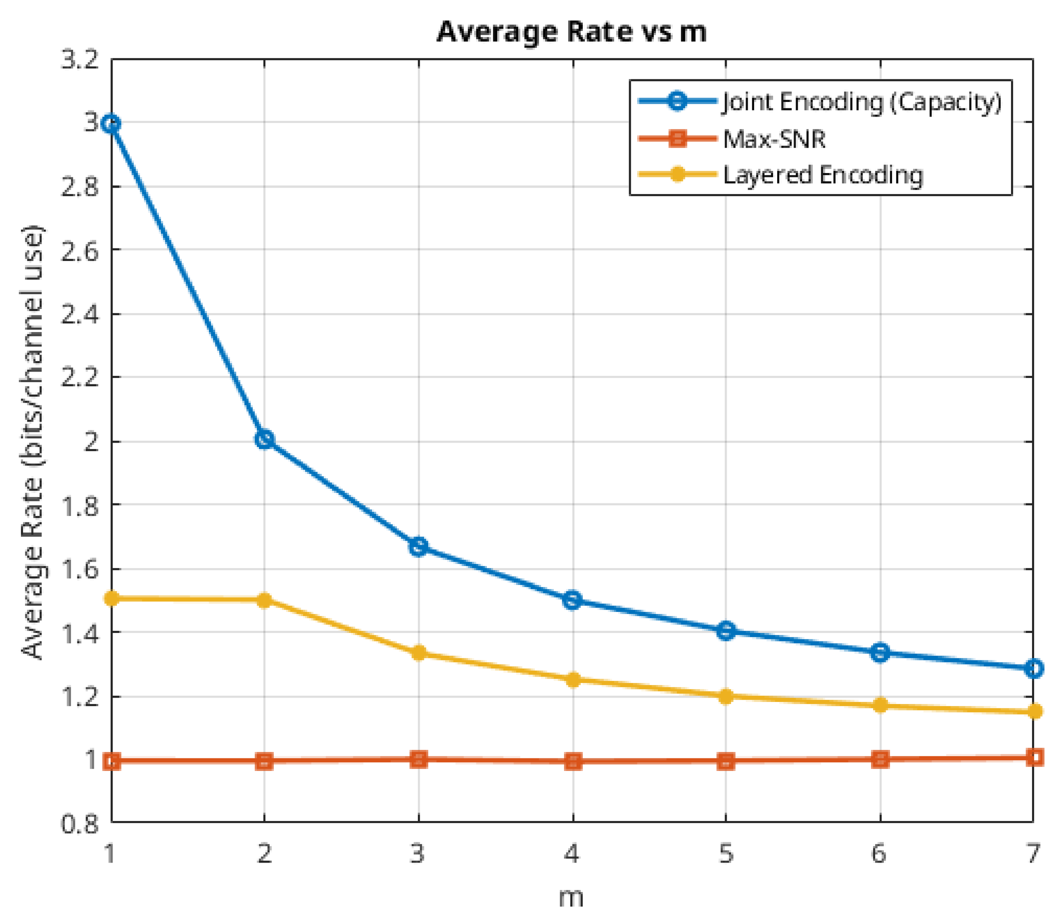


Fig. 2. Average rate vs the RIS control rate factor m for 2-ASK input constellation $\mathcal{B} = \{\beta, 3\beta\}$ ($\beta = \sqrt{\frac{P}{5}}$).

Open Problems

- Characterize the tradeoff between the rate allocated to control signals and that used for data transmission.
- Extend the point-to-point communication fundamental bounds to the multi-user communication cases, i.e., multiple access channel (MAC) and broadcast channel (BC).
- Extend the asymptotical fundamental bounds to the finite blocklength regime.

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[2] T. Weissman, "Capacity of channels with action-dependent states," in *2009 IEEE International Symposium on Information Theory*, pp. 1794–1798, 2009.
[3] H. V. Cheng and W. Yu, "Degree-of-freedom of modulating information in the phases of reconfigurable intelligent surface," *IEEE Transactions on Information Theory*, vol. 70, no. 1, pp. 170–188, 2024.
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[5] R. Karasik, O. Simeone, M. D. Renzo, and S. Shamai Shitz, "Adaptive coding and channel shaping through reconfigurable intelligent surfaces: An information-theoretic analysis," *IEEE Transactions on Communications*, vol. 69, no. 11, pp. 7320–7334, 2021.
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