Energy-Efficient Transmission in 5G Communications

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Agenda

- **Introduction to 5G New Radio**
- Problems and Motivation
- Metrics of Transmit Energy Efficiency
- Energy-Efficient 5G NR Systems with Adaptive Transmission
- Conclusions

Introduction to 5G New Radio

Use Cases

- Enhanced Mobile Broadband (eMBB): extremely fast data speeds
- Ultra Reliable and Low Latency Communications (URLLC): real-time services that requires ultra low latency and prompt responses
- Massive Machine-Type Communications (mMTC): million IoT devices within 1 km^2 can be connected

Massive MIMO and Beamforming

- From 2/4/8 to massive number of antennas 16, 32, even 256 or 1024
- Benefits: **capacity gains, spectral efficiency, and energy efficiency**
- Support up to 8 layers for SU-MIMO and up to 12 layers for MU-MIMO
- More accurate channel state information (CSI) feedback: type I and type II CSI

Problems and Motivation

Problems

Energy-efficient operation of battery-powered radios demands on energy management in link-based radio systems, interference-tolerant and spectrum-sharing environments.

Motivation

The primary focus is to investigate reliable, energy-efficient and interference-tolerant communications strategies to extend times of battery-powered 5G NR UE radios equipped with multiple antennas.

- The use of CSI and adaptive transmission based on linear precoding and beamforming is anticipated to improve the energy efficiency (EE) over frequency-selective fading channels.
- The transmit energy consumption of battery-powered UE radios can be minimized using an optimization technique in the presence of co-channel interference (CCI).

Metrics for Transmit Energy Efficiency

Packet-based Transmit Energy Efficiency (EE) η_{ee}

The average transmit EE η_{ee} is defined by a ratio of the number of successfully received bits to the total energy consumption after erasures (successful bit per Joule).

$$\eta_{ee} = \frac{N_{good}^{pk}}{E_T} = \frac{N_{good}^{pk}}{T_{tx}\left(P_{pa} + P_{tx} + P_{bb}\right)} \text{ (bit/J)}.$$

Spectral Efficiency (SE) η_{se}

The SE η_{se} quantifies the successful data rate that can be reliably achieved at the receiver over the occupied bandwidth.

$$\eta_{se} = \frac{N_{good}^{pk}}{T_{tx} \cdot B_w} \text{(bit/s/Hz)}$$

where E_T is the transmit energy, N_{good}^{pk} is the total number of successfully decoded data bits in packets. T_{tx} is the total transmit time for a given number of bits. P_{tx} and P_{bb} represent the average power consumption of the TX and baseband (BB) subsystems respectively. B_w is the 3-dB noise bandwidth.

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Hybrid Beamforming Architecture of 5G NR System

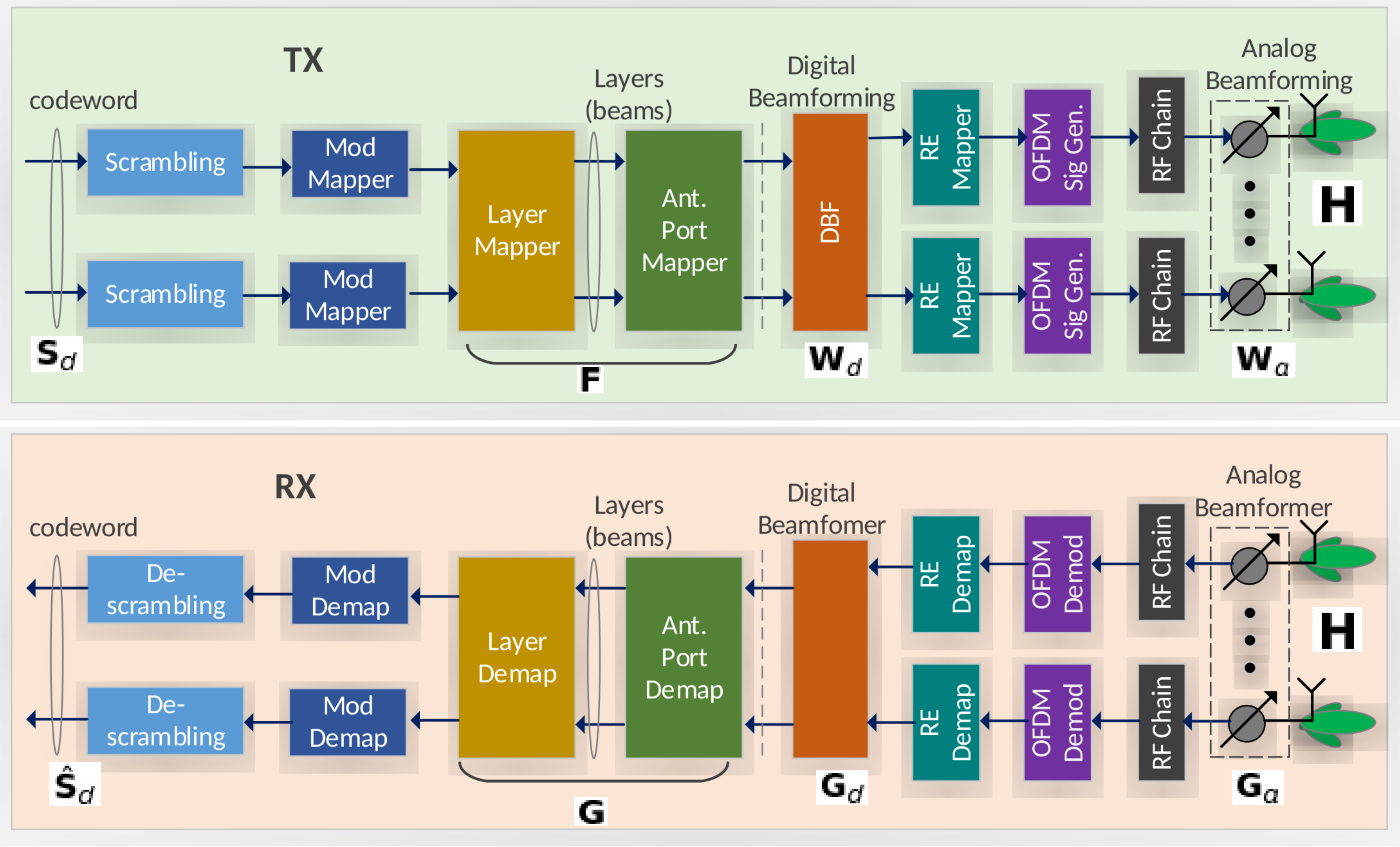


Figure: Block diagram of hybrid beamforming implementation of 5G NR systems in the time division duplex (TDD) mode.

Adaptive TX-RX Schemes In the Presence of Interference

Uplink Data Transmission and Receiving

The adaptively transmitted and received can be modeled for the i^{th} OFDM data symbol on the kth subcarrier (k=0, 1, $\cdots$, $N_d - 1$) as

$$\hat{\boldsymbol{S}}^i_{d,k} = \sqrt{P_T}\,\underbrace{\boldsymbol{G}^i_k \boldsymbol{G}^i_{d,k} \boldsymbol{G}^i_{a,k}}_{\text{RX Processing}} \boldsymbol{H}^i_k \underbrace{\boldsymbol{W}^i_{a,k} \boldsymbol{W}^i_{d,k} \boldsymbol{F}^i_k}_{\text{TX Processing}} \boldsymbol{S}^i_{d,k} + \underbrace{\boldsymbol{G}^i_k \boldsymbol{G}^i_{d,k} \boldsymbol{G}^i_{a,k}}_{\text{RX Processing}} \left(\boldsymbol{V}^i_k + \boldsymbol{N}^i_k\right)$$

where N_d is the number of data subcarriers, $\boldsymbol{S}^i_{d,k}$ is the transmitted data vector, $\boldsymbol{H}^i_k$ is the channel transfer matrix in the frequency domain. $\boldsymbol{G}^i_k$ and $\boldsymbol{F}^i_k$ are the precoding decoder and encoder matrices used at the Rx and the Tx respectively. $\boldsymbol{W}^i_{d,k}$ and $\boldsymbol{W}^i_{a,k}$ are digital and analog beamforming steering matrices respectively. $\boldsymbol{G}^i_{d,k}$ are $\boldsymbol{G}^i_{a,k}$ are digital and analog beamformer matrices at the RX. $\boldsymbol{V}^i_k$ and $\boldsymbol{N}^i_k$ are the overall interference signal vector and AWGN noise vector respectively on the kth subcarrier sampled at the Rx.

Optimal Precoding and Beamforming Matrices

The optimal $\boldsymbol{G}^i_k$, $\boldsymbol{F}^i_k$, $\boldsymbol{G}^i_{d,k}$, $\boldsymbol{G}^i_{a,k}$, $\boldsymbol{W}^i_{d,k}$ and $\boldsymbol{W}^i_{a,k}$ are obtained based on equal MSE errors across linear precoded beams and beamforming branches.

Co-channel Interference Model

CCI Model

For the ith OFDM symbol period, the interference signal vector from co-channel interferers on subcarrier k in the frequency domain can be represented as

$$\boldsymbol{V}_k^i = \sum_{i_0=1}^{i} \sum_{m_c=1}^{M_c^{i_0}} G_{m_c}^{\frac{1}{2}} L_{NF}^{\frac{1}{2}} \frac{\lambda_k}{4\pi} r_{m_c}^{-\gamma_p/2} P_{T,m_c}^{1/2} \boldsymbol{H}_{m_c,k}^i \boldsymbol{X}_{m_c,k}^{i_0}$$

where the number of active interferers $M_c^{i_0}$. $M_c^{i_0}$ is the number of active co-channel interferers. G_{m_c} represents transmit antenna power gains of the m_cth co-channel interferer. L_{NF} is the loss factor due to the Rx noise figure. λ_k denotes the wavelength of center frequency of subcarrier k. r_{m_c} is the average distance from the m_cth co-channel interferer to the gNB. γ_p is the propagation path loss exponent. P_{T,m_c} represents the total transmit power of the m_cth co-channel interferer. $\boldsymbol{H}_{m_c,k}^i$ denotes the channel frequency responses and modeled as i.i.d. RVs. The $\boldsymbol{X}_{m_c,k}^{i_0}$ are the random BB signals transmitted from the active m_cth co-channel interferer.

Transmit Energy Efficiency

Assumptions

- Reciprocal channels or approximately reciprocal channels in the time division duplex (TDD) mode, the UE Tx therefore has channel state knowledge
- The CSI reference signal (CSI-RS) upon DL is exploited to estimate the channel state between the gNB and UEs
- The CSI changes slowly during a frame period (10 ms)

Transmit Energy Efficiency η_{ee}

The average transmit EE, η_{ee}, on the UL can be approximated as a nonlinear function of estimated channel transfer matrix $\hat{\boldsymbol{H}}$ and average SINR per bit γ_b

$$\eta_{ee} = \frac{N_{good}^{pk}}{E_t} \approx \eta_{ee}(\hat{\boldsymbol{H}}, \gamma_b)$$

Optimization Algorithm

The energy-constrained problem for transmit EE upon the UL can be modeled as

$$\text{minimize } f_\eta(\gamma_r) = -\eta_{ee}(\hat{\boldsymbol{H}}, \gamma_r), \text{ subject to } \; 1 \le \gamma_r \le \gamma_r^{max}$$

The UE computes the maximize transmit EE and obtains the optimal SINR γ_r^{opt}.

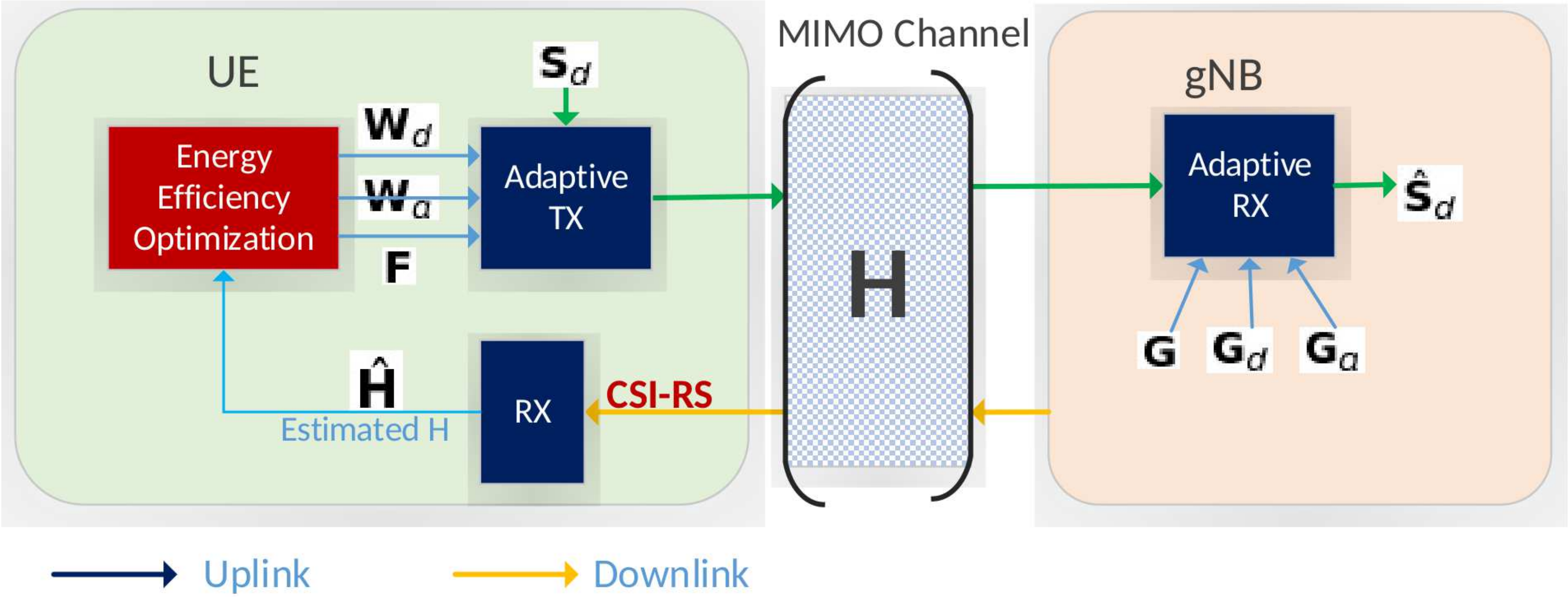
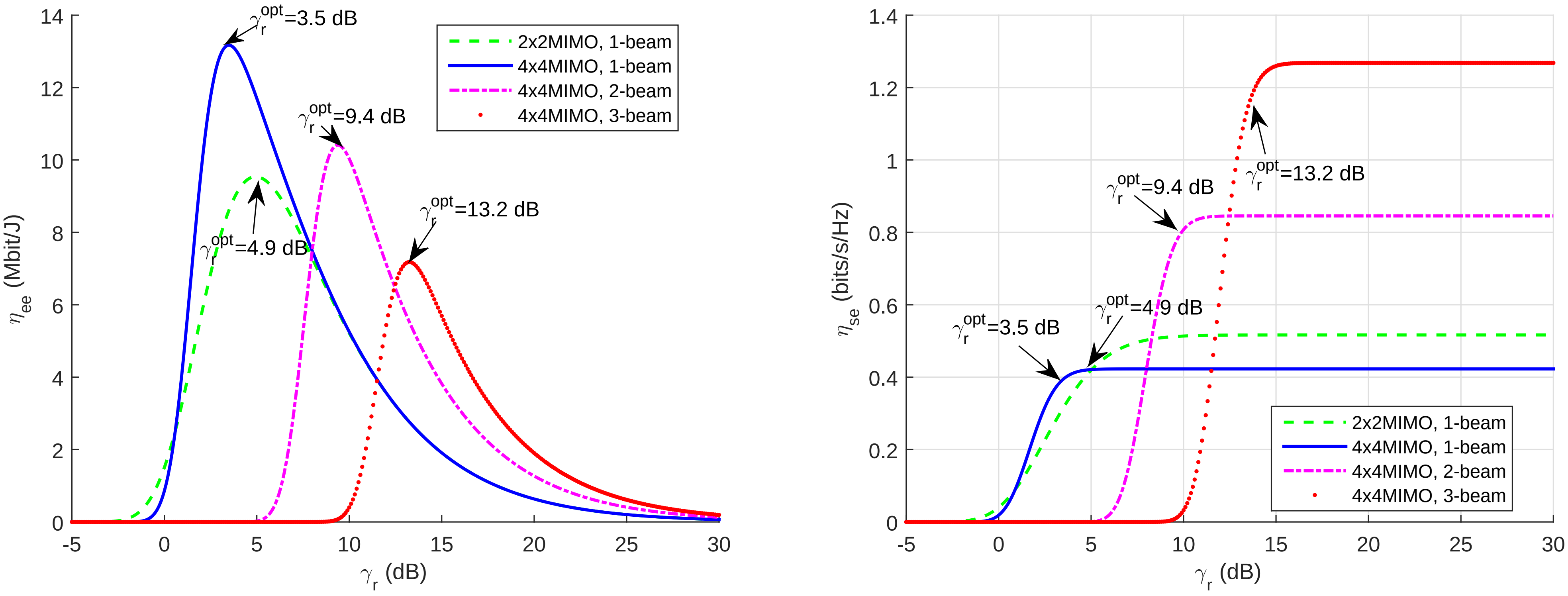


Figure: Illustration of EE optimization process between UE and gNB

Numerical Results: Transmit EE η_{ee} and SE η_{se}

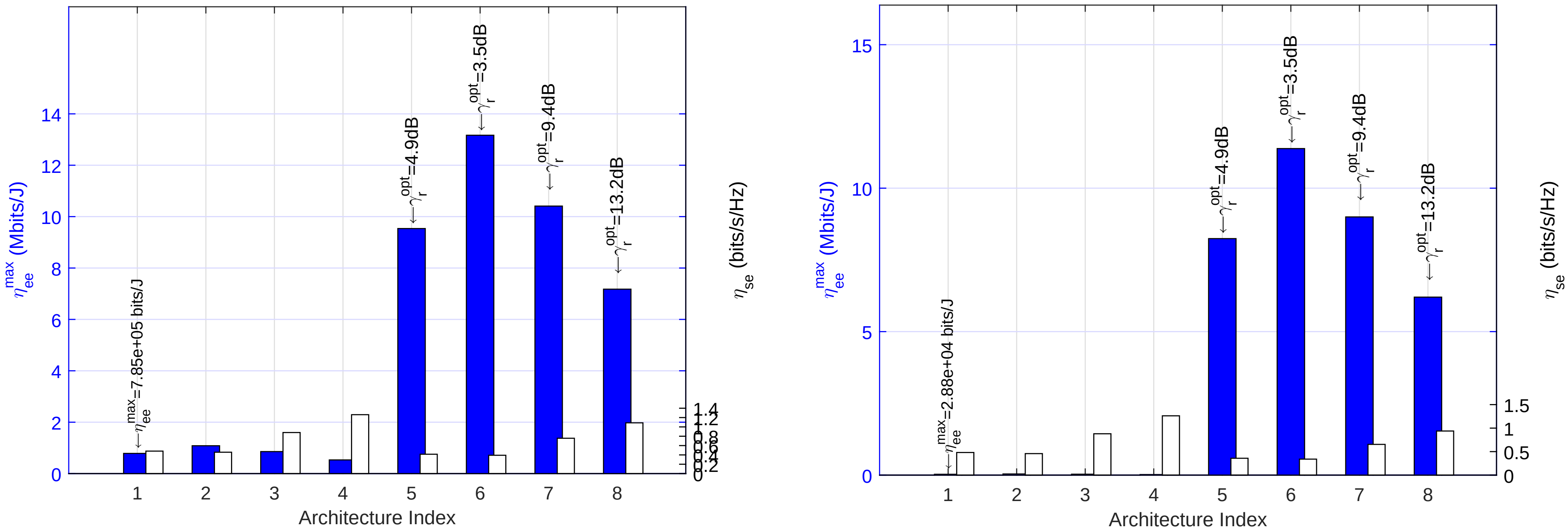


(a) Transmit EE η_{ee}

(b) SE η_{se}

Figure: Transmit EE η_{ee} and SE η_{se} of 2×2 and 4×4 MIMO systems with 1/2/3-spatial beam (N_B=1, 2 and 3) vs. SINR γ_r over a low correlated Rayleigh channel model.

Numerical Results: Maximum EE η_{ee}^{max}, SE η_{se} and Optimal SINR γ_r^{opt}

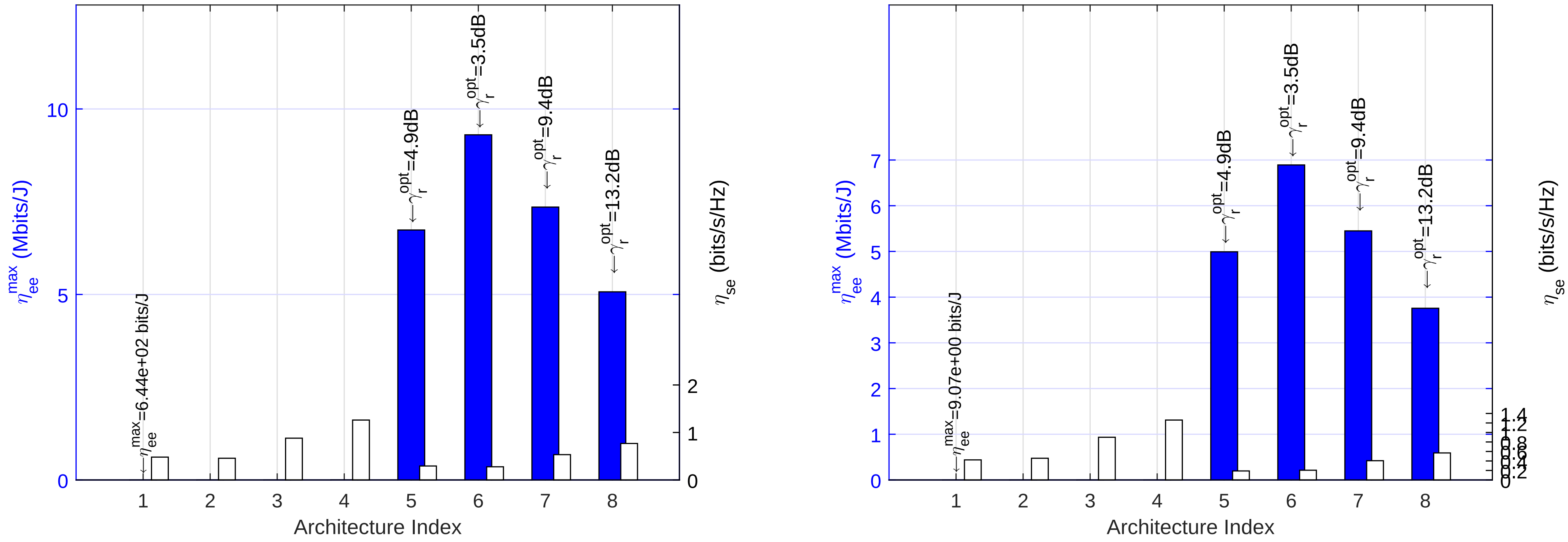


(a) p_{cc}=0.15

(b) p_{cc}=0.30

Figure: Maximum transmit EE η_{ee}^{max}, corresponding SE η_{se} and optimal SINR γ_r^{opt} for Non-AT and AT schemes varying with the probabilities of CCI p_{cc}=0.15 and 0.3 over the Rayleigh channel model. Architecture indices 1 $\sim$ 8 on the x-axis denote "2x2 MIMO-1b,Non-AT", "4x4 MIMO-1b,Non-AT", "4x4 MIMO-2b,Non-AT", "4x4 MIMO-3b,Non-AT", "2x2 MIMO-1b,AT","4x4 MIMO-1b,AT", "4x4 MIMO-2b,AT", and "4x4 MIMO-3b,AT" respectively.

Numerical Results: Maximum EE η_{ee}^{max}, SE η_{se} and Optimal SINR γ_r^{opt} (Continued)



(a) p_{cc}=0.50

(b) p_{cc}=0.80

Figure: Maximum transmit EE η_{ee}^{max}, corresponding SE η_{se} and optimal SINR γ_r^{opt} of 2×2 MIMO 1-spatial beam and 4×4 MIMO with 1-/2-/3-spatial beam architectures for Non-AT and AT schemes varying with the probabilities of CCI p_{cc}=0.5 and 0.8 over the Rayleigh channel model.

Conclusions

- In 5G NR systems, significant EE gains have been achieved through the use of adaptive transmission schemes based on precoding and beamforming techniques when the CSI is available to the Tx. Operating points exist that minimize energy consumption while providing near maximum SE.
- In the presence of co-channel interference, the transmit EE has been optimized using adaptive transmission technique over the subcarriers.

The End

Thanks For Your Attention!