ECE5884 Wireless Communications

Week 11: Multi-antenna systems: From theory to standardization in 5G-NR

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Multi-antenna systems

From theory to standardization in 5G-NR

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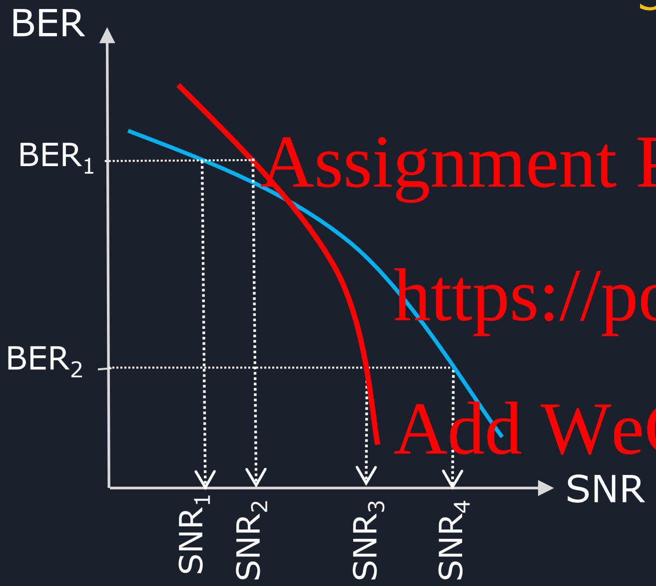
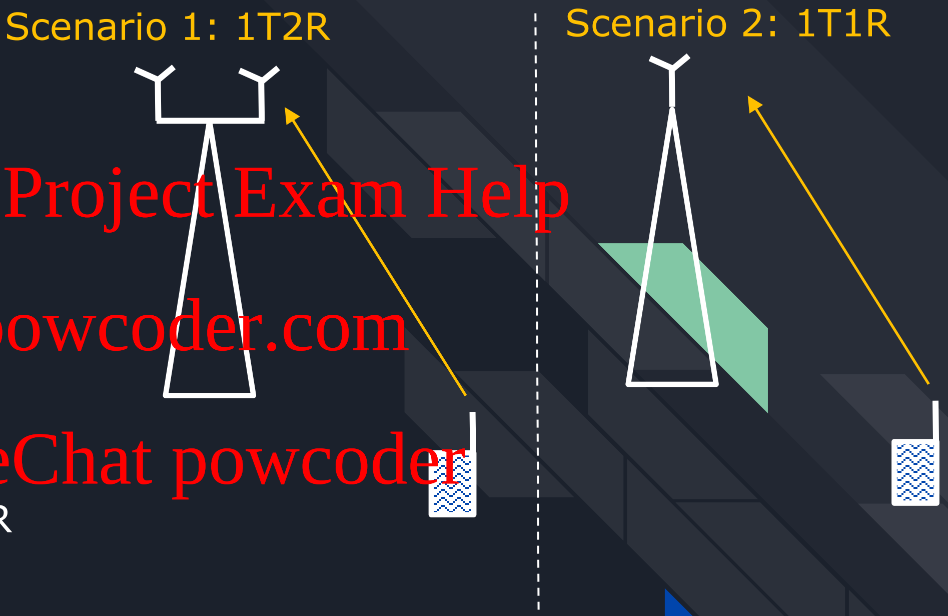
Outline

- Motivation examples
- Analog & digital multi-antenna processing
- Multi-antenna precoding (Downlink and uplink)
- Beam management

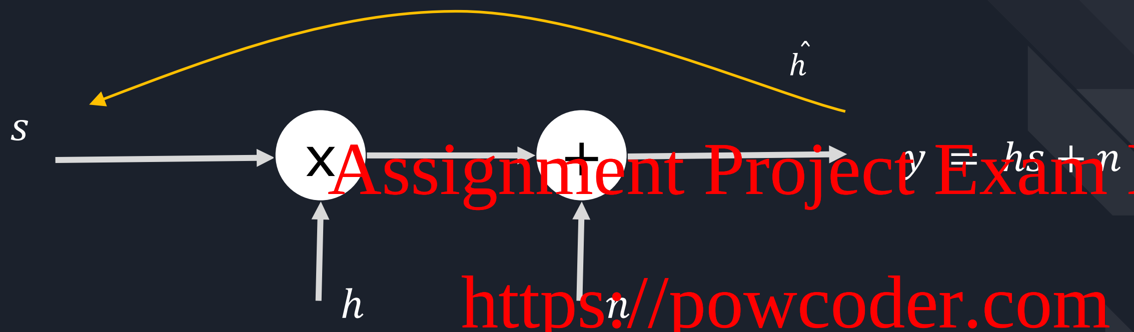
Motivation example 1: Interpretation of BER curves





- Q1: Two curves for T1R1 and T1R2 system. Label them?
- Q2: Which curve is better, Red or blue? Channel estimation overhead, cost/complexity
- Q3: What is the significance of value BER$_1$, SNR$_1$, SNR$_2$?
- Q4: What is the significance of value BER$_2$, SNR$_3$, SNR$_4$?

Motivation example 2: Closed loop transmission



- Set up: Improve the BER/Capacity of the fading channel by knowing $\hat{h}$ at the transmitter where $\hat{h}$ is an estimate of h
- Q1: Knowing an estimate of h at the transmitter better or not?
  - The performance of the closed loop transmission is better than open loop transmission?
  - How to account for feedback overhead?
  - What is the impact in MIMO?

Multi-Antenna Processing

Diversity gain:

- Multiple antennas at the transmitter and/or receiver side can provide diversity against fading
- Channels experienced by different antennas may be at least partly uncorrelated
  - Sufficient inter-antenna distance
  - Different polarization between the antennas

Spatial multiplexing:

- Multiple antennas at both the transmitter and the receiver sides can be used to enable transmission of multiple “layers/streams” in parallel using the same time/frequency resources

Transmit beamforming:

- Adjust the phase and/or the amplitude of each antenna element, provide directivity to signals
- **Directivity:** Focus the overall transmitted power in a certain direction, i.e, beam forming
  - Increase the achievable data rates and range due to higher power reaching the target receiver
  - Directivity can also reduce the interference to other links (improves the overall spectrum efficiency)

Receive beamforming:

- Multiple receive antennas to provide receiver-side directivity (focusing the reception in the direction of a target signal while suppressing interference arriving from other directions)

Quiz

- Higher the operating frequency, what happens to the propagation loss?
- In high frequency, what is more important, diversity, spatial multiplexing or beam-forming?

Background

Higher frequencies are associated with higher propagation loss

- Correspondingly reduced communication range

Receive antennas

- The dimensions of the receiver antenna scale with the wavelength (the inverse of the carrier frequency)
- Ten times increase in the carrier frequency, corresponding to a reduction in the wave length
- Assume ten times reduction in the physical dimensions of the receiver antenna or a factor of 100 reduction in the physical antenna area
- This corresponds to a 20 dB reduction in the energy captured by the antenna

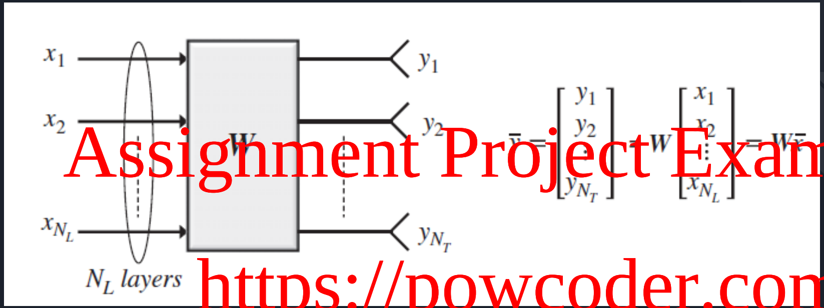
Receive antenna size vs directivity

- If the receiver antenna size would instead be kept unchanged as the carrier frequency increases, the reduction in captured energy could be avoided
- Imply that the antenna size would increase relative to the wave length
- Directivity of an antenna is proportional to the physical antenna area normalized with the square of the wave length
- The gain with the larger antenna size can thus be realized if the receive antenna is well directed towards the target signal
- In practice increasing the transmit-antenna directivity, the link budget at higher frequencies can be improved

Transmit antennas

- In practice increasing the transmit-antenna directivity, the link budget at higher frequencies can be improved

Multi-antenna processing

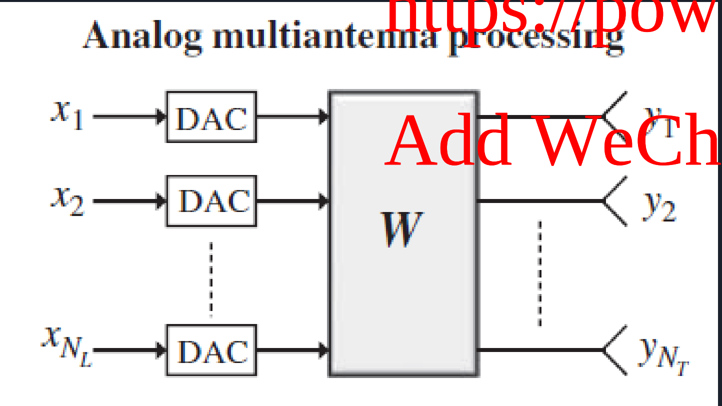


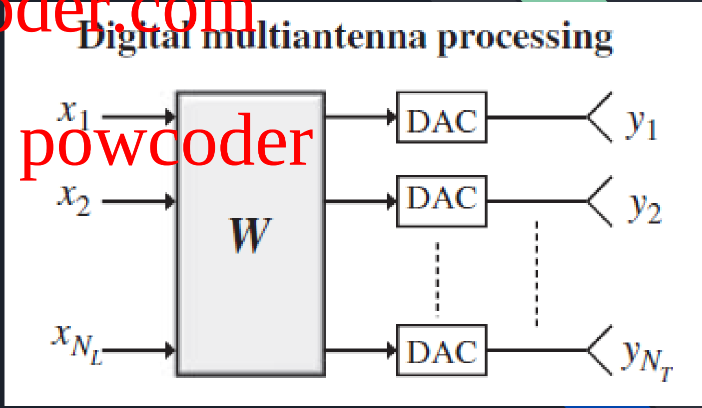
Any linear multi-antenna transmission scheme can be modeled according

- N_L layers (vector $\boldsymbol{x}$)
- Mapped to N_T transmit antennas (vector $\boldsymbol{y}$)
- Multiplication with a matrix $\boldsymbol{W}$ of size $N_T \times N_L$

Analog and Digital Multi-Antenna Processing

- The multi-antenna processing is applied within the analog part of the transmitter chain (after digital-to-analog conversion (left))
- The multi-antenna processing is applied within the digital part of the transmitter chain (before digital-to-analog conversion (right))





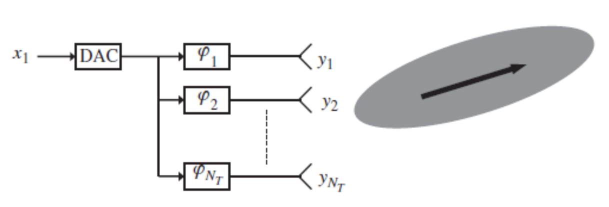
Analog and Digital Multi-Antenna Processing

- Implementation complexity DAC per antenna element is the main drawback of digital processing
- At higher frequencies with large number of closely spaced antenna elements, analog multi-antenna processing is the most common case

- The multi-antenna transmission will typically be limited to per-antenna phase shifts providing beam forming

- High frequencies: Not a severe limitation as operation at higher frequencies is typically more power-limited than bandwidth-limited, making beam forming more important than, high-order spatial multiplexing

- Lower frequencies: The spectrum is a more sparse resource with less possibility for wide transmission bandwidths



Downlink Multi-Antenna Precoding

- In the case of digital processing (control both amplitude and phase), the transmission matrix $\boldsymbol{W}$ is referred as a precoder matrix (multi-antenna processing is referred as multi-antenna precoding)
- Coherent demodulation is achieved by demodulation reference signal (DMRS)
- Precoder-related measurements and reporting are part of the more general CSI reporting framework:

1. Rank Indicator (RI): What the device believes is a suitable transmission rank (number of layers N_L)
2. Precoder-Matrix Indicator (PMI): What the device believes is a suitable precoder matrix for given RI
3. Channel-Quality Indicator (CQI): What the device believes is a suitable channel-coding rate and modulation scheme, given the selected precoder matrix.

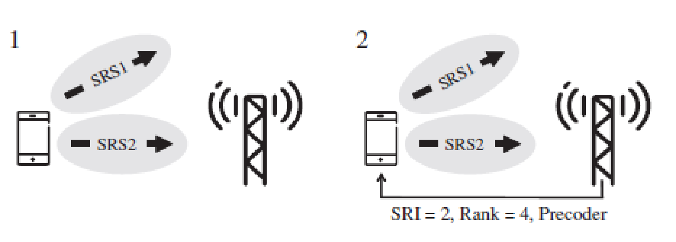
- MU-MIMO: Simultaneously transmit to different devices taking the PMI reports into account
- Suppress the interference to other devices

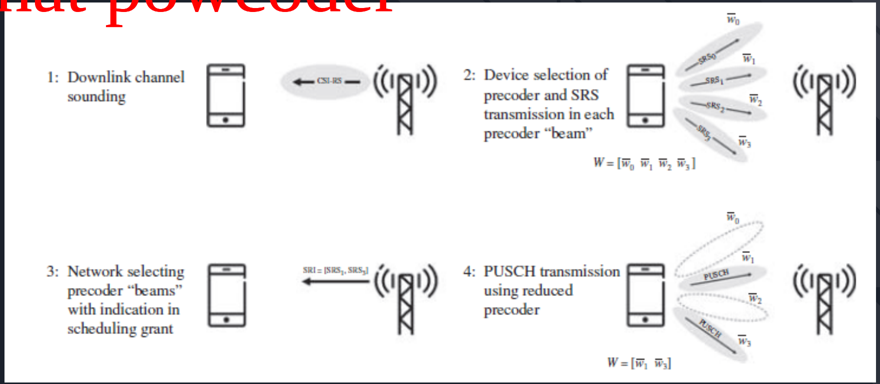
Quiz

- Higher the number of antennas, higher the reference signal overhead?
- What is the channel state information known at the transmitter means?

Uplink Multi-Antenna Precoding

- Support precoding in uplink direction
- Coherent demodulation is achieved by demodulation reference signal (DMRS)
- Codebook-based precoding: The scheduling includes information about a precoder and the device is assumed to use the precoder provided by the network
- Device configured to transmit a reference signal (i.e., SRS) and based on the measurements from transmitting SRS, precoder is chosen by the network
- Non-codebook-based precoding: Based on device measurements on downlink reference signal (CSI-RS) and precoder indications to the network



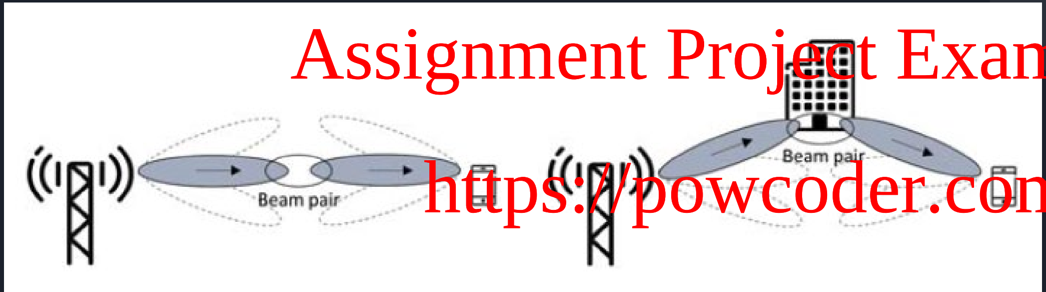


Quiz

- Precoding based transmission only has overhead of DMRS (demodulation reference signal) for coherent detection?

Beam Management

- Transmit and receiver beam for uplink and downlink transmission

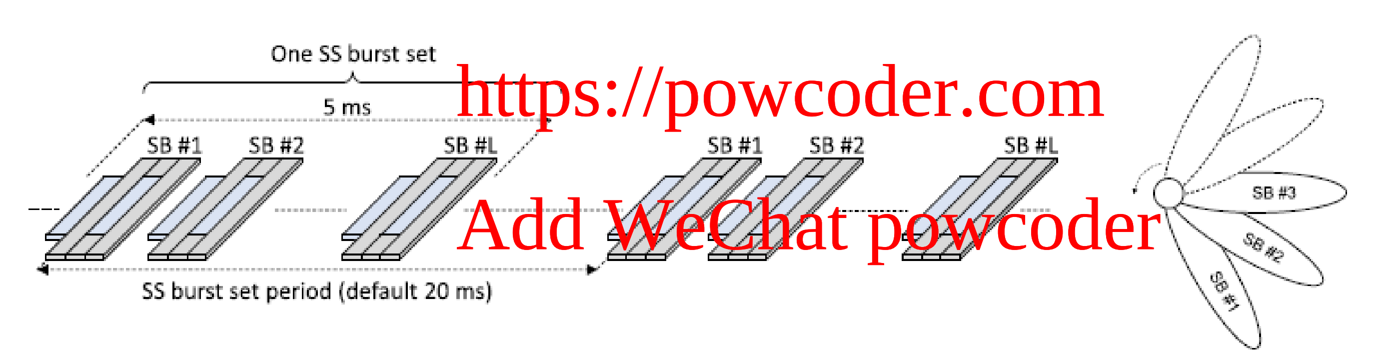


Beam management consists mainly three parts:

- Initial beam establishment
- Beam adjustment: Primarily to compensate for movements and rotations of the mobile device, but also for gradual changes in the environment
- Beam recovery: To handle the situation when rapid changes in the environment disrupt the current beam pair

Initial beam establishment

- Multiple SS blocks being transmitted in sequence within different downlink beams
- Subsequent uplink random-access transmission can be used by the network to identify the downlink beam acquired by the device and establishes the initial beam pair
- Correspondence of SS block to the beam



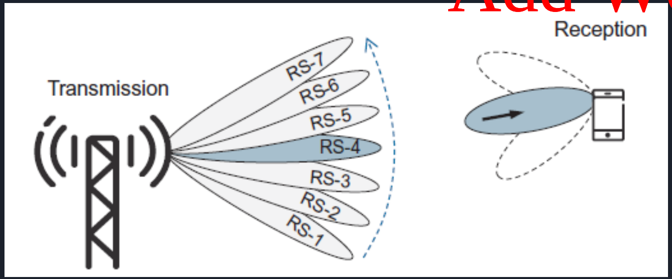
Beam adjustment

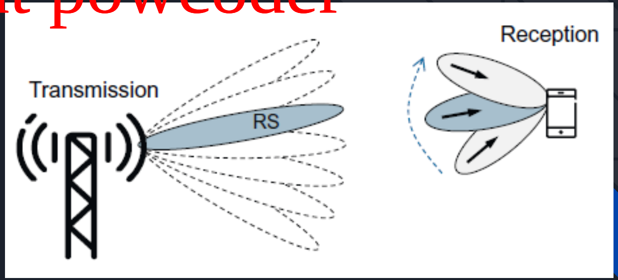
Why beam adjustment: Once an initial beam pair has been established, there is a need to regularly reevaluate the selection of transmitter-side and receiver-side beam directions

- Movements and rotations of the mobile device block or unblock different beam pairs
- Even for stationary devices, movements of other objects in the environment may block or unblock different beam pairs

Beam adjustment may also include refining the beam shape

- Example: Making the beam more narrow compared to a relatively wider beam used for initial beam establishment





SSB/CSI-RS

Beam recovery

Why beam recovery:

- In some cases, movements in the environment or other events, may lead to a currently established beam pair being rapidly blocked without sufficient time for the regular beam adjustment to adapt
- The NR specification includes specific procedures to handle such beam-failure events/beam (failure) recovery

Beam failure/recovery steps

- Beam-failure detection: The device detecting that a beam failure has occurred
- Candidate-beam identification: The device trying to identify a new beam (i.e., a new beam pair by means of which connectivity may be restored)
- Recovery-request transmission: The device transmitting a beam recovery request to the network
- Network response to the beam-recovery request

Quiz

- Beam failure can happen because of the user mobility?
- Beam management has some overheads in uplink and downlink directions?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