MU5EES08 - Unit IV
Advanced Physical Layer Concepts in 5G

1. 5G features and numerology
2. Channel diversity with multiple antenna systems
3. **MIMO processing**
4. Millimeter-wave arrays

by Julien Sarrazin, Sorbonne University

Overview of different schemes

- Diversity-based schemes
  - SIMO: example of Maximum Ratio Combining (MRC)
  - MISO: example of transmit MRC/matched beamforming
  - MISO: example of Alamouti (STBC)
- Spatial Multiplexing-based schemes
  - MIMO
- Adaptive Beamforming
  - Well-suited for massive MIMO in 5G: enhancement of throughput + cell coverage. Benefit of BF gain + spatial MUX
  - Eigen-based beamforming (SVD) or codebook-based beamforming

Diversity

- Diversity provides the receiver with different replicas of the same signal
- Each replica constitutes a diversity branch
- If the number of branches increases, the probability that a fading occurs on all of them decreases sharply

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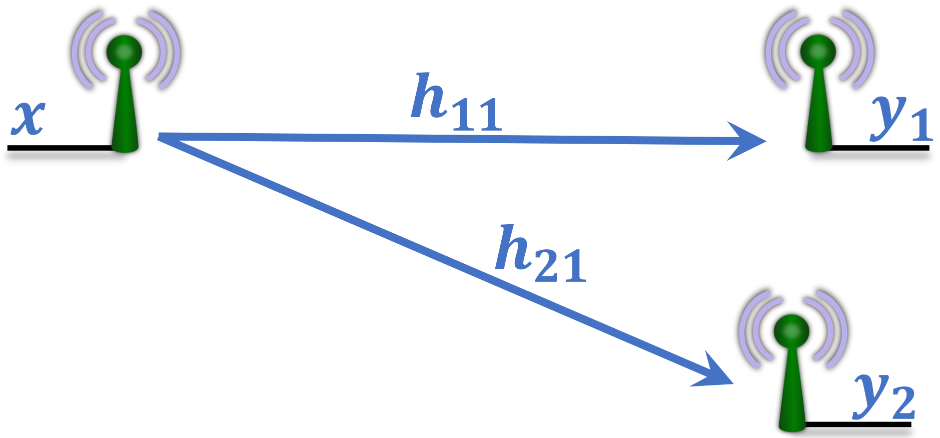
Maximum Ratio Combining

- SIMO configuration



Received signals

$$y_1 = h_{11}x + n_1$$
$$y_2 = h_{21}x + n_2$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} \\ h_{21} \end{bmatrix} x + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

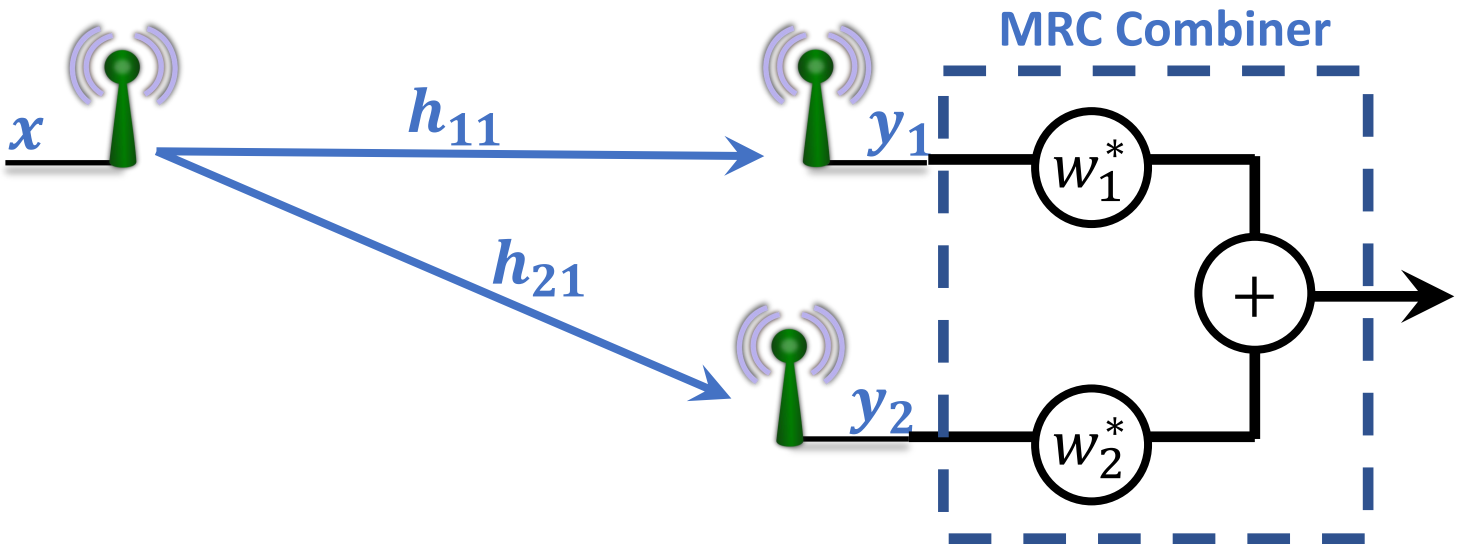
System model

$$\boldsymbol{y} = \boldsymbol{h}x + \boldsymbol{n}$$ with $$\boldsymbol{h} = \begin{bmatrix} h_{11} \\ \vdots \\ h_{N_R 1} \end{bmatrix}$$

$$\mathrm{E}[|n_i|^2] = \sigma^2$$

Maximum Ratio Combining

- SIMO configuration



Received signals

$$\boldsymbol{y} = \boldsymbol{h}x + \boldsymbol{n}$$

MRC output

$$y_{MRC} = \boldsymbol{w}^H \boldsymbol{y}$$

$$y_{MRC} = \boldsymbol{w}^H \boldsymbol{h}x + \boldsymbol{w}^H \boldsymbol{n}$$

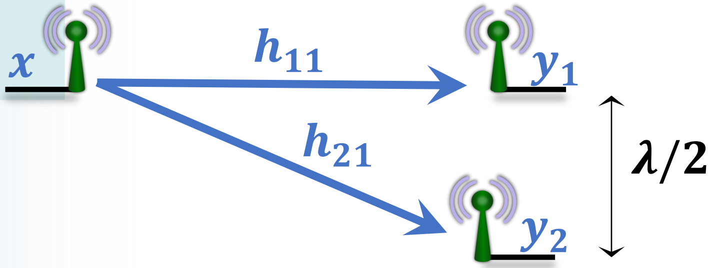
$$y_{MRC} = \|\boldsymbol{h}\|x + \boldsymbol{w}^H \boldsymbol{n}$$

➡ **Optimal MRC vector** $\boldsymbol{w} = \dfrac{\boldsymbol{h}}{\|\boldsymbol{h}\|}$

➡ $$\boxed{SNR = \frac{|\boldsymbol{w}^H \boldsymbol{h}x|^2}{\mathrm{E}[|\boldsymbol{w}^H \boldsymbol{n}|^2]} = \frac{|\boldsymbol{w}^H \boldsymbol{h}|^2 P_x}{\|\boldsymbol{w}^H\|^2 \sigma^2} = \frac{\|\boldsymbol{h}\|^2 P_x}{\sigma^2}}$$

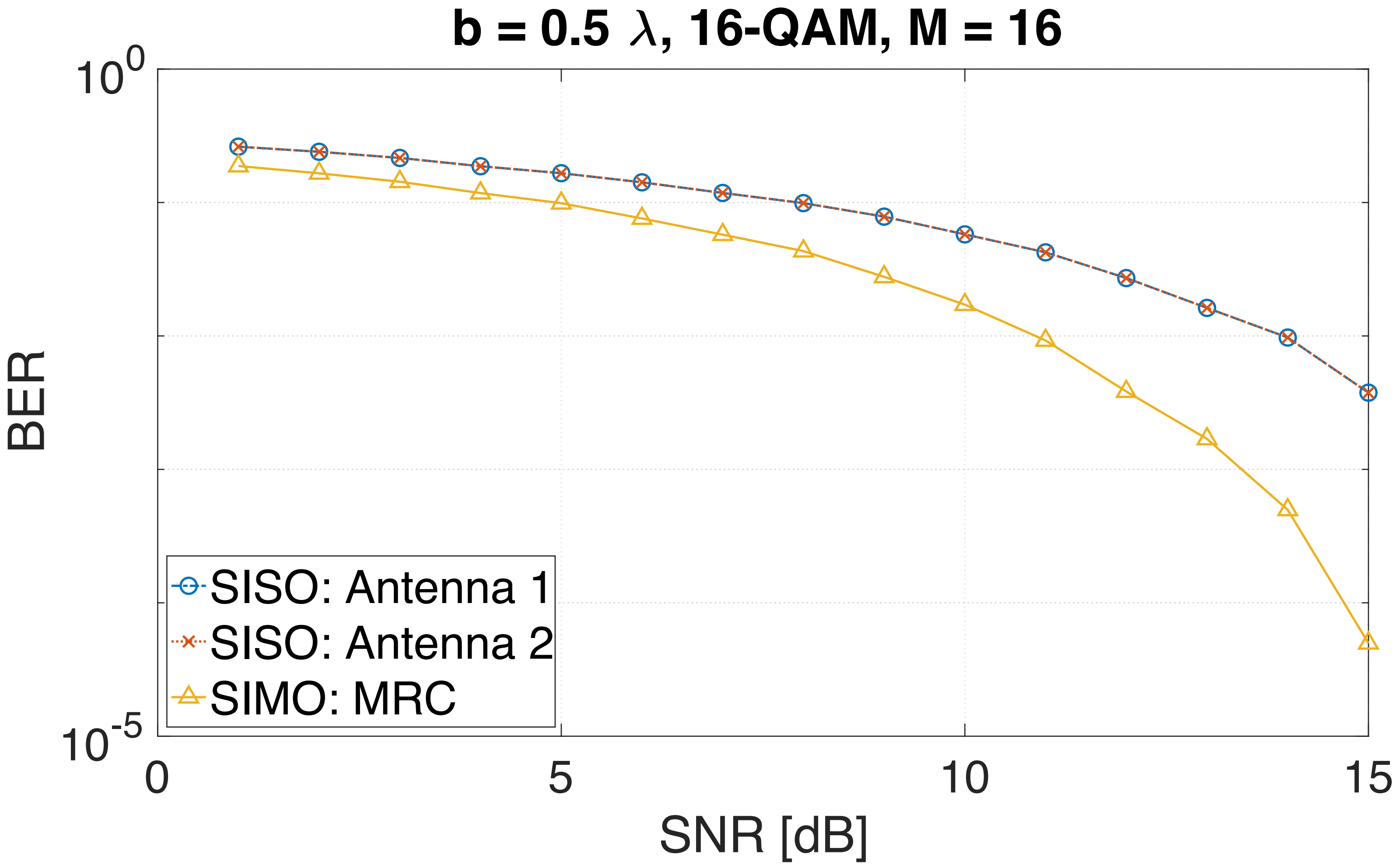
Maximum Ratio Combining

Scenario



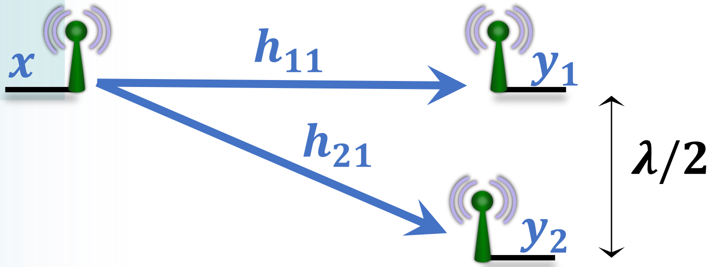
One-wave channel (no fading)

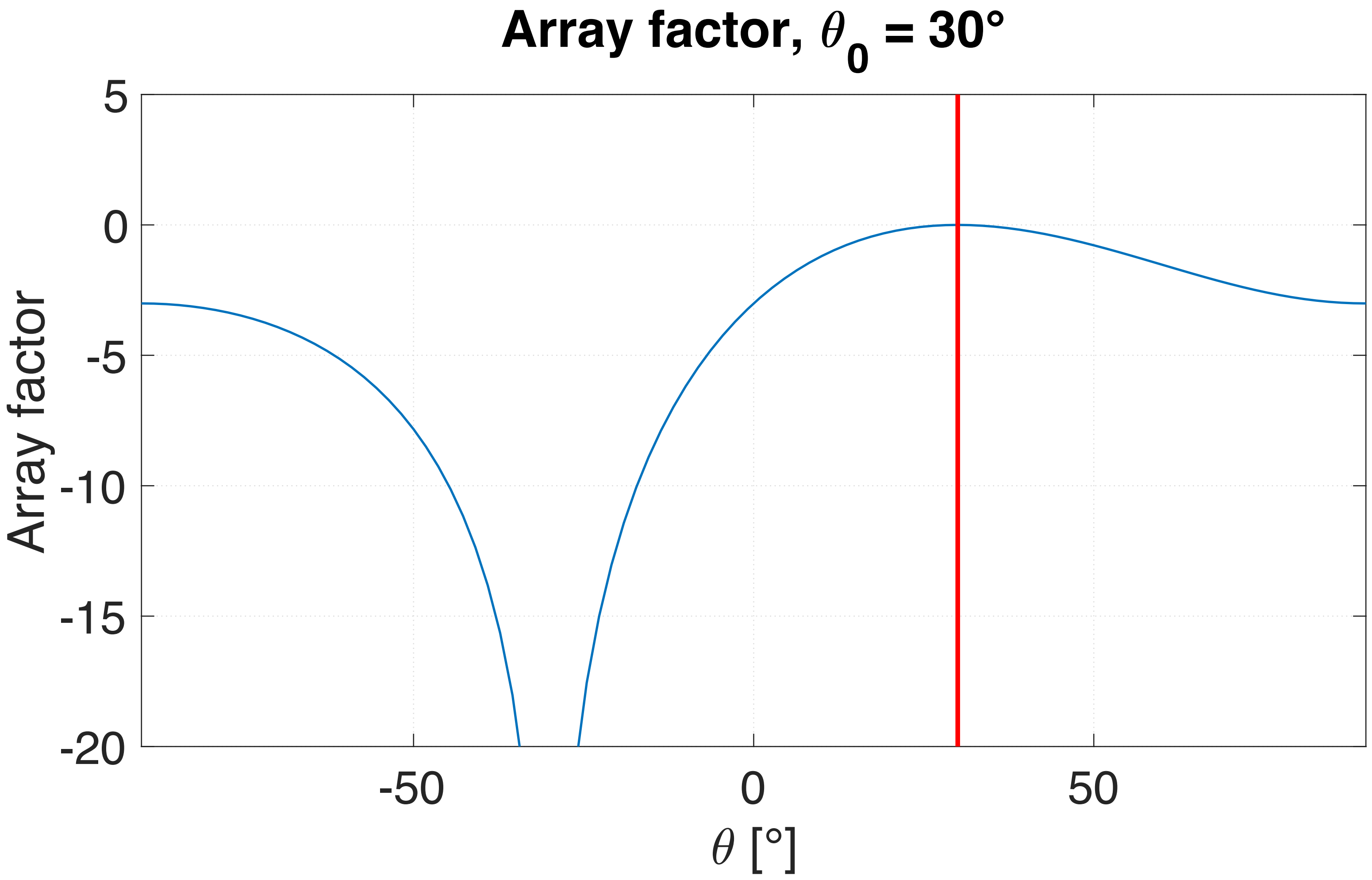
$$h_{11} = e^{j\frac{\sqrt{3}}{4}\pi}$$
$$h_{21} = e^{-\frac{\sqrt{3}}{4}\pi}$$



Maximum Ratio Combining

Scenario





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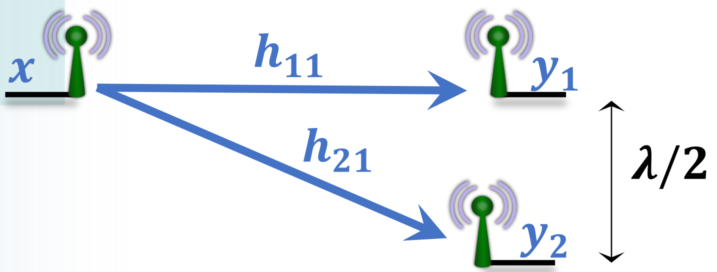
Maximum Ratio Combining

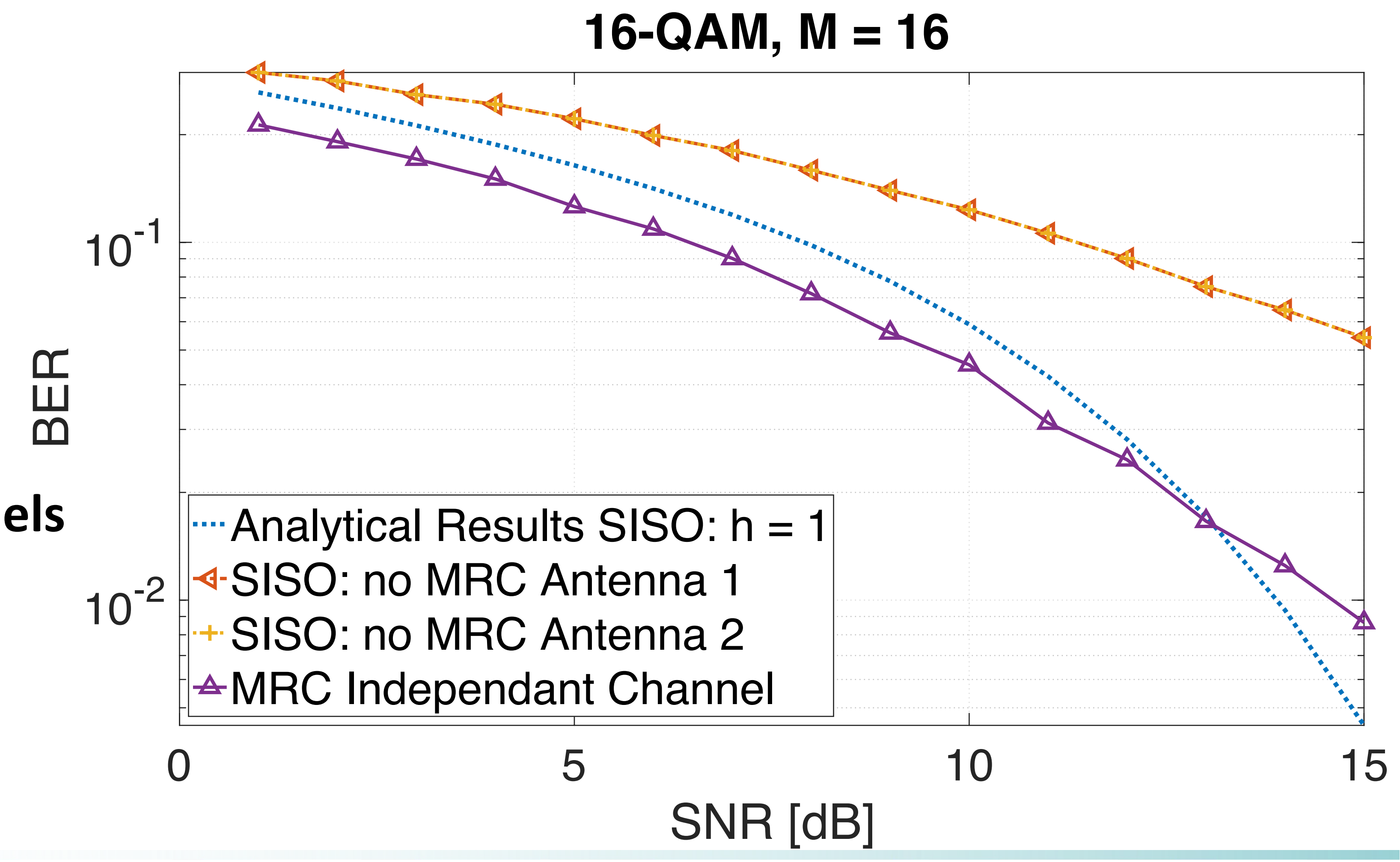
Scenario



Independent Rayleigh Channels

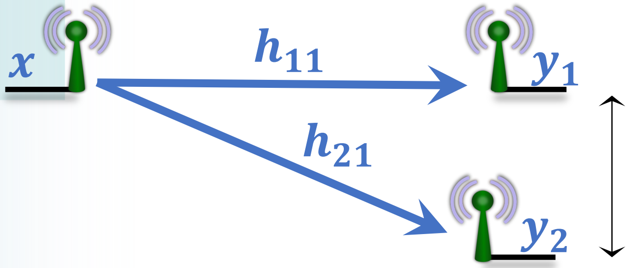
$$h_{11} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$

$$h_{21} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$



Maximum Ratio Combining

Scenario

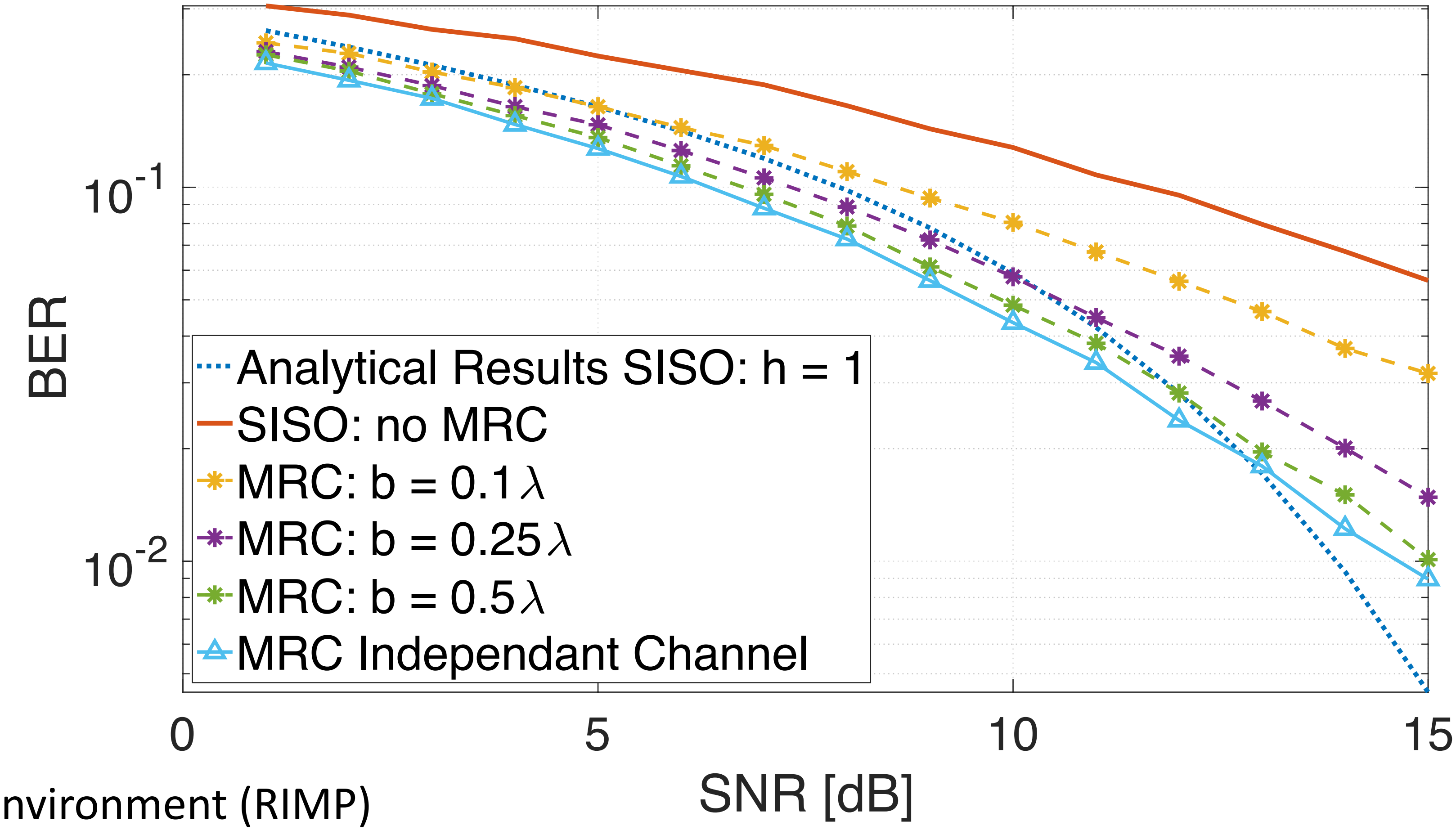


Correlated Rayleigh Channels

$$h_{11} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$

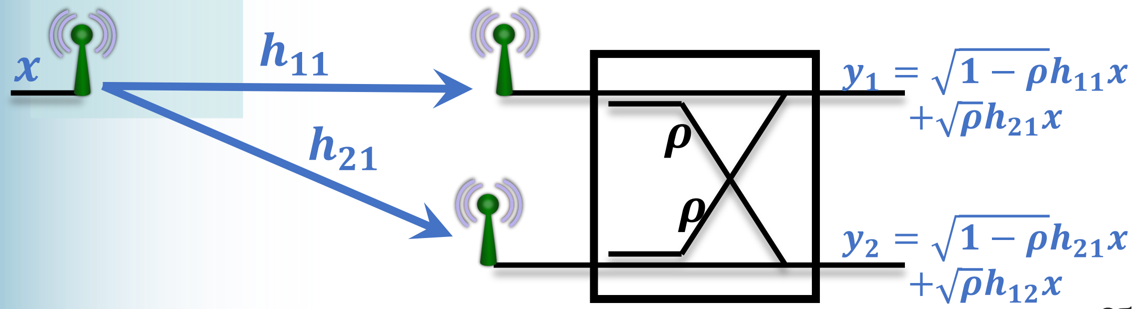
Assuming Rich Isotropic Multipath environment (RIMP)

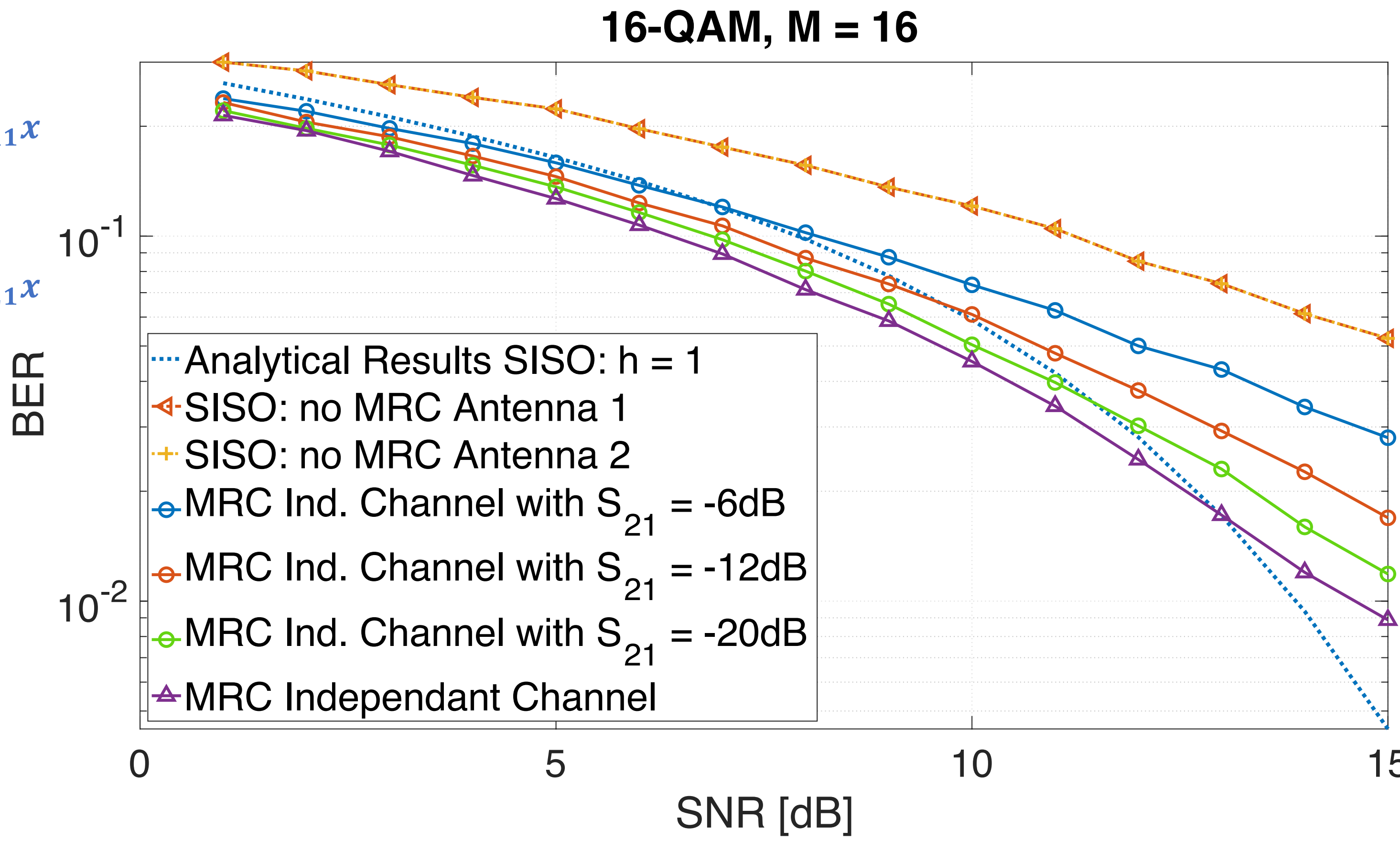
16-QAM, M = 16



Maximum Ratio Combining

Scenario





Mutual coupling effect

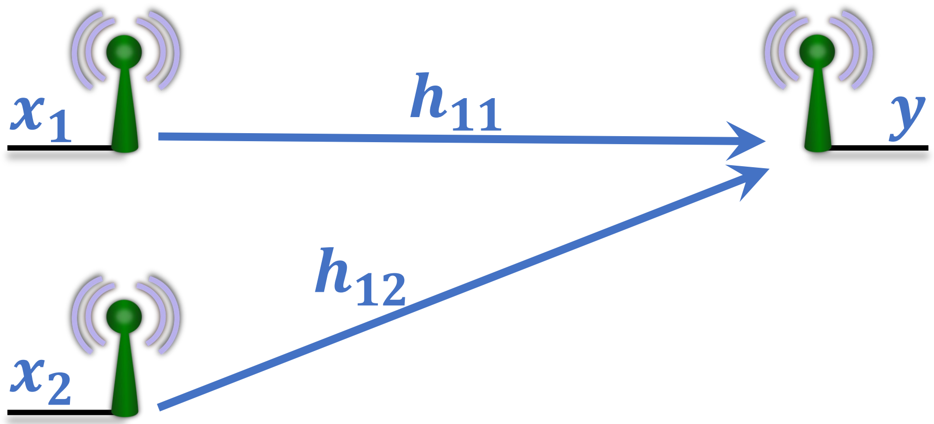
Independent Rayleigh Channels

$$h_{11} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$

$$h_{21} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$

Beamforming

- MISO configuration



Received signals

$$y = h_{11}x_1 + h_{12}x_2 + n$$

System model

$$y = \boldsymbol{hx} + n$$

with $\boldsymbol{h} = [h_{11} \quad \dots \quad h_{N_T 1}]$

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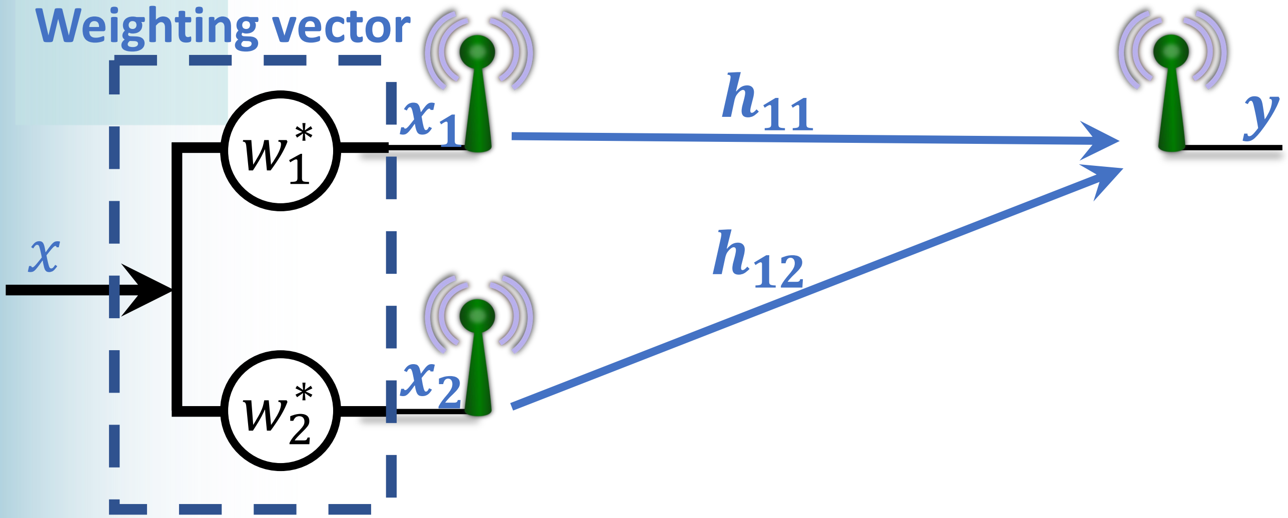
Beamforming

- MISO configuration



Received signals with beamforming

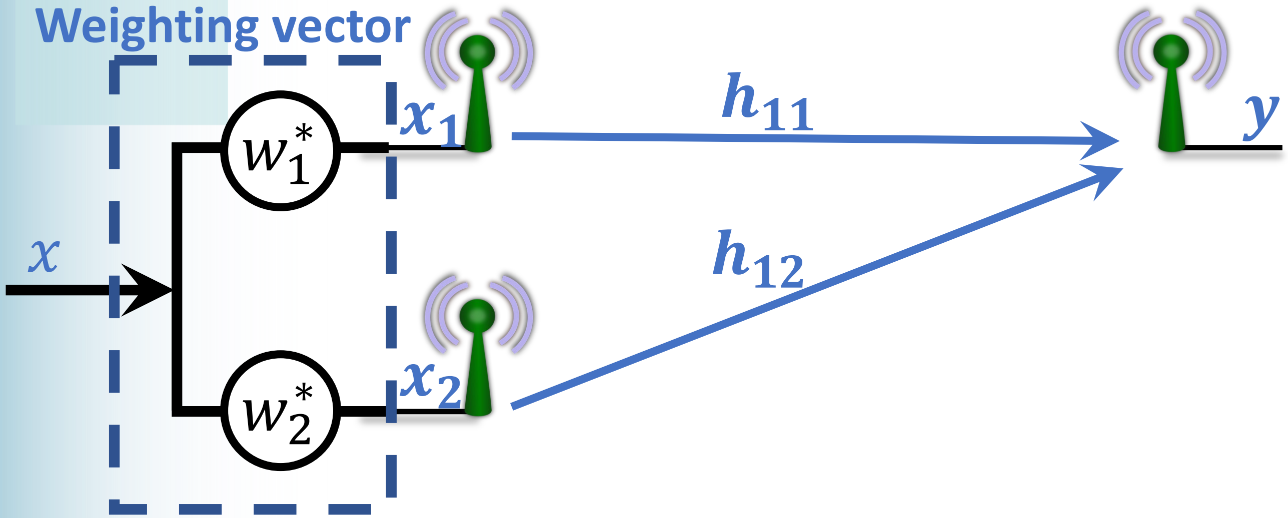
$$y_{BF} = \boldsymbol{hx} + n$$

$$\boldsymbol{x} = \boldsymbol{w}^H x \quad \text{with} \quad \boldsymbol{w} = [w_1 \quad \ldots \quad h_{N_T}]$$

$$y_{BF} = \boldsymbol{hw}^H x + n$$

Matched Beamforming (= transmit MRC)

- MISO configuration: CSI known at TX



Received signals with beamforming

$$y_{BF} = \boldsymbol{h}\boldsymbol{x} + n$$

$$\boldsymbol{x} = \boldsymbol{w}^H x \quad \text{with} \quad \boldsymbol{w} = [w_1 \quad \dots \quad h_{N_T}]$$

$$y_{BF} = \boldsymbol{h}\boldsymbol{w}^H x + n$$

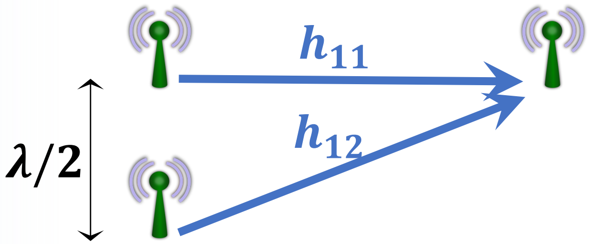
CSI at TX → **Optimal BF vector:** $\boldsymbol{w} = \frac{\boldsymbol{h}}{\|\boldsymbol{h}\|}$

$$y_{BF} = \|\boldsymbol{h}\| x + n$$

$$\boxed{SNR = \frac{|\boldsymbol{h}\boldsymbol{w}^H|^2 P_x}{\sigma^2} = \frac{\|\boldsymbol{h}\|^2 P_x}{\sigma^2}}$$

Matched Beamforming

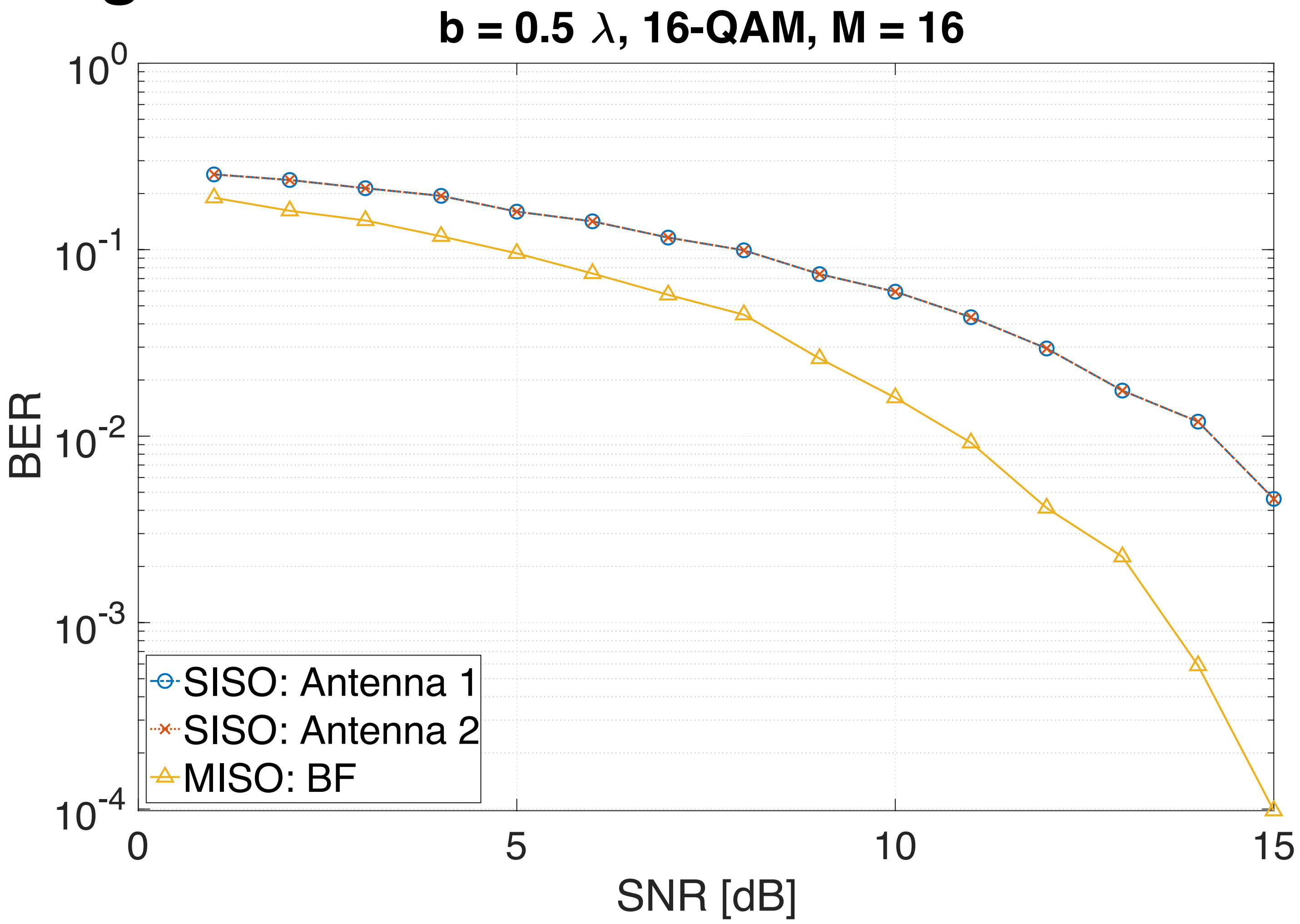
Scenario



Channel

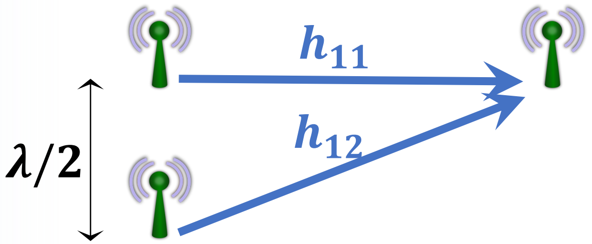
One-wave model:

- AoA = 30°



Matched Beamforming

Scenario



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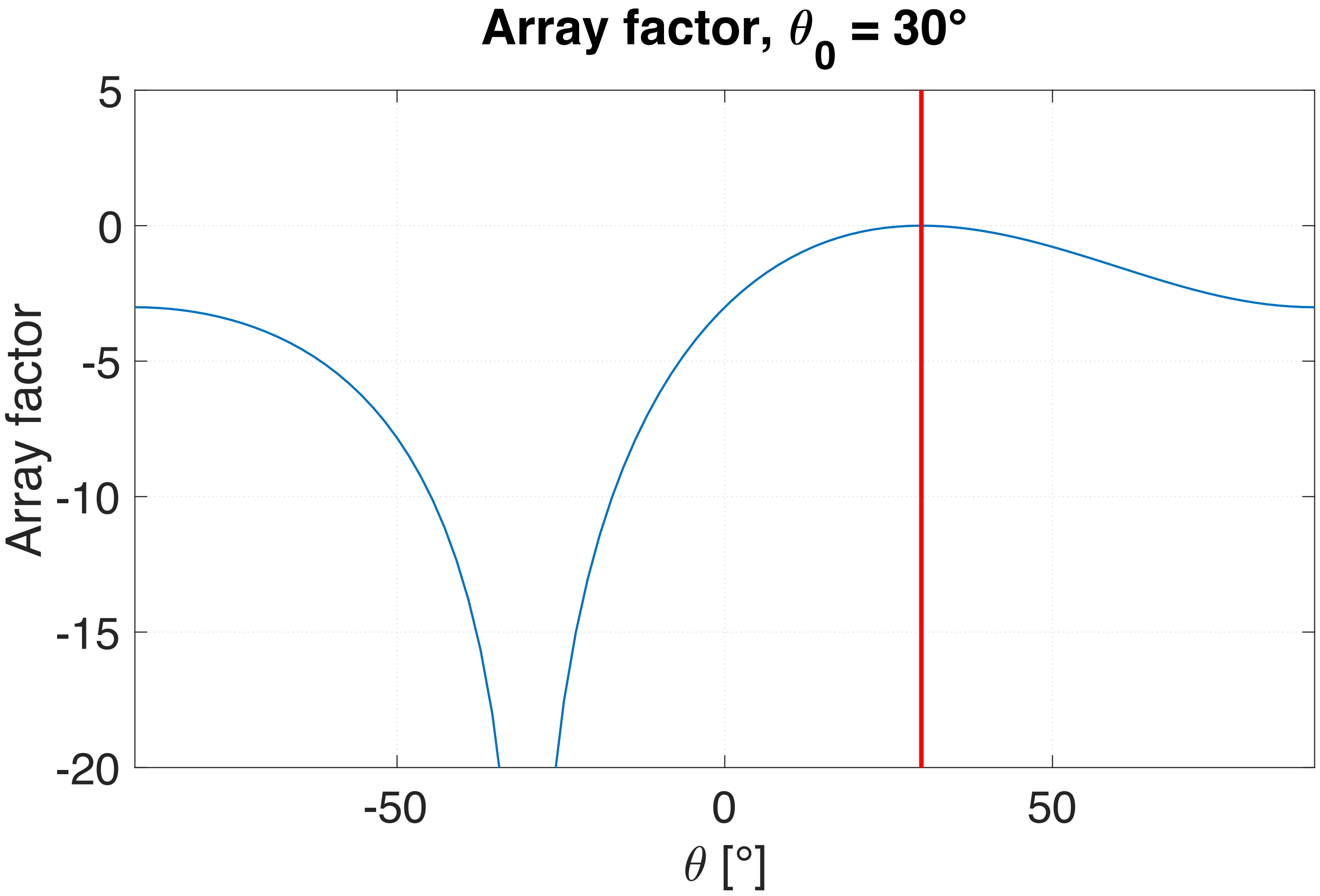
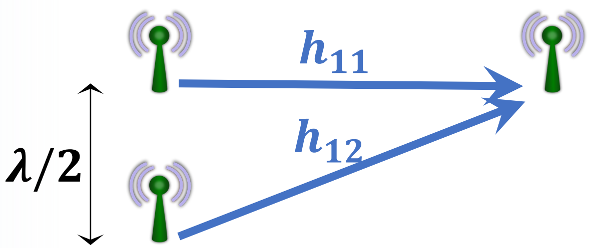


Matched Beamforming

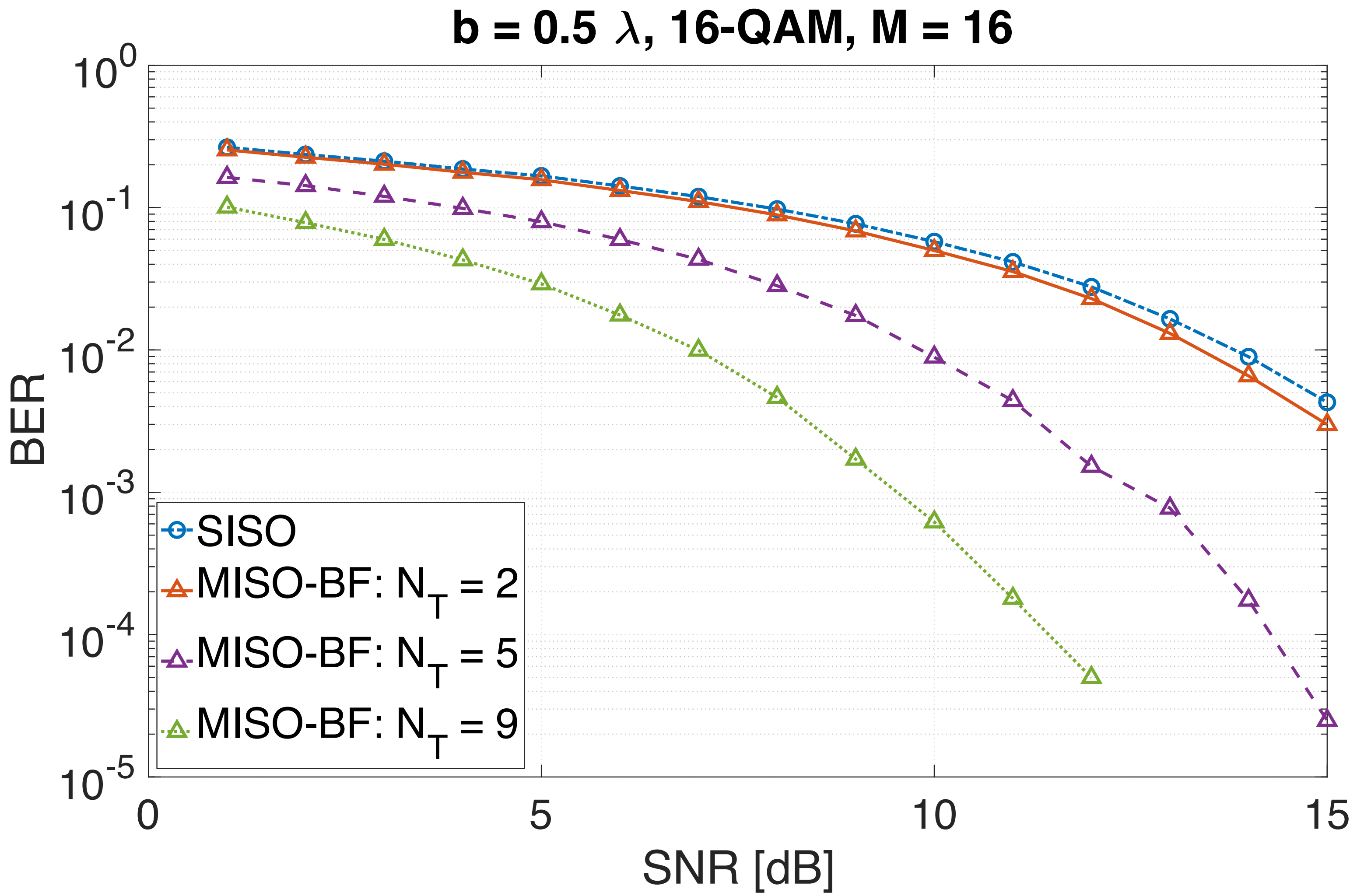
Scenario



Channel

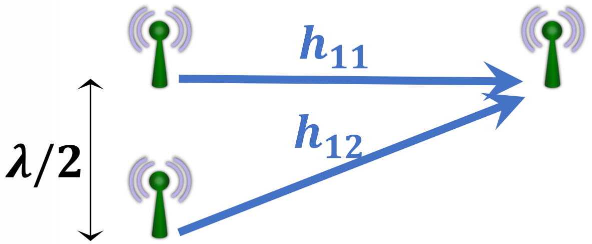
Two-wave model:

- AoA = 30°
- AoA = -45°



Matched Beamforming

Scenario



Channel

Two-wave model:

- AoA = 30°
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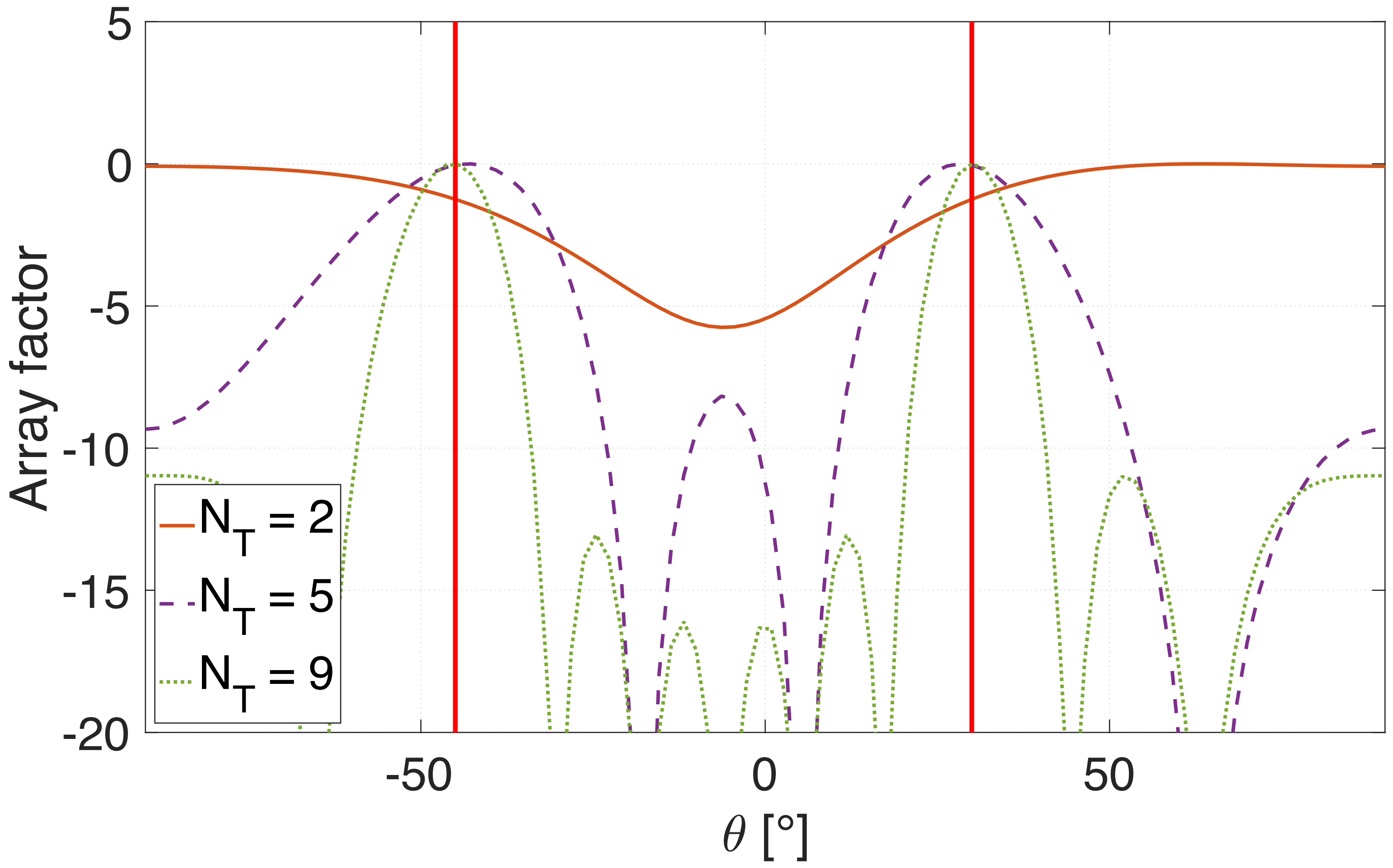
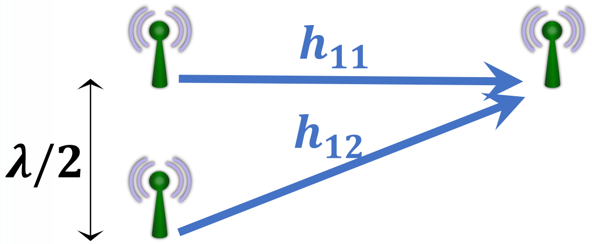


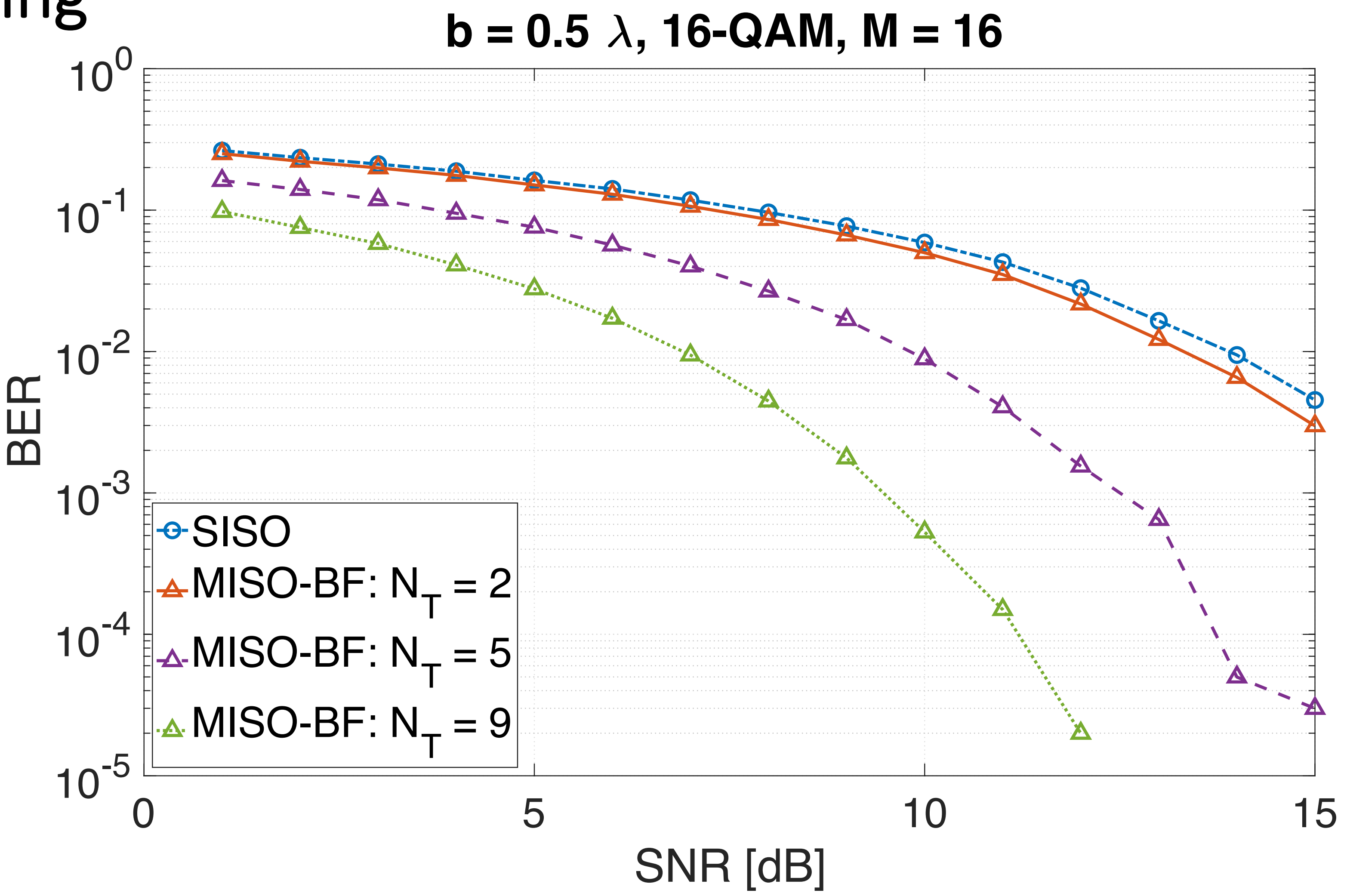
Matched Beamforming

Scenario



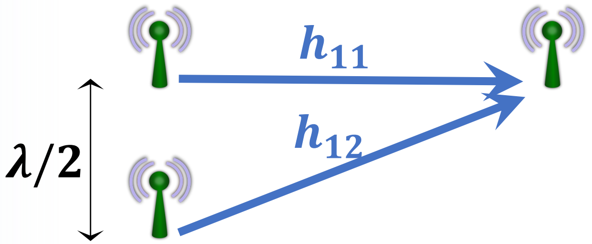
Channel

Two-wave model:
- AoA = 30°
- AoA = -45° (half-power)



Matched Beamforming

Scenario



Channel

Two-wave model:

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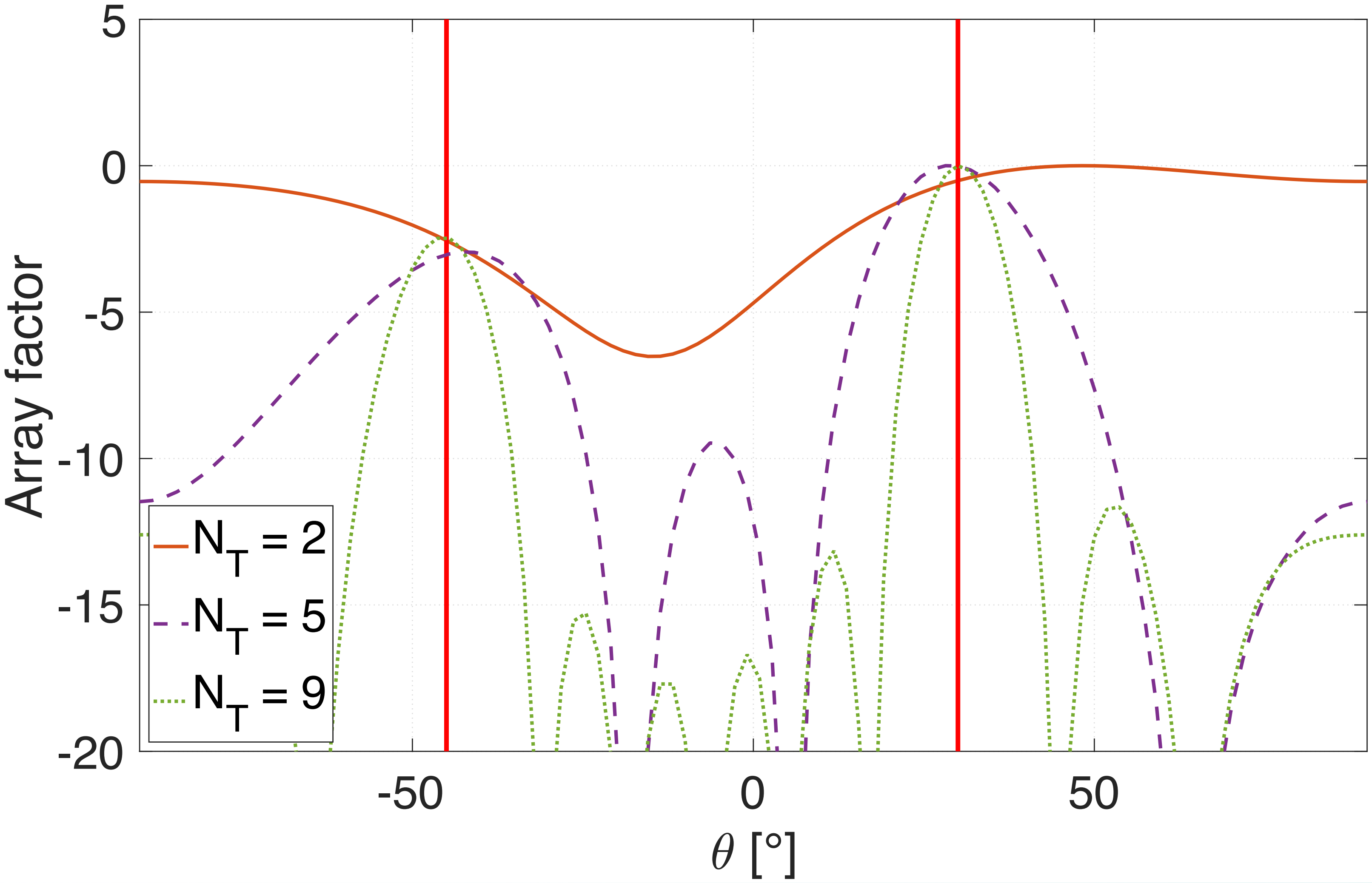
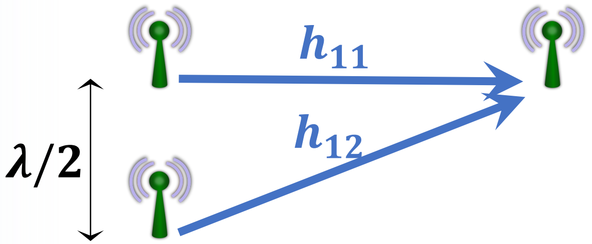


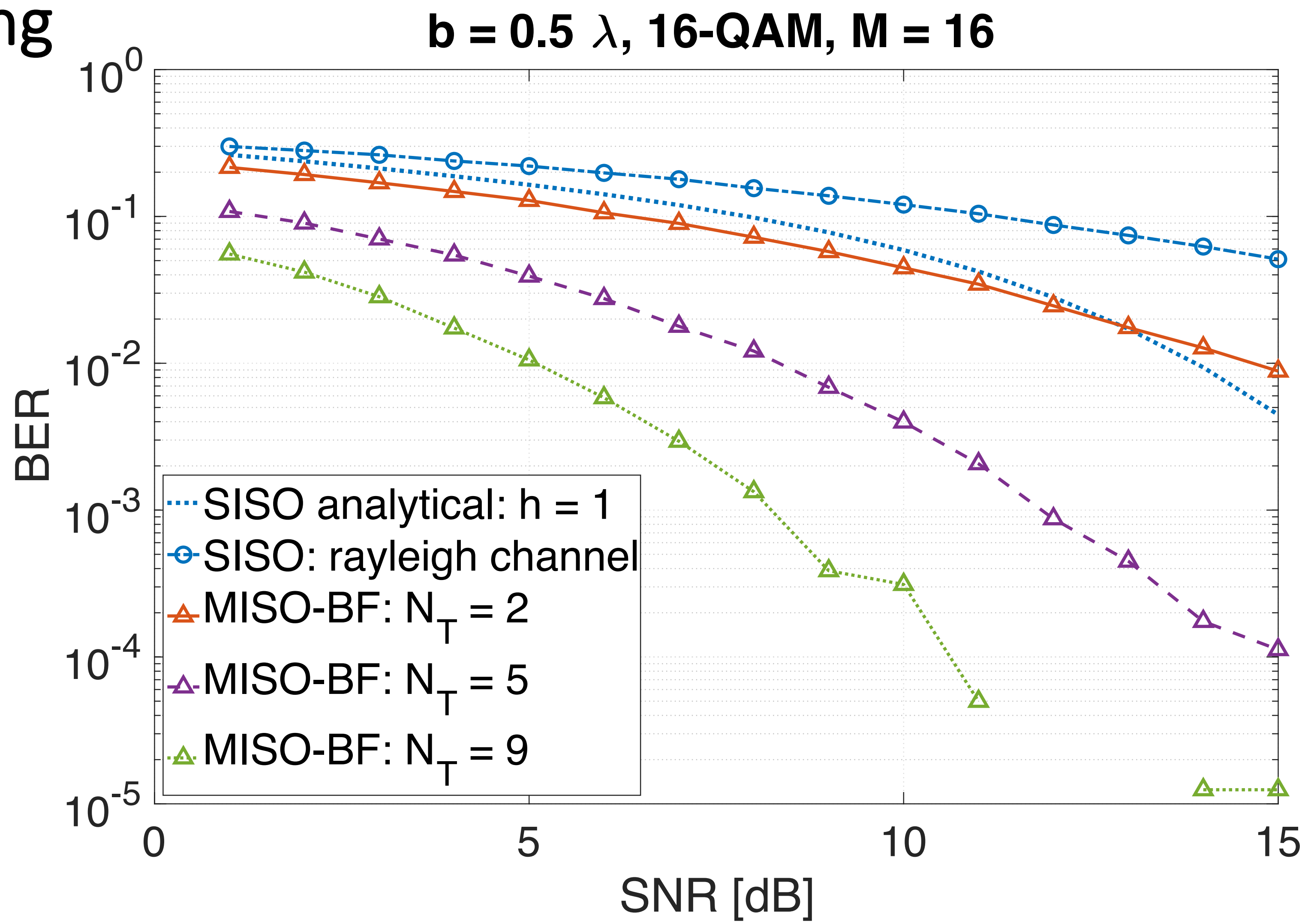
Matched Beamforming

Scenario



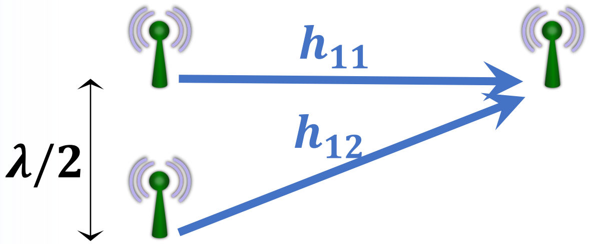
Independent Rayleigh Channels

$$h_{1i} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$



Matched Beamforming

Scenario



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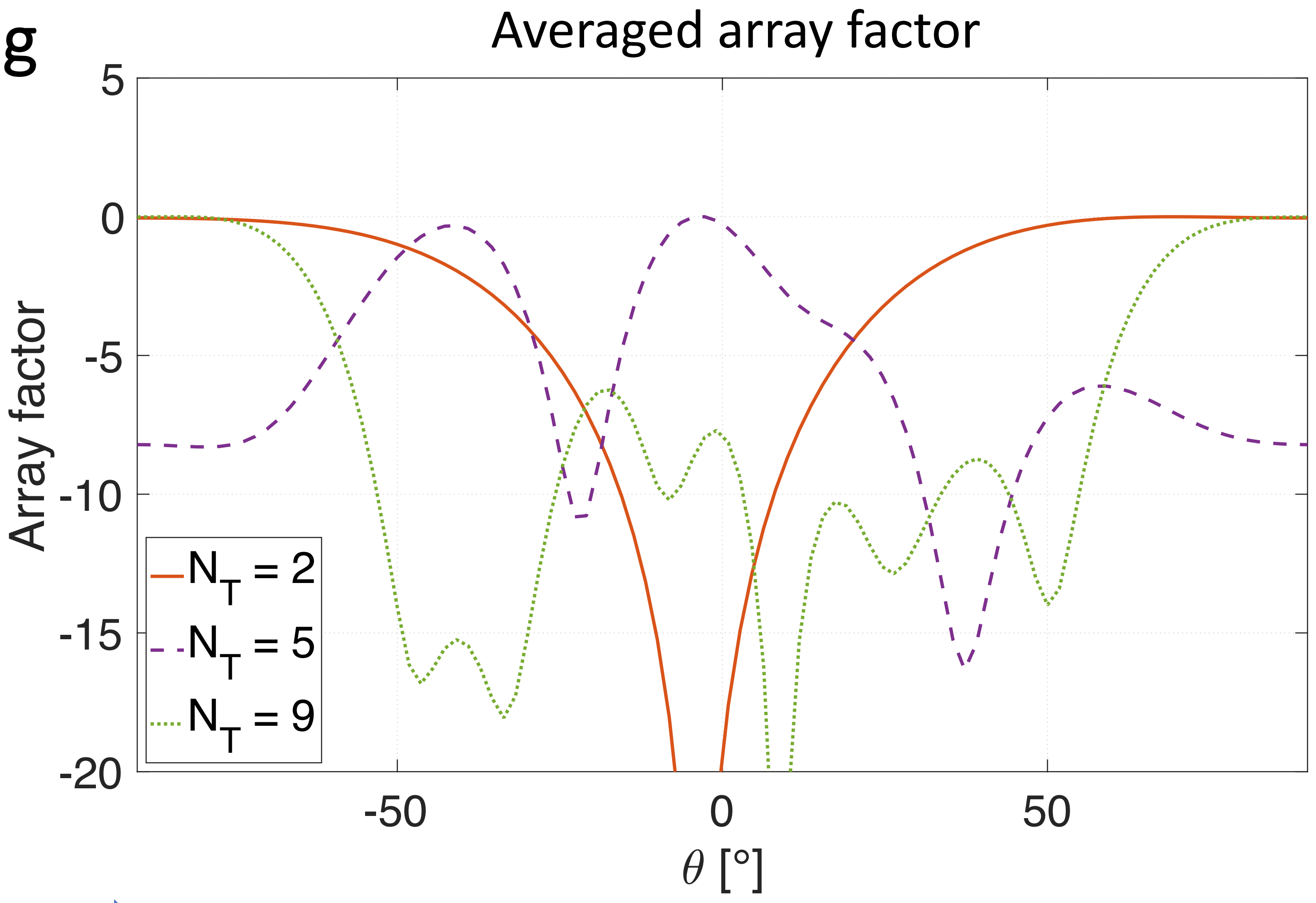
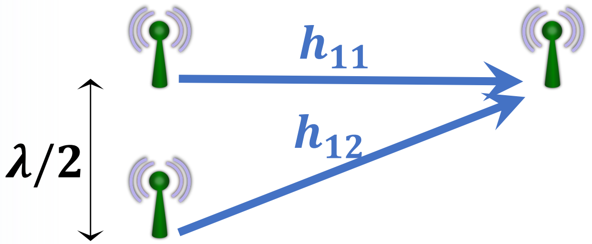


➡ Random AF: a different data stream would have led to different AF!

Matched Beamforming

Scenario

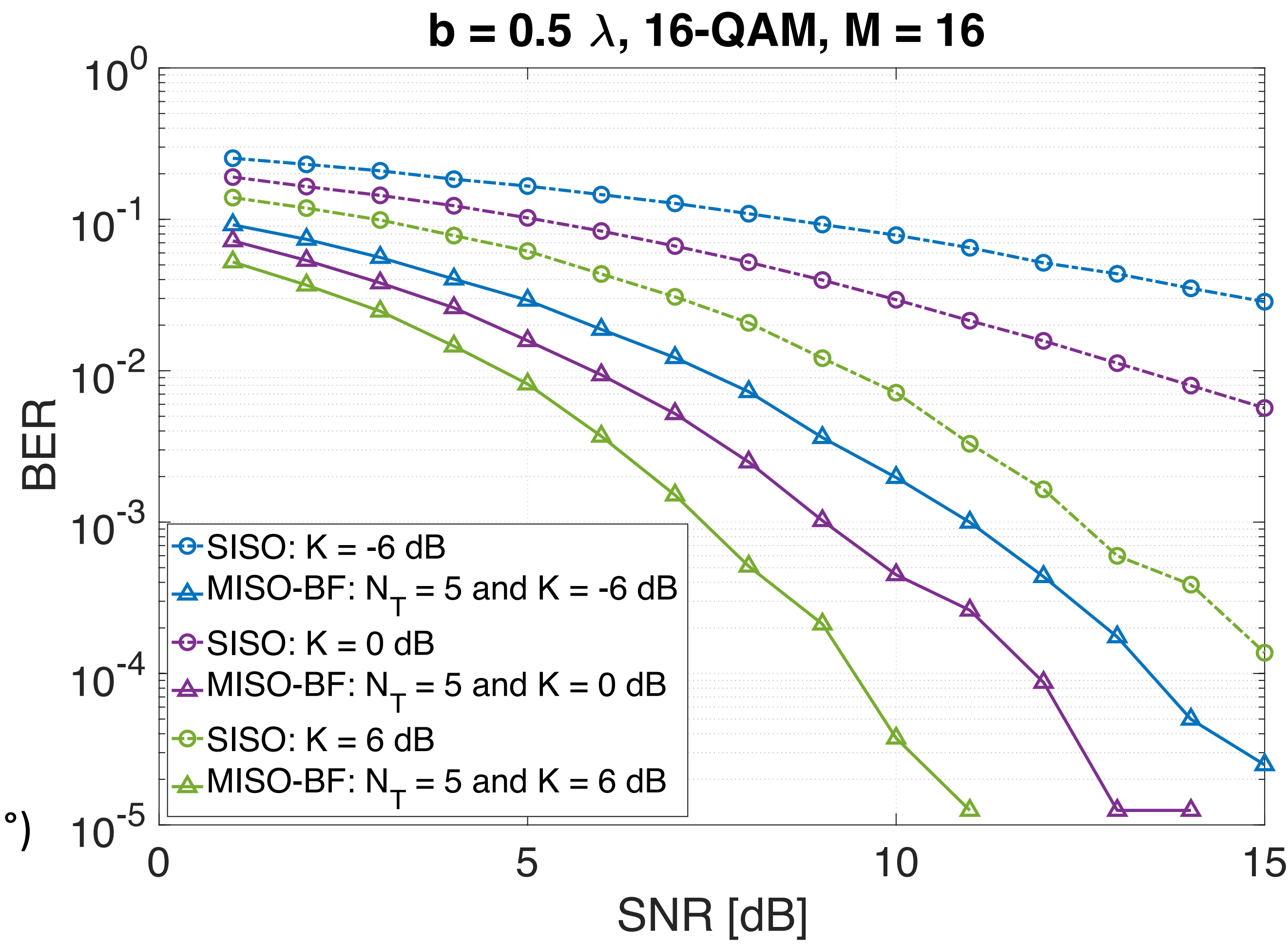


Rice channel Channels

$$\boldsymbol{h}_{rice} = \sqrt{\frac{K}{1+K}}\boldsymbol{h}_{LOS} + \sqrt{\frac{1}{1+K}}\boldsymbol{h}_{NLOS}$$

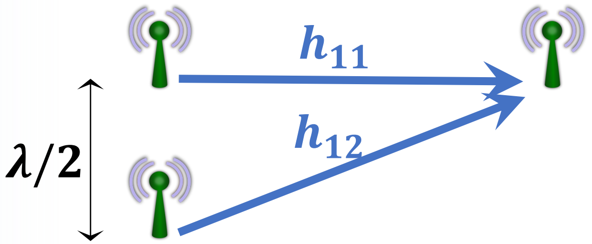
with $\boldsymbol{h}_{LOS}$: two-wave model (AoA = 30° & -45°)

$$h_{NLOS_{1i}} = \frac{1}{\sqrt{2}}\left(\mathcal{N}(0,1) + j\mathcal{N}(0,1)\right)$$



Matched Beamforming

Scenario



Rice channel Channels

$$\boldsymbol{h}_{rice} = \sqrt{\frac{K}{1+K}}\boldsymbol{h}_{LOS} + \sqrt{\frac{1}{1+K}}\boldsymbol{h}_{NLOS}$$

with $\boldsymbol{h}_{LOS}$: two-wave model (AoA = 30° & -45°)

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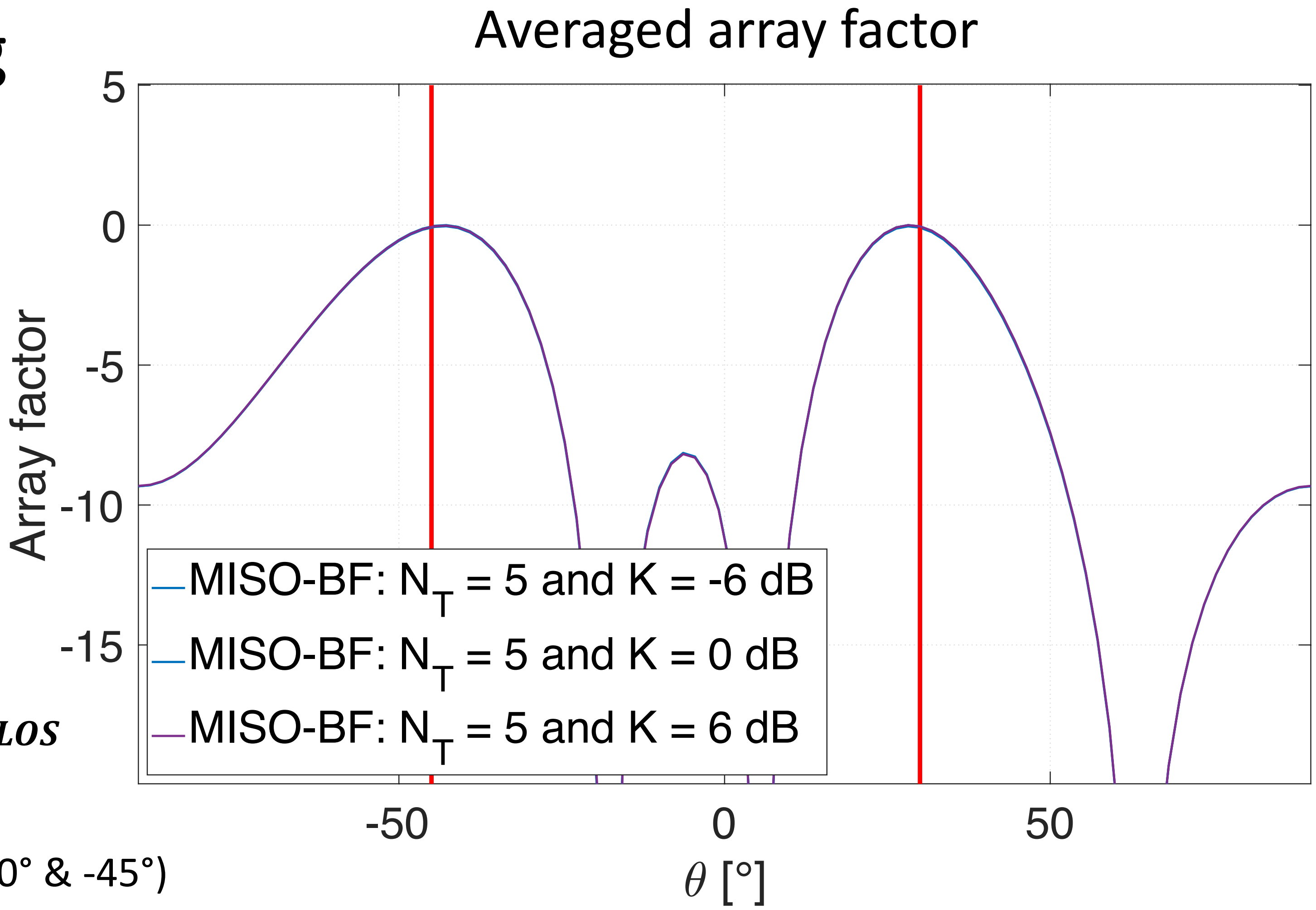
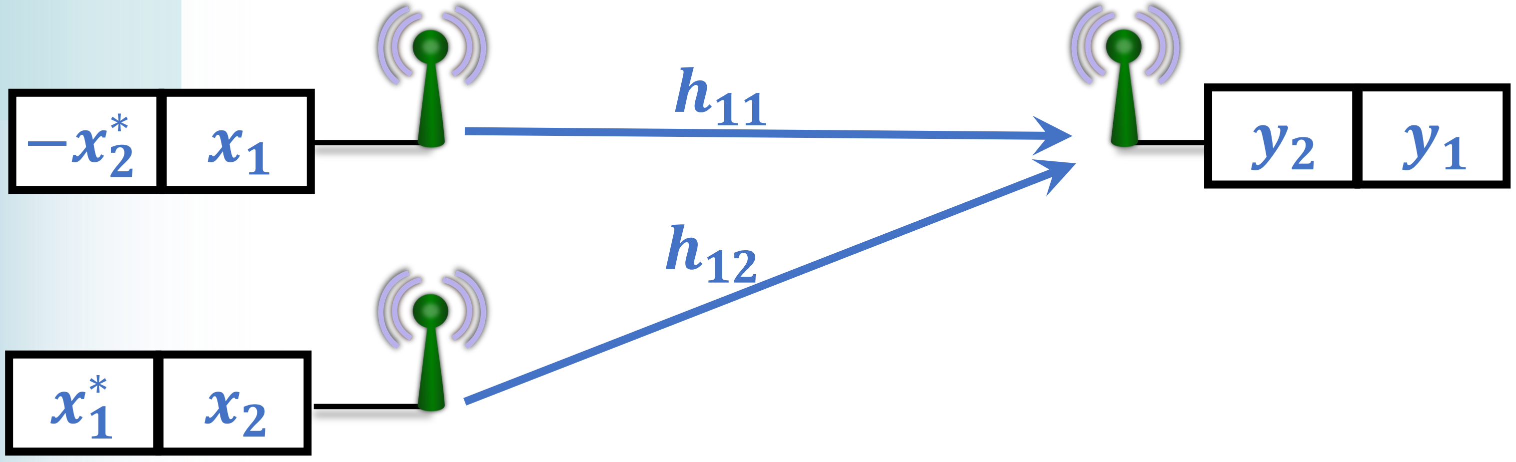


Transmit diversity

- MISO: CSI unknown at TX => Alamouti scheme



Received signals:

$$y_1 = \frac{1}{\sqrt{2}}(h_{11}x_1 + h_{12}x_2) + n_1$$

$$y_2 = \frac{1}{\sqrt{2}}(-h_{11}x_2^* + h_{12}x_1^*) + n_2$$

Alamouti RX performs:

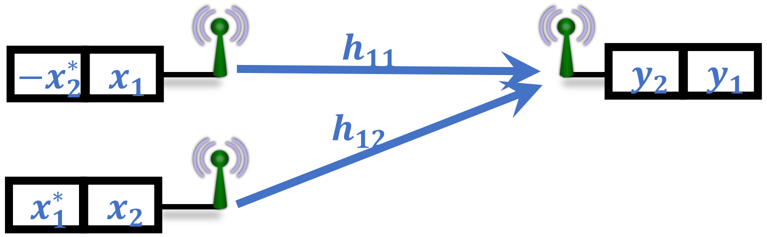
$$\boldsymbol{y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix}$$

Spatial code rate $R_s = 1$
(2 symbols over 2 time slots)

$\frac{1}{\sqrt{2}}$ *factor because no array gain (x_1 and x_2 are independent)*

Transmit diversity

- MISO: CSI unknown at TX => Alamouti scheme



Received signals

$$y_1 = \frac{h_{11}x_1 + h_{12}x_2}{\sqrt{2}} + n_1$$

$$y_2 = \frac{-h_{11}x_2^* + h_{12}x_1^*}{\sqrt{2}} + n_2$$

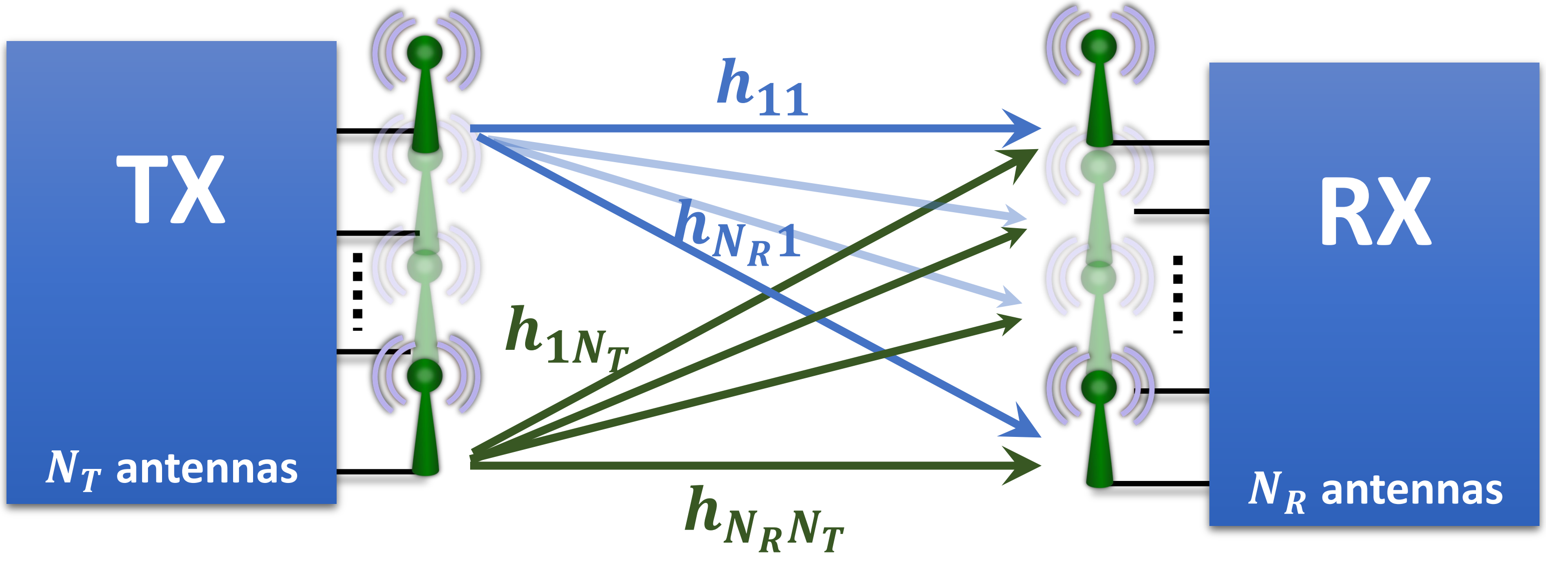
Alamouti RX

$$\boldsymbol{y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} \Rightarrow \boldsymbol{y} = \frac{1}{\sqrt{2}}\begin{bmatrix} h_{11} & h_{12} \\ h_{12}^* & -h_{11}^* \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \Leftrightarrow \boldsymbol{y} = \boldsymbol{H_A x} + \boldsymbol{n}$$

$$\boldsymbol{z} = \boldsymbol{H_A^H y} = \boldsymbol{H_A^H H_A x} + \boldsymbol{H_A^H n} \Leftrightarrow \boldsymbol{z} = \frac{|h_{11}|^2 + |h_{12}|^2}{2}\boldsymbol{I_2 x} + \boldsymbol{H_A^H n}$$

- ➡ $z_i = \frac{|h_{11}|^2+|h_{12}|^2}{2}x_i + \tilde{n}_i$ (perfect orthogonality between z_i)
- ➡ Scheme similar to MRC (but no array gain)
- ➡ Diversity gain of 2, like MRC (but no array gain)

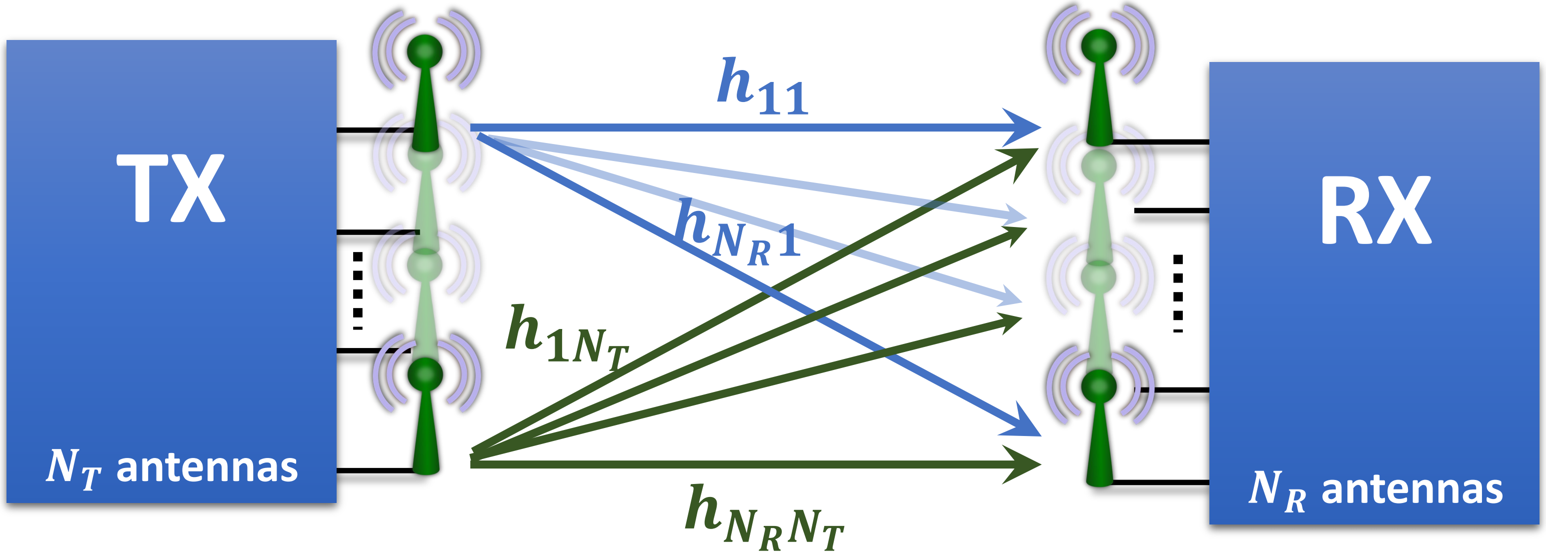
MIMO configuration



- Open-loop (TX has no CSI knowledge)
- Closed-loop (TX has total or partial CSI knowledge)

Spatial multiplexing

- MIMO configuration



$$\boldsymbol{H} = \begin{bmatrix} h_{11} & \cdots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R1} & \cdots & h_{N_RN_T} \end{bmatrix}$$

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Spatial multiplexing: SVD

- Singular value decomposition (SVD) = MIMO Beamforming

$$\boldsymbol{H} = \underbrace{\boldsymbol{U}}_{[N_R \times N_R]}\underbrace{\boldsymbol{\Sigma}}_{[N_R \times N_T]}\underbrace{\boldsymbol{V}^{\boldsymbol{H}}}_{[N_T \times N_T]}$$

$\boldsymbol{U}, \boldsymbol{V}$: Unitary matrices:

$$\boldsymbol{U}^{\boldsymbol{H}}\boldsymbol{U} = \boldsymbol{I}_{\boldsymbol{R}}$$
$$\boldsymbol{V}^{\boldsymbol{H}}\boldsymbol{V} = \boldsymbol{I}_{\boldsymbol{T}}$$

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & \vdots \\ 0 & 0 & \sigma_{R_H} \end{bmatrix}$$

$\boldsymbol{\Sigma}$: matrix composed with R_H singular values σ_i (with R_H, the rank of the matrix)

$\sigma_i = \sqrt{\lambda_i}$ with λ_i, the eigenvalues of $\boldsymbol{H}\boldsymbol{H}^{\boldsymbol{H}}$

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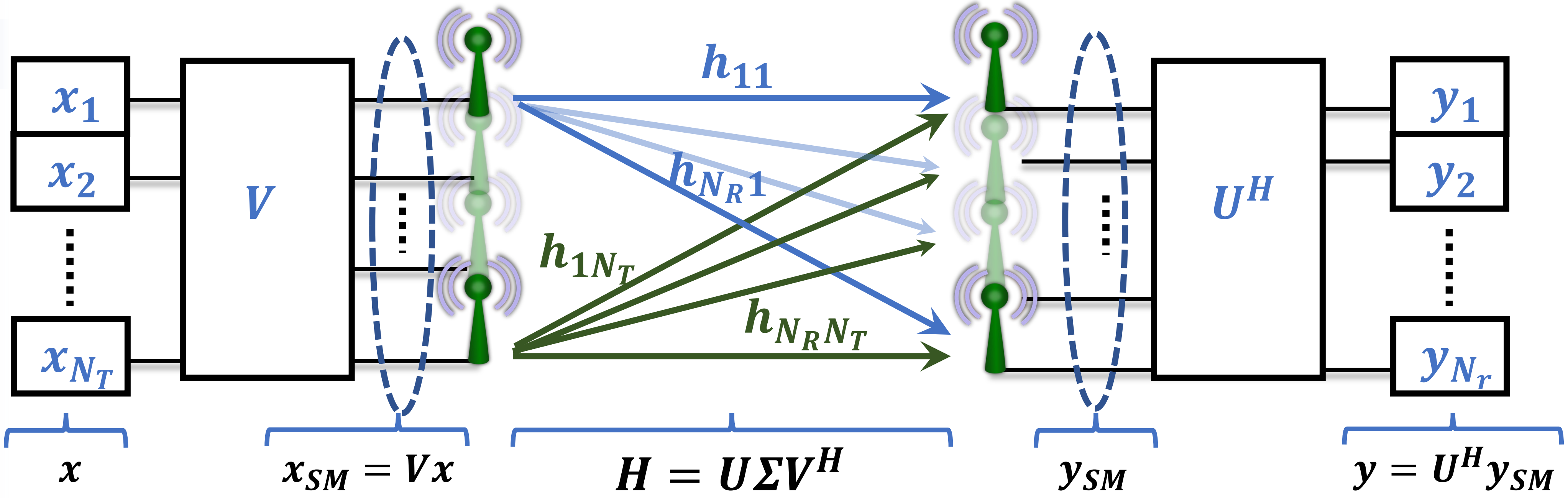
Spatial multiplexing: SVD

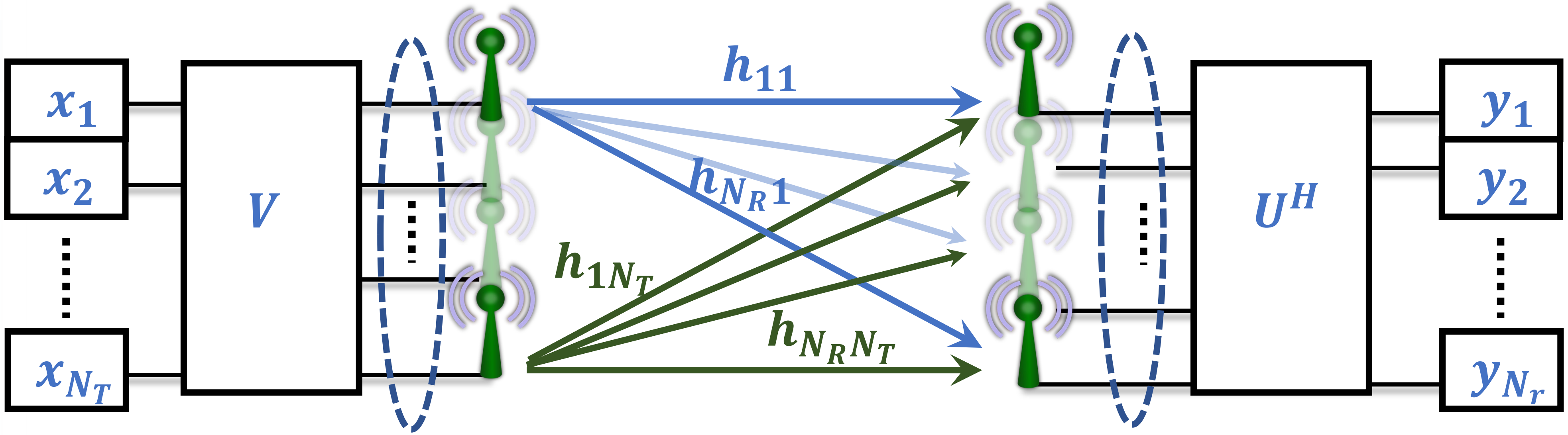


Received signal:

$$y = U^H y_{SM} = U^H H x_{SM} = U^H H V x \quad \text{with} \quad H = U\Sigma V^H$$

$$\Rightarrow \quad y = U^H U \Sigma V^H V x \quad \Rightarrow \quad \boxed{y = \Sigma x}$$

Spatial multiplexing: SVD



$\boxed{\boldsymbol{y} = \boldsymbol{\Sigma x}}$

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & \vdots \\ 0 & 0 & \sigma_{R_H} \end{bmatrix}$$

➡ $\boldsymbol{\Sigma}$ is diagonal: SM can send R_H symbols simultaneously

$$\begin{bmatrix} y_1 \\ y_2 \\ y_{N_R} \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & \vdots \\ 0 & 0 & \sigma_{R_H} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_{N_T} \end{bmatrix}$$

➡ $$y_i = \sigma_i x_i$$

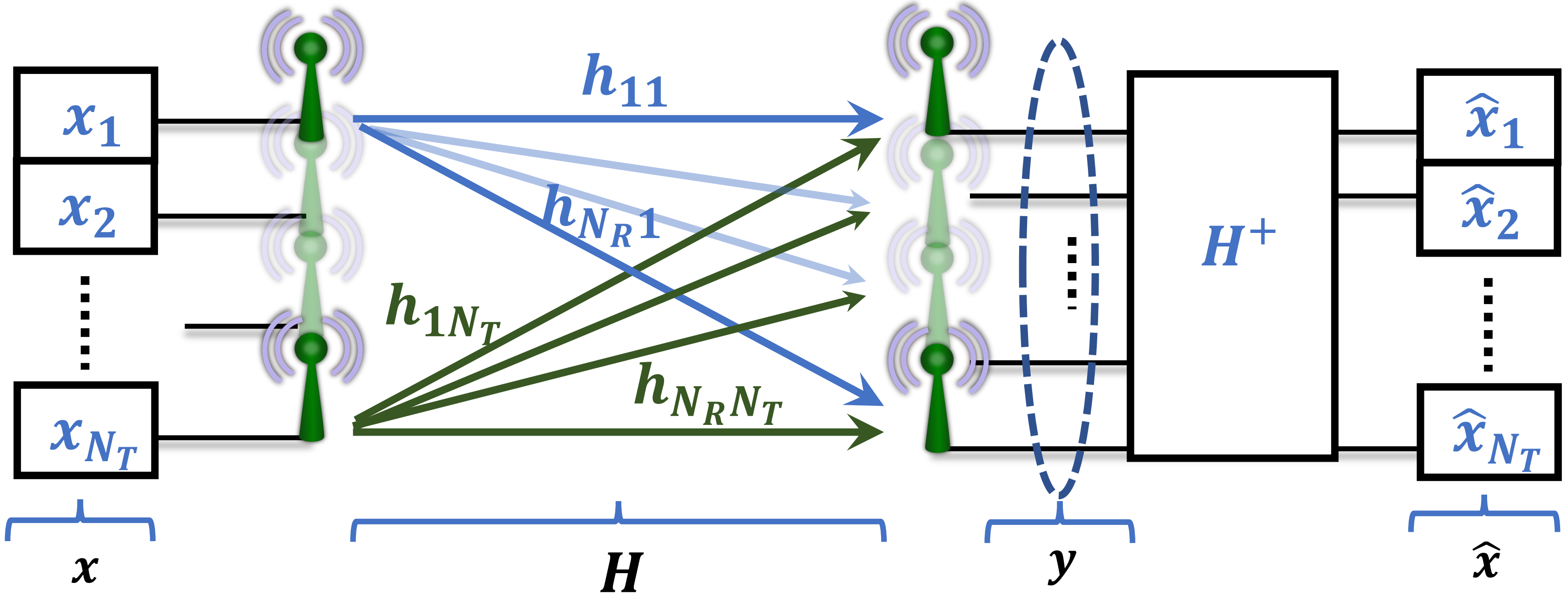
$$R_H \leq min(N_T, N_R)$$

Spatial multiplexing: SVD

- Using eigen vectors of **H** (**U** and **V**) as array weights produces eigen patterns that create independent (spatially orthogonal) parallel communications channels
- It allows spatial multiplexing of data (increase data rate)
- Each spatial channel (named layers in 3GPP releases) benefits from the array gain (increase SNR)
- Very efficient but requires CSI at TX (requires overheads, feedbacks)
- If no CSI at TX available, SM is still possible but without array gain

Spatial multiplexing: no CSI at TX

- Maximum likelihood estimate using the pseudo-inverse of **H**



$\boxed{\hat{x} = H^+ y}$

➡ requieres $N_R \geq N_T$

➡ no array gain

LTE and 5G

3GPPP Release 15 – New Radio (NR)

- 5G phase 1 (release 15) done in 2019
- 5G phase 2 (release 16) expected in 2020
- Enhanced capabilities to support new usages
- Versatility to support vertical applications
- Massive MTC and Internet of Things (IoT)
- Vehicle-to-Everything Communications (V2x) - Phase 2
- WLAN and unlicensed spectrum use
- Further LTE improvements
- …

Multiple-layer beamforming (Adaptive Beamforming)

- In LTE and 5G, combination of Array Gain and Spatial Multiplexing gain

➡ Beamforming-based spatial multiplexing

Spatial Channels = layers

➡ Multiple-layer beamforming (to multiplex multiple data)

- Creation of *L* “radiation patterns” thanks to *L* beamforming vectors
- These *L* “radiation patterns” introduce *L* Spatial Channels, i.e., *L* layers
- The precoding matrix concatenates the *L* beamforming vectors
- Eigen-based beamforming (based on SVD) is such a technique

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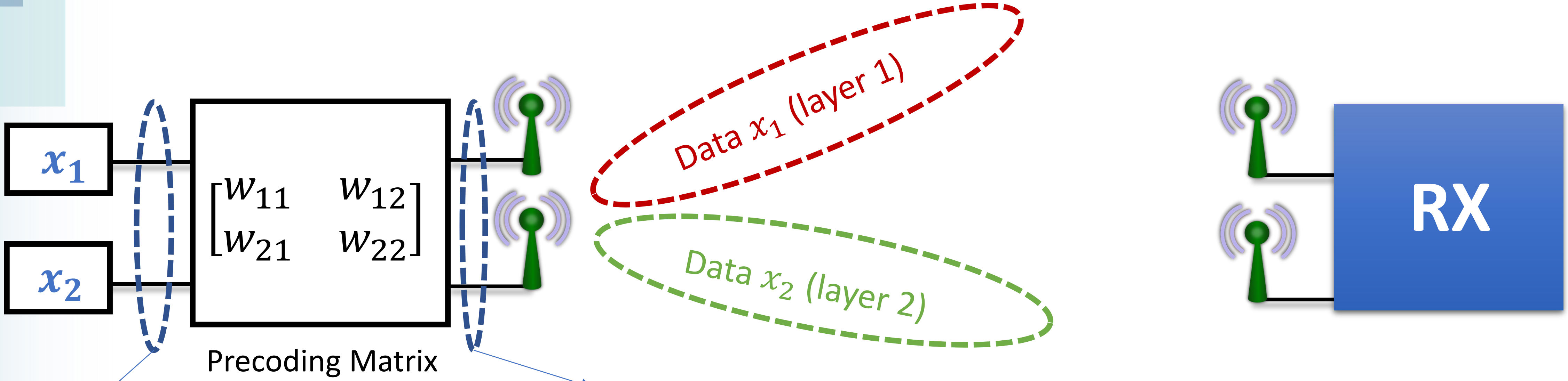
Multiple-layer beamforming (Adaptive Beamforming)

- 2x2 MIMO: dual-layer transmission



$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\begin{bmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} w_{11}x_1 + w_{12}x_2 \\ w_{21}x_1 + w_{22}x_2 \end{bmatrix}$$

BF vector for layer 1

BF vector for layer 2

Practical aspects of MIMO in LTE/5G

- Some MIMO coding are not practical due to the difficulty to obtain CSI at TX in real systems
- Obtaining CSI at TX requires feedback in FDD systems (UL and DL channels are different)
- Obtaining CSI at TX in TDD systems is somehow easier thanks to channel reciprocity (but interferences are not reciprocal and RF chains are different for TX/RX)
- MIMO coding depends on CSI which in turns depends on Reference Signal (RS) design and management procedure
- Precoding matrix design strategy depends on the Transmission Mode (TM)

Codebook concept

- In LTE and 5G, both TDD and FDD are supported
- Concept of codebook is used to reduce overhead

Codebook concept

- BTS send Reference Signals (RS)
- UE estimate the MIMO channel and determine the best precoding to be used within a given codebook (whose length depends on the transmission mode and the number of antennas)
- UE feedbacks the Precoding Matrix Indicator (PMI) of the best choice
- Enable (sub-optimal) beamforming with no CSI at TX
- Requires a light feedback: PMI index and Channel Quality Indicator (CQI)

Codebook concept in LTE

- Number of precoding matrix available (codebook length)

Transmission Mode (TM)	2-antenna ports	4-antenna ports	8-antenna ports
TM 3	2	4	
TM 4	6	64	
TM 5	4	16	
TM 6	4	16	
TM 8	6	32	
TM 9 or 10	6	64	109

Codebook concept in LTE

- Example of precoding matrix for a 2-antenna system (defined codebook known at both BTS and UE)

Codebook index	1 layer	2 layers
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	--

➡ Predefined codebook limits the choice of precoding matrix (this limitation is relaxed from Release 10 onwards)

Reference Signals (RS)

- Common Reference Signal (CRS) in LTE Rel. 8
  - The same CRS are broadcasted for all UE
  - Each UE estimate its channel and feedback the PMI/CQI
  - The BTS combine orthogonal PMI to address multiple UE
  - To demodulate, the UE estimates the non-precoded channel based on CRS and derives the precoded channel based on the transmit precoder signaled by the BTS **[cle2013]**
- Demodulation RS (DM-RS) in LTE Rel. 9 and LTE-A
  - DM-RS are sent already precoded, so UE uses those directly for demodulation
  - No need for the BTS to signal the precoder
  - Non-codebook precoder are therefore possible (such as ZFBF and JLS)

Concept of SU-MIMO VS MU-MIMO

- Massive MIMO has $N_T >> N_R$
- So SU-MIMO gain is limited

$$C_{SU-MIMO} = \min(N_T, N_R)\log_2\left(1 + \frac{\rho_R}{N_T}\min(N_T, N_R)\right)$$

- With MU-MIMO, each UE is seen as N_R receiving antennas
- With N_{UE} UE, the MIMO system becomes of size N_T x $(N_R.N_{UE})$
- The MU-MIMO sum capacity is therefore:

$$C_{MU-MIMO} = \min(N_T, N_R.N_{UE})\log_2\left(1 + \frac{\rho_R}{N_T}\min(N_T, N_R.N_{UE})\right)$$

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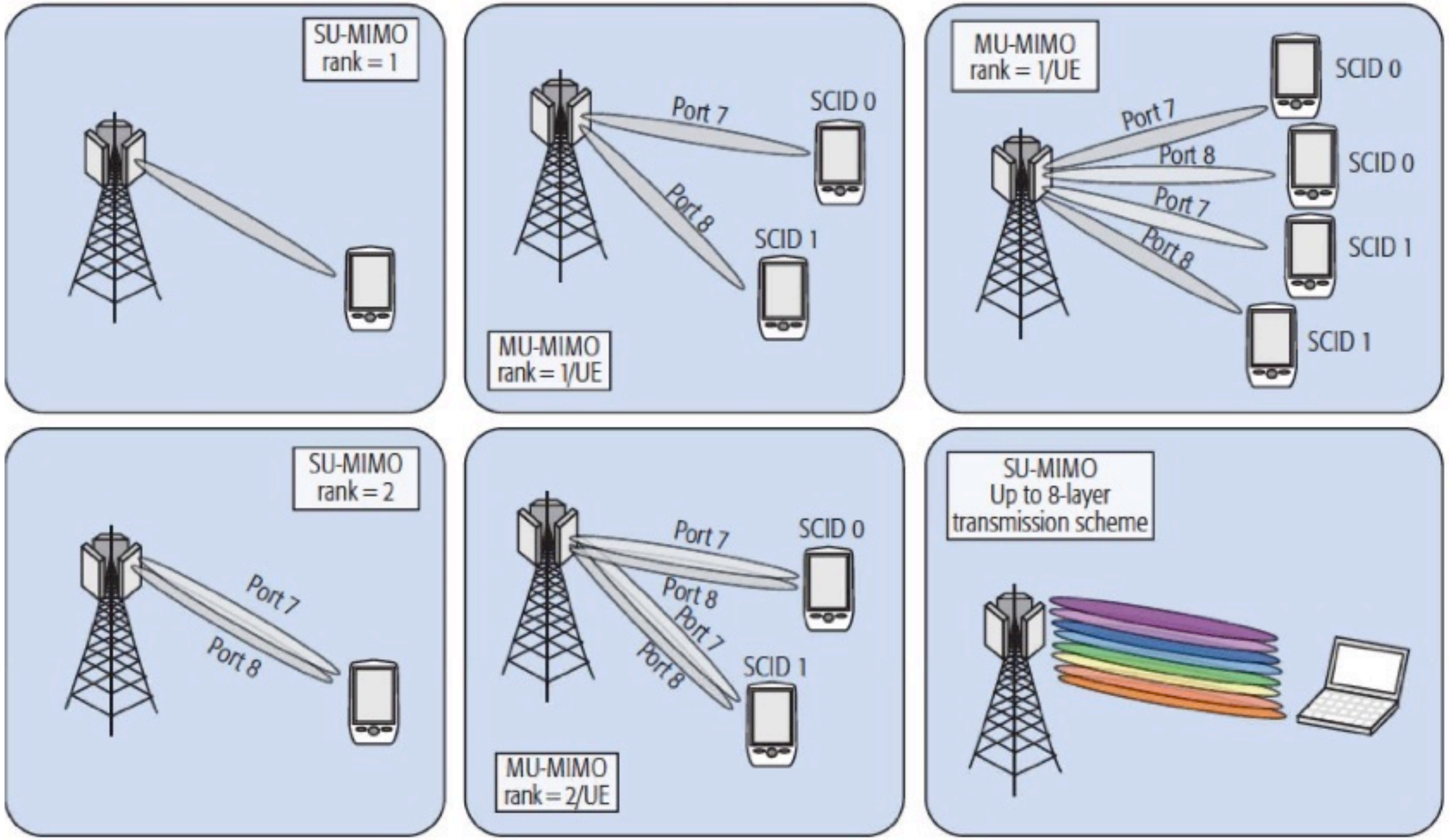
Concept of SU-MIMO VS MU-MIMO



[che2016]

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Concept of SU-MIMO VS MU-MIMO

- Enhanced diversity: distance between UE much larger than λ (leads to higher-rank *H* matrix)
- Resource allocation becomes challenging
- CSI and CQI feedbacks are also challenging in MU schemes
- (UE in MU-MIMO cannot accurately estimate its SINR due to the lack of knowledge of the BTS beam selections for co-scheduled UE devices)

[lim2013]

Concept of transmission layer (LTE-A): DL

Downlink Transmission modes in LTE Release 12			
Transmission modes	**Description**	**DCI (Main)**	**Comment**
1	Single transmit antenna	1/1A	single antenna port port 0
2	Transmit diversity	1/1A	2 or 4 antennas ports 0,1 (…3)
3	Open loop spatial multiplexing with cyclic delay diversity (CDD)	2A	2 or 4 antennas ports 0,1 (…3)
4	Closed loop spatial multiplexing	2	2 or 4 antennas ports 0,1 (…3)
5	Multi-user MIMO	1D	2 or 4 antennas ports 0,1 (…3)
6	Closed loop spatial multiplexing using a single transmission layer	1B	1 layer (rank 1), 2 or 4 antennas ports 0,1 (…3)
7	Beamforming	1	single antenna port, port 5 (virtual antenna port, actual antenna configuration depends on implementation)
8	Dual-layer beamforming	2B	dual-layer transmission, antenna ports 7 and 8
9	8 layer transmission	2C	Up to 8 layers, antenna ports 7 - 14
10	8 layer transmission	2D	Up to 8 layers, antenna ports 7 - 14

[sch2015]

Concept of transmission layer: UL

- In LTE-A and 5G-NR, up to 4 layers are considered for the uplink
- Codebook-based precoding
- Non-codebook-based precoding available for 5G-NR

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