Adaptive Beamforming Technology

IN THE FAR-FIELD SCENARIOS AND SOME NOTES CONCERNING NEAR-FIELD

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About me

- College of Electrical and Information Engineering, Sichuan University, China, 2016.
- Ph. D degree in Southwest Jiaotong University, China, 2013. (visiting Ph. D. student in Univ. of Tennessee, US, 2010~2012)
- The Ph. D. dissertation: frequency-hopping system and FH sequence design.
- Interesting topic of research: FH, OFDM, antenna array, interference rejection, physical-layer technology (e.g., NOMA, Random-BF) in 5G.

Outline

- Basic idea of Beamforming (in far-field setting)
- Introduction of Adaptive BF algorithm
- Some notes on BF in MIMO system
- Some notes on MIMO+BF concerning near-field setting

Part I:

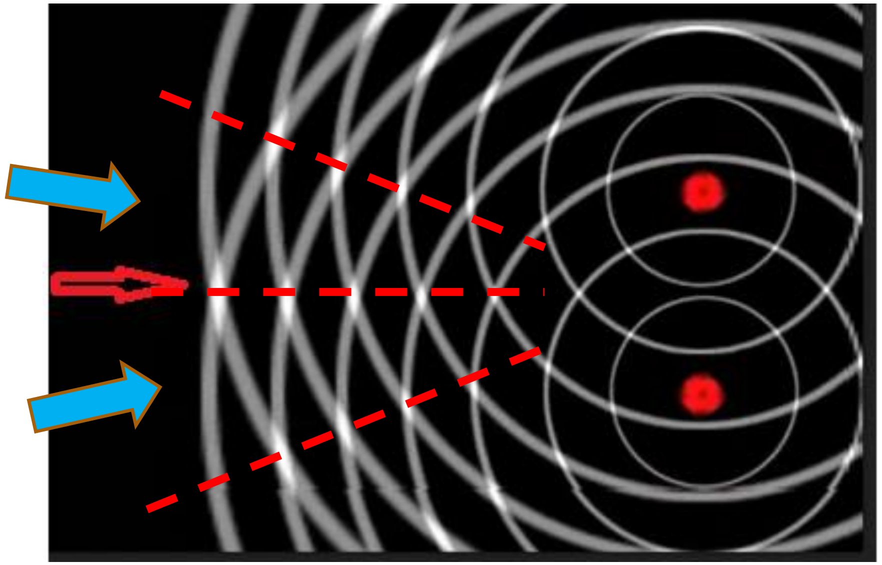
Basic Idea of Beamforming

BF & non-BF

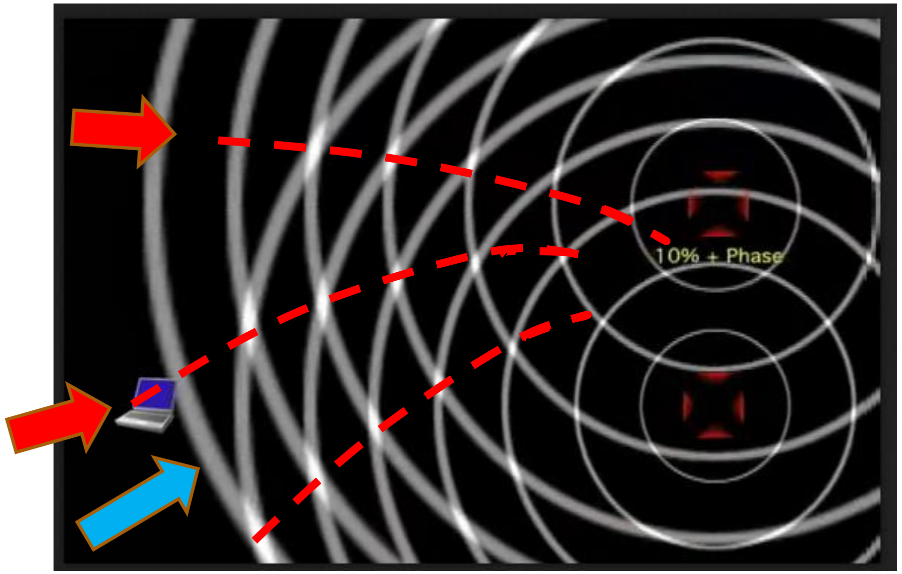
- BF technology is implemented by multiple-antenna (or antenna array).
- BF can be implemented in Transmitter and Receiver (e.g., MIMO system).

- Demonstration of non-BF & BF (https://www.youtube.com/watch?v=8rMtqRObvvU&feature=youtu.be)

non-BF



BF



How to BF?

- Tx model based on BF:

$$x(t-\tau) \overset{FT}{\Rightarrow} X(f)e^{-j2\pi f\tau}$$

$$w_m = \alpha_m e^{j\beta_m}$$

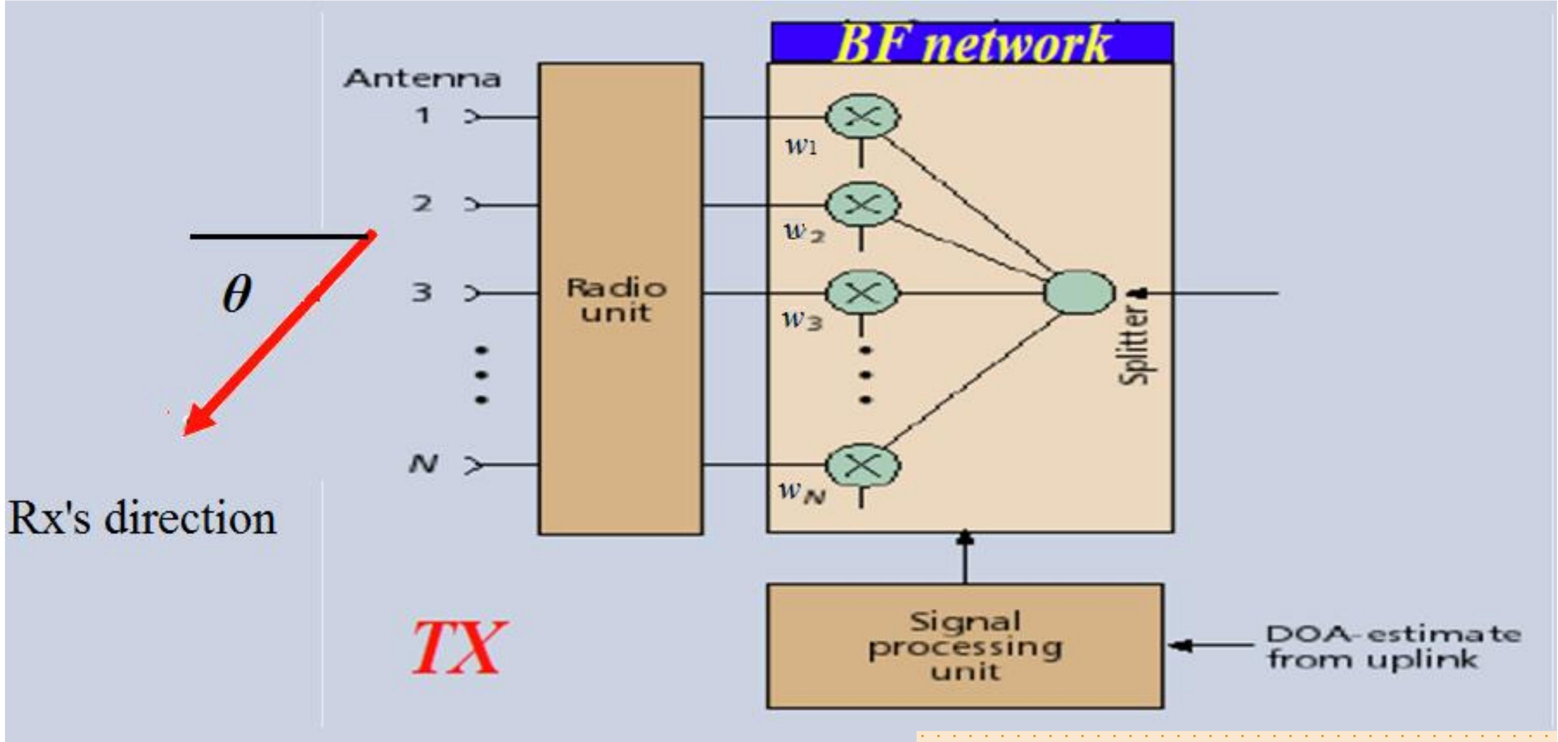
w_m ***is the complex weight***

α_m ***is the amplitude weight***

β_m ***is the phase weight***

- Steering vector

$$W = [w_1 \quad w_2 \quad . \quad . \quad w_M]^T$$



Uniformly Linear array (ULA): #1 element is the referred one, then

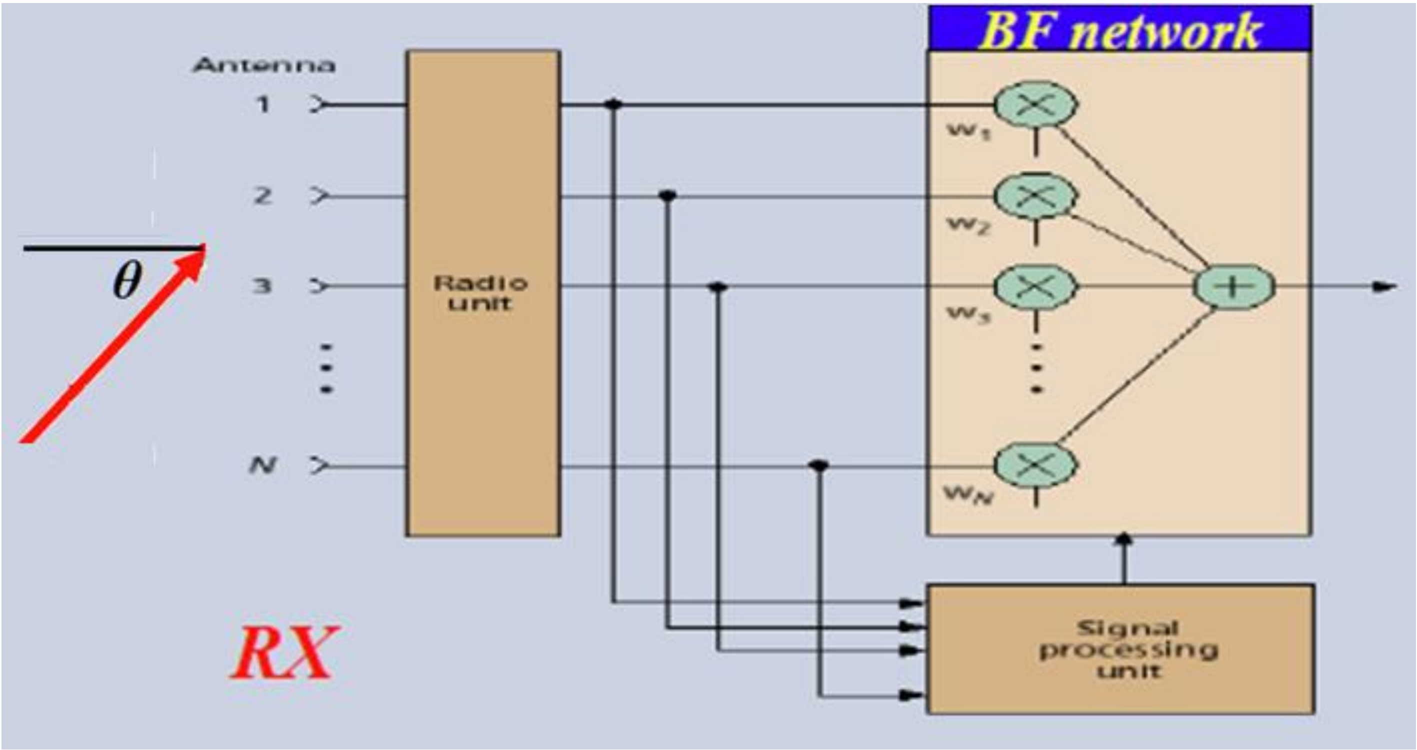
$$\beta_m = -2\pi d(m-1)/\lambda \sin\theta$$

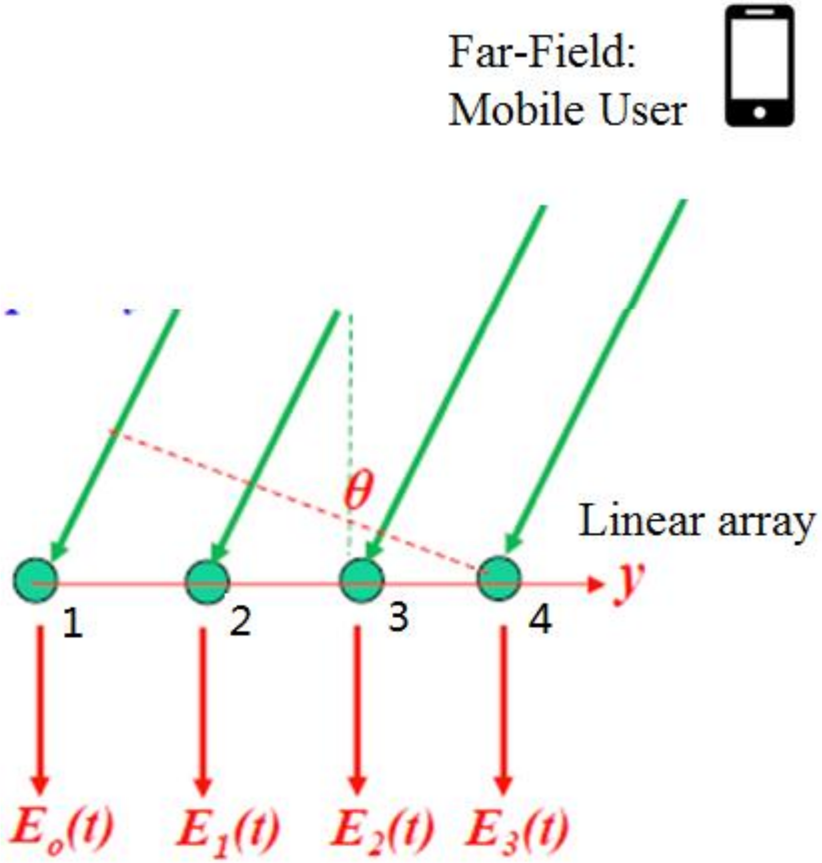
d: space of neighbor elements
λ : wavelength of radio signal

How to BF?

- BF in Rx: Similar to the Tx case. The Rx wants to receive the signal from DoA (θ)

$$w_m = \alpha_m e^{j\beta_m} \qquad \beta_m = -2\pi d(m-1)/\lambda \sin\theta$$



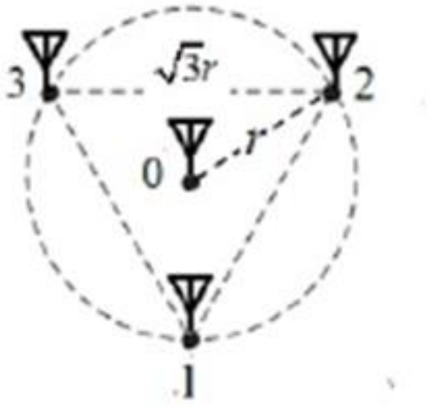


Array pattern--UCA

- BF based on the Uniform Circular Array (UCA)

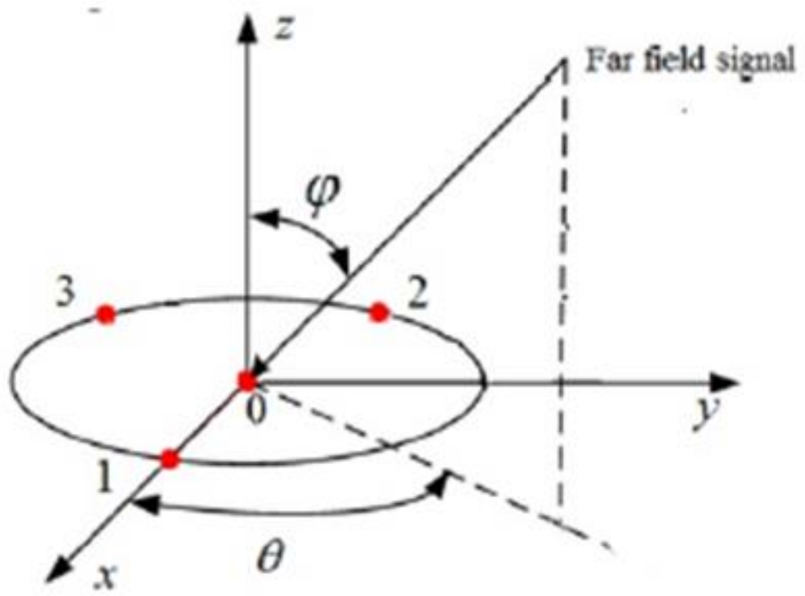
The direction of desired Rx (or Tx): (φ, θ)

the elevation angle $\varphi \in [0, \pi/2]$ the azimuth angle $\theta \in [0, 2\pi)$



- Steering-vector of UCA

$$W = \begin{bmatrix} 1, \\ \exp\left(-j\pi \sin(\varphi)\cos(\theta)d/\lambda\right), \\ \exp\left(-j\pi \sin(\varphi)\cos(\theta - \frac{2\pi}{3})d/\lambda\right), \\ \exp\left(-j\pi \sin(\varphi)\cos(\theta - \frac{4\pi}{3})d/\lambda\right) \end{bmatrix}$$

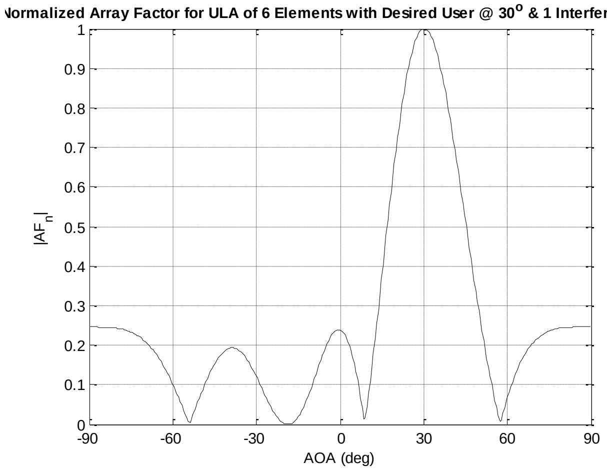


The beam-form pattern: the main-lobe directs towards (φ, θ)

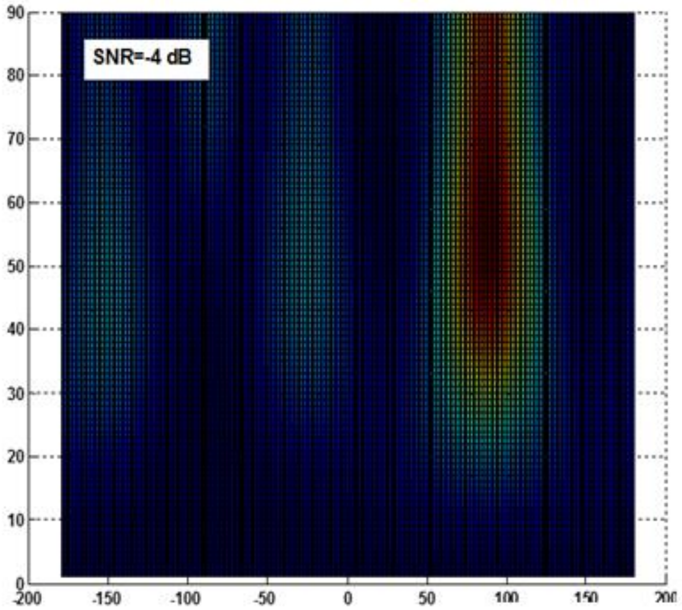
Beam-pattern: ULA & UCA

CASE 2: Beam-pattern of UCA, M=4

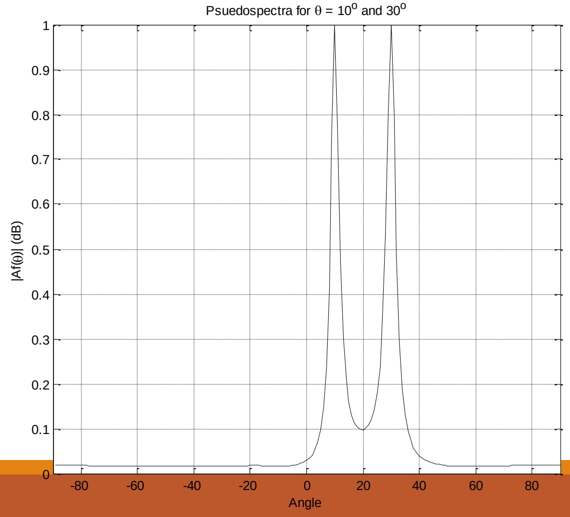
CASE 1: Beam-pattern of ULA in Tx: M=6



Direction:
$\theta = 30^\circ$

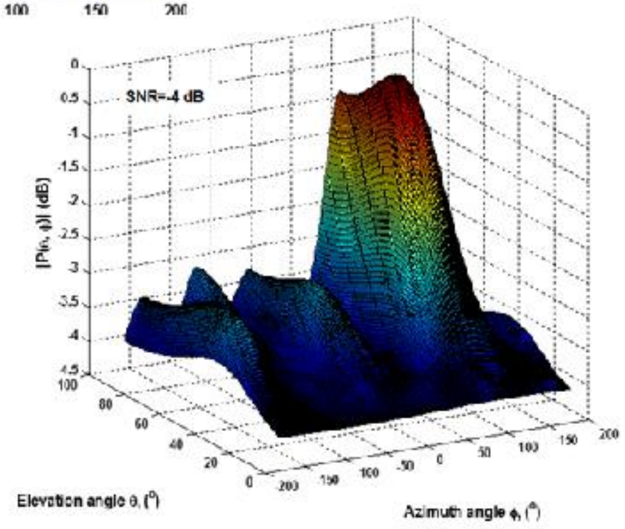


3-D Pattern



2-D Pattern

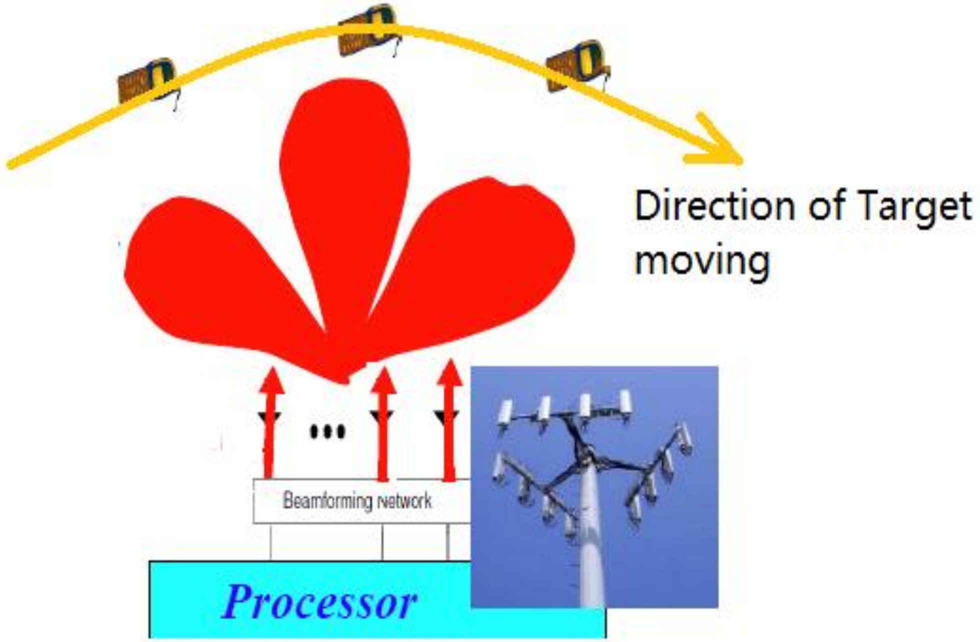
Direction:
$\theta = 10^\circ$
And 40°



Part II

Adaptive BF algorithm

Adaptive BF



- Scenario:

In the mobile communications, the position of Rx and Tx are moving. Thus, the beam-pattern (the direction of main-lobe and the direction of null-lobe) is required to change accordingly.

- Challenge:

1. How to change the beam-pattern? 2. How FAST the beam-pattern is changed? i.e., the convergence rate of adaptive BF

- Methods:

The Beamformer needs the referred signal to switch the beam-pattern. According to the signal detection method, the rule of adaptive BF is categorized as

Least mean square; Sample Matric Inversion; Constant Modulus ….[1]

[1] A. Sharma and S. Mathur, "Performance analysis of adaptive array signal processing algorithms," *IETE Tech. Review*, 2016.

Case 1 : LMS algorithm

The referred signal: d(k); The desired signal: x(k)

- The LMS algorithm is depicted as

$$\mathbf{W}: \quad \min\left\{\left|d(k) - \mathbf{W}^H \mathbf{x}(k)\right|^2\right\}$$

The updating weight is calculated as[1]

$$\mathbf{W}(k+1) = \mathbf{W}(k) + \mu e(k)\mathbf{x}(k)$$

the faster convergence rate is desired

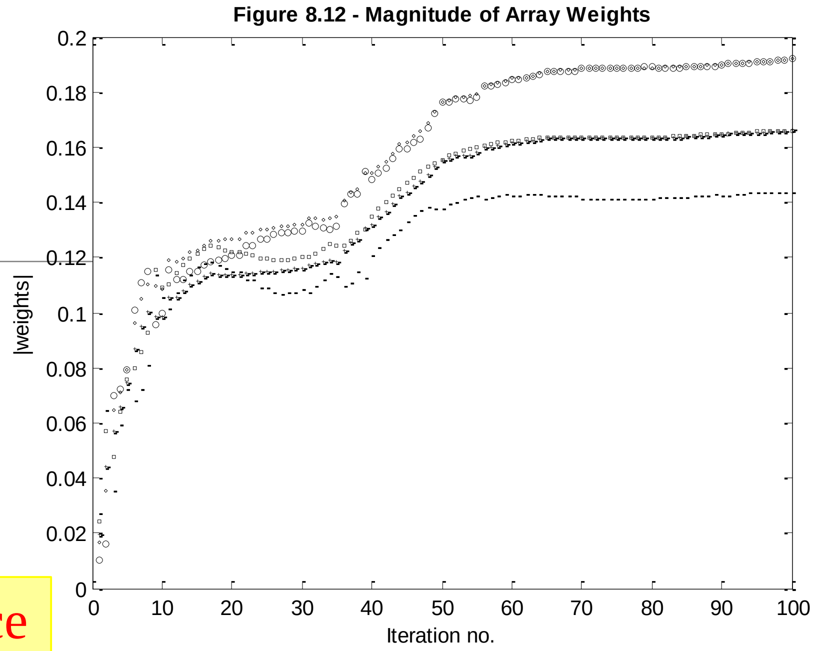
- Example:

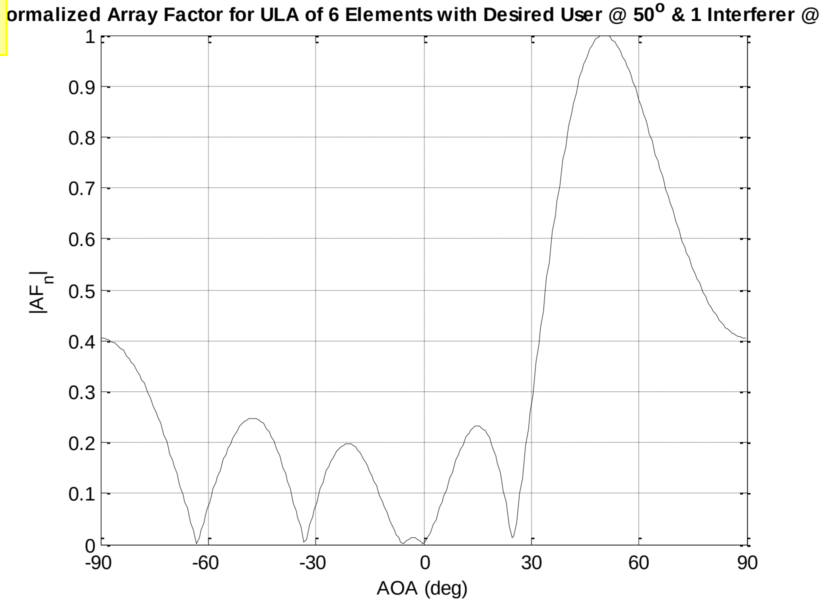
M=8, ULA, Adaptive BF is equipped in Rx.

One desired user ($\theta = 50^\circ$) and one interference user($\theta = -5^\circ$).

After achieving convergence, the main-lobe at $\theta = 50^\circ$.

the null-lobe at $\theta = -5^\circ$





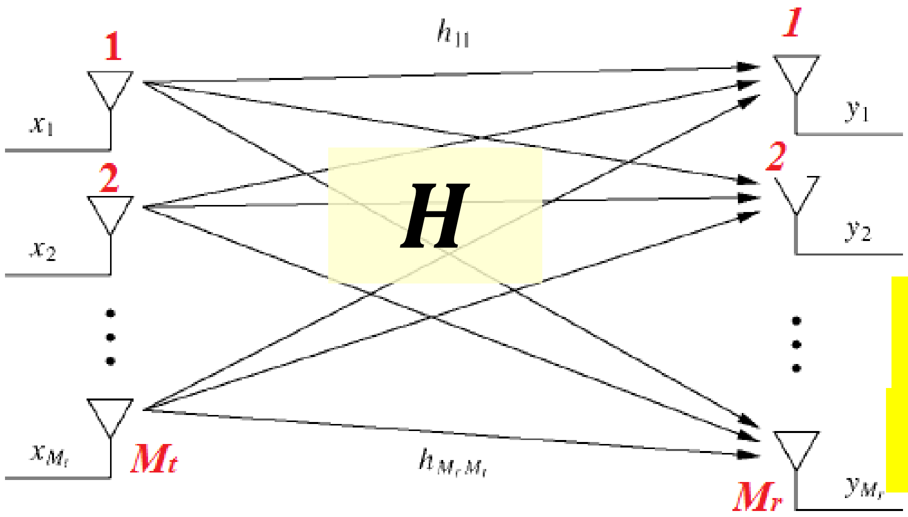
Part III

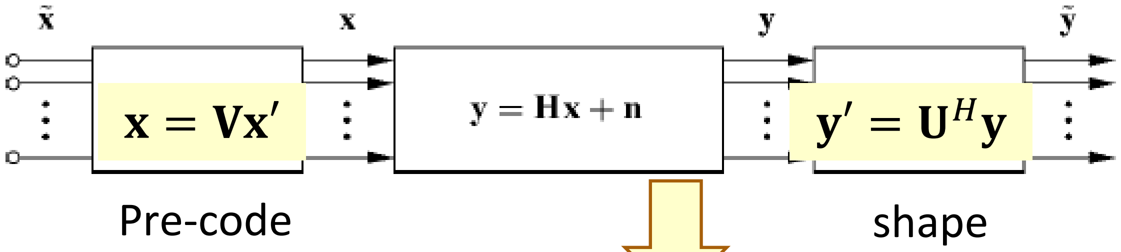
Some notes on BF in MIMO system

MIMO system

- h_{ij} : is the channel gain of the link from ith element in Tx to jth element Rx
- singular value decomposition (SVD) on $\mathbf{H}=\mathbf{U}\Sigma\mathbf{V}^H$
- **Σ:** a diagonal matrix with entries σi (singular values)

- Two main functions of MIMO: **Multiplexing gains (Capacity gains) ; Diversity gains**



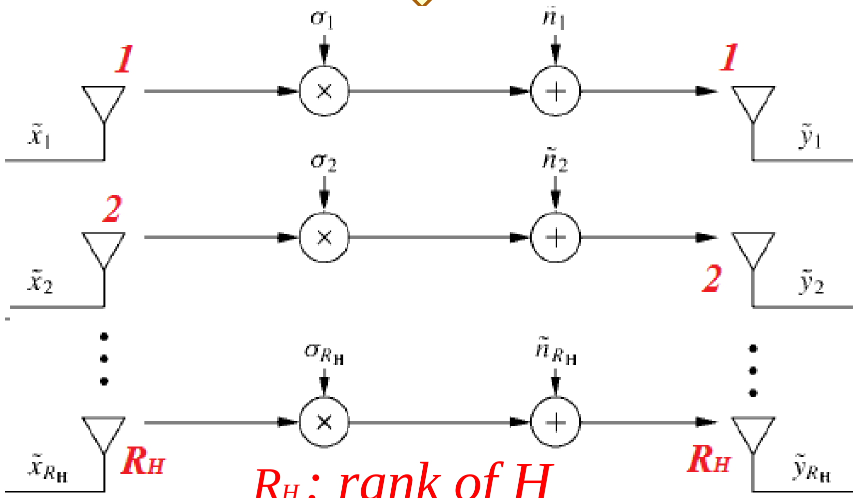


$$\mathbf{H}=\mathbf{U}\Sigma\mathbf{V}^H$$ (SVD),

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \boldsymbol{\eta}$$

$$\mathbf{x} = \mathbf{V}\mathbf{x}' \qquad \mathbf{y}' = \mathbf{U}^H\mathbf{y}$$

$$\mathbf{y}' = \Sigma\mathbf{x}' + \boldsymbol{\eta}'$$



R_H : rank of H

SISO: Independently parallel channels

1. different data in each antenna in Tx;

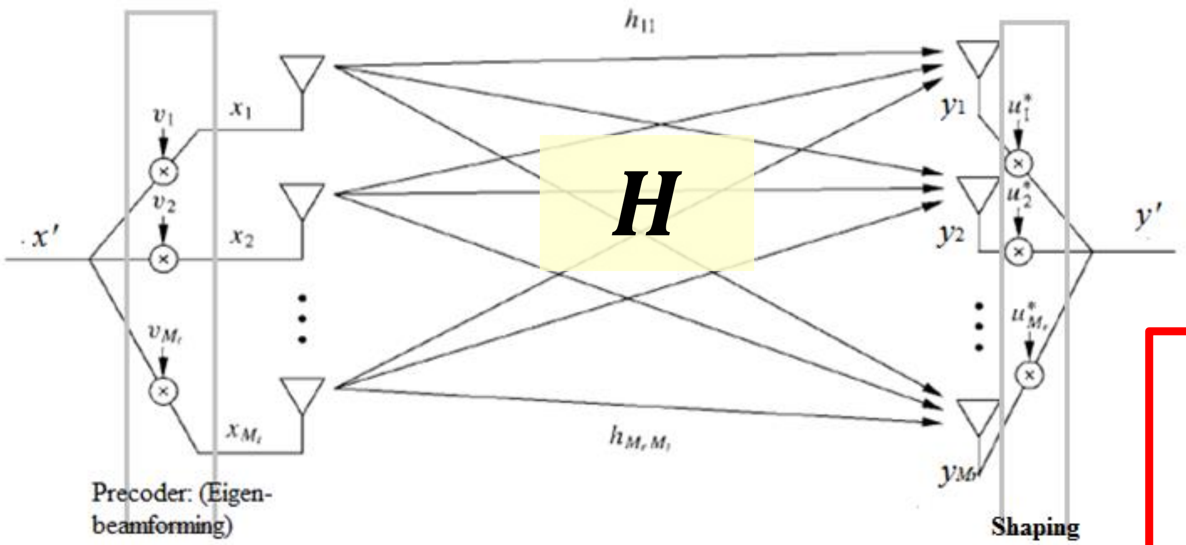
2. *M*tM*r MIMO system is equalvatlent to R_H SISO systems.**

3. Capacity gains: R_H times with just one Rx/Tx antenna

MIMO+BF

[2] A. Goldsmith et. al., Wireless Communication, Cambridge Univ. Press, London, 2005, pp. 334.

- Diversity Gains: Beamforming based on MIMO *[2]. Wireless. Commn., A. Goldsmith*



$\mathbf{x} = \mathbf{v}x'$

$y' = \mathbf{u}^{\mathrm{H}}y$

$$y' = \mathbf{u}^{\mathrm{H}}\mathbf{H}\mathbf{v}x' + \boldsymbol{\eta}'$$

Σ , Eigen-Beamforming

1. Each antenna in Tx transmits the duplication of signal *x'*
2. The **v** and **u** is similar to MIMO (**V** and **U**), but they are one column of **V** and **U**, respectively.
3. Normally, in order to get the maximum received SNR, **v** and **u** are the column of **V** and **U, which corresponds to the maximum singular value of H. (that is, if** $\sigma_1 = \sigma_{\max}$ **in Σ , v** and **u choose the first column of V and U.**)
4. Further to 3, and if || **v** ||=|| **u** ||=1, then the received SNR equals to $\gamma = \sigma_{\max}^2\rho$, where ρ is original SNR.

Improve anti-fading capability and the error-rate performance

Part IV

- Some notes on MIMO+BF in near-field setting

Notes on MIMO+BF in near field

- **Question 1: MIMO in near-field setting: Multiplexing gains? Diversity gains? Or both?**

1. Multiplexing gains:

   Capacity/ data-rate increases with R_H times. The BER in each parallel paired-Tx/Rx is determined by the corresponding singular value σ_i (BER increases or decreases).

Tradeoff: Multiplexing gains Diversity gains

2. diversity gains:

   each antenna sends the duplication of data, which decreases the data-rate; but the SNR increases by $\sigma_{\max}^2$ times. BER performance becomes better.

3. Tradeoff: combination of CASE 1 and CASE 2

   Some antennas are for multiplexing gains, others are for diversity gains (Space-time code [3])

[3] H. Gamal, G. Caire, andM. Damon, "Lattice coding and decoding achieve the optimal diversity multiplexing trade-off of MIMO channels," *IEEE Trans. Inform. Theory*, pp. 968–85, June 2004.

Notes on MIMO+BF in near field

- **Questions 2: How to implement MIMO+BF in near field?**

1. Is channel quasi-static/ complete-static in near filed? What is the difference between the near-filed channel and the traditional MIMO channel?

2. Can channel matrix ***H*** be decomposed to $\mathbf{H=U\Sigma V^H}$?

3. Is channel matrix ***H*** known for both of Tx and Rx?

4. Is the near-field setting rich of the scatter? (richer→ more independent channel)

If all answers of above questions, **YES**, the MIMO+BF is easily implemented in near-field.

(The locations of Rx/Tx are fixed, no need the adaptive algorithm.

Only H is known for Tx/Rx, PERFECT ! No matter what the exact detail about channel is, e.g., obstacle, reflection.)

Research route: Diversity gains → tradeoff case

Thanks for your attention !

Food, Panda, Scenery in Sichuan