5G PHY Layer Part0: Analog Beamforming, Digital Beamforming and Hybrid Beam-Forming with mmWave

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Disclaimer

All opinions and statements in this presentation are mine and do not in any way represent Ericsson

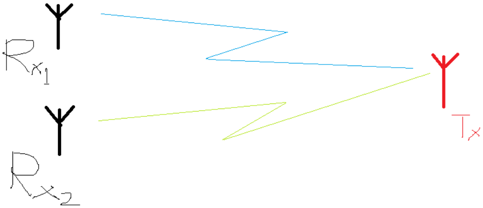
Right before We Introduce

- Usually, math explain itself as code does. But I suppose no one is interested in seeing math...
- No worries, I will explain everything in detail but without(or with a little) math. For any place we have to use math, we use the mathematical conclusion directly rather than derivation.
- If anyone is interested in mathematical derivation, I could explain the details in math as well after this presentation.
- Any question (including math) is welcome.

Overview

1. Everything Starts From Receiver Diversity
2. Three Types of MIMO
   - Transmit Diversity
   - (Analog)Beam-Forming
   - Spatial Multiplexing(Digital Beam-Forming)
     - Multi-user MIMO: Industrial Way of Spatial Multiplexing
3. MIMO in Standard: 2G to 4G
4. What will Happen if Number of Antennas Goes to More than 100?
   - Multi-user Massive MIMO
   - Practical Implementation of Multi-user Massive MIMO: mmWave upon High Freq
5. Is Hybrid Beam-Forming Standard of 5G?
   - How to Combat with Problem Which Comes from Combination of Multi-user Massive MIMO and mmWave

Everything Starts From Receiver Diversity



Question

What if we use more than one antenna at transmitter?(downlink)?

Three Types of MIMO

Multiple antennas, usually called as multiple input and multiple output(MIMO).

- Transmit Diversity
- Spatial Multiplexing, called as digital beam-forming as well
- Beam-forming, which is called as analog beam-forming nowadays

Transmit Diversity

Example (Alamouti Coding)

Alamouti, a famous engineer, who designed first transmit diversity algorithm which is called as **Alamouti Code**.

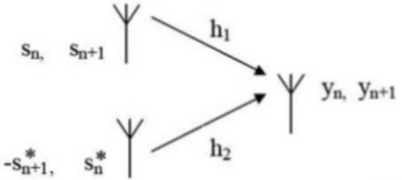
$$C_2 = \begin{bmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{bmatrix},$$

where * denotes complex conjugate.

Transmit Diversity

2x1 Alamouti Precoding & Decoding

Tx Side:



Rx Side:

- $y_n = h_1 s_n - h_2 s^*_{n+1} + b_n$
- $y_{n+1} = h_1 s_{n+1} + h_2 s^*_n + b_{n+1}$

$$\Longleftrightarrow \begin{bmatrix} y_n \\ y^*_{n+1} \end{bmatrix} = \underbrace{\begin{bmatrix} h_1 & -h_2 \\ h^*_2 & h^*_1 \end{bmatrix}}_{\text{H (orthogonal matrix)}} \begin{bmatrix} s_n \\ s^*_{n+1} \end{bmatrix} + \begin{bmatrix} b_n \\ b^*_{n+1} \end{bmatrix}$$

Decoding: (inverse ~ transpose & conjugate) (power constraint ignored here)

$$\begin{bmatrix} R_n \\ R_{n+1} \end{bmatrix} = \begin{bmatrix} h^*_1 & h_2 \\ -h^*_2 & h_1 \end{bmatrix} \begin{bmatrix} y_n \\ y^*_{n+1} \end{bmatrix} = \begin{bmatrix} |h_1|^2+|h_2|^2 & 0 \\ 0 & |h_1|^2+|h_2|^2 \end{bmatrix} \begin{bmatrix} s_n \\ s^*_{n+1} \end{bmatrix} + \begin{bmatrix} h^*_1 & h_2 \\ -h^*_2 & h_1 \end{bmatrix} \begin{bmatrix} b_n \\ b^*_{n+1} \end{bmatrix}$$

Exercise: Find instantaneous & average decoded SNR

Transmit Diversity

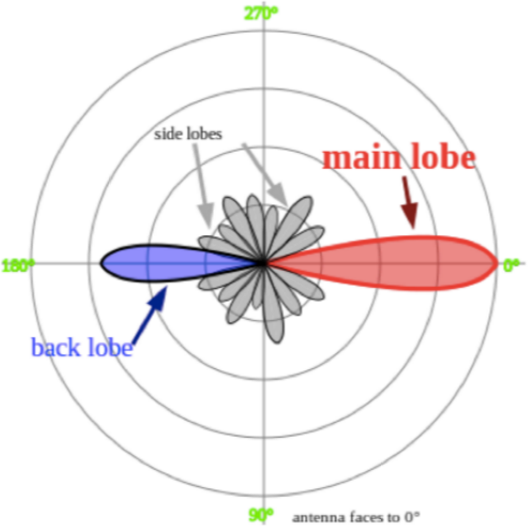
Remark

The purpose of Transmit Diversity, is gain more reliability(lower BER) on poor propagation environment(e.g. cell edges)

Low SNR, minimize error rate

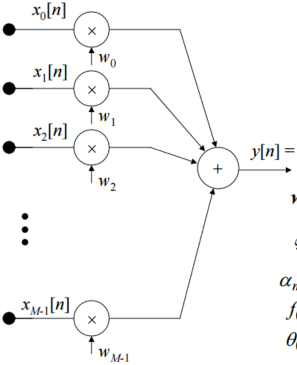
Succeed 99 out of 100 times
Otherwise, 50 out of 100 times

According to antenna course..



(Analog)Beam-Forming

Beamforming is the method used to create the radiation pattern of the antenna array by adding constructively the phases of the signals in the direction of the targets/mobiles desired, and nulling the pattern of the targets/mobiles that are undesired/interfering targets.



$$\boldsymbol{w} = \left[\alpha_0, \alpha_1 e^{-j\varsigma}, \cdots, \alpha_{M-1} e^{-j(M-1)\varsigma}\right]^T,$$

$$\varsigma = \frac{2\pi f_0 d}{c} \sin\theta_0,$$

α_m = amplitude weight for sensor m,

f_0 = bandpass center frequency, Hz,

θ_0 = direction of max response.

(Analog)Beam-Forming

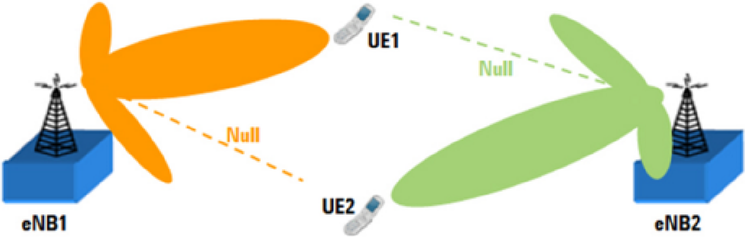


Figure 2: Beamforming improves CNIR by matching antenna gain to UE position.

Purpose

The purpose of (Analog)Beam-Forming, is suppress interference to other users by making directivity

(Analog)Beam-Forming

Remark

- Analog Beam-Forming needs to **steer all antenna elements** in **analog phase** and **send same signal in each element** in the antenna array, to **serve one single user** by **concentrating energies to a direction**(directivity), in a **line of sight(LOS)** propagation environment, in one time slot and one frequency band

Spatial Multiplexing

Question

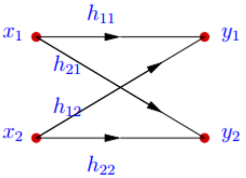
What if we use more than one antennas on both?

Arogyaswami J. Paulraj, an Indian PhD invented the Spatial Multiplexing Method when he worked for Stanford Univ.

Spatial Multiplexing(Digital Beam-Forming)

What We have with multiple antennas(two Tx two Rx)

A multiple antenna (MIMO) fading channel

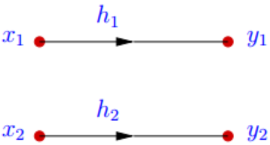


$$y = Hx + \eta$$

$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}$$

What We want with multiple antennas(two Tx two Rx)

Two parallel single antenna fading channels



$$y = Hx + \eta$$

$$H = \begin{pmatrix} h_1 & 0 \\ 0 & h_2 \end{pmatrix}$$

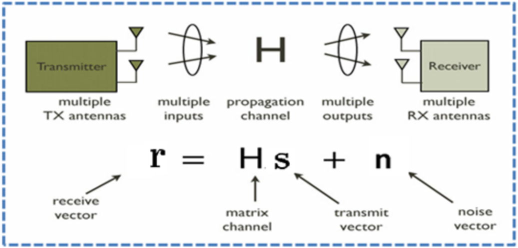
Spatial Multiplexing(Digital Beam-Forming)

Question

It seems we can solve vector x in the example(without noise), why we need two parallel sub-channels/layer rather than the original (interfered)channels?

- Yes you do, for 2 X 2 case. What if we have 2 X 4 matrix?
- Yes you do, by using the received information y_1 and y_2. What if you do NOT know y_1 and y_2 at same duration? e.g. two mobiles in downlink.
- Further more, you have unknown noise(but known the distribution)

Magic comes



$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^*$$

$$\tilde{\mathbf{r}} = \mathbf{D}\tilde{\mathbf{s}} + \tilde{\mathbf{n}}$$

$$\text{where } \tilde{\mathbf{r}} = \mathbf{U}^*\mathbf{r},\ \tilde{\mathbf{s}} = \mathbf{V}\cdot\mathbf{s} \text{ and } \tilde{\mathbf{n}} = \mathbf{U}^*\mathbf{n}$$

In mathematics, a complex square matrix U is **unitary** if

$$U^*U = UU^* = I$$

where I is the identity matrix and U^* is the conjugate transpose of U.

Decompose the MIMO channel into m several equivalent parallel SISO channels by performing singular value decomposition (SVD) of **H**. Then **U** and **V** are unitary and **D**=*diag*($\sqrt{\lambda_1}$, $\sqrt{\lambda_1}$, … , $\sqrt{\lambda_m}$, 0 , … , 0). m = rank(**H**). The above equation represents the system as m equivalent parallel SISO eigen- channels with channel distornation given by the eigenvalues λ_1 , λ_2 , … , λ_m.

Spatial Multiplexing(Digital Beam-Forming)

- As we figure out from last slide, if we apply U^* at receiver side and V at transmitter side, the interference between sub-(spatial) channel with be removed.
- The drawback of using U^* and V is, we have to estimate the channel H accurately! The complexity of channel estimation will be very costly as increase of antennas.

Question

Way to lower the complexity?

- Yes, that is how pre-coding matrix doing. The pre-coding matrix and "equalization matrix"(we already used in LTE) is predefined, try to match the U^* and V for different cases as accurate as possible.
- That is reason why the feedback of channel estimation in LTE system needs to have PMI(pre-coding matrix indicate, stands for which precoding matrix to be used), RI(rank information, stands for how many layers can be gotten in current propagation channel).

Spatial Multiplexing(Digital Beam-Forming)

Purpose

The purpose of Spatial Multiplexing, is gain more throughput(capacity) with same usage of bandwidth and time slots on fine propagation environment(e.g. NOT cell edges)

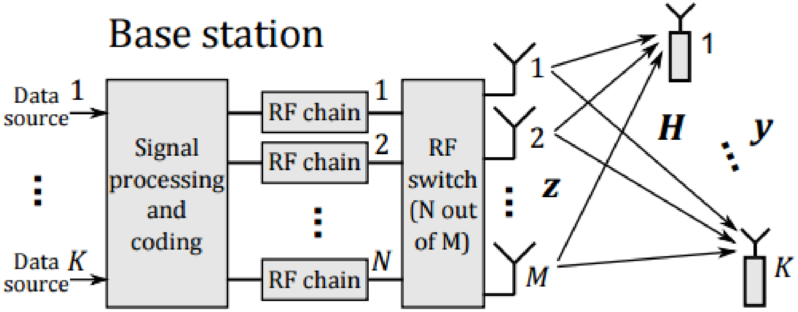
Remark

- Digital Beam-Forming needs to **precoding all antenna elements** in **digital phase** and **send different signal in each element** in the antenna array, to **serve multiple users/multiple data streams** by **allocate different power in each stream/layer**, in a **non-line of sight(NLOS)** propagation environment, in one time slot and one frequency band

Problem

Problem Is multiple antennas reliable in product? Definitely yes in RBS, but in mobile...

So,we still use one antenna per mobile.



where M = N, N about 10

MIMO in Standard: 2G to 4G

MIMO in 3GPP standards

1. 2G GSM: Receiver Diversity(at RBS, 2 antennas).
2. 3G WCDMA: Transmit-Receiver Diversity(at RBS, up to 4 antennas);
3. 4G LTE: Transmit Diversity(at RBS, up to 8 antennas); Spatial Multiplexing(at RBS, up to 8 antennas); (Analog)Beam-Forming.

3GPP	Diversity	Spatial Multiplexing	Beam-Forming
2G	2	x	x
3G	4	x	4
4G	8	8	8

Table: MIMO in 3GPP

Question

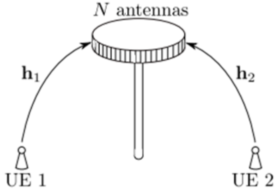
What if we increase the number of antennas to more than 100 on RBS. Could we get almost hundreds time of gain compared with SISO?

This brilliant question has been asked and answered by Dr Marzetta from Bell Lab, Alcatel-Lucent in 2010(Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas, IEEE Trans. Wireless Communications, vol. 9, no. 11, pp. 3590-3600, Nov. 2010).This question leaded the brand new area: Massive MIMO.

Multi-user Massive MIMO

Yes

By assuming an infinite number of antennas at the BS, the multi-user MIMO channel can be turned into an orthogonal channel and the effect of small-scale fading and thermal noise can be eliminated



$$\boxed{\mathbf{y} = \mathbf{h}_1 x_1 + \mathbf{h}_2 x_2 + \mathbf{n}}$$

Assumptions

- $\mathbf{h}_1, \mathbf{h}_2 \in \mathbb{C}^{N\times 1}$ have i.i.d. entries with zero mean and unit variance
- $\mathbf{h}_1, \mathbf{h}_2$ perfectly known at the base station (BS)
- $\mathbb{E}\left[|x_1|^2\right] = \mathbb{E}\left[|x_2|^2\right] = \mathrm{SNR}$
- $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$

The BS applies a simple matched filter to detect the symbol of UE 1:

$$\frac{1}{N}\mathbf{h}_1^H\mathbf{y} = \underbrace{x_1 \frac{1}{N}\sum_{i=1}^{N} |h_{1i}|^2}_{\text{useful signal}} + \underbrace{x_2 \frac{1}{N}\sum_{i=1}^{N} h_{1i}^* h_{2i}}_{\text{interference}} + \underbrace{\frac{1}{N}\sum_{i=1}^{N} h_{1i}^* n_i}_{\text{noise}}$$

By the strong law of large numbers:

$$\frac{1}{N}\sum_{i=1}^{N} h_{1i}^* h_{2i} \xrightarrow[N\to\infty]{\text{a.s.}} \mathbb{E}\left[h_{11}^* h_{21}\right] = 0 \quad \text{(interference vanishes)}$$

$$\frac{1}{N}\sum_{i=1}^{N} h_{1i}^* n_i \xrightarrow[N\to\infty]{\text{a.s.}} \mathbb{E}\left[h_{11}^* n_1\right] = 0 \quad \text{(noise vanishes)}$$

Multi-user Massive MIMO

Remark

Multi-user Massive MIMO, also called as massive digital beam-forming, has same purpose as SM which gains (lots)more throughput(capacity) but with less complexity on precoding and equlization(cause of natural characteristic of matrix in high dimension, matrix is almost diagonal and full rank) by same usage of bandwidth and time slots

Multi-user Massive MIMO

Theorem

In order to cancel the correlation between adjacent antennas(cause we need un-similar sub-propagation channels for SM/diversity), the space between them needs to be bigger than $\frac{\lambda}{2}$

Problem

But physical space on RBS is problem...How to arrange more than 100 antennas on same(even smaller) space compared to 3G/4G RBS(because femto/small cell will become more popular in 5G), still fulfill $\frac{\lambda}{2}$ space?

mmWave upon High Freq

Yes, use higher frequency

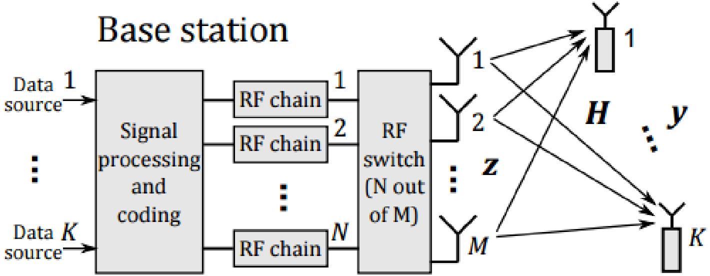
Theorem

$\lambda = \frac{c}{f}$

If we increase f, λ becomes smaller.

mmWave upon High Freq

Recall multi-user MIMO diagram



Problem

Question: For multi-user massive MIMO, M is around 100. The cost of each RF chain(such as RF amplifier, mixer and AD/DA converter) is far more costly for higher freq(e.g. higher than 6 GHz) than 2.4 GHz.

- We need to reduce N cause cost! What to do with this new drawbacks?

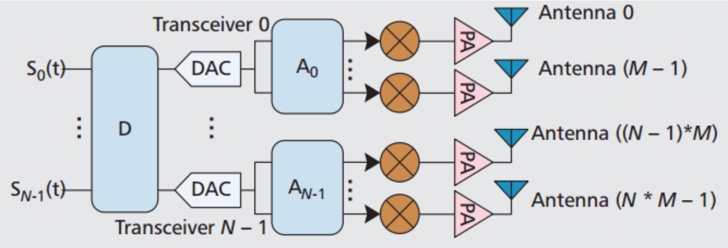
How to Combat with Problem Which Comes from Combination of Multi-user Massive MIMO and mmWave

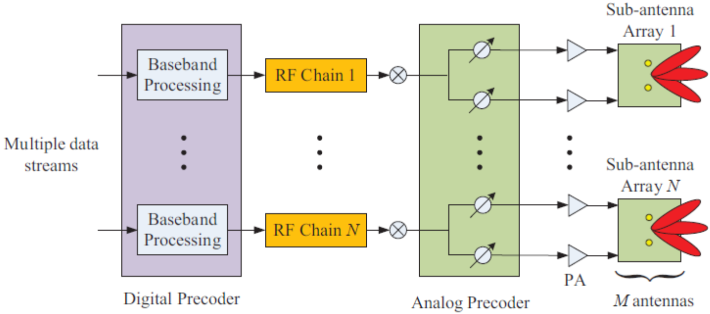
Yes, we turn back to analog beam-forming! But together with digital one.

- Hybrid Beam-Forming!

Lagom, You're not supposed to be too good, or too rich(i.e. digital beam-forming only)

Hybrid Beam-Forming





Hybrid Beam-Forming

Recall Table

3GPP	Diversity	Spatial Multiplexing+Analog Beam-Forming
5G	?	possible

Table: MIMO in 3GPP

Why We Could Use (massive)MIMO in 4G and 5G?

Problem

Question: We have already noticed the channel matrix H represents the fast fading between multi-TXRXantennas in SPACE. But influence from fast fading in time and frequency must also somehow effect the received signals, why can we omit those problems on modeling channel matrix H for MIMO system?

- That is due that we do have OFDM has been used to handle the ICI(inter-carrier-interference) on freq and ISI (inter-symbol-interference)in time
- Let us move to part1: Basic Signal Wave-Form Resource and Multiple Access - OFDM

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Question?

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