

# EE401: Advanced Communication Theory

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## **Multi-Antenna Wireless Communications**

### **Part-A: An Introductory Overview**

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# SISO Wireless Channel Tx & Rx

- A wireless system can be partitioned into 3 main parts:
  - ① **Tx** (a "source" that sends/transmits some information using wave propagation)
  - ② **Wireless Channel** (the physical propagation paths)
  - ③ **Rx** (a "sink" that receives the transmitted waves)

and the objective in general is

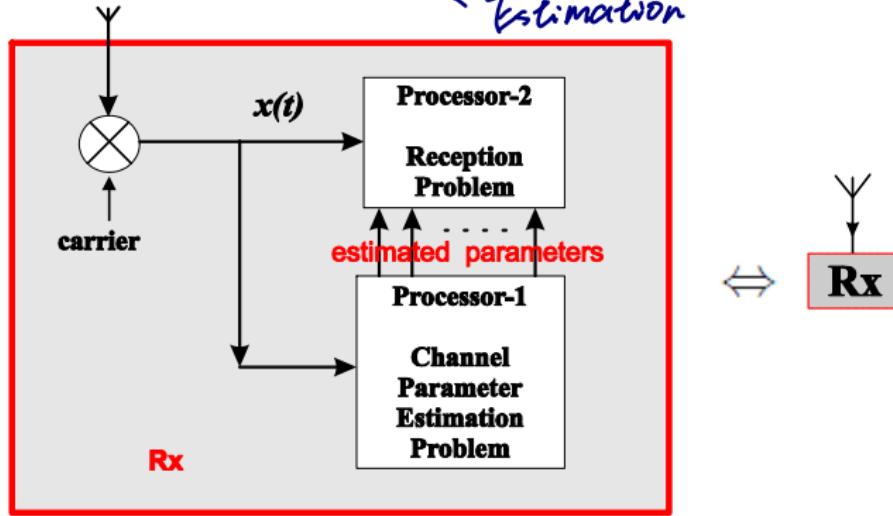
- ▶ to increase the **communication speed** (which is known as channel capacity)  
without sacrificing the **quality of service** (for a given energy + bandwidth)  
- Reliability (QoS)

Signal processing: baseband.



# Generic Rx Architecture

$R_x$  - Reception  
- Estimation



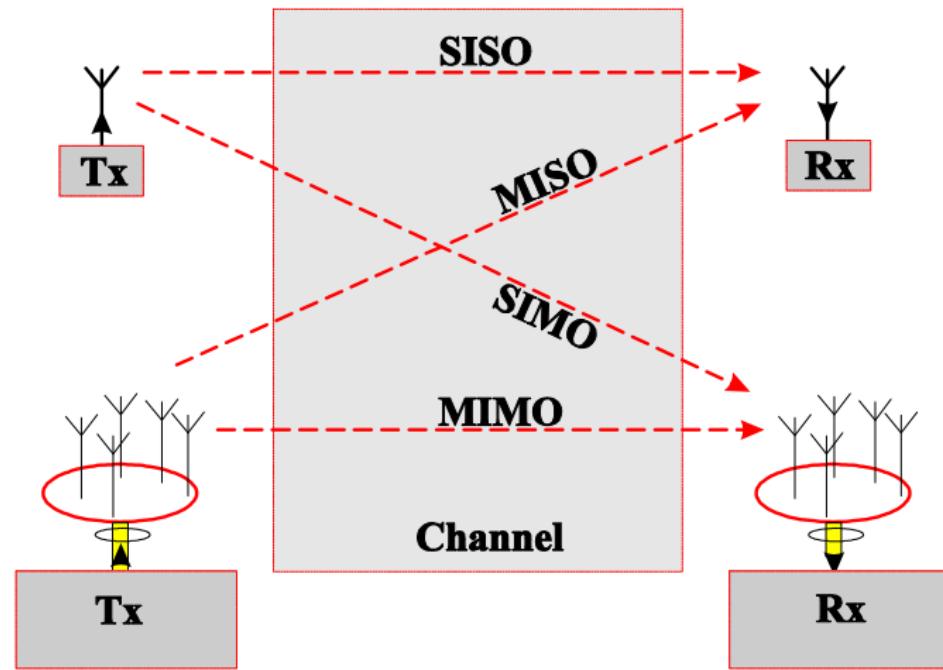
- The **quality of the receiver (Rx)** is a function of the quality of the estimated channel parameters
- Note that the receiver is **continuously designed** (based on these estimates) from **time frame to time frame.** *time-varying based on estimation*

# Wireless Systems Classification

- There are many classifications. For instance:
  - ① according to the **bandwidth/carrier**: **narrowband** or **wideband**
  - ② according to the **spreading capabilities**: **conventional** or **spread spectrum**
  - ③ according to the **number of carriers**: **single carrier** or **multicarrier**
  - ④ according to the "generation": 1G, 2G, **3G**, **3G+**
  - ⑤ according to the "access": **TDMA, FDMA**, **CDMA**,
- The **overall aims**:
  - ▶ **speed = ↑**,
  - ▶ **but maintaining reliability** (quality of service) & **spectral efficiency** (EUE,BUE)
- The current speed is expected to increase by the utilisation of the new technology of multiple antennas (MIMO) and this gives rise to a new classification which super-sets all the above.

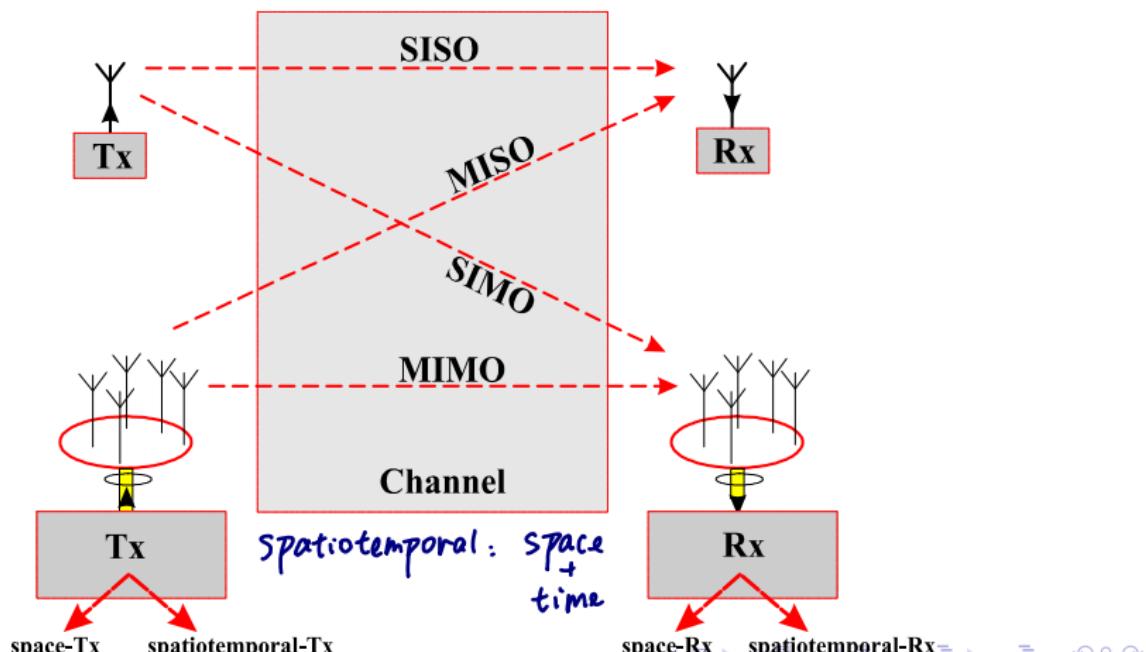
# New Wireless Systems Classification

- This **new** classification is according to the **number of antennas** used in both Tx and Rx



# New Wireless Systems Classification

- This **new** classification is also according to the **number of antennas** and the space-only or spatiotemporal signal processing used in both Tx and Rx (this is the main focus of this topic)



- **My Terminology**

**Terminology-1 (More Representative)**

<b>1</b>	SISO:	Scalar-Input-Scalar-Output Channel
<b>2</b>	SIVO:	Scalar-Input-Vector-Output Channel
<b>3</b>	VISO:	Vector-Input-Scalar-Output Channel
<b>4</b>	VIVO:	Vector-Input-Vector-Output Channel

- **Alternative Terminology**

**Terminology-2 (Initial)**

<b>1</b>	SESE:	from Single-Element (SE) Tx to Single-Element (SE) Rx
<b>2</b>	SEME:	from Single-Element (SE) Tx to Multiple-Element (ME) Rx
<b>3</b>	MESE:	from Multiple-Element (ME) Tx to Single-Element (SE) Rx
<b>4</b>	MEME:	from Multiple-Element (ME) Tx to Multiple-Element (ME) Rx

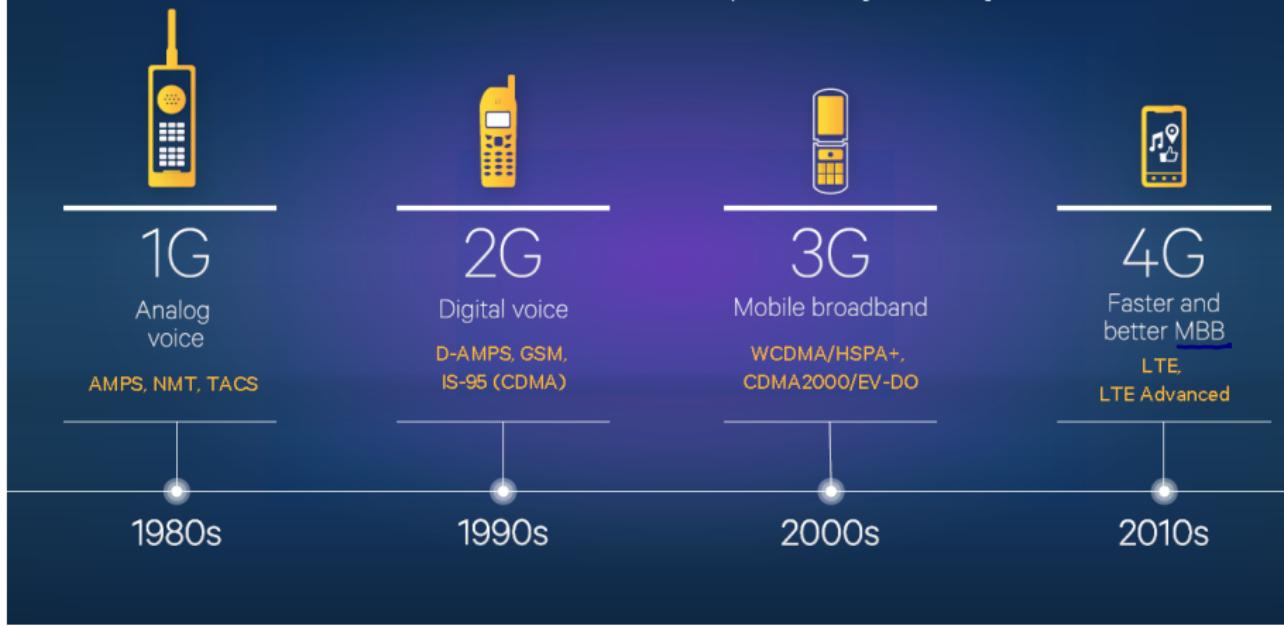
**Terminology-3 (More Popular)**

<b>1</b>	SISO:	Single-Input-Single-Output
<b>2</b>	SIMO:	Single-Input-Multiple-Output
<b>3</b>	MISO:	Multiple-Input-Single-Output
<b>4</b>	MIMO:	Multiple-Input-Multiple-Output

# Mobile Evolution - Motivation

*MBB = mobile broadband*

Mobile has made a leap every ~10 years



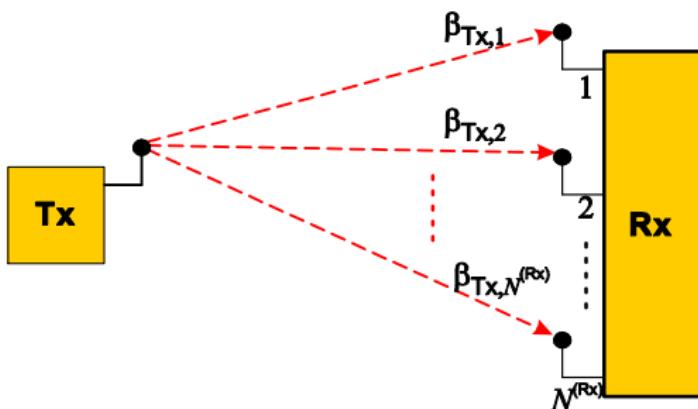
# Mobile Evolution - Motivation (cont.)

In parallel: driving 4G and 5G to their fullest potential

Expanding and evolving LTE Advanced – setting the path to 5G



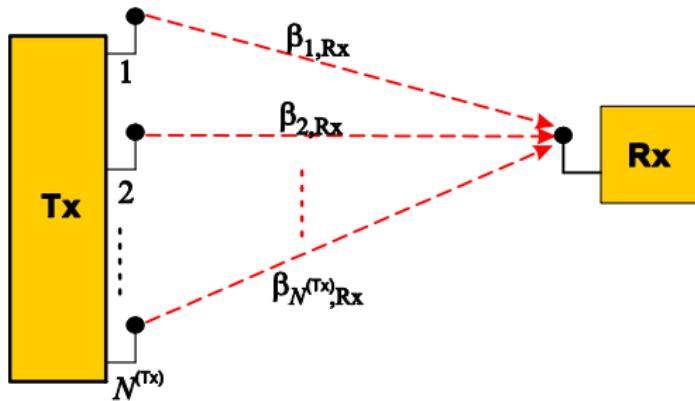
# SIMO Wireless Systems (non-parametric)



Single-Input Multiple-Output (SIMO)

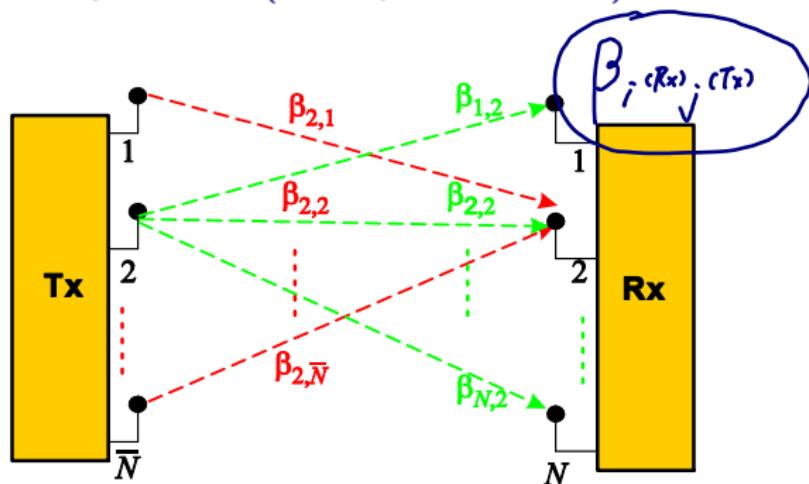
- Remember: SISO - one complex number  $\beta$  per path

# MISO Wireless Systems (non-parametric)



Multiple-Input Single-Output (MISO)

# MIMO Wireless Systems (non-parametric)



Multiple-Input Multiple-Output (MIMO)

$$\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,N^{(Tx)}} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,N^{(Tx)}} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{N^{(Rx)},1} & \beta_{N^{(Rx)},2} & \dots & \beta_{N^{(Rx)},N^{(Tx)}} \end{bmatrix}$$

# Parametric Approaches

## Introduction

Statistical

vs

Parametric

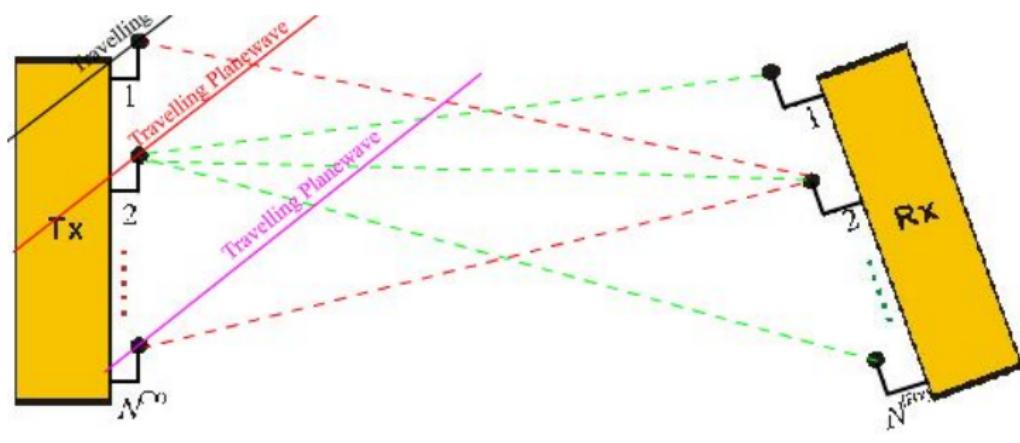
comprehensive

Tx Rx  
geometric signal propagation  
direction model

simple  
classical

- The above modelling will result into a statistical approach (~~used in Wiener's estimation theory and Shannon's communication theory~~).  
e.g. many MIMO books, papers and tutorials: non parametric  
*SISO*      *MIMO*
- Although this approach is suitable for single antenna systems (i.e. SISO), it does not properly fit multiple antennas since it
  - ignores the **Cartesian coordinates** and orientations of Tx and Rx (i.e. ignoring the geometry/location of the multiple antennas),
  - ignores the **directions** of the signals,
  - ignores **propagation models** (planewaves or spherical waves),
  - etc.

# Revisiting Multiple-Input Multiple-Output (MIMO)



# Summary Table of SISO, MISO, SIMO and MIMO

	Non-Parametric	Parametric (Array Processing)
SISO:	$\beta$	
SIMO:	$\begin{bmatrix} \beta_{Tx,1} \\ \beta_{Tx,2} \\ \dots \\ \beta_{Tx,N^{(Rx)}} \end{bmatrix}$	$= \underline{\beta} \underline{a}^{(Rx)}$ <p style="margin-left: 20px;"> <i>propagation gain</i>  <i>array manifold vector</i> </p>
MISO:	$\begin{bmatrix} \beta_{1,Rx} \\ \beta_{2,Rx} \\ \dots \\ \beta_{N^{(Tx)},Rx} \end{bmatrix}$	$= \underline{\beta} \underline{a}^{(Tx)}$
MIMO:	$\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,N^{(Tx)}} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,N^{(Tx)}} \\ \dots & \dots & \dots & \dots \\ \beta_{N^{(Rx)},1} & \beta_{N^{(Rx)},2} & \dots & \beta_{N^{(Rx)},N^{(Tx)}} \end{bmatrix}$	$= \underline{\beta} \underline{a}^{(Rx)} \underline{a}^{(Tx)^H}$ $\Leftrightarrow \underline{\beta} \underline{a}^{(virtual)}$

# The Structure of the Array Response Vector

- From now on in this presentation the vector  $\underline{a}$  will represent all multiple antenna wireless systems, i.e.

$$\underline{a} \triangleq \left\{ \begin{array}{ll} \underline{a}^{(\text{Rx})} & \text{SIMO} \\ \underline{a}^{(\text{Tx})} & \text{MISO} \\ \underline{a}^{(\text{virtual})} = \underline{a}^{(\text{Tx})} \otimes \underline{a}^{(\text{Rx})} & \text{MIMO} \end{array} \right\}$$

- The vector  $\underline{a}$  is known as
  - ▶ Array Manifold Vector or
  - ▶ Array Response Vector (alternative symbol  $S$ )
- The vector  $\underline{a}$  has a **profound mathematical structure** and is a function of a number of parameters such as Directions, carrier,etc

$$\underline{a}(\theta, \phi, F_c, c, \underline{r}_1, \underline{r}_2, \underline{r}_3, \dots, \underline{r}_N)$$

# Note

- we can also add more wireless parameters from the Tx and Rx.

- For instance

$\underline{a}(\theta, \phi, F_c, c, r_x, r_y, r_z,$   
pseudorandom sequ, delay, polarisation parameters,  
No.of subcarriers/carriers, bandwidth, Doppler frequency).

- Various forms of  $\underline{a}$  have different dimensions but always a **profound mathematical structure**

This leads to Differential Geometry which complements the statistical signal processing and Shannon's communication theory in array processing problems and wireless systems.

# Differential Geometry

- **Differential geometry** is a branch of mathematics that is concerned with the application of differential calculus for the investigation of the properties of geometric **curves , surfaces** and **other objects** known as '**manifolds**'.
- Manifolds have a **deep** and **profound mathematical structure** and have been **an area of intense pure mathematical analysis**.

$\underline{p} \mapsto$  mathematical object

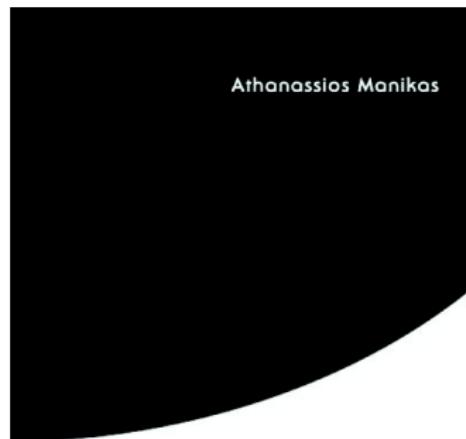
- In Physics, Albert Einstein (Nobel 1921) used differential geometry to express his **general theory of relativity**  
► where the universe is a **smooth manifold** equipped with <sup>*diffn exists.*</sup> pseudo-Riemannian metric (described the curvature of space-time).

# Fundamental Questions

problem  $\rightarrow$  manifold  $\rightarrow$  design

- Diff. Geom. helps **answering some fundamental questions** such as:

- Q1 Is it possible to **express** a wireless system as a space curve or a surface (or a manifold - in general)?
- Q2 Is it possible to **analyse** a wireless system **by analysing** a curve or a surface?
- Q3 Is it possible to **design** a wireless system **by designing** a curve or a surface?
- Q4 What do we **stand to gain** by expressing wireless systems as mathematical objects such as curves or surfaces?



## DIFFERENTIAL GEOMETRY IN **ARRAY PROCESSING**

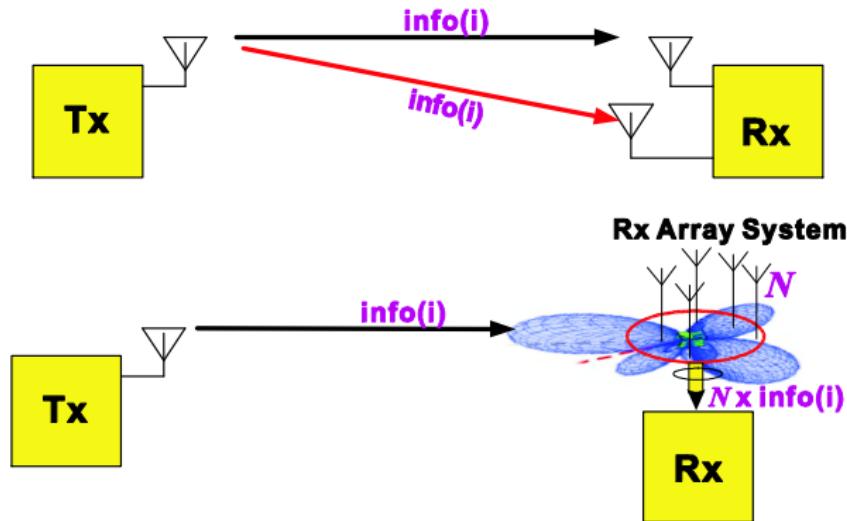
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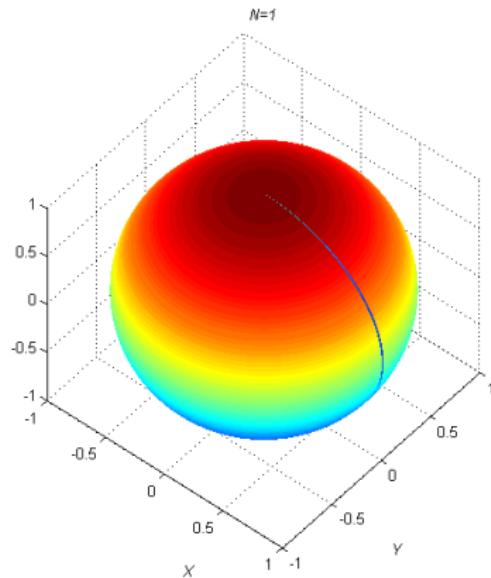
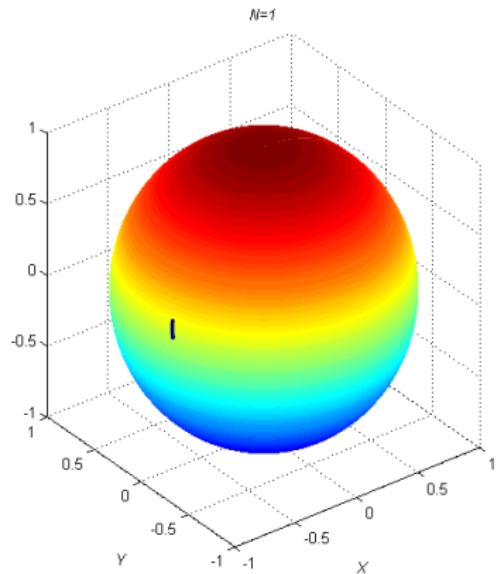
# Antenna Array Space Response

- **SIMO Example: Rx-Array Diversity**



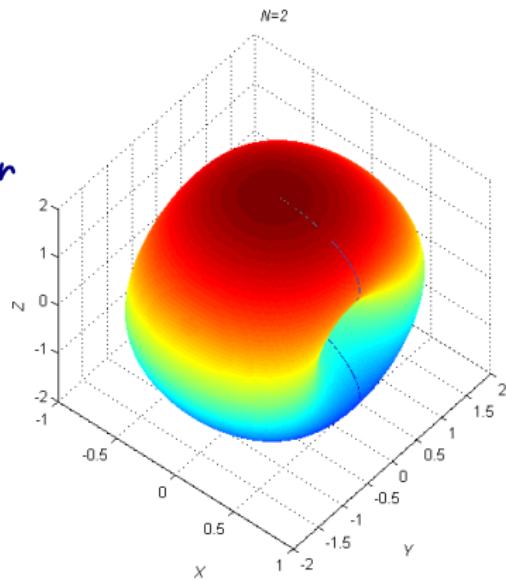
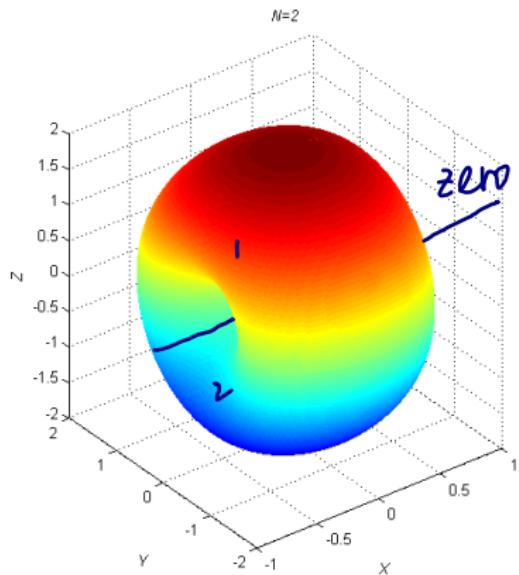
- Array systems (smart antennas) and techniques can be seen as the most sophisticated and advanced space diversity systems/techniques. (This type of systems/techniques will be considered in this course.)

# Single Antenna ( $N=1$ ): Space Response



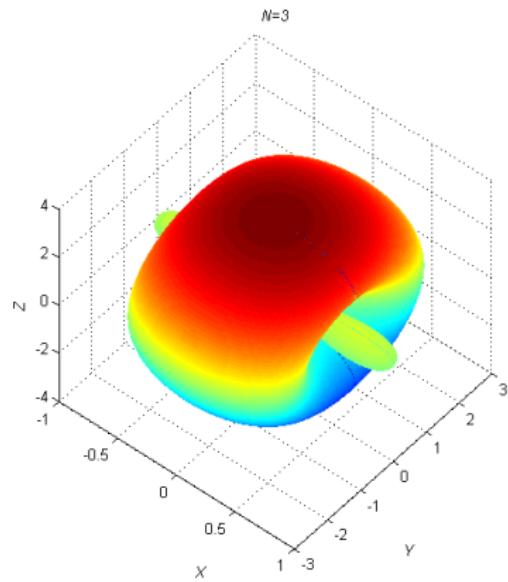
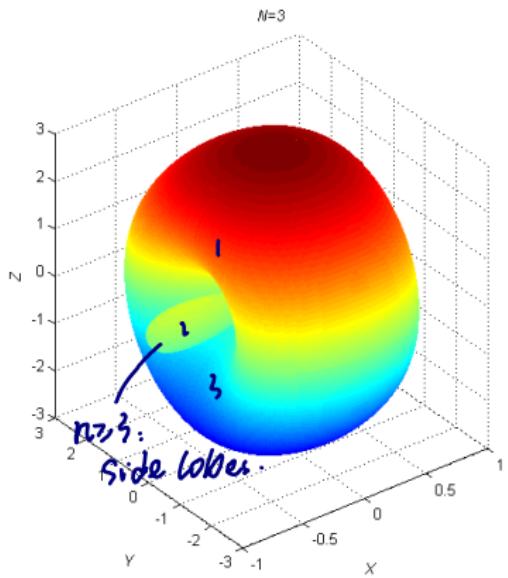
(rotated by  $90^\circ$ )

# Two Antennas ( $N=2$ ): Space Response



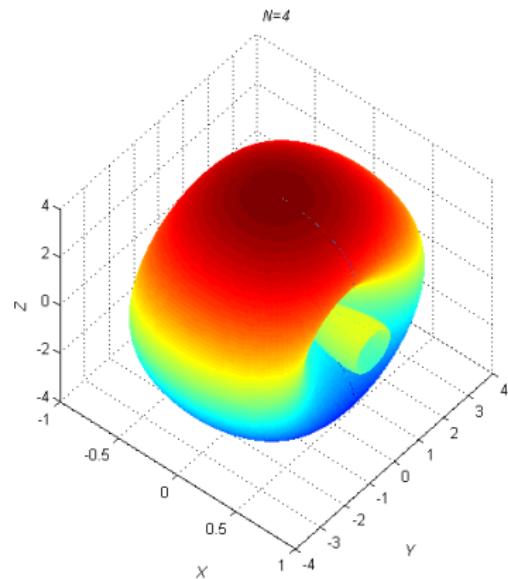
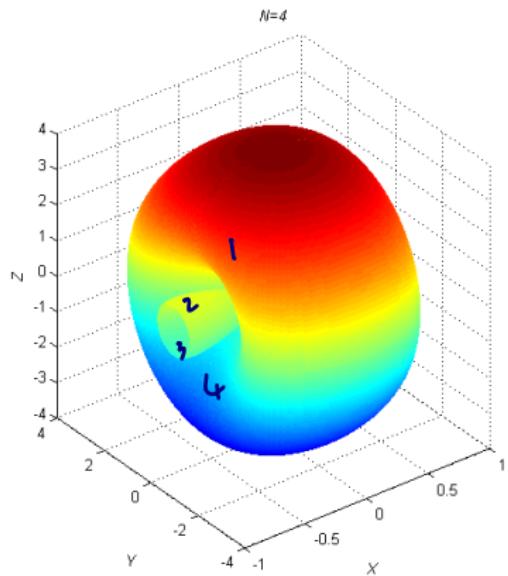
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# Three Antennas ( $N=3$ ): Space Response



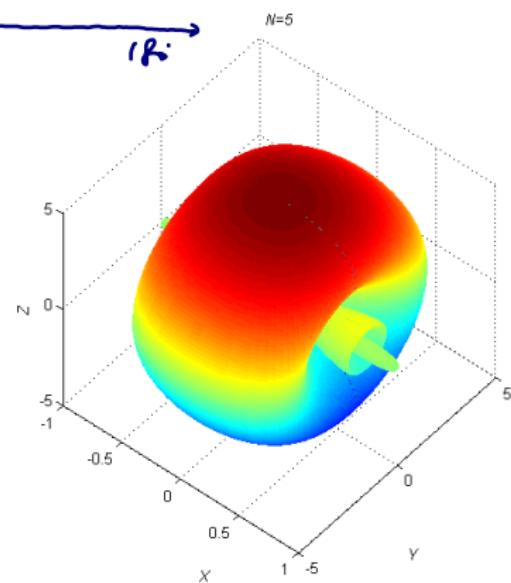
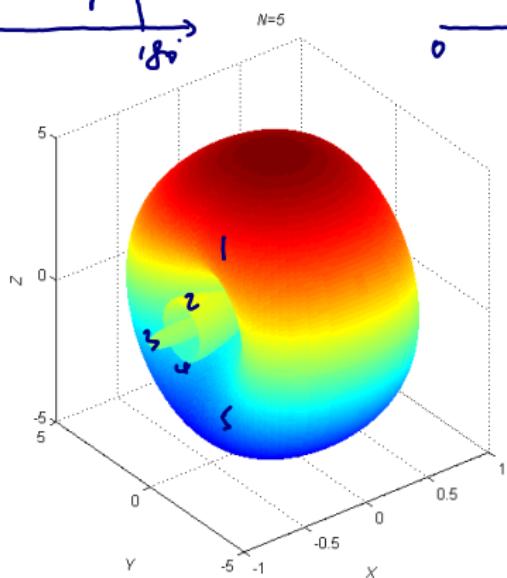
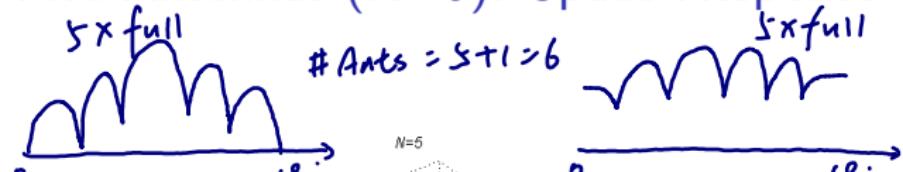
(rotated by 90°)

# Four Antennas ( $N=4$ ): Space Response



(rotated by  $90^\circ$ )

# Five Antennas ( $N=5$ ): Space Response



(rotated by  $90^\circ$ )

# Space-Only Example: Uniform Linear Array (ULA)

- Intersensor spacing =  $\lambda/2$ ;

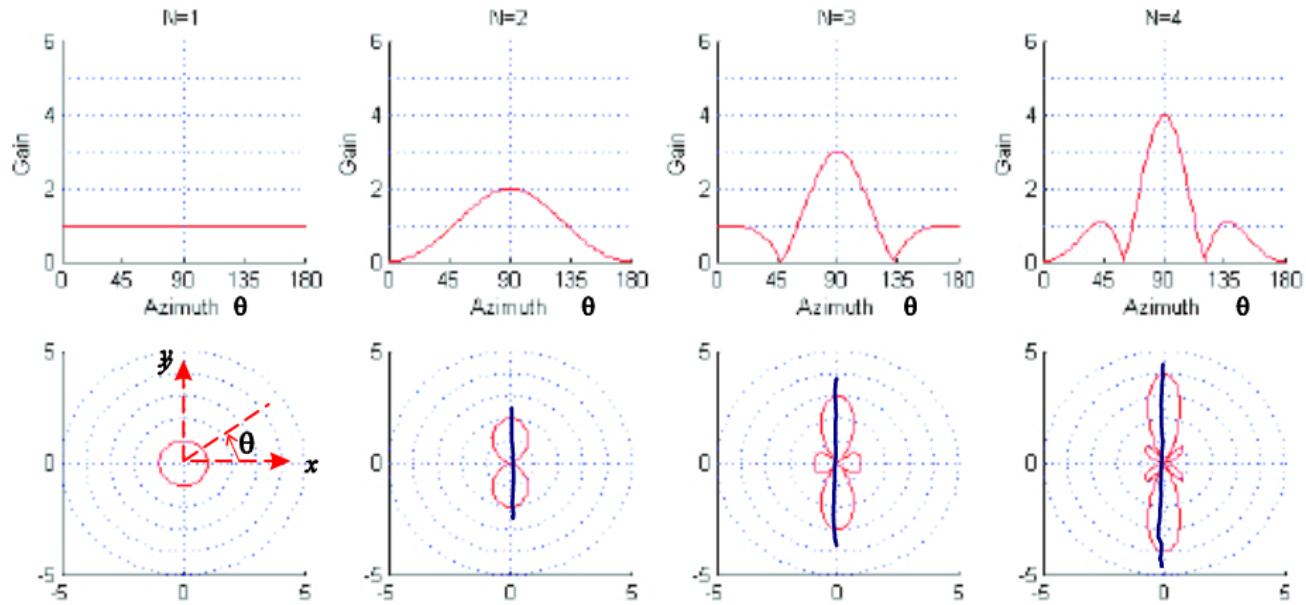
- $N$  = number of antennas (located on the x-axis). *(can be  $T_x$  or  $R_x$ ).*
- Channel Capacity (AWGN):

$$\begin{aligned}
 C &= B \log_2 \left( 1 + N \frac{P_s}{(N_0 + N_j) B} \right) \xrightarrow{(N_0 + N_j) B} B \log_2 (1 + N \times \text{SNIR}_{in}) \\
 &= \log_2 \left( 1 + N \frac{P_s}{(N_0 + N_j) B} \right) B \xrightarrow{NP_s} \frac{NP_s}{N_0 + N_j} C \longrightarrow N \times 1.44 \frac{P_s}{N_0 + N_j} \quad (1)
 \end{aligned}$$

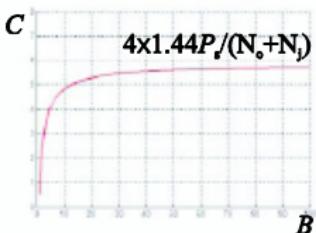
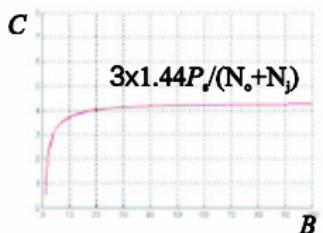
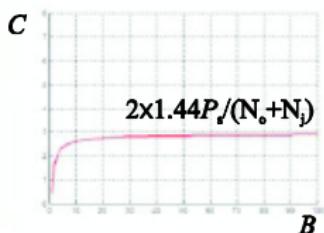
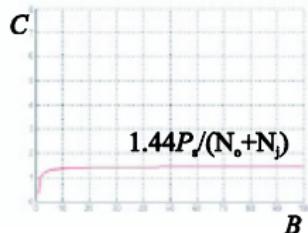
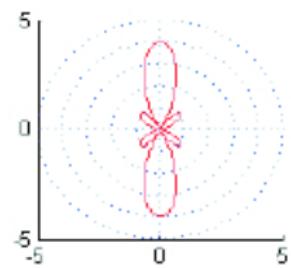
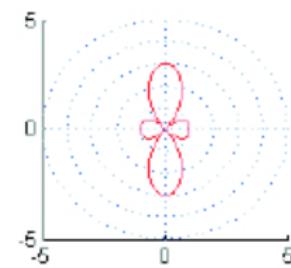
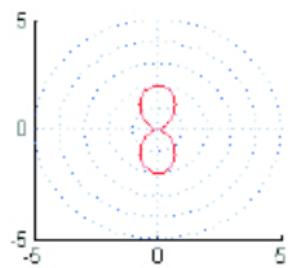
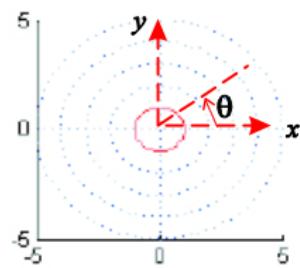
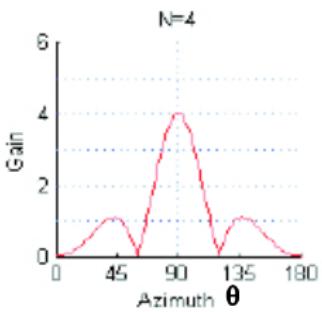
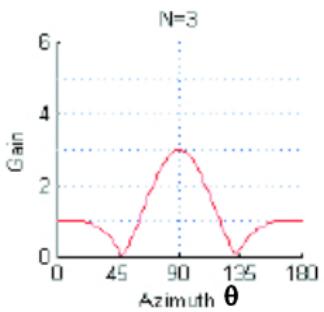
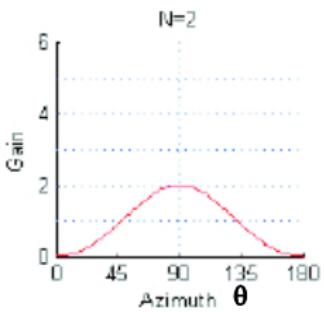
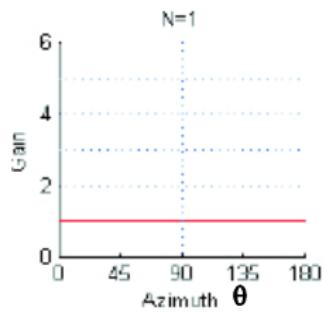
array jamming parameter <sup>(2)</sup>

$$\boxed{C = (\log_2 e) \frac{NP_s}{N_0 + N_j} \Rightarrow 1.44N \frac{P_s}{N_0 + N_j}}$$

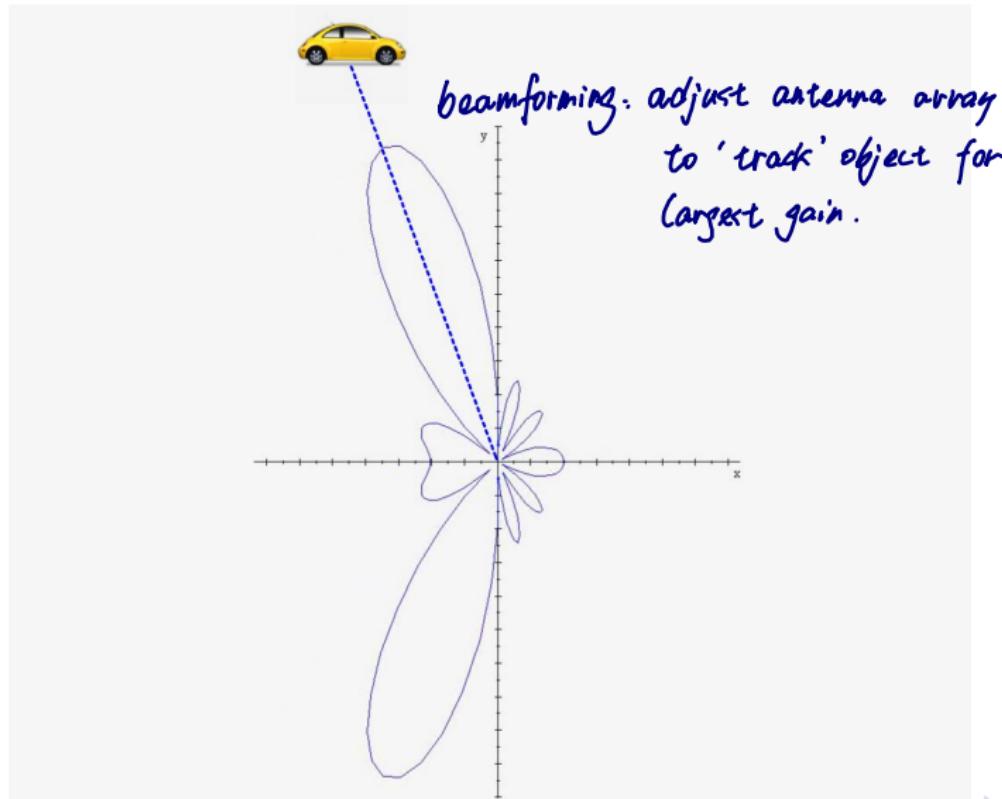
circular: # Ants = # full peaks + 1



Cardian: # Ants = # peaks in LHP/RHP.



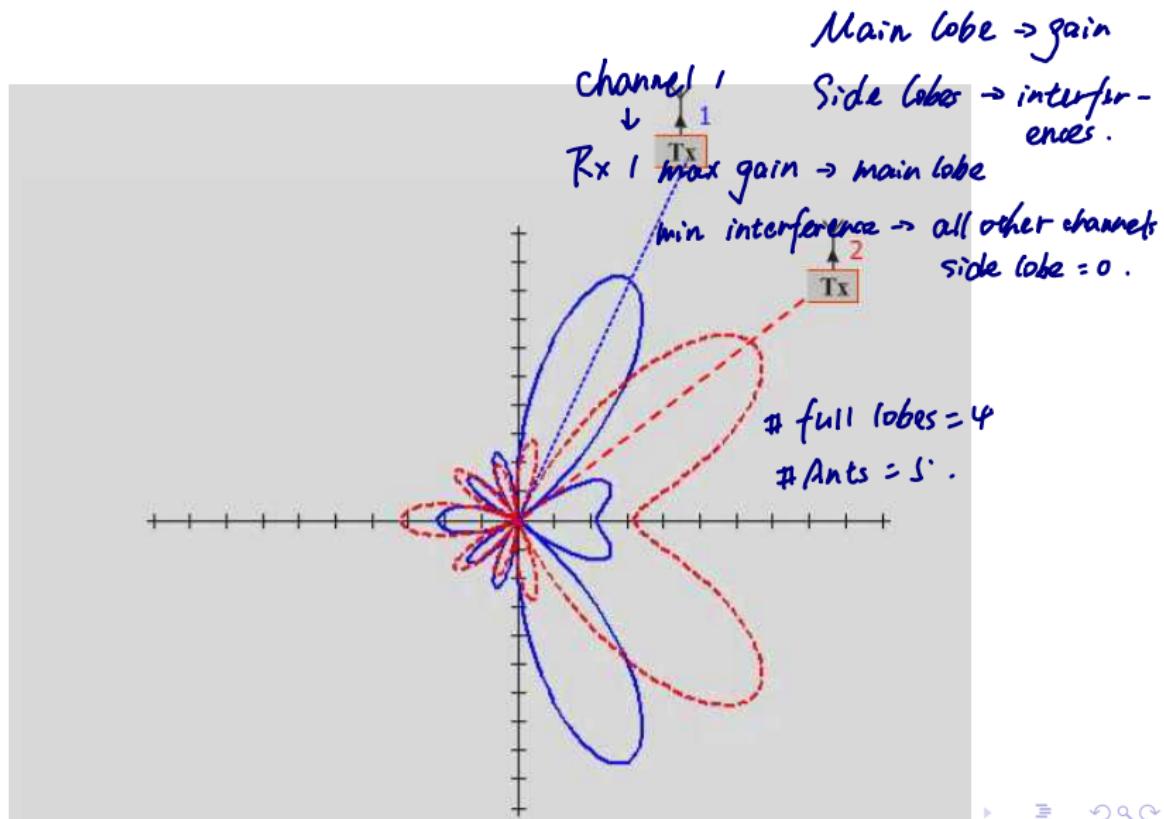
# SIMO Wireless Reception and Tracking (ULA, N=5)



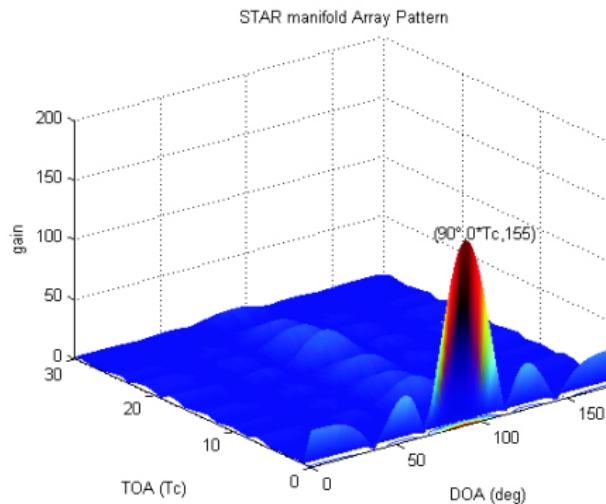
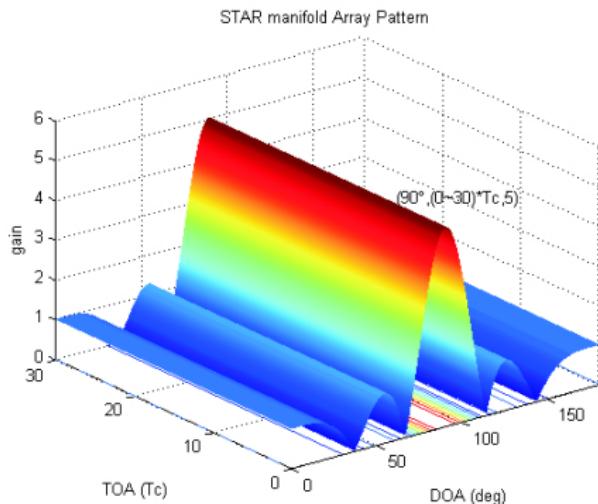
# Multiple Access Interference Cancellation (ULA, N=5)



# Co-Channel Interference Cancellation with Motion (ULA, N=5)

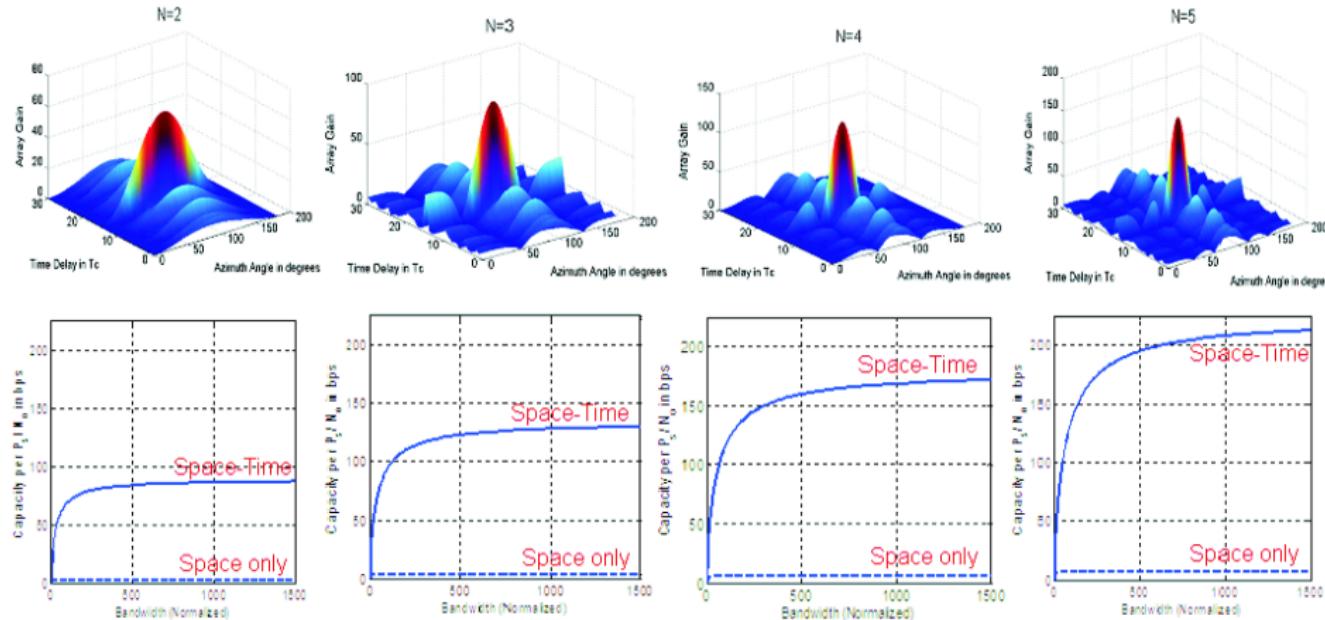


# Example: Space-only & Spatiotemporal Gain Patterns



# Spatio-Temporal Example:

PN-code of period 31; Uniform Linear Array (ULA) with intersensor spacing =  $\lambda/2$ ;  $N$  = number of antennas



- **SISO capacity :**

$$C = B \log_2(1 + \text{SNIR}_{out}) \text{ bits/sec} \quad (3)$$

- **MIMO Capacity :**

$$C = B \log_2 \left( \frac{\det(\mathbb{R}_{xx})}{\det(\mathbb{R}_{nn})} \right) \text{ bits/sec} \quad (4)$$

- If **bandwidth B**  $\rightarrow \infty$  then  $C = ?$

SISO :  $\lim_{B \rightarrow \infty} C = 1.44 \frac{P_s}{N_0 + N_J}$  (5)

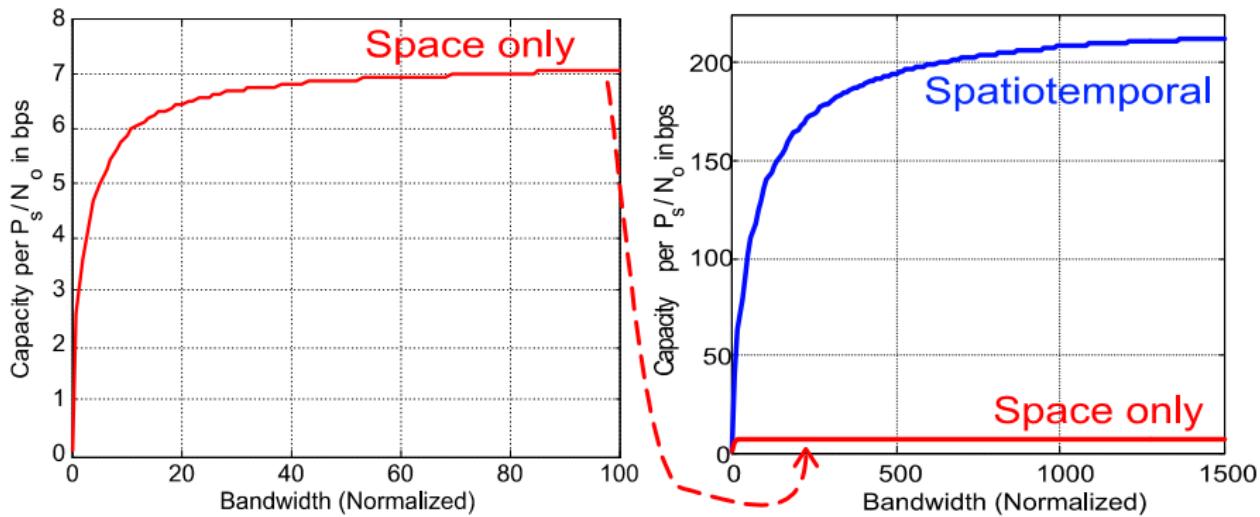
space-only SIMO :  $\lim_{B \rightarrow \infty} C = N \times 1.44 \frac{P_s}{N_0 + N_J} \downarrow 0$  (6)

spatiotemporal-SIMO :  $\lim_{B \rightarrow \infty} C = N \times \underbrace{N_{SP}}_{\substack{\parallel \\ \approx N \cdot N_c}} \times 1.44 \frac{P_s}{N_0 + N_J} \downarrow 0$  (7)

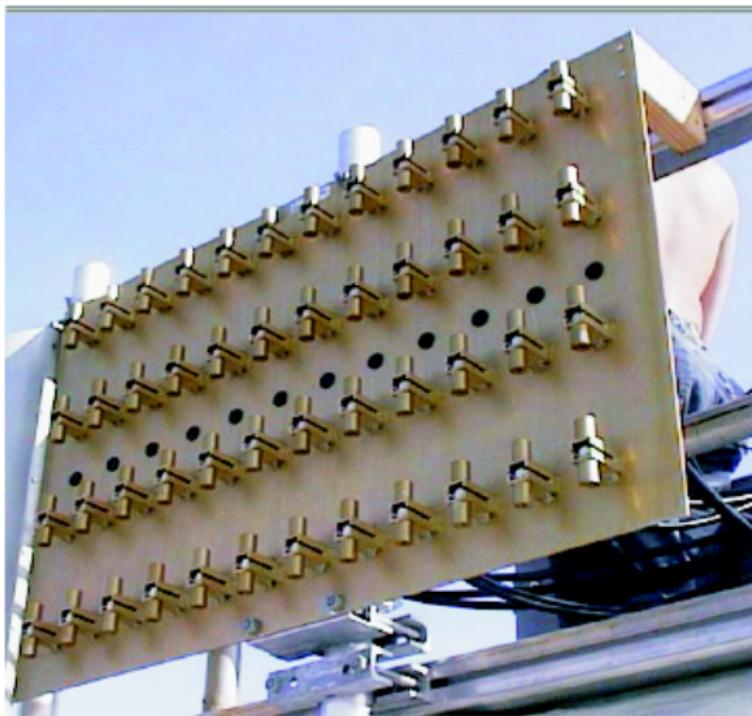
where  $N$  denotes the number of array elements (antennas)

# Space and Spatiotemporal Capacity Curves

$N = 5$  antennas



# A 2GHz Antenna Array of 48 Elements



# Owens Valley Radio Observatory Array

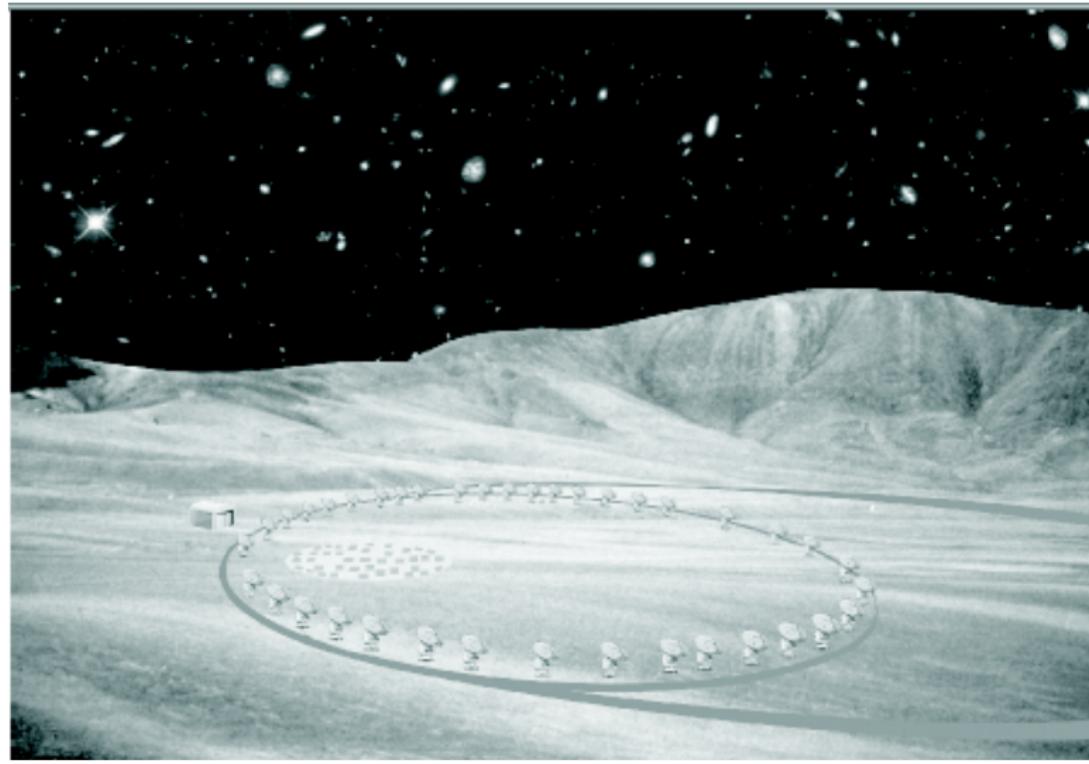


# The New Mexico Very Large Array of 27 Elements



(along rail road tracks - 35km)

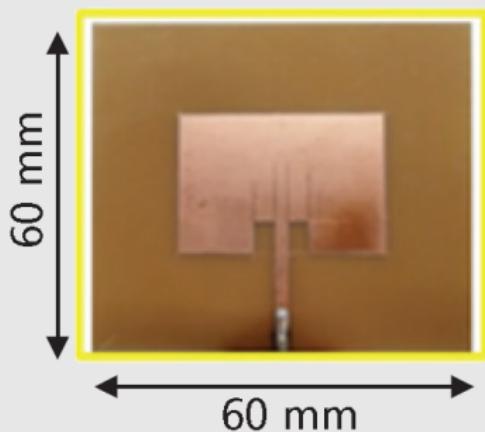
# A Large Circular Array



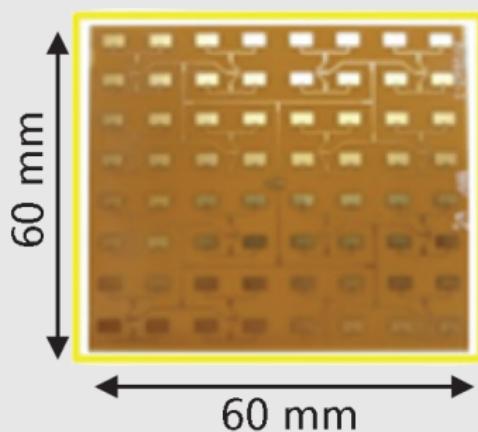
# Antenna Arrays for Modern Wireless Systems

- Array
- HF diversity  $\rightarrow$  larger capacity
  - multiple elements  $\rightarrow$  stability, reliability

Patch antenna  
(3 GHz)



Array antenna  
(30 GHz)



# Antenna Arrays for Modern Wireless Systems (cont.)

Intel modular RFEM (60GHz)

The slide displays the Intel modular RFEM (60GHz) antenna array system. It includes two main views: 'Antenna Side' and 'Shield Side'. The 'Antenna Side' shows a grid of 16 elements. The 'Shield Side' shows a larger grid of 16 elements. To the right, technical specifications are listed: '60GHz Operation', '16 Elements', and '25.2 mm x 9.8 mm'. Below these, four smaller images show variations in element count: '16 elements', '32 elements', '64 elements', and '128 elements'. The '128 elements' variation is shown in a much larger scale, illustrating the progression of the array size.

60GHz Operation  
16 Elements  
25.2 mm x 9.8 mm

Antenna Side      Shield Side

16 elements      32 elements      64 elements      128 elements

128 elements