

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

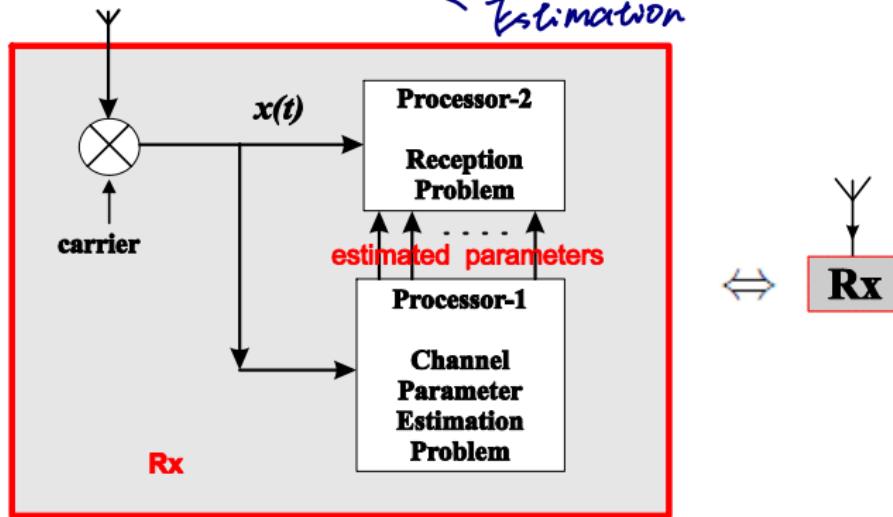
- ▶ to increase the **communication speed** (which is known as channel capacity)
without sacrificing the **quality of service** (for a given energy + bandwidth)
- Reliability (QoS)

Signal processing: baseband.



Generic Rx Architecture

R_x - Reception
- Estimation



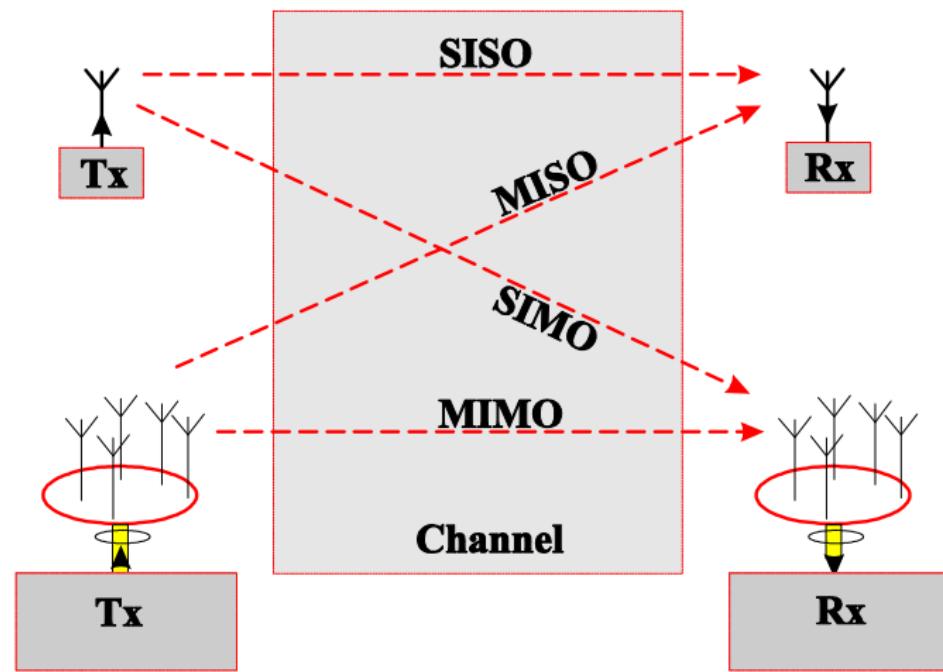
- The **quality of the receiver (Rx)** is a function of the **quality of the estimated channel parameters**
- Note that the receiver is **continuously designed** (based on these estimates) from **time frame to time frame.** *time-varying based on estimation*

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**.

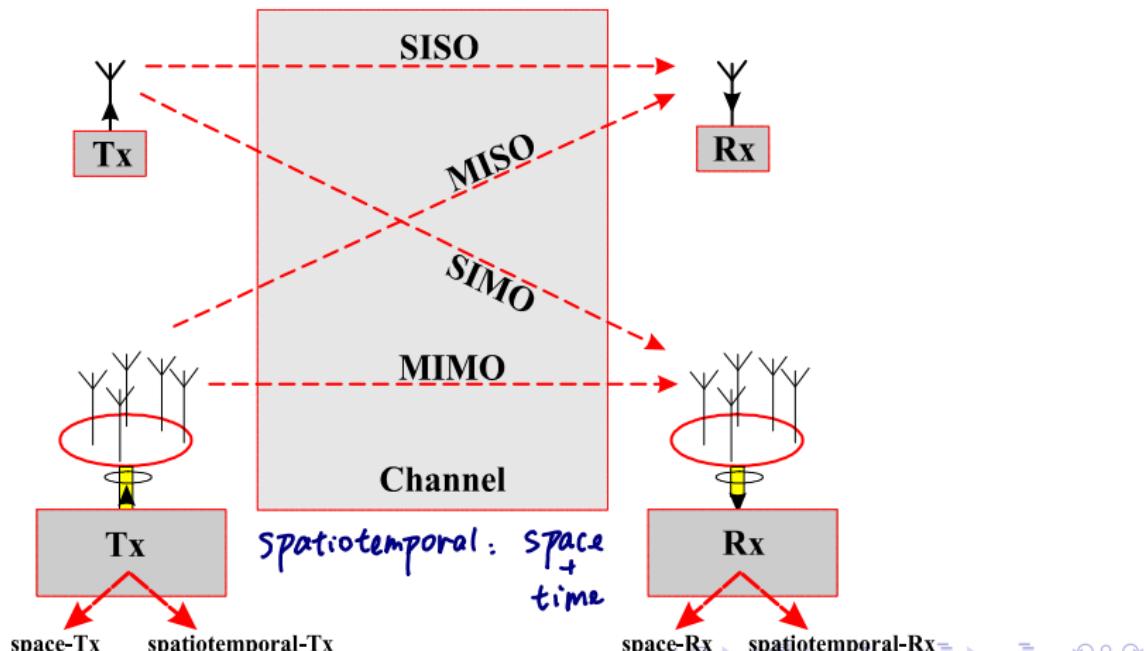
New Wireless Systems Classification

- 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)

1	SISO:	Scalar-Input-Scalar-Output Channel
2	SIVO:	Scalar-Input-Vector-Output Channel
3	VISO:	Vector-Input-Scalar-Output Channel
4	VIVO:	Vector-Input-Vector-Output Channel

- **Alternative Terminology**

Terminology-2 (Initial)

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

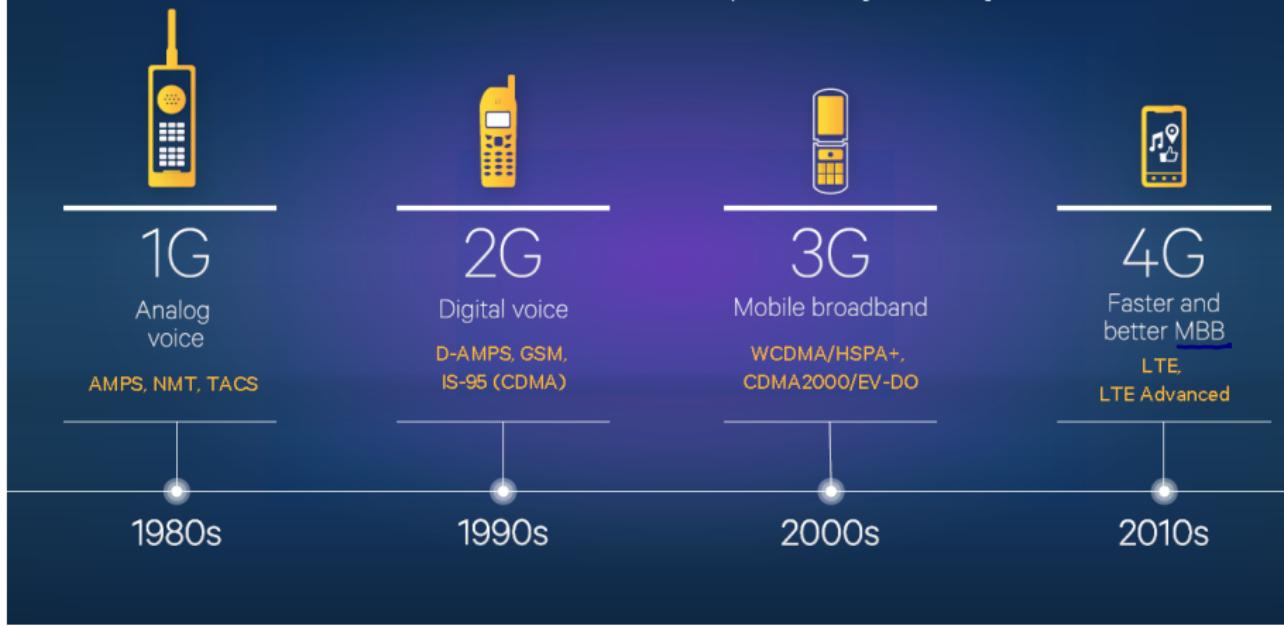
Terminology-3 (More Popular)

1	SISO:	Single-Input-Single-Output
2	SIMO:	Single-Input-Multiple-Output
3	MISO:	Multiple-Input-Single-Output
4	MIMO:	Multiple-Input-Multiple-Output

Mobile Evolution - Motivation

MBB = mobile broadband

Mobile has made a leap every ~10 years



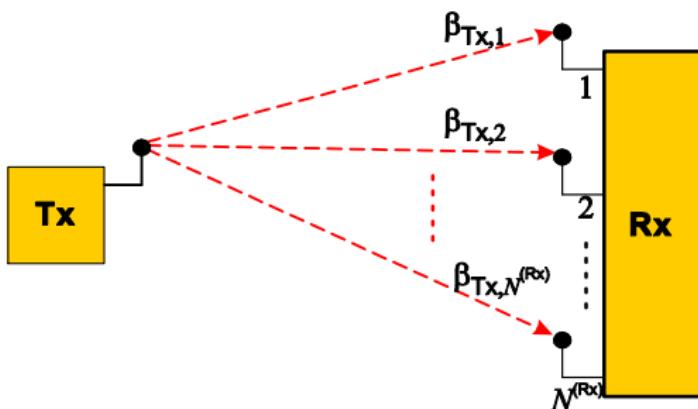
Mobile Evolution - Motivation (cont.)

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

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



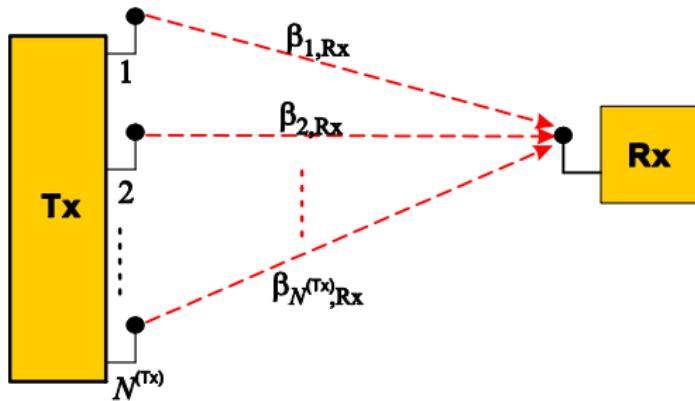
SIMO Wireless Systems (non-parametric)



Single-Input Multiple-Output (SIMO)

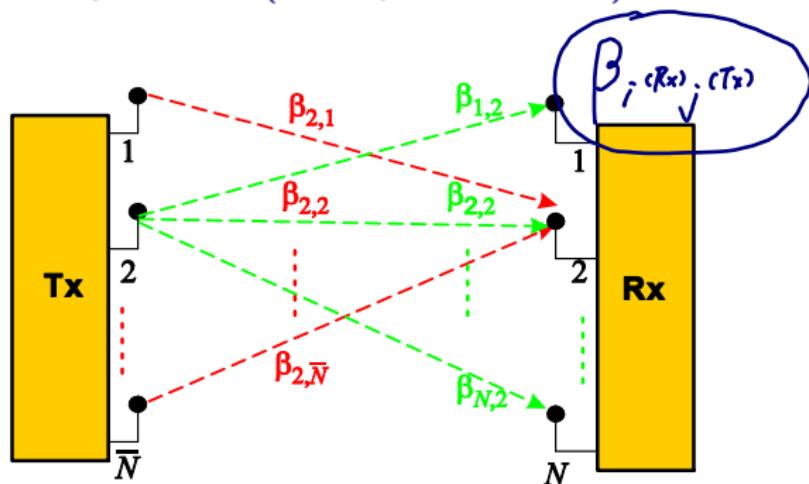
- Remember: SISO - one complex number β per path

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

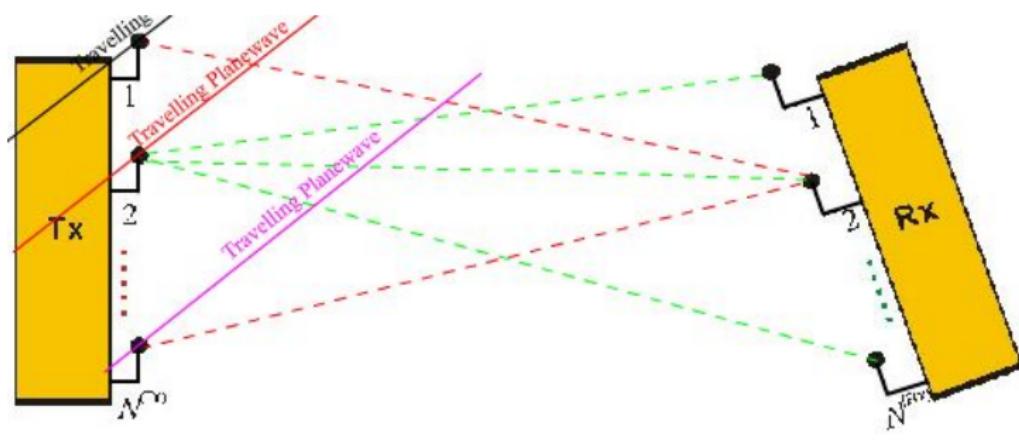
comprehensive

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:	β	
SIMO:	$\begin{bmatrix} \beta_{Tx,1} \\ \beta_{Tx,2} \\ \dots \\ \beta_{Tx,N^{(Rx)}} \end{bmatrix}$	$= \beta \underline{a}^{(Rx)}$
MISO:	$\begin{bmatrix} \beta_{1,Rx} \\ \beta_{2,Rx} \\ \dots \\ \beta_{N^{(Tx)},Rx} \end{bmatrix}$	$= \beta \underline{a}^{(Tx)}$
MIMO:	$\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,N^{(Tx)}} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,N^{(Tx)}} \\ \dots & \dots & \dots & \dots \\ \beta_{N^{(Rx)},1} & \beta_{N^{(Rx)},2} & \dots & \beta_{N^{(Rx)},N^{(Tx)}} \end{bmatrix}$	$= \beta \underline{a}^{(Rx)} \underline{a}^{(Tx)^H}$ $\Leftrightarrow \beta \underline{a}^{(virtual)}$

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

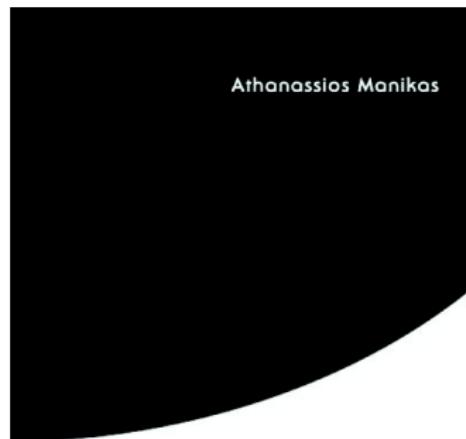
- In Physics, Albert Einstein (Nobel 1921) used differential geometry to express his **general theory of relativity**
► where the universe is a **smooth manifold** equipped with ^{*if it exists.*} pseudo-Riemannian metric (described the curvature of space-time).

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?

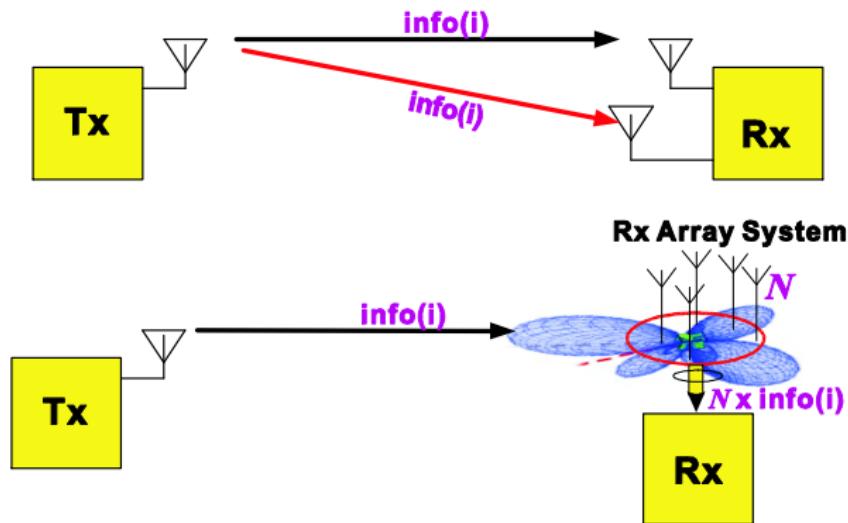


DIFFERENTIAL GEOMETRY IN **ARRAY PROCESSING**

Imperial College Press

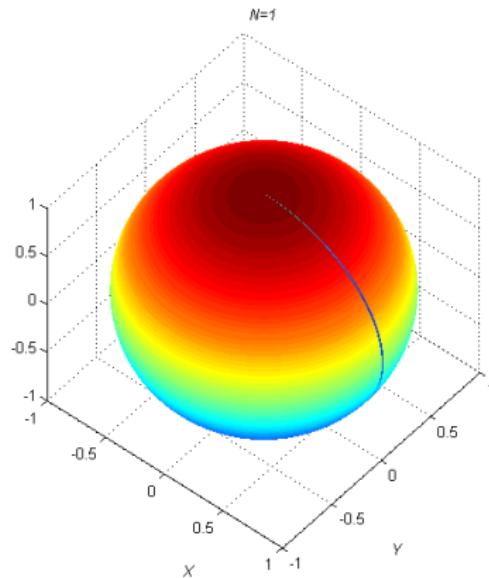
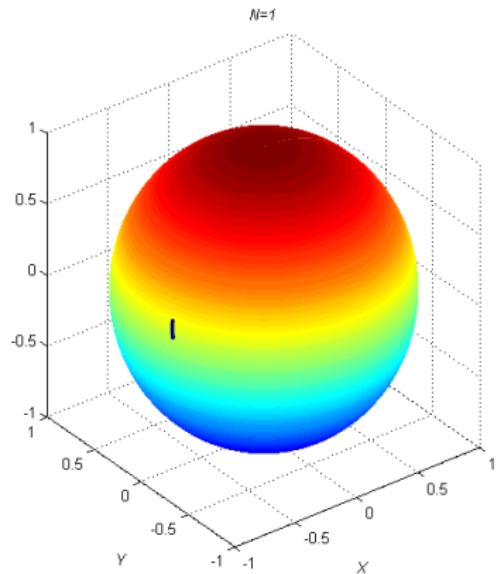
Antenna Array Space Response

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



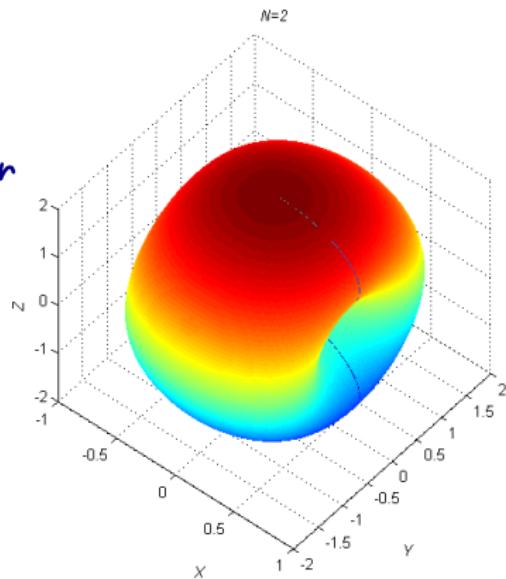
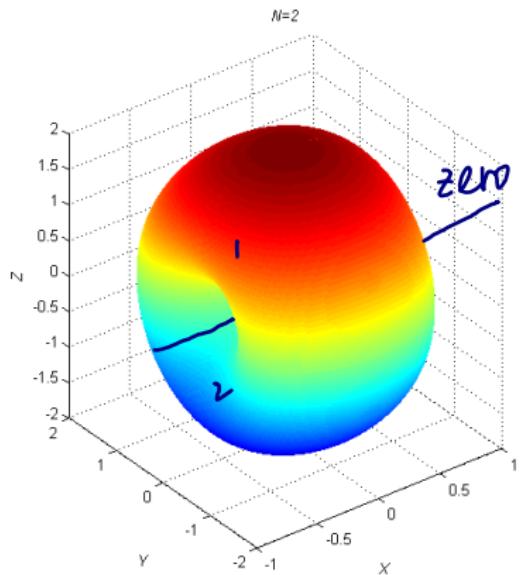
- Array systems (smart antennas) and techniques can be seen as the most sophisticated and advanced space diversity systems/techniques. (This type of systems/techniques will be considered in this course.)

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



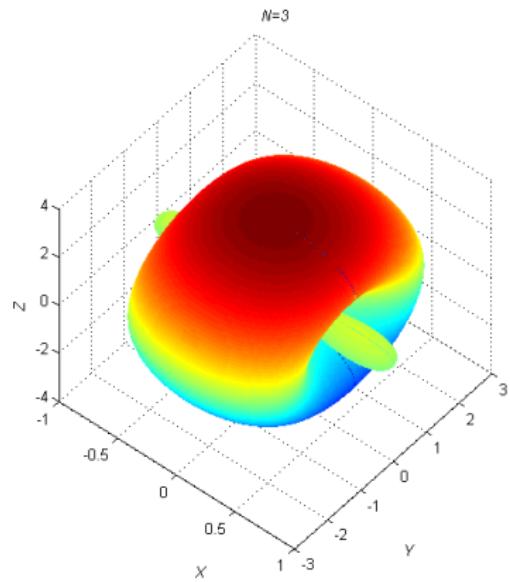
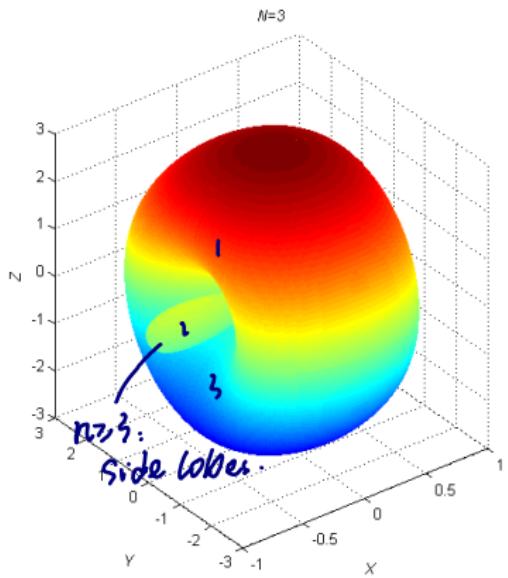
(rotated by 90°)

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



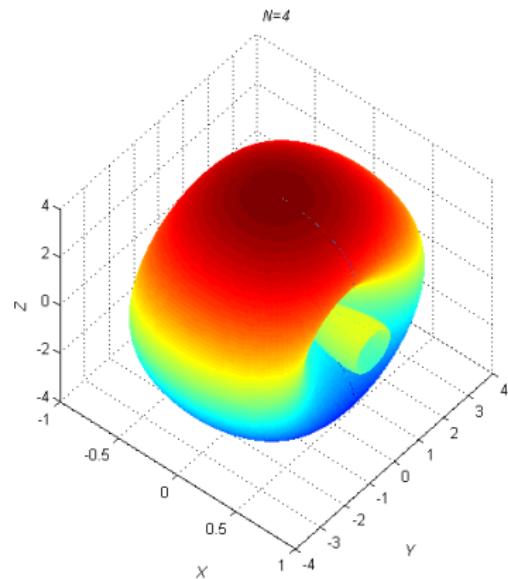
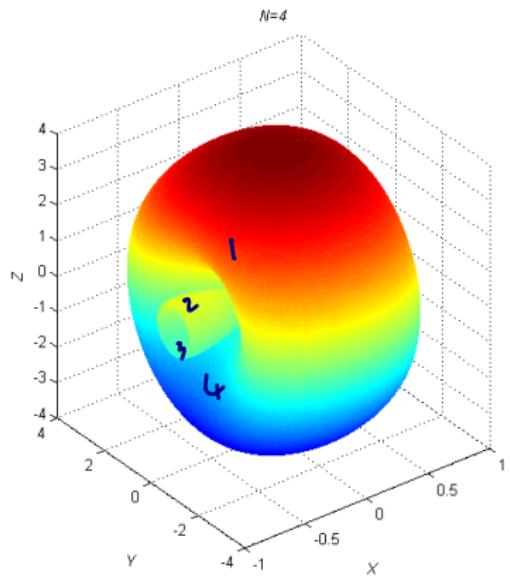
(rotated by 90°)

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



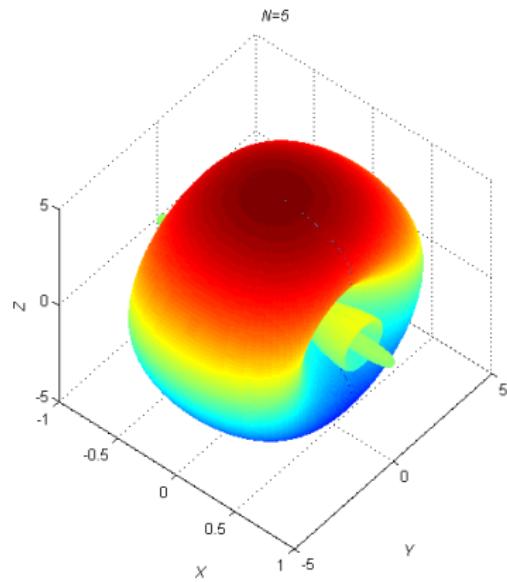
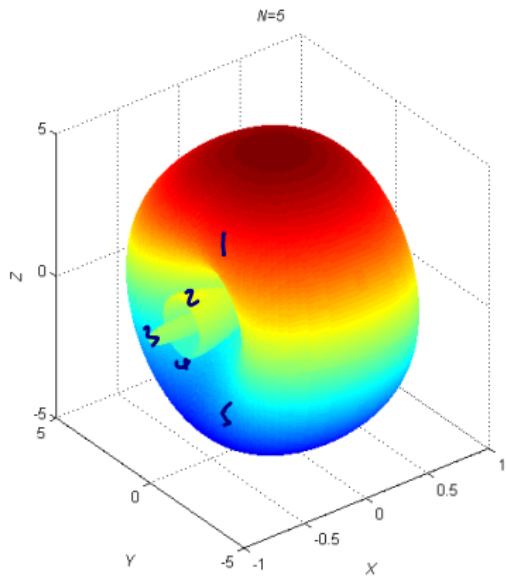
(rotated by 90°)

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



(rotated by 90°)

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



(rotated by 90°)

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).*

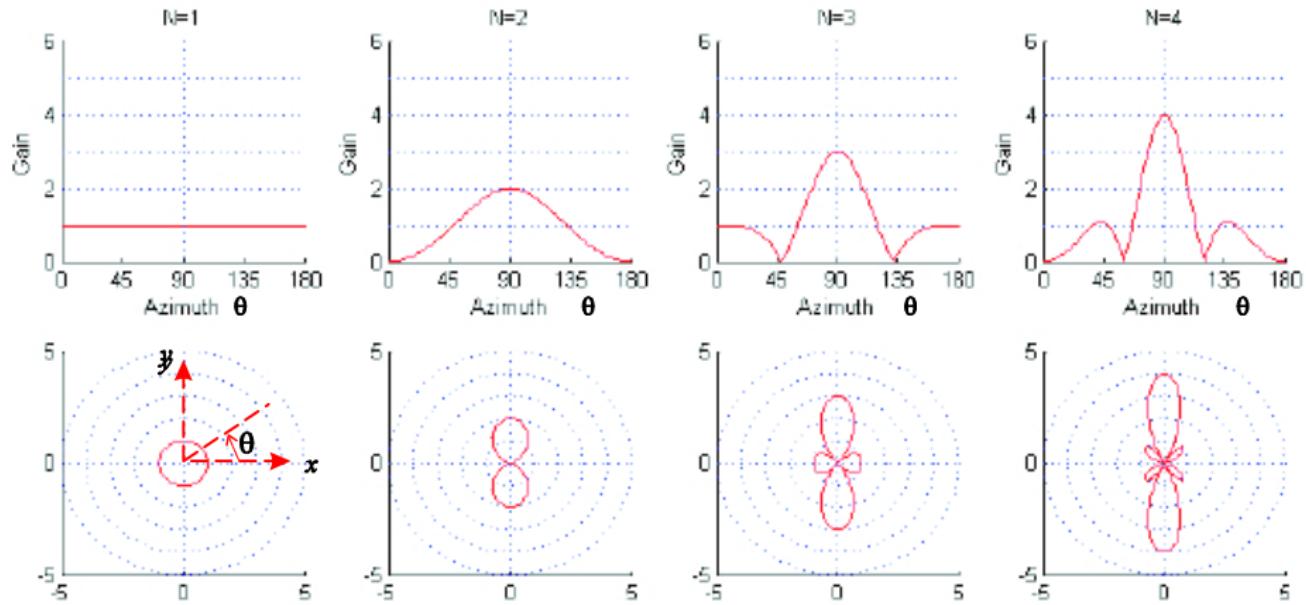
- Channel Capacity (AWGN):

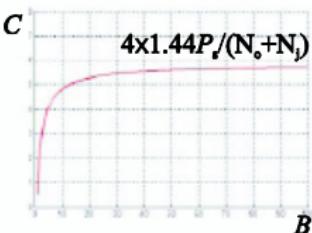
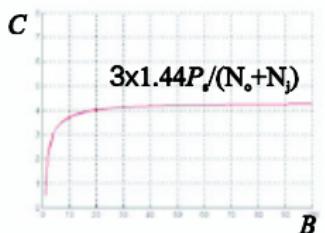
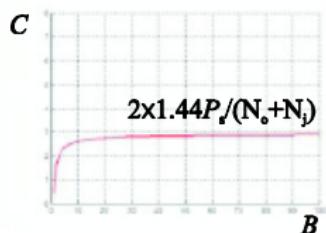
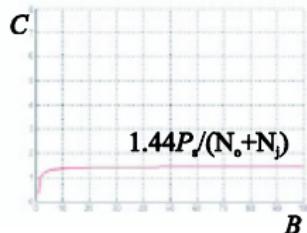
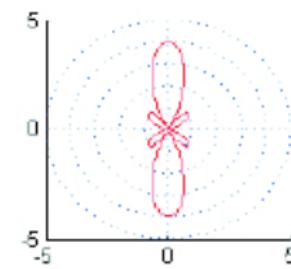
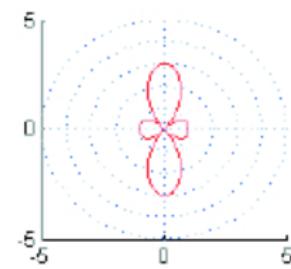
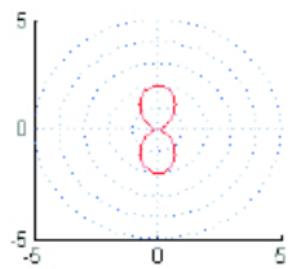
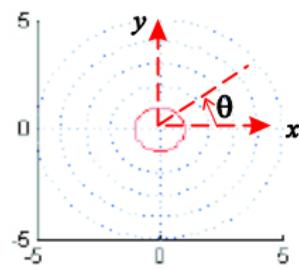
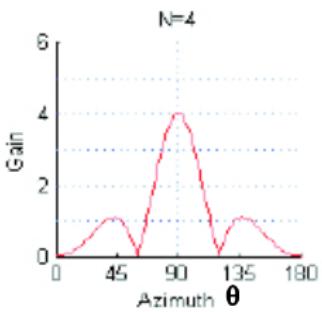
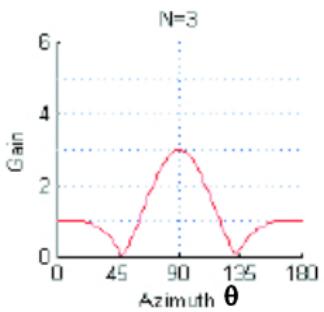
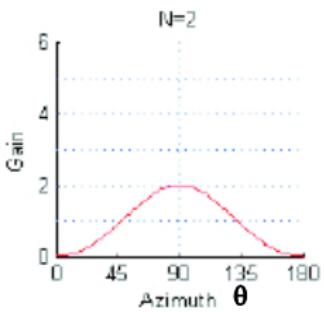
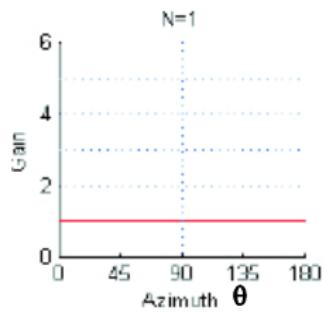
$$C = B \log_2 \left(1 + N \frac{P_s}{(N_0 + N_j) B} \right) \xrightarrow{(N_0 + N_j) B} B \log_2 (1 + N \times \text{SNIR}_{in}) \quad (1)$$

$$= \log_2 \left(1 + N \frac{P_s}{(N_0 + N_j) B} \right) B \xrightarrow{NP_s} \frac{NP_s}{N_0 + N_j} C \longrightarrow N \times 1.44 \frac{P_s}{N_0 + N_j} \quad \text{array joint parameter} \quad (2)$$

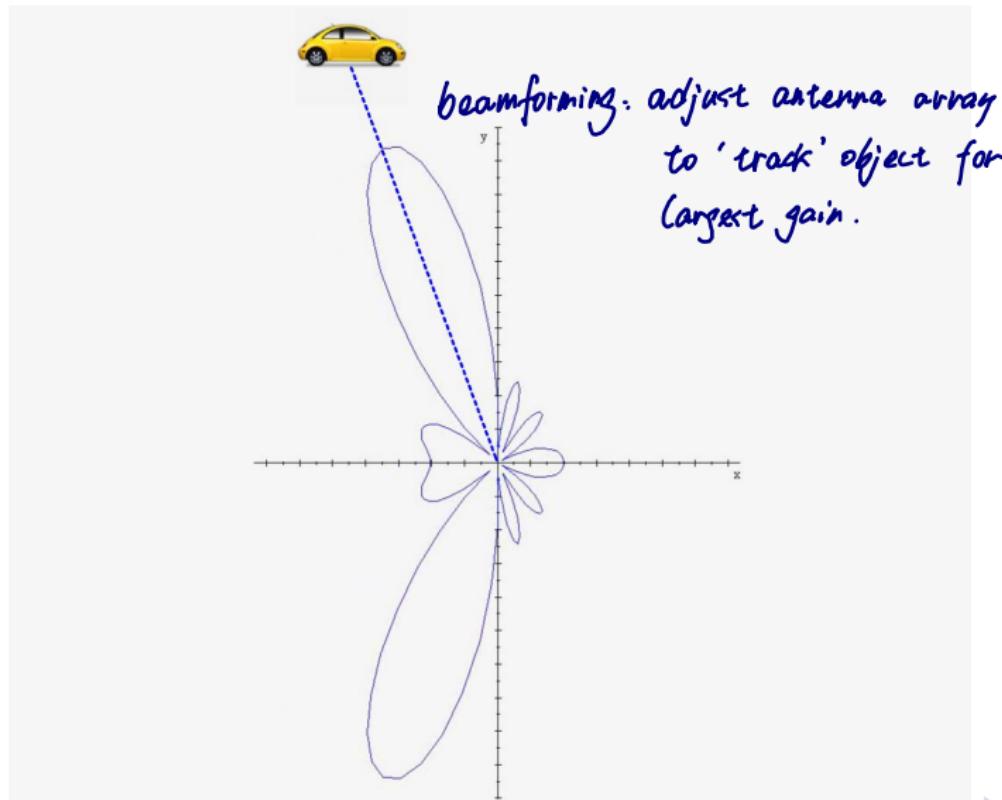
$B \approx 0$

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





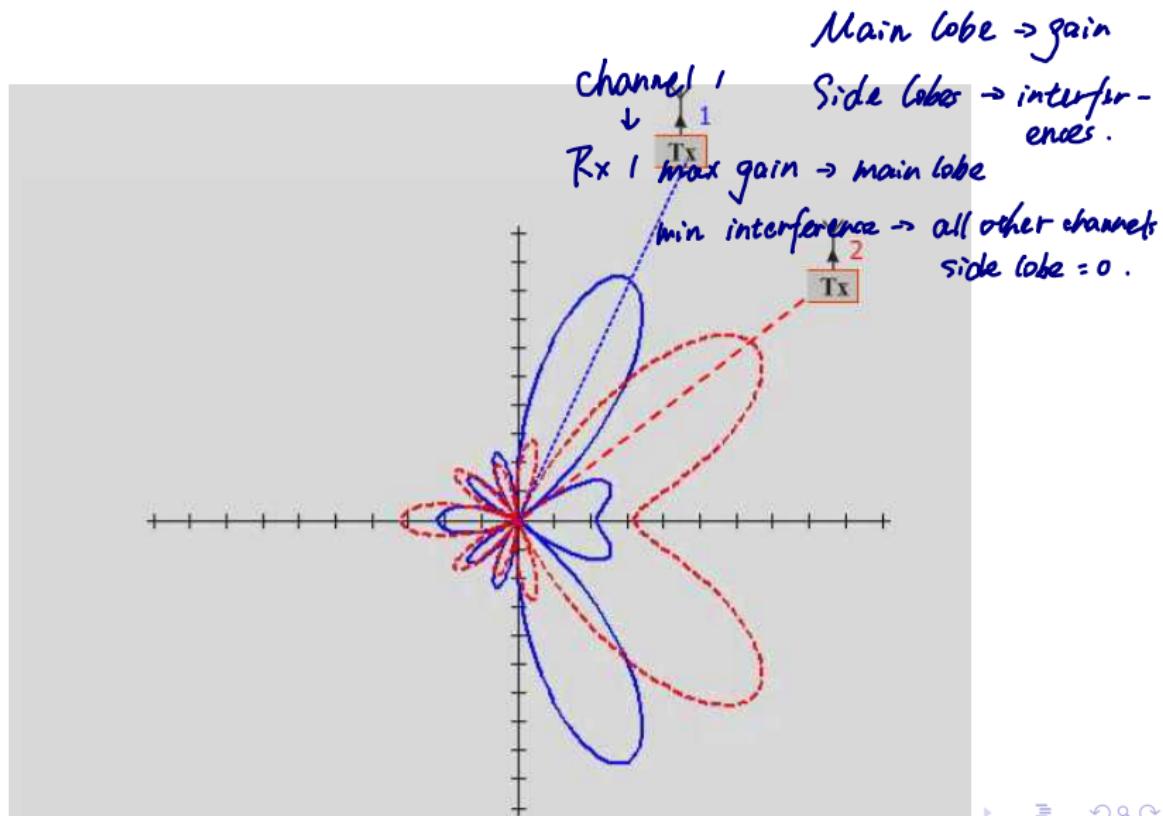
SIMO Wireless Reception and Tracking (ULA, N=5)



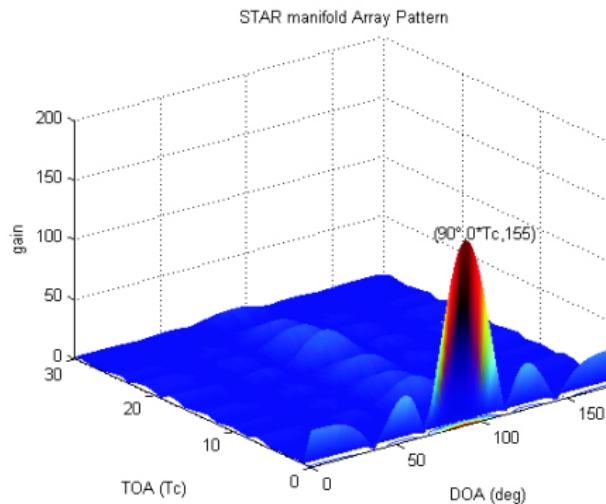
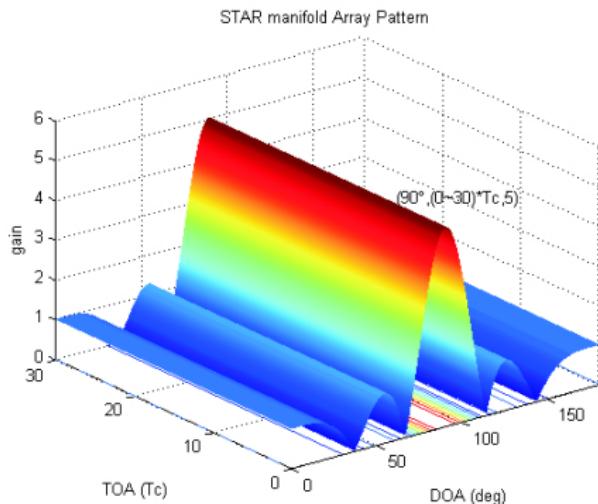
Multiple Access Interference Cancellation (ULA, N=5)



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

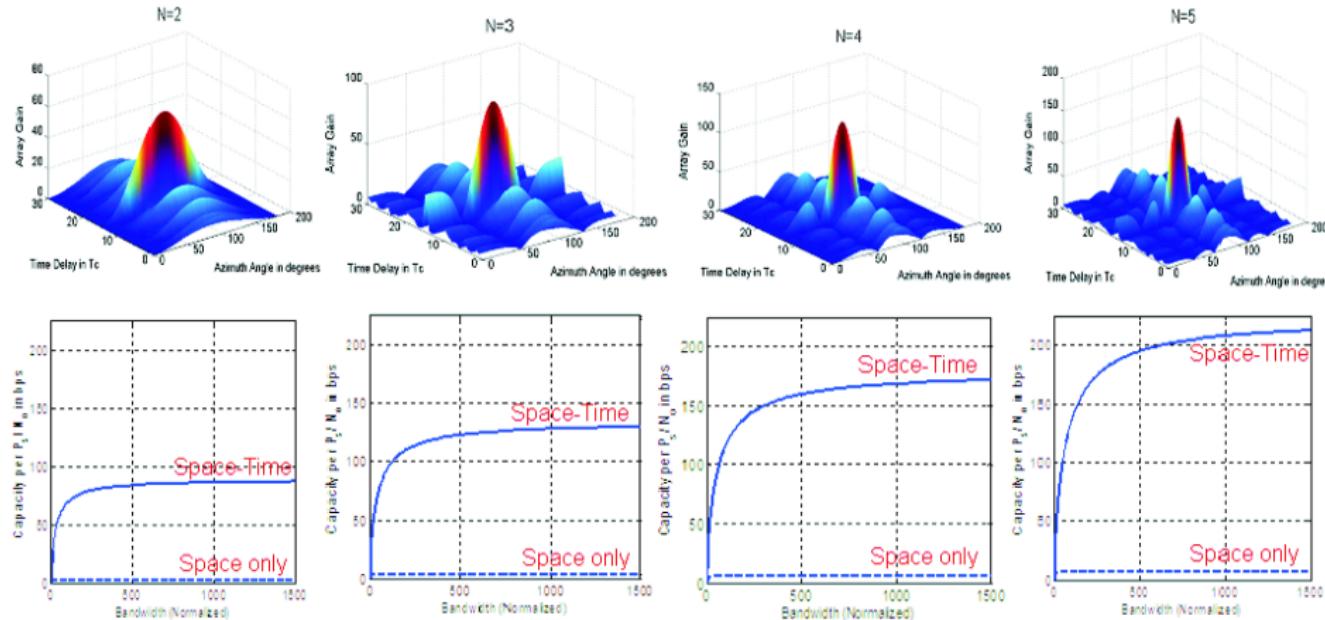


Example: Space-only & Spatiotemporal Gain Patterns



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)

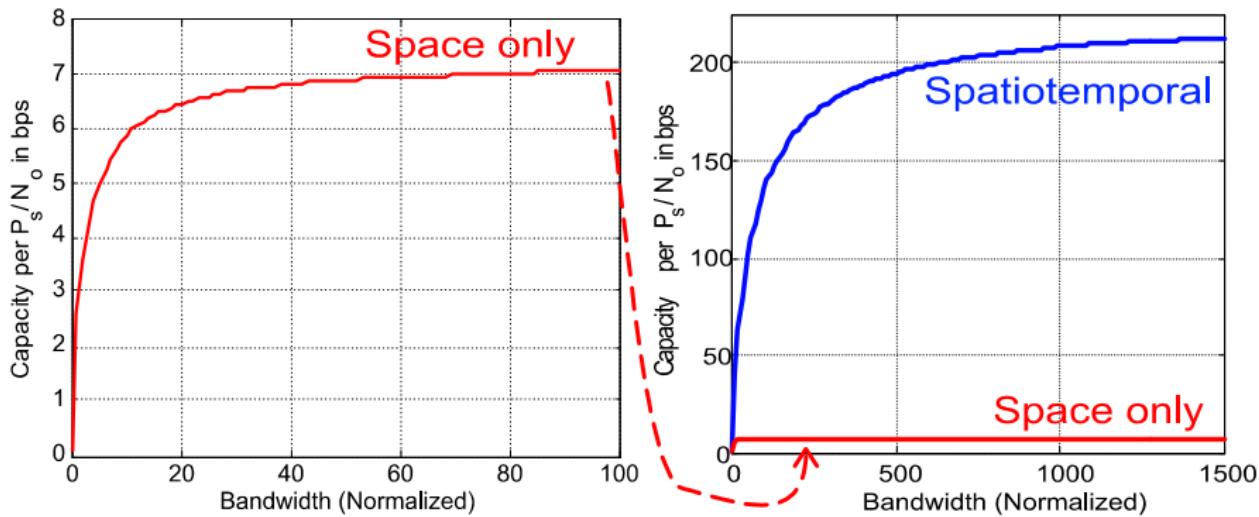
space-only SIMO : $\lim_{B \rightarrow \infty} C = N \times 1.44 \frac{P_s}{N_0 + N_J} \downarrow 0$ (6)

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

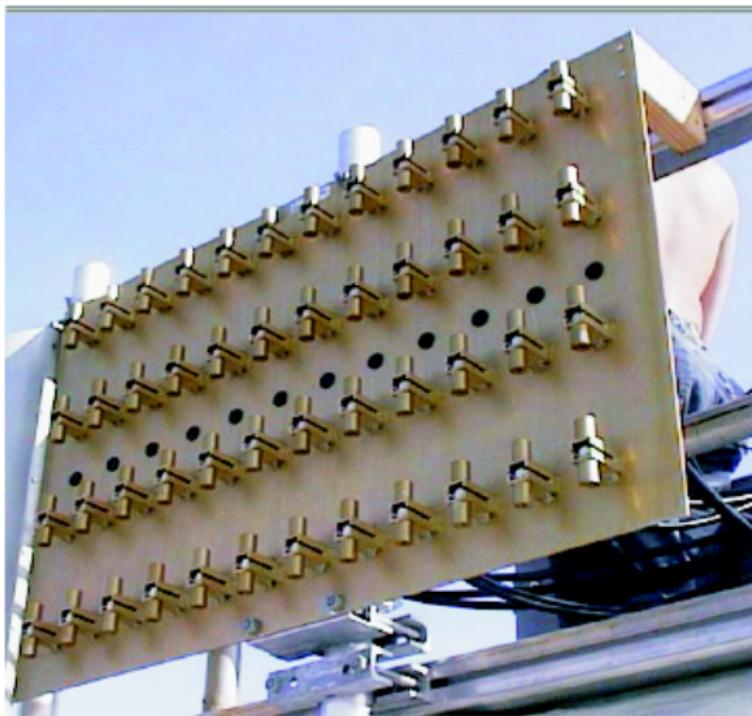
where N denotes the number of array elements (antennas)

Space and Spatiotemporal Capacity Curves

$N = 5$ antennas



A 2GHz Antenna Array of 48 Elements



Owens Valley Radio Observatory Array

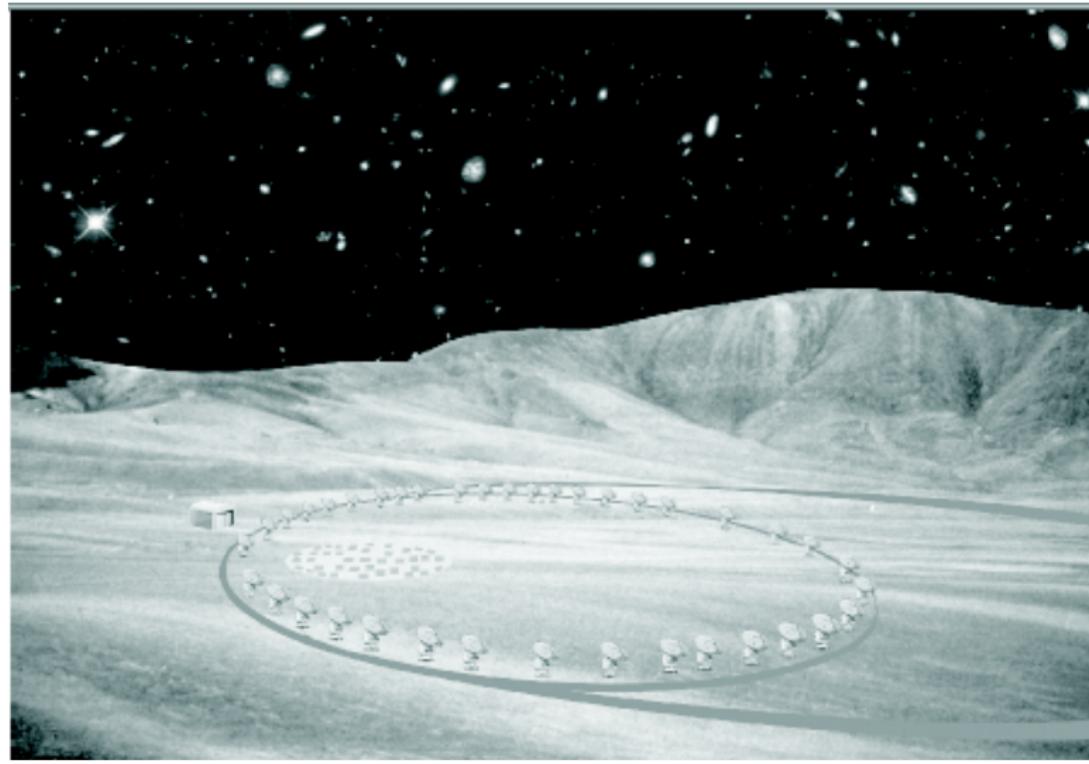


The New Mexico Very Large Array of 27 Elements



(along rail road tracks - 35km)

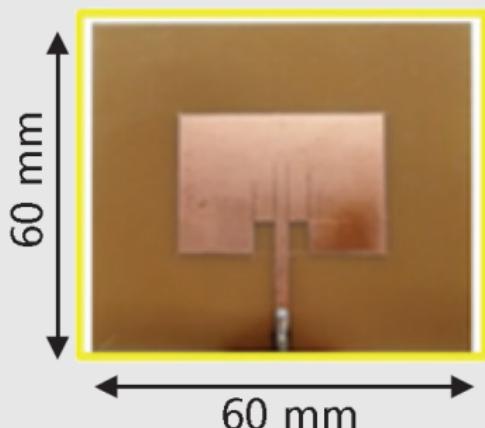
A Large Circular Array



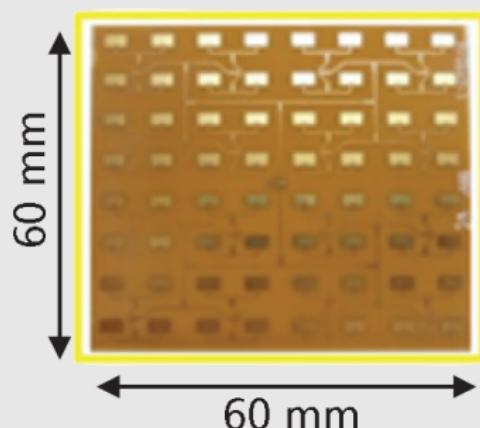
Antenna Arrays for Modern Wireless Systems

- 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 shows a full 8x16 grid.

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