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

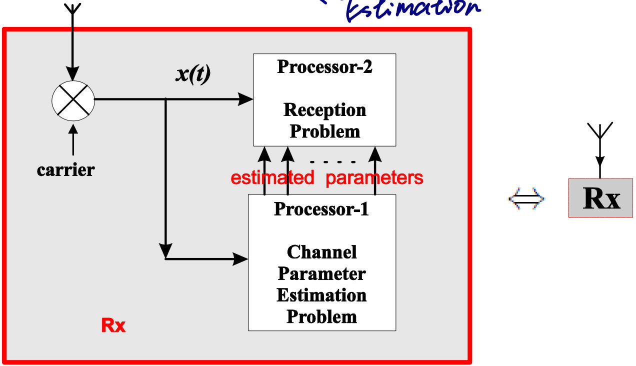
  - to increase the **communication speed** (which is known as channel capacity) without sacrificing the **quality of service** (for a given energy + bandwidth)

Aim:
- capacity
- energy effic.
  bandwidth
- Reliability (Q.S)

Signal processing: baseband.

Generic Rx Architecture

Rx – Reception
– Estimation



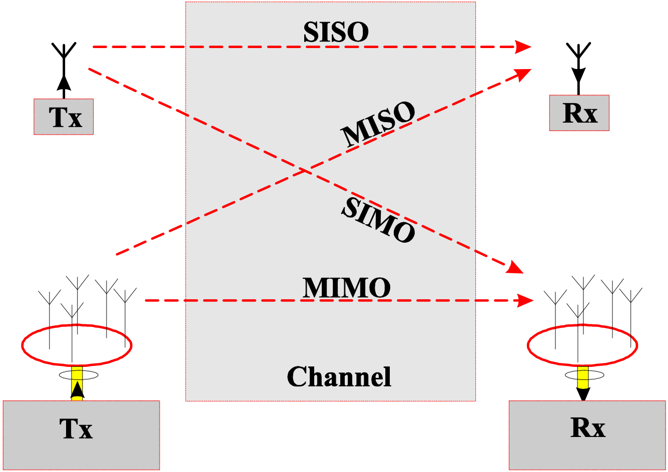
- The **quality of the receiver (Rx)** is a function of the **quality of the estimated channel parameters**
- Note that the receiver is **continuously designed** (based on these estimates) from **time frame** to **time frame**. → time-varying based on estimation.

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** $= \uparrow$,
  - **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.

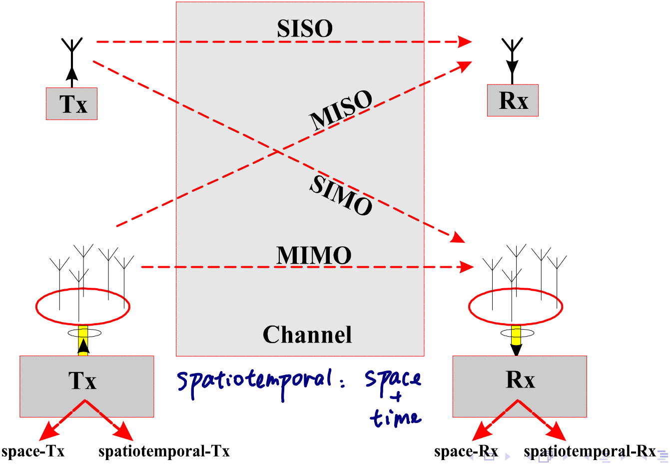
New Wireless Systems Classification

- 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

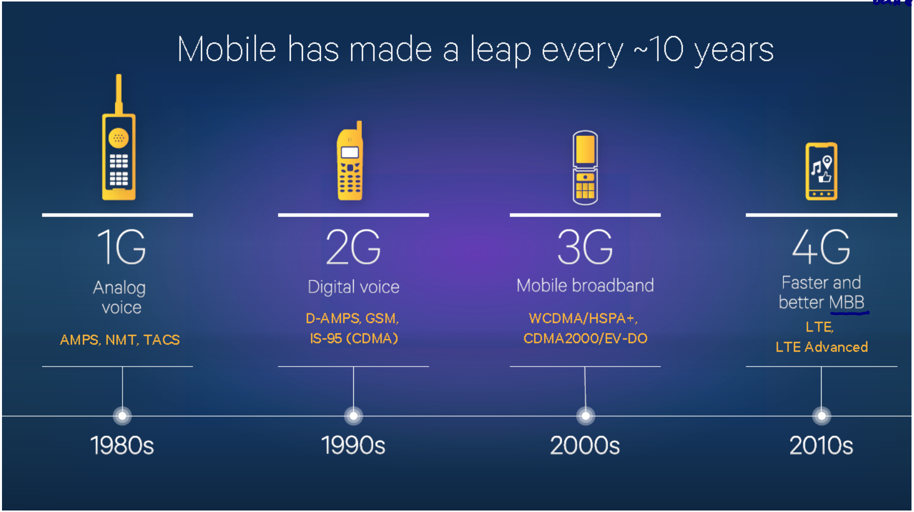
- **Alternative Terminology**

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

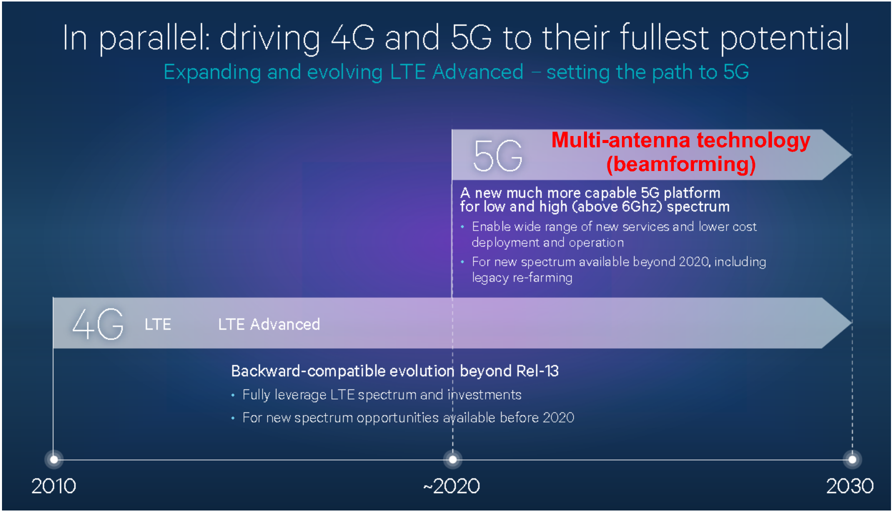
Terminology-3 (More Popular)		
1	SISO:	Single-Input-Single-Output
2	SIMO:	Single-Input-Multiple-Output
3	MISO:	Multiple-Input-Single-Output
4	MIMO:	Multiple-Input-Multiple-Output

Mobile Evolution - Motivation

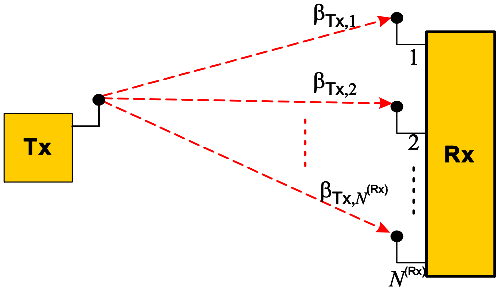
MBB: mobile broad-band.



Mobile Evolution - Motivation (cont.)



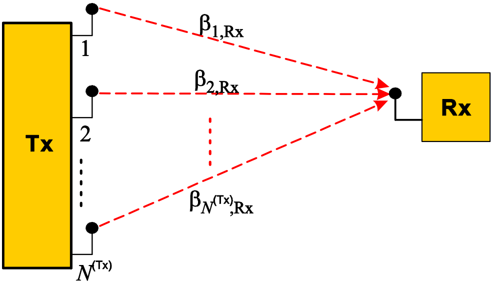
SIMO Wireless Systems (non-parametric)



Single-Input Multiple-Output (SIMO)

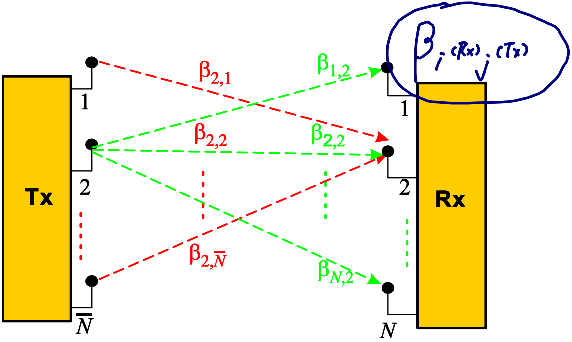
- Remember: SISO - one complex number β per path

MISO Wireless Systems (non-parametric)



Multiple-Input Single-Output (MISO)

MIMO Wireless Systems (non-parametric)



Multiple-Input Multiple-Output (MIMO)

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

Parametric Approaches

Introduction

Statistical vs Parametric

· simple
· classical

· comprehensive

Tx·Rx geometric   signal direction   propagation model

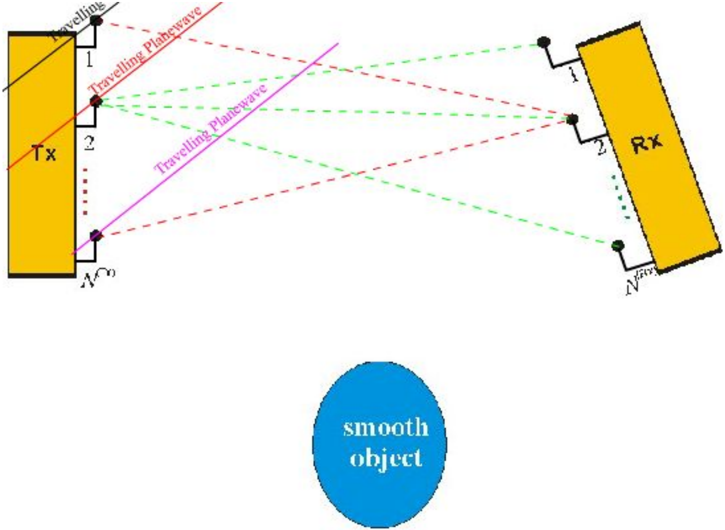
- The above modelling will result into a statistical approach (used in Wiener's estimation theory and Shannon's communication theory). e.g. many MIMO books, papers and tutorials: non parametric

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:	$\begin{bmatrix} \beta_{Tx,1} \\ \beta_{Tx,2} \\ \cdots \\ \beta_{Tx,N^{(\mathrm{Rx})}} \end{bmatrix}$	propagation gain; array manifold vector; $=\beta\underline{a}^{(\mathrm{Rx})}$
MISO:	$\begin{bmatrix} \beta_{1,\mathrm{Rx}} \\ \beta_{2,\mathrm{Rx}} \\ \cdots\cdot \\ \beta_{N^{(\mathrm{Tx})},\mathrm{Rx}} \end{bmatrix}$	$=\beta\underline{a}^{(\mathrm{Tx})}$
MIMO:	$\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \cdots & \beta_{1,N^{(\mathrm{Tx})}} \\ \beta_{2,1} & \beta_{2,2} & \cdots & \beta_{2,N^{(\mathrm{Tx})}} \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{N^{(\mathrm{Rx})},1} & \beta_{N^{(\mathrm{Rx})},2} & \cdots & \beta_{N^{(\mathrm{Rx})},N^{(\mathrm{Tx})}} \end{bmatrix}$	$=\beta\underline{a}^{(\mathrm{Rx})}\underline{a}^{(\mathrm{Tx})^H}$ $\Leftrightarrow \beta\underline{a}^{(virtual)}$

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.

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

- The vector $\underline{a}$ is known as
  - Array Manifold Vector or
  - Array Response Vector (alternative symbol $\underline{S}$)

- The vector $\underline{a}$ has a **profound mathematical structure** and is a function of a number of parameters such as Directions, carrier,etc

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

Note

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

- For instance

  $\underline{a}(\theta, \phi, F_c, c, \underline{r}_x, \underline{r}_y, \underline{r}_z,$
  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**.

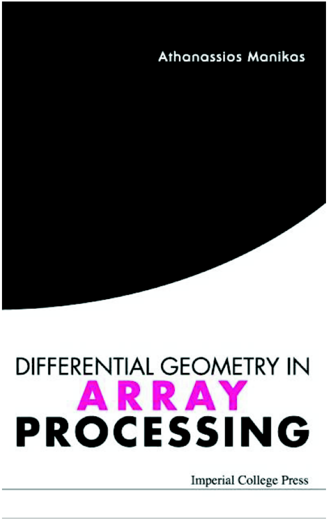
$$\underline{p} \longmapsto \text{mathematical object}$$

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

Fundamental Questions

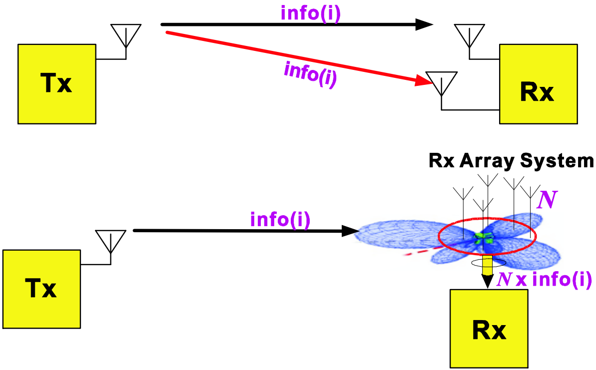
problem → manifold → design

- 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?



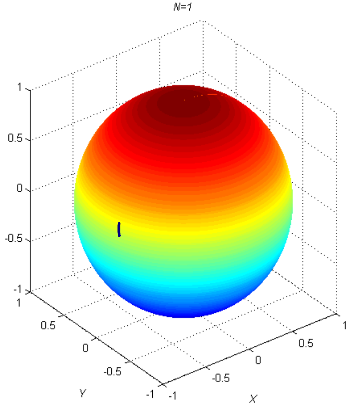
Antenna Array Space Response

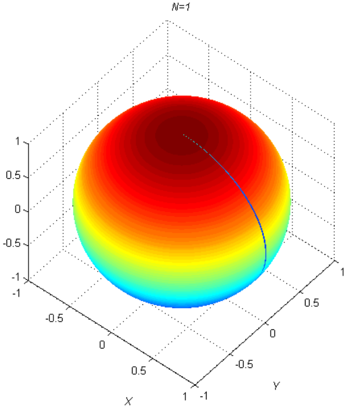
- **SIMO Example: Rx-Array Diversity**



- 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.)

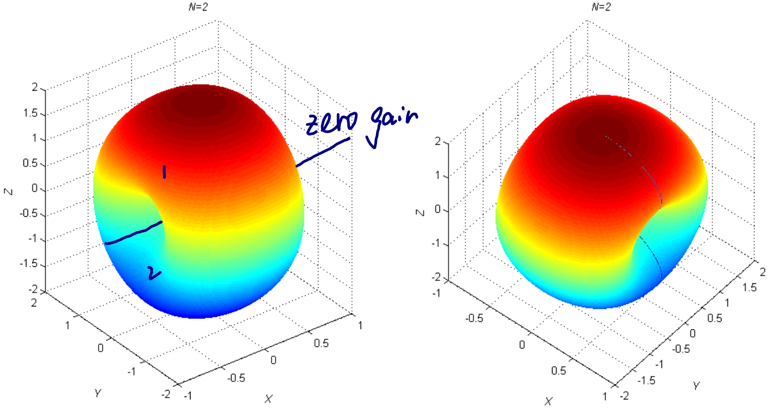
Single Antenna (N=1): Space Response





(rotated by 90°)

Two Antennas (N=2): Space Response



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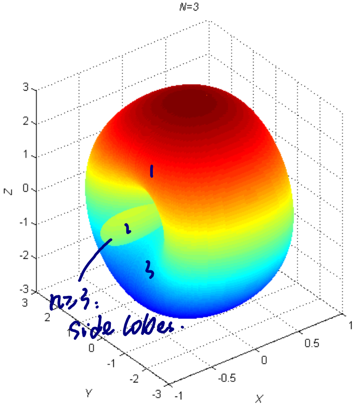
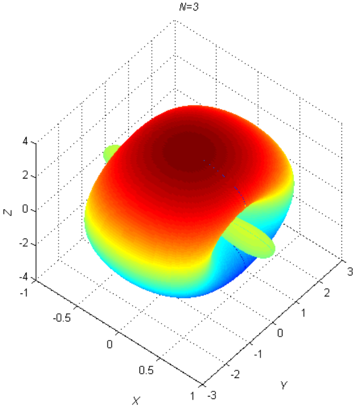
Three Antennas (N=3): Space Response





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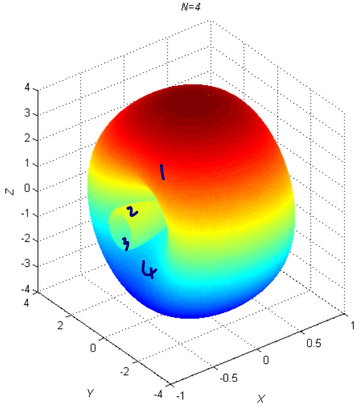
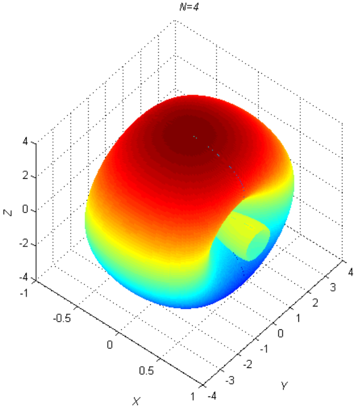
Four Antennas (N=4): Space Response

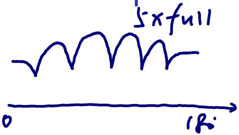


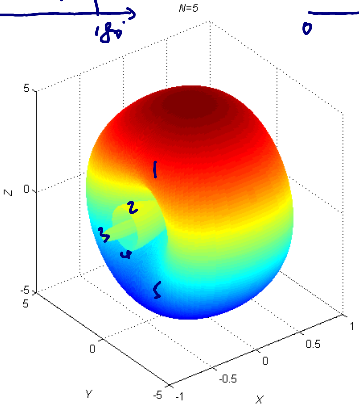


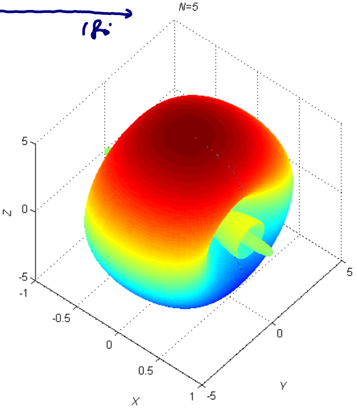
(rotated by 90°)

Five Antennas (N=5): Space Response

Ants = 5+1 = 6







(rotated by 90°)

Space-Only Example: Uniform Linear Array (ULA)

- Intersensor spacing$=\lambda/2$;
- N = number of antennas (located on the x-axis). $N \rightarrow$ antenna array. (can be Tx or Rx).
- Channel Capacity (AWGN):

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

$$\stackrel{B}{\longrightarrow}\infty \quad C \longrightarrow N\times 1.44\frac{P_s}{N_0+N_j} \quad (2)$$

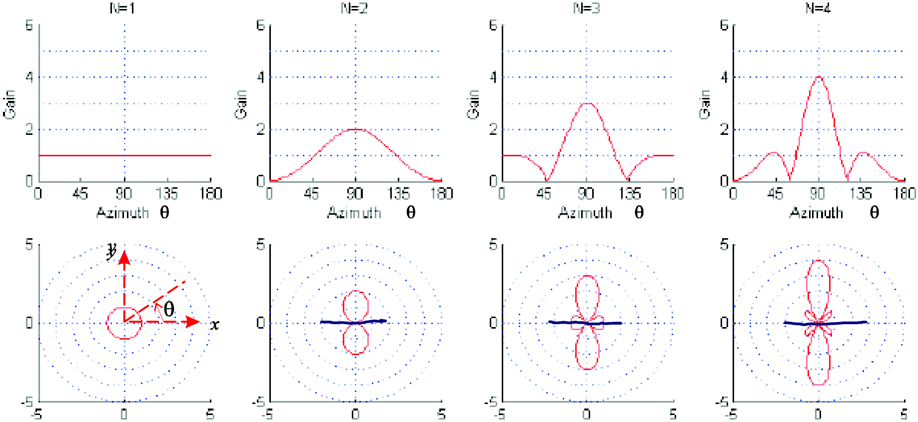
array jamming parameter

$$C = B\log_2\left(1+N\frac{P_s}{(N_0+N_j)B}\right)$$

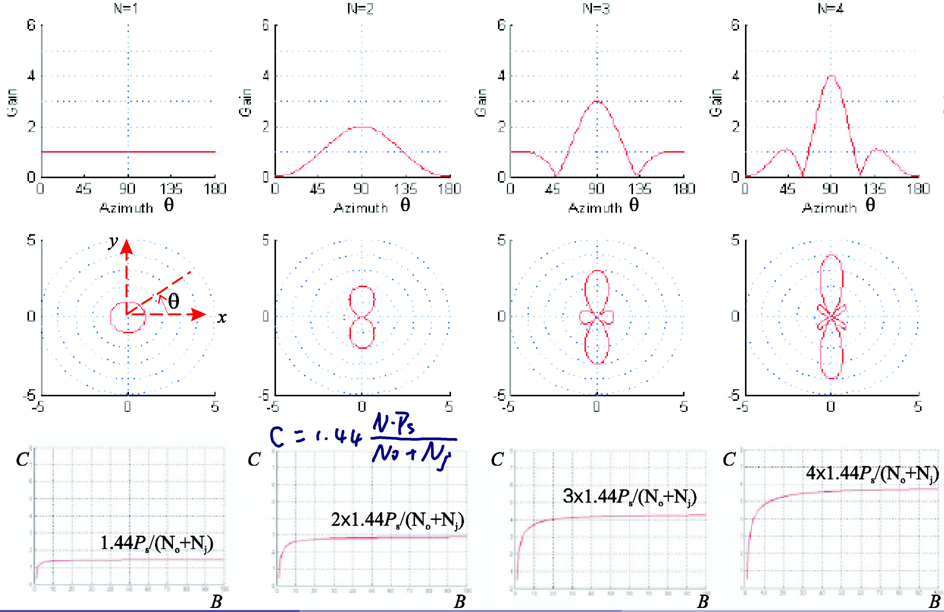
$$= \log_2\left(1+N\frac{P_s}{(N_0+N_j)B}\right)^{B\frac{(N_0+N_j)B}{NP_s}\cdot\frac{NP_s}{N_0+N_j}}$$

$$\underset{B\to\infty}{C} = (\log_2 e)\frac{NP_s}{N_0+N_j} = \boxed{1.44N\frac{P_s}{N_0+N_j}}$$

Circular: # Ants = # full peaks + 1

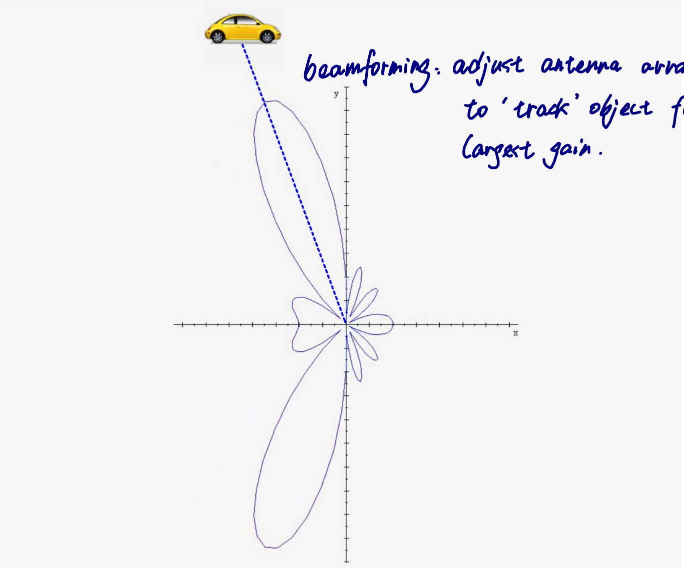


Cardian: # Ants = # peaks in half plane.



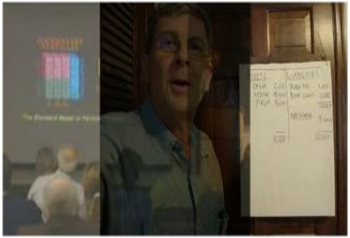
$$C = 1.44 \frac{N \cdot P_s}{N_o + N_j}$$

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



beamforming: adjust antenna array to 'track' object for largest gain.

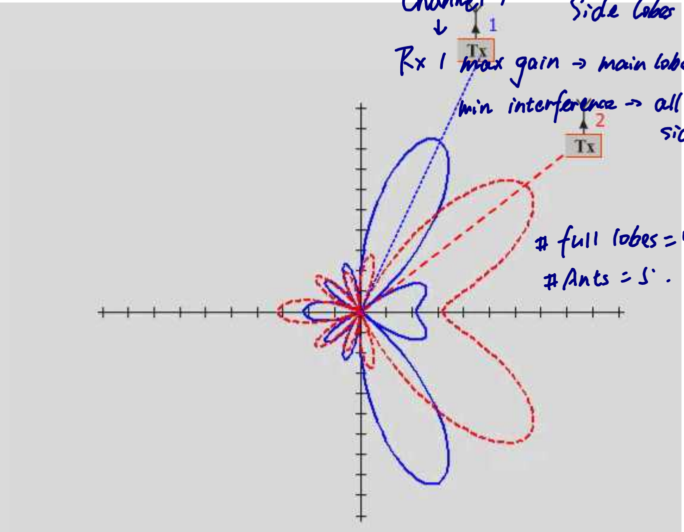
Multiple Access Interference Cancellation (ULA, N=5)



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

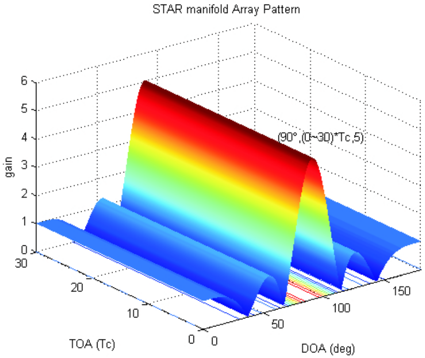
Main lobe → gain
Side lobes → interfer-ences.

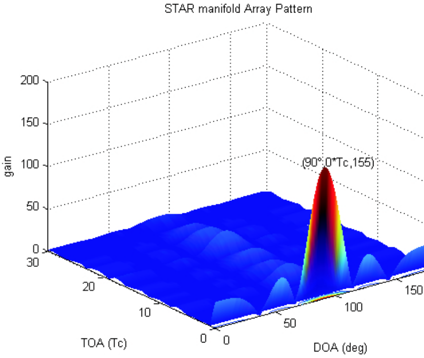
channel 1
↓
Rx 1 max gain → main lobe
min interference → all other channels side lobe = 0.



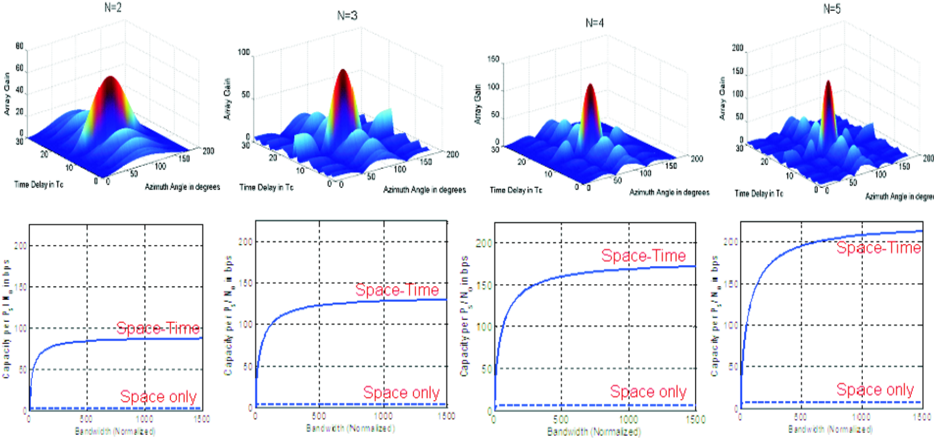
full lobes = 4
Ants = 5.

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** :

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

- **MIMO Capacity** :

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

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

$$\text{SISO} \quad : \quad \lim_{B\to\infty} C = 1.44\frac{P_s}{N_0 + N_J} \tag{5}$$

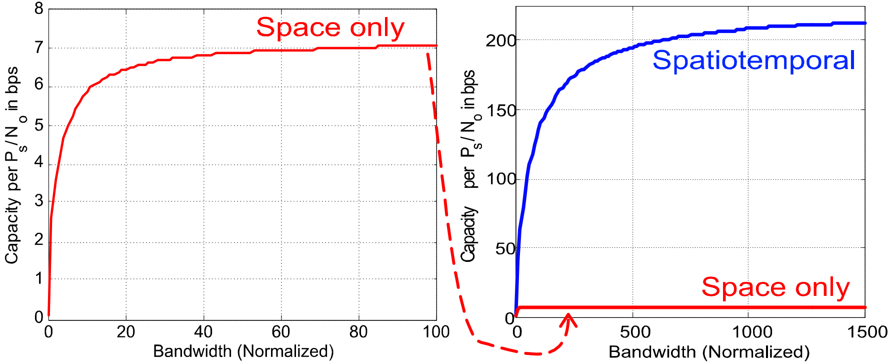
$$\text{space-only SIMO} \quad : \quad \lim_{B\to\infty} C = N \times 1.44\frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{6}$$

$$\text{spatiotemporal-SIMO} \quad : \quad \lim_{B\to\infty} C = N \times \underset{\substack{\| \\ 2N \cdot N_c}}{N_{SP}} \times 1.44\frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{7}$$

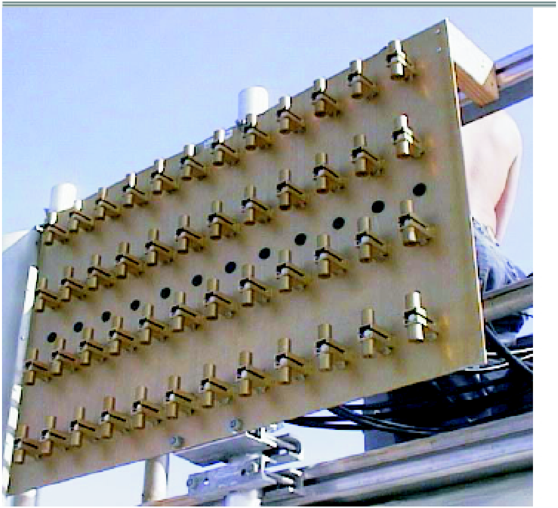
where N denotes the number of array elements (antennas)

Space and Spatiotemporal Capacity Curves

$N = 5$ antennas

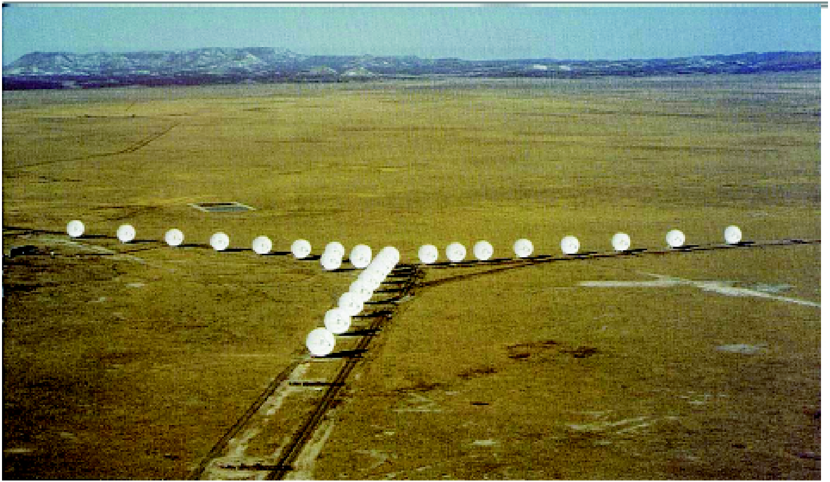


A 2GHz Antenna Array of 48 Elements



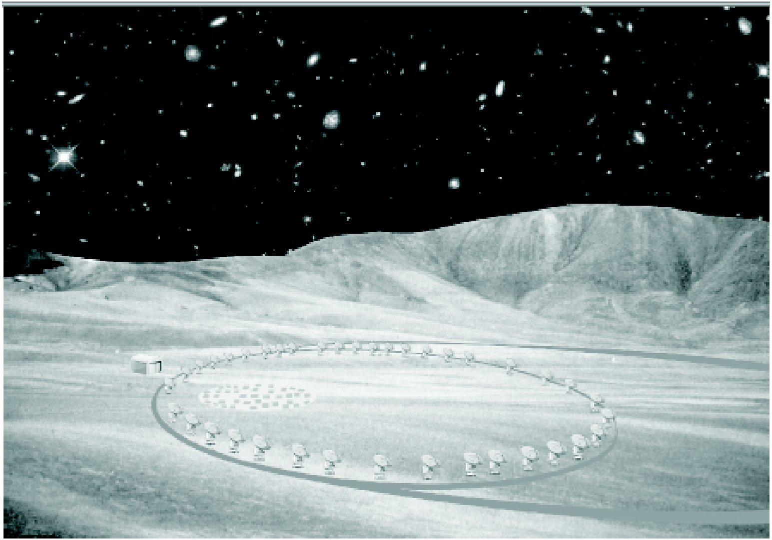
Owens Valley Radio Observatory Array

The New Mexico Very Large Array of 27 Elements



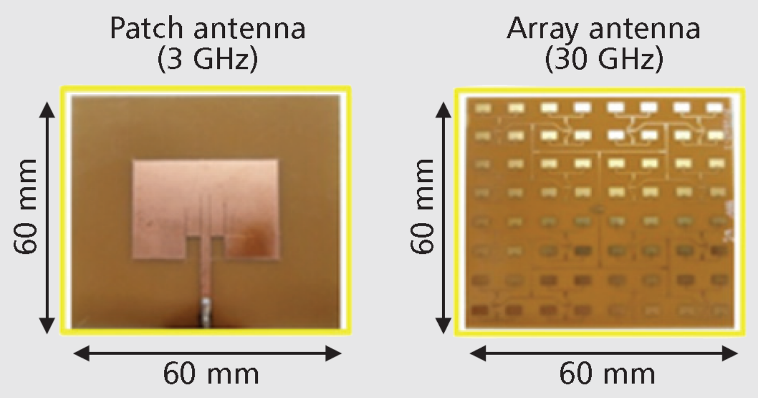
(along rail road tracks - 35km)

A Large Circular Array



Antenna Arrays for Modern Wireless Systems

Array - HF. diversity → larger capacity
- multiple elements → stability/reliability



Antenna Arrays for Modern Wireless Systems (cont.)