Advanced Topics In Wireless

A.k.a.
Future Communication + Information Systems

EURECOM
Sophia Antipolis
Fall 2024

New Overview Course – ATW(2) (Future of Communications)

- Advanced Techniques For Cellular Communications
- Quantum Communications and Computing
- Computing and Communications
- ML for Comm / AI in Networks
- Vehicular Communications / Control / Robotics / Drones
- <u>Several industry leaders present their perspectives</u>

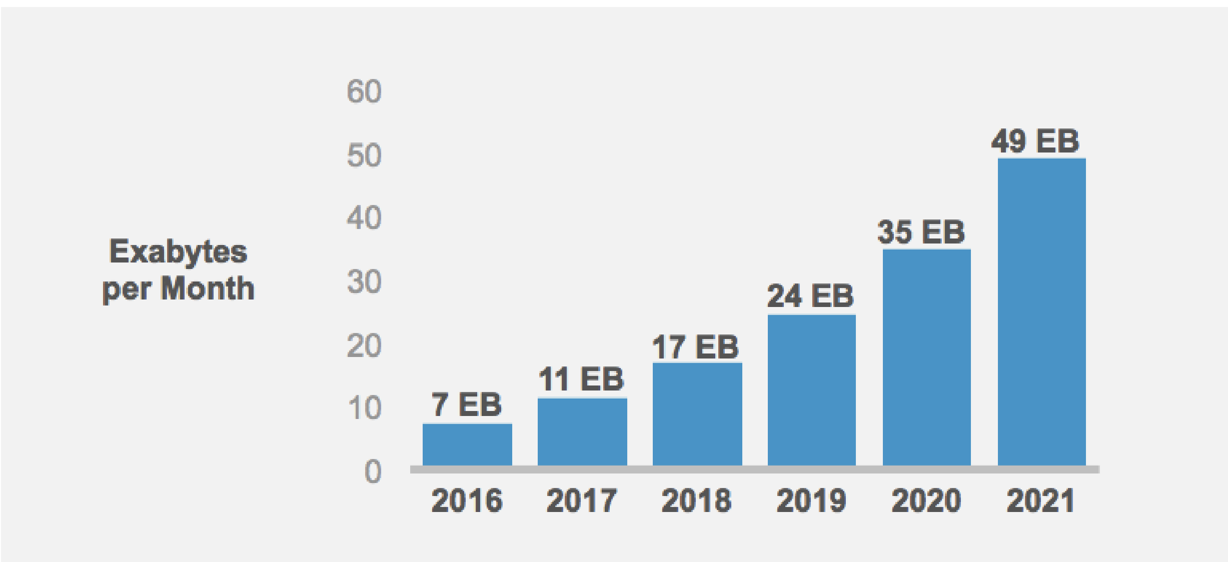
Heinrich Hertz (1857-1894)

"I do not think that the wireless waves I have discovered will have any practical application." **(H.R.Hertz)**

Mobile data storm

Global Mobile Data Traffic Growth / Top-Line

Global Mobile Data Traffic will Increase 7-Fold from 2016—2021



1EX=1+18 zeroes

5G node density:
2 millions per km2

Source: Cisco VNI Global Mobile Data Traffic Forecast, 2016–2021

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A technology perspective from 1G to 6G

1980	1992	2003	2011	2020	?
10kb/s	100kb/s	10Mb/s	100 Mb/s	1Gb/s	?
1G	2G	3G	4G	5G	6G

Analog voice

Low speed data

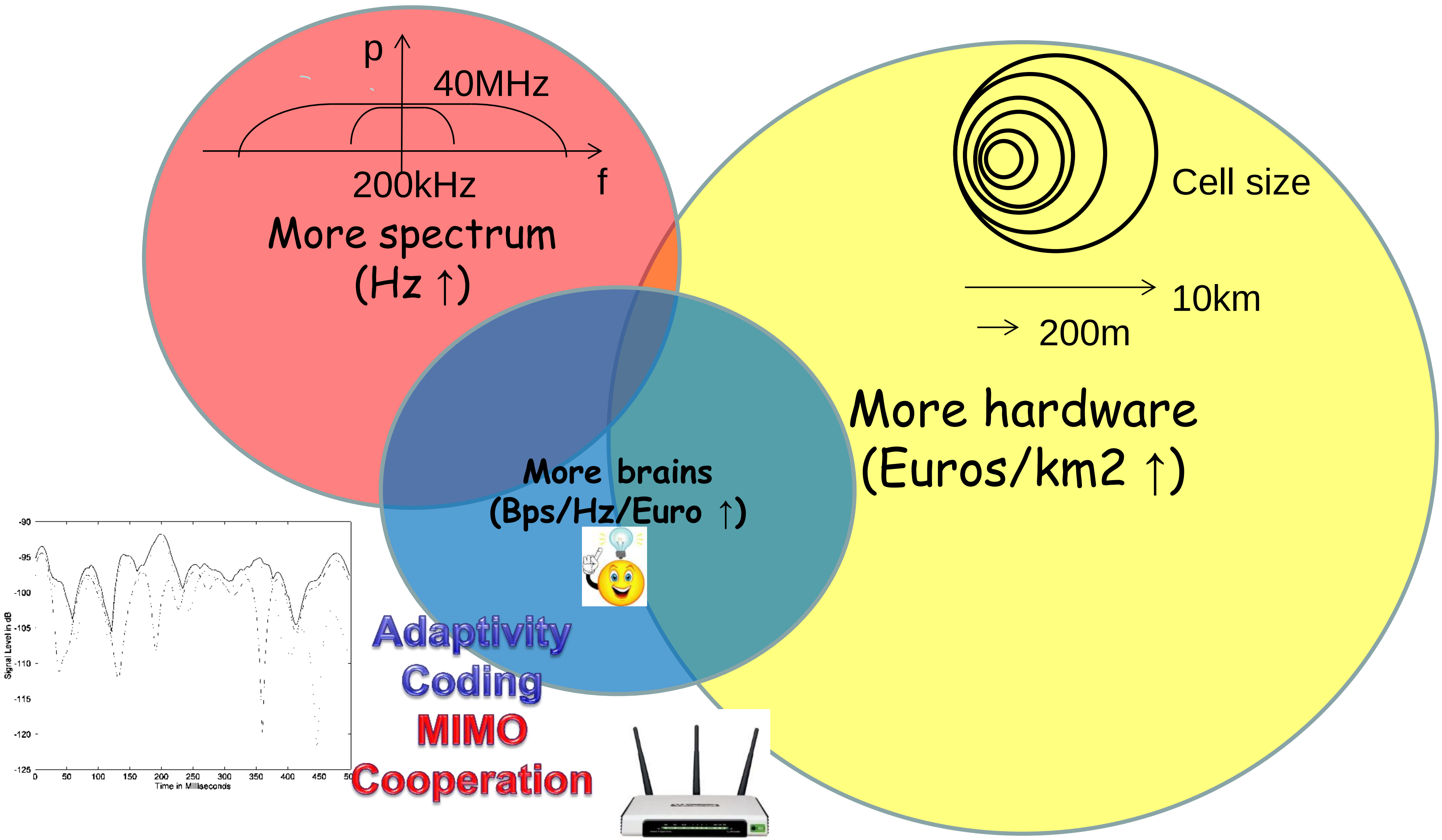
Digital voice
Digital signal processing

High speed data
OFDM
Smart Antennas

Mission critical services
New 5G enabling technologies

Holography, VR
Artificial intelligence
self-organized network
Open-source for radio
Tera-Herz

How did we gain a performance factor X100 000 ?



Some hot wireless design topics

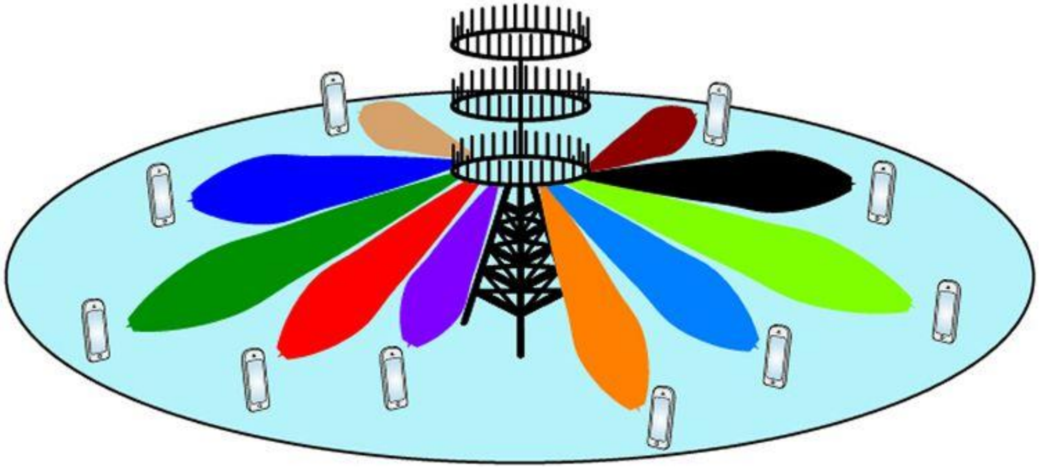
- Network softwarization and slicing
- Millimeter-wave communications
- X-MIMO (X=multiuser, network, massive, metasurface, etc.)
- New Radio interface for URLLC (ultra-reliable low latency)
- Open source (not a technology but an unstoppable trend)

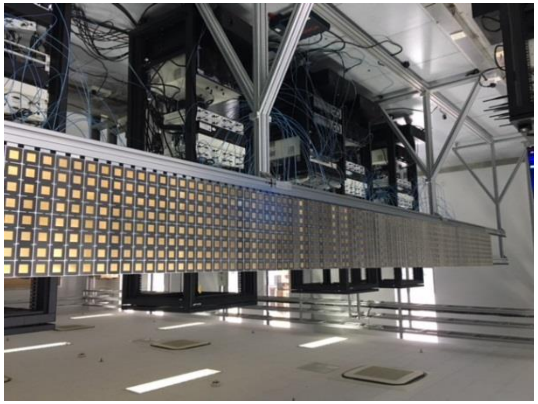
Hot New Areas

- Automotive Communications
- Quantum Communications and Computing
- AI for Comm --- Comm for AI
- AI - Control - Comm
- Advanced Distributed Computing

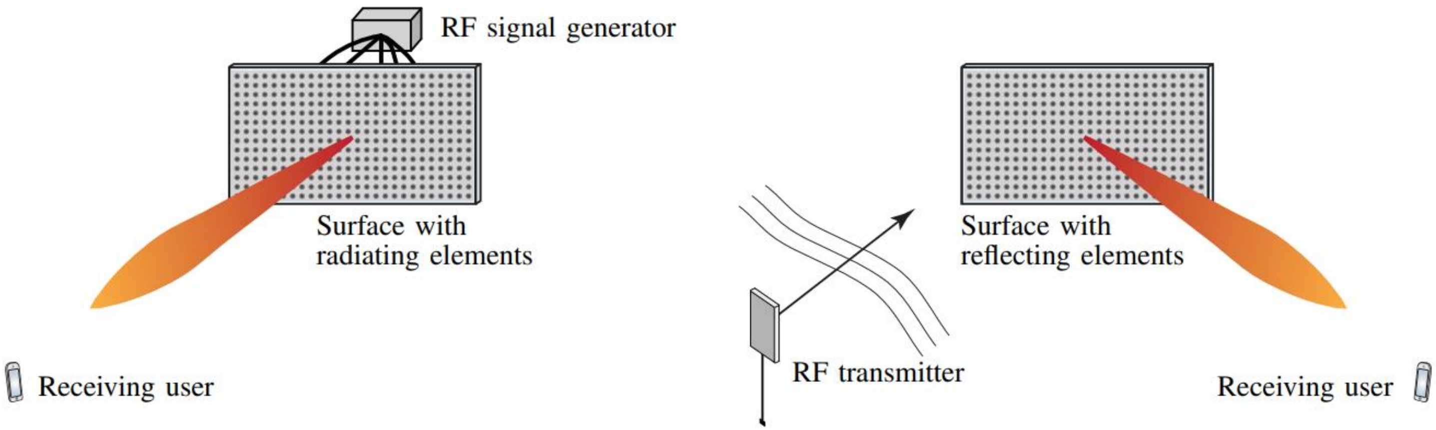
Massive MIMO for 5G (multiple-input multiple-output)

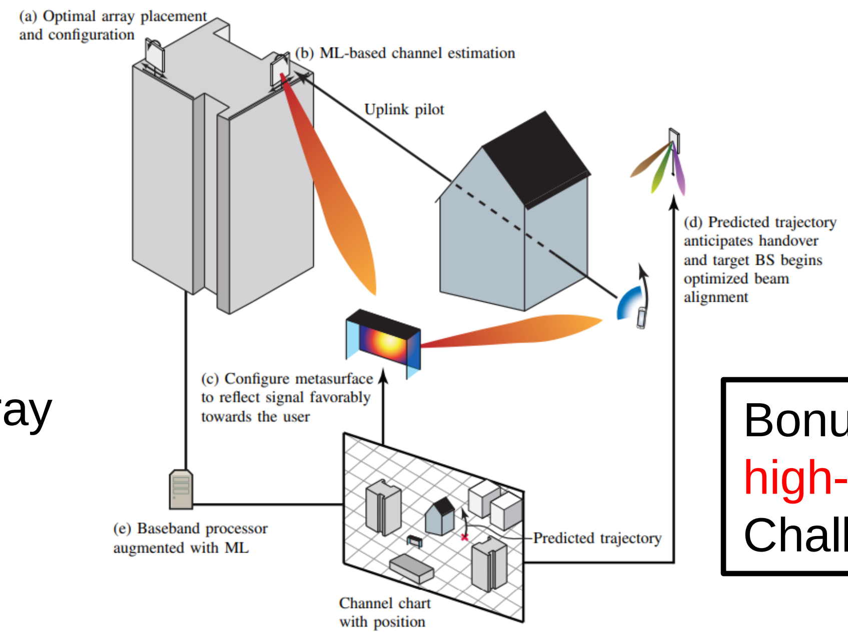
- Multi-element antenna panels (64,128 elements)
- Highly directive radio transmission
- Reduced interference
- Reduced transmission power
- Spatial multiplexing





Next MIMO revolution (for 6G): Ultra directivity via smart surfaces

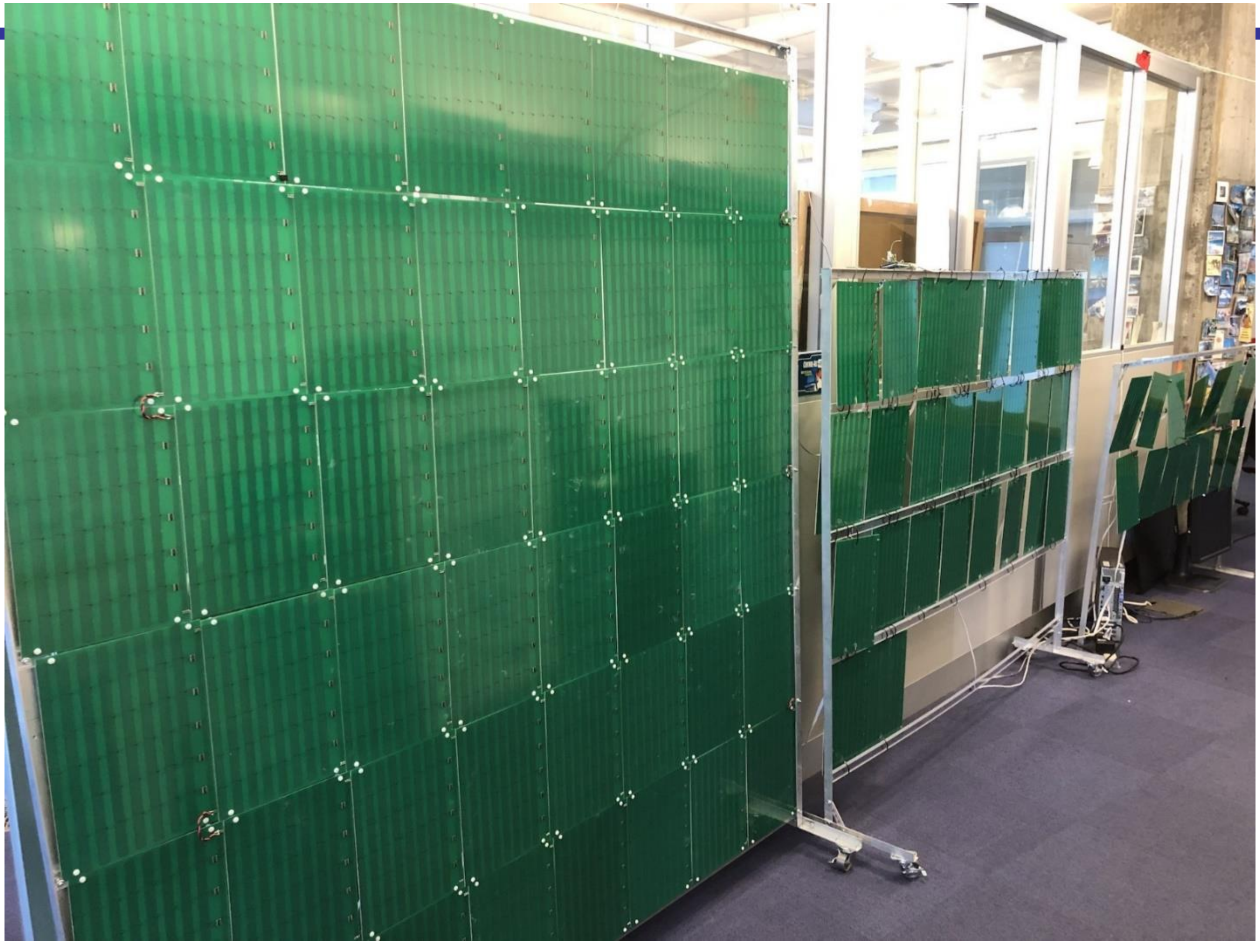




1 Full digital array
2 Phase shifter array
3 Switched reflector array
4 Meta material array

Bonus +++:
high-resolution positioning!
Challenge: (AI-driven) control

Ultra directivity via smart surfaces



6M2 surface
3.7K elements
Switched reflectors
2.5GHz
10-20x SNR gain (indoor)

[Arun et al (MIT), May 2019]

Why study Communications??

- **Telecommunications EXPONENTIAL GROWTH**:
  - A trillion dollar industry – with consistent growth!!
  - Seminal research objectives + Towering engineering challenges
  - Problems at the core of our lives
    - **Smart Cities**
    - **Sustainable Environment**
    - **Smart Roads**
    - **Health**
    - **Virtual Reality**

- **FINANCIALLY REWARDING – INDUSTRY IS WAITING FOR YOU:**
  - Wireless network architect: FT, Bouygues, SFR,..
  - Creating devices: Nokia, Ericsson, Alcatel, Motorola, Siemens…
  - Creating new wireless service software (games, positioning, interactive)
  - Advancing the theory of information: Research labs
  - Management and even … finance
  - Startups

- **EXTREMELY REWARDNG, INTERESTING, DIVERSE AND PLAYFUL**

NO LACK OF JOBS IN THIS AREA – UNCLE COMM WANTS YOU !!!

Additional telecommunication-related careers

AUTOMOTIVE

INFOCOM

TRANSPORT,
ENVIRONMENT &
POWER ENGINEERING

AERONAUTICS

SPACE

DEFENCE &
SECURITY

ATW Course Structure

- ~ Half academic lectures
- ~ Half experts from Industry
- In-class exercises
- 1 lab session (MATLAB based) and/or HW
- 1 Interactive session (paper presentations)
- 1hr Written Midterm exam
- 2hr Written exam (on academic part only)

Pre-requisites/advisable

- Digital Communications
- Statistical Signal Processing
- Probabilities and Stochastic Processes
- Networking

If you are unsure please meet me after class!

Wireless Basics

EURECOM, Dept. of Communication Systems

SophiaTech Campus, Sophia Antipolis, France

Fall 2024

Course Outline

- General introduction to the course
- Challenges of wireless network design
- Introduction to MIMO networks
- Introduction to MIMO networks and network-MIMO
- The degrees of freedom of wireless networks

General introduction to the course

- General information
- Supporting material for the course
- Some useful definitions
- Some useful acronyms

Quick math backgrounder

- Notations
- Orthogonality, special matrices
- Matrix rank
- Eigenvalue decomposition
- Singular value decomposition

Mathematical notations

- u: scalar
- $\mathbf{u}$: vector
- $\mathbf{U}$: Matrix
- $\mathbf{U}^T$: Transpose operator
- $\mathbf{U}^*$: Complex-conjugate operator
- $\mathbf{U}^H$: Transpose conjugate operator (i.e. $\mathbf{U}^H = \mathbf{U}^{*T}$
- $\mathbf{U}^{\#}$: Pseudo-inverse operator
- $E()$: Expectation operator
- $\mathbf{I}_N$: identity matrix of size $N \times N$
- $(x)^+$: x if x is positive, zero otherwise.

Orthogonality

Vector Orthogonality: Let $\mathbf{u} = [u_1, .., u_N]$ and $\mathbf{v} = [v_1, .., v_N]$ be complex vectors of size N. $\mathbf{u}$ and $\mathbf{v}$ are *orthogonal* iff:

$$\mathbf{u}^H \mathbf{v} = \sum_{i=1}^{N} u_i^* v_i = 0$$

Special matrices

Hermitian: Matrix $\mathbf{U}$ is *hermitian* iff

$$\mathbf{U} = \mathbf{U}^H$$

Unitary: Matrix $\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, .., \mathbf{u}_N]$ is *unitary* (or "orthogonal") iff

$$\mathbf{U}^H \mathbf{U} = \mathbf{I}_N$$

which means that vectors $\mathbf{u}_1, \mathbf{u}_2, .., \mathbf{u}_N$ are *unit norm* and orthogonal to each other.

Matrix rank

The rank r of matrix $\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, .., \mathbf{u}_K]$ of size $N \times K$ is defined by the dimension spanned by its columns $\mathbf{u}_1, \mathbf{u}_2, .., \mathbf{u}_K$ (or by its rows).

$$r = \mathrm{dimension}(\mathrm{span}(\mathbf{u}_1, \mathbf{u}_2, .., \mathbf{u}_K))$$

Therefore $r \leq \min(N, K)$.
If $r = \min(N, K)$ the matrix is said to be "full rank".
The matrix is left (resp. right) invertible iff it is full column (resp. row) rank .

Matrix eigenvalue-decomposition

Let the $N \times N$ matrix $\mathbf{A}$. The EVD of this matrix is the set of unit-norm eigenvectors $\mathbf{u}_1,..,\mathbf{u}_N$ and eigenvalues $\lambda_1,..,\lambda_N$ such that:

$$\mathbf{A}\mathbf{u}_i = \lambda_i \mathbf{u}_i$$

in other terms:

$$\mathbf{A} = [\mathbf{u}_1, .., \mathbf{u}_N] \begin{bmatrix} \lambda_1 & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \lambda_N \end{bmatrix} [\mathbf{u}_1, .., \mathbf{u}_N]^{-1}$$

i.e.:

$$\mathbf{A} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^{-1}$$

EVD of hermitian matrix

- Hermitian matrices are important. All covariance matrices, of the type $E(\mathbf{x}\mathbf{x}^H)$, are hermitian.
- The eigenvalues of complex hermitian matrices are positive real. The eigenvectors are orthogonal.

$$\mathbf{A} = \mathbf{A}^H$$

Then:

$$\mathbf{A} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H$$

with $\lambda_i \geq 0$ and $\mathbf{U}^H\mathbf{U} = \mathbf{I}_N$

Singular value decomposition

Let the $N \times K$ matrix $\mathbf{A}$. The SVD of this matrix is given by:

$$\mathbf{A} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H$$

where

- $\mathbf{U} = [\mathbf{u}_1,..,\mathbf{u}_N]$ is the $N \times N$, unitary matrix, containing the *left singular vectors*
- $\mathbf{V} = [\mathbf{v}_1,..,\mathbf{v}_K]$ is the $K \times K$, unitary matrix, containing the *right singular vectors*
- $\boldsymbol{\Sigma}$ is the $N \times K$ matrix containing the *singular values*. Example for $N \geq K$:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \sigma_K \\ \mathbf{0} & & \mathbf{0} \end{bmatrix}$$

SVD versus EVD

Let the $N \times K$ matrix $\mathbf{A}$. The SVD relates to the EVD by the relation:

$$\mathbf{A}\mathbf{A}^H = \mathbf{U}\boldsymbol{\Sigma}^2\mathbf{U}^H$$

and

$$\mathbf{A}^H\mathbf{A} = \mathbf{V}\boldsymbol{\Sigma}^2\mathbf{V}^H$$

The left singular vectors of $\mathbf{A}$ are the eigen-vectors of hermitian matrix $\mathbf{A}\mathbf{A}^H$. The right singular vectors of $\mathbf{A}$ are the eigen-vectors of hermitian matrix $\mathbf{A}^H\mathbf{A}$.
Finally $|\sigma_i| = \sqrt{(\lambda_i(\mathbf{A}^H\mathbf{A}))} = \sqrt{(\lambda_i(\mathbf{A}\mathbf{A}^H))}$.

Challenges of wireless network design

- Metrics for wireless performance
- Challenges of the wireless channel
- State-of-the-art solutions

Metrics for wireless performance

Key metrics

- Rates (Bits/Sec)
- Range (kms), under a target rate constraint
- Mobility support (km/h), under a target rate constraint
- Latency (ms), under a target rate constraint

Perspective on Wireless Performance

- Coverage in km (matters most in early deployment stages)
- spectral efficiency in Bit/Sec/Hz/Cell (mature deployments):

$$SE = \frac{rM}{K} \quad (1)$$

M =average modulation order (bits/symbol), r = code rate (1/2, 3/4, ..), K = Frequency reuse or

$$SE = \frac{R}{KB} \quad (2)$$

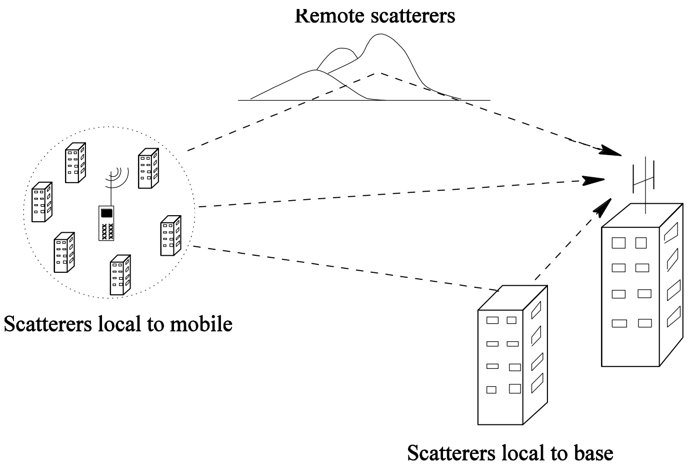
R =average user rate (Bits/sec) B = bandwidth

Challenges of the wireless channel

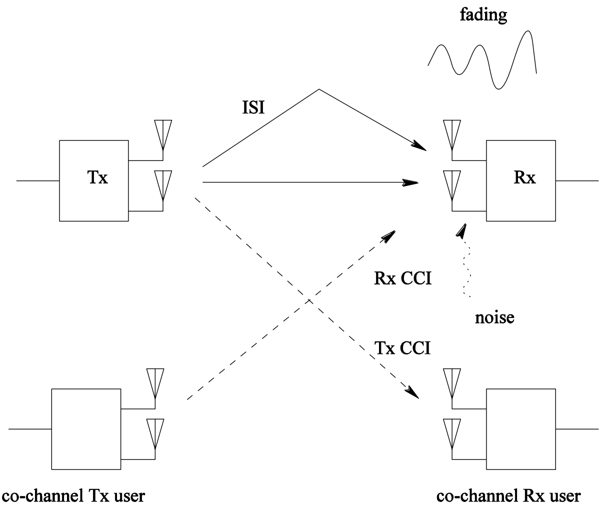
Wireless transmission introduces:

- Fading: multiple paths with different phases add up at the receiver, giving a random (Rayleigh/Ricean) amplitude signal.
- ISI: multiple paths come with various delays, causing intersymbol interference.
- CCI: Co-channel users create interference to the target user
- Noise: electronics suffer from thermal noise, limiting the SNR.
- Doppler: The channel varies over time, needs to be tracked.

Multipath Propagation



MIMO link diagram



Some solutions

Tricking the wireless channel to improve performance

- Advanced coding and filtering (turbo)
- Hybrid retransmission protocols
- Fast link adaptation
- multi-antenna (MIMO) techniques
- multi-user
  - filtering
  - scheduling
  - inter-cell coordination (for interference control)
  - cooperation

Introduction to MIMO

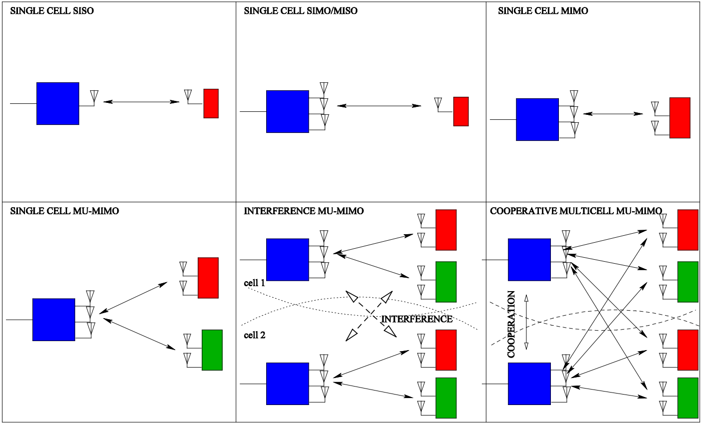
Using the space dimension (i.e. space-time processing)

- MIMO is multiple inputs multiple outputs
- Using antenna arrays permits to process radio signals in space, not only time.

...to improve performance in presence of fading/interference

- coverage
- quality (BER, MOS, outage)
- capacity: Bit/sec/Hz/BTS or # users/Hz/BTS
- peak data rates: Bit/sec

MIMO Configurations



We first focus on the single-user scenario:

- Multiple antennas at receive side
- Multiple antennas at transmit side (without feedback)
- Joint transmit-receive side without channel feedback
- Joint transmit-receive side with channel feedback

MIMO link diagram (single user)