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Fundamentals of Wireless Networks

The Why's and the How's

David Lopez-Perez

Painless Summer School

Nicosia, Cyprus

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This presentation only includes Bell Labs research ideas/work and there is no commitment by the business divisions of Nokia to support them. The views expressed in this tutorial are solely the authors' and do not necessarily reflect those of Nokia or the European Union.

Why?

Outline: Fundamentals of Wireless Networks

- The past and the present and the future issues
- Industry 4.0
- Capacity scaling
- Energy efficiency
- Low-latency and reliability challenges

The speaker

David Lopez-Perez

NOKIA Bell Labs

Background

- Distinguished Member of Technical Staff at Nokia Bell Labs (2012-present)
- PostDoc at King's College London, UK (2011-2012)
- Marie Curried PhD from University of Bedfordshire, UK (2011)

Current research

- Future indoor networks and next generation Wi-Fi

About me

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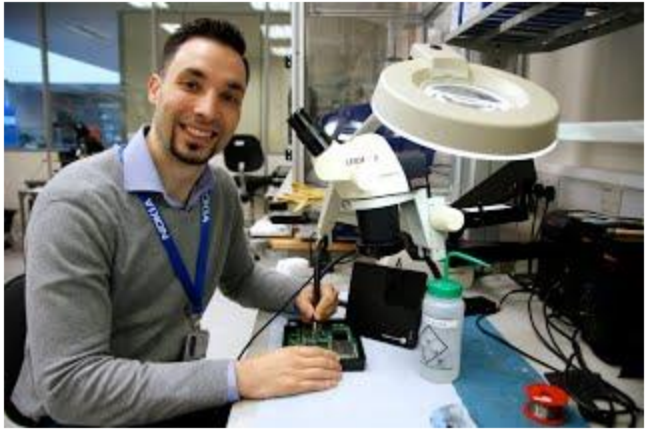

Research Interest

- Wireless networks and standards
- New technology features
- Performance analysis
- Optimization

KPIs

- >150 publications
- > 6500 citations
- > h-index=33
- >50 filed patents

Acknowledgments

Collaborators:

- Adrian Garcia and Lorenzo Galati Giordano (Nokia Bell Labs, Ireland)
- Giovanni Geraci (Universitat Pompeu Fabra, Spain)

Acknowledgments

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The past and the present and the future issues

Wireless Networks Has Transforming the World

Social Impact

- Communication networks have changed the world we are living in
  - Interactions between people and between people and digital content
  - Medical and health assistance
  - Education, work and entertainment activities

Economic Impact

- Wireless communication have also enabled new business forms
  - More efficient agriculture & manufacturing, innovative e-commerce, new vertical markets
  - The global economic value of Wi-Fi, alone, is estimated to be $1.96 trillion today, and expected to grow to $3.47 trillion by 2013 [1]

[1] Telecom Advisory Services, LLC, “The Economic Value of Wi-Fi: A Global View (2018 and 2023),” Aug. 2018.

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Communication While Outdoors

Cellular networks provided for the first time the capability to communicate while **outdoors** and **on the move**

- GSM was deployed in 1991 and targeted to voice services
- UMTS and LTE expanded service offering to data
- Broadband speeds of up to 100Mbps [LTE]

[2] H. Holma, et. al. , “WCDMA for UMTS: Radio Access for Third Generation Mobile Communications,” Wiley, Apr. 2000.

[3] S. Sesia, et. al. , “LTE – The UMTS Long Term Evolution: From Theory to Practice,” Wiley, Jul. 2011.

Communication While at High Speed

Communicating while moving at **high velocities** was—and still is—the main cellular network differentiator

- Most people uses UMTS/LTE while on cars, buses or trains
- Mobile velocities of up to 500km/h [LTE]

Communication While at Home

Wi-Fi—and not cellular—is the king **indoors**

- Free unlicensed spectrum
- No need to involve mobile operators to manage and operate indoor private networks
- Wi-Fi devices are widely diffused, 13 Billions installed
- Broadband speeds of up to 14Gbps [Wi-Fi 6]

[4] D. B. Perahia, et. al. , “Next Generation Wireless LANs,” Cambridge University Press, Jan. 2014.

Decoupling of Network Traffic and Generated Revenue

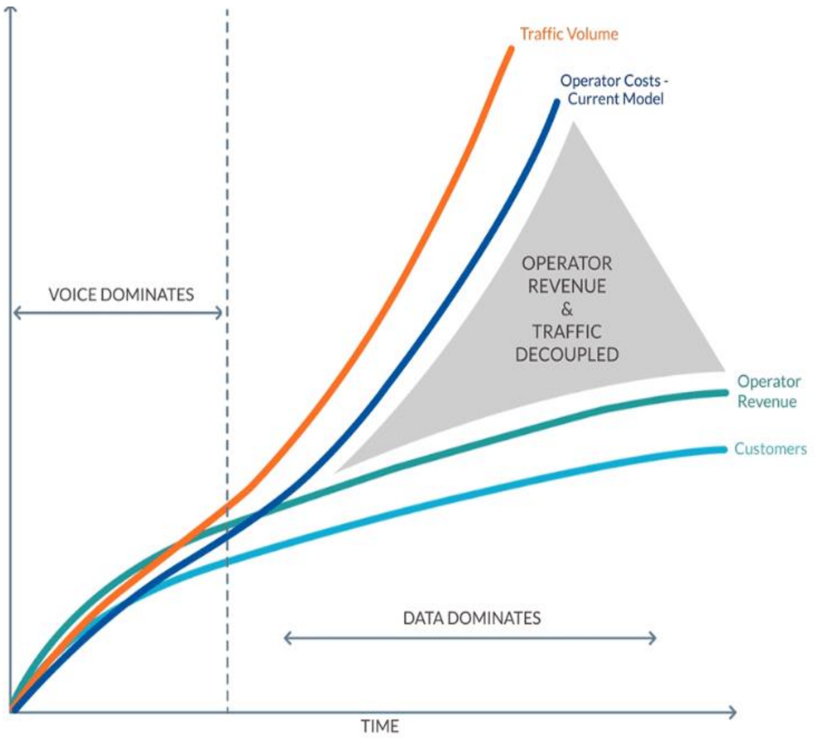
The good news

- Traffic volume keeps increasing in an exponential manner
  - More devices per person
  - More demanding applications

The bad news

- Generated revenue is flatting
  - Lower or same-order subscription fees per person
  - More and more expensive networks

Business is not looking great



Source: Accenture Research

The Issue of the Energy Consumption

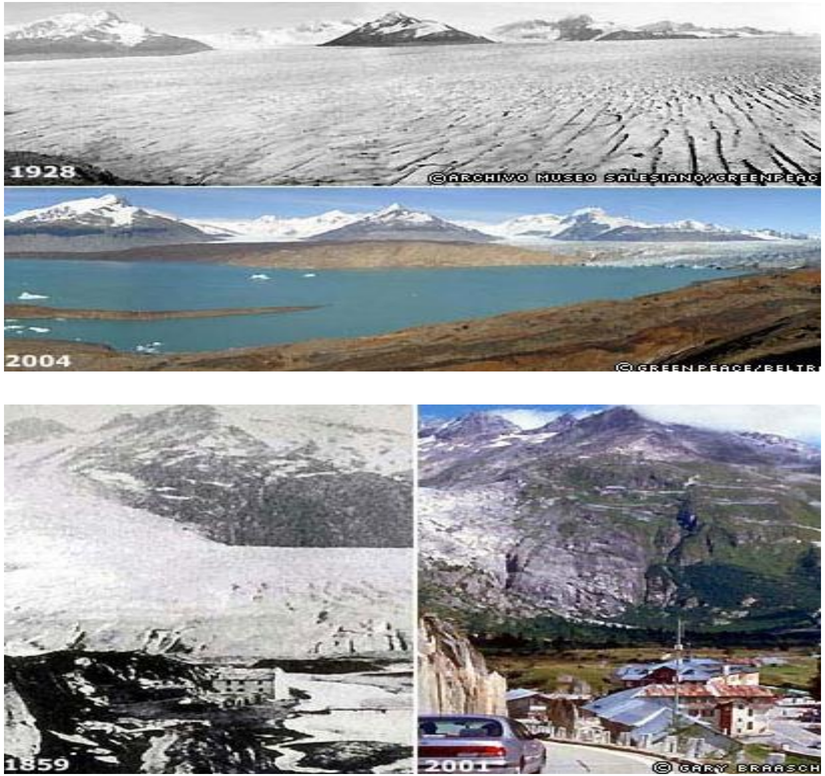
Energy consumption facts

- Telecommunication equipment is a large consumer of energy
  - Telecom Italia uses 1% of Italy's total energy
  - NTT uses 0.7% of Japan's total energy

Can't do more of the same

- Upcoming denser deployments will further increase energy needs
  - 50M small cells x 12W = 600 MW = 5.2 TWh/a
    - Nuclear Reactor Sizewell B, Suffolk, UK: 1195MW
    - Annual UK energy production: ~400 TWh/a

Need for much greener networks



Source: BBC News - How the world is changing

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Industry 4.0

The new opportunity for business

Megatrends Are Changing The World

Network, compute & storage

Broadband every-where, distributed cloud, near infinite storage

Internet of Things

Connectivity for a trillion things

Augmented intelligence

Human assistance and task automation at machine scale

Human & machine interaction

Virtual and augment-ed reality, reshaping how we interact with machines

Social & trust economics

Sharing economy and digital currencies making trust and security essential

Digitalization & ecosystems

Digitalization of operations expand-ing into consumer and biology

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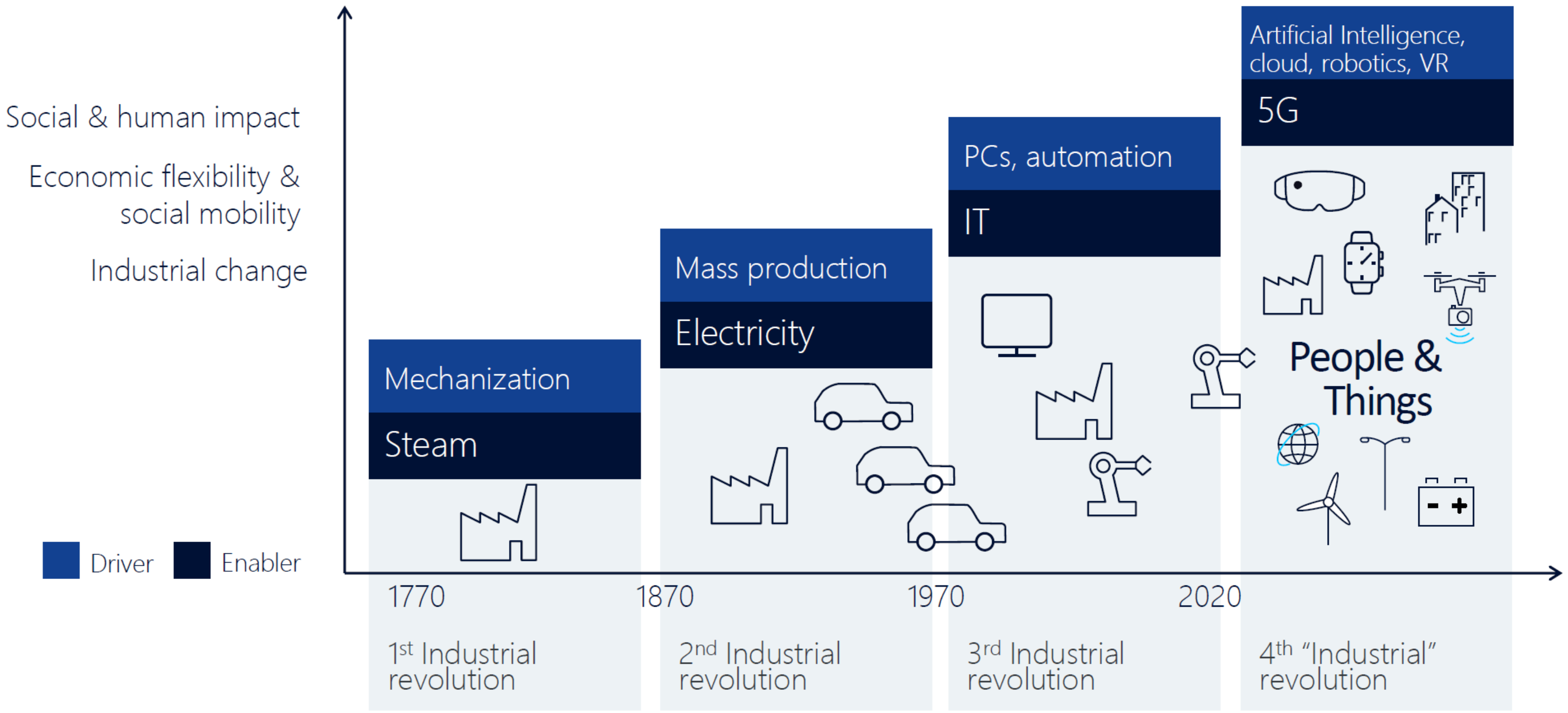
Megatrends Are Leading to The Fourth Industrial Revolution



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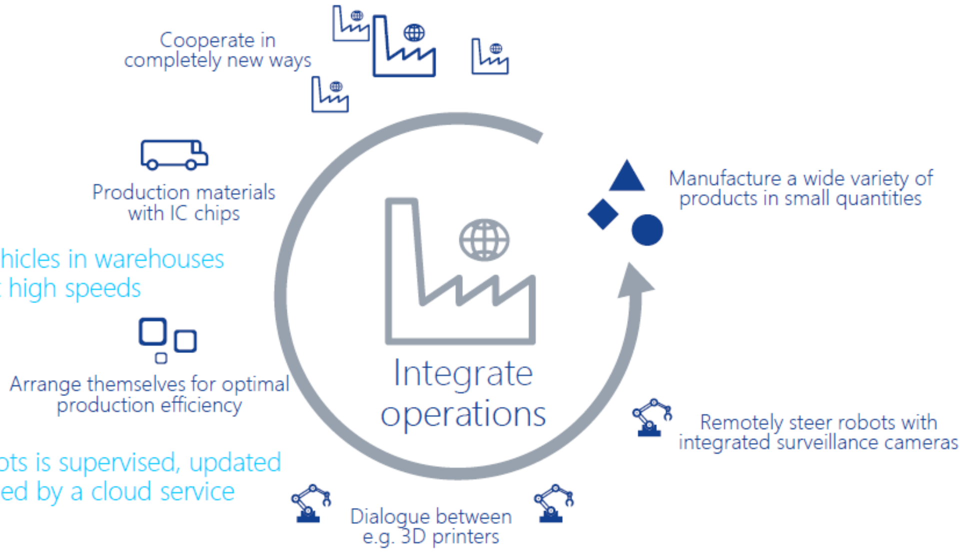
Example of Future 4.0 Factory



Autonomous vehicles in warehouses move around at high speeds

Fleet of robots is supervised, updated and controlled by a cloud service

50% Improvement of manufacturing productivity in 10 years

0 Zero-inventory production system; Minimized labor and energy costs

"4th industrial revolution: Creating an artificially intelligent production system – drastically increase industrial competitiveness"

Nikkei Asian Review

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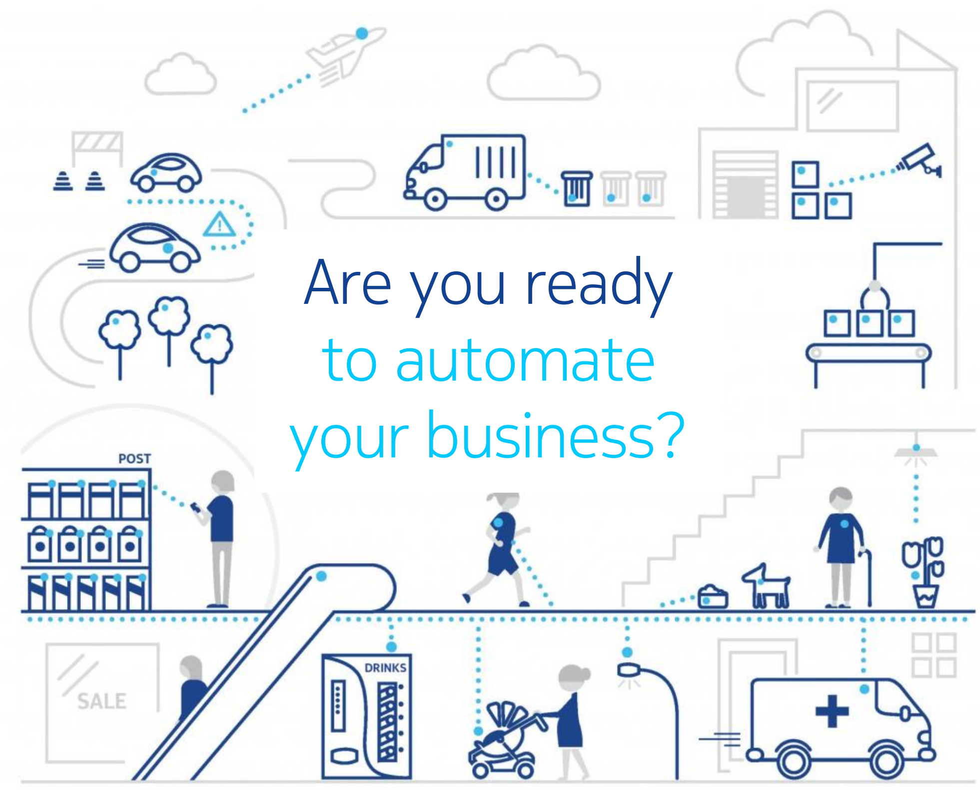
Automation: The Enabler of Industry 4.0



Future networks must support the wireless connectivity needed to fuel smart businesses, and

- Increase productivity, and flexibility of production
- Deliver personalised products
- Decrease costs
- Operate more safely and sustainably

Autonomous machinery and remote control will play a key role

Industry 4.0 Communication Requirements

High Reliability

Communication service availability >99.999%

Ultra-low latency

End-to-end transmission latency < 1ms

High capacity

Average link capacity >1Gbps

Human aware

Intelligently adapt and customize access to each individual

Seamless integration

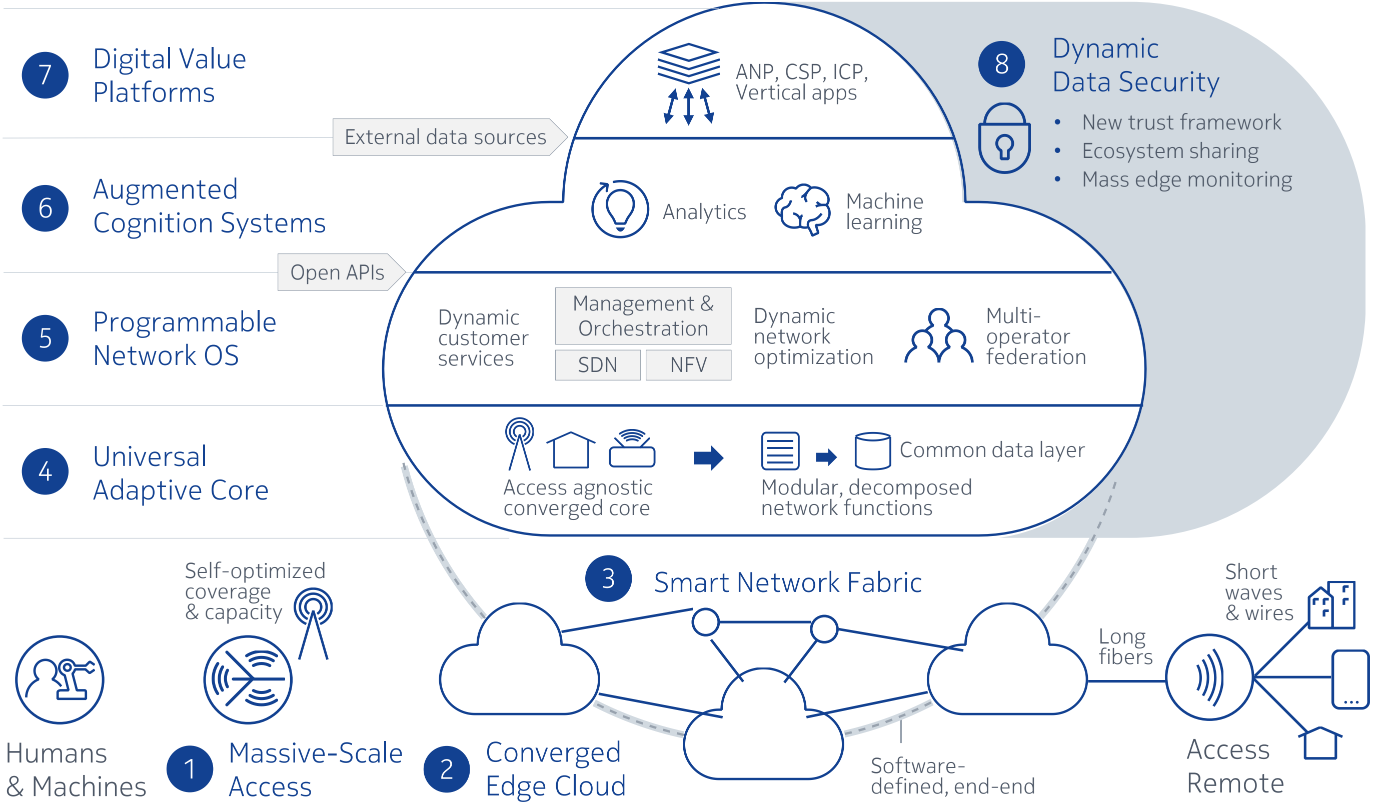
Seamless interplay with current industry solutions

Safety & Security

No compromises, tailored/optimized solutions

Bell Labs Future X Network

Bell Labs Future X Network provides a clear vision of how networks need to evolve



[1] M. K. Weldon, et. al. , "The Future X Network: A Bell Labs Perspective," CRC-Press, Feb. 2016.

Capacity scaling

System model

Capacity definition

Signal quality calculation

Capacity computation

Capacity Definition

Shannon-Hartley Theorem

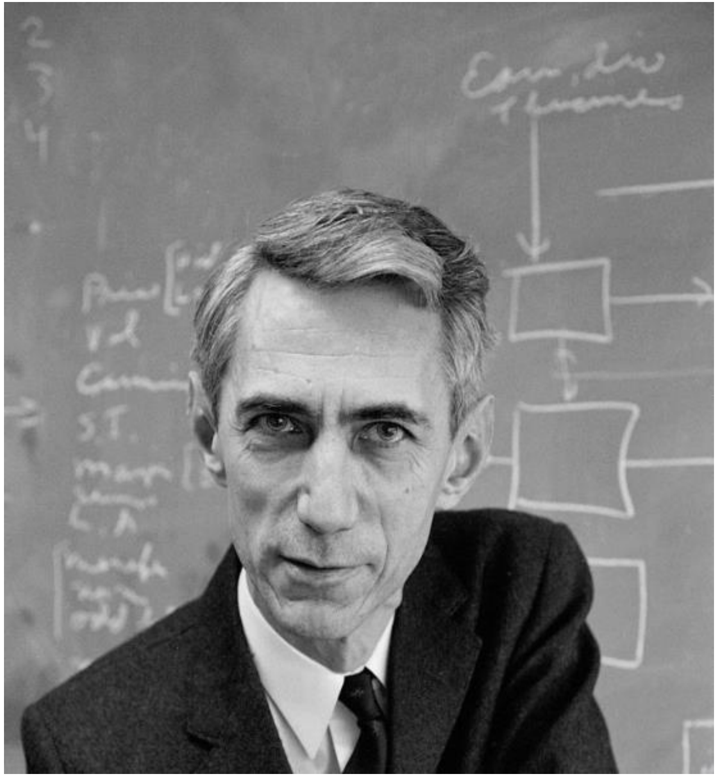
- The Shannon–Hartley theorem states the capacity—the theoretical tightest upper bound on the information rate—of data that can be communicated at an arbitrarily low error rate

$$C = B\log_2\left(1 + \frac{S}{I+N}\right)$$

→ SINR

  - C [bps] := capacity
  - B [Hz] := bandwidth
  - S [w] := signal power
  - I + N [w] := interference plus noise power
    - Both interference plus noise must be Gaussian

[1] C. E. Shannon (1998) [1949]. The Mathematical Theory of Communication. Urbana, IL: University of Illinois Press.



Claude Shannon, father of information theory

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How Do We Compute SINR, $\frac{S}{I+N}$, and thus Capacity?

- Received signal (interference) strength

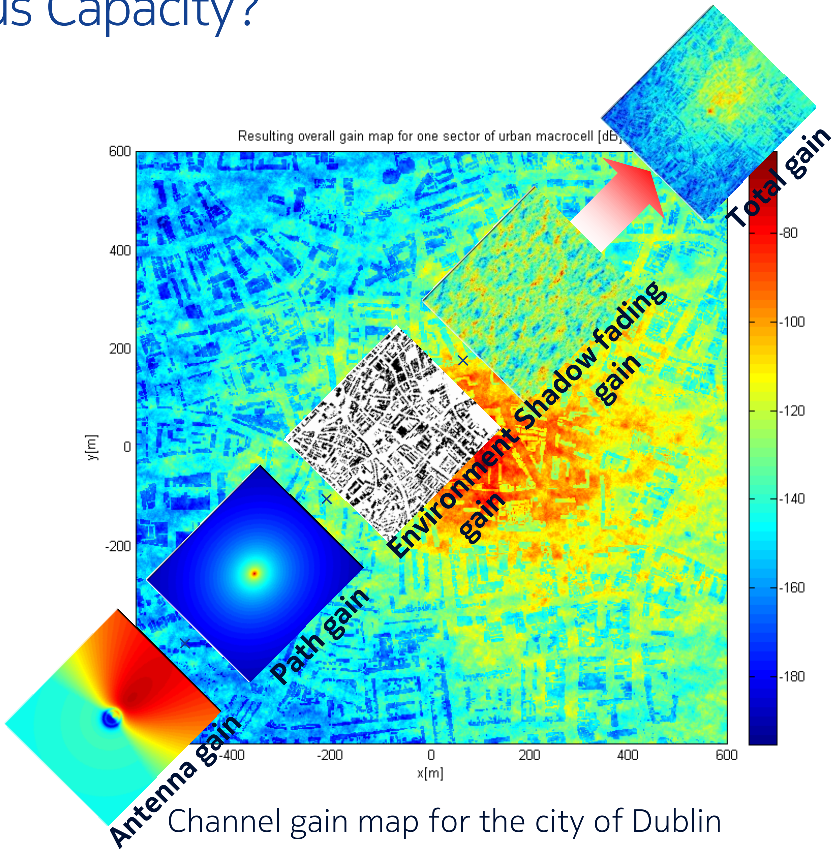
  $$S\,[\mathrm{dBm}]\ (I\,[\mathrm{dBm}]) = P_T + G_A + G_P + G_E + G_S + G_M$$

  - P_T [dBm] = transmit power
  - G_A [dB] = antenna gain
  - G_P [dB] = path gain (loss)
  - G_E [dB] = environmental gain
  - G_S [dB] = shadow fading gain
  - G_M [dB] = Multi-path fading gain

- Additive white Gaussian noise (AWGN)

  $$N\,[\mathrm{dBm}] = -174[\mathrm{dBm/Hz}] \cdot B_T - NF_R$$

  - B_T [Hz] = transmit bandwidth
  - NF_R [dB] = receiver noise figure



Channel gain map for the city of Dublin

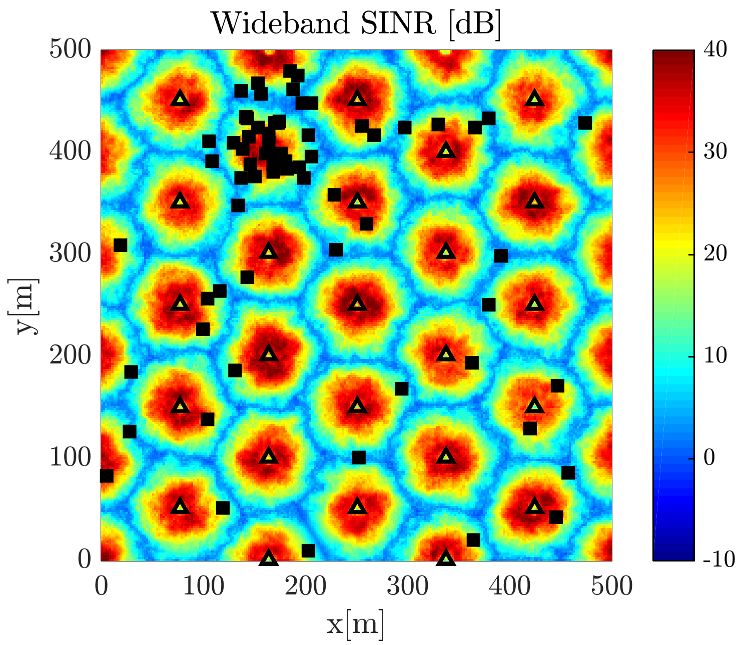
Simulation-based Capacity Analysis

Characteristic

- Very accurate but generally complex and time consuming

System-level simulation framework

- Scenario with
  - Base station deployment, e.g. hexagonal
  - User deployment, e.g. random
- Antenna model for
  - Base station, e.g. directional antenna(s)
  - User, e.g. omnidirectional antenna(s)
- Channel model
  - Path gain, e.g. free space
  - Shadowing, e.g. lognormal
  - Multi-path fading, e.g. Rayleigh
- Environment model
  - Building model, e.g. deterministic map
  - Vegetation, e.g. statically



Example of an outdoor hexagonal small cell BS deployment with a non-uniform UE distribution (100m ISD)

[2] H. Claussen, et. al., "Small Cell Networks: Deployment, Management, and Optimization," Wiley/IEEE Press, Nov. 2017.

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Simulation-based Capacity Analysis

Characteristic

- More tractable and intuitive but less accurate

Stochastic geometry as framework

- Probability of coverage (the CCDF of SINR)

$$p^{\text{cov}}(\lambda, \gamma) = \Pr[\text{SINR} > \gamma]$$

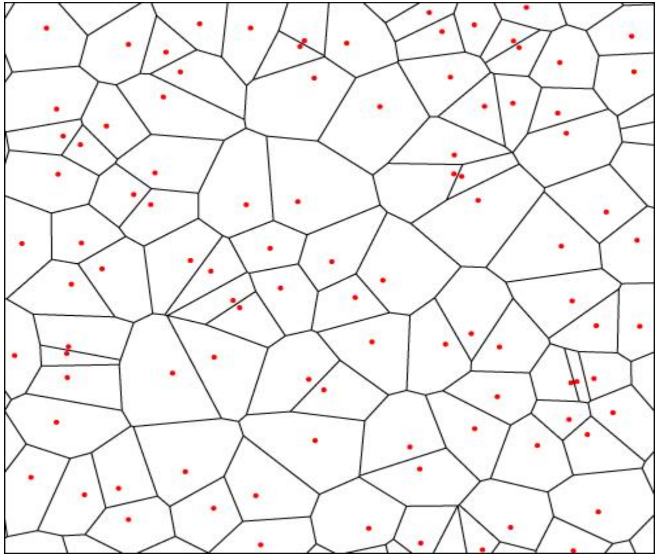
  - λ is the Poisson point process density
  - γ is the SINR threshold that defines the coverage

- Area spectral efficiency [bit/s/Km^2]

$$A^{\text{ASE}}(\lambda, \gamma_0) = \lambda \int_{\gamma_0}^{\infty} \log_2(1+x) f_X(\lambda, x)\, dx$$

  - $f_X(\lambda, x) = \dfrac{\partial\left(1 - p^{\text{cov}}(\lambda, x)\right)}{\partial x}$
  - γ_0 is the minimum working SINR

Note that practical SINR-dependent ASE—different that the standard model presented in [3]



Example of an outdoor spatial Poisson point process BS deployment

[3] J. G. Andrews, et. al. , "A tractable approach to coverage and rate in cellular networks," IEEE Trans. Commun., vol. 59, no. 11, pp. 3122–3134, Nov. 2011.

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How do we enhance capacity?

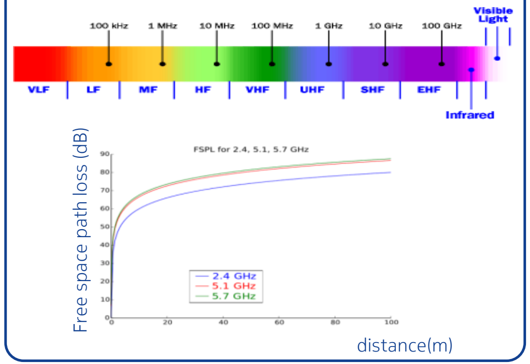
The triangle of truth

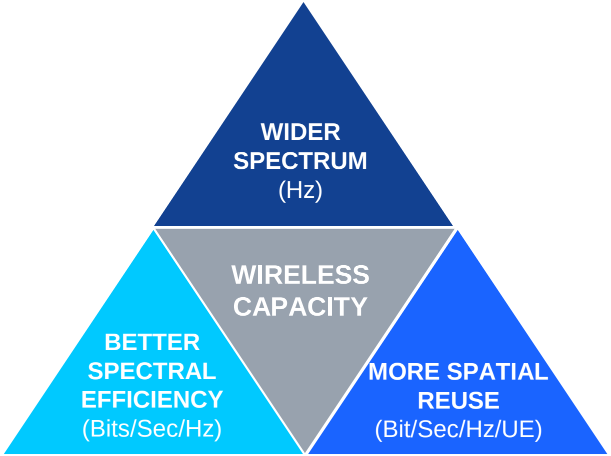
- More cells
- More bandwidth
- More antennas

Approaches to enhance wireless capacity

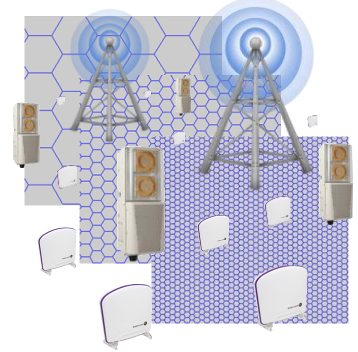
More cells, more bandwidth, more antennas

Higher carrier frequencies

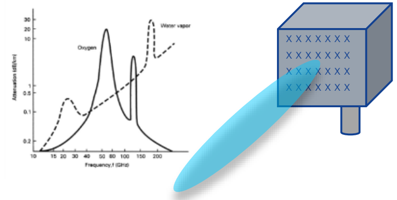




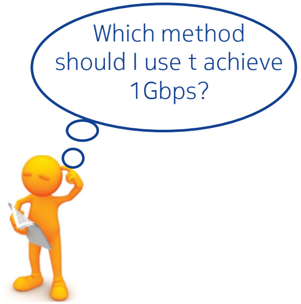
Network densification



Larger antenna arrays



All these approaches have limitations, and cannot be infinitively abused



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How can we achieve a significant capacity growth?

Wireless Capacity Gains 1950-2000

- 10x by improving spectral efficiency (coding, MAC and modulation methods)
- 15x by using more spectrum (3 GHz vs 150 Mhz)
- 2700x from smaller cells

Total gain 1 million fold

Source: William Webb, Ofcom.

Can always further increase spatial efficiency by reducing cell size?

US Army Communications Control Center, Pentagon, 1950

AT&T Global Operations Center, 2012

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Industry is already going down this path

Light radio

It is all about having the right targets and developing the right products

Significant efforts in reducing cost, volume and energy consumption of base stations

PAINLESS

Network Densification

Myths about densification

Stronger interference power

Bounded carrier signal power

More base stations than active users

- One user per cell – the limit of spatial re-use

Myths about densification – Lot's of misunderstanding

User signal quality independent of base station (BS) density

[1] J. G. Andrews, F. Baccelli, and R. K. Ganti, "*A tractable approach to coverage and rate in cellular networks*," IEEE Trans. Commun., vol. 59, no. 11, pp. 3122–3134, Nov. 2011.

Prob. of coverage independent of BS density and # tiers

[2] H. Dhillon, R. Ganti, F. Baccelli, and J. Andrews, "*Modeling and Analysis of K-Tier Downlink Heterogeneous Cellular Networks*," IEEE J. Sel. Areas Commun., vol. 30, no. 3, pp. 550–560, April 2012.

and many others

Network capacity linear with BS density and # tiers

[3] M. Haenggi, *Stochastic Geometry for Wireless Networks*. Cambridge University Press, 2012.

[4] S. Mukherjee, *Analytical Modeling of Heterogeneous Cellular Networks*, Cambridge University Press, 2013.

in interference power. This matches empirical observations in interference-limited urban networks as well as predictions

MYTHS

Lessons learned from macrocell only networks do not always apply to dense small cell networks

Dense small cell networks are different:

- Stronger interference power
- Bounded carrier signal power
- More base stations than active users
- Less active users per base station
- Bustier traffic in downlink and uplink

[4] D. Lopez-Perez, M. Ding, H. Claussen, A. Jafari, "Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments," IEEE Comm. Surveys & Tutorial, 2015.

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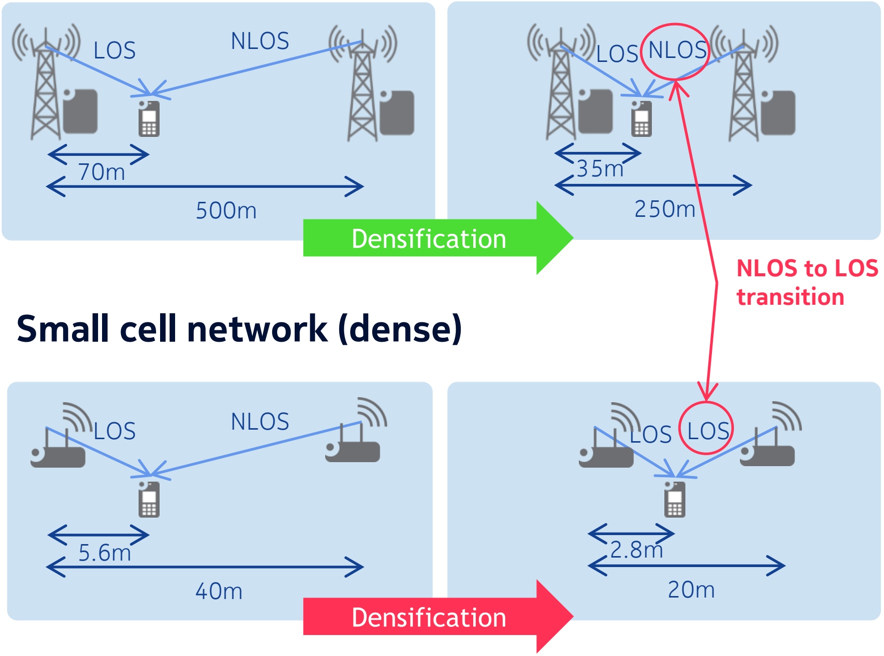
Stronger interference power

Non-line-of-sight (NLOS) to line-of-sight (LOS) transition

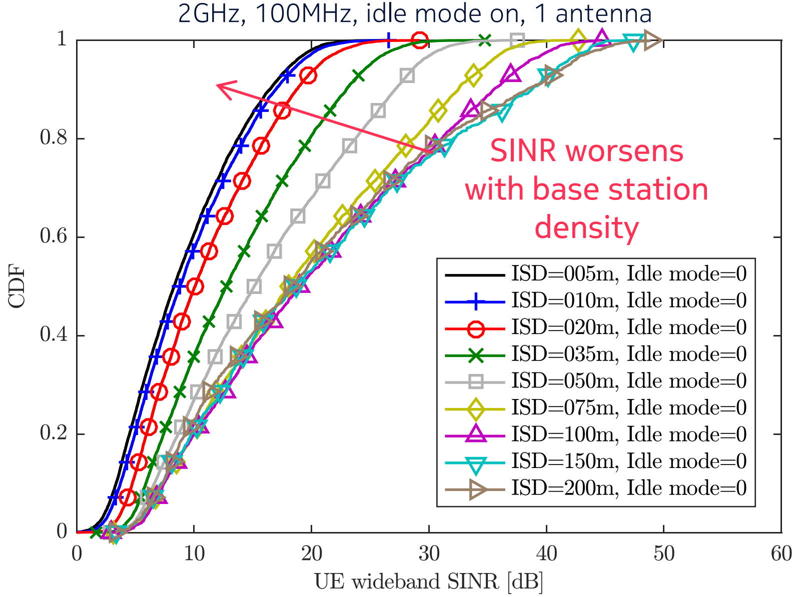
Macrocell network (sparse)

Small cell network (dense)



Signal to interference plus noise ratio (SINR)

ISD = inter-site distance



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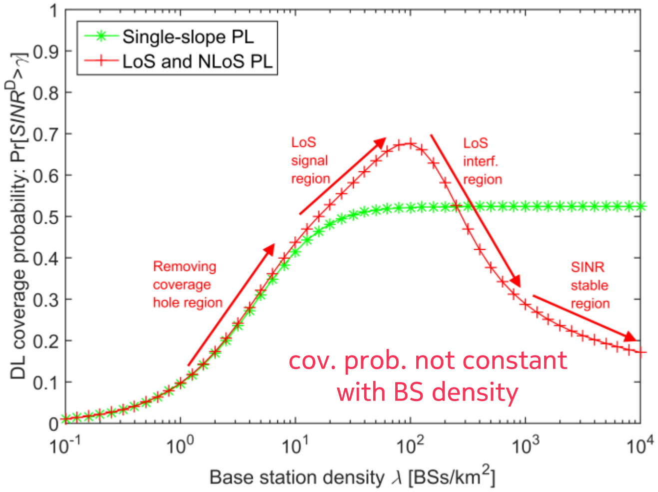
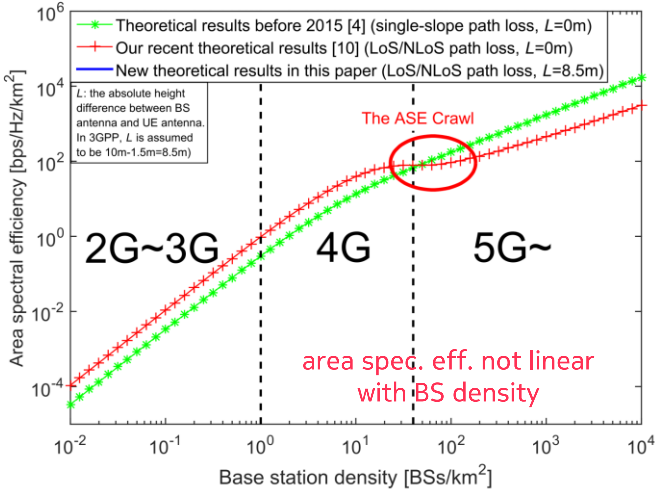
Stronger interference power – The ASE Crawl

Non-line-of-sight (NLOS) to line-of-sight (LOS) transition





After a certain BS density,
the inter-cell interference power will grow faster
than the carrier signal power
due to the NLoS to LoS transition of interfering paths

When considering such transition,
the ASE does not grow linearly with the BS density.
For λ=10^4 BSs/km^2,
it decreases from 17510 to 3593bps/Hz/km^2 (80%↓)

Base station density matters!

[5] M.Ding, P. Wang, D. López-Pérez, G. Mao, and Z. Lin "Performance Impact of LoS and NLoS Transmissions in Dense Cellular Networks," in IEEE Transactions on Wireless Communications, vol. 15, no 3, Page(s):1536- 1276, 2015.

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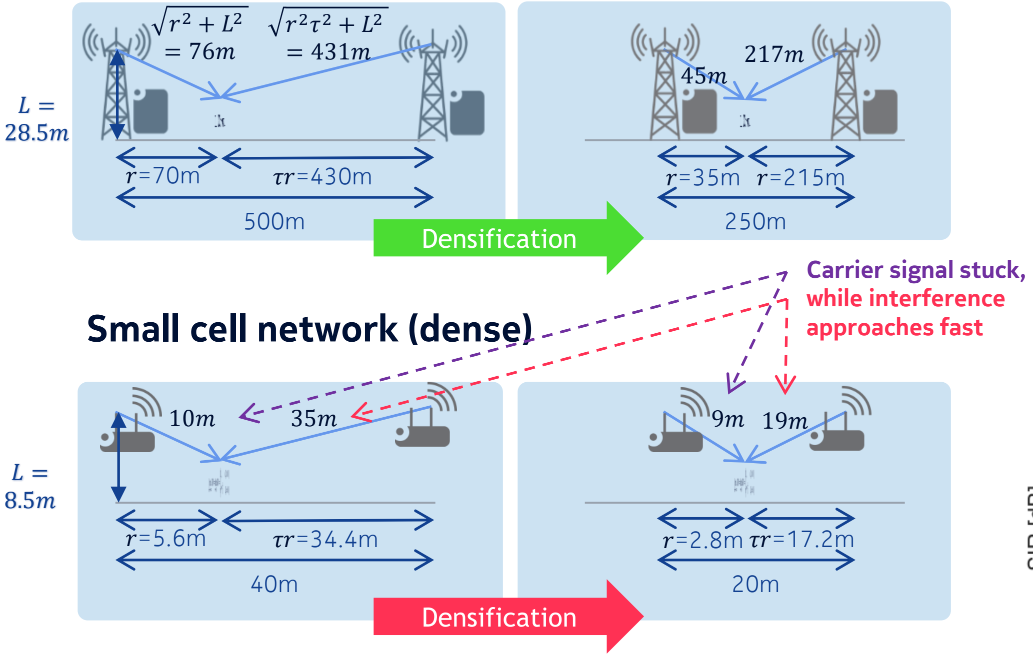
Bounded carrier signal power

Non-negligible antenna height difference between base stations (BSs) and users (UEs)

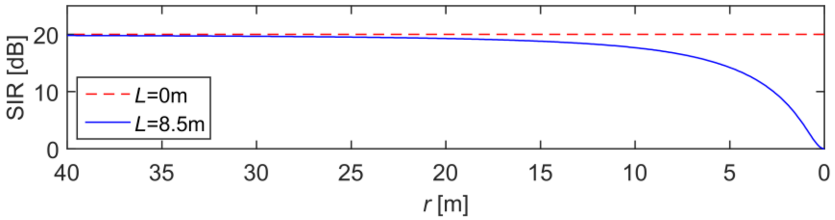
Macrocell network (sparse)



Toy example showing signal quality trend with the densification

$$SIR = \frac{A_1^L\left(\sqrt{r^2+L^2}\right)^{-\alpha_1^L}}{A_1^L\left(\sqrt{r^2\tau^2+L^2}\right)^{-\alpha_1^L}} = \left(\sqrt{\frac{1}{1+\frac{r^2-1}{1+\frac{L^2}{r^2}}}}\right)^{-\alpha_1^L}$$

$$\lim_{\lambda\to+\infty} SIR = \lim_{r\to 0} SIR = \begin{cases} 1, & (L>0) \\ r^{-\alpha_1^L}, & (L=0) \end{cases}$$



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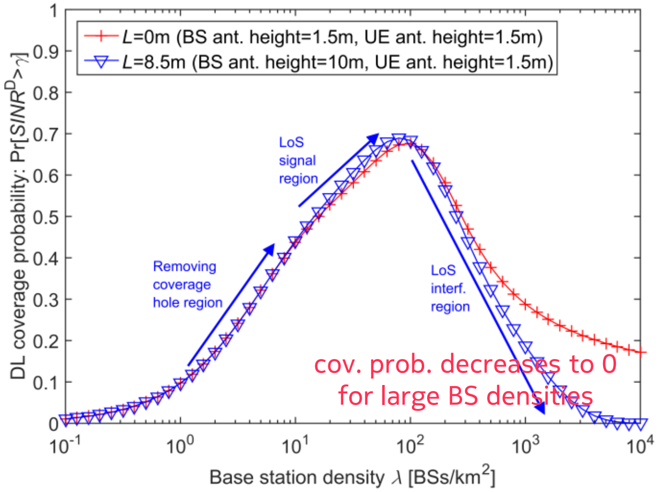
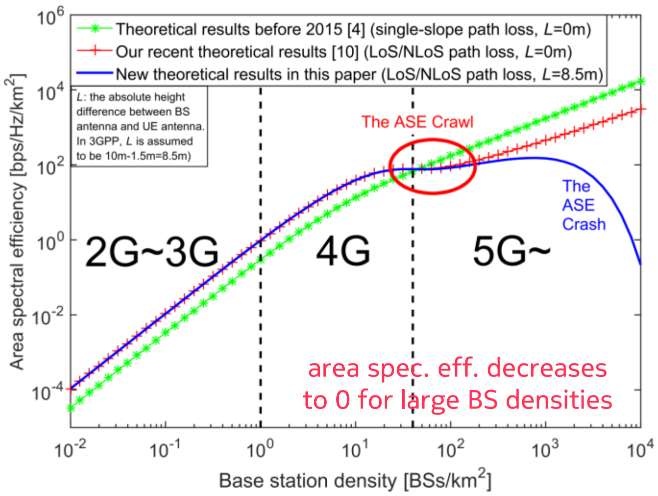
Bounded carrier signal power – The ASE CRASH

Non-negligible antenna height difference between base stations (BSs) and users (UEs)



After a certain BS density,
there is a cap in the carrier signal power due to BS antenna height (UE cannot get closer to BS),
while the inter-cell interference power continues to grow



When considering such cap,
the ASE dramatically decreases for large BS densities.
For $\lambda=10^4$ BSs/km², it decreases from 3593 (L=0m) to just 1.78bps/Hz/km² (L=8.5m) (99%↓)

Important to lower small cell base stations height!

[6] M. Ding, D. López-Pérez, G. Mao, and Z. Lin, "Performance Impact of Base Station Antenna Heights in Dense Cellular Networks," in IEEE Transactions on Wireless Communications, vol. 16, no. 12, Page(s): 8147-8161, Dec. 2017.

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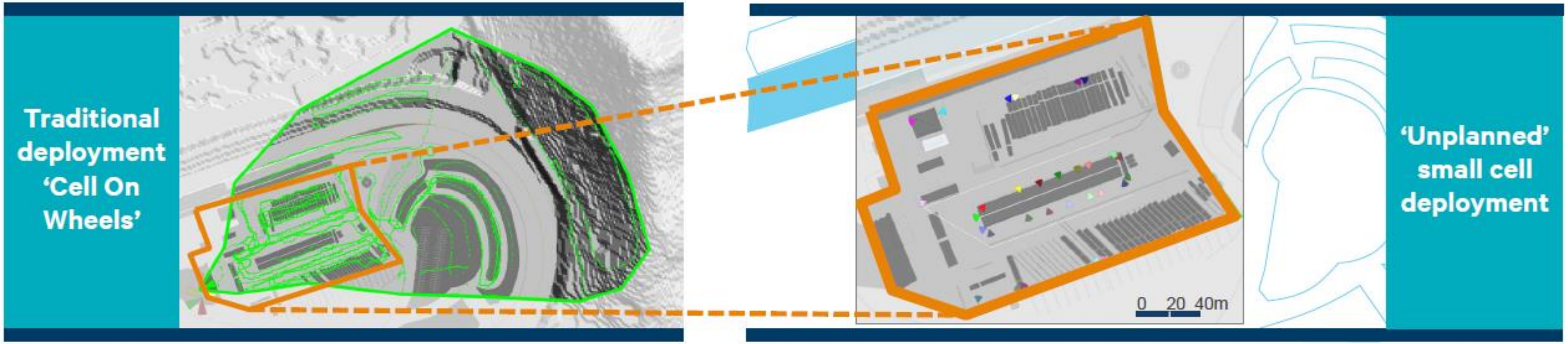
Measurements validate our hypothesis on ASE Crawl/Crash

Qualcomm, "1000x: More small cells -- Hyper-dense small cell deployments," Jun., 2014.



Equivalent cell density: 9 cells/km^2
Average site-to-site: 519m
Spectrum: 5 + 5 MHz, LTE FDD
Coverage: 0.11 km^2

Measured Efficiency
~16 bps/Hz/km^2

More than 40x capacity

Equivalent cell density: 1107 cells/km^2
Average site-to-site: 22m
Spectrum: 20 MHz, LTE TDD (60%DL/40%UL)
Coverage: 0.028 km^2

Measured Efficiency
~660 bps/Hz/km^2

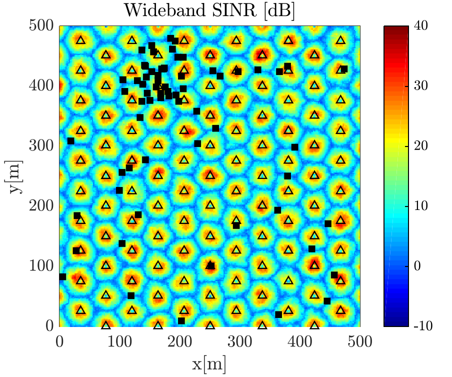
100x of SSR increase => 40x of network capacity

More base stations (BSs) than users (UEs) (I)

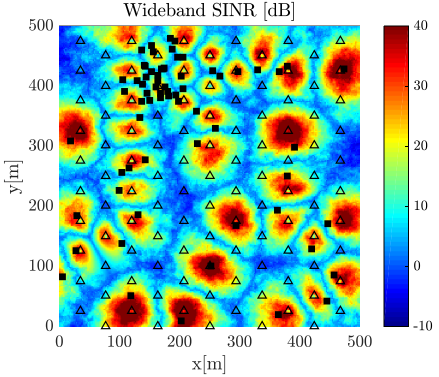
The surplus of BSs with respect to UEs allows to dynamically switch ON/OFF the formers

Idle mode → Cells with no user switch off,
thus reducing energy consumption and interference

Idle mode not available

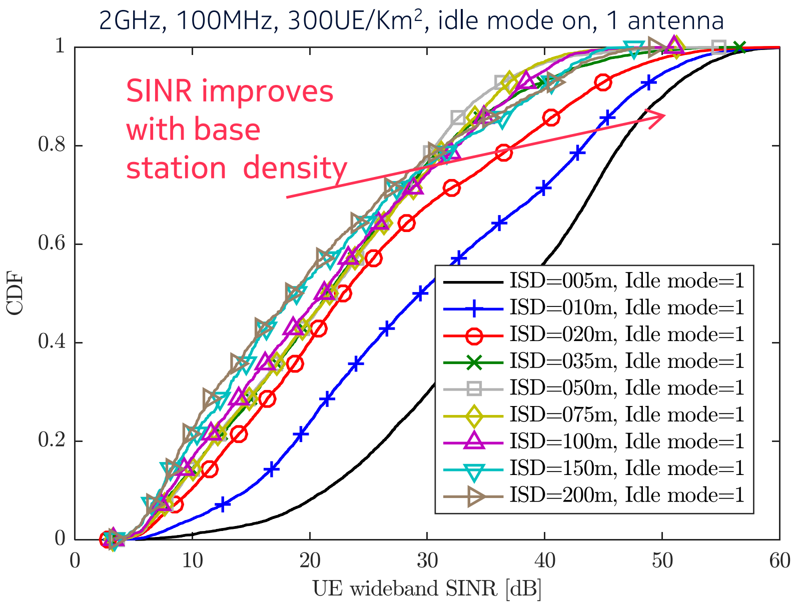


Idle mode available



Signal to interference plus noise ratio (SINR)

ISD = inter-site distance



Simulation insights

- Significant SINR distribution enhancement despite densification
- Transition to noise limited scenarios occurs for sparse networks

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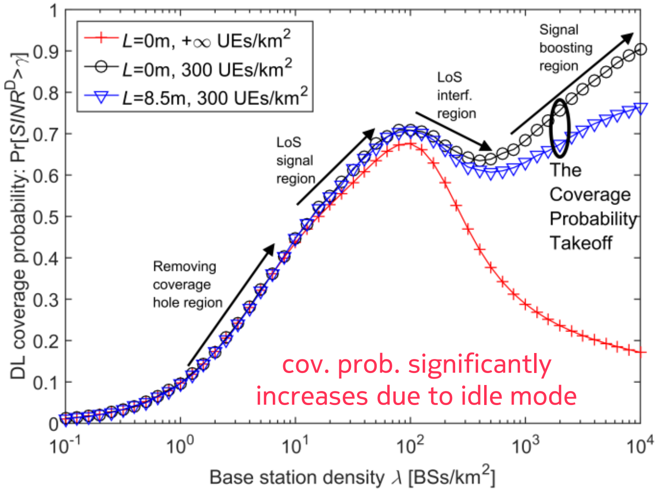
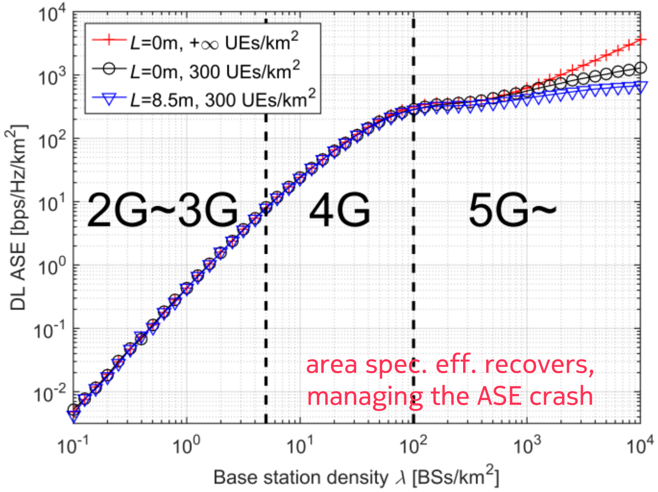
More base stations (BSs) than users (UEs) (II)

The surplus of BSs with respect to UEs allows to dynamically switch ON/OFF the formers



Thanks to the idle mode,
interferers are pushed away and interference reduced.
For a constant UE density,
the larger the BS density the larger the benefit



When considering the idle mode,
the ASE recovers from the previously presented ASE crash.
Note that the ASE is also smaller for a smaller UE density
(less UEs reusing spectrum)

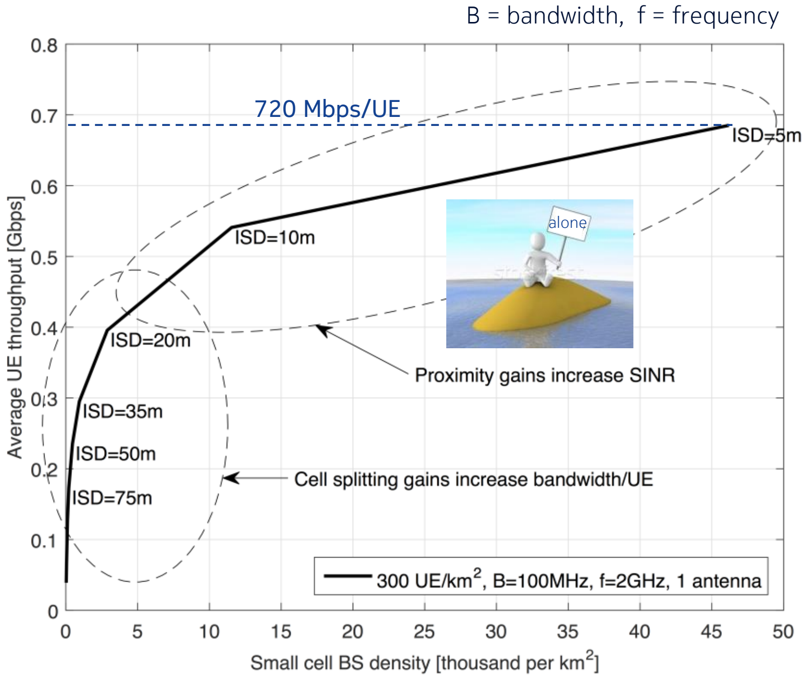
Idle modes are key for getting the most of ultra dense networks!

[7] M. Ding, D. López-Pérez, G. Mao, and Z. Lin, "Performance Impact of Idle Mode Capability on Dense Small Cell Networks," IEEE Transactions on Vehicular Technology, vol. 66, no 11, Page(s):10446-10460, Nov. 2017.

Less active users (UEs) per base station (BSs)

Attention please: Reaching the limit of spatial reuse

- **One-UE-per-cell** is the limit to spatial reuse, capping the cell split gains
  - 1 UE/cell at 50m ISD for 300 UE/km2
- When the 1 UE/cell limit is reached, the average UE throughput gain slows down with densification
- UE-to-base station proximity still provides noticeable gains, mostly at the cell-edge
- Understanding UE distribution and density is vital for cost-effective small cell deployments



18x average capacity gain (48x at the cell-edge) with densification

[4] D. Lopez-Perez, et. al., "Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments," IEEE Comm. Surveys & Tutorial, 2015.

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More Bandwidth

Capacity scaling with bandwidth and power

More bandwidth – Always welcome in terms of capacity

Effects of higher carrier frequencies

higher carrier freq.
benefits from ↓
wider bandwidth
leads to ↓
higher capacity

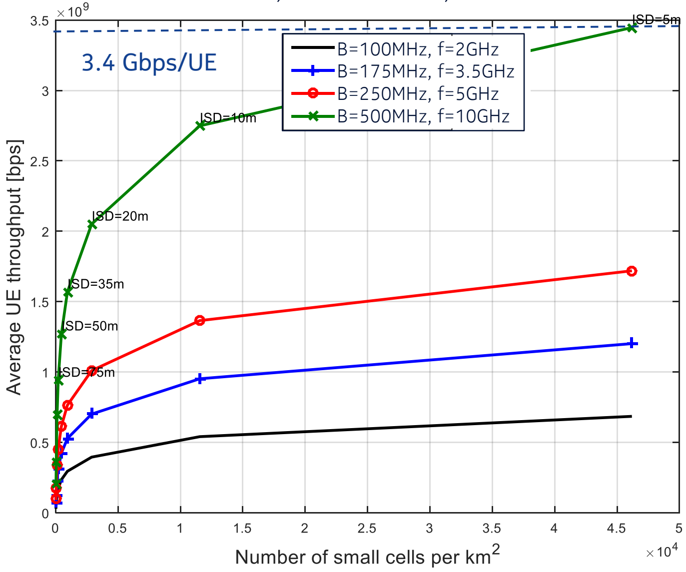
Results

- Linear increase of user throughput with bandwidth, as can be derived from that Shannon-Hartley theorem
  - From 100MHz to 500MHz bandwidth, the average UE throughput increases from 720Mbps to 3.4Gbps

Average UE throughput with densification

B = bandwidth, f = frequency

300UE/Km², idle mode on, 1 antenna



5x average capacity gain with the bandwidth

[4] D. Lopez-Perez, et. al., "Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments," IEEE Comm. Surveys & Tutorial, 2015.

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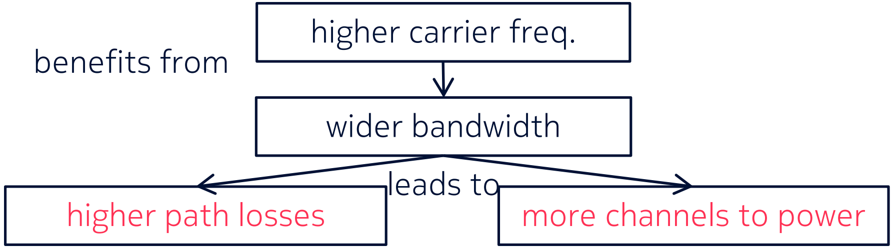
More bandwidth – Incurs a cost in terms of power

Effects of higher carrier frequencies



Results

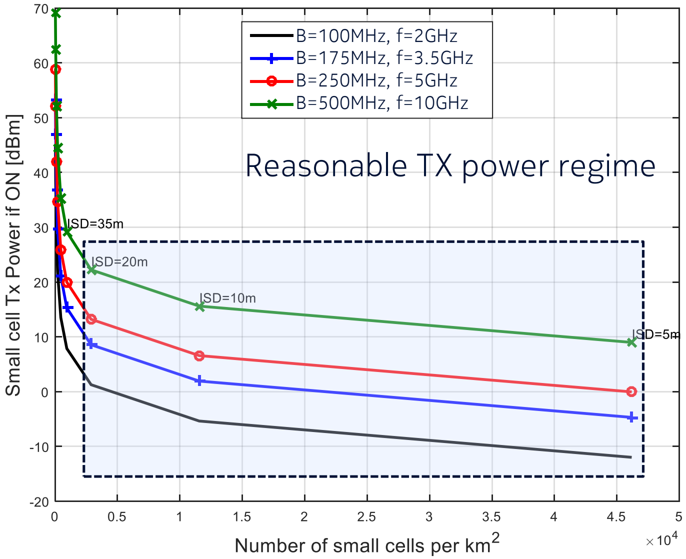
- TX power increases with bandwidth, as can also be derived from that Shannon-Hartley theorem
  - For an ISD=200m and 500MHz bandwidth , the required TX power ≈ 70dBm. This is prohibitive

Note: Larger bandwidths pose important challenges to efficient HW development

Small cell TX power with densification

B = bandwidth, f = frequency

300UE/Km², idle mode on, 1 antenna



Large bandwidths only usable for small cells

[4] D. Lopez-Perez, et. al., "Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments," IEEE Comm. Surveys & Tutorial, 2015.

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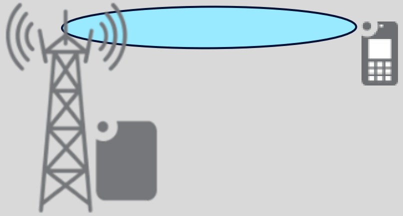
More Antennas

Capacity scaling with beamforming

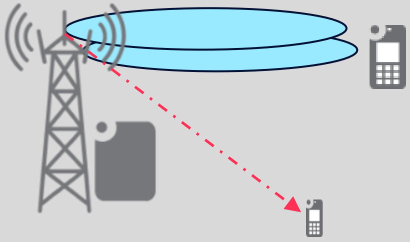
Multi-antenna techniques

TX Beamforming



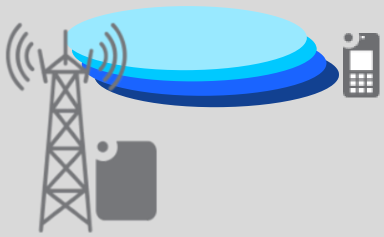
- Serves a single user with a single data stream directing energy towards it
- Multiple antennas needed at the TX

Generalised TX beamforming



- Serves a single user with a single data stream directing energy towards multiple directions
- Multiple antennas needed at the TX

Single User-MIMO



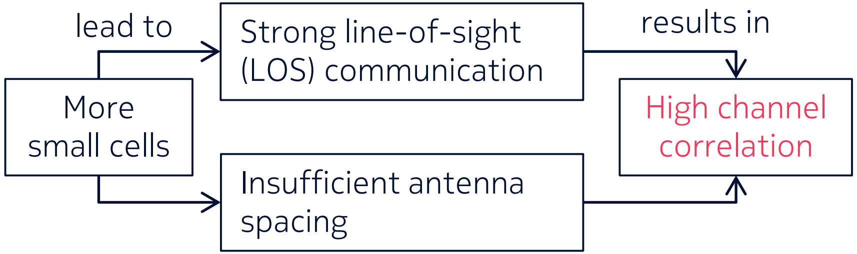
- Serves a single user with multiple data streams
- Multiple antennas needed at the TX & RX
- Increases RX throughput

Multiuser-MIMO

- Serves multiple users with a single or multiple data streams
- Multiple antennas needed at the TX
- Increases system throughput

Capacity scaling with beam-forming

Effects of densification on multi-antenna technology

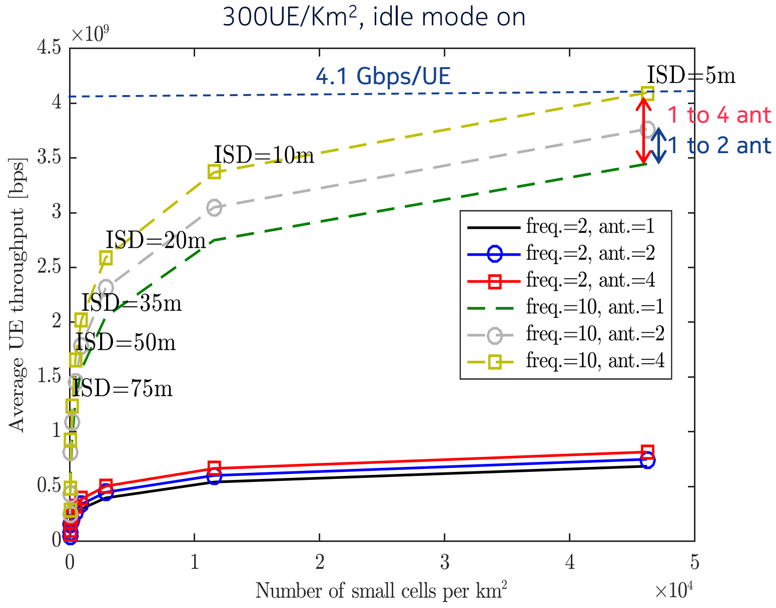


Results

- BF gains
  - diminish with the number of antennas,
  - are larger for larger cell ranges (better carrier signal),
  - are larger at the cell-edge (better interference mitigation)

Average UE throughput with densification

ant = number of antennas



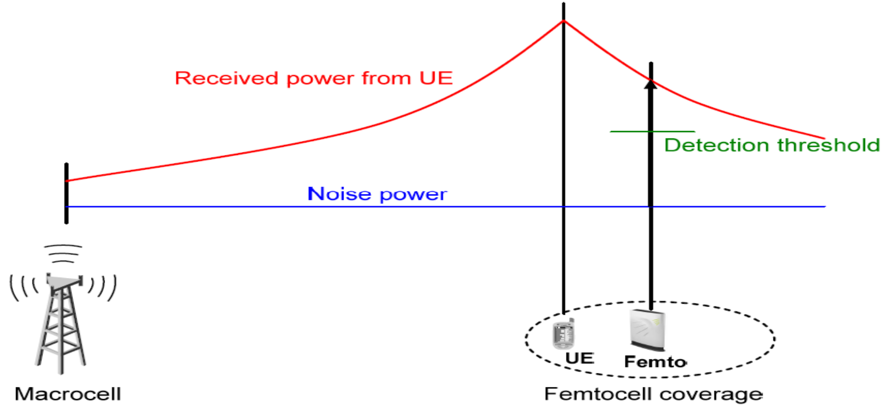
1.3x average capacity gain (2x at the cell-edge) with beam-forming

[4] D. Lopez-Perez, et. al., “Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments,” IEEE Comm. Surveys & Tutorial, 2015.

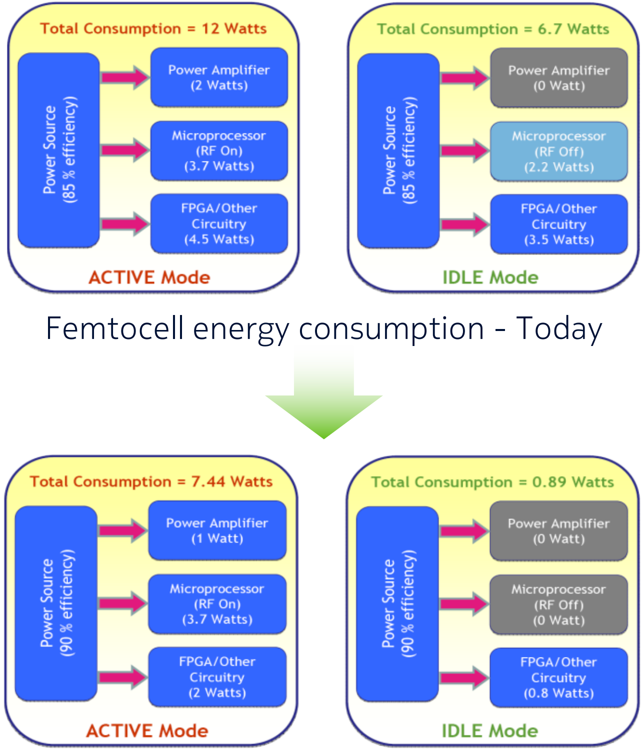
Energy efficiency

Idle mode techniques

- A simple idle mode based on a power sniffer can
  - Significantly reduce energy consumption
  - Reduce power density in the home
  - Reduce mobility procedures and associated signalling
  - Reduce interference caused by pilot transmissions



Small cell activation based on noise rise from active UE allows to activate the small cell only for serving a call



Femtocell energy consumption – Optimized design

[7] H. Claussen, et. al., "Dynamic idle mode procedures for femtocells," Bell Labs Technical Journal, vol. 15, no. 2, pp. 95-116, Aug. 2010.

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Energy efficiency scaling with idle modes

Idle modes considered

- Sleep mode 1 -> slow idle mode (for 2015)
- Sleep mode 2 -> shutdown (view for 2020)
- Sleep mode 3 -> 15% sleep mode 1
- Sleep mode 4 -> 0% sleep mode 1

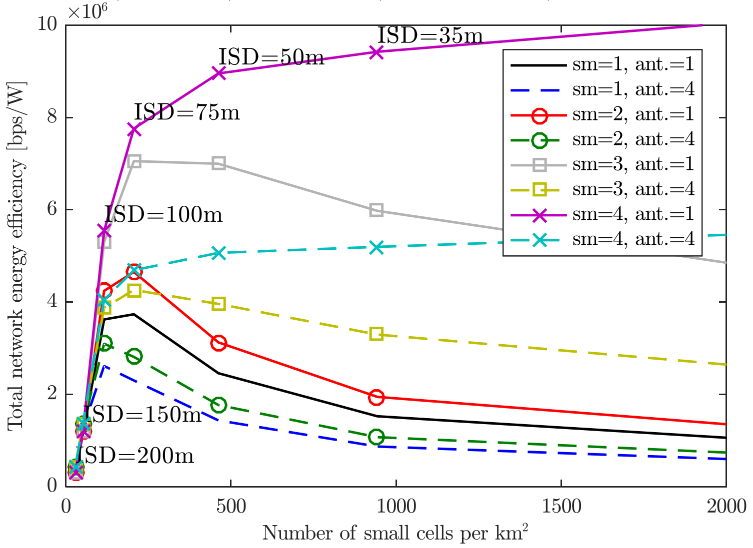
Results

- Power consumption with today's idle modes make ultra dense networks not energy efficient
- There is a need to avoid power consumption from the grid while in idle mode
- Harvesting 0.5W per small cell while in idle mode would allow making dense networks energy efficient

Network energy efficiency with densification

sm = sleep mode, ant = number of antennas

2GHz, 100MHz, 300UE/Km^2, idle mode on, 1 antenna



Ultra dense networks can be energy efficient if dealing with consumption while in idle mode

[4] D. Lopez-Perez, et. al., "Towards 1Gbps/UE: Understanding Ultra Dense Small Cell Deployments," IEEE Comm. Surveys & Tutorial, 2015.

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Low-latency and reliability challenges

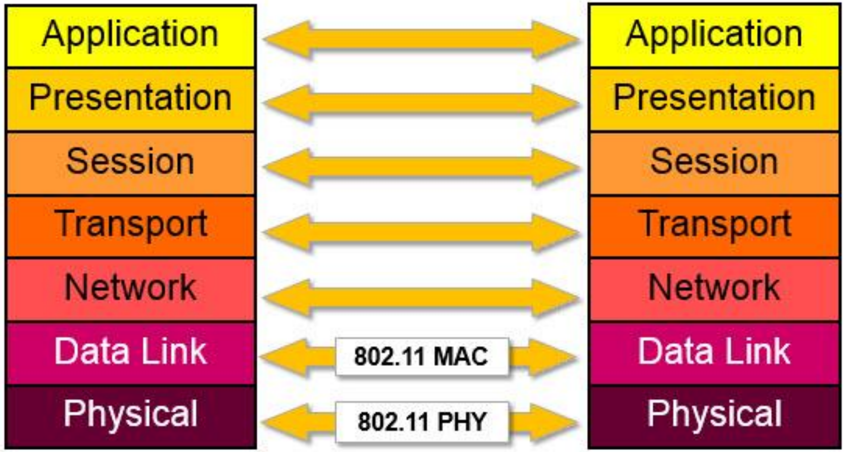
Latency and Reliability Definition

Delay

- Delay is the amount of time spanned from the moment that {the first bit of an SDU enters the layer of reference at the TX} {until the last bit of such PDU is decoded in the peer layer at the RX}
  - Delay is measured among peer layers
  - End2End delay is measured at the application layer

Reliability

- A communication is said to be x% reliable if more than x% of its packets are successfully decoded with a delay smaller than that required by the service
  - 99.999% reliable means that at most 1 of every 100000 packets arrives within the deadline



OSI reference model (with Wi-Fi example)

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Ultra reliable low latency networking – a key enabler for wireless automation

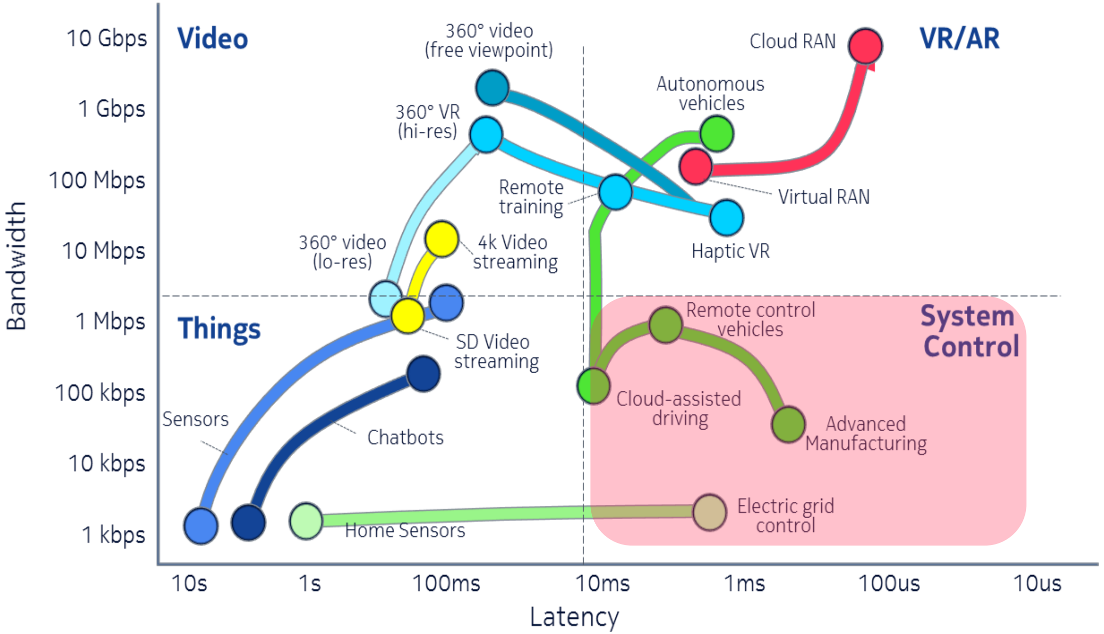
Industry 4.0 key requirement

- Reliable low latency communications is key enabler for industrial wireless automation and system control

5G requirement

- 1 x 10^{-5} probability of error transmitting layer-2 PDU of 32 bytes in size within 1 ms

[https://www.itu.int/md/R15-SG05-C-0040/en]



Can we enable ultra-reliable low latency communications via Wi-Fi?

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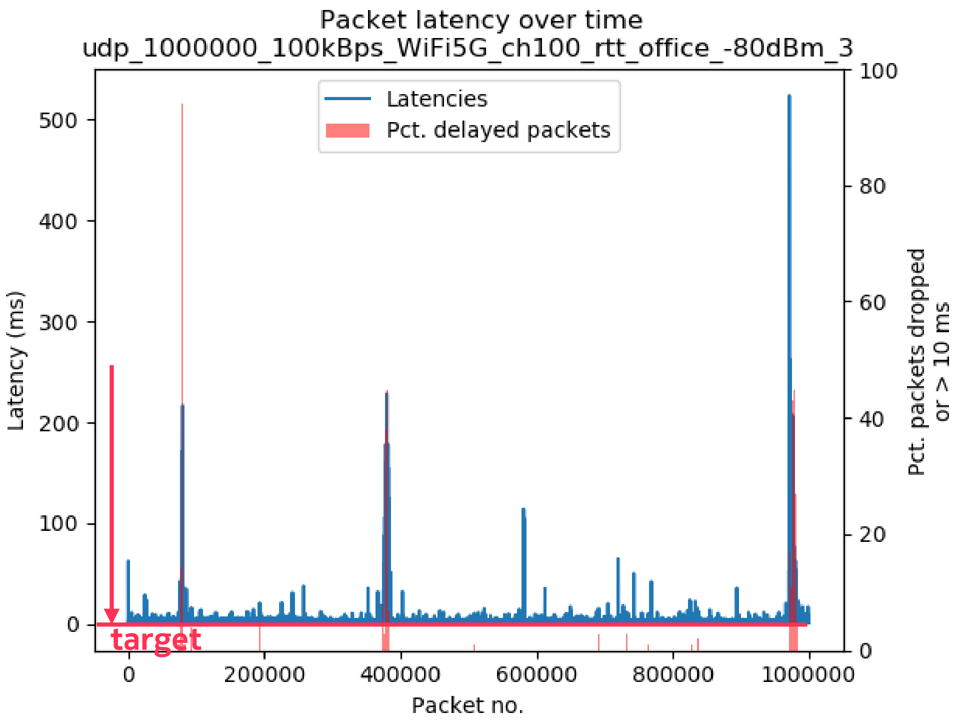
How to achieve ultra-reliable communications in Wi-Fi

Challenge

- Wi-Fi currently does not meet reliable low latency requirements and latencies vary from sub-ms to hundreds of ms
- Uncontrolled interference + listen before talk (LBT) in unlicensed bands results in unpredictable delay and dropped packets

Concept for achieving reliability:

- Replicate RLLC packets over multiple links on different channels
- Uncorrelated delays on different links allows reducing end-to-end latency



How many Wi-Fi links are required to meet 5G requirements today?

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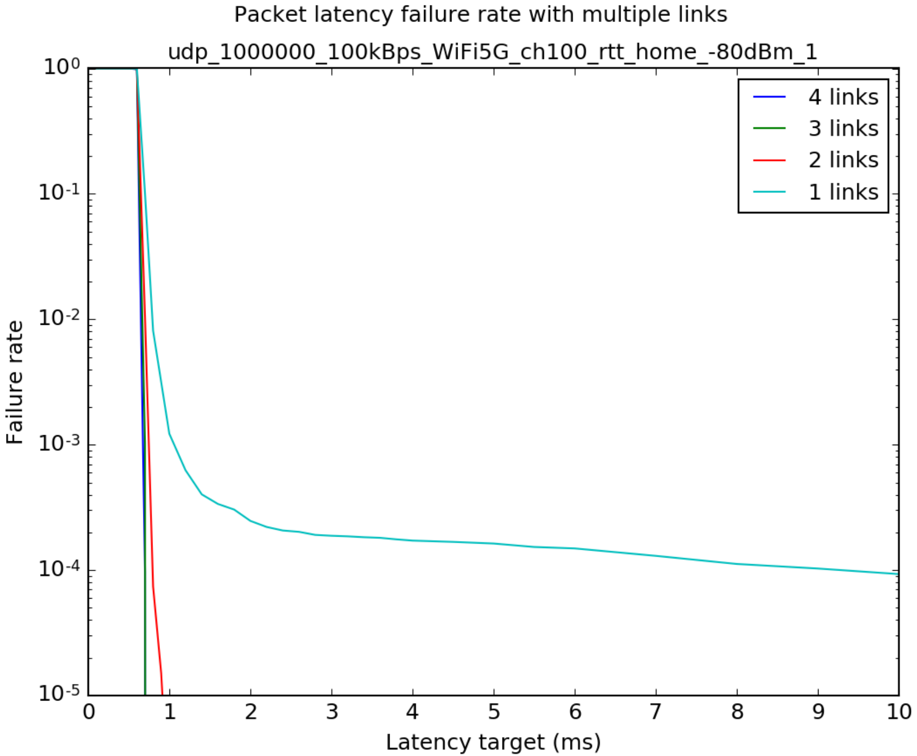
Results: Interference Free Residential

Scenario

- Interference free residential
- Location with poor signal -80dBm



Without interference, 3 Wi-Fi links achieve 600 us link latency with 99.999% reliability

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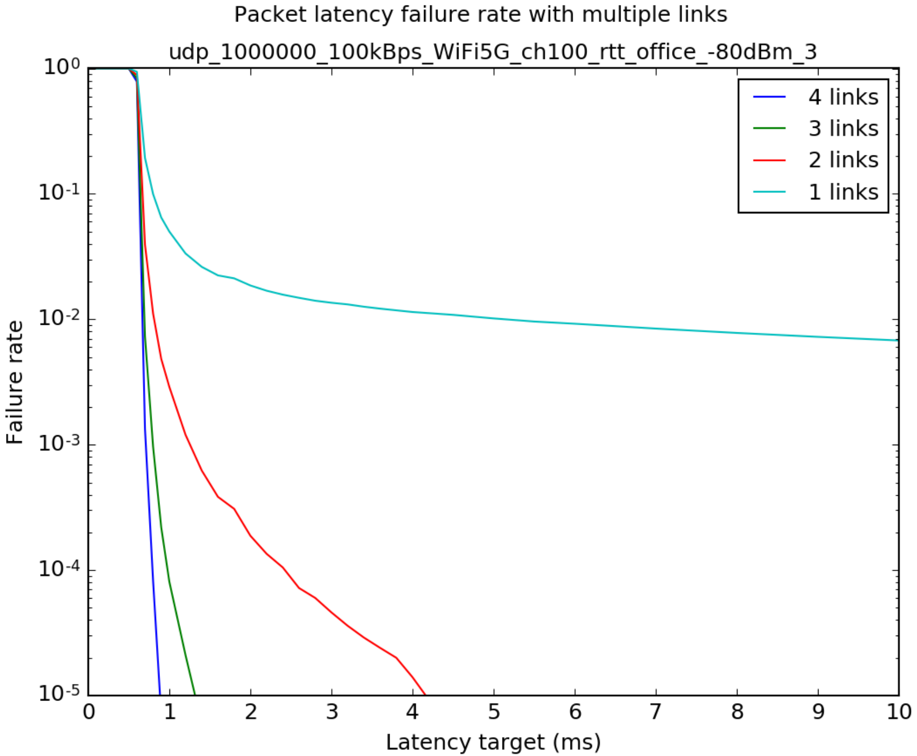
Results: Typical office environment

Scenario

- Nokia office Dublin
- Channel shared with 2 other Wi-Fi networks (NOSI, Nokia Guest Network)
- Location with poor signal -80dBm



In Nokia's Dublin office, 4 Wi-Fi links achieve <1ms link latency with 99.999% reliability

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Fundamentals of Wireless Networks

The Why's and the How's

David Lopez-Perez

Painless Summer School

Nicosia, Cyprus

Sep. 9th 2019

Q&A


NOKIA

Antennas, Antenna Systems & Radio Propagation in Next Generation Communication Systems – Part I

Dimitrios K. Ntaikos
PhD Electrical Engineer, Researcher
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AIT

Short course given to the PAINLESS 1st Summer School, University of Cyprus, Sept. 9, 2019

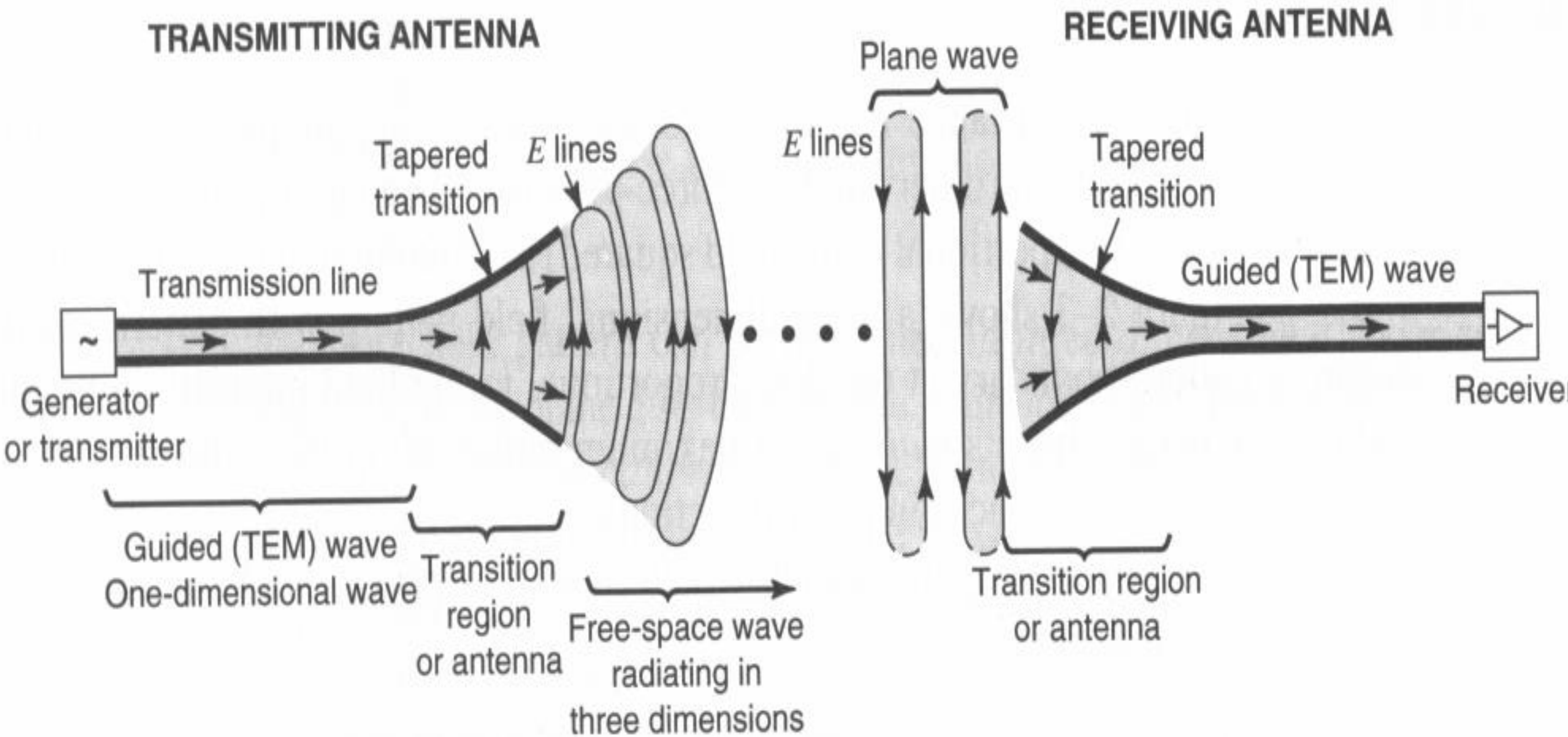
What is an antenna?

- An antenna is a way of converting the guided waves present in a waveguide, feeder cable or transmission line into radiating waves travelling in free space, or vice versa.

- An antenna is a passive structure that serves as transition between a transmission line and air used to transmit and/or receive electromagnetic waves.

- An antenna converts electrons to photons of EM energy.

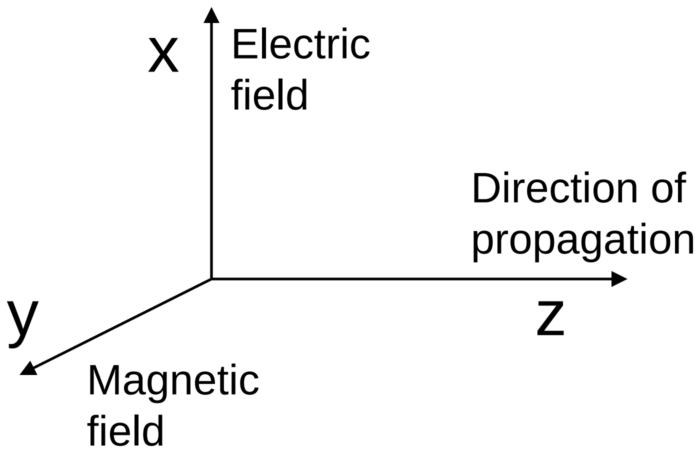
What is an antenna?

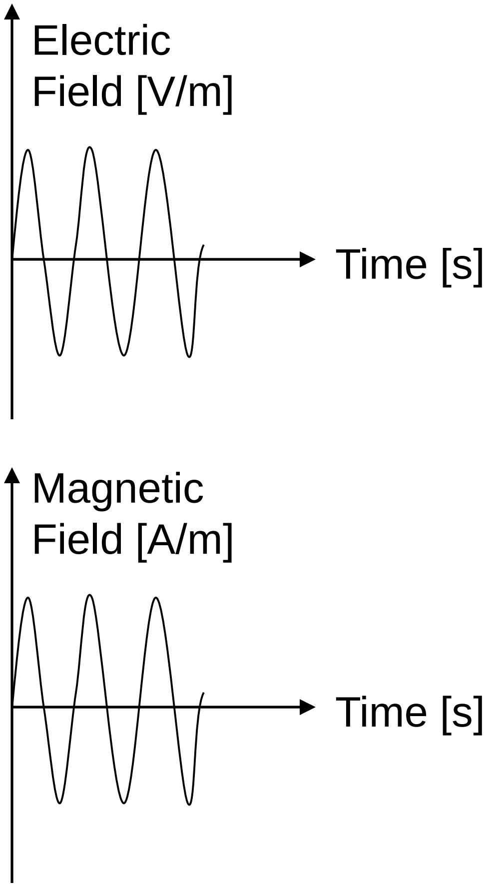


Only accelerated (or decelerated) charges radiate EM waves.

A current with a time-harmonic variation (AC current) satisfies this requirement.

Free space electromagnetic wave





- Disturbance of EM field
- Velocity of light (~300 000 000 m/s)
- E and H fields are orthogonal
- E and H fields are in phase
- Impedance, Z_0: 377 ohms

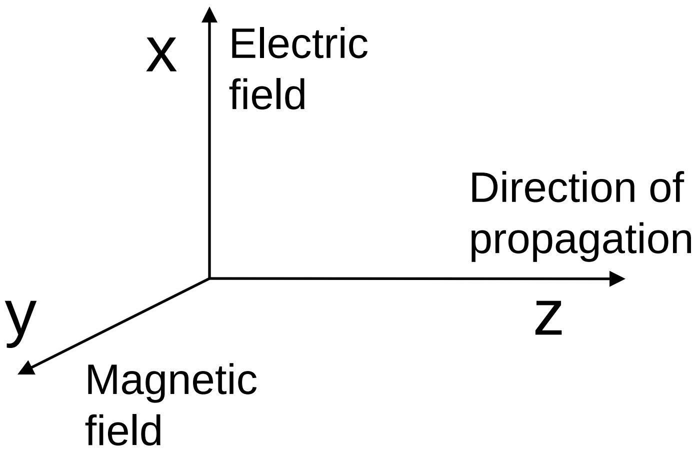
EM wave in free space

$$\frac{\partial^2 E_x}{\partial t^2} = \frac{1}{\mu_0 \varepsilon_0} \frac{\partial^2 E_x}{\partial z^2}$$

$$\frac{\partial^2 H_y}{\partial t^2} = \frac{1}{\mu_0 \varepsilon_0} \frac{\partial^2 H_y}{\partial z^2}$$

$$E_x = E_0 e^{j(\omega t \pm \beta z)}$$

$$H_y = H_0 e^{j(\omega t \pm \beta z)}$$



frequency $f = \frac{\omega}{2\pi}$

wavelength $\lambda = \frac{1}{\sqrt{\mu_0 \varepsilon_0} f}$

Phase constant $\beta = \frac{2\pi}{\lambda}$

$Z_0 = \frac{E_0}{H_0}$ $\quad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$

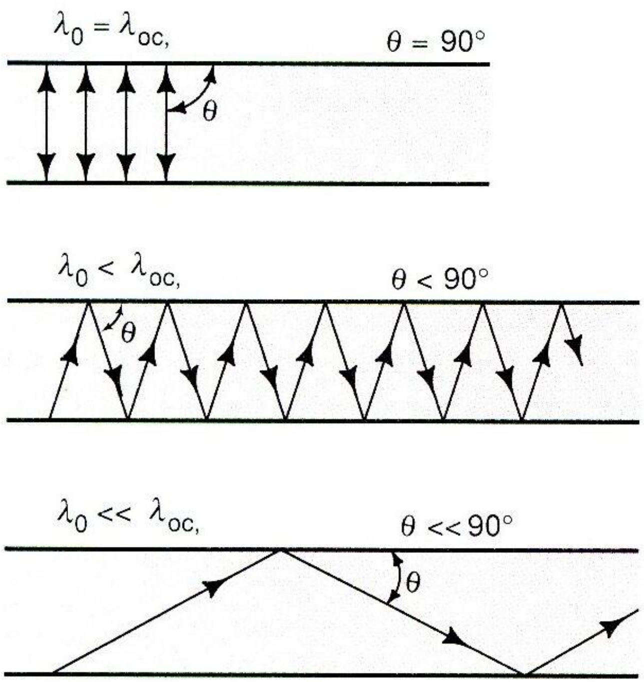
Guided electromagnetic wave

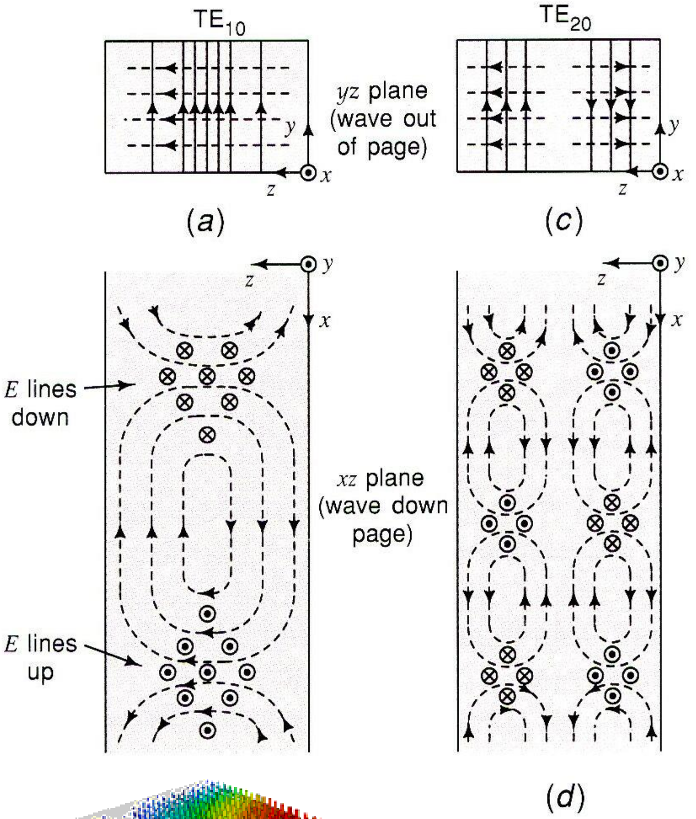
- Cables
  - Used at frequencies below 35 GHz
- Waveguides
  - Used between 0.4 GHz to 350 GHz
- Quasi-optical system
  - Used above 30 GHz

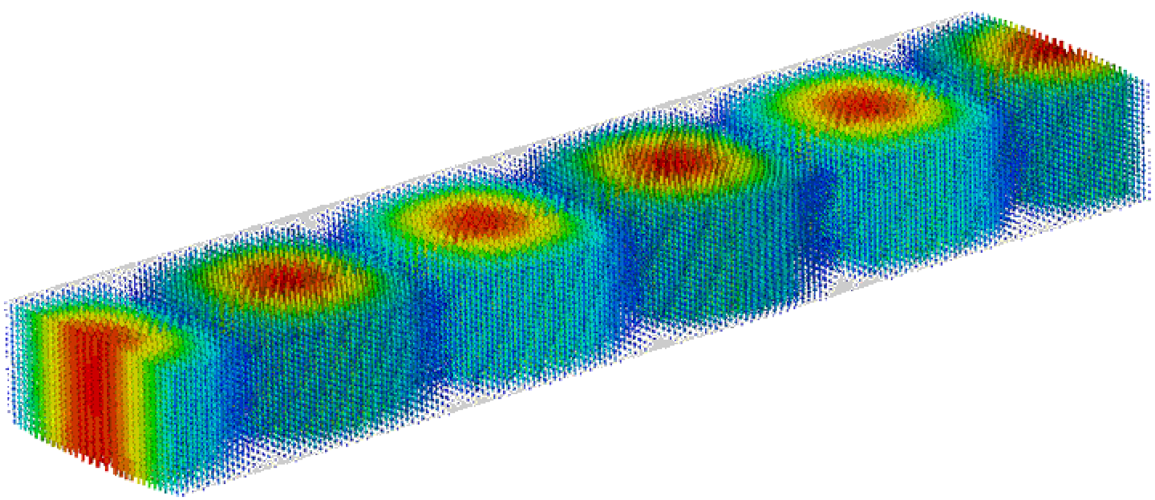
Guided electromagnetic wave (2)

- TEM wave in cables and quasi-optical systems (same as free space)
- TH, TE and combinations in waveguides
  - E or H field component in the direction of propagation
  - Wave bounces on the inner walls of the guide
  - Lower and upper cut-off frequency limits
  - Cross section dimensions proportional to wavelength

Rectangular waveguide







Launching of EM wave

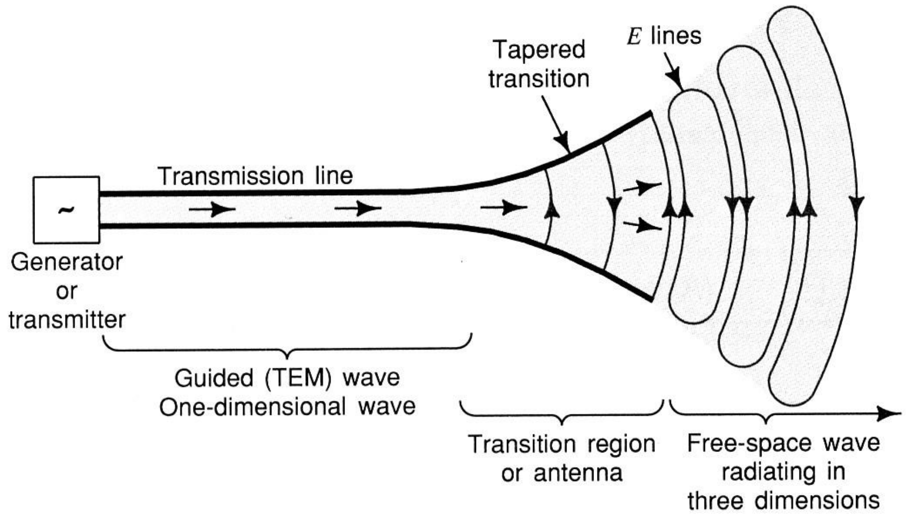
Open up the cable and separate wires

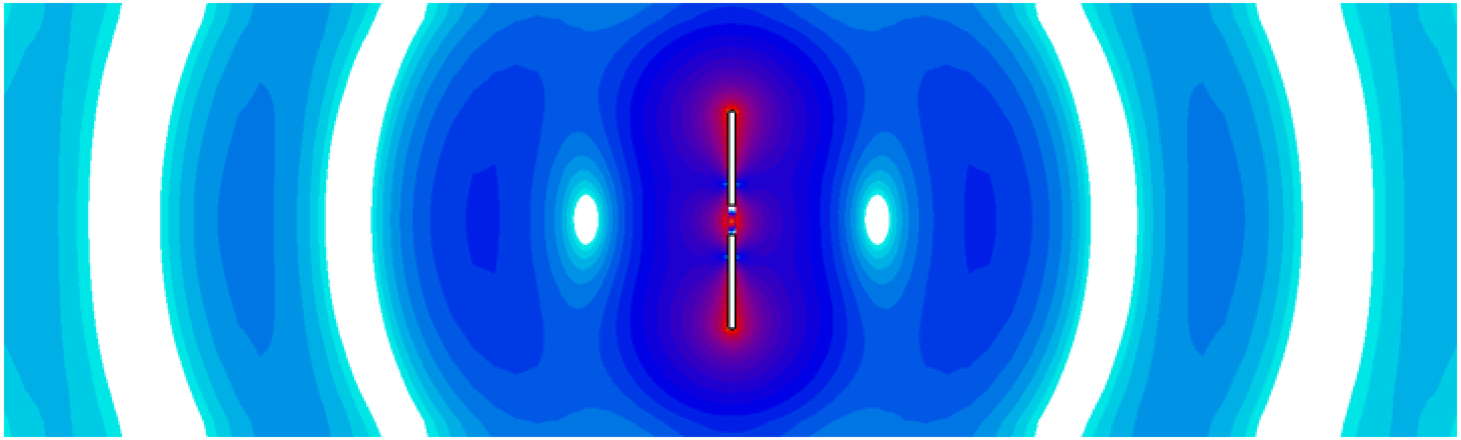
Dipole antenna

Open and flare up wave guide

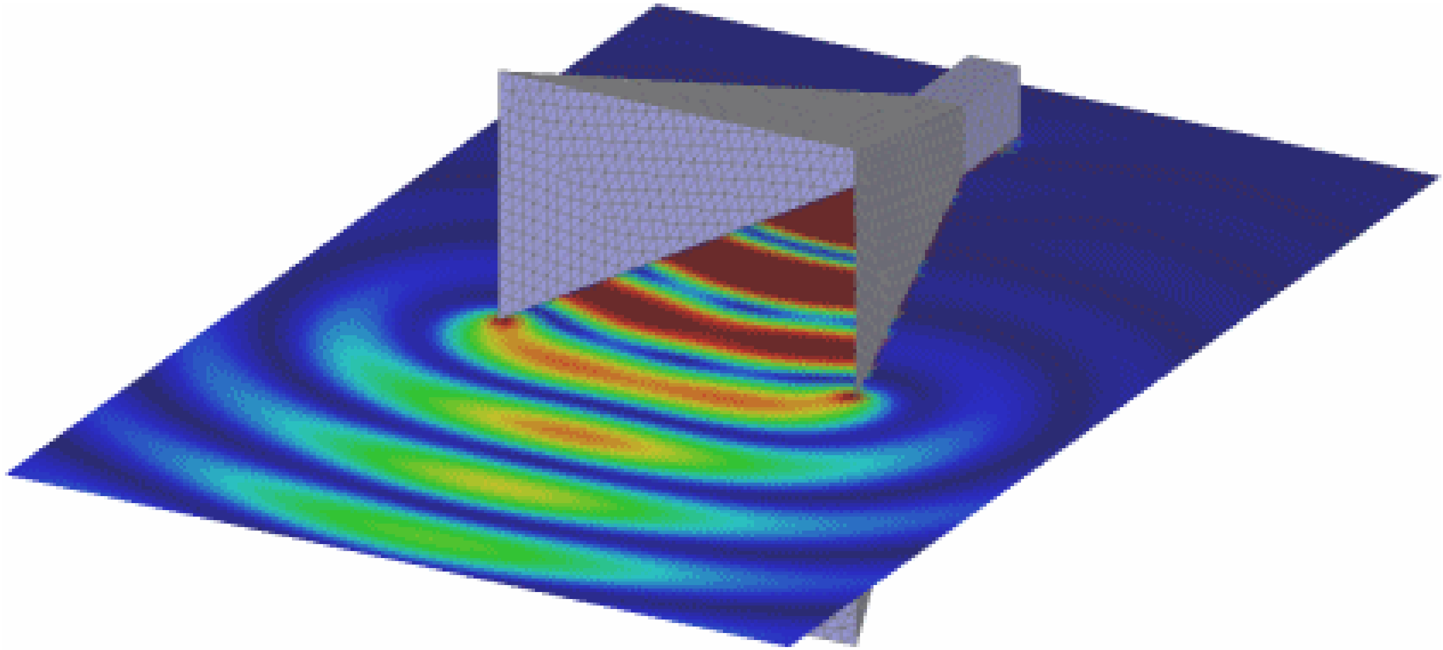
Horn antenna

Transition from guided wave to free space wave (wire antenna)





Transition from guided wave to free space wave (horn antenna)



Reciprocity

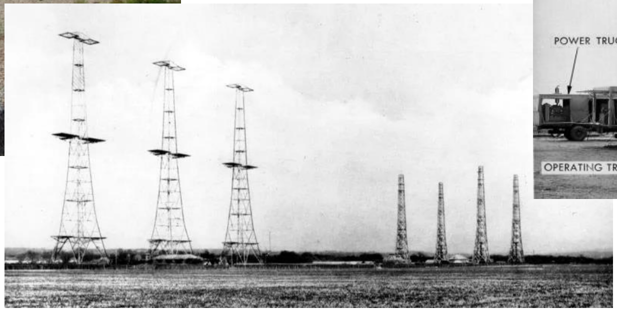
- Transmission and reception antennas can be used interchangeably.
- Medium must be linear, passive and isotropic.
- Common practice: Antennas are usually optimised for reception or transmission (depending on the problem), not both simultaneously!

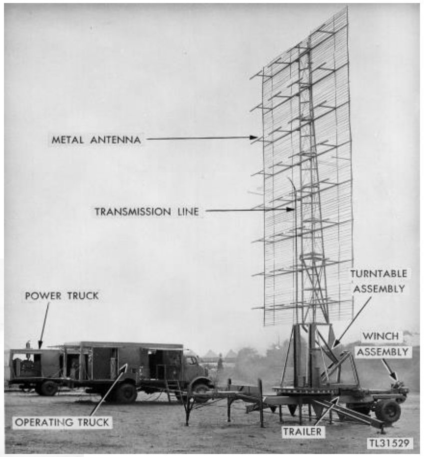
Fundamentals of Antennas

- Definition of antenna parameters:
  - Gain,
  - Directivity,
  - Effective aperture,
  - Radiation Resistance,
  - Band width,
  - Beam width,
  - Input Impedance
    - Matching – Baluns,
    - Polarization mismatch,
    - Antenna noise temperature
- All these parameters are expressed in terms of a **transmission** antenna but are identically applicable to a **receiving** antenna.

Antenna Background

- Maxwell (1831-79) Fundamental equations. (Scottish)
- Hertz (1857-94) First aerial propagation (German)
- Marconi (1874-1937) Transatlantic transmission (Italian)
- DeForest (Triode tube 1920) Signal generators (American)
- World War II (1939-45) Intense war-driven development



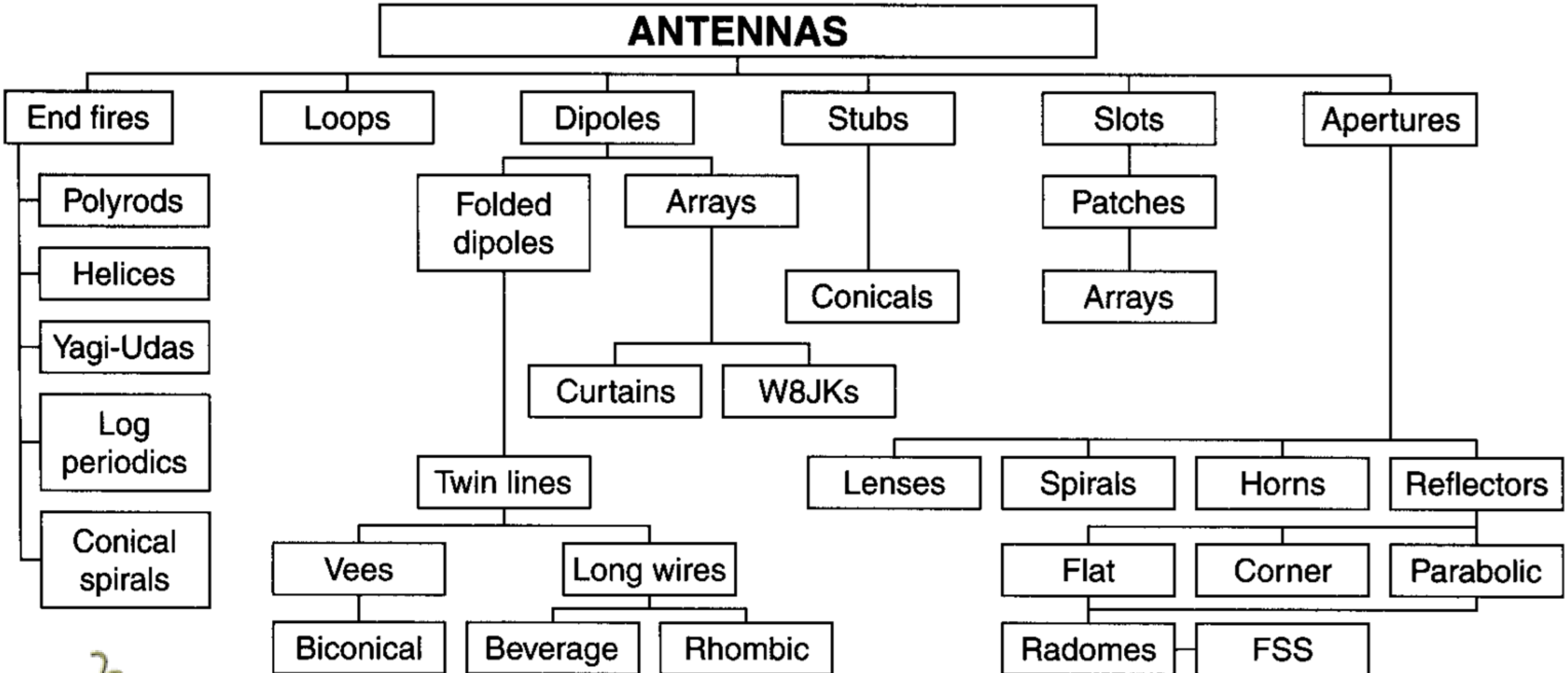


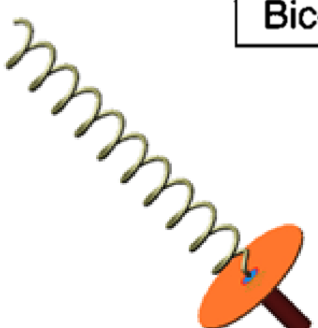
The role of antennas

Antennas serve four primary functions:

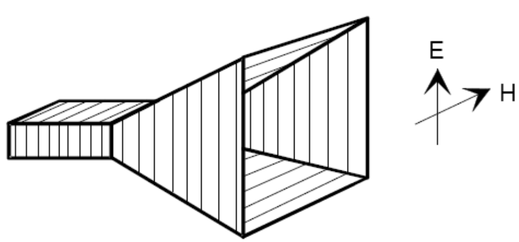
- ❑ Spatial filter: directionally-dependent sensitivity.
- ❑ Polarization filter: polarization-dependent sensitivity.
- ❑ Impedance transformer: 50Ω to 377Ω transition between free space and transmission line.
- ❑ Propagation mode adapter: from free-space fields to guided waves (e.g., transmission line, waveguide).

Antenna types

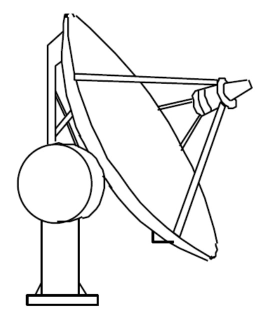




Helical antenna



Horn antenna



Parabolic reflector antenna

Isotropic antenna

- It's a hypothetic antenna, i.e., it does not exist in real life, yet it's used as a measuring bar for real antenna characteristics.

- It's a point source that occupies a negligible space. Has no directional preference.

- Its pattern is simply a sphere, so it has,

  beam area (Ω_A) = $\Omega_{isotropic}$= 4π [steradians].

$$\Omega_{isotropic} = \iint_{4\pi} (1) d\Omega$$

$$\int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} (1) \sin\theta \, d\theta \, d\phi = 4\pi$$

Isotropic Radiator:

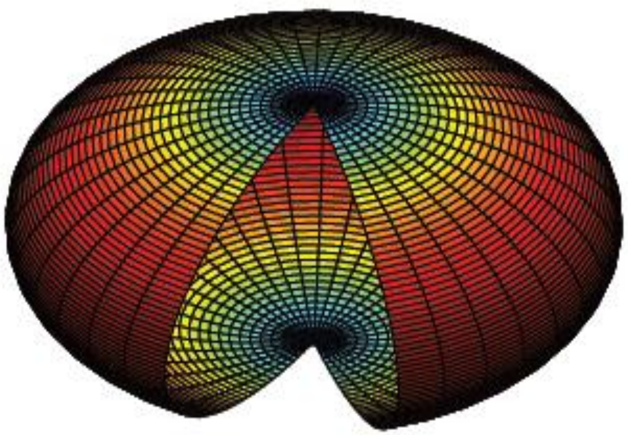
A hypothetical lossless antenna having equal radiation in all directions.

Omnidirectional Radiator:

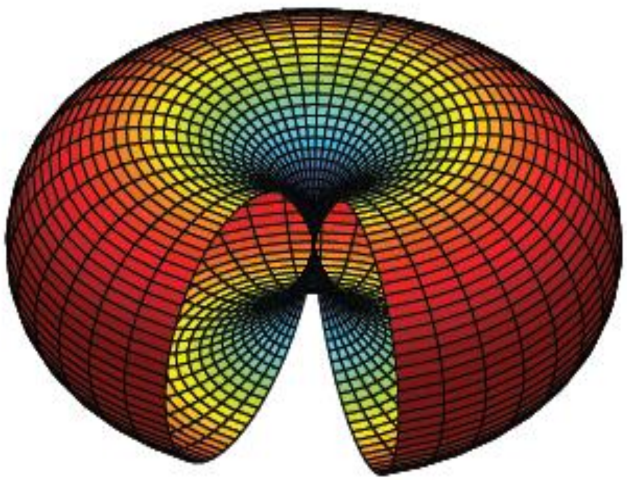
An antenna having an essentially nondirectional pattern in a given plane (e.g., in azimuth) and a directional pattern in any orthogonal plane.

Directional Radiator:

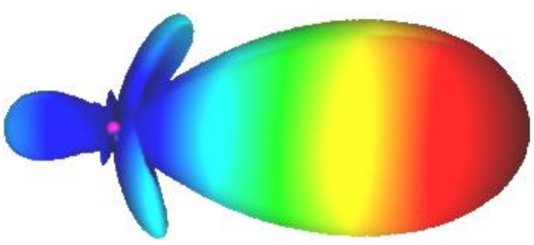
An antenna having the property of radiating or receiving more effectively in some directions than in others. Usually the maximum directivity is significantly greater than that of a half-wave dipole.



Isotropic

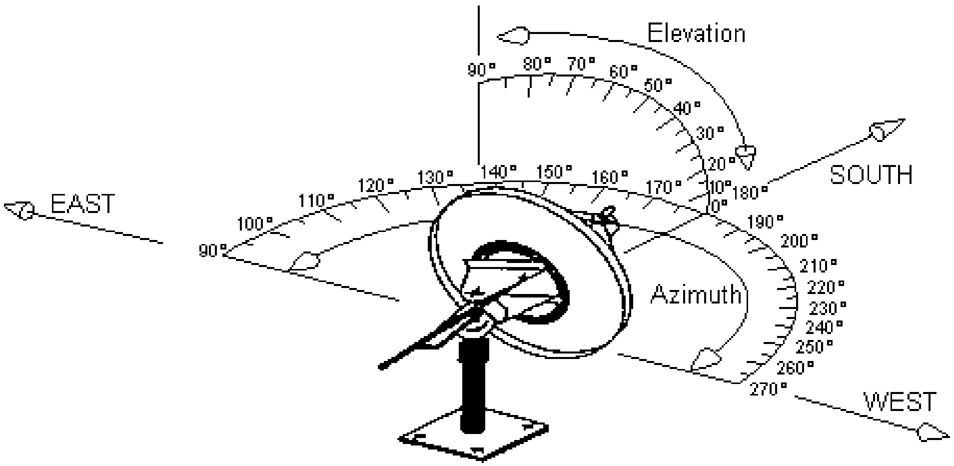


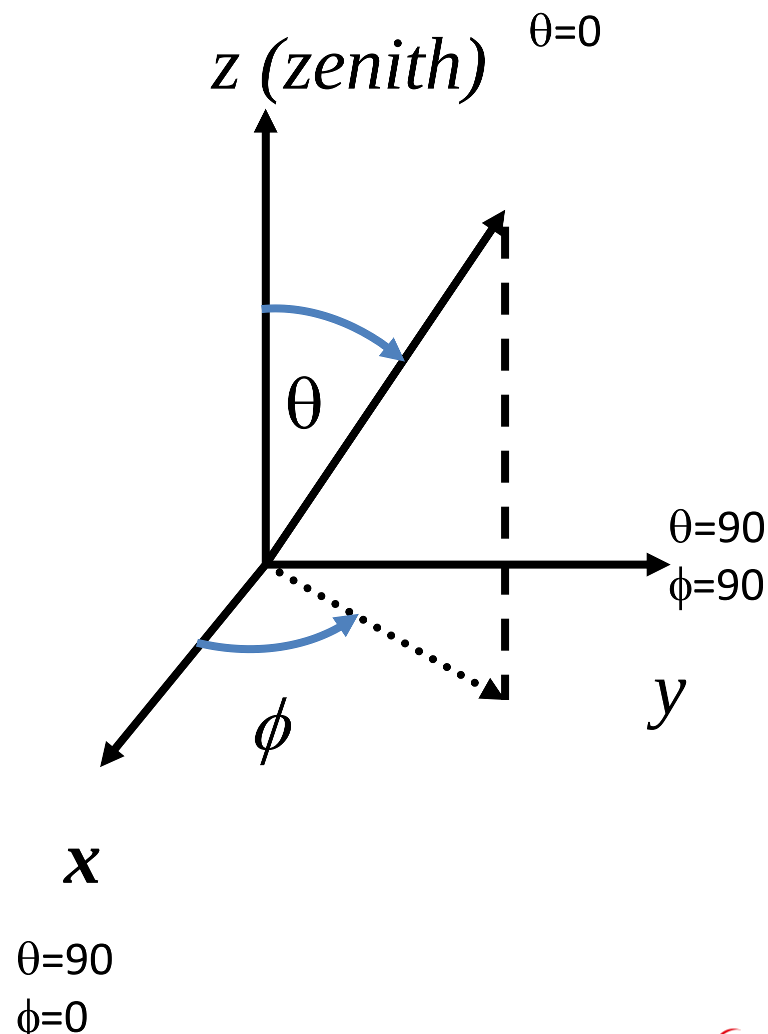
Omni-directional



Directional

Spherical coordinates

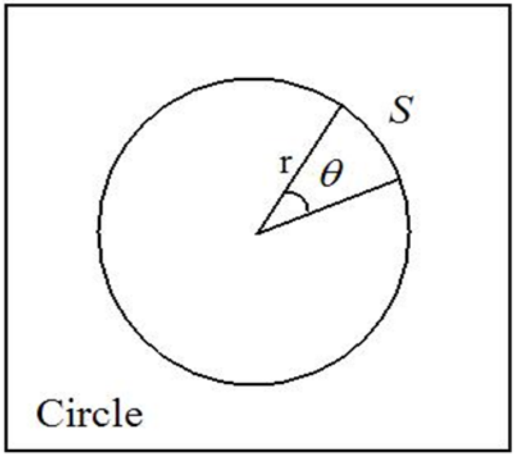


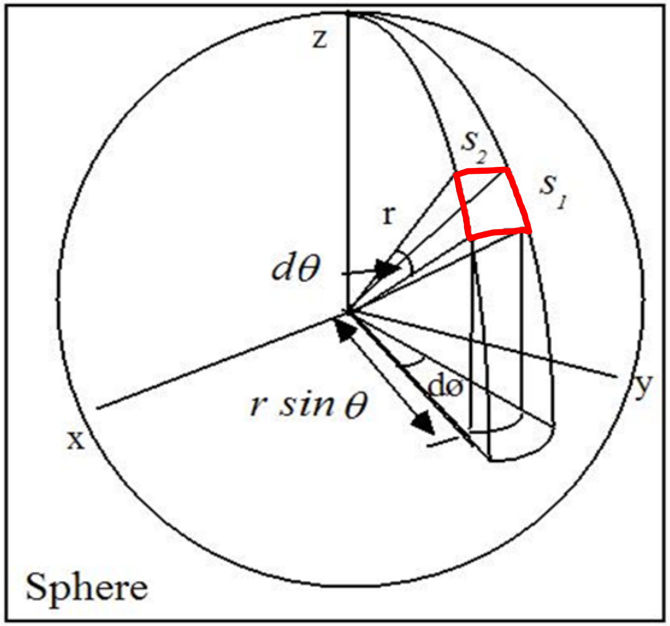


ϕ = azimuth

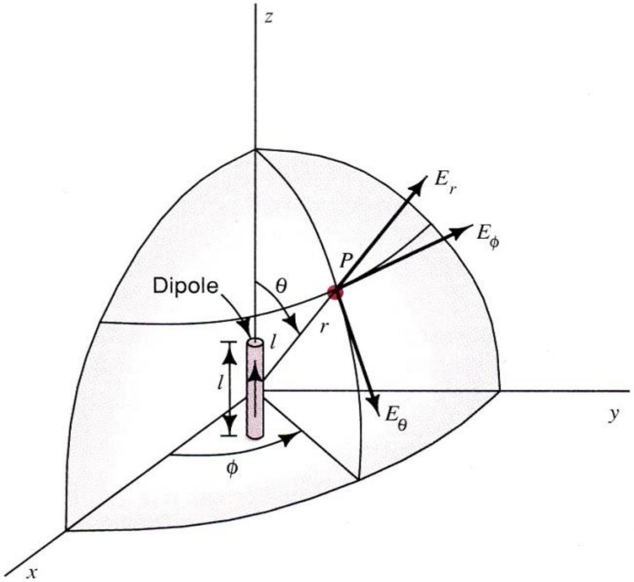
θ = elevation

Solid Angle





$S = r\theta$



$s_1 = r\, d\vartheta \qquad s_2 = r \sin\theta\, d\varphi$

$dA = s_1\, s_2$

$dA = r^2 \sin\theta\, d\varphi\, d\vartheta$

$= r^2\, d\Omega$

Radiation Intensity

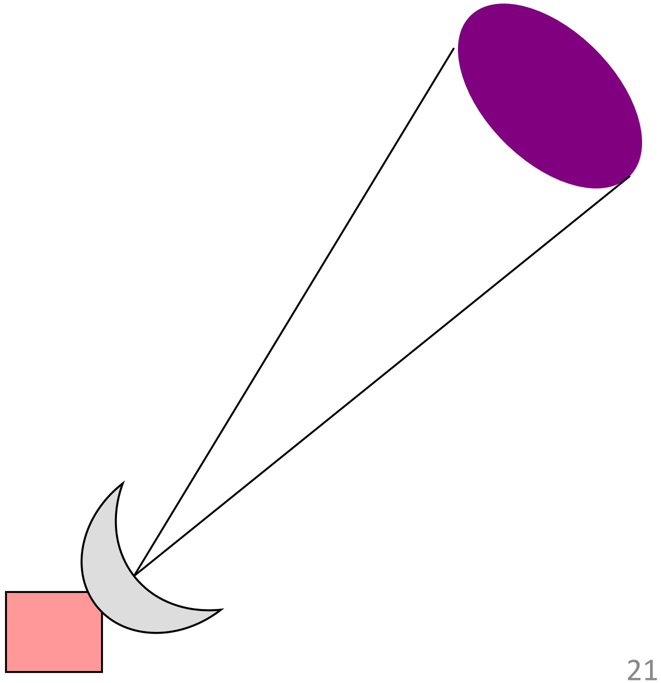
- Is the **power density per solid angle**:

$$U = r^2 \mathcal{P}_{\mathrm{r}} \qquad [\mathrm{W/sr}]$$

where

$$\mathcal{P}_r = ½ \ \mathrm{Re}\{E \times H^*\}\hat{r} \ [\mathrm{W/m^2}]$$

is the power density also known as Poynting vector.



Radiation Pattern

- A **radiation pattern** is a three-dimensional, graphical representation of the **far-field** radiation properties of an antenna as a function of space coordinates.
- The far-field region is a region far enough for the radiation pattern to be independent of the distance from the antenna.
- The radiation pattern of an antenna can be measured in an anechoic chamber or calculated, if the current distribution is known.
- Typically measured in two planes:
  - **E** Plane
  - **H** Plane

Field pattern:

$$E_n(\theta,\phi) = \frac{E(\theta,\phi)}{E_{\max}(\theta,\phi)}$$

Power pattern:

$$F_n(\theta,\phi) = \frac{\mathcal{P}(\theta,\phi)}{\mathcal{P}_{\max}(\theta,\phi)} = \frac{U(\theta,\phi)}{U_{\max}(\theta,\phi)}$$

Radiation pattern – variation of the field intensity of an antenna as an angular function with respect to the axis

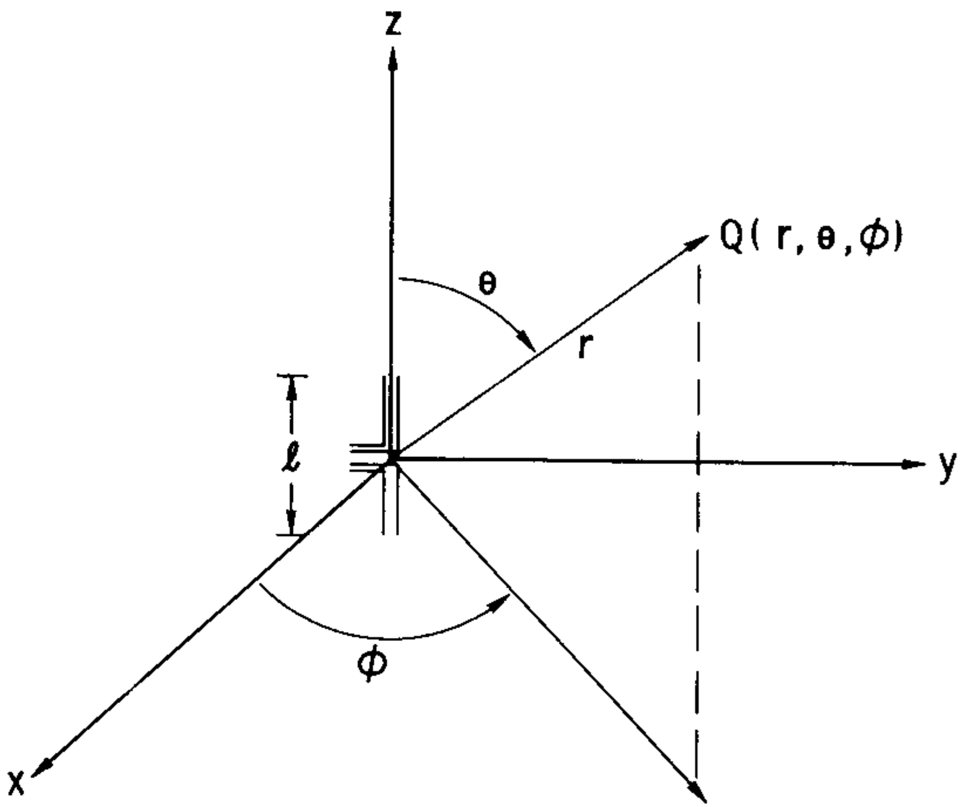
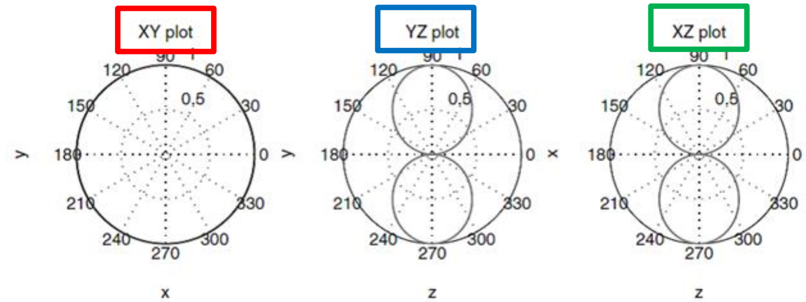
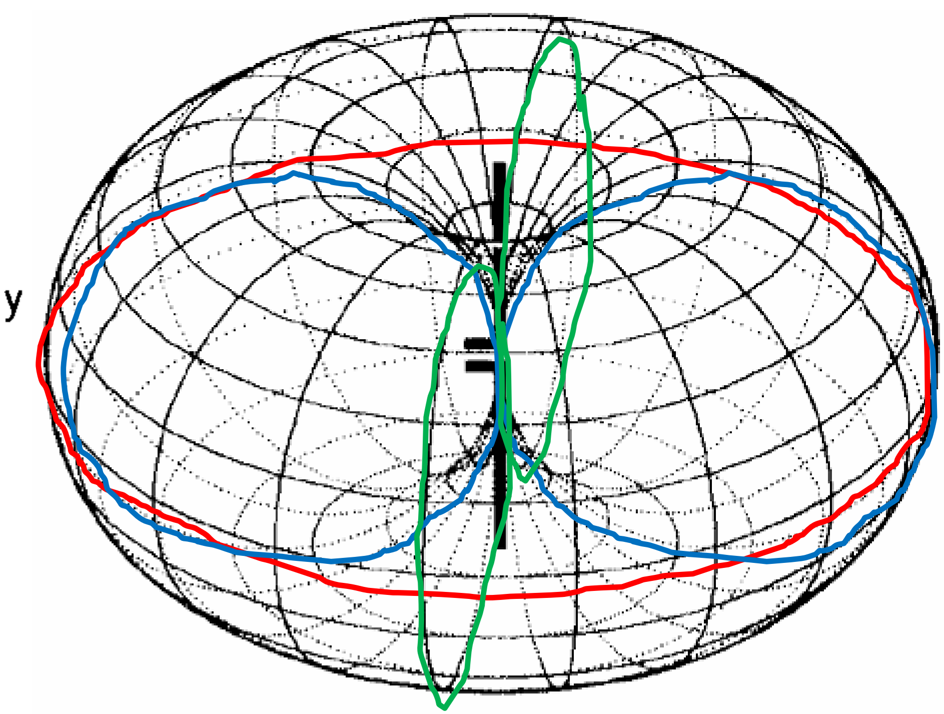


Fig. 3.7 Short dipole placed at the origin of a spherical coordinate system.

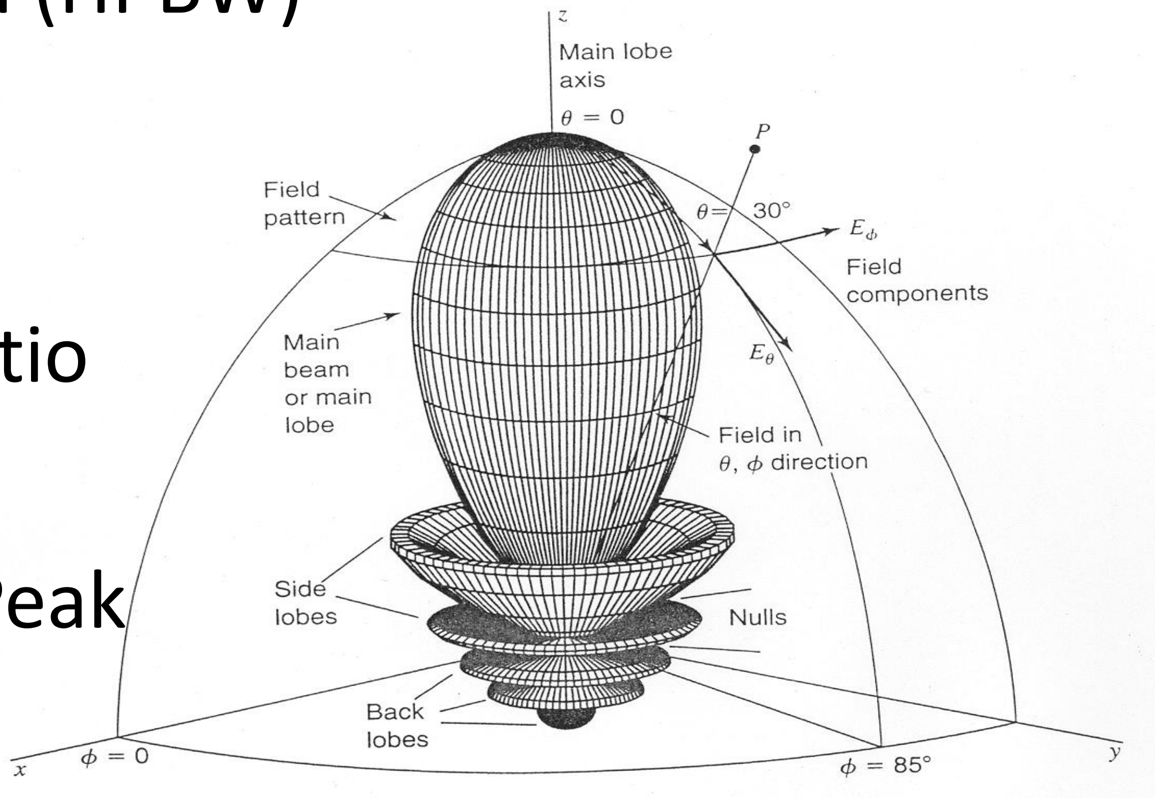




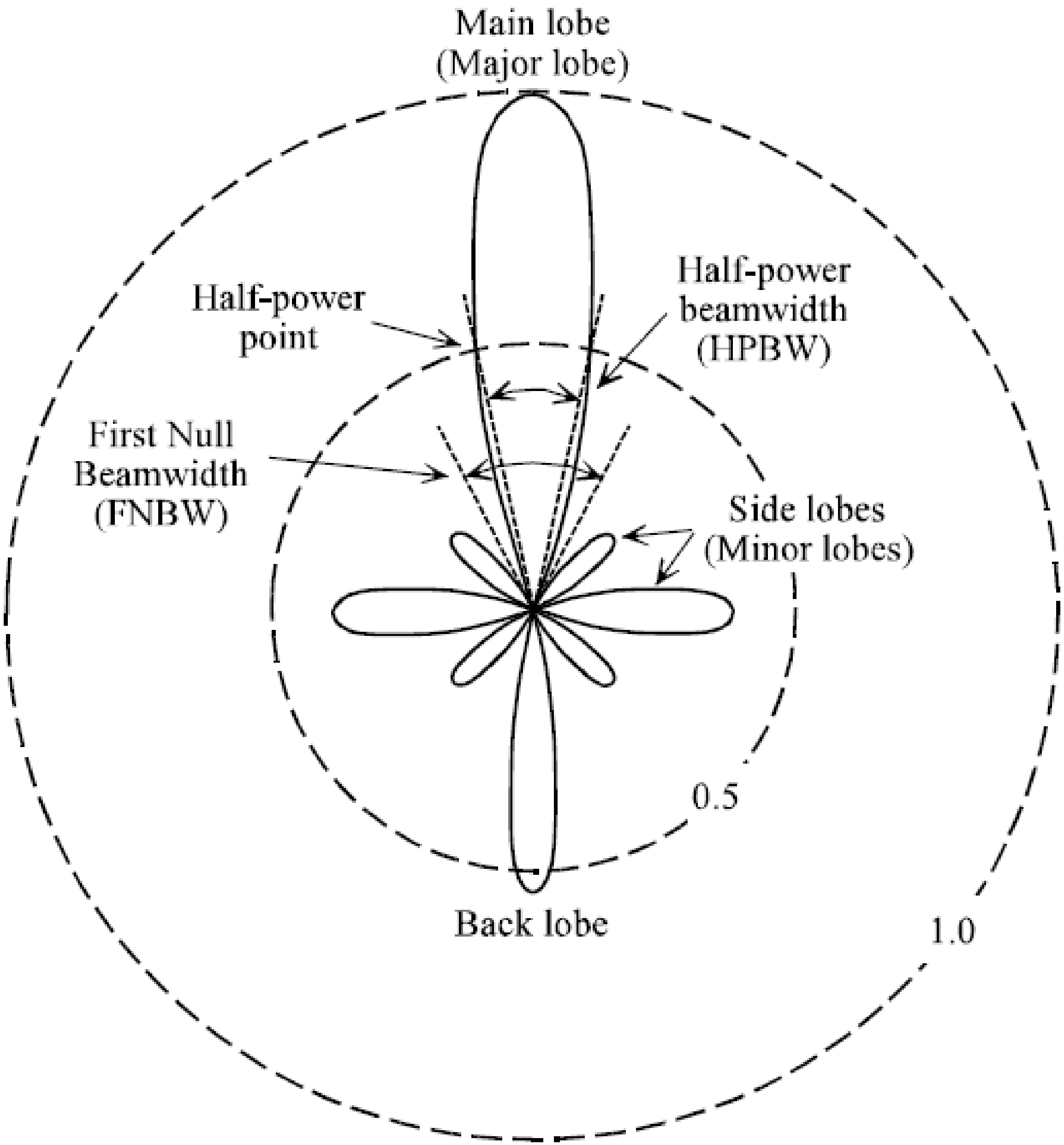
Three-dimensional representation of the radiation pattern of a dipole antenna

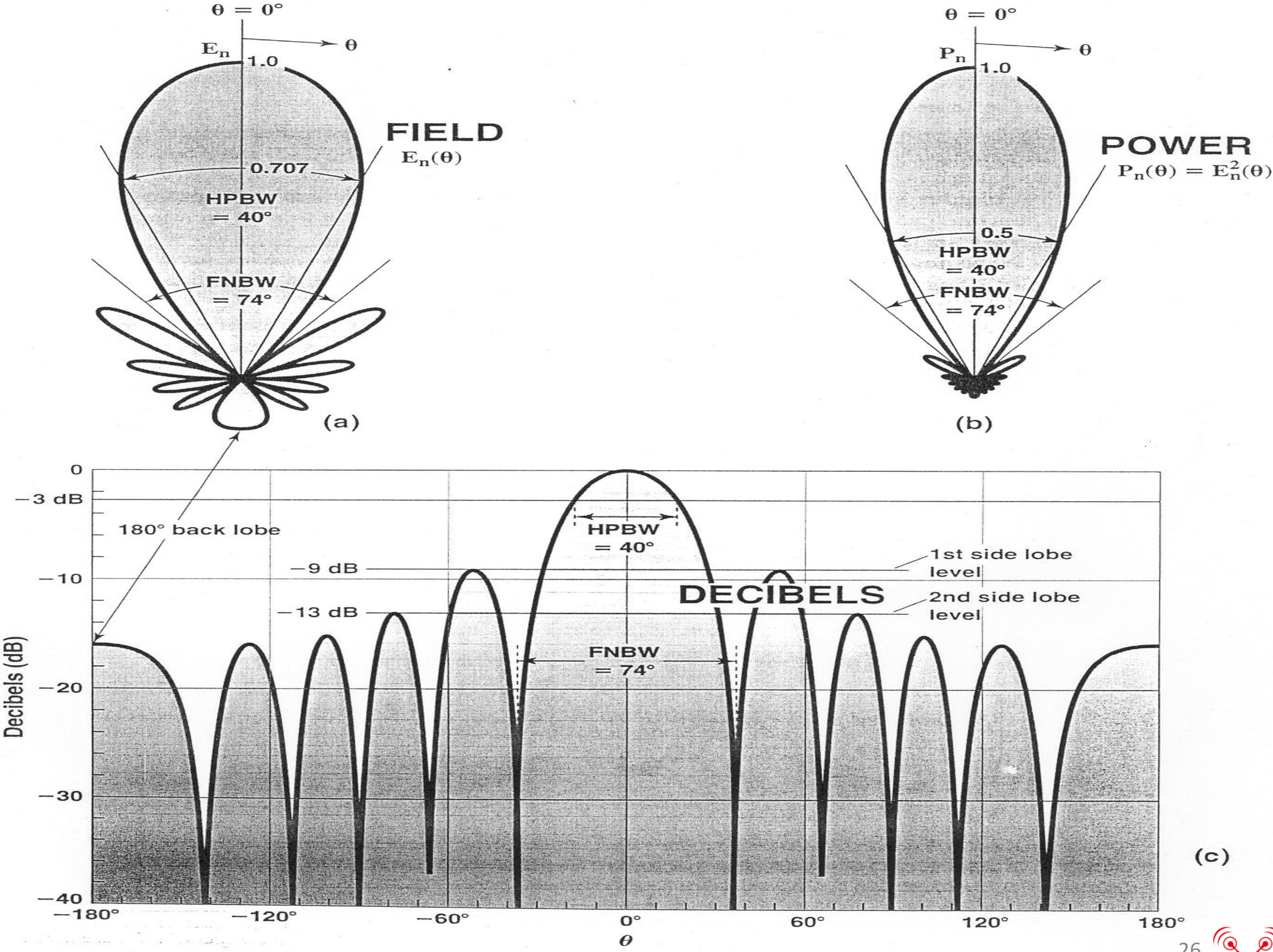
Radiation Pattern Characteristics

- 3dB beam-width (HPBW)
- Sidelobes
- Nulls
- Front-to-back ratio
- Gain
- Position of the Peak



Antenna Pattern Parameters





θ = 0°
E_n
1.0
θ
FIELD
$E_n(\theta)$
0.707
HPBW
= 40°
FNBW
= 74°
(a)
θ = 0°
P_n
1.0
θ
POWER
$P_n(\theta) = E_n^2(\theta)$
0.5
HPBW
= 40°
FNBW
= 74°
(b)
0
−3 dB
180° back lobe
HPBW
= 40°
−9 dB
1st side lobe level
−10
DECIBELS
−13 dB
2nd side lobe level
FNBW
= 74°
Decibels (dB)
−20
−30
(c)
−40
−180°
−120°
−60°
0°
60°
120°
180°
θ

Directivity and Gain of an Antenna

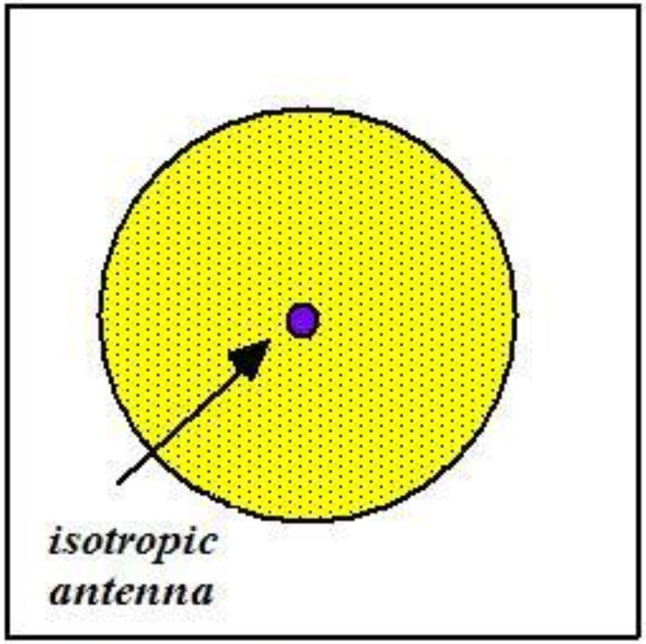
- The ***Directivity*** or ***Gain*** of an antenna is defined as the ratio of the maximum value of the power radiated per unit solid angle to the average power radiated per unit solid angle

- **Directivity** is a fundamental antenna parameter. It is a measure of how '***directional***' an antenna's radiation pattern is. An antenna that radiates equally in all directions would have effectively zero directionality, and the directivity of this type of antenna would be 1 (or 0 dB). *Remember Isotropic Antenna???*

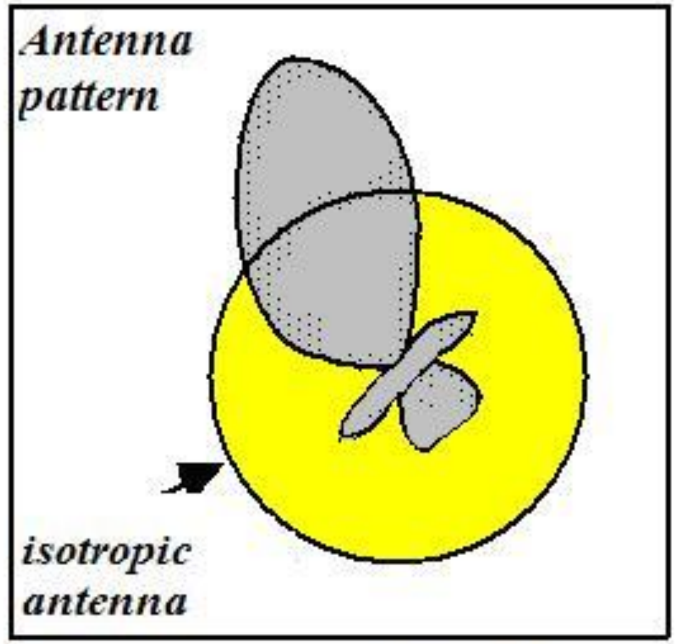
- It measures the power density of the antenna radiates in the direction of its strongest emission, versus the power density radiated by an ideal Isotropic Radiator (which emits uniformly in all directions) radiating the same total power.

- Directivity is a component of its Gain, If lossless antenna, $G=D$

Gain or Directivity



Isotropic Pattern



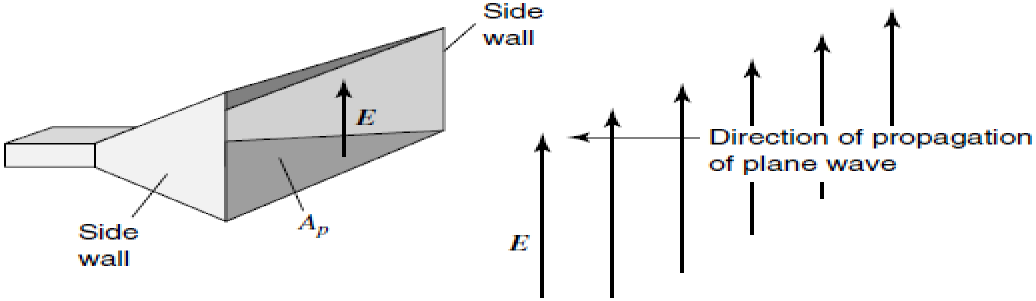
Comparison of regular antenna pattern with isotripic

An isotropic antenna and a practical antenna fed with the same power. Their patterns would compare as in the figure on the right.

dBi: Gain of our antenna when compared to the isotropic.

Effective Aperture

"A useful parameter in calculating the received power of an antenna is the ***effective area*** or ***effective aperture***"



Effective area or Effective aperture (square meters)

The effective area corresponds to the effective absorbance area presented by an antenna to an incident plane wave. For an aperture antenna, it is equal to or smaller than the physical aperture. The relationship between the gain and the wavelength is:

$$G = \frac{4\pi}{\lambda^2} A_e$$

Antenna Impedance

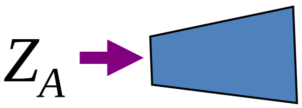
Antenna *Input impedance* is very important because it is generally desired:

- to supply maximum available power from the transmitter to the antenna or
- to extract maximum amount of received energy from the antenna.

Antenna Impedance

- An antenna is "seen" by the generator as a load with impedance Z_A, connected to the line.

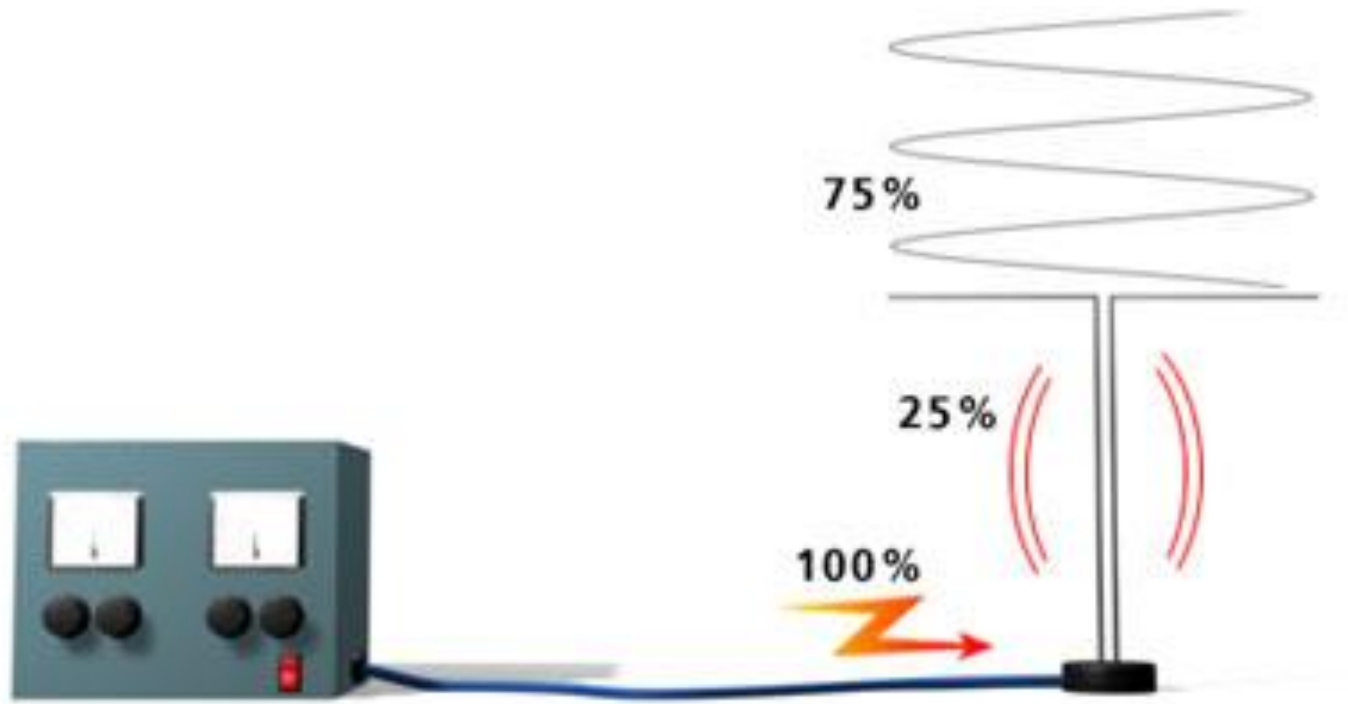
$$Z_A = (R_{rad} + R_L) + jX_A$$



- **The real part is the radiation resistance plus the ohmic resistance**.
  - Minimizing impedance differences at each interface will reduce SWR and maximize power transfer through each part of the antenna system.
  - Complex impedance, Z_A, of an antenna is related to the electrical length of the antenna at the wavelength in use.
    - The impedance of an antenna can be matched to the feed line and the generator by adjusting the impedance of the feed line, using the feed line as an impedance transformer.
    - More commonly, the impedance is adjusted at the load with an antenna tuner, a balun, which is a matching transformer. Usually matching networks are composed of inductors and capacitors.

Antenna Impedance

The radiation resistance does not correspond to a real resistor present in the antenna, but to the resistance of space coupled via the beam to the antenna terminals.



Radiation Resistance

- The antenna is a radiating device in *which power is radiated into space in the form of electromagnetic waves*. Hence there must be power dissipation which may be expressed in usual manner as

$$W=I^2R$$

- If it is assumed that all this power appears as electromagnetic radio waves, then this power can be divided by the square of the current, i.e.

$$R_r=W/I^2$$

at the point where it is fed to the antenna and obtain a fictitious resistance called ***Radiation resistance***.

Radiation Resistance

- Thus "Radiation Resistance can be defined as that fictitious resistance which when substituted in series with the antenna will consume the same power as is actually radiated".

- The Total Power Loss in an antenna is sum of the two losses

  Total Power Loss = Ohmic Loss + Radiation Loss

$$
\begin{aligned}
W &= W' + W'' \\
&= I^2 R_r + I^2 R_l \\
&= I^2 (R_r + R_l) \\
&= I^2 R
\end{aligned}
$$

Radiation Resistance

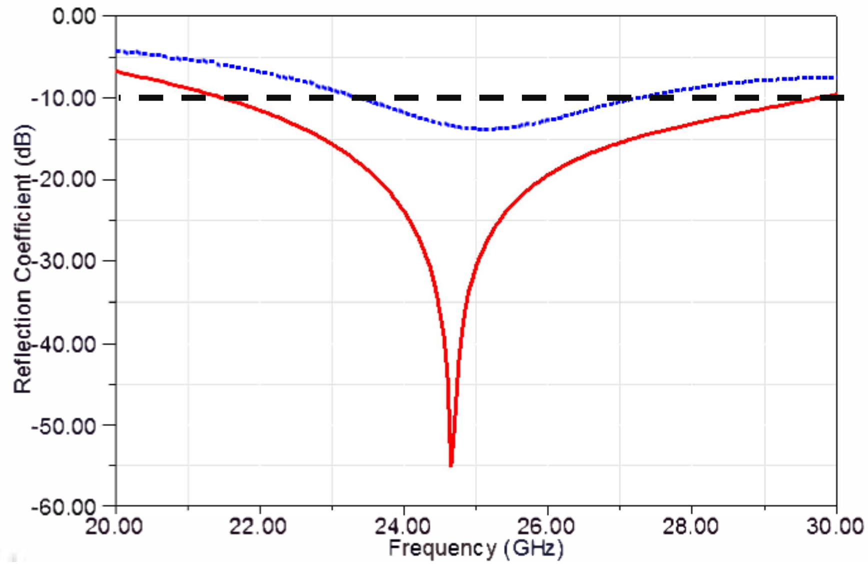
The value of Radiation Resistance depends on:

- ✓ Configuration of Antenna
- ✓ Point where radiation resistance is considered
- ✓ Location of antenna with respect to ground and other objects
- ✓ Ratio of length of diameter of conductor used
- ✓ Corona Discharge-a luminous discharge round the surface of antenna due to ionization of air etc.

Antenna Bandwidth

- Antenna Bandwidth is the range of frequency over which the antenna maintains certain required characteristics like gain, front to back ratio or SWR pattern (shape or direction), polarization and impedance

- It is the bandwidth within which the antenna maintains a certain set of given specifications.



Antenna Bandwidth (2)

- The **bandwidth** of an antenna is the range of frequencies over which it is effective, and it is usually centered around the operating or resonant frequency.
  - The bandwidth of an antenna may be increased by several techniques, including
    - using thicker wires,
    - replacing wires with *cages* to simulate a thicker wire,
    - tapering antenna components (like in a feed horn),
    - and combining multiple antennas into a single assembly(Arrays) and allowing the natural impedance to select the correct antenna.

Antenna Bandwidth (3)

Most antenna technologies can support operation over a frequency range that is 5 to 10% of the central frequency.

(e.g., 100 or 200 MHz bandwidth at 2 GHz)

To achieve wideband operation requires specialized antenna technologies.

(e.g., Vivaldi, bowtie, spiral)

Baluns

- Balun = BALanced – Unbalanced

- A balun is a device that joins a balanced line (one that has two conductors, with equal currents in opposite directions, such as a twisted pair cable) to an unbalanced line (one that has just one conductor and a ground, such as a coaxial cable).

- So it is used to convert an unbalanced signal to a balanced one or vice versa.

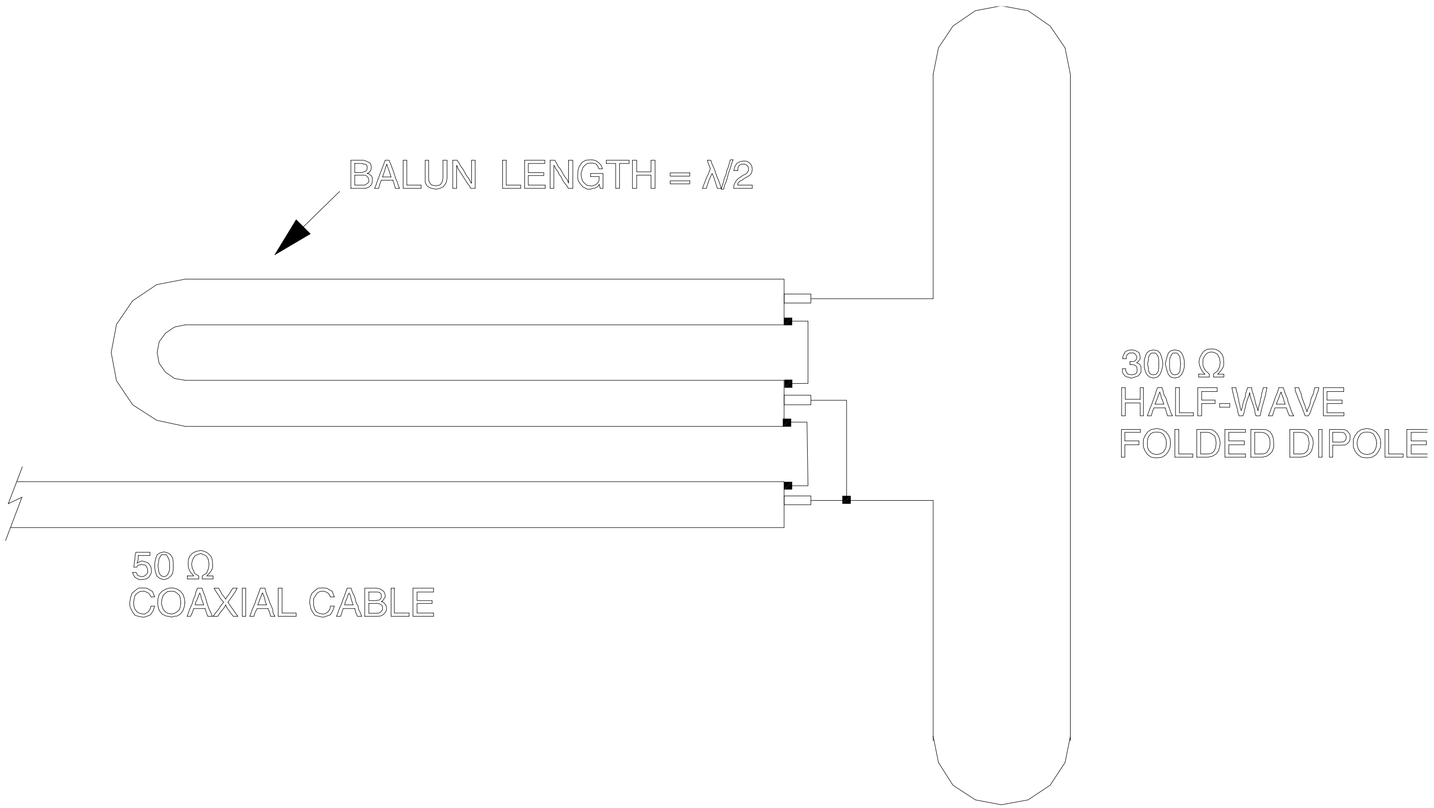
- **Baluns** isolate a transmission line and provide a balanced output.

- A typical use for a **balun** is in television antennas.

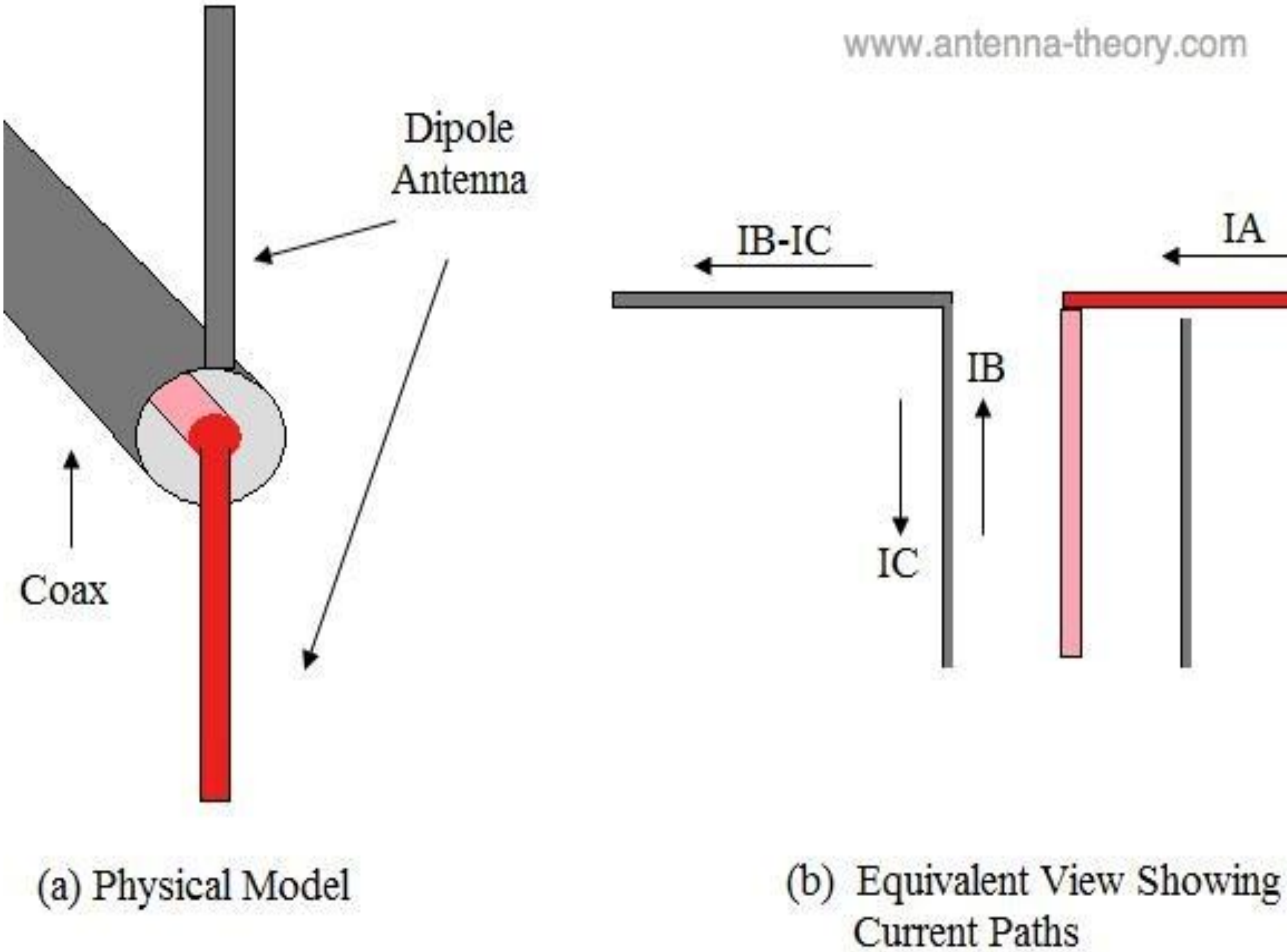
Baluns (2)

- A **balun** is a type of transformer used at RF
  - Impedance-transformer baluns having a 1:4 ratio are used between systems with impedances of 50 or 75 ohms (unbalanced) and 200 or 300 ohms (balanced). Most television and FM broadcast receivers are designed for 300-ohm balanced systems, while coaxial cables have characteristic impedances of 50 or 75 ohms. Impedance-transformer baluns with larger ratios are used to match high-impedance balanced antennas to low-impedance unbalanced wireless receivers, transmitters, or transceivers.
- Usually band-limited
- Improve matching and prevent unwanted currents on coaxial cable shields
- As in differential signaling, the **rejection of common mode current** is the most important metric for an antenna feed balun, although performance also requires proper impedance ratios and matching to the antenna.

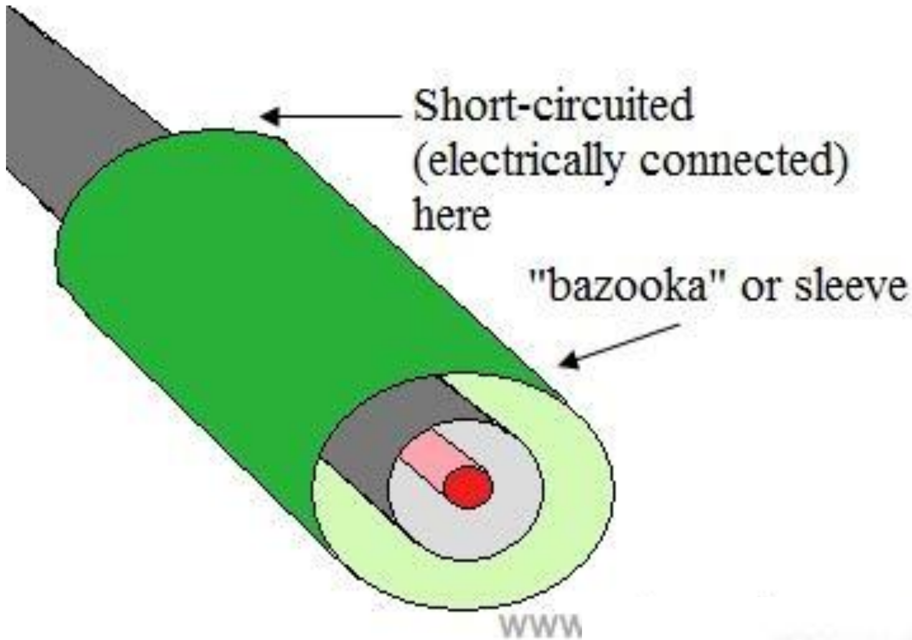
Baluns as impedance transformers



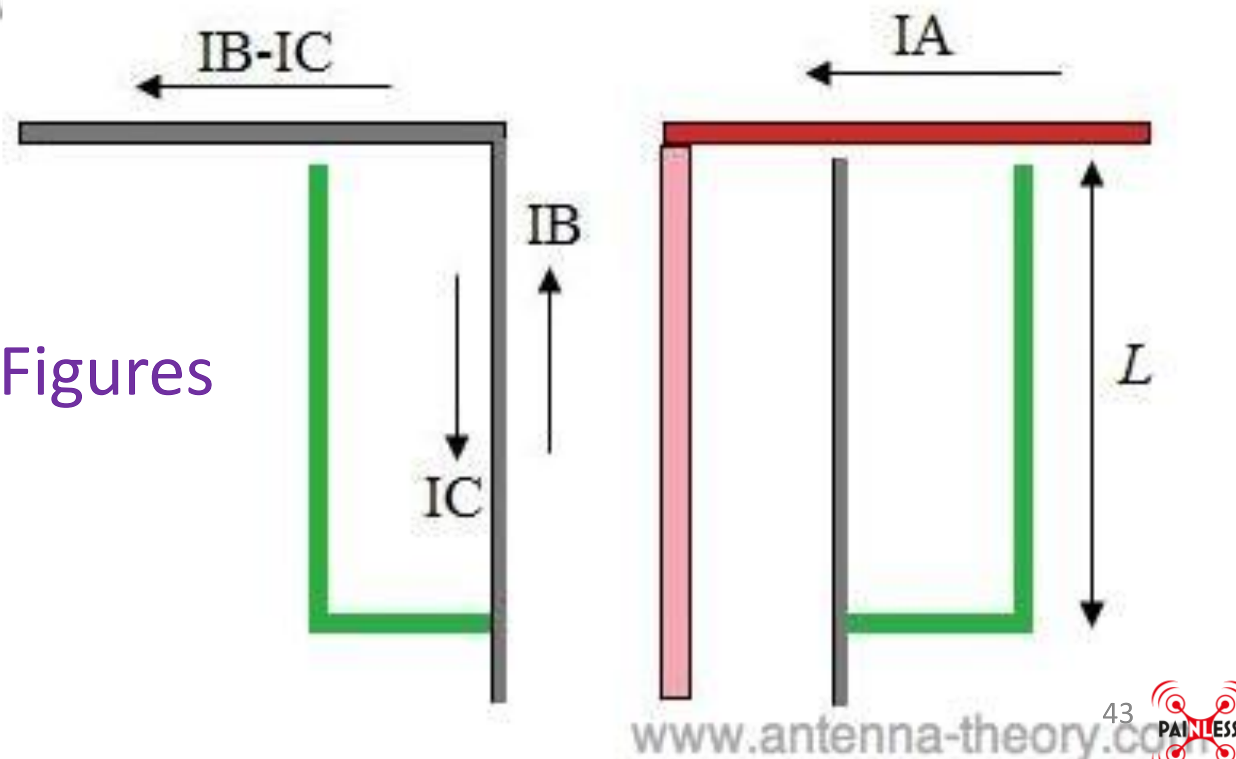
Transition from a 50Ώ coaxial cable to a 300Ώ half-wave folded dipole through a four-to-one impedance transformation balun



Forcing *IC* to be zero somehow - this is often called choking the current or a current choke is needed.



This <u>balun</u> adds a short-circuited sleeve around the coaxial cable to choke the ***Ic***



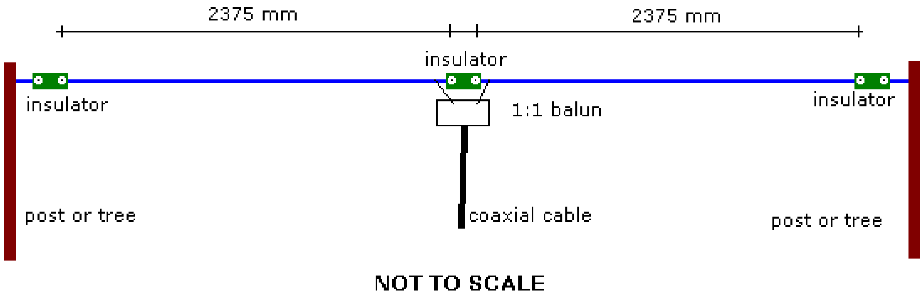
The green sleeve in Figures 1 and 2 acts as a transmission line

Types of Antennas

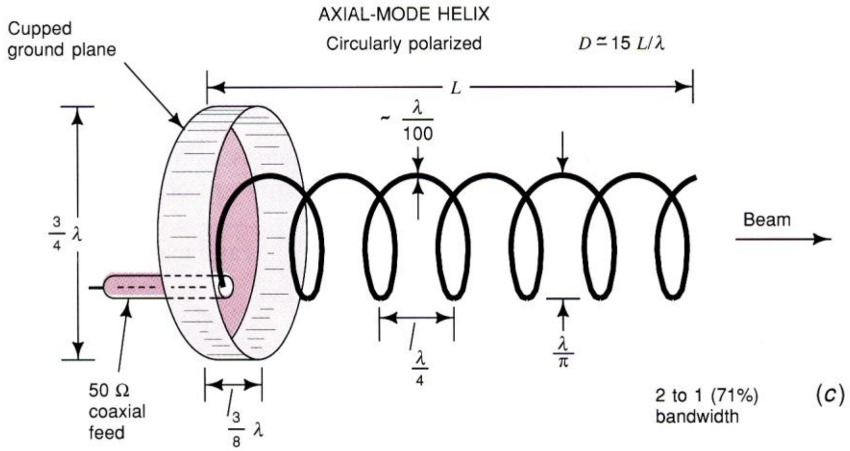
- Wire antennas
- Aperture antennas
- Arrays of antennas

Wire Antennas

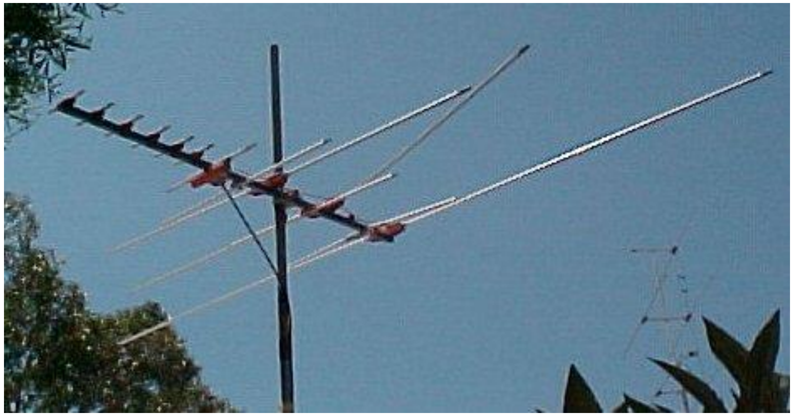
- Dipole
- Loop
- Folded dipoles
- Helical antenna
- Yagi-Uda (array of dipoles)
- Corner reflector
- Many more types



Horizontal dipole



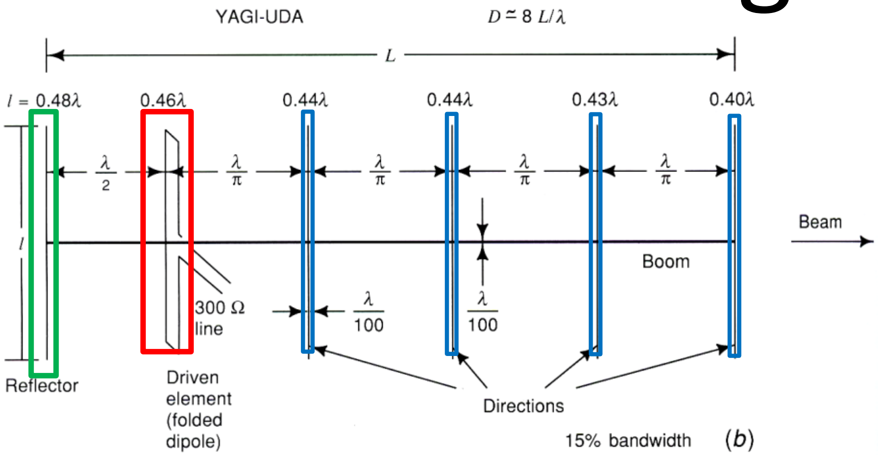
Yagi-Uda antenna

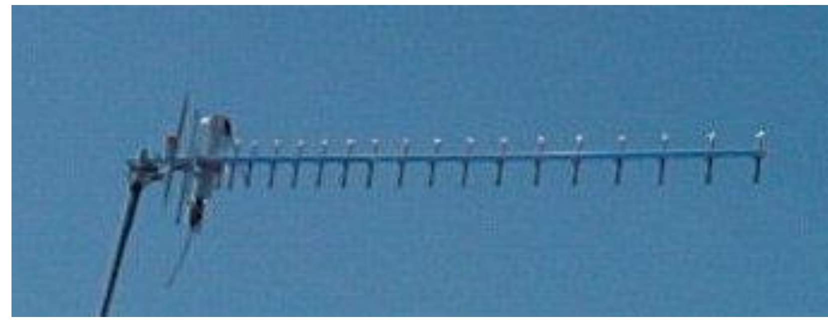


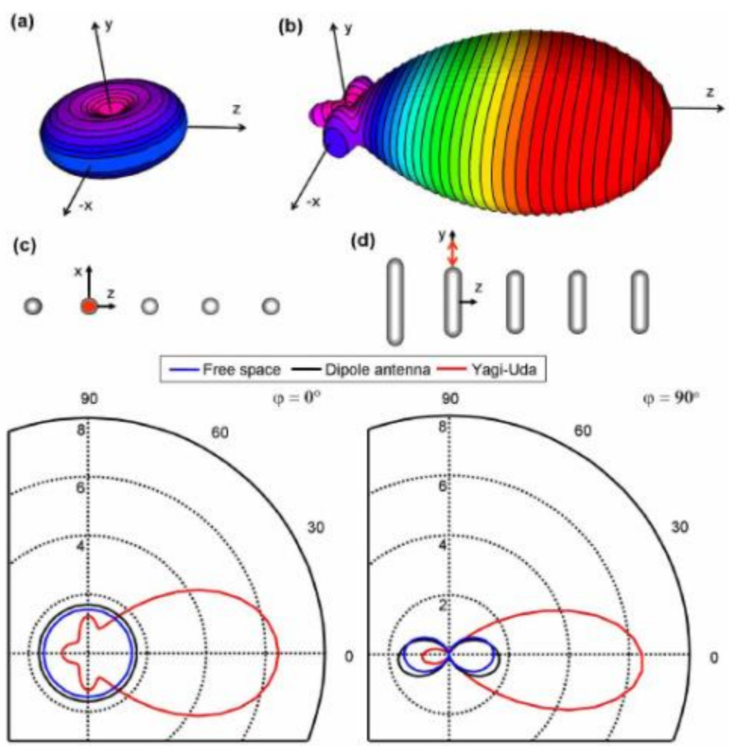
Wire Antennas – Resonance

- Many wire antennas (but not all) are used at or near resonance
- Some times it is not practical to built the whole resonant length
- The physical length can be shortened using loading techniques
  - Inductive load: e.g. center, base or top coil (usually adjustable)
  - Capacitive load: e.g. capacitance “hats” (flat top at one or both ends)

Yagi – Uda







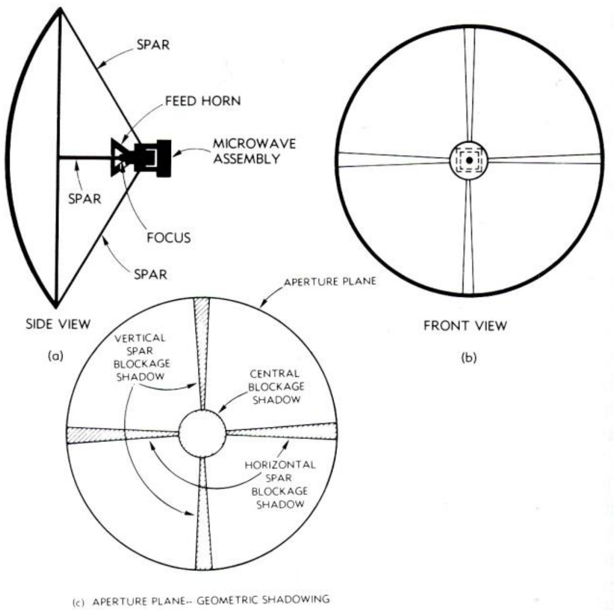
Elements	Gain dBi	Gain dBd
3	7.5	5.5
4	8.5	6.5
5	10	8
6	11.5	9.5
7	12.5	10.5
8	13.5	11.5

Aperture Antennas

- Collect power over a well defined aperture
- Large compared to wavelength
- Various types:
  - Reflector antennas
  - Horn antennas
  - Lens antennas

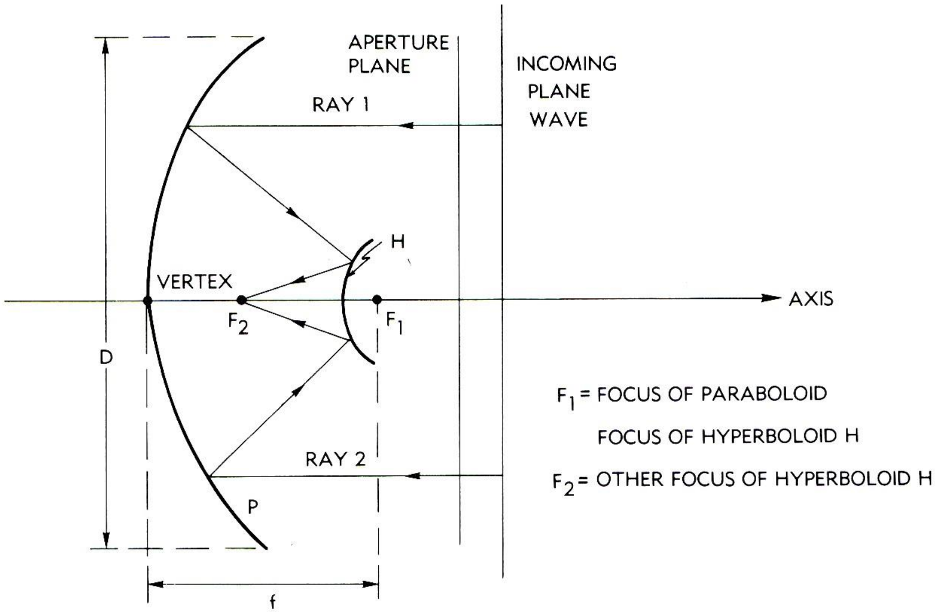
Reflector Antennas

- Shaped reflector: parabolic dish, cylindrical antenna …
  - Reflector acts as a large collecting area and concentrates power onto a focal region where the feed is located
- Combined optical systems: Cassegrain, Nasmyth …
  - Two (Cassegrain) or three (Nasmyth) mirrors are used to bring the focus to a location where the feed including the transmitter/receiver can be installed more easily.



Cassegrain Antennas

- Less prone to back scatter than simple parabolic antenna
- Greater beam steering possibility: secondary mirror motion amplified by optical system
- Much more compact for a given frequency/dimension ratio



The Arecibo Observatory Antenna System

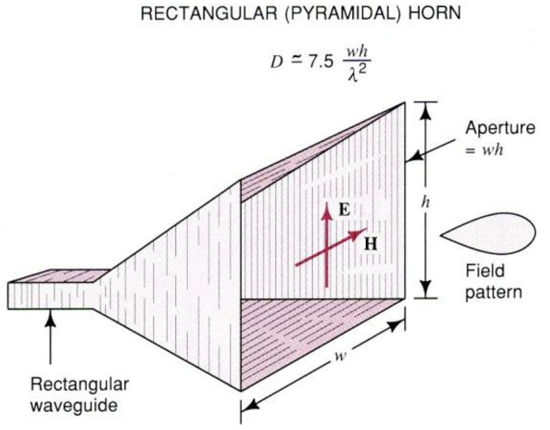
The world’s largest single radio telescope

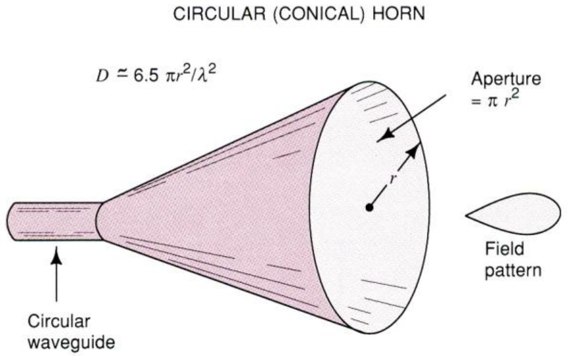
304.8m spherical reflector

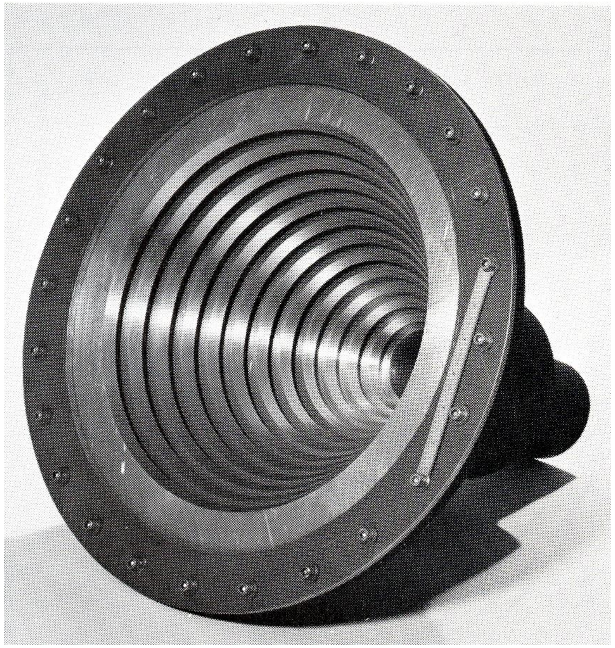
National Astronomy and Ionosphere Center (USA), Arecibo, Puerto Rico

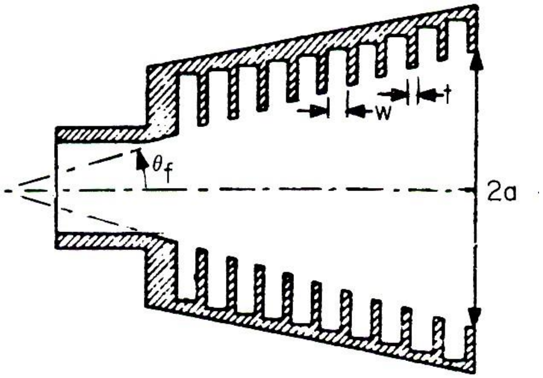
Horn Antennas

- Rectangular or circular waveguide flared up
- Spherical wave fronts from phase centre
- Flare angle and aperture determine gain

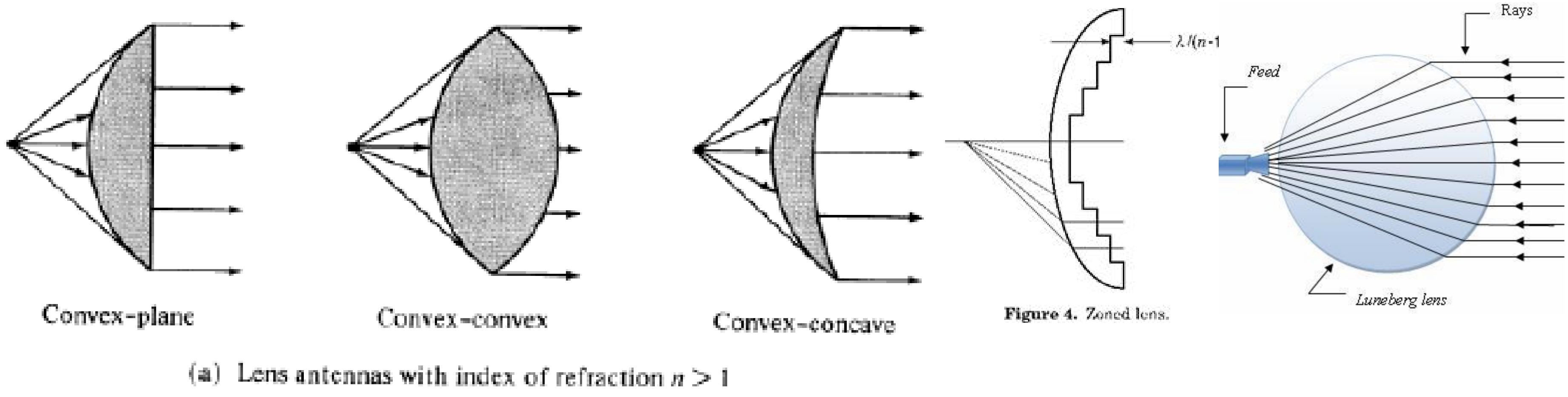








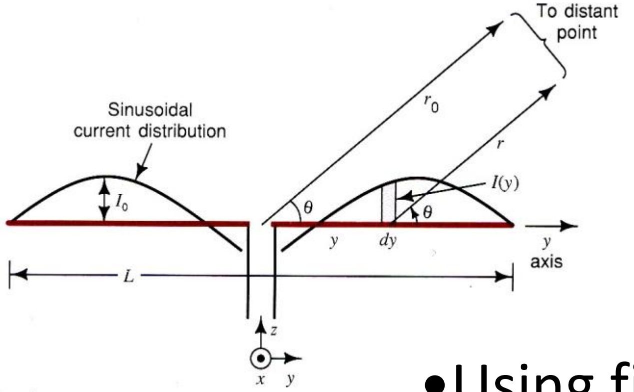
Lens antennas



- Lenses play a similar role to that of reflectors in reflector antennas: they collimate divergent energy
- Often preferred to reflectors at frequencies > 100 GHz.

Thin Wire Antenna

- Wire diameter is small compared to wavelength
- Current distribution along the wire is no longer constant



$$\text{e.g.}\quad I(y) = I_0 \sin\left(\frac{2\pi}{\lambda}\left(\frac{L}{2} \pm y\right)\right)$$

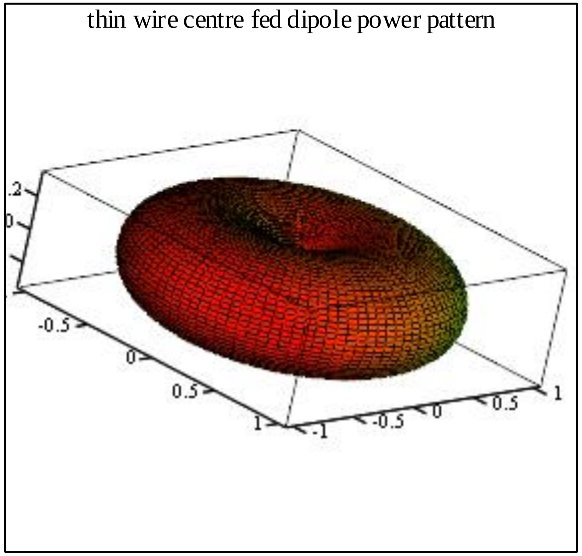
centre-fed dipole

- Using field equation for short dipole, replace the constant current with actual distribution

$$E_\theta = \frac{j60 I_0 e^{j(\omega t - \beta r)}}{r}\left(\frac{\cos\left(\frac{\beta L \cos(\theta)}{2}\right) - \cos\left(\frac{\beta L}{2}\right)}{\sin(\theta)}\right)$$

centre-fed dipole, I_0 = current at feed point

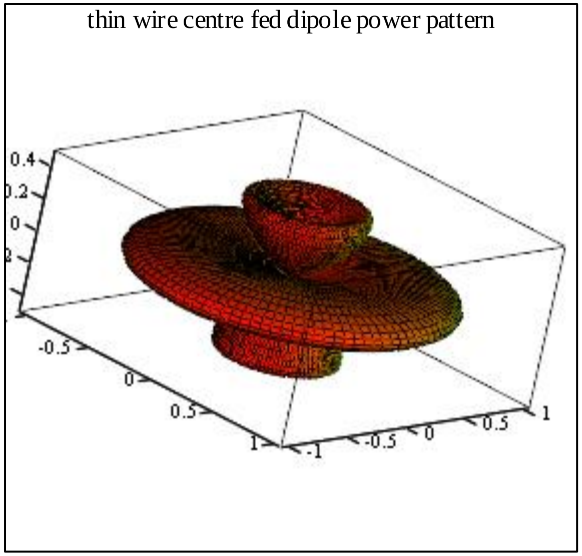
Thin Wire Patterns



(X, Y, Z)

$l = 1\frac{\lambda}{2}$

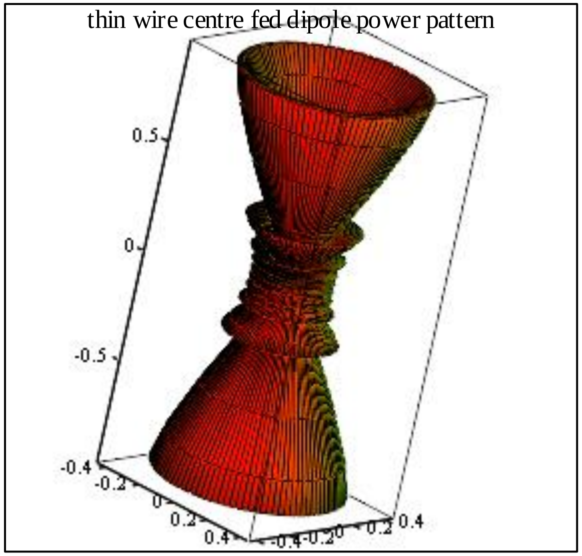
$\Omega_A = 7.735$ $D = 1.625$



(X, Y, Z)

$l = 1.395\lambda$

$\Omega_A = 5.097$ $D = 2.466$



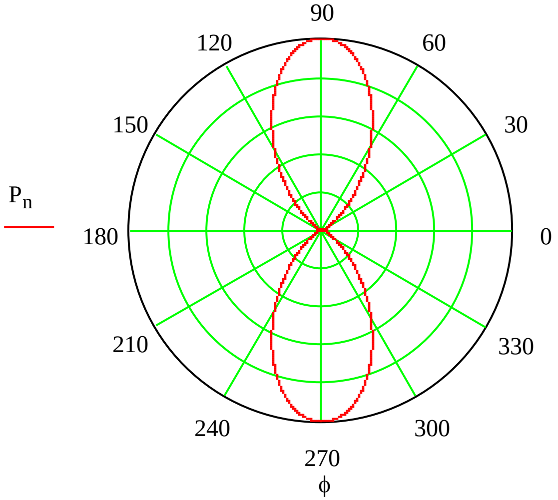
(X, Y, Z)

$l = 10\lambda$

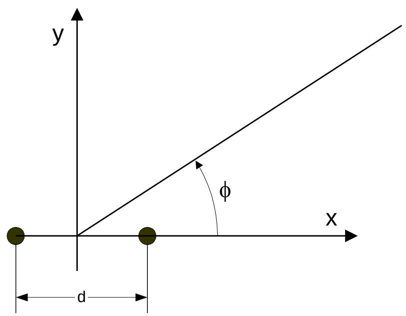
$\Omega_A = 1.958$ $D = 6.417$

Array of isotropic point sources – beam shaping

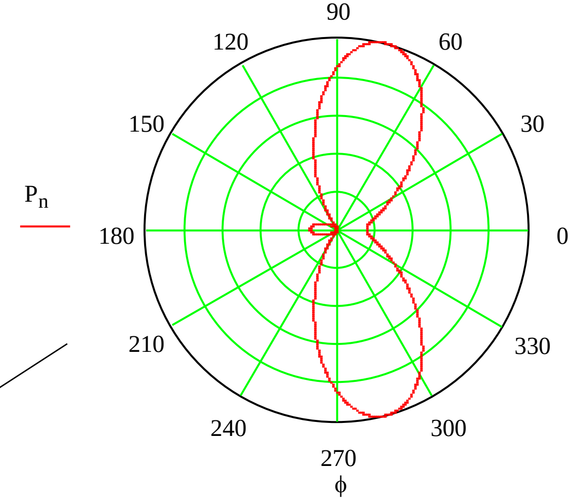
Power pattern of 2 isotropic sources



$d = 1\frac{\lambda}{2}$ $\delta = 0\,\text{deg}$

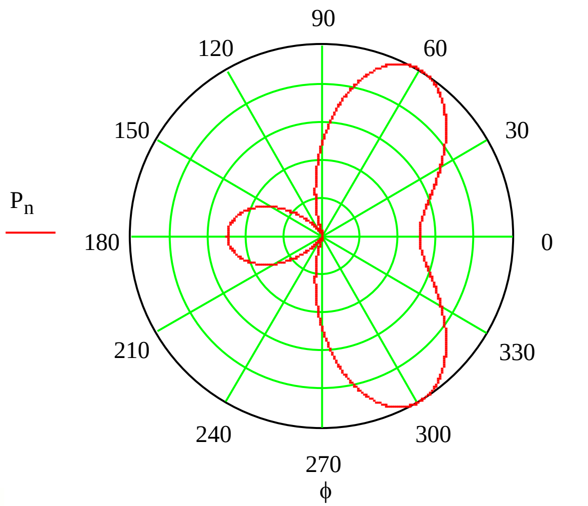


Power pattern of 2 isotropic sources



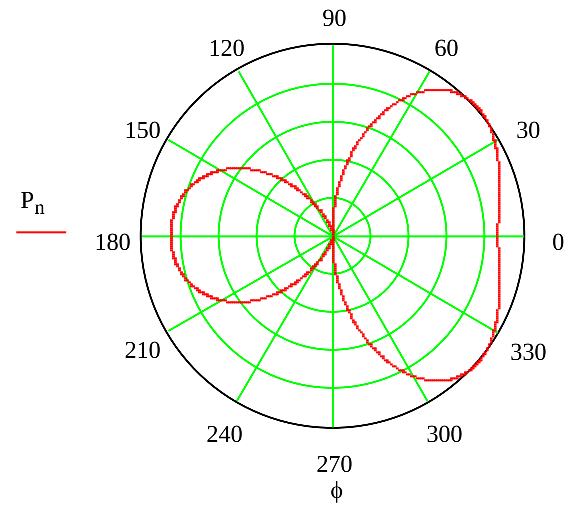
$d = 1\frac{\lambda}{2}$ $\delta = -45\,\text{deg}$

Power pattern of 2 isotropic sources



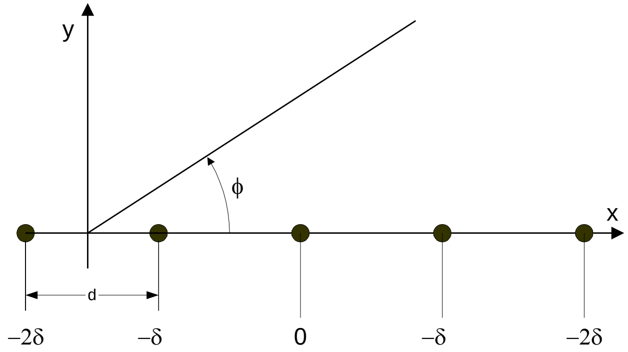
$d = 1\frac{\lambda}{2}$ $\delta = -90\,\text{deg}$

Power pattern of 2 isotropic sources



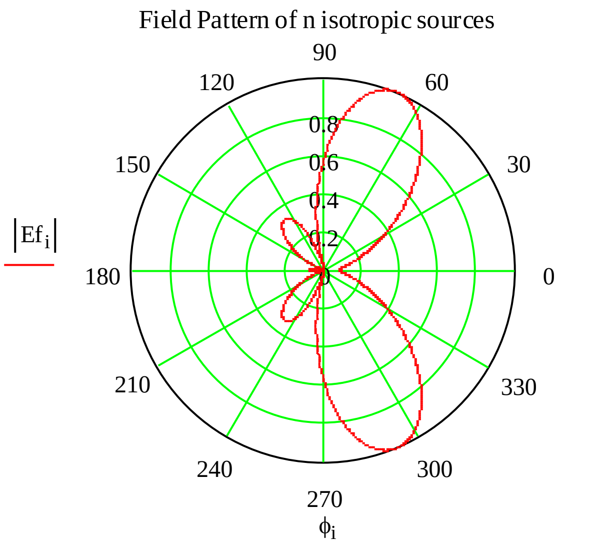
$d = 1\frac{\lambda}{2}$ $\delta = -135\,\text{deg}$

Array of isotropic point sources – center fed

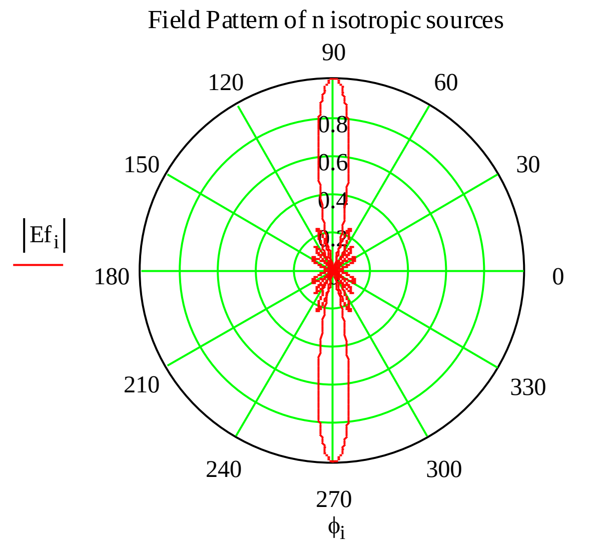


$$\psi(\phi) = \frac{2\pi d}{\lambda}\cos(\phi) + \delta$$

$$E_n(\psi) = \frac{1}{n}\frac{\sin\left(\frac{n\psi}{2}\right)}{\sin(\psi/2)}$$



n = 3 δ = −67.5deg d = 0.5λ

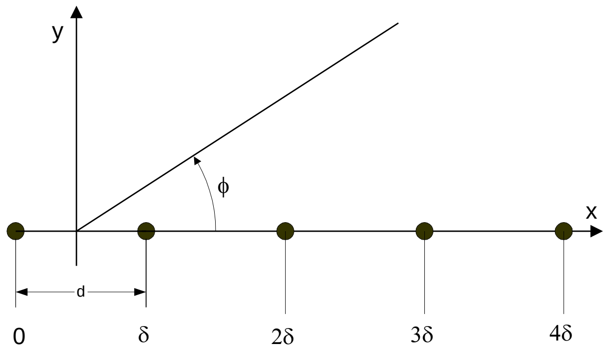


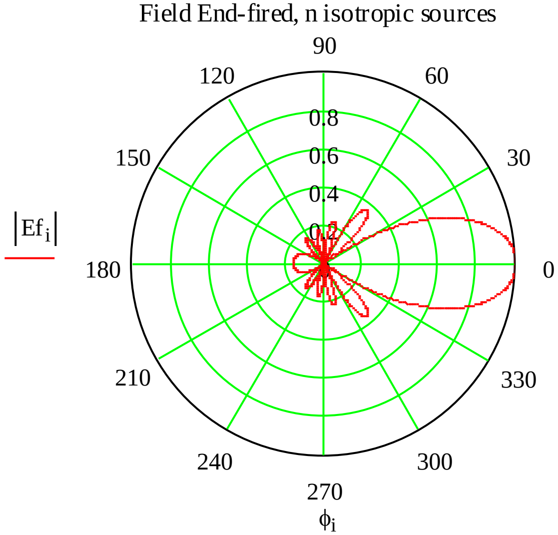
n = 8 δ = 0 deg d = 0.5λ

Array of isotropic point sources – End-fire fed

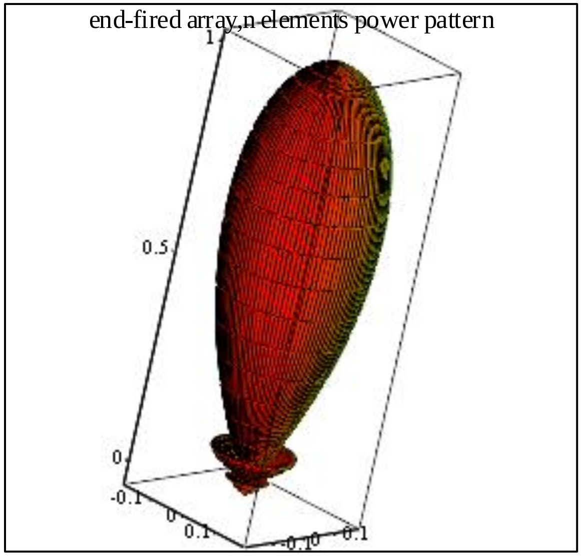
$$\psi(\phi) = \frac{2\pi d}{\lambda}(\cos(\phi) - 1) - \frac{\pi}{n}$$

$$E_n(\psi) = \sin\left(\frac{\pi}{2n}\right)\frac{\sin\left(\frac{n\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)}$$





n = 10 $\delta = -108\text{deg}$ $d = 1\frac{\lambda}{4}$

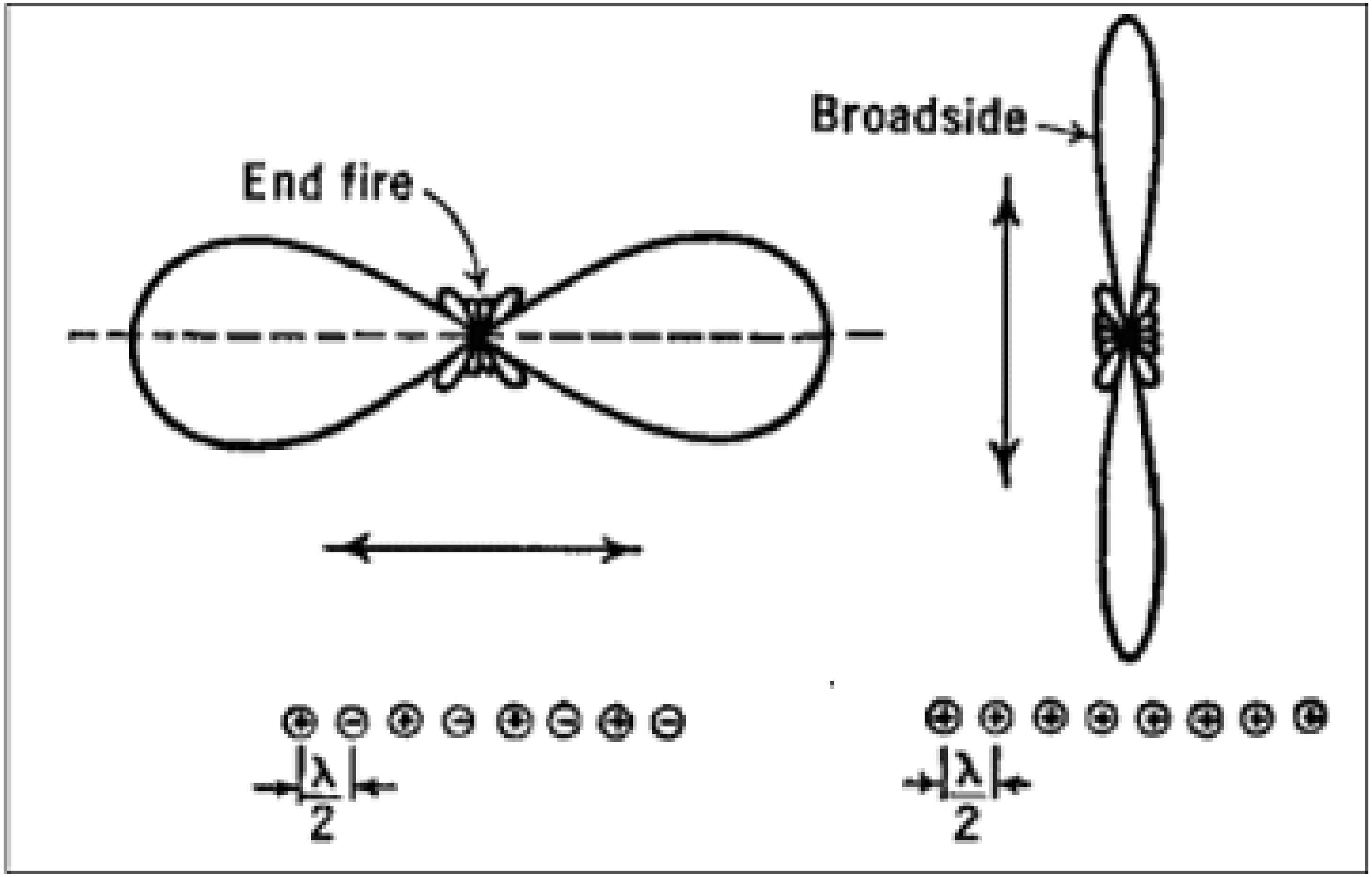


(X, Y, Z)

n = 10 $d = 0.25\lambda$

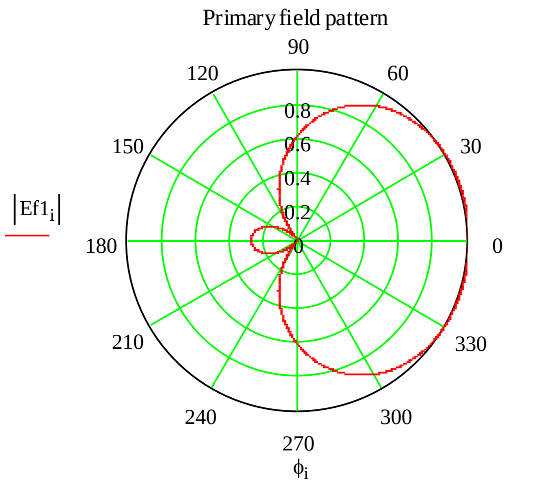
$\Omega_A = 0.713$ $D = 17.627$

Array of isotropic point sources – End-fire vs Broadside

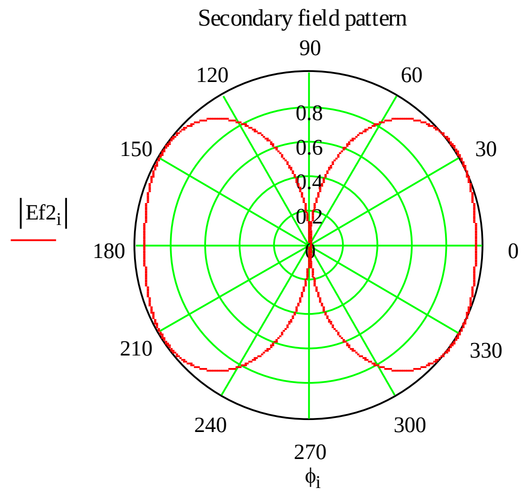


Pattern Multiplication

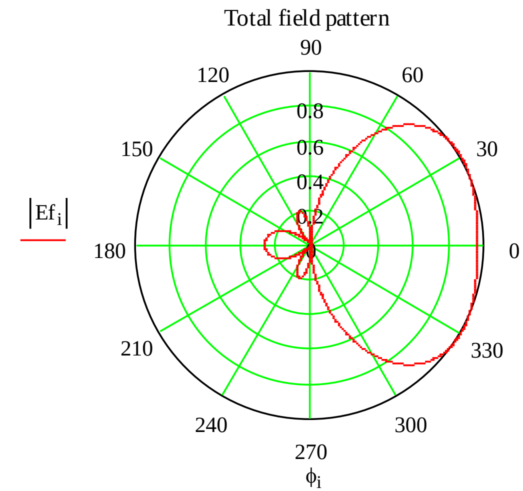
The total field pattern of an array of non-isotropic but similar point sources is the product of the individual source pattern and the pattern of an array of isotropic point sources having the same locations, relative amplitudes and phases as the non-isotropic point sources.



$n = 2$ $\delta 1 = -104deg$ $d1 = 0.3\lambda$



$n = 2$ $\delta 2 = 180deg$ $d2 = 0.6\lambda$

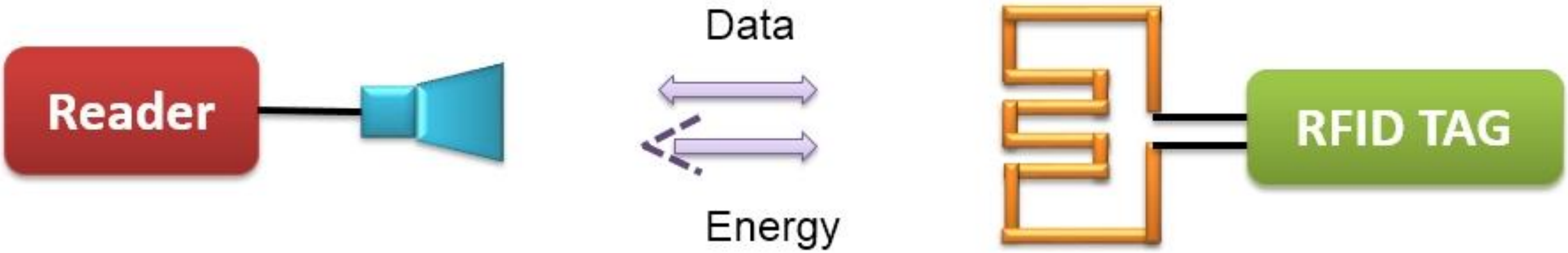


Total pattern of two primary sources (each an array of two isotropic sources) replacing two isotropic sources (4 sources in total).

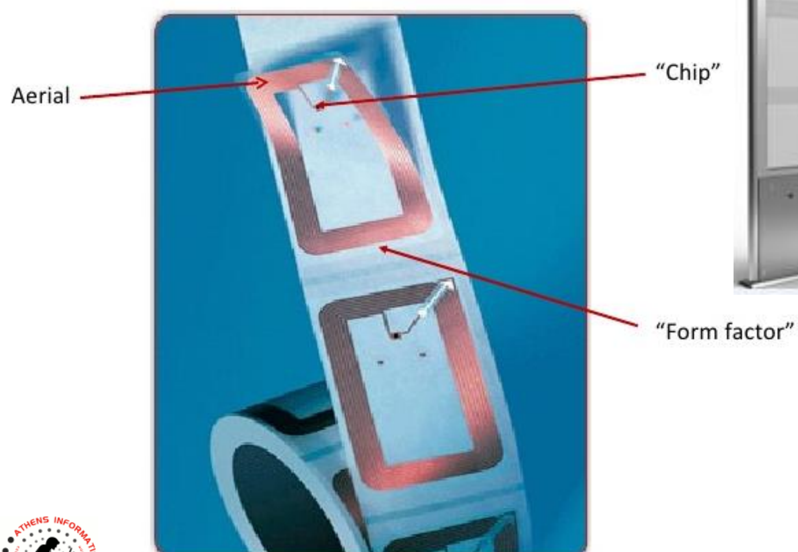
Typical Gain and Beamwidth

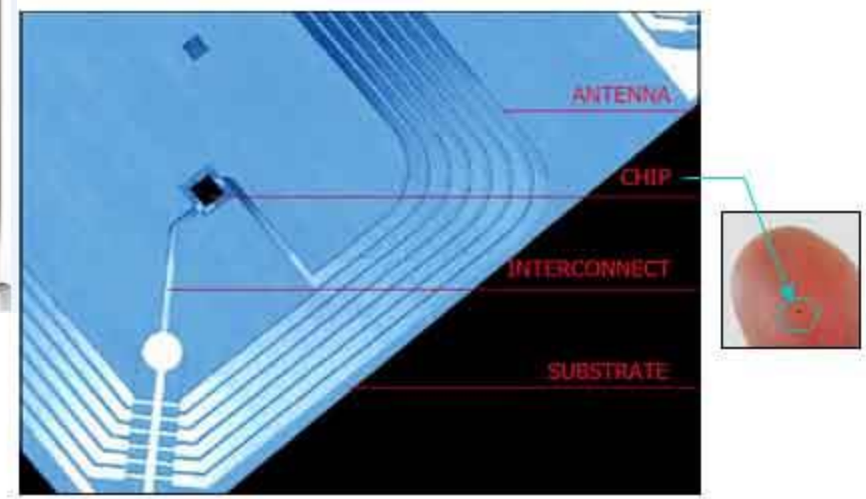
Type of antenna	G_i [dB]	BeamW.
Isotropic	0	$360^o x 360^o$
Half-wave Dipole	2	$360^o x 120^o$
Helix (10 turn)	14	$35^o x 35^o$
Small dish	16	$30^o x 30^o$
Large dish	45	$1^o x 1^o$

RFID Tags - Antennas



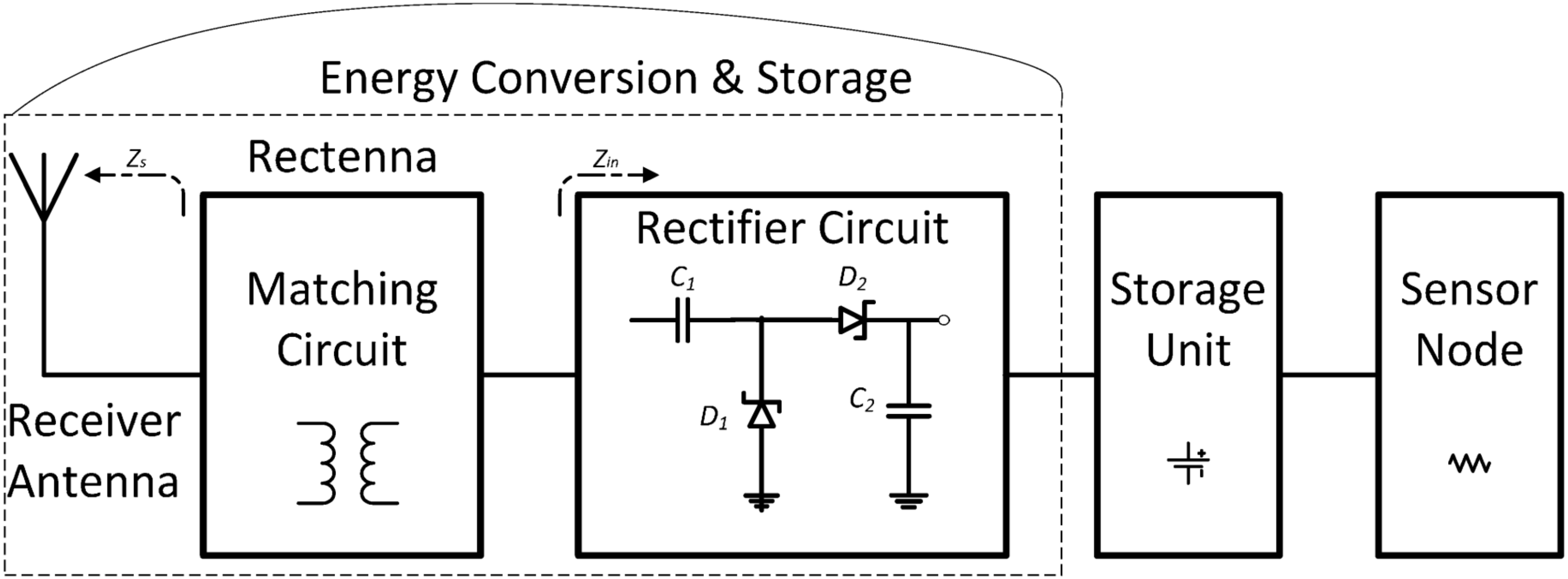
Typical RFID Tag Structure





Energy Harvesting using Antennas

The received signal is fed to the rectifier circuit. A matching (impedance) circuit is in between. The collected power is directed to the storage unit (battery). It can then be fed to a sensor node or any other device that requires energy.

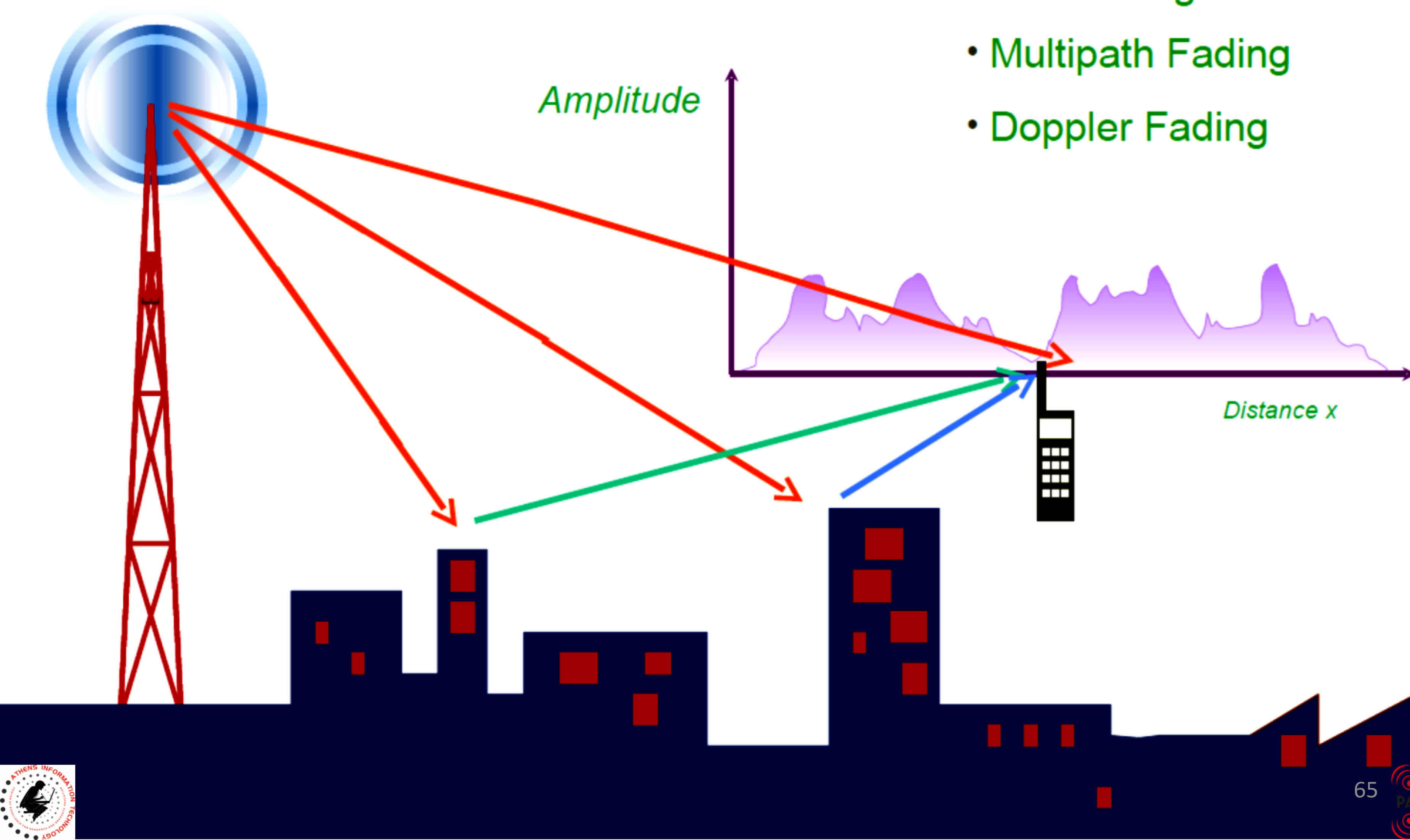


Wireless Channel Modelling Basics

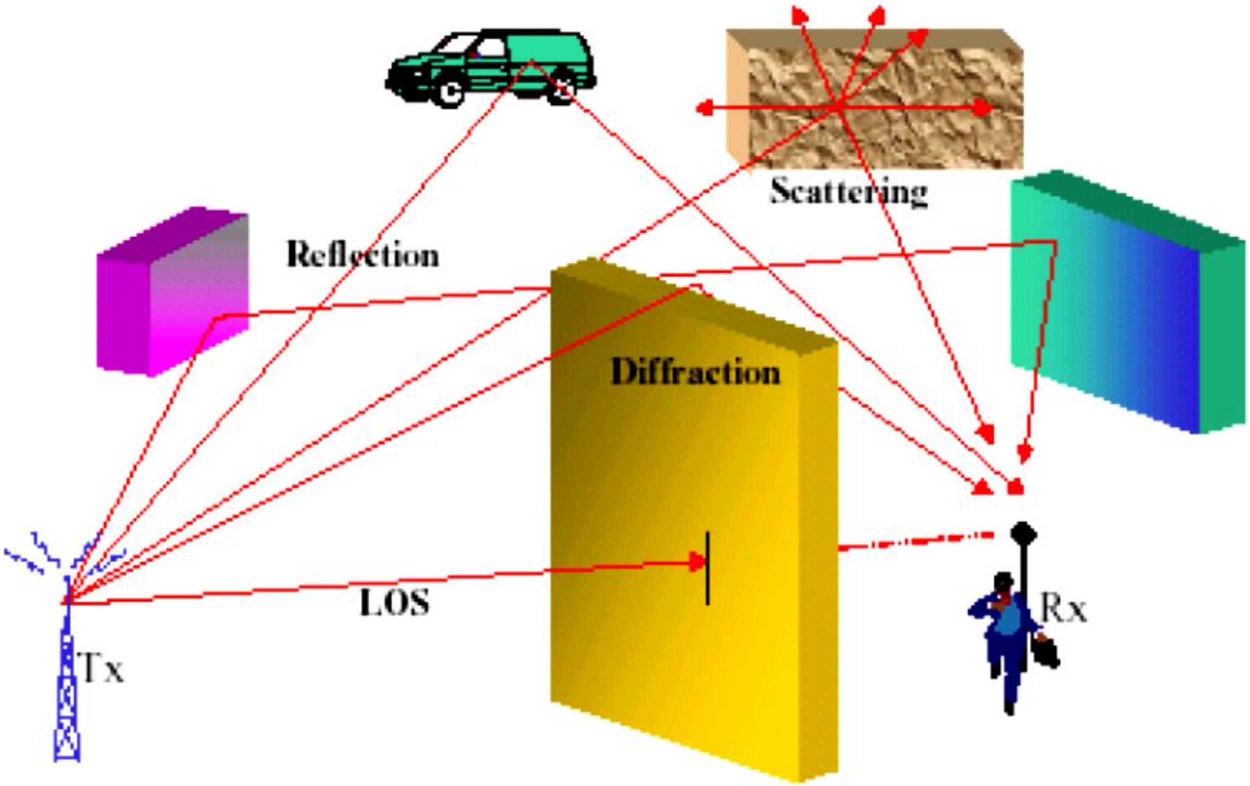
- **Physical Phenomena**
- **Path Loss Model**
- **Shadow Fading**
- **Large and small scale fading**
- **Multipath Fading**
- **Rayleigh Fading**
- **Time dispersion**
  - **Delay spread**
  - **Flat and frequency selective fading**
- **Time variance**
  - **Doppler fading**
  - **Slow and fast fading**

The Wireless Channel

- Path Loss
- Shadowing
- Multipath Fading
- Doppler Fading



Physical Phenomena



Physical Phenomena

- **Reflection –** caused by smooth surface with very large dimensions compared to the wavelength.

- **Diffraction –** obstruction caused by a dense body with large dimenstions compared to the wavelength. EM waves get bend around objects. It is the reason for shadowing and RF energy being present without LOS.

- **Scattering –** caused by large rough surfaces with dimensions comparable to the wavelength.

Path Loss Model

- If there are no objects which are between the transmitter and the reiceiver so that no reflection, refraction or absorbtion/diffraction happens.
- Atmosphere is s uniform and non-absorbing medium.
- Earth is treated as being infinitely far away from the propagation signal with a negligible reflection coefficient.
- Under these conditions, RF power attenuates as per inverse square law. For an isotropic antenna, this attenuation of Tx power is: $\left(\frac{4\pi d}{\lambda}\right)^2$ where λ is the RF's wavelength and d is the distance between Tx and Rx.

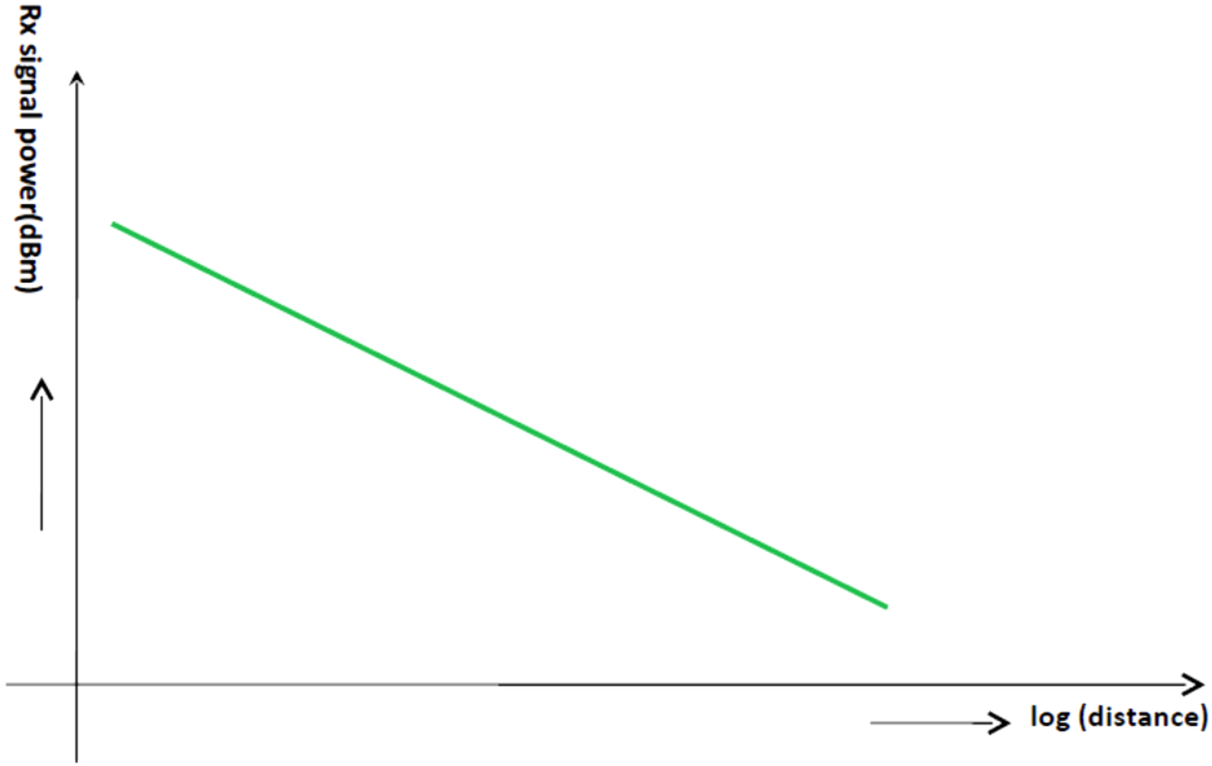
Wireless Propagation

- Path loss inversely proportional to $1/d^n$ where n = 2 ~ 4 for mobile channels: Large scale attenuation in signal strength.
- Shadowing – Terrain dependent, medium scale variation in signal strength, comes into play because of big obstacles like buildings, hills etc.
- Multipath Fading – Small scale or short-term variation on the order of λ/2.

Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Free Space Path Loss



Shadow Fading

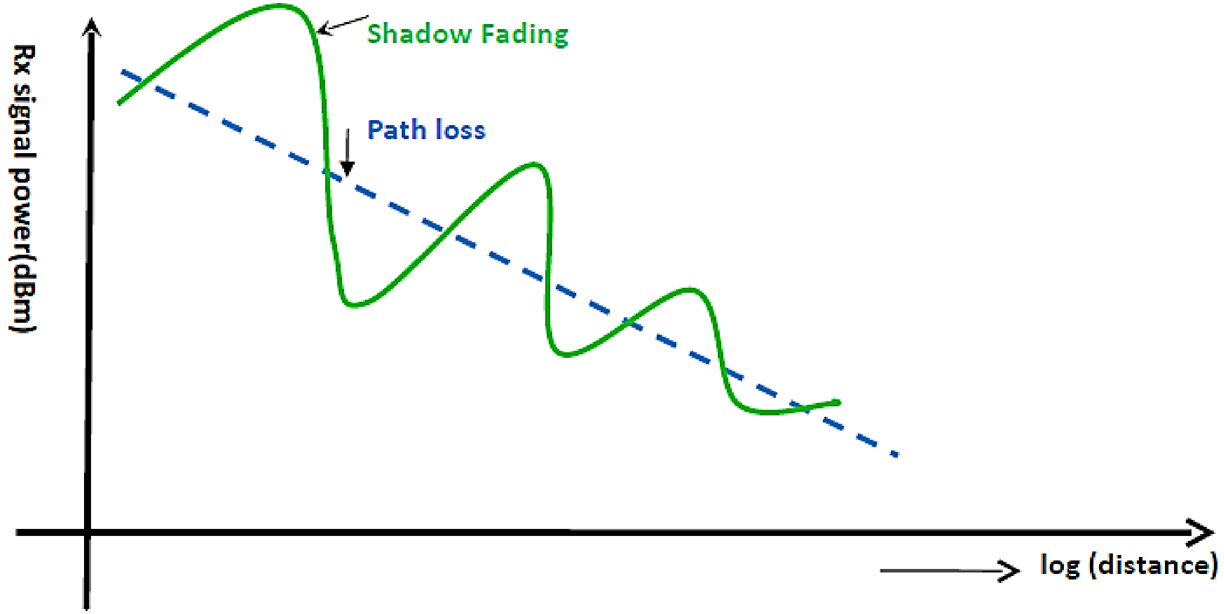
- As mentioned before, when the received signal is shadowed by obstacles such as hills and buildings, it results in variation of local mean received power,

$$P_r(dB) = \bar{P}_r(dB) + G_s$$

Where $P_r(dB)$ is the received signal power due to path loss and $G_s \sim N(0, \sigma_s^2), 4 \leq \sigma_s \leq 10dB$.

- Implications on telecommunication:
  - Non-uniform coverage
  - Increases the required transmit power

With Shadow Fading



Large, Medium and Small Scale Fading

- Large Scale Fading: Average signal power attenuation/path loss due to motion over large areas.
- Medium Scale Fading: Local variation in the average signal power around mean average power due to shadowing by local obstructions.
- Small Scale Fading: Large variation in the signal power due to small changes in the distance between Tx and Rx (also called Rayleigh fading when no LOS is available). It is called Rayleigh fading due to the fact that various multipaths at the receiver with random amplitude and delay add-up together to create a rayleigh PDF for the total signal.

Large-scale fading

- The phenomenon of variation of signal strength around the location of a receiver is called *fading*.
- The type of fading that is due to the variability of the obstacles that a single Tx-Rx path (wave) encounters as the receiver moves, is called *large-scale fading*.
- To capture this phenomenon, the path loss at a specific distance from the transmitter is better modelled as a random variable.

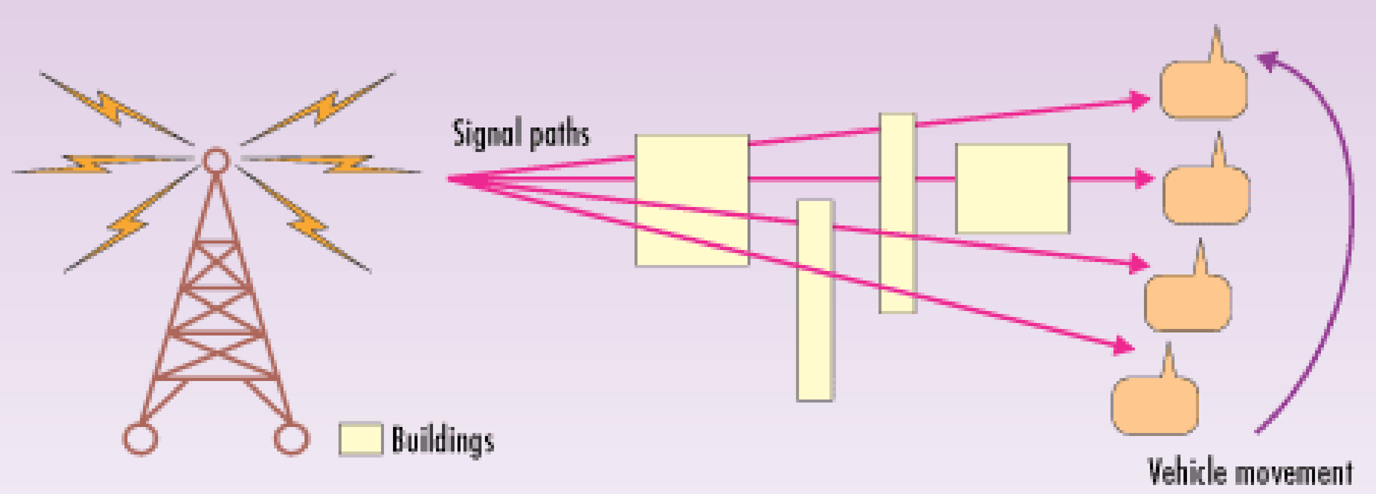


FIGURE 1: As the propagation path changes because of motion, the statistical nature of the signal envelope becomes lognormal due to changing attenuation constants.

Small-scale ("fast") fading

- This type of fading (typically of larger dynamic range) is related to the phenomenon of *multipath*, wherein, due to multiple obstacles in the way of transmission, two or more replicas of the original signal arrive at the receiver.
- When this happens, the received signal strength can be very sensitive to small movements of the receiver.

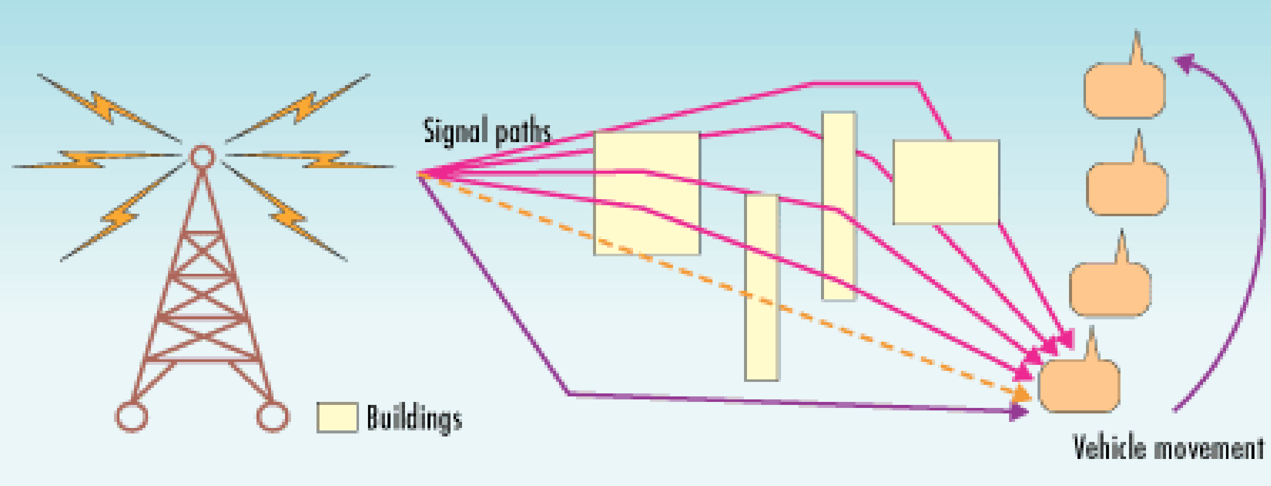
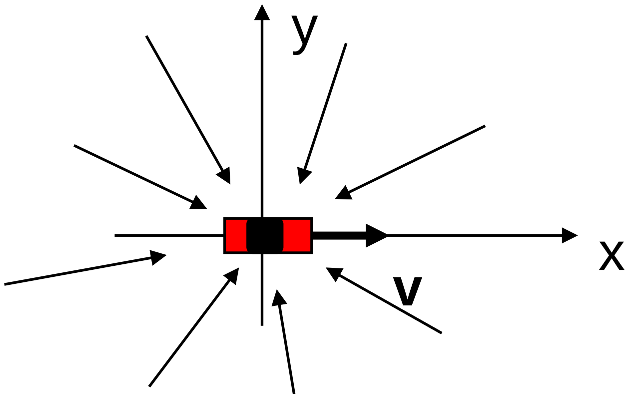


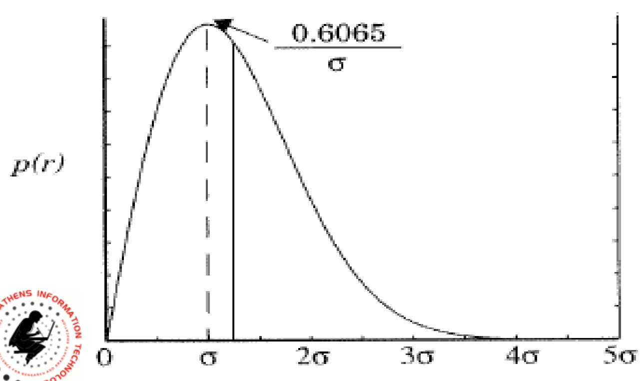
FIGURE 2: When two or more versions of a signal arrive at the receiver, the impairing mechanism is dispersion. Now, Rayleigh and Ricean multi-path fading come into play.

Rayleigh fading

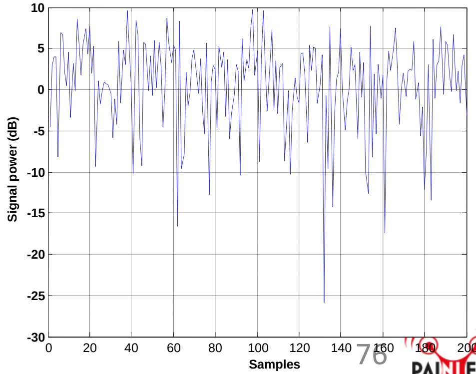
- Similar to the way that several attenuators contributed to a Gaussian exponent in log-normal fading, a large number of reflections add up in the case of multipath transmission.
- If we assume:
  - *A large number of paths*
  - *Uniformly distributed in angle*
  - *All paths incident from the horizontal plane*
  - *No dominant path; all are comparable in amplitude*



- Then, the composite signal itself (not the composite attenuation constant) will be Gaussian distributed, due to the Central Limit Theorem.
- The resulting (so-called "Rayleigh" fading) is described by the distribution of the envelope (amplitude) *r(t)* of the received signal:

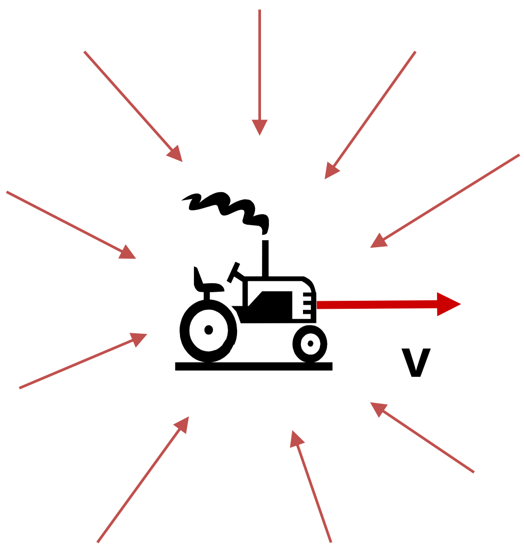


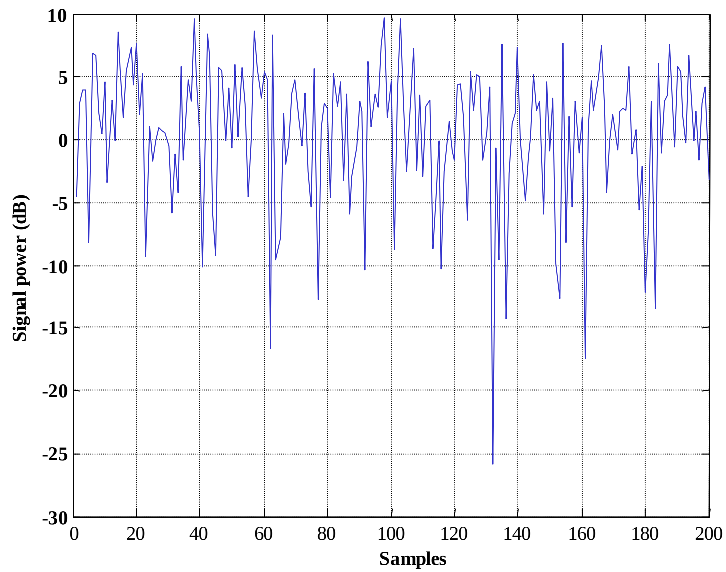
$$p(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} & 0 \le r \le \infty \\ 0 & r < 0 \end{cases}$$

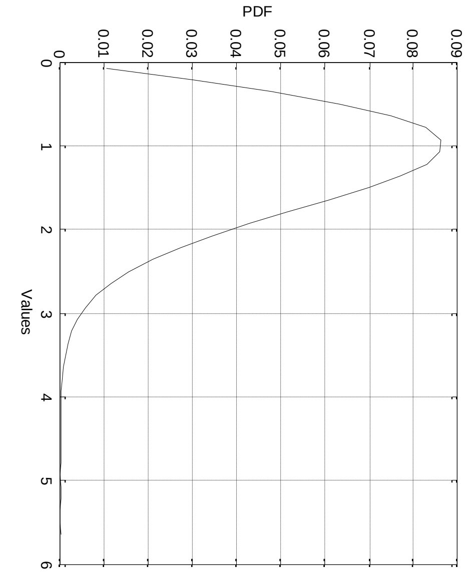


Moving Nodes

- For a moving node, the spatial fading is perceived as a temporal variation of the signal strength.
- As we have seen, this fading may be typically Rayleigh due to scatterers that are uniformly distributed in space.







Distance "=" Time

Fast fading in the presence of a Line of Sight (LOS)

- Sometimes (especially in sub-urban environments), despite the rich clutter of the environment, there is also a LOS direct wave between the transmitter and receiver.
- When this happens, the received signal deviates from the Gaussian distribution.
- The received signal envelope is then well described by a *Ricean* distribution.

$$p(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} \mathrm{I}_0\left(\frac{\mathrm{A}r}{\sigma^2}\right) & \text{for } (\mathrm{A} \geq 0, r \geq 0) \\ 0 & \text{for } (\mathrm{r} < 0) \end{cases}$$

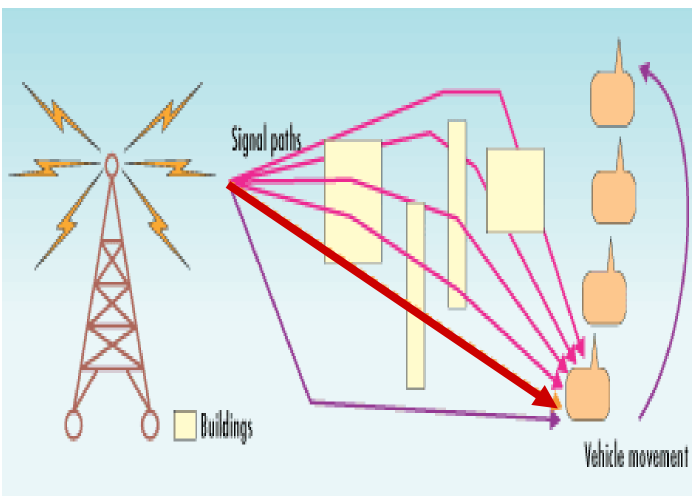
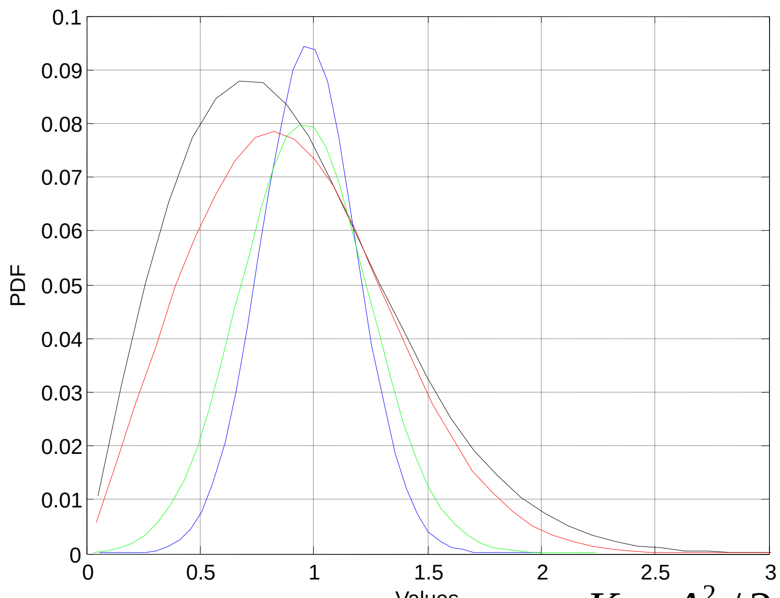


FIGURE 2: When two or more versions of a signal arrive at the receiver, the impairing mechanism is dispersion. Now, Rayleigh and Ricean multi-path fading come into play.

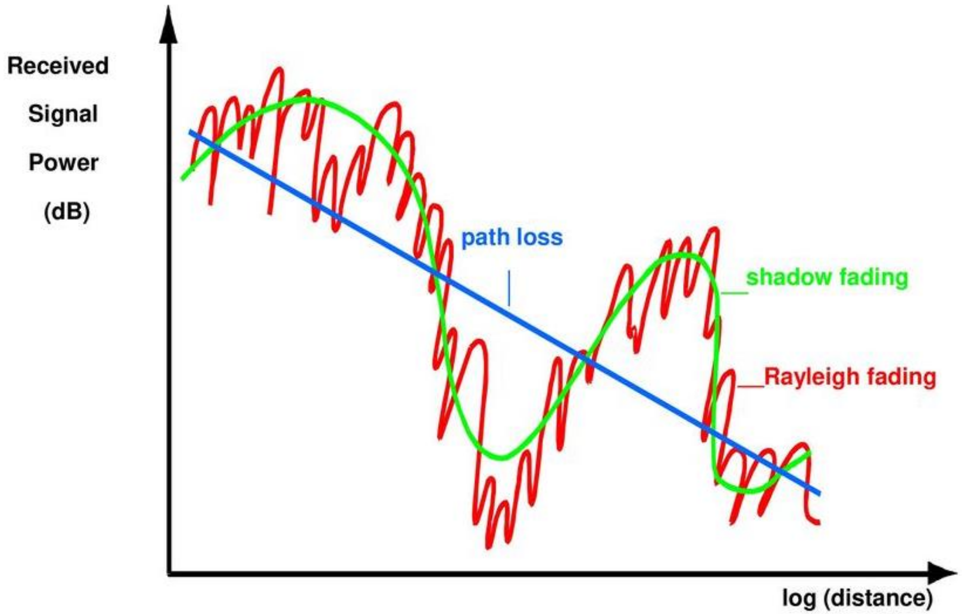


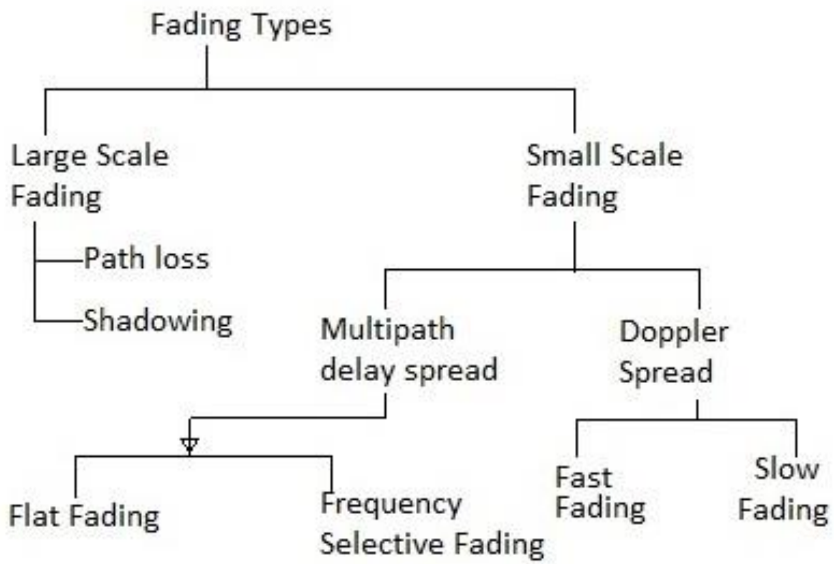
I_0(.) is the modified Bessel function of the first kind and zero order

Ricean factor: $K = A^2 / 2\sigma^2$

The three types of fading

- Free-space path loss (blue)
- Large scale fading (green)
- Small scale fading (red)





Antennas, Antenna Systems & Radio Propagation in Next Generation Communication Systems – Part I

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THE END

AIT

Short course given to the PAINLESS 1st Summer School, University of Cyprus, Sept. 9, 2019

Antennas, Antenna Systems & Radio Propagation in Next Generation Communication Systems – Part II

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Short course given at the

PAINLESS 1st Summer School

University of Cyprus

Nicosia, Cyprus, Sept. 9, 2019

Outline

Smart Antennas Basics

- Diversity gain, beamforming, Interference mitigation
- Spatial reuse
- Direction finding

Multiple Input / Multiple Output (MIMO) Systems

- Link capacity
- Transmission & reception techniques
- Over-the-air results

Advanced Multi-Antenna Systems

- Cooperative techniques
- Massive MIMO

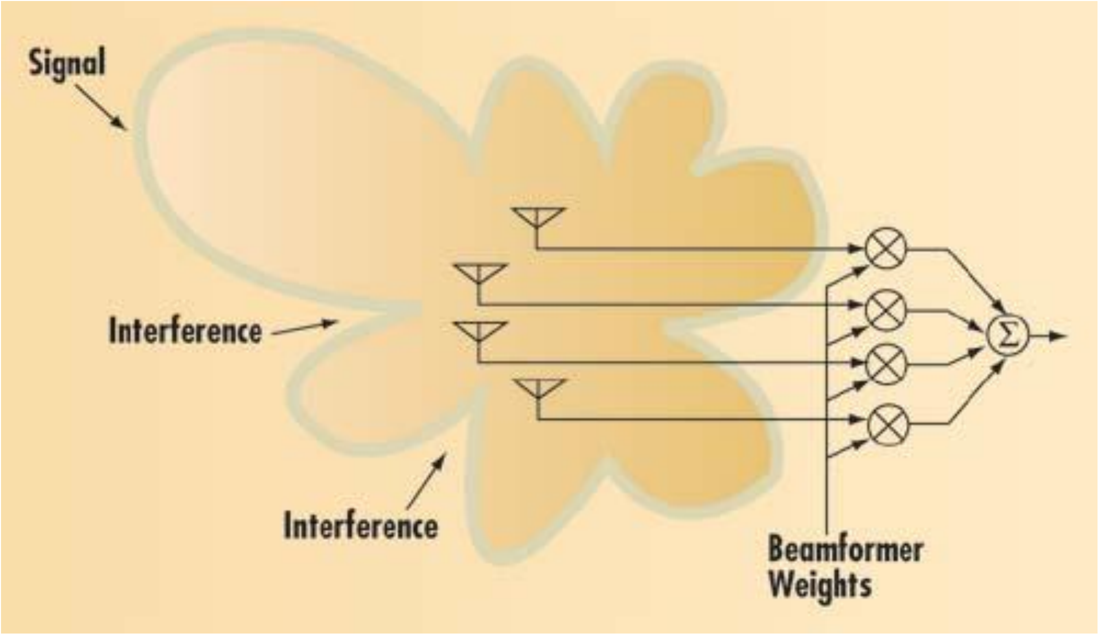
mmWave communications

- Channel modelling
- The synergy with Massive MIMO and its importance for 5G

Hybrid antenna arrays for Massive MIMO based on parasitic antennas

Examples & Applications

What is a “smart” antenna system / array?



- A **Smart Antenna system** combines multiple standard antenna elements with a **signal-processing capability** to **optimize its radiation and / or reception pattern** automatically in response to the signal environment [1].
- A Smart Antenna is an antenna array system aided by some **“smart” algorithm to combine the signals**, designed to adapt to different signal environments – The antenna can typically automatically adjust to a dynamic signal environment [2].

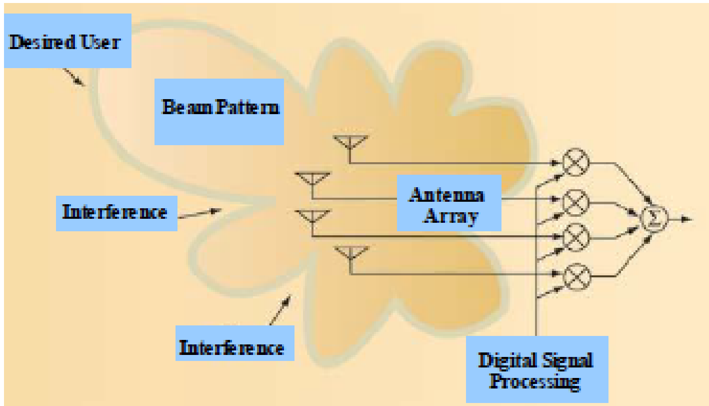
1. International Engineering Consortium (www.iec.org)
2. Software Defined Radio Forum

Typical smart antenna attributes

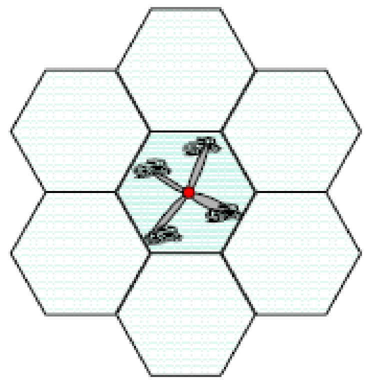
- Enhanced **signal quality**
- Improved (wireless link & total system) **throughput**
- Improved (electromagnetic) **coverage**
- Improved **Quality of Service**
- Reduced **interference**
- Reduced **power requirements**
- Improved **direction finding** / **localization** capability
- More..

A few things we can do with antenna arrays: [the basics]

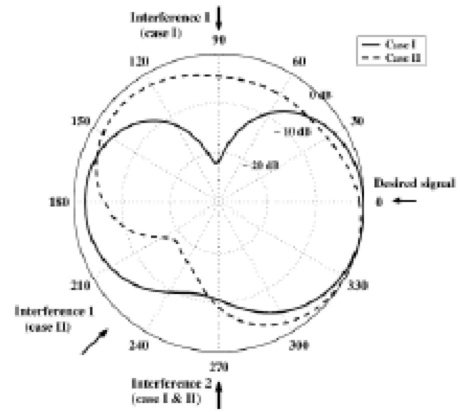
- **Power boosting**



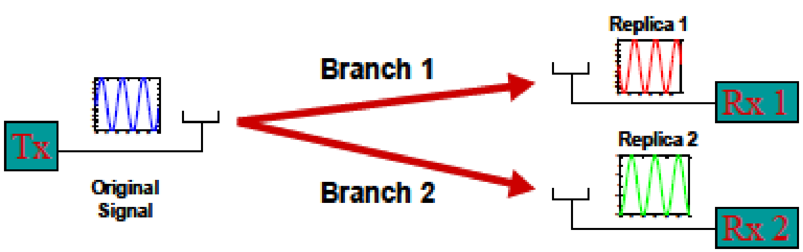
- **Spatial Reuse**



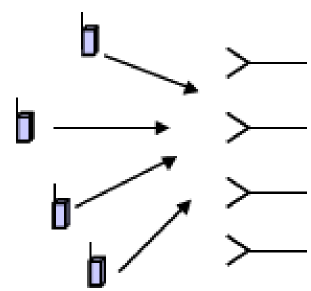
- **Interference nulling**



- **Diversity combining**



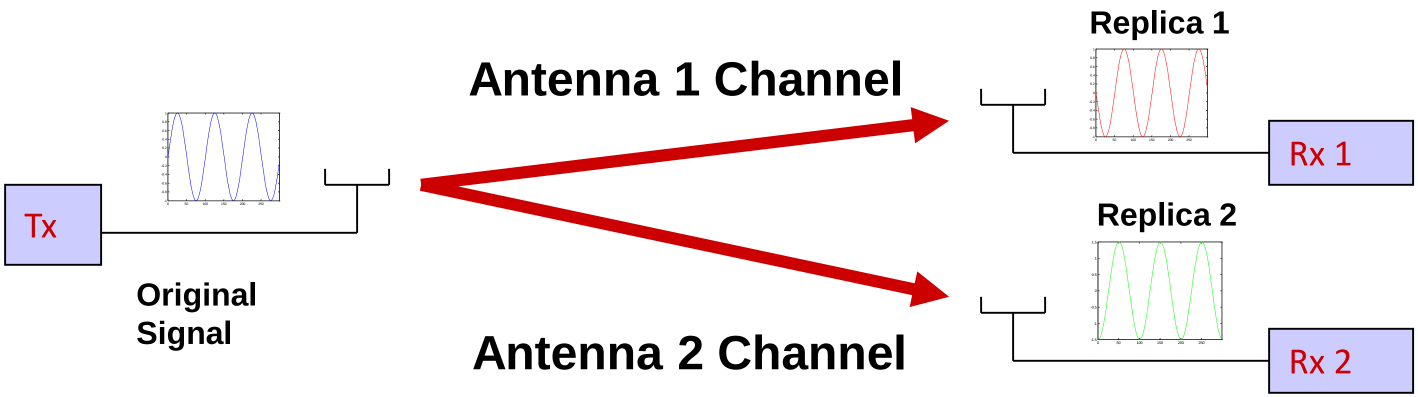
- **Direction finding**



See: A. Paulraj and C. B. Papadias, "Space-Time Processing for Wireless Communications," *IEEE Signal Processing Magazine*, vol. 14, No. 6, pp. 49-83, Nov. 1997.

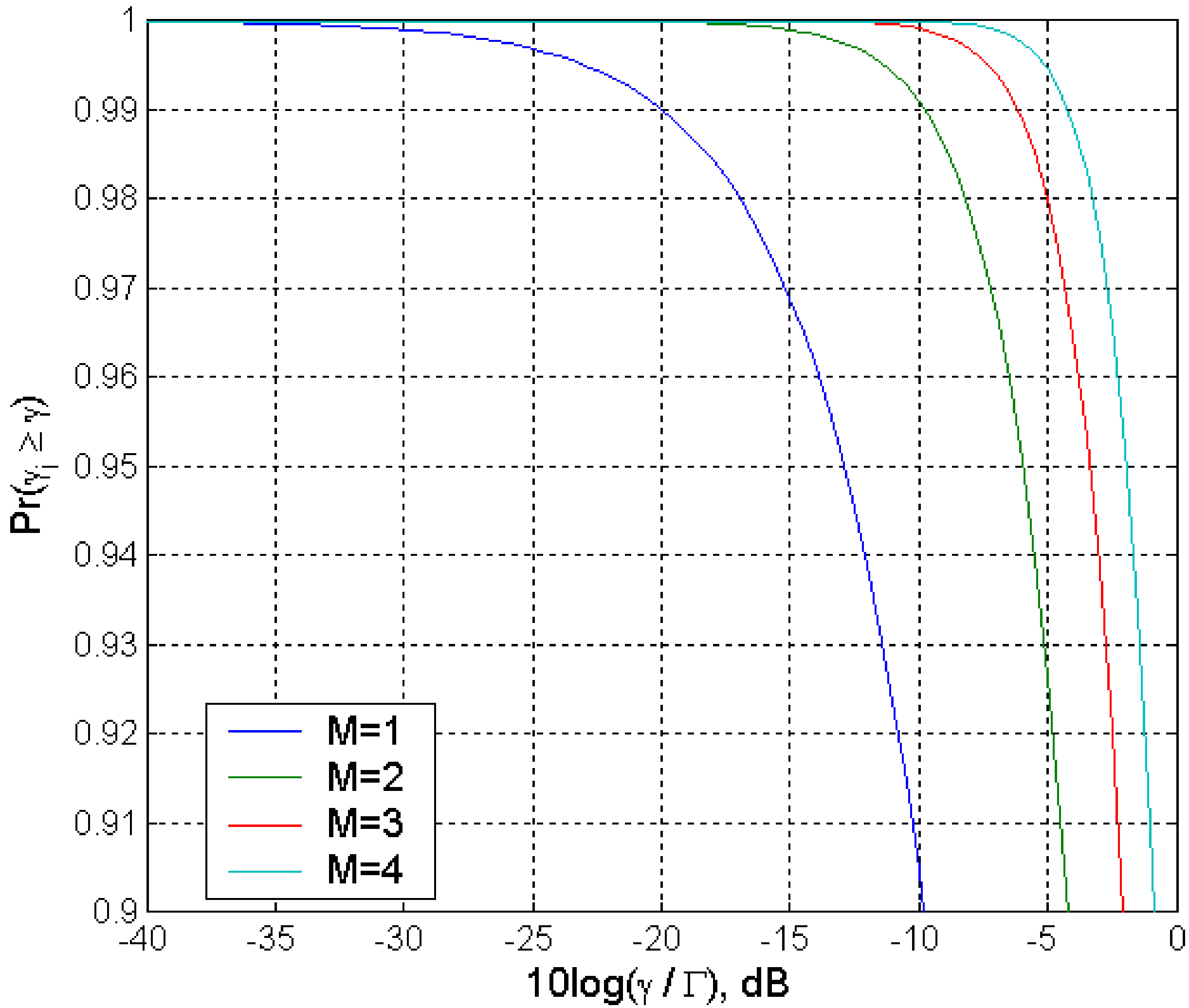
Space / antennas diversity

- **Antenna (space) diversity can be used in order to increase the chances of good signal reception without causing any penalties in terms of bandwidth expansion or delay.**

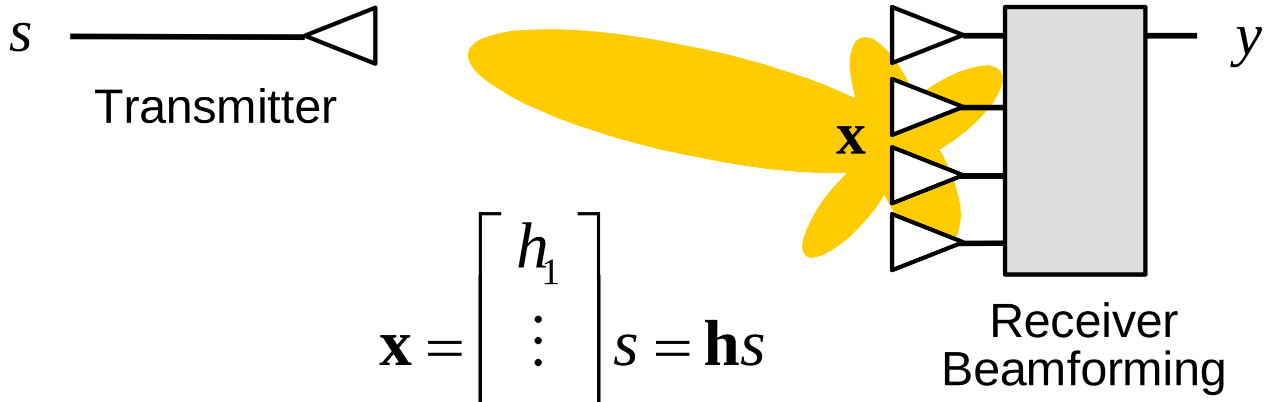


- **All that is needed, is the availability of multiple (more than one) antennas, and the associated signal processing to take advantage of them**
- **The antennas need to be sufficiently spaced apart from each other**
- **Also, the environment must have enough scattering to produce a fading channel**
- **The only price paid is the cost of the extra hardware and computational power**

The scaling of diversity gain



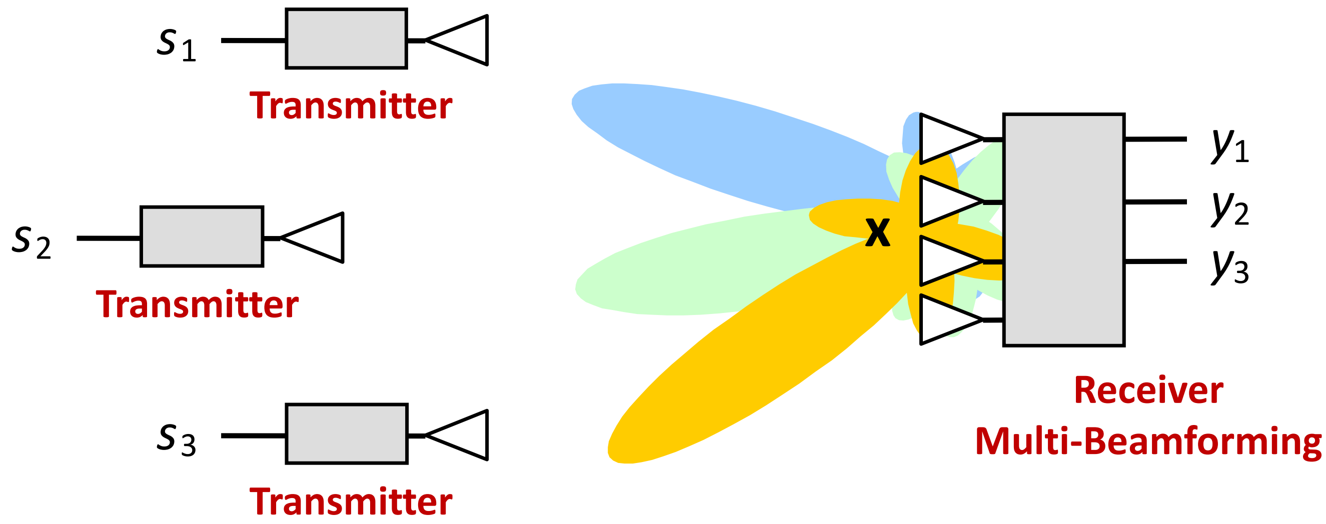
Enhancing the signal quality



$$\mathbf{x} = \begin{bmatrix} h_1 \\ \vdots \\ h_N \end{bmatrix} s = \mathbf{h}s$$

- By pointing a beam, at the receiver, towards the signal of interest, the signal-to-noise ratio of the received signal is enhanced by a factor proportional to the number of antenna elements
- Example: Maximal Ratio Combining (MRC): $y(k) = \mathbf{h}^{\dagger}\mathbf{x}(k)$
- Throughput gain: $C = \log_2\left(1 + \rho \sum_{i=1}^{N} |h_i|^2\right)$
- Asymptotic SNR gain: N

Mitigating the interference



- **Received signal:**

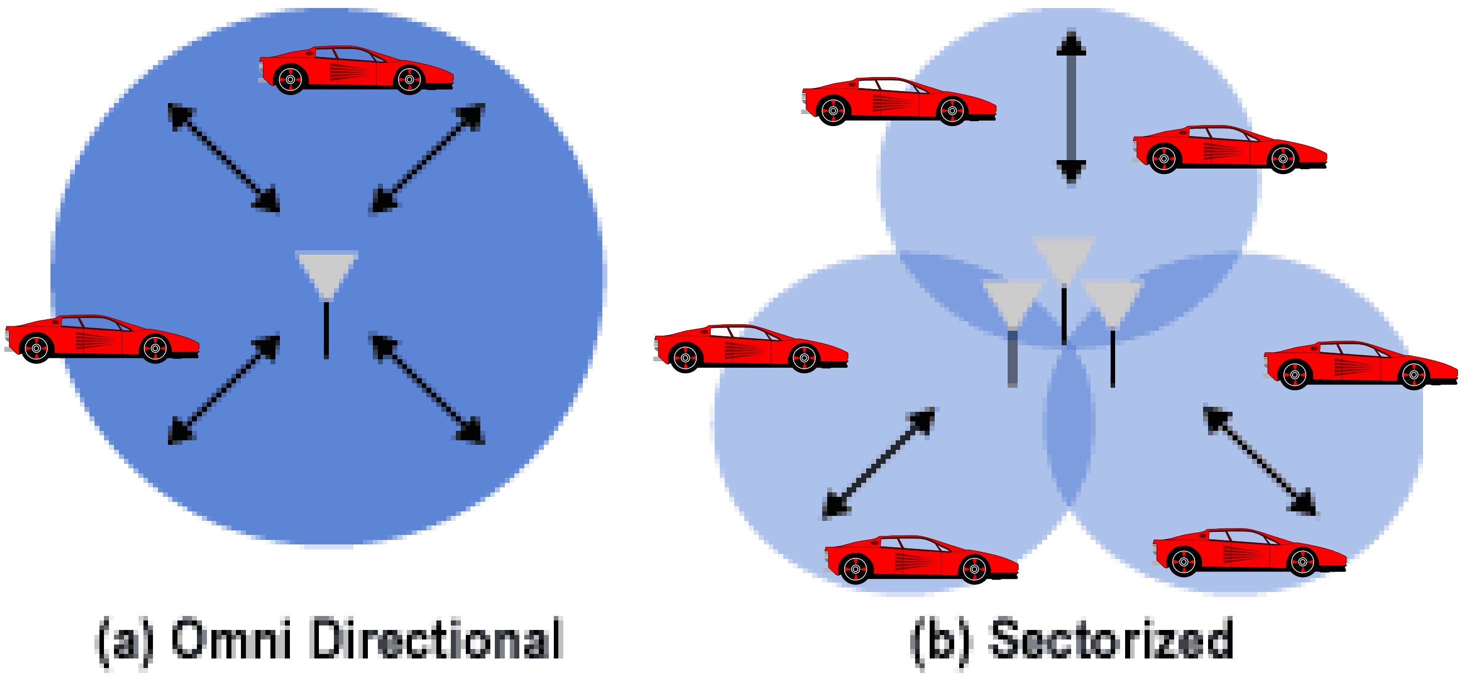
$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ \vdots & \vdots & \vdots \\ h_{N1} & h_{N2} & h_{N3} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_N \end{bmatrix} = \mathbf{Hs}$$

- **A possible solution:**

$$\mathbf{y} = (\mathbf{H}^{\dagger}\mathbf{H})^{-1}\mathbf{H}^{\dagger}\mathbf{x} = \mathbf{H}^{\#}\mathbf{x}$$

- **In the absence of noise, yields:** $\mathbf{y} = \mathbf{s}$ → ***perfect interference "clean-up"***

System level capacity gains of smart antennas

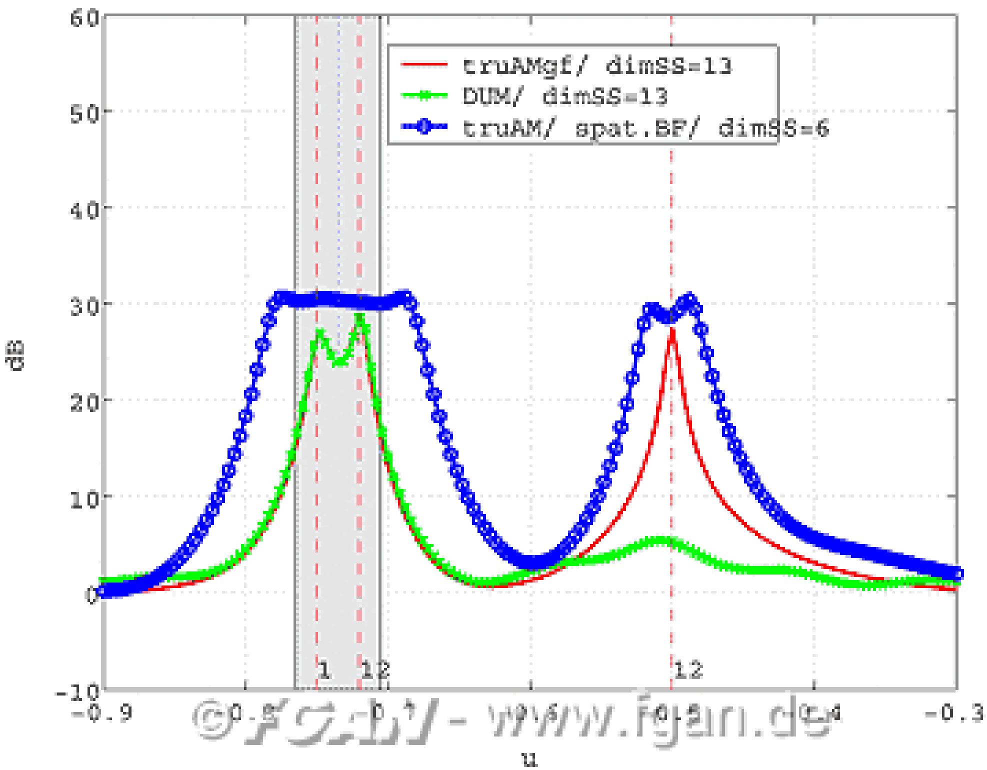


- By shaping beams ("sectors") at the base station, the interference between spatially separated users is avoided
- Assuming a uniform user population and perfectly separated sectors, the cell capacity scales linearly with the number (L) of employed sectors:

$$C_L = LC_1$$

Another application of smart antennas: Direction finding via super-resolution techniques

ATHENS INFORMATION TECHNOLOGY



$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

$$\mathbf{R}_\mathbf{x} = E\{\mathbf{x}(t)\mathbf{x}^H(t)\} = \mathbf{A}\mathbf{R}_s\mathbf{A}^H + \sigma_0^2\mathbf{I}$$

Partition the N-dimensional vector space into the signal subspace $\mathbf{U}_s$ and the noise subspace $\mathbf{U}_n$

$$[\mathbf{U}_s \quad \mathbf{U}_n] = [\underbrace{\mathbf{u}_1 \ \cdots \ \mathbf{u}_I}_{\mathbf{U}_s:(\sigma_i^2-\sigma_0^2)>0 \text{ eigenvalues}} \quad \underbrace{\mathbf{u}_{I+1} \ \cdots \ \mathbf{u}_N}_{\mathbf{U}_n:0 \text{ eigenvalues}}]$$

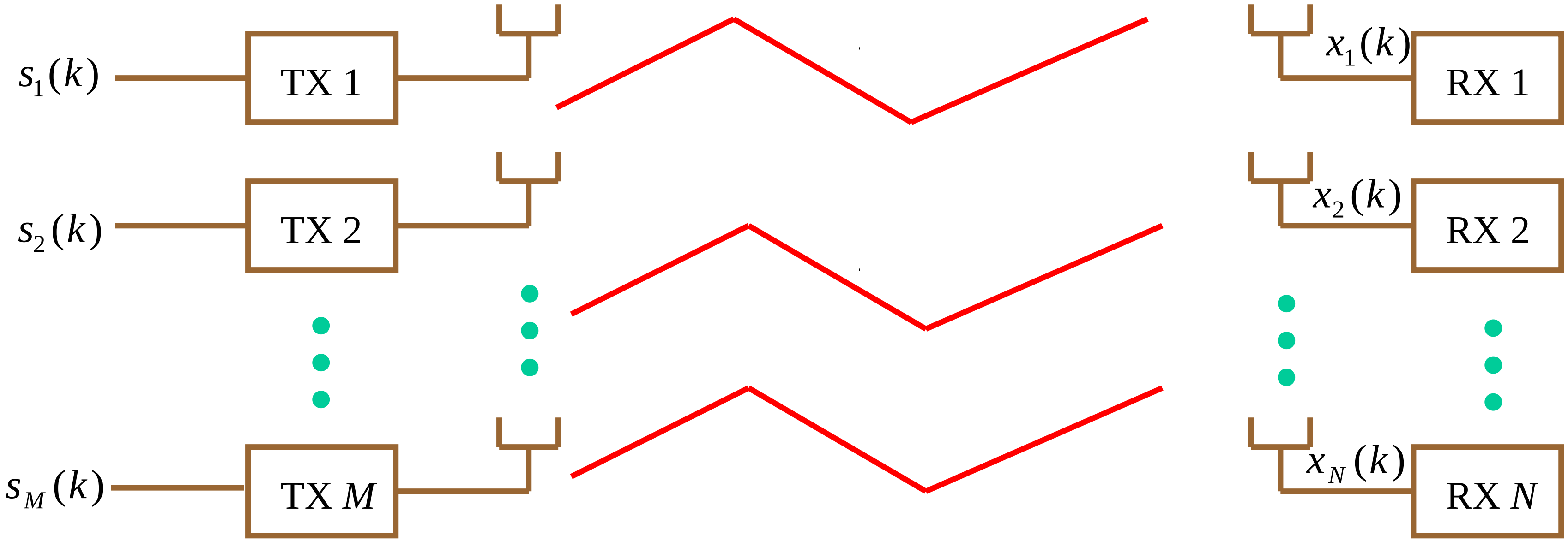
The steering vector $\mathbf{a}(\theta_i)$ is in the signal subspace
Signal subspace is orthogonal to noise subspace
This implies that $\mathbf{a}^H(\theta_i)\mathbf{U}_n = \mathbf{0}$
So the MUSIC algorithm searches through all angles θ, and plots the "spatial spectrum"

$$P(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{U}_n}$$

- **With *N* antenna elements and using so-called "super-resolution" signal processing techniques, one can estimate reliably the directions of arrival of *N*-1 signals that hit the antenna from different angles**
- **The above figure shows an example of two signals impinging on the array**

http://www.girdsystems.com/pdf/GIRD_Systems_Intro_to_MUSIC_ESPRIT.pdf

MIMO: Multiple Input / Multiple Output links



$$\mathbf{x}(k) = \mathbf{H}\mathbf{s}(k) + \mathbf{n}(k)$$

Ground rules:

- **The total TX power is fixed irrespective of the # of transmit antennas**
- **Each antenna is fed by its own RF chain**

Block diagram of point-to-point MIMO link

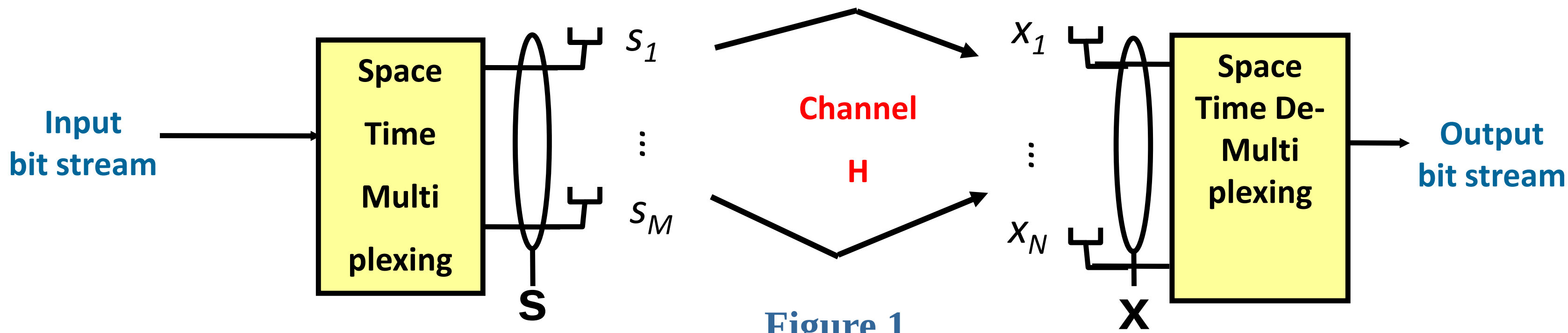


Figure 1

- The channel **H** can be assumed either deterministic or random
- Signal model:

$$\begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{M1} \\ \vdots & \cdots & \vdots \\ h_{1N} & & h_{MN} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_M \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_N \end{bmatrix}$$

or equivalently:

$$\mathbf{x} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

Open-loop MIMO capacity derivation

"Open-loop" MIMO case: transmitter **does not know the channel**

SVD-based derivation:

- The proof is based in the orthogonalization of the channel, i.e. its decomposition in non-interfering components:
- SVD of $\mathbf{H}$:

$$\underbrace{\mathbf{H}}_{N\times M} = \underbrace{\mathbf{U}}_{N\times N}\underbrace{\Sigma}_{N\times M}\underbrace{\mathbf{V}^\dagger}_{M\times M}$$

where both *U* & *V* are unitary: $UU^\dagger = U^\dagger U = I_N ; VV^\dagger = V^\dagger V = I_M$

· and $\sum$ is diagonal

- Each element of diag($\sum$) is a singular value of $\mathbf{H}$

(or equivalently, the >0 sq. root of an eigenvalue of $\begin{cases} \mathbf{HH}^\dagger & \text{if } N \le M \\ \mathbf{H}^\dagger\mathbf{H} & \text{if } N \ge M \end{cases}$

- Moreover, the columns of $\mathbf{U}$ are eigenvectors of $\mathbf{HH}^\dagger$.

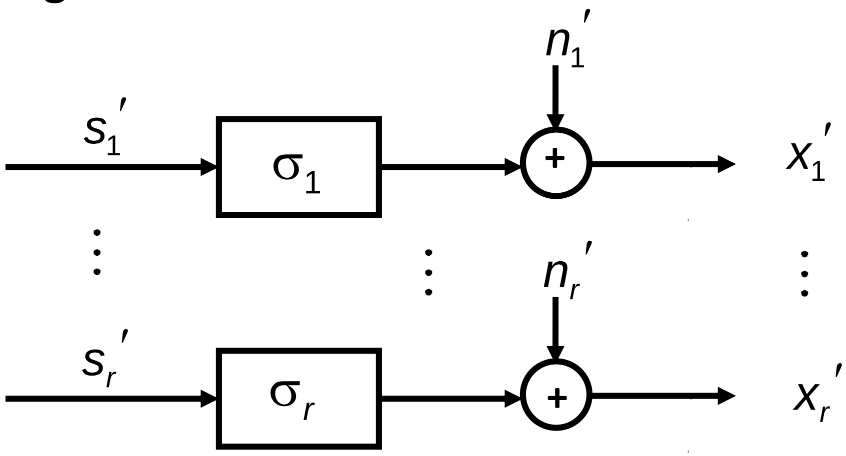
whereas the columns of $\mathbf{V}$ are eigenvectors of $\mathbf{H}^\dagger\mathbf{H}$.

Parallel channels

- The final signal model can be written as:

$$x_i' = \sigma_i s_i' + n_i' \qquad i = 1, \ldots, r$$

- Recalling that rank($\mathbf{H}$)=r ($r \leq \min(M, N)$), we can rewrite the equivalent signal model as follows:



- Notice that for full rank $\mathbf{H}$, $r=M$ if $M \leq N$ and $r=N$ if $N \leq M$

Sub-channel capacities

- The capacity (to be more exact, spectral efficiency) of each sub-channel can be now easily computed via the standard Shannon formula:

$$C_i = \log_2\left(1+\rho_i\right) \qquad i=1,\ldots,r$$

where

$$\rho_i = \frac{E\left|\sigma_i s_i'\right|^2}{E\left|n_i\right|^2} = \frac{\lambda_i E\left|s_i'\right|^2}{\sigma_n^2} = \frac{\lambda_i E\left|s_i\right|^2}{\sigma_n^2}$$

$$\Rightarrow \quad C_i = \log_2\left(1+\frac{\lambda_i P_T}{M\sigma_n^2}\right) \qquad i=1,\ldots,r$$

- Notice we have assumed *no knowledge of Channel State Information (CSI) at the transmitter*, resulting in an *even split of power* over the M Tx antennas

Total capacity (after some more algebra..):

$$C = \log\det\left(I_m + \frac{P_T}{M\sigma_n^2}\mathbf{Q}\right)$$

where
$$\begin{cases} \text{if } M \geq N : m = N \quad \& \quad \mathbf{Q} = \mathbf{H}\mathbf{H}^\dagger \\ \text{if } M \leq N : m = M \quad \& \quad \mathbf{Q} = \mathbf{H}^\dagger\mathbf{H} \end{cases}$$

- It can also be shown that:

$$\log\det\left(I_N + \frac{P_T}{M\sigma_n^2}\mathbf{H}\mathbf{H}^\dagger\right) = \log\det\left(I_M + \frac{P_T}{M\sigma_n^2}\mathbf{H}^\dagger\mathbf{H}\right)$$

- In conclusion, the open-loop capacity of a MIMO channel is given by:

$$C = \log\det\left(I_N + \frac{P_T}{M\sigma_n^2}\mathbf{H}\mathbf{H}^\dagger\right)$$

“Closed loop” case: Channel known at the Transmitter

- Assuming now that we can vary the Tx power of the different transmit antennas, the capacity takes the form:

$$C = \sum_{i=1}^{r} \log_2 \left(1 + \frac{E|s_i|^2}{\sigma_n^2} \lambda_i \right) = \sum_{i=1}^{r} \log_2 \left(1 + \frac{\gamma_i \lambda_i}{\sigma_n^2} \right)$$

where $\gamma_i = E|s_i|^2$ and $\sum_{i=1}^{r} \gamma_i = P_T$

- The capacity can be then maximized through:

$$\max_{\gamma_i} \left(\sum_{i=1}^{r} \log_2 \left(1 + \frac{\gamma_i \lambda_i}{\sigma_n^2} \right) \right)$$

$$\text{s.t. } \sum_{i=1}^{r} \gamma_i = P_T$$

Closed loop capacity maximization

- The expression is concave to the variables γ_i and can be maximized using Lagrangian methods, yielding the following solution:

$$\gamma_i^{\mathrm{OPT}} = \left(\mu - \frac{\sigma_n^2}{\lambda_i}\right)^+ \qquad \text{with} \qquad \sum_{i=1}^{r} \gamma_i = P_T$$

where: $\left(a\right)^+ = \max\left(a, 0\right)$

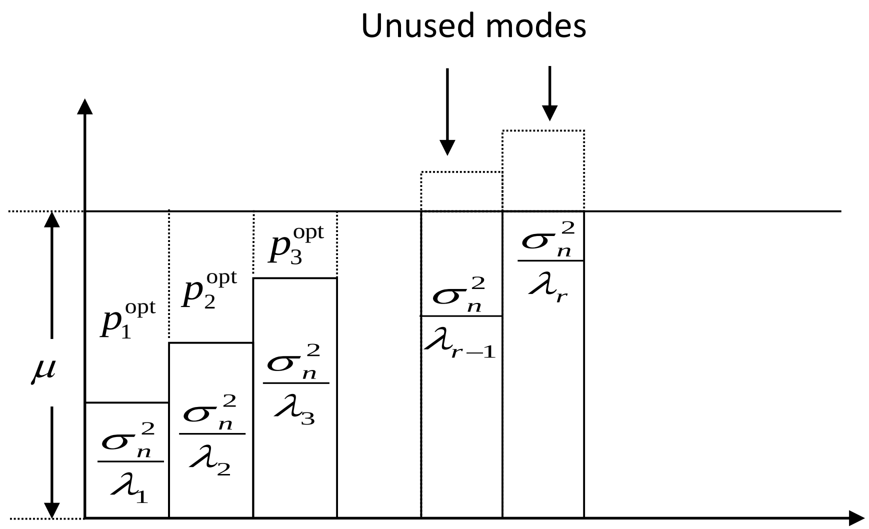
- The computation of these power allocations is done iteratively as per the water-filling algorithm of Cover & Thomas (see next slide)
- The closed-loop capacity of the channel is then given by:

$$C_{\mathrm{CL}} = \sum_{i=1}^{r} \log_2\left[1 + \frac{1}{\sigma_n^2}\left(\lambda_i \mu - \sigma_n^2\right)^+\right]$$

- Notice that the covariance matrix of the Tx signal in that case is given by:

$$\mathbf{R}_{\mathbf{ss}} = \mathbf{V}\mathrm{diag}\left(\gamma_1, \cdots, \gamma_M\right)\mathbf{V}^\dagger$$

The Waterfilling algorithm



Iteration count c=1:

$$\mu = \frac{P_T}{r-c+1}\left[1+\sigma_n^2 \sum_{i=1}^{r-c+1} (1/\lambda_i)\right]$$

Power computation:

$$\gamma_i = \left(\mu - \sigma_n^2/\lambda_i\right) \; ; \; i = 1, \ldots, r - c + 1$$

In summary: spatial modes and capacity scaling

- No channel knowledge at the transmitter ("open loop"):

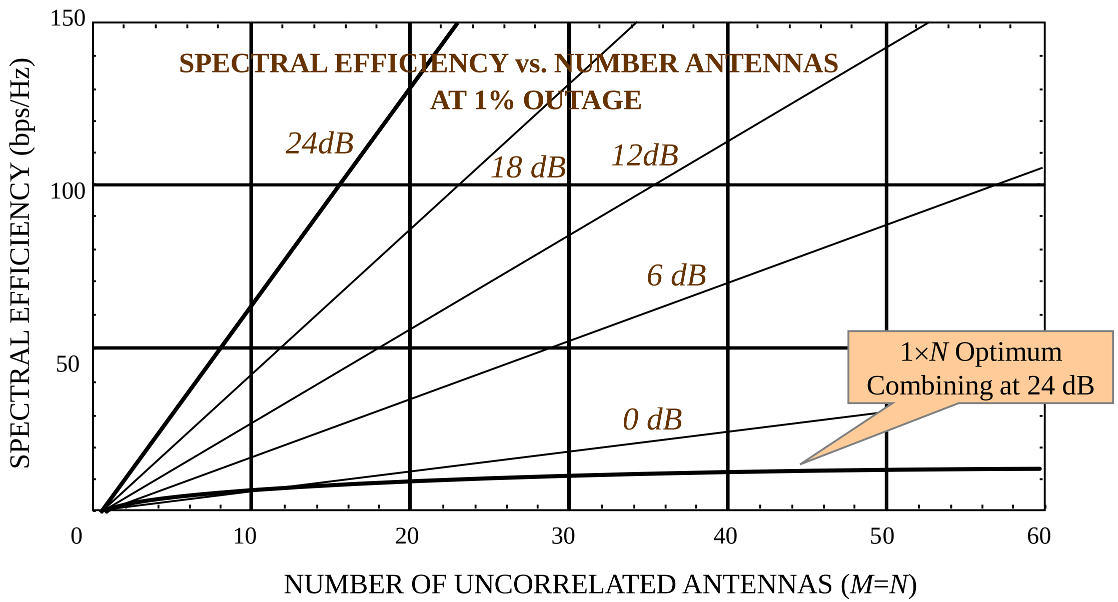
$$C_{OL} = \log\det\left\{ I_N + \frac{P_T}{M\sigma_n^2}\mathbf{H}\mathbf{H}^{\dagger} \right\}$$

- Full channel knowledge at the transmitter ("closed loop"):

$$C_{CL} = \sum_{i=1}^{r} \log_2\left(1 + \frac{1}{\sigma_n^2}\left(\lambda_i \mu - \sigma_n^2\right)^{+}\right)$$

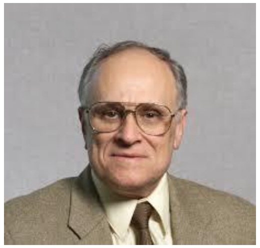
- At high SNR:

$$\lim_{SNR\to\infty} C_{OL} = \lim_{SNR\to\infty} C_{CL} = \min(M, N)\log(\mathrm{SNR})$$

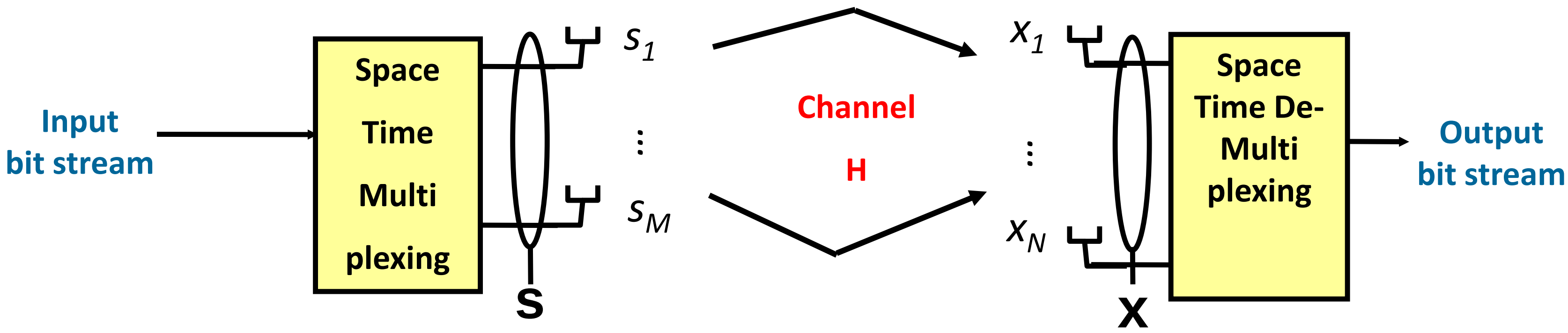


[Telatar '95]

[Foschini '96]

Reminder: signal model

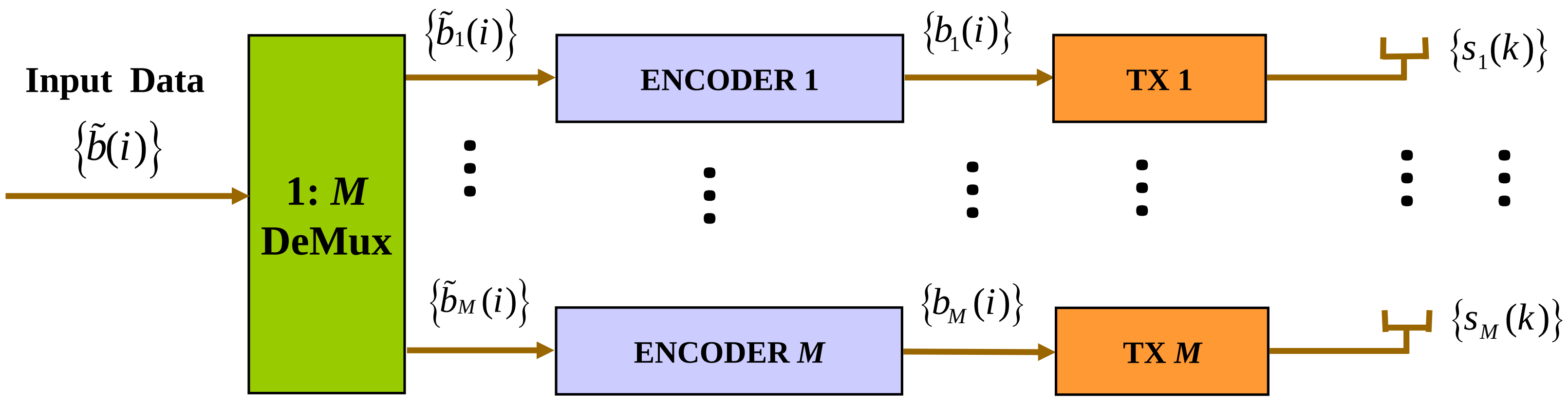


- Signal model:

$$\begin{bmatrix} x_1(k) \\ \vdots \\ x_N(k) \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{M1} \\ \vdots & \cdots & \vdots \\ h_{1N} & & h_{MN} \end{bmatrix} \begin{bmatrix} s_1(k) \\ \vdots \\ s_M(k) \end{bmatrix} + \begin{bmatrix} n_1(k) \\ \vdots \\ n_N(k) \end{bmatrix}$$

or equivalently: $\mathbf{x}(k) = \mathbf{H}\mathbf{s}(k) + \mathbf{n}(k)$

A Basic MIMO Transmitter Architecture ("V-BLAST")



- Demultiplexing operates on the original (uncoded) bit stream
- Each data sub-stream is encoded individually
- Different data sub-streams are transmitted from different antennas

Simple MIMO Receiver Processing Options

- Recall the narrowband MIMO signal model:

$$\mathbf{x}(k) = \mathbf{H}\mathbf{s}(k) + \mathbf{n}(k)$$

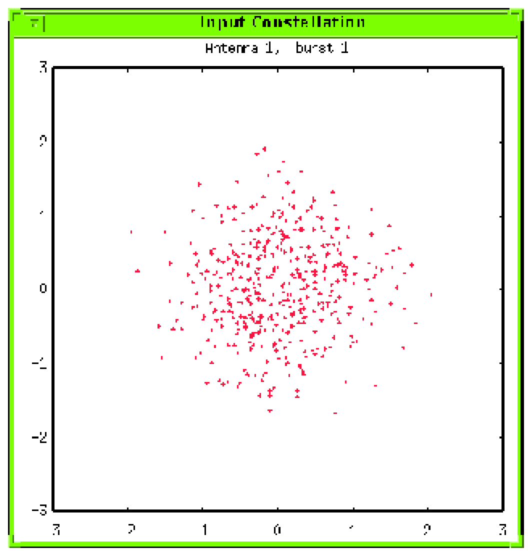
- Linear receivers: $\boxed{\mathbf{z}(k) = \mathbf{W}^{\dagger}(k)\mathbf{x}(k)}$ (**W** is MxN)
  - Decorrelating (ZF) receiver: $\mathbf{W}(k) = \mathbf{H}^{\#} = \mathbf{H}\left(\mathbf{H}^{\dagger}\mathbf{H}\right)^{-1}$
  - Maximum SNR (MMSE) receiver: $\mathbf{W}(k) = \left(\mathbf{H}\mathbf{H}^{\dagger} + \frac{M}{\mathrm{SNR}}\mathbf{I}_N\right)^{-1}\mathbf{H}$

Over-the-air validation of MIMO

ATHENS INFORMATION TECHNOLOGY

Lucent Technologies
Bell Labs Innovations

Over-the-air Typical Received Signal at any antenna (before receiver signal processing)



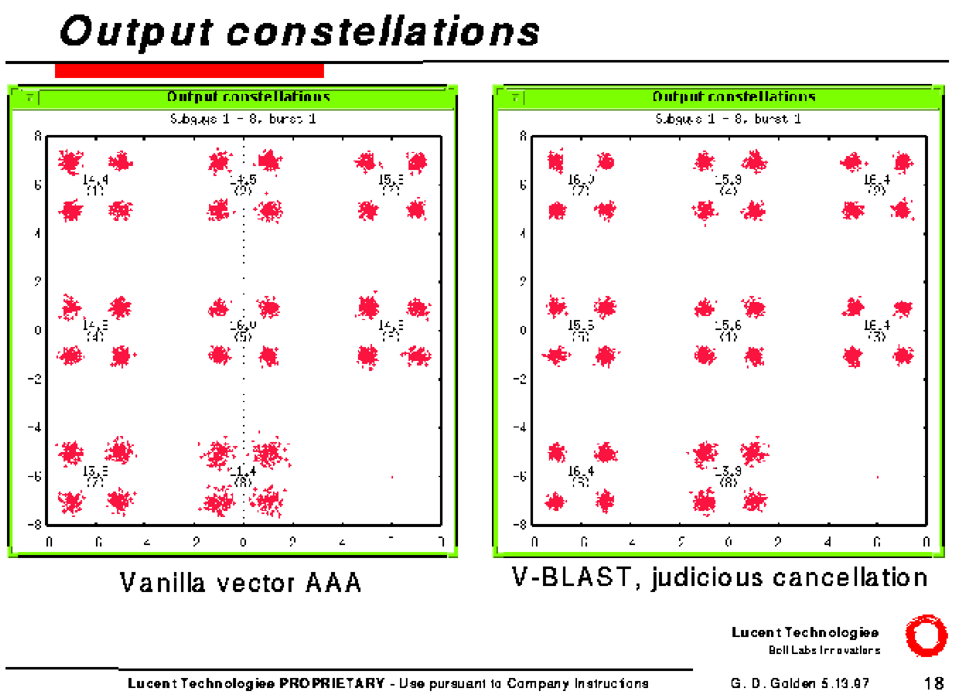
Typical input constellation

Lucent Technologies
Bell Labs Innovations

Lucent Technologies PROPRIETARY - Use pursuant to Company Instructions

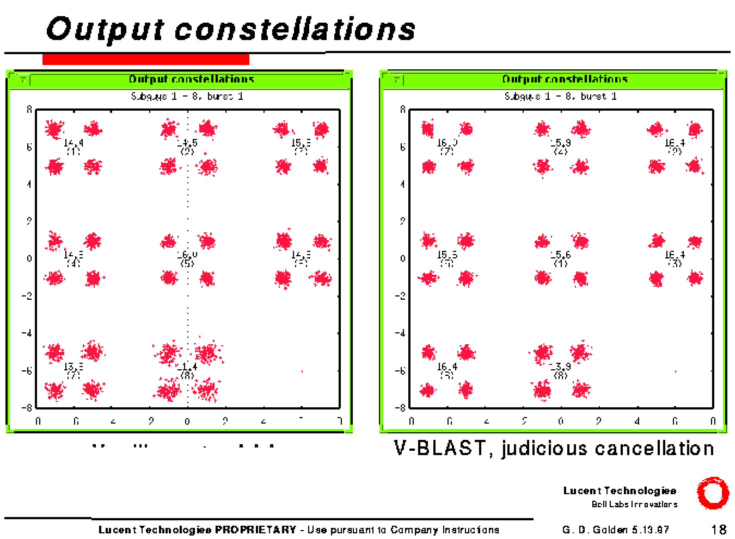
G. D. Golden 5.13.97 19

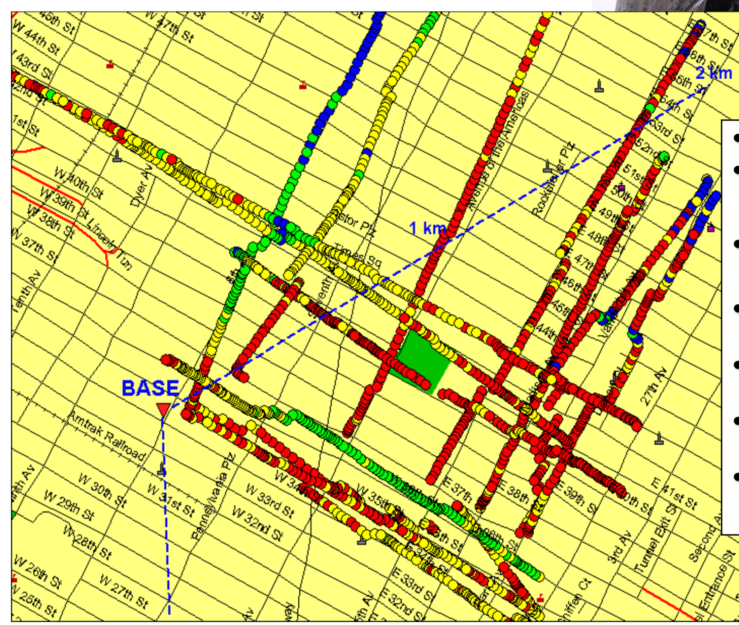
Over-the-air Processed Signals



1st ever indoor and outdoor MIMO experimental setups & results

- Indoor
- Outdoor





- 16Tx by 16 Rx
- 10 dB System SNR >10 dB Measured SNR
- 2 km Range
- RED Very High 35 to 44 bps/Hz
- YELLOW High 25 to 35 bps/Hz
- GREEN Med. 15 to 25 bps/Hz
- BLUE Low. 5 to 15 bps/Hz

An earlier work from a signal processing viewpoint @ Stanford

US005345599A

United States Patent [19]   [11] **Patent Number: 5,345,599**

Paulraj et al.   [45] **Date of Patent: Sep. 6, 1994**

("spatial multiplexing")

[54] **INCREASING CAPACITY IN WIRELESS BROADCAST SYSTEMS USING DISTRIBUTED TRANSMISSION/DIRECTIONAL RECEPTION (DTDR)**

[75] Inventors: **Arogyaswami J. Paulraj,** Palo Alto; **Thomas Kailath,** Stanford, both of Calif.

[73] Assignee: **The Board of Trustees of the Leland Stanford Junior University,** Stanford, Calif.

[21] Appl. No.: **839,624**

FOREIGN PATENT DOCUMENTS

0164749 12/1985 European Pat. Off. 375/38

Primary Examiner—Reinhard J. Eisenzopf
Assistant Examiner—Chi Pham
Attorney, Agent, or Firm—Townsend and Townsend Khourie and Crew

[57] **ABSTRACT**

A method and apparatus for increasing the capacity of wireless broadcast communications system from a central studio to a plurality of users in a service area is disclosed. Given a source signal whose high information rate exceeds the practical information carrying

U.S. Patent   Sep. 6, 1994   Sheet 1 of 7   5,345,599

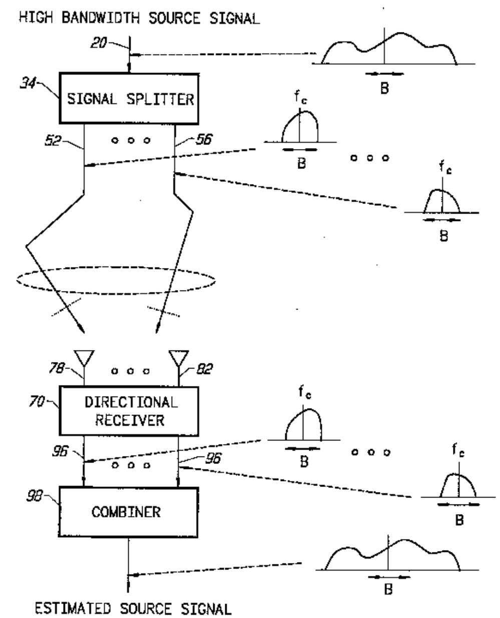
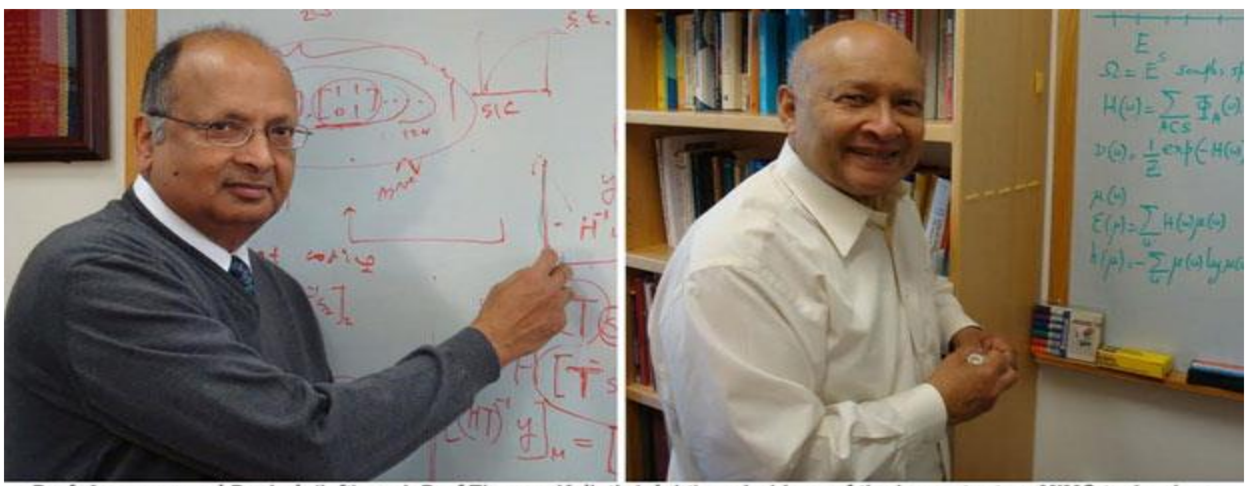


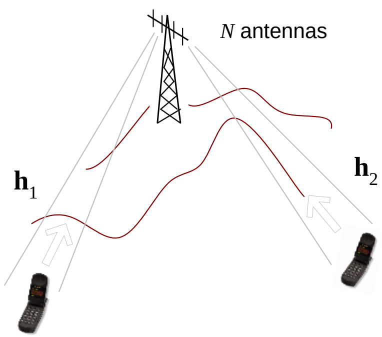
FIG. 1



Prof Arogyaswami Paulraj (left) and Prof Thomas Kailath (right), co holders of the key patent on MIMO technology

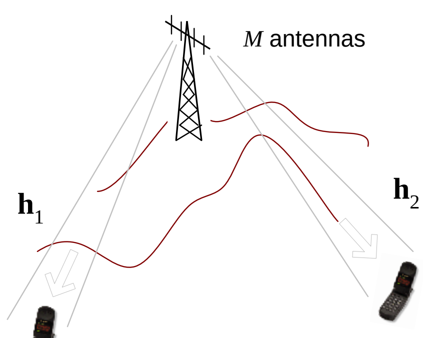
Moving into the user dimension: Multi-user (MU) MIMO

- **(*M*,*K*,*N*) MIMO multiaccess channel (MAC)**
  - *K* users, each with *N* antennas, transmit to a base with *M* antennas



Transmitted signals	$\mathbf{s}_k \in \mathbb{C}^N; \quad k = 1,\ldots,K$
Covariances	$\mathbf{Q}_k \triangleq E\left[\mathbf{s}_k \mathbf{s}_k^H\right]$
Individual power constraints	$P_k \in \mathbb{R}^+$
MIMO channels	$\mathbf{H}_k^H \in \mathbb{C}^{M \times N}$

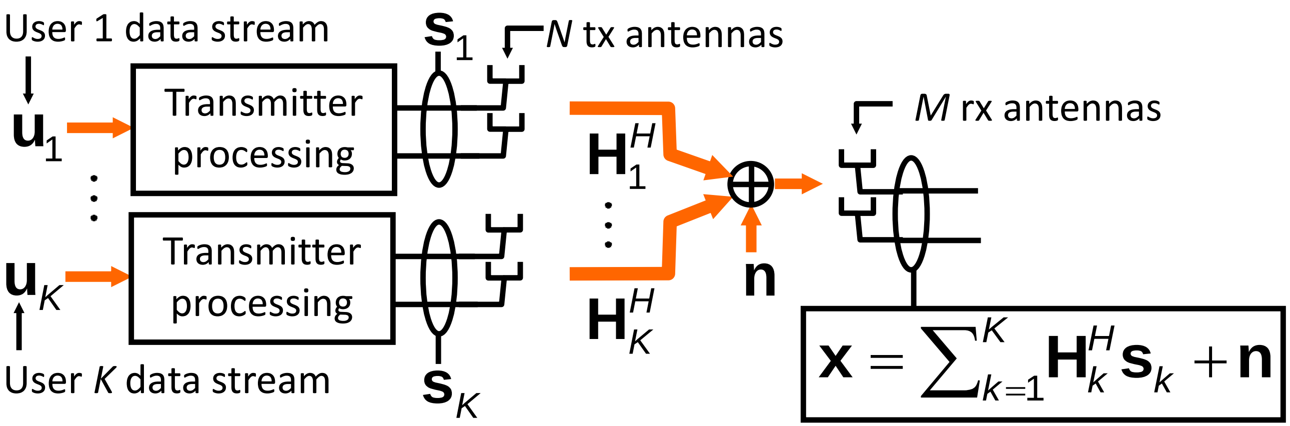
- **(*M*,*K*,*N*) MIMO broadcast channel (BC)**
  - Base with *M* antennas transmits to *K* users, each with *N* antennas.



Transmitted signal	$\mathbf{s} \in \mathbb{C}^M$
Covariance	$\mathbf{Q} \triangleq E\left[\mathbf{s}\mathbf{s}^H\right]$
Total power constraint	$P \in \mathbb{R}^+$
MIMO channels	$\mathbf{H}_k \in \mathbb{C}^{N \times M}$

MU-MIMO system-level models

Multiple Access Channel (MAC)



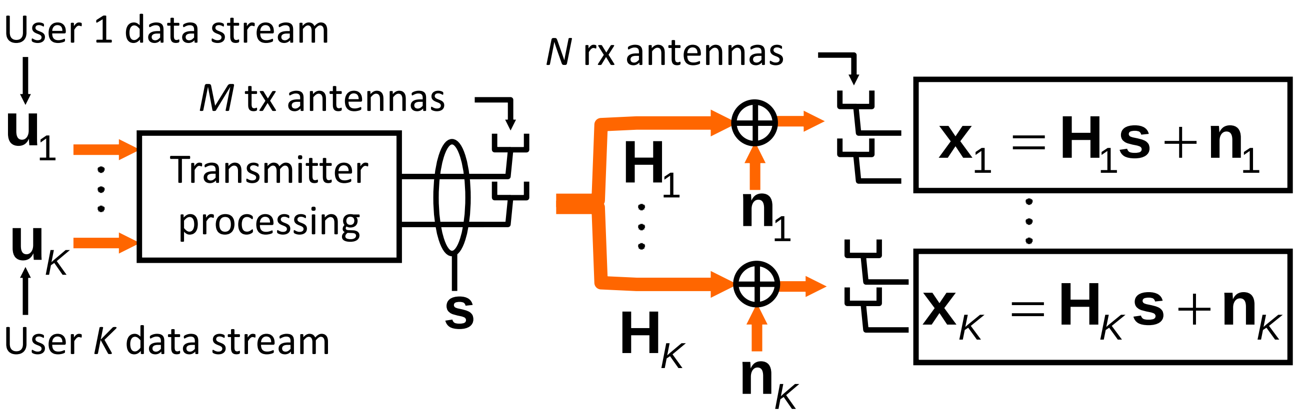
$$\mathbf{Q}_k \triangleq E\left[\mathbf{s}_k \mathbf{s}_k^H\right]$$

$$tr\ \mathbf{Q}_k = P_k$$

$$\mathbf{n} \in \mathbb{C}^{M\times 1}$$

$$\mathbf{n} \sim N(\mathbf{0}, \mathbf{I}_M)$$

Broadcast Channel (BC)



$$\mathbf{Q} \triangleq E\left[\mathbf{s}\mathbf{s}\right]$$

$$tr\ \mathbf{Q} = P$$

$$\mathbf{n}_k \in \mathbb{C}^{N\times 1}$$

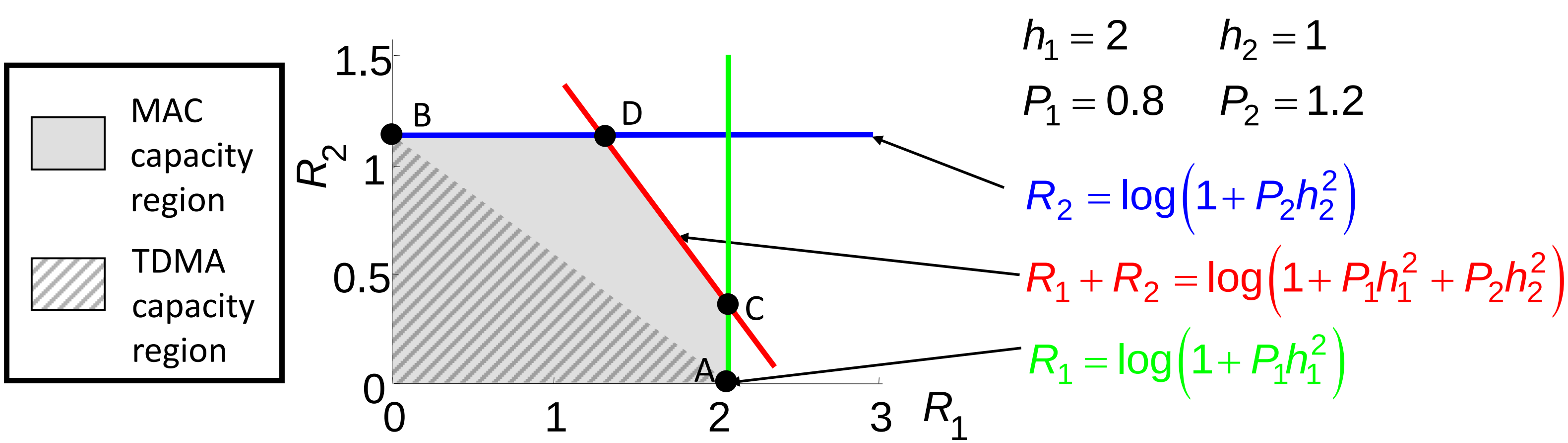
$$\mathbf{n}_k \sim N(\mathbf{0}, \mathbf{I}_N)$$

MIMO MAC capacity region

- For a given set of MIMO channels $\mathbf{H}_k^H$ and power constraints P_k, $k = 1,\ldots,K$, the capacity of the Gaussian MIMO MAC is

$$C_{MAC}(\mathbf{H}^H,\mathbf{P}) \triangleq \bigcup_{\substack{\mathbf{Q}_1,\ldots,\mathbf{Q}_K \\ tr(\mathbf{Q}_k)\le P_k}} \left\{ (R_1,\ldots,R_K) : \sum_{k\in S} R_k \le \log\left| \mathbf{I} + \sum_{k\in S} \mathbf{H}_k^H \mathbf{Q}_k \mathbf{H}_k \right|, \forall S \subseteq \{1,\ldots,K\} \right\}$$

- In general, the capacity region is a polymatroid
- Vertices of the capacity region are achieved using an MMSE detector and doing successive interference cancellation [Telatar99],[Verdu89].



Duality between MIMO BC and MIMO MAC

- **The capacity regions of the MIMO BC and MIMO MAC are related by the following remarkable duality property:**

$$C_{BC}(\mathbf{H},P) = \bigcup_{\substack{P_1,\ldots,P_K \\ \sum_{k=1}^{K} P_k \le P}} C_{MAC}(\mathbf{H}^H,\mathbf{P})$$

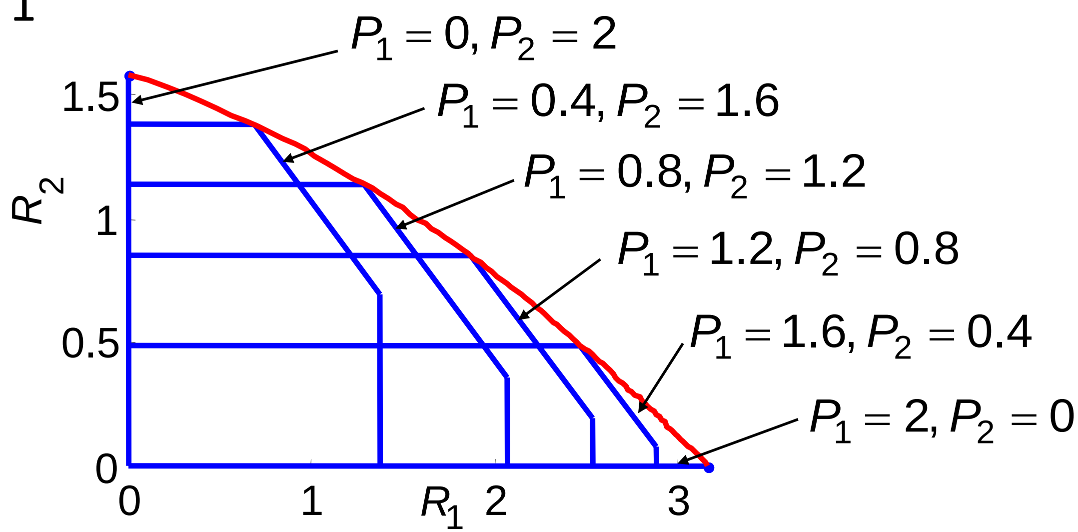
  – The MAC region is contained within the BC region for a given total power.

- **Example, $K = 2$, $M = 1$, $N = 1$, $P = 2$**

  SISO channels: $h_1 = 2$, $h_2 = 1$

Red line: BC capacity region

Blue lines: MAC capacity regions



MIMO BC capacity scaling

- Consider an (M,K,N) MIMO BC with power P where the entries of $\mathbf{H}_1,\ldots,\mathbf{H}_K$ and $\mathbf{n}_1,\ldots,\mathbf{n}_K$ are zero-mean complex Gaussian i.i.d. random variables with unit variance σ^2. We define the SNR as $\mathrm{SNR}=\mathrm{P}/\sigma^2$ where P is the total Tx power from the base station.
- Then the BC sum rate capacity scales as follows asymptotically:

$$\lim_{SNR\to\infty} R_{BC} = \min(M, KN)\log(\mathrm{SNR})$$
$$\lim_{K\to\infty} R_{BC} = \min(M, KN)\log\log(KN)$$

- Assuming that $M<KN$, this gives:
  - **Linear growth w.r.t. *M*** due to spatial multiplexing of users
  - *Very slow growth w.r.t. KN* due to serving users with favorable fading states
- In the opposite regime (e.g. $N=1$ and $M>K$), we get:

$$\lim_{SNR\to\infty} R_{BC}(M/K>1, N=1) = K\log(\mathrm{SNR})$$

  - ***Linear growth w.r.t. the number of served users K*** (assumed smaller than M)
  - This relates to the **large-scale / Massive antenna regime** mentioned later

MIMO BC capacity scaling (cont.)

- Define the single-user maximum rate as

$$R_{SU}(\mathbf{H}(K),P) = \max_{k=1,\dots,K} \max_{tr\,\mathbf{Q}\le P} \log\left|\mathbf{I}_N + \mathbf{H}_k \mathbf{Q} \mathbf{H}_k^H\right|$$

  – Transmit to the single best user with closed-loop MIMO.

- If we assume $M \geq N$, then it turns out that:

$$\lim_{K\to\infty} R_{SU}(\mathbf{H}(K),P) = N \log(\log K)$$

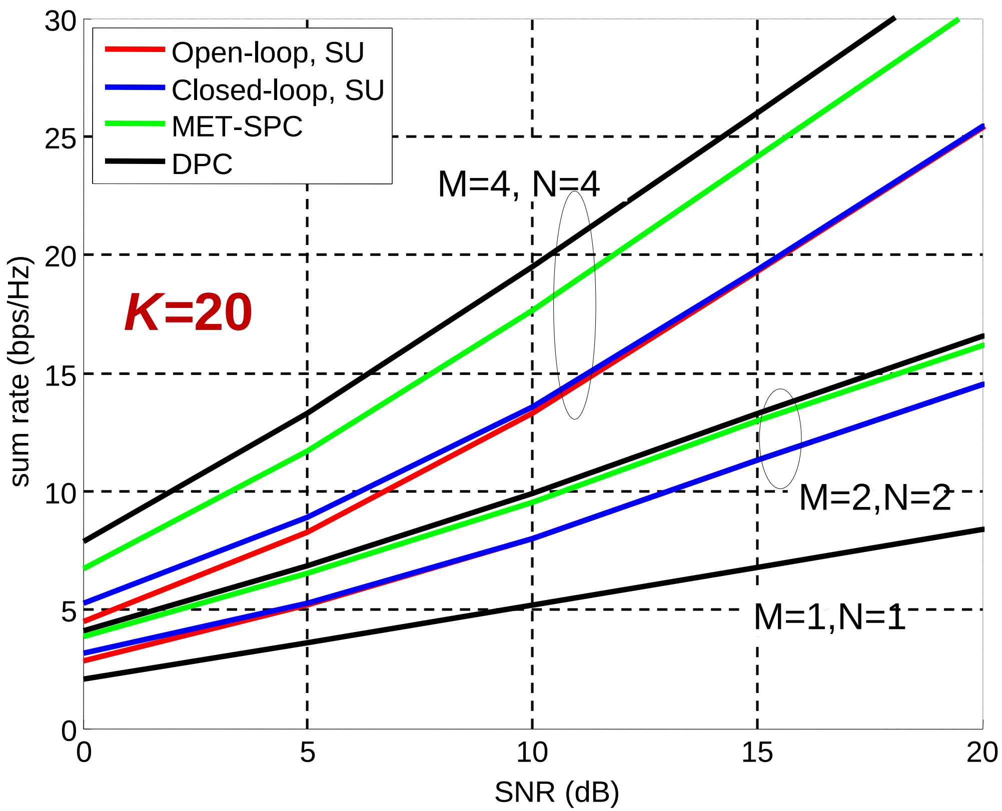
  – Linear gain with respect to the number of receive antennas *N*.

- Furthermore,

$$\lim_{K\to\infty} \frac{R_{BC}(\mathbf{H}(K),P)}{R_{SU}(\mathbf{H}(K),P)} = \frac{M}{N}$$

  – BC gains over single-user transmission diminish as *N* grows.
  – If $M = N$, DPC is asymptotically equivalent to TDMA!

Average sum rate performance, fixed SNR



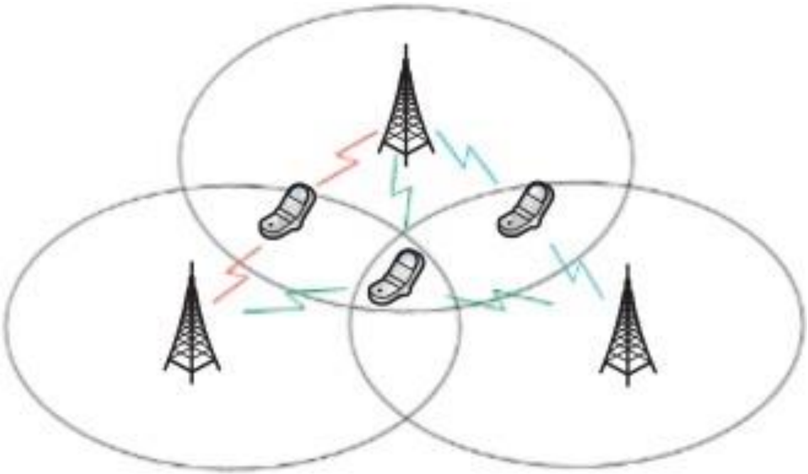
- Compare sum-rate performance of single-user SM with MET and DPC.
- For SM, transmit to the single user out of *K* with highest achievable rate.
- Systems are equivalent for $M = N = 1$.
- As the number of antennas increase,
  - Gains of beamforming over SM increase.
  - Gains of DPC over MET increase.

DPC: Dirty paper coding: the nonlinear, capacity-achieving technique for the MIMO Broadcast Channel
MET: Multiuser eigenmode transmission: A near-optimal, linear precoding technique for the MIMO BC

H. C. Huang, S. Venkatesan and C. B. Papadias, MIMO Communication for Cellular Networks, Springer, Nov. 2011, ISBN 978-0-387-77521-0

Cooperative MIMO ("Network MIMO")

- When the base stations of a number of cells are allowed to cooperate with each other, we have the so-called "cooperative" or "network" MIMO setup:



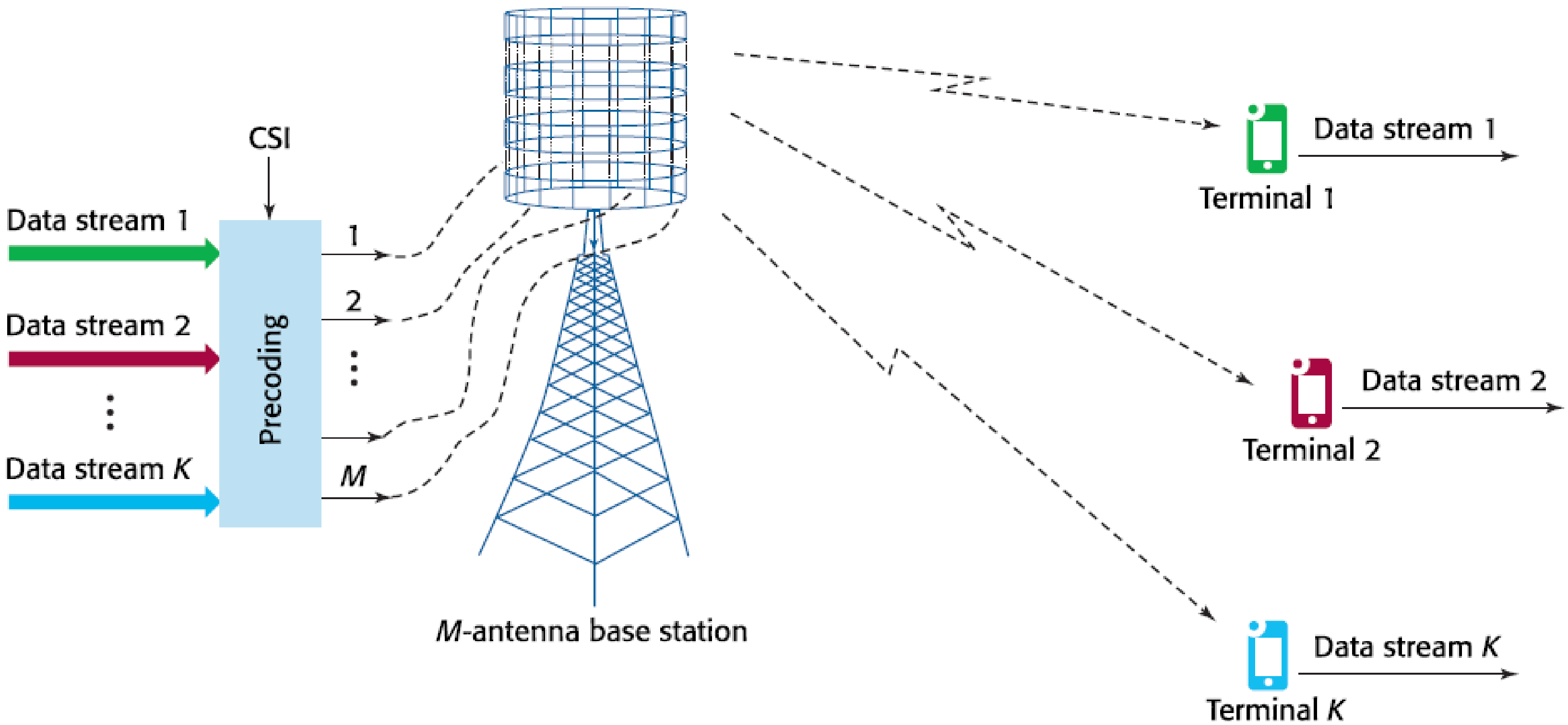
- Assuming full cooperation (FC) between the cells, the cluster of L cooperating base stations acts as a gigantic distributed antenna array, hence the sum rate at high SNR (ignoring interference from other cells) will scale as:

$$\lim_{SNR \to \infty} R_{FC} = \min(ML, KN) \log(\text{SNR})$$

- For $N=1$ and assuming $ML>K$, the N/W MIMO rate scales as:

$$\lim_{SNR \to \infty} R_{FC} = K \log(\text{SNR})$$

Massive (/ large scale) MIMO



- **The base station antennas are allowed to grow to very large numbers (*M*>>*K*)**
- **Each terminal unit is equipped with a single receiver antenna**
- **Coordination between cells is to be avoided**

Figure taken from: T. Marzetta, "Massive MIMO: An introduction," BLTJ vol. 20, pp. 11-22, March 20, 2015.

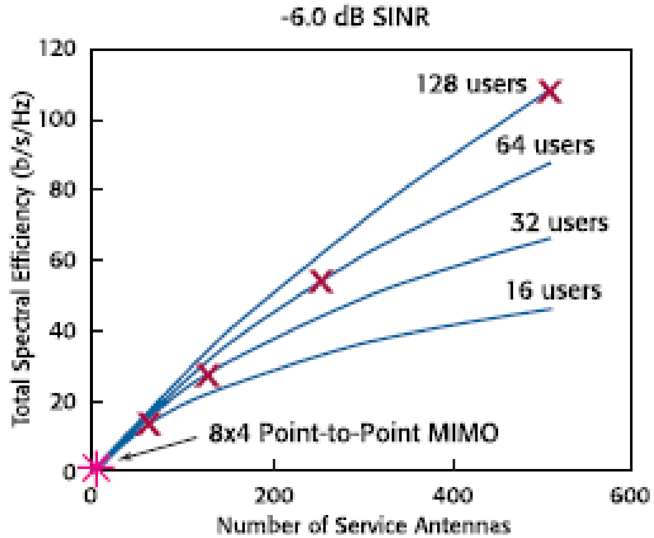
Key properties of large scale / Massive MIMO

- **The sum rate lower bound grows linearly with *K*:**

$$B_{\text{sum,cj}} = K \log_2 \left[1 + \frac{M}{K} \frac{\rho_f \tau_r \rho_r}{(\rho_f + 1)(\tau_r \rho_r + 1)}\right]$$

$$B_{\text{sum,zf}} = K \log_2 \left(1 + \frac{M-K}{K} \frac{\rho_f \tau_r \rho_r}{\rho_f + 1 + \tau_r \rho_r}\right)$$

- **Reasonably small ratios of *M/K* suffice:**



X points: *M/K=4*

- **The performance is asymptotically equivalent to that of n/w cooperation:**

$$C(SNR) = K \log_2(SNR) + o(\log(SNR))$$

Equations taken from: H. Yang and T. L. Marzetta, "Performance of Conjugate and Zero forcing Beamforming in Large-Scale Antenna Systems," IEEE J. Sel.Areas Commun., vol. 31, no. 2, pp. 172–179, Feb. 2013.

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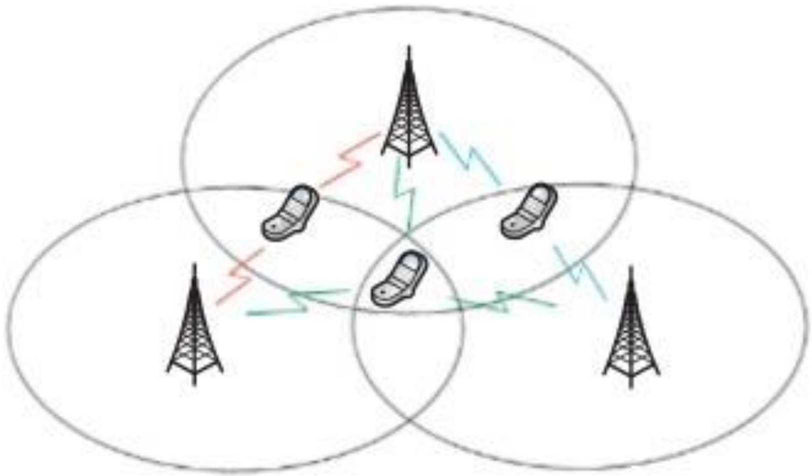

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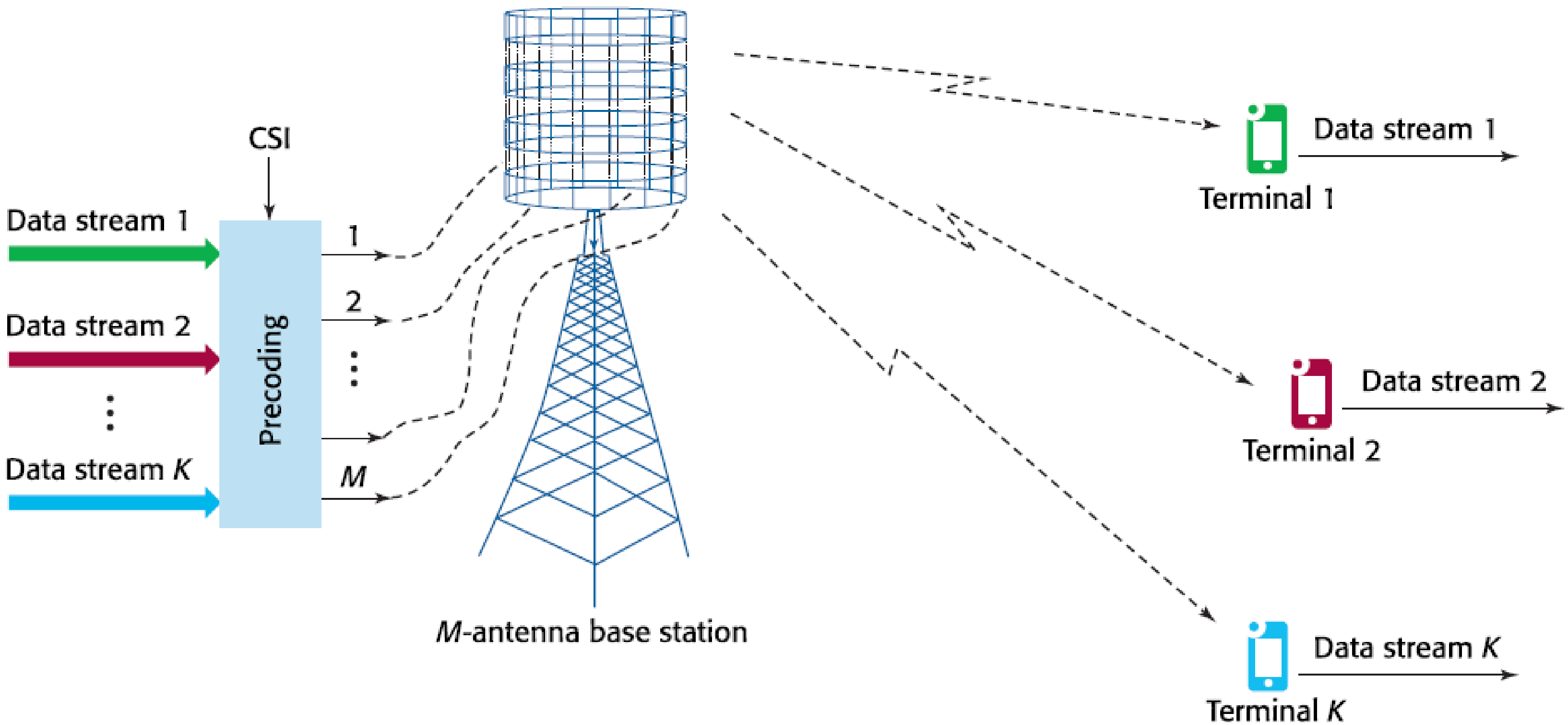

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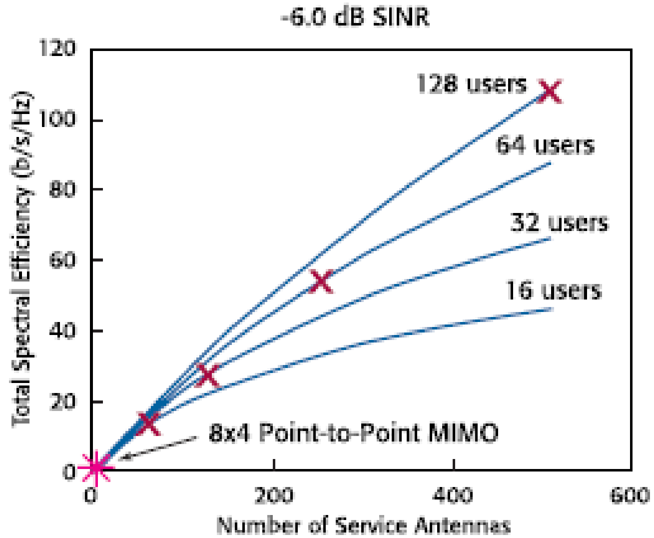
- **Reasonably small ratios of *M/K* suffice:**



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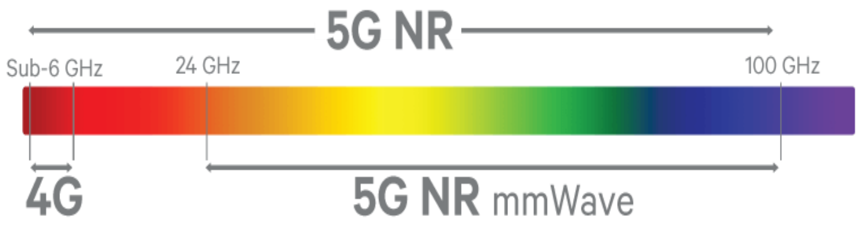
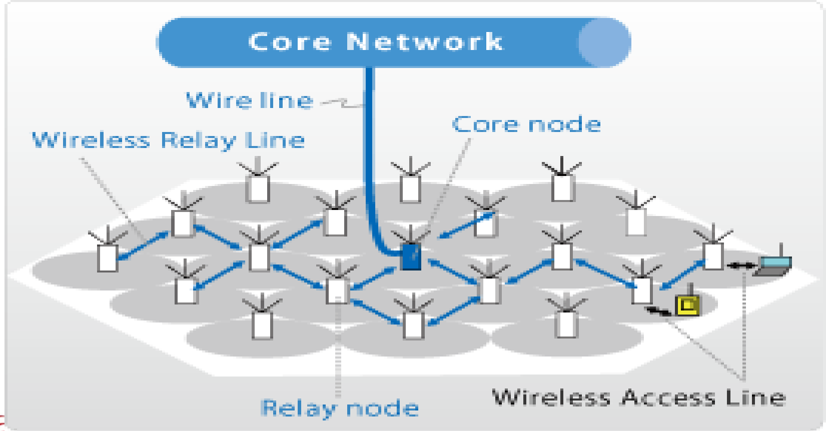
So where do multi-antenna systems stand today?

- Cellular MIMO: a reality from 3G on

- mmWave: will be in 5G



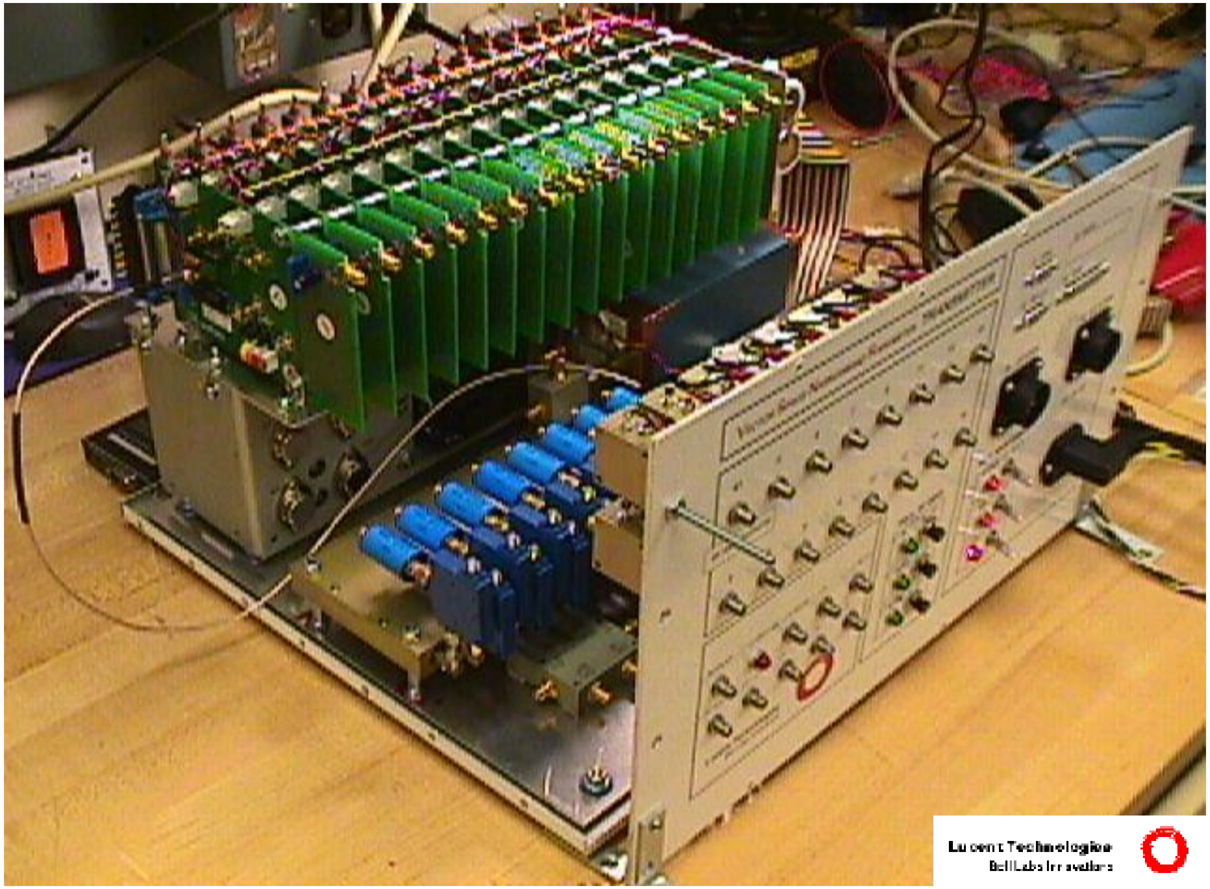
- Network MIMO: is in 4G (CoMP)



- Massive MIMO: discussed in 5G

But the antenna numbers, have been quite small up to (and including) 4G!

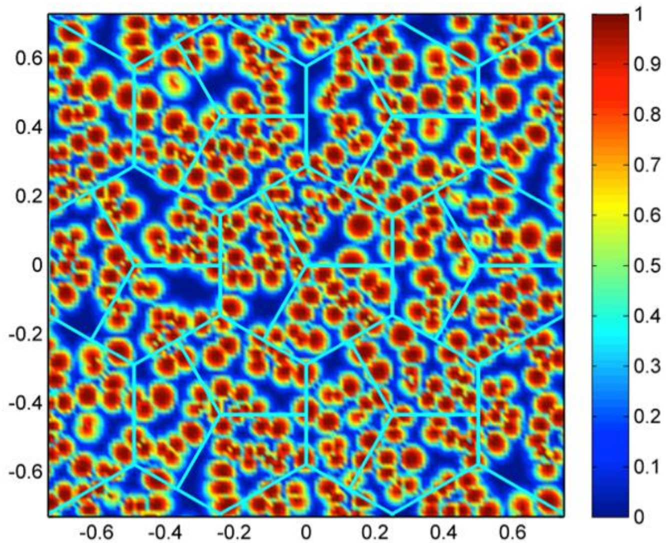
This is mostly due to the required Radio Frequency (RF) circuitry – it takes space, adds cost, burns battery!



Clearly, this situation of modest numbers of antennas at the base station will change from 5G and Beyond, with the introduction of both Massive MIMO & mmWave!

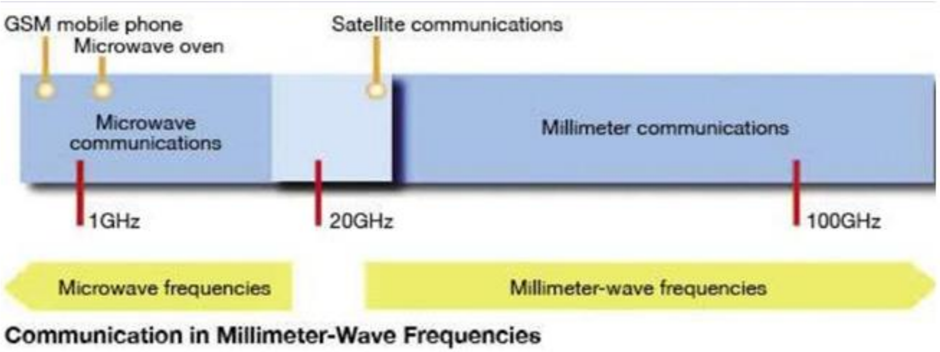
Key trends in next generation wireless networks

- **Cell densification**

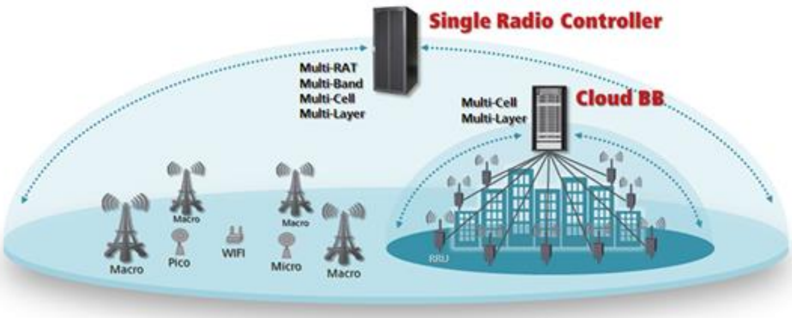


- **More antennas**

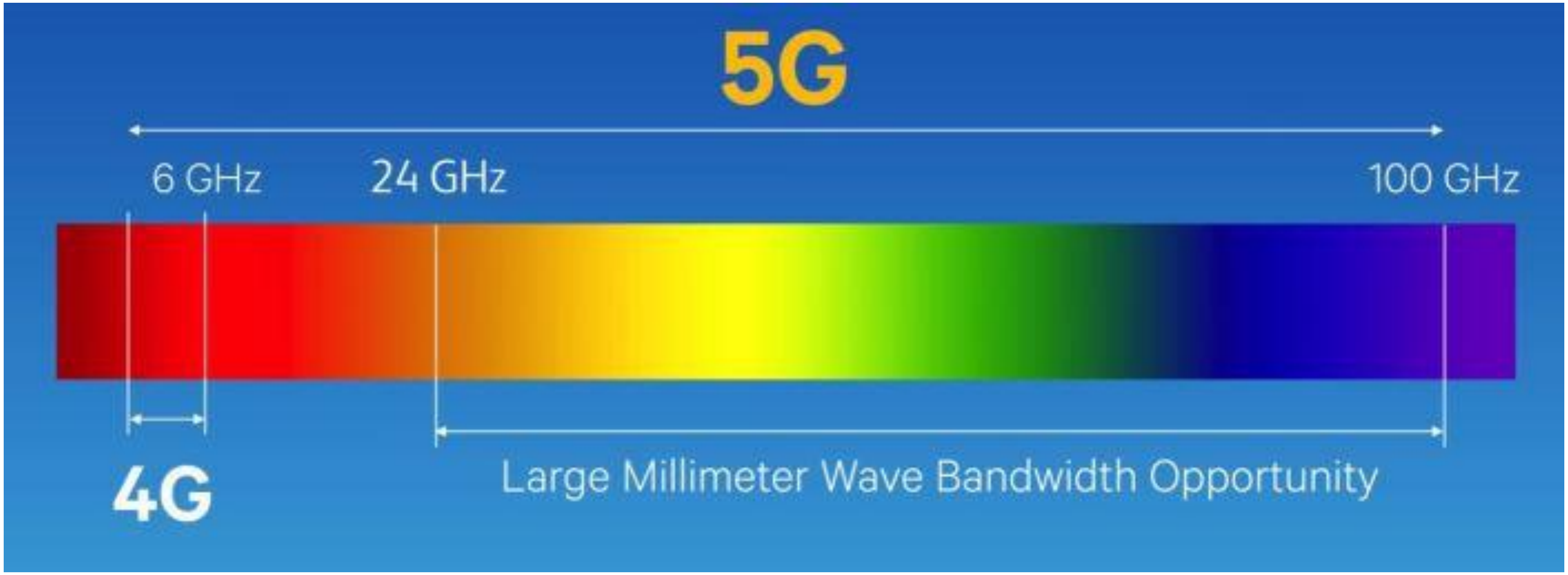
- **More spectrum & better sharing**



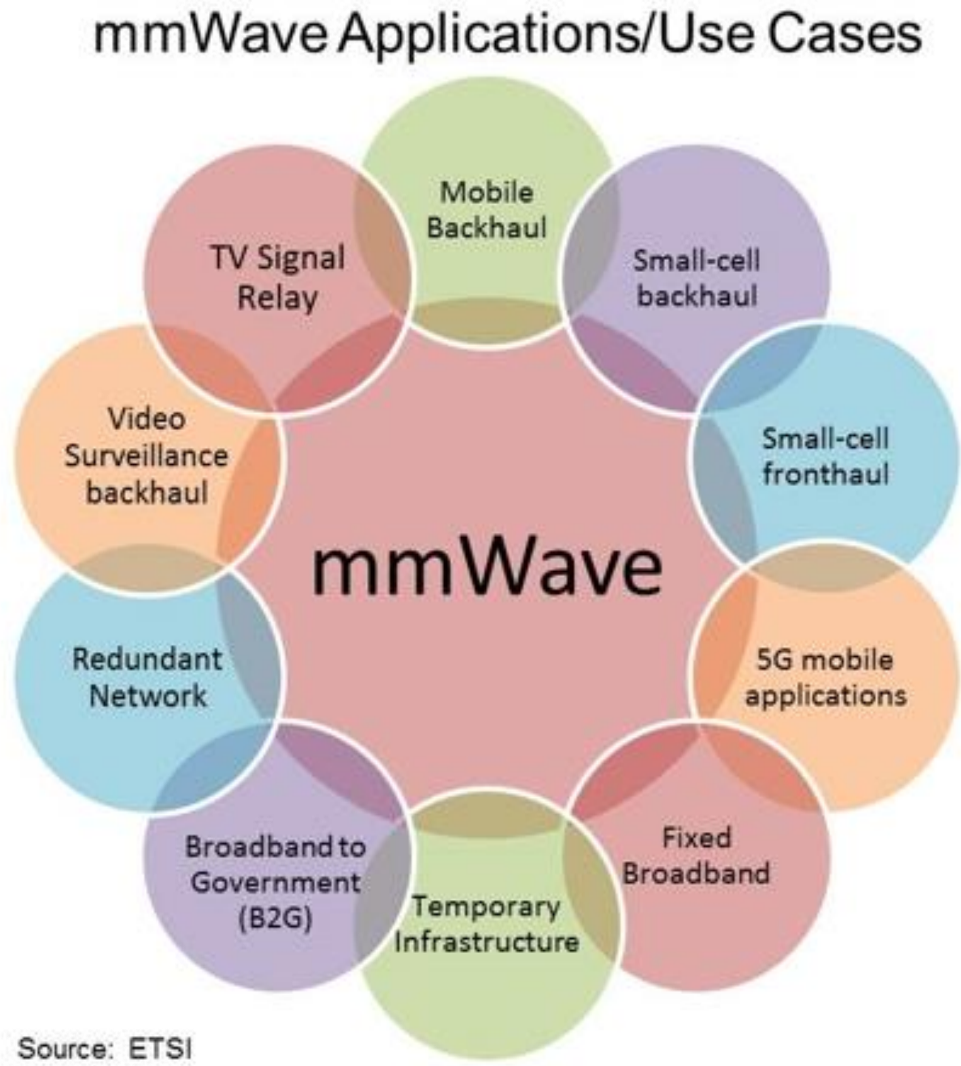
- **More coordination / cloud radio**



A few things about mmWave

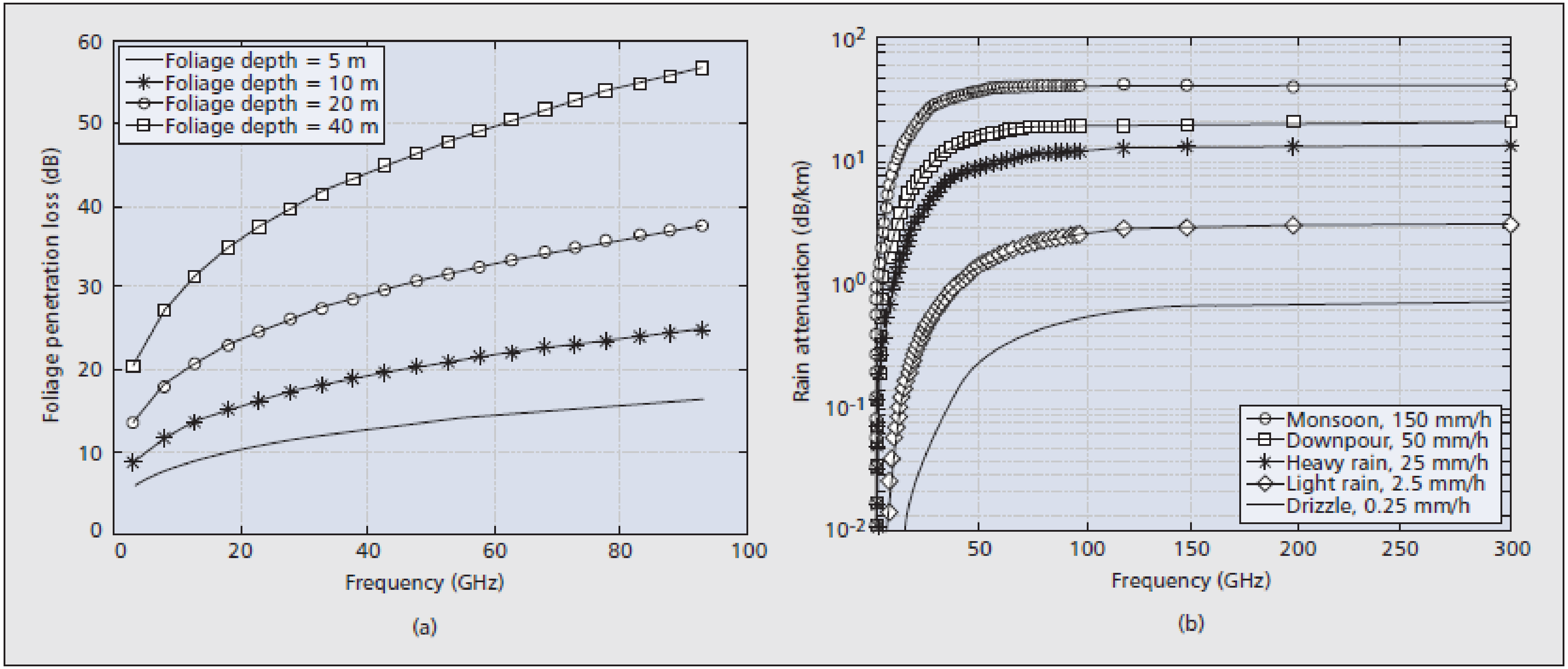


Envisioned millimeter wave applications



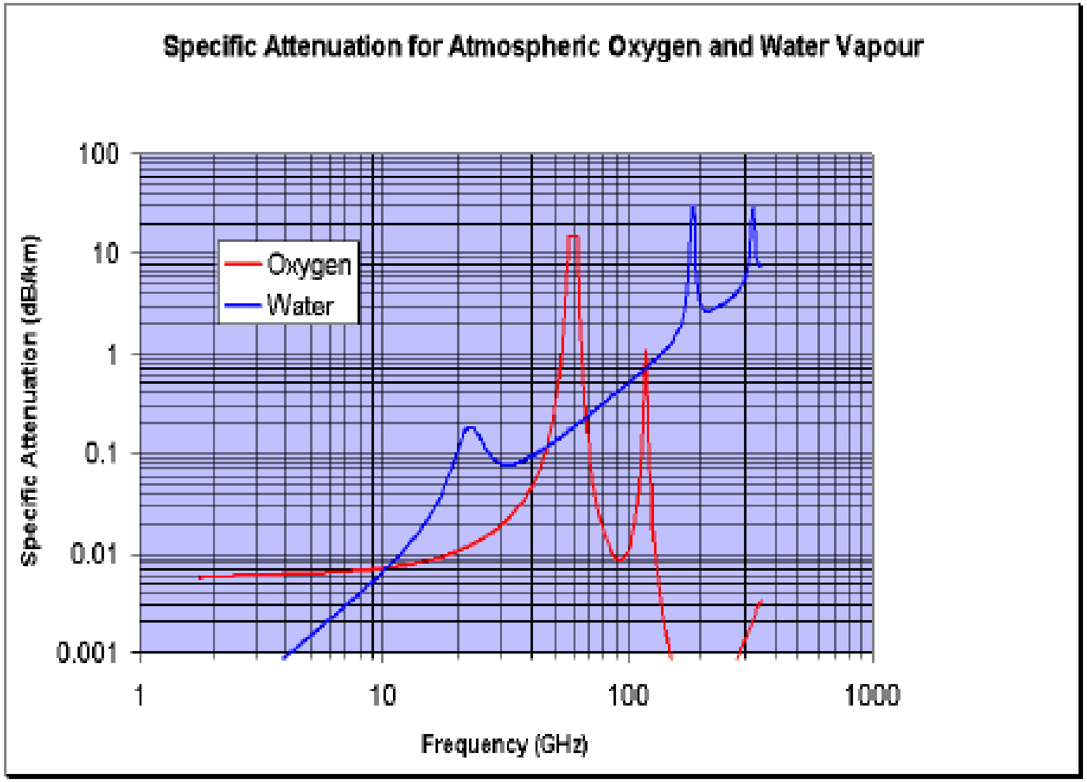
Basics of mmWave propagation

Foliage penetration loss and rain attenuation



- **Foliage losses for millimeter waves are significant and can be a limiting impairment.**
- **Millimeter-wave transmissions can experience significant attenuations in the presence of heavy rain. Raindrops are roughly the same size as the radio wavelengths (millimeters) and therefore cause scattering of the radio signal.**

Atmospheric and rain attenuation



- **Oxygen: in the frequency range of 57.5 GHz to 62.5 GHz in the lower part of the atmosphere, the attenuation due to oxygen is typically 14.7 dB/Km.**
- **At 60 GHz there is a maximum of absorption caused by the oxygen in the atmosphere.**
- **As mentioned, rain also reduces the received power depending on the rain rate.**

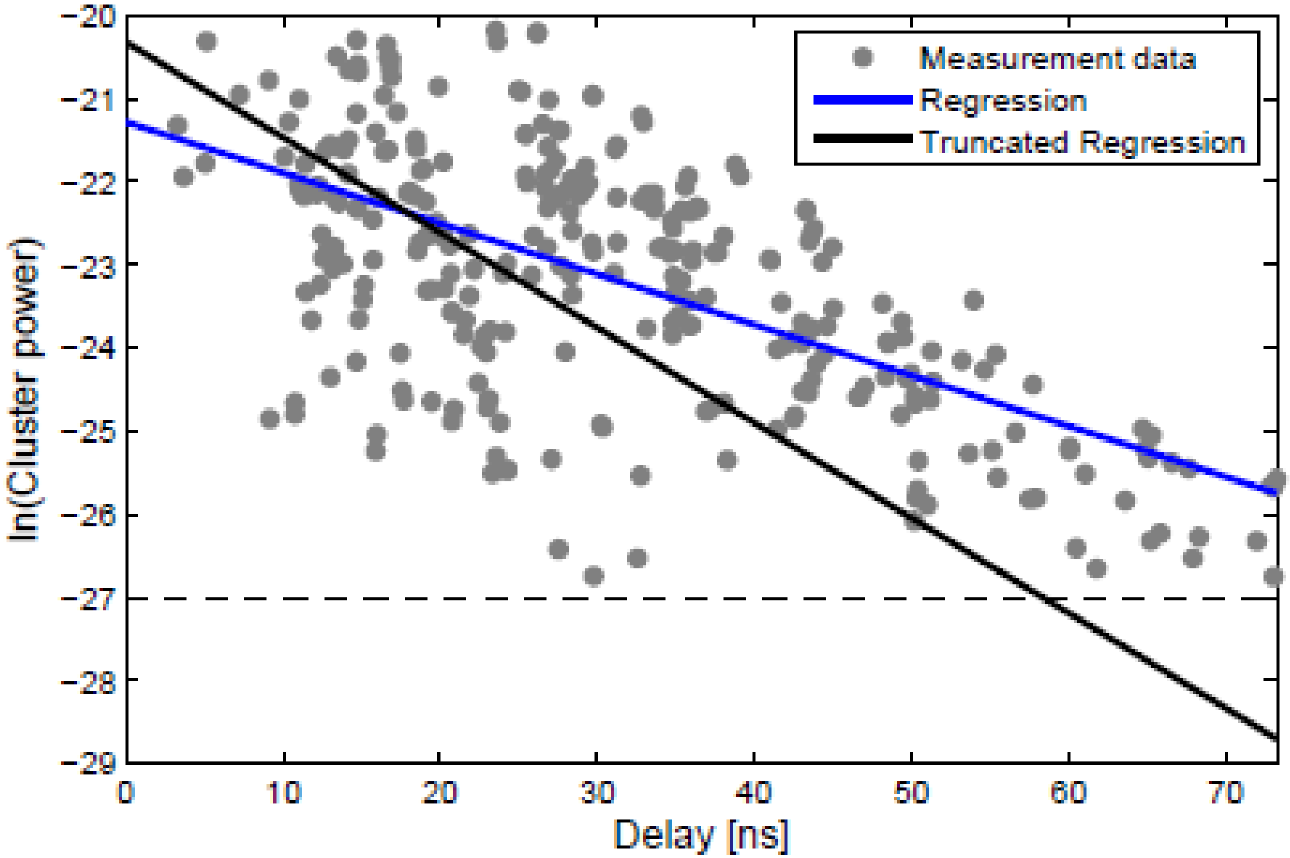
[For the max. rain rate in Europe it results in an additional absorption of about 17dB/km]

The effect of materials

		Attenuation (dB)		
Material	Thickness (cm)	< 3 GHz [6, 8]	40 GHz [7]	60 GHz [6]
Drywall	2.5	5.4	–	6.0
Office whiteboard	1.9	0.5	–	9.6
Clear glass	0.3/0.4	6.4	2.5	3.6
Mesh glass	0.3	7.7	–	10.2
Chipwood	1.6	–	.6	–
Wood	0.7	5.4	3.5	–
Plasterboard	1.5	–	2.9	–
Mortar	10	–	160	–
Brick wall	10	–	t178	–
Concrete	10	17.7	175	–

- **Almost no penetration through building walls at frequencies above 40 GHz!**

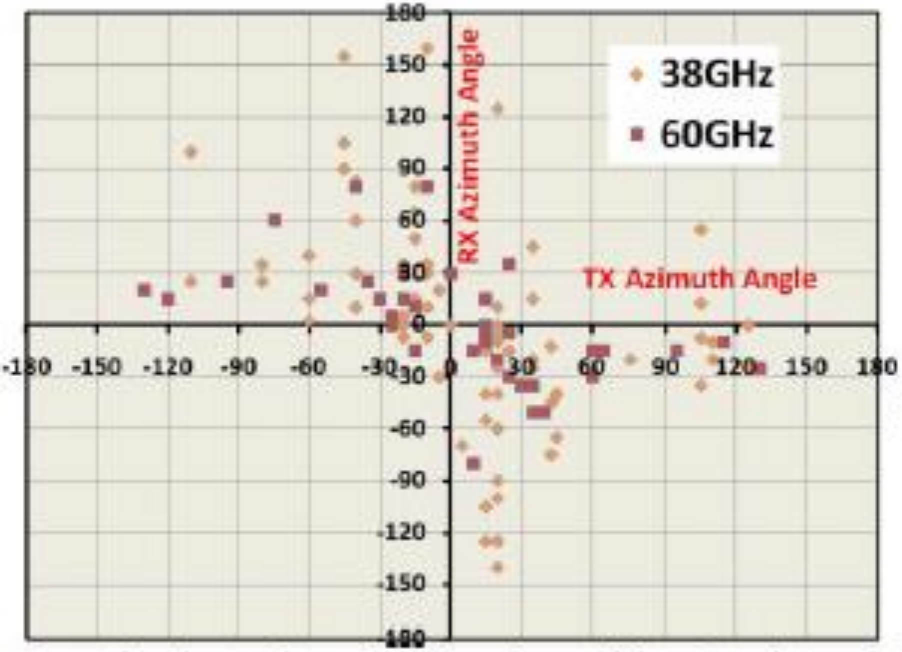
Measurements: Indoor at 62 GHz

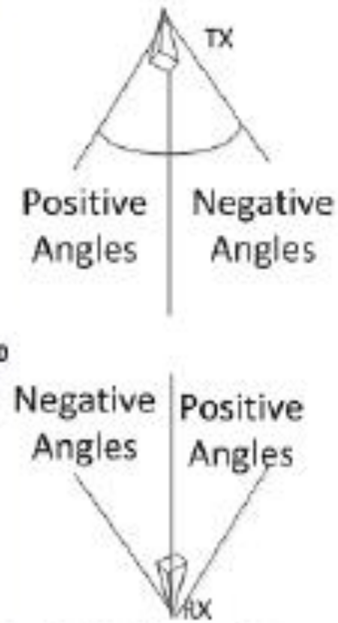


- **The measurement data consists of 17 different line-of-sight (LOS) and 15 obstructed line-of-sight (OLOS) scenarios.**

C. Gustafson, "60 GHz Wireless Propagation Channels: Characterization, Modeling and Evaluation," Lund University.

Measurements: Outdoor P2P @ 38 & 60 GHz

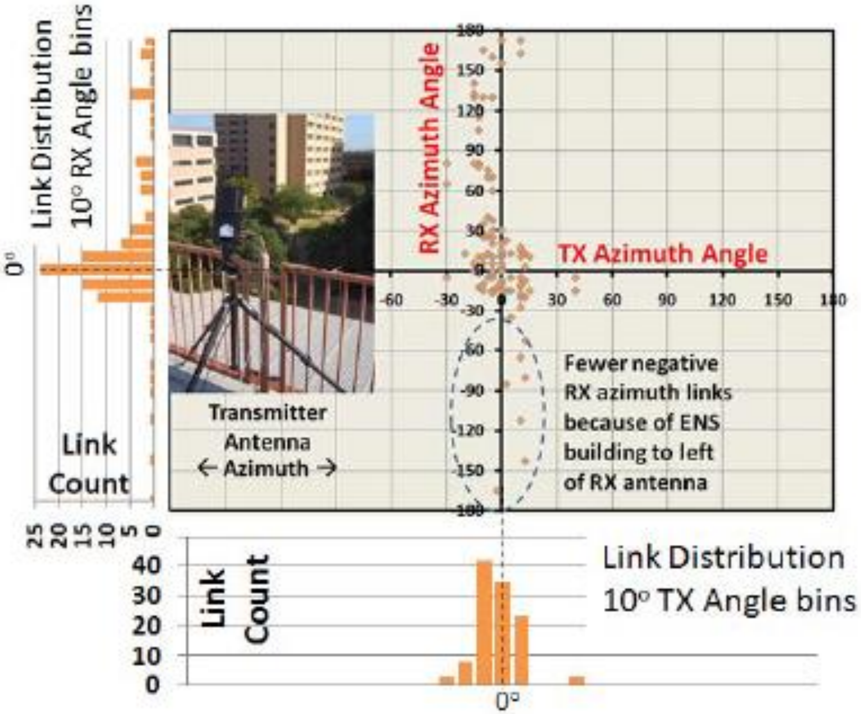


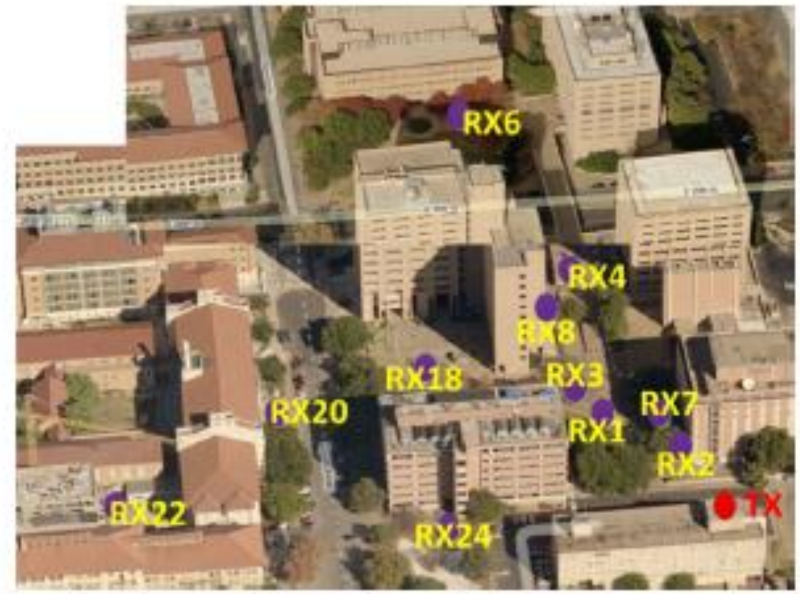


- **Scatter plot of receiver & transmitter azimuth angles that resulted in successful links.**
- **The results suggest a single bounce scattering.**

T. S. Rappaport, E. Ben-Dor, J. N. Murdock, Y. Qiao, 38 GHz and 60 GHz
Angle-dependent Propagation for Cellular & Peer-to-Peer Wireless Communications.

Measurements: Outdoor Cellular @ ~38 GHz

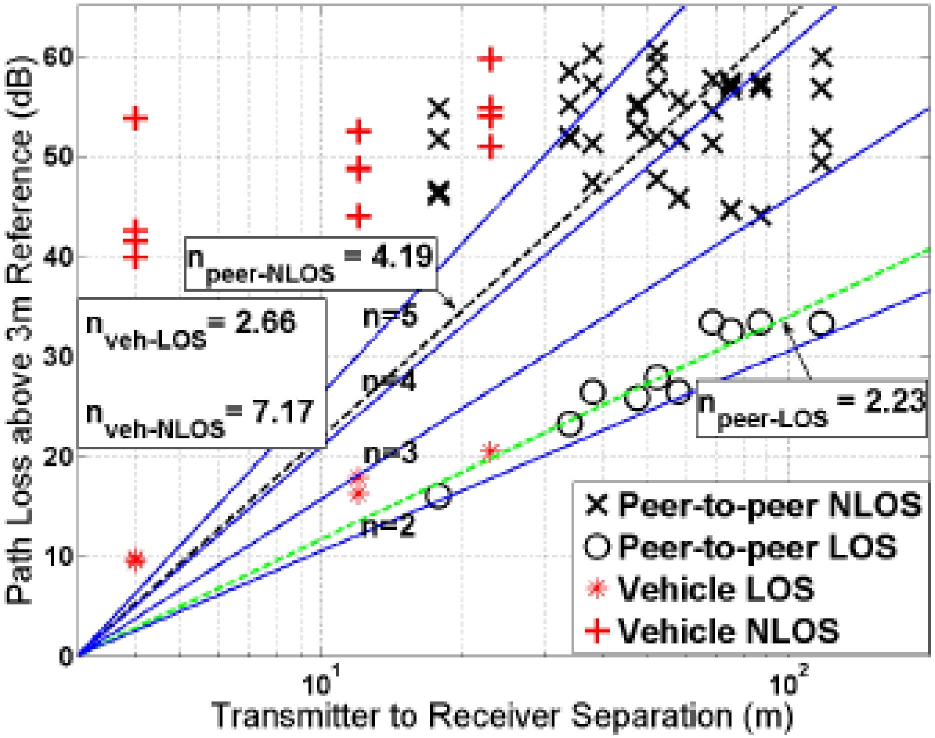




- **Scatter plot of transmitter and receiver azimuth angles at which unique links were found.**
- **The results suggest an "urban canyon" propagation.**

T. S. Rappaport, E. Ben-Dor, J. N. Murdock, Y. Qiao, 38 GHz and 60 GHz
Angle-dependent Propagation for Cellular & Peer-to-Peer Wireless Communications.

Measurements: Path loss for pedestrian at 60 GHz



- **Path loss scatter plot for peer-to-peer and vehicle environments.**
- **LOS measurements: n=2.23 (σ=1.87dB) [P2P]; n=2.66 (σ=5.4dB) [in-vehicle].**
- **NLOS measurements: n=4.19 (σ=9.98dB) [P2P]; n=7.17 (σ=23.8dB) [in-vehicle].**

E. Ben-Dor, T. S. Rappaport, Y. Qiao, S. J. Lauffenburger, Millimeter-wave 60 GHz Outdoor and Vehicle AOA Propagation Measurements using a Broadband Channel Sounder.

Measurements: RMS delay spread for pedestrian 60 GHz channel

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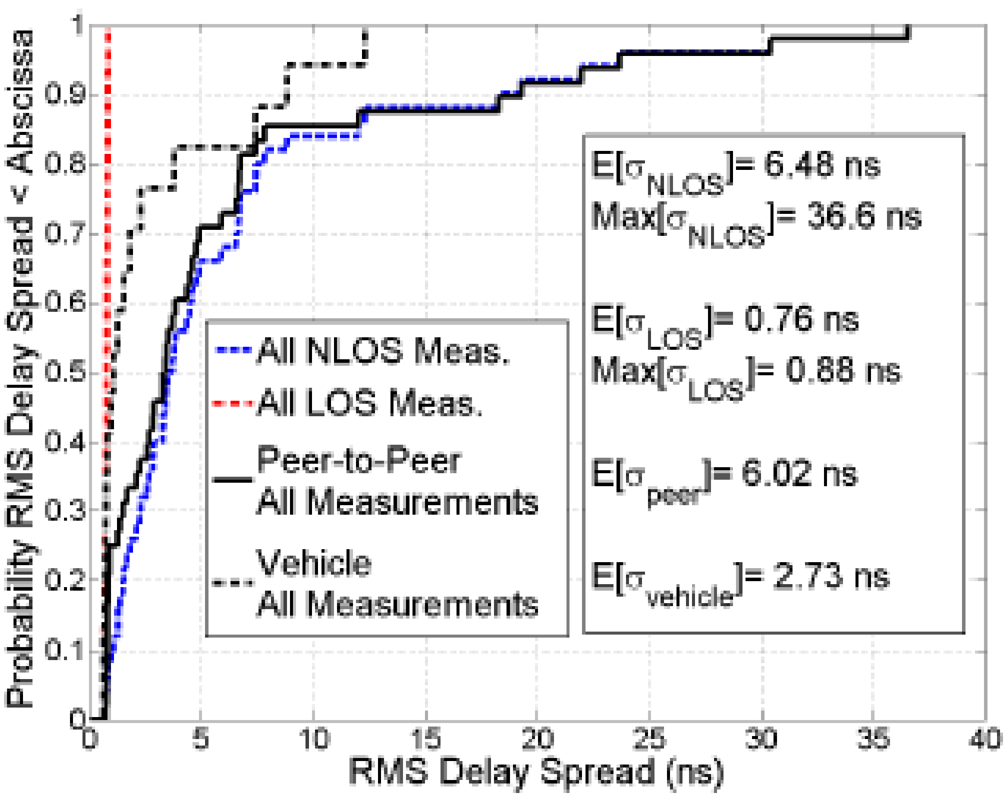


- **Pedestrian LOS channels had minimal RMS delay spread (less than 0.9 ns).**
- **Non-LOS: highly variable RMS delay spreads with a mean of 7.39 ns and max of 36.6 ns.**
- **In-vehicle LOS measurements were also always less than 0.9 ns.**
- **Non-LOS: values up to 12.3 ns.**

E. Ben-Dor, T. S. Rappaport, Y. Qiao, S. J. Lauffenburger, Millimeter-wave 60 GHz Outdoor and Vehicle AOA Propagation Measurements using a Broadband Channel Sounder.

mmWave: Path loss models

ABG Model:

$$\mathrm{PL}^{\mathrm{ABG}}(f,d)[\mathrm{dB}] = 10\alpha\log_{10}\left(\frac{d}{1\ m}\right) + \beta + 10\gamma\log_{10}\left(\frac{f}{1\ GHz}\right) + \chi_\sigma^{\mathrm{ABG}}$$

- **α and γ express the dependence on distance and frequency, respectively.**
- **β is an optimized offset value for path loss in dB.**
- **d is the 3D transmitter-receiver (T-R) separation distance in meters.**
- **χ_σ^{ABG} is the standard deviation describing large-scale signal fluctuations about the mean path loss over distance.**

CI Model:

$$\mathrm{PL}^{\mathrm{CI}}(f,d)[\mathrm{dB}] = \mathrm{FSPL}(f,1\ m)[\mathrm{dB}] + 10n\log_{10}(d) + \chi_\sigma^{\mathrm{CI}}$$

- **n denotes the single model parameter, the path loss exponent (PLE).**
- **d is the 3D T-R separation distance.**
- **FSPL(f, 1 m) denotes the free space path loss in dB at a T-R separation distance of 1 m at the carrier frequency f.**

Path loss model parameter estimates from measurements

PARAMETERS IN THE ABG AND CI PATH LOSS MODELS IN UMI OPEN SQUARE (OS) SCENARIO IN NLOS ENVIRONMENTS (ENV.) FOR DIFFERENT FREQUENCY (FREQ.) RANGES AND DISTANCE (DIST.) RANGES. M DENOTES MEASUREMENT DATA, WHILE R MEANS RAY-TRACING DATA.

Sce.	Env.	Freq./Freq. Range (GHz)	Company	# of Data Points	Dist. Range (m)	Type	n^{CI}	α^{ABG}	β^{ABG} (dB)	γ^{ABG}	σ^{CI} (dB)	σ^{ABG} (dB)	$\sigma^{CI} - \sigma^{ABG}$ (dB)
UMi OS	NLOS	2	Nokia/AAU	10377	17-138	M	2.9	4.7	-2.2	2	7.9	7.4	0.5
		2.9	Qualcomm	34	109-235	M	2.9	3.9	10.2	2	3.3	3.2	0.1
		18	Nokia/AAU	6073	23-138	M	2.8	4.9	-7.7	2	8.7	7.9	0.8
		29	Qualcomm	34	109-235	M	3.2	4.2	11.0	2	5.4	5.3	0.1
		60	Aalto	246	8-36	M	3.2	2.2	46.5	2	2.2	1.8	0.4
		2-18	-	21888	17-235	M	2.8	4.7	-3.1	1.8	8.3	7.6	0.7
		29-60	-	280	8-235	M	3.2	2.4	74.2	0.3	2.8	2.6	0.2
		2-60	-	22168	8-235	M	2.8	4.4	2.4	1.9	8.3	7.8	0.5

- **Urban microcellular (UMi) opens square environment.**
- **Non-Line of Sight measurements.**

S. Sun, T. S. Rappaport, S. Rangan, T. A. Thomas, A. Ghosh, I. Z. Kovacs, I. Rodriguez, O. Koymen, A. Partyka, and J. Jarvelainen, Propagation Path Loss Models for 5G Urban Micro and Macro-Cellular Scenarios.

Path loss model parameter estimates from measurements (2)

PARAMETERS IN THE ABG AND CI PATH LOSS MODELS IN UMI AND UMA SCENARIOS. SC DENOTES STREET CANYON, OS MEANS OPEN SQUARE, FREQ. RANGE REPRESENTS FREQUENCY RANGE, AND DIST. RANGE DENOTES DISTANCE RANGE.

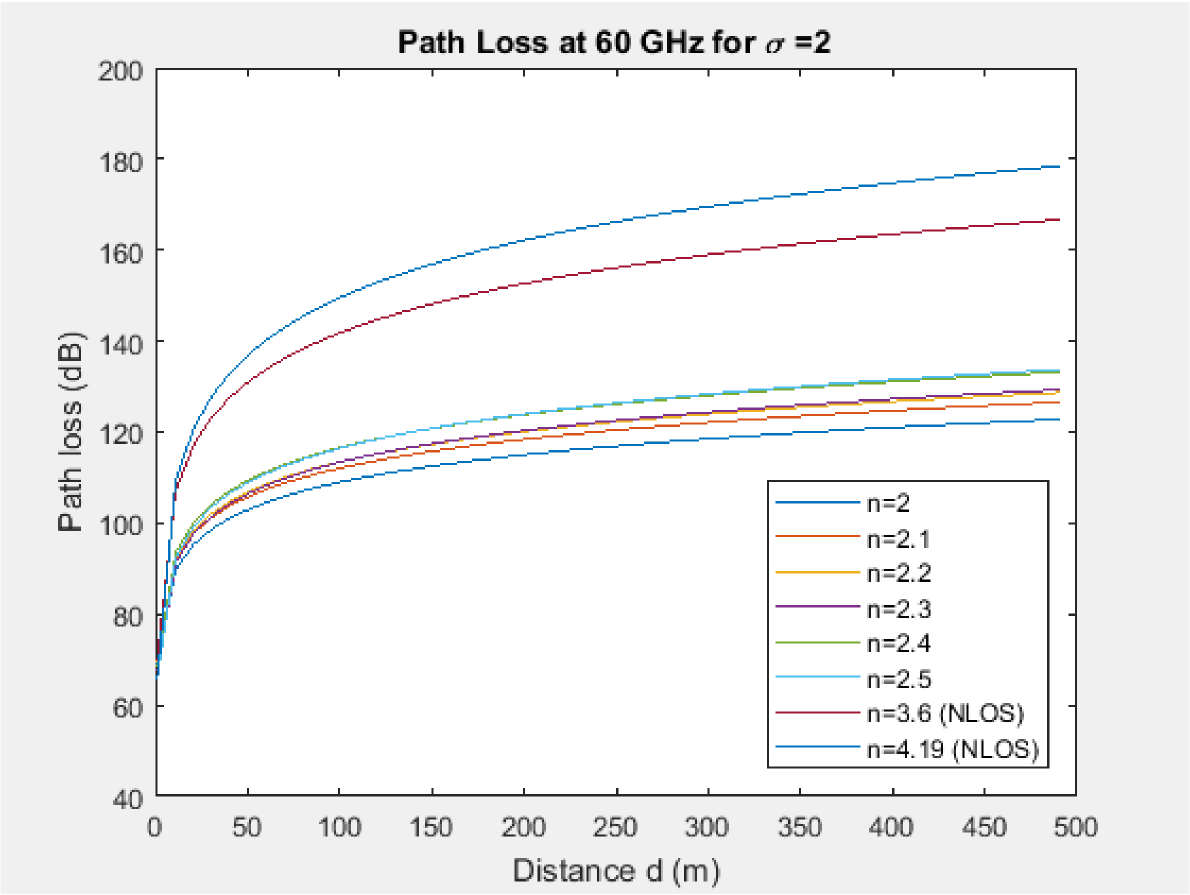
Sce.	Env.	Freq. Range (GHz)	Dist. Range (m)	Model	PLE /α	β (dB)	γ	σ (dB)
UMi SC	LOS	2-73.5	5-121	ABG	2.0	31.4	2.1	2.9
				CI	2.0	-	-	2.9
	NLOS	2-73.5	19-272	ABG	3.5	24.4	1.9	8.0
				CI	3.1	-	-	8.1
UMi OS	LOS	2-60	5-88	ABG	2.6	24.0	1.6	4.0
				CI	1.9	-	-	4.7
	NLOS	2-60	8-235	ABG	4.4	2.4	1.9	7.8
				CI	2.8	-	-	8.3
UMa	LOS	2-73.5	58-930	ABG	2.8	11.4	2.3	4.1
				CI	2.0	-	-	4.6
	NLOS	2-73.5	45-1429	ABG	3.3	17.6	2.0	9.9
				CI	2.7	-	-	10.0

- **Urban micro-cellular street canyon (SC) and open square (OS), LoS & N-LoS**
- **Urban macro-cellular, LoS & N-LoS**

S. Sun, T. S. Rappaport, S. Rangan, T. A. Thomas, A. Ghosh, I. Z. Kovacs, I. Rodriguez, O. Koymen, A. Partyka, and J. Jarvelainen, Propagation Path Loss Models for 5G Urban Micro and Macro-Cellular Scenarios.

Some simulations based on the CI model

$$PL(d) = PL(d_0) + 10n\log(d/d_0) + X_\sigma$$



- **Where d_0= 1m, 2< n <2.5 (for LOS) or n = 3.6 or 4.19 (NLOS) or n = 4.19.**
- **Xσ is a zero mean Gaussian random variable of std dev. σ (in dB).**

Some of our own recent measurements @ 60 GHz

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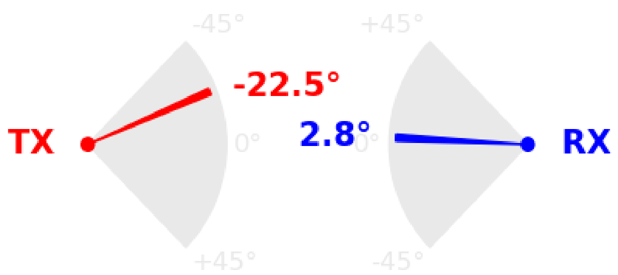
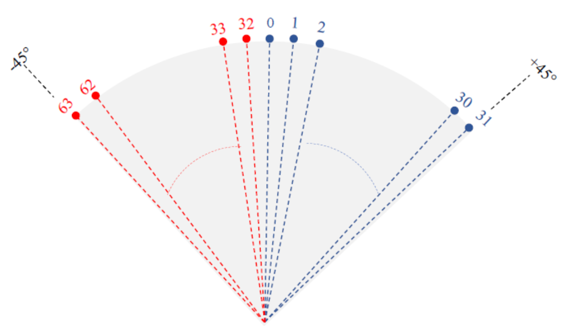
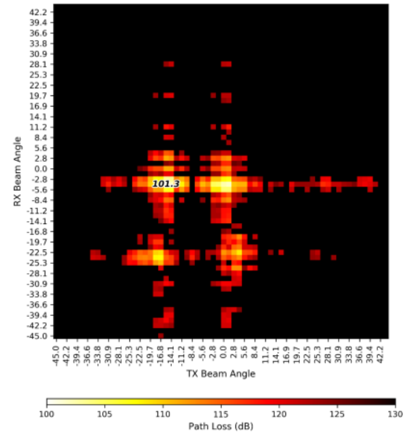
Example Tx / Rx beam setup



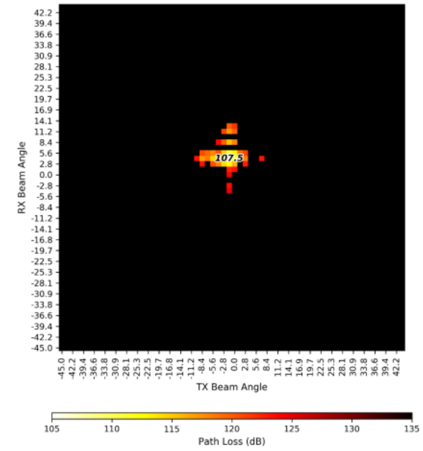
Beam selection resolution



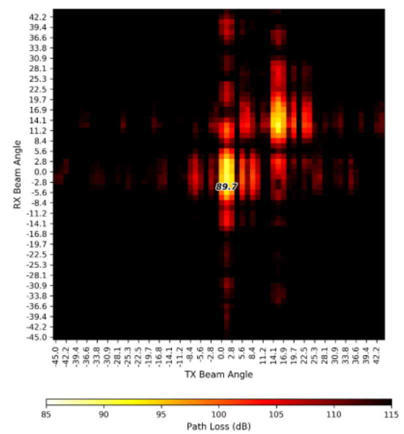
LOS including window reflections



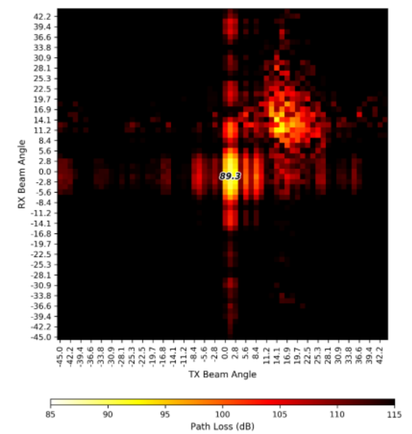
LOS through window



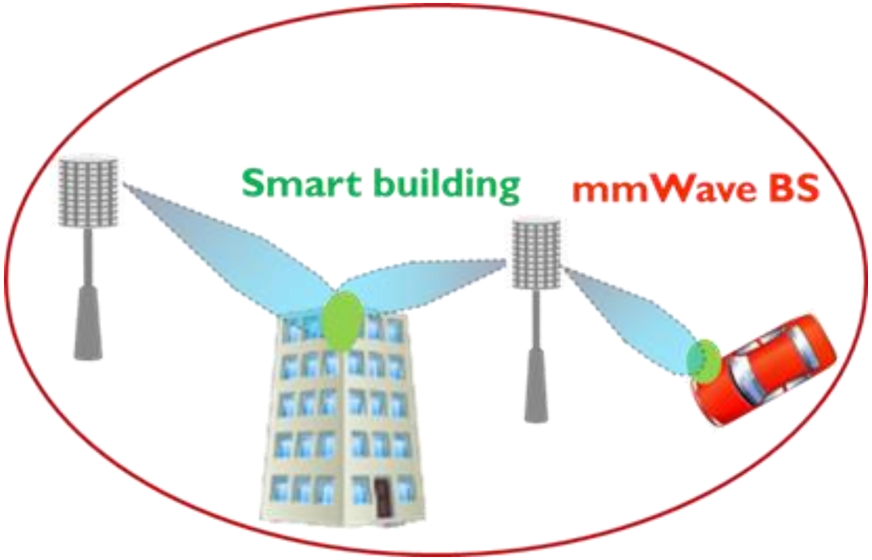
NLOS over calm water



NLOS over turbulent water



Millimeter wave & Massive MIMO: a good match!



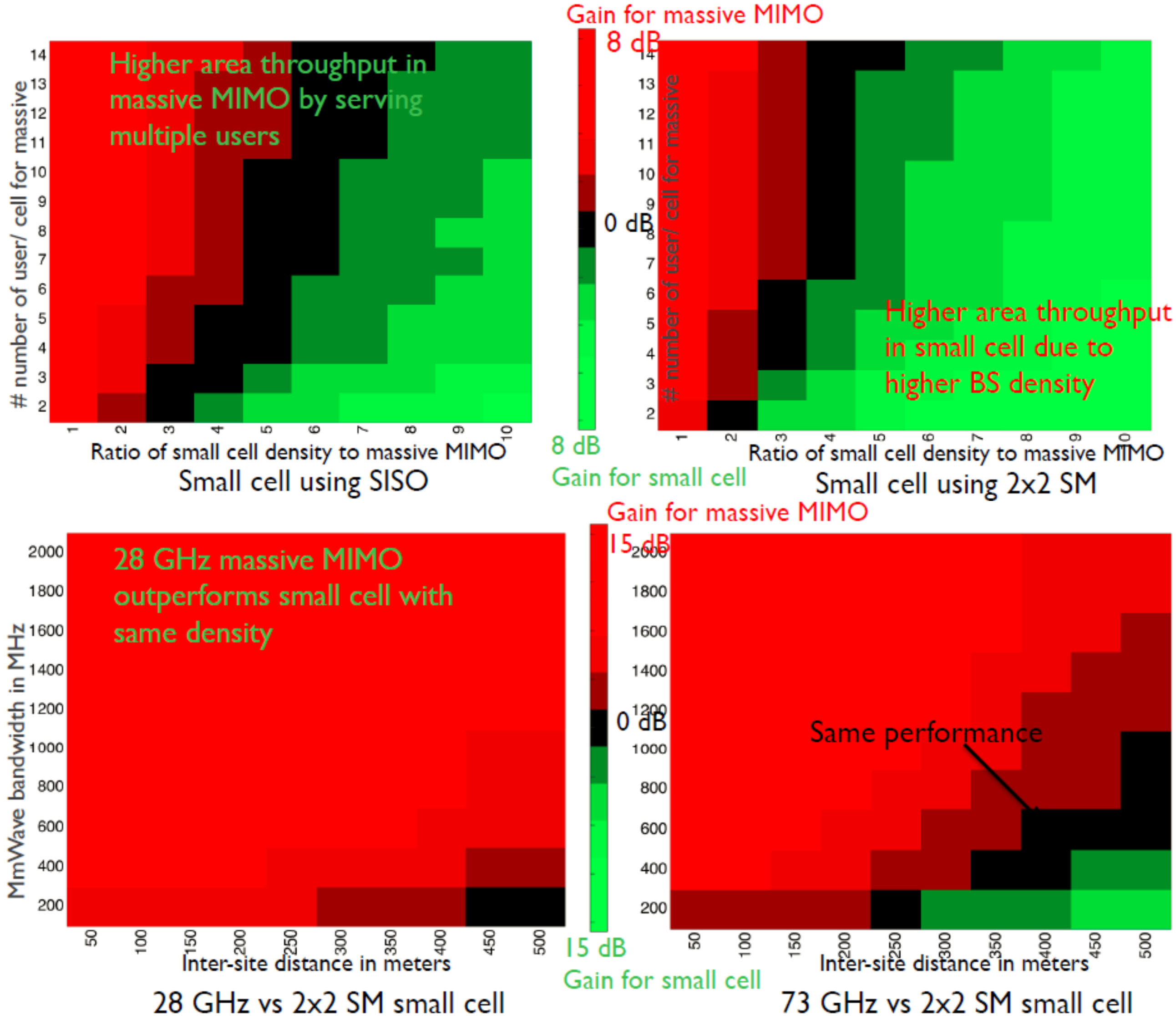
Some key advantages:

- **The high directivity by massive arrays helps overcome the severe path loss and noise of mmWave links.**
- **The steep path loss, combined with the directional gain allows denser cells.**
- **In sparser deployment, the high antenna gains allow to reach target range.**
- **Combined with the high bandwidth, the high gain beamforming provides very high cell throughputs.**

Massive MIMO, mmWave and cell size

< 6 GHz

> 6 GHz



Figures taken by R. Heath, "Comparing Massive MIMO at Sub-6 GHz and Millimeter Wave Using Stochastic Geometry," http://users.ece.utexas.edu/~rheath/presentations/2015/ComparingMassiveMIMOSub6GHzAndMmWaveICC2015Heath.pdf.

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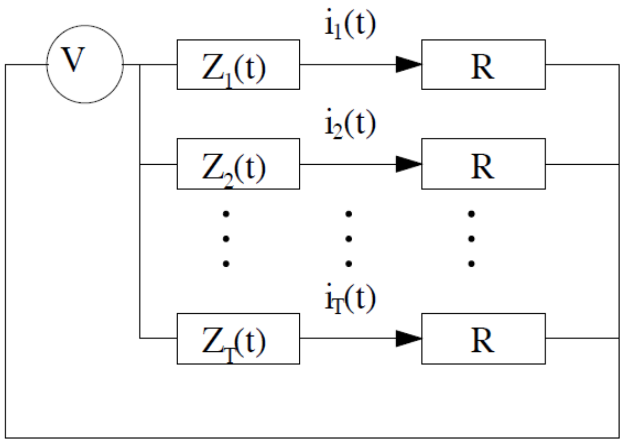
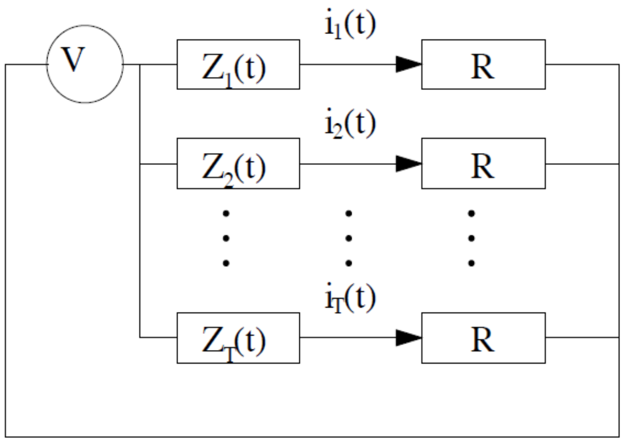
So how to build these large arrays that are required for Massive MIMO?

A suggested approach:
Multi-Active / Multi-Passive (MAMP) Parasitic Antenna Arrays

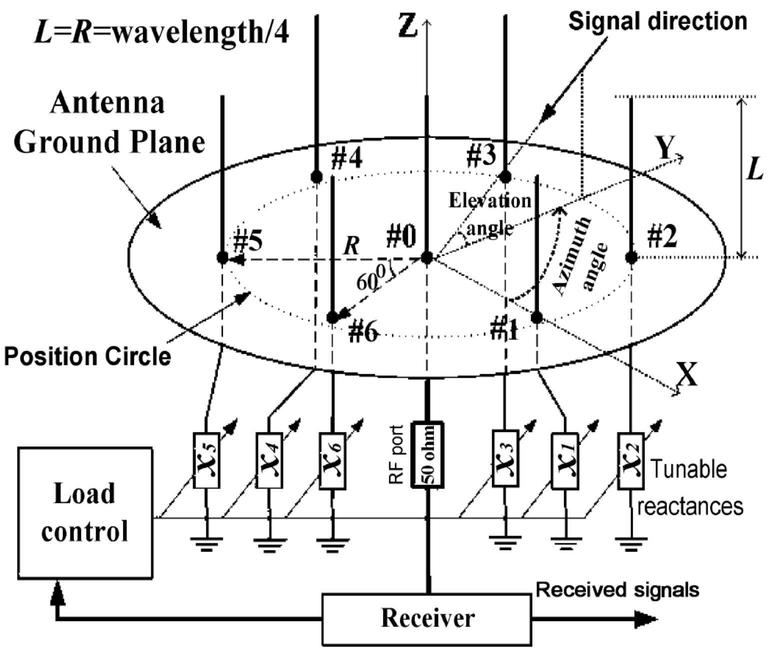
The MAMP concept

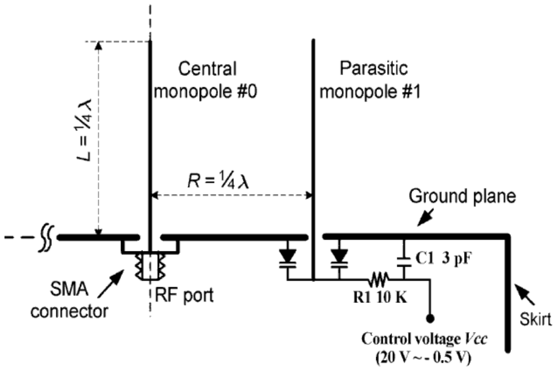
- A combination of active and passive elements form the array.
- If the active elements are sufficiently spaced from each other, then the equivalent circuit is as shown to the right.
- Otherwise, there is, in principle, coupling between all the elements, active or passive.
- The structure allows for good trade-offs of performance vs complexity.

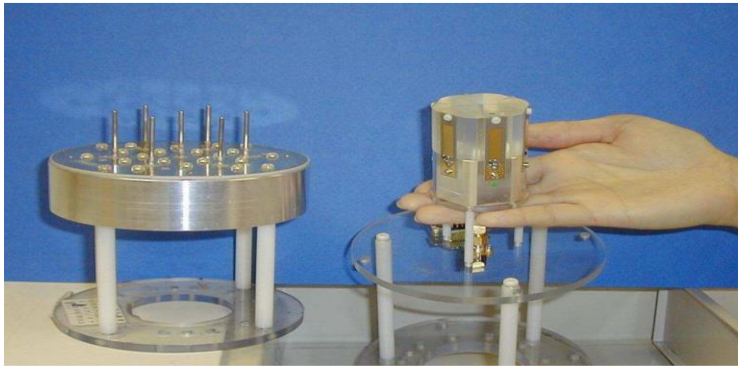




Electronically steerable passive array radiators (ESPAR)







ESPAR arrays adjust adaptively the analog loads of their parasitic antennas in order to control the mutual coupling and hence the array's radiation pattern.

Gyoda, K., Ohira, T. Design of electronically steerable pasive array radiator (ESPAR) antennas. Proc. IEEE Antennas Propag Soc Int Symp, 2000, 922-955.

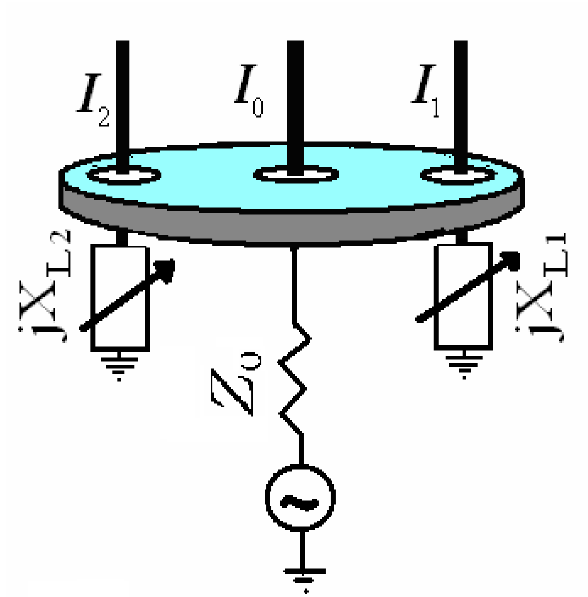
Single-RF 3-element ESPAR

$$\mathbf{i} = \frac{v_s}{2Z_s}\mathbf{w}$$

$$\mathbf{w} := [\mathbf{Z}+\mathbf{X}]^{-1}\,\mathbf{u}_0$$

$$\mathbf{Z} = \begin{pmatrix} Z_{00} & Z_{01} & Z_{01} \\ Z_{01} & Z_{11} & Z_{12} \\ Z_{01} & Z_{12} & Z_{22} \end{pmatrix}$$

$$\mathbf{X} := diag\left([Z_0 \;\; jX_{L1} \;\; jX_{L2}]\right)$$



$$v_s = I_0 Z_{00} + I_1 Z_{01} + I_2 Z_{01}$$

$$-I_1 \cdot jX_{L1} = I_0 Z_{01} + I_1 Z_{11} + I_2 Z_{12}$$

$$-I_2 \cdot jX_{L2} = I_0 Z_{01} + I_1 Z_{12} + I_2 Z_{11}$$

O. N. Alrabadi, A. Kalis, C. Papadias and A. Kanatas, ``Spatial Multiplexing by decomposing the far-field of a compact ESPAR antenna," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 15-18 Sept 2008.

A signal model for parasitic antenna arrays

The well-known baseband model can be adopted as:

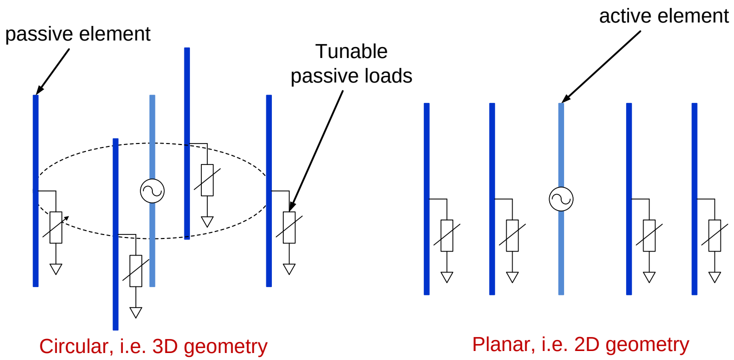
$$\mathbf{y} = \mathbf{H}\mathbf{i} + \mathbf{n}$$

$\mathbf{y} : (M_R \times 1)$ Contains the open-circuit voltages of the Rx antennas

$\mathbf{H} : (M_R \times M_T)$ Is the channel matrix. The *(m,n)* entry represents the complex gain between the *m*-th Tx current and the *n*-th Rx antenna element voltage

$\mathbf{i}_T : (M_T \times 1)$ holds the ESPAR's currents $\quad \mathbf{i}_T = (\mathbf{Z}_T + \mathbf{Z}_G)^{-1}\mathbf{v}_T$

$\mathbf{n} : (M_R \times 1)$ Gaussian noise vector

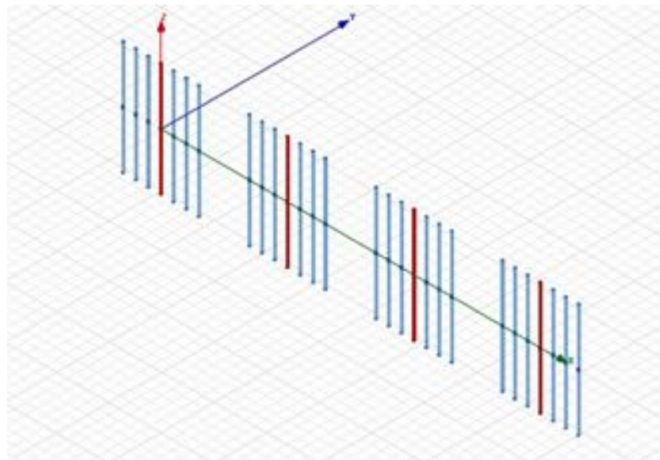


$$\mathbf{i} = (\mathbf{Z}_T + \mathbf{Z}_G)^{-1}\mathbf{v}_T$$
$$\mathbf{v}_T = [v_{T1} \quad 0 \quad \ldots \quad 0]^T$$

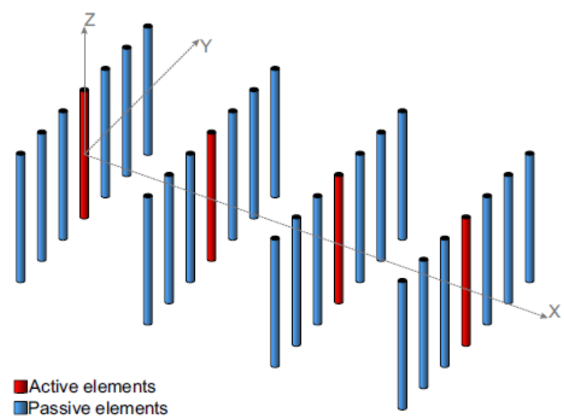
V. Barousis, C. B. Papadias and R. R. Müller, "A new signal model for MIMO communication with compact parasitic arrays," In Proc. International Symposium on Communications, Control and Signal Processing, Athens, Greece, May 21-23, 2014.

Multiple RF (MAMP) extensions

- **Linear MAMP (L-MAMP) arrays with passive elements equally placed on the x-axis (dipoles parallel to the z-axis).**



- **Rectangular MAMP (R-MAMP) arrays with PEs equally spaced on the y-axis.**



Basic theory

- The **radiation pattern** of the MAMP antenna at azimuth angle φ is:

$$\mathrm{a}(\phi) = i^T s(\phi),$$

where $s(\varphi)$ is the respective **steering vector** and i is the normalized current vector (complex) on the antenna elements:

$$i := i(\mathbf{X}, v) = (\mathbf{Z} + \mathbf{X})^{-1} v$$

where Z is the **coupling matrix**, v is the voltage vector (with zero values except for indices corresponding to the AEs) and the load reactance matrix is:

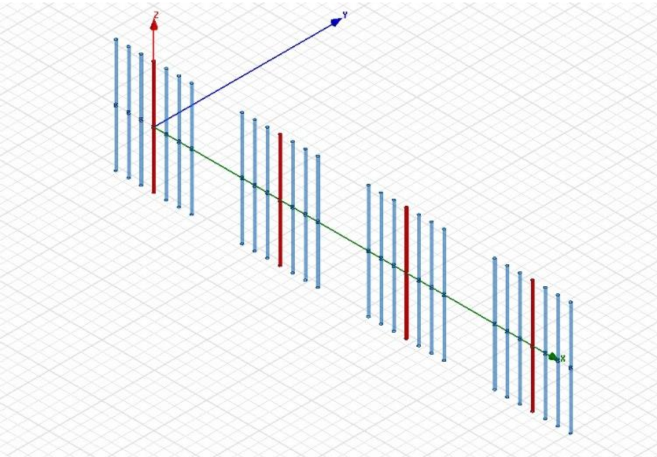
$$\mathbf{X} = (x), \;\; x^T = [x_1^T, \ldots, x_{N_a}^T].$$

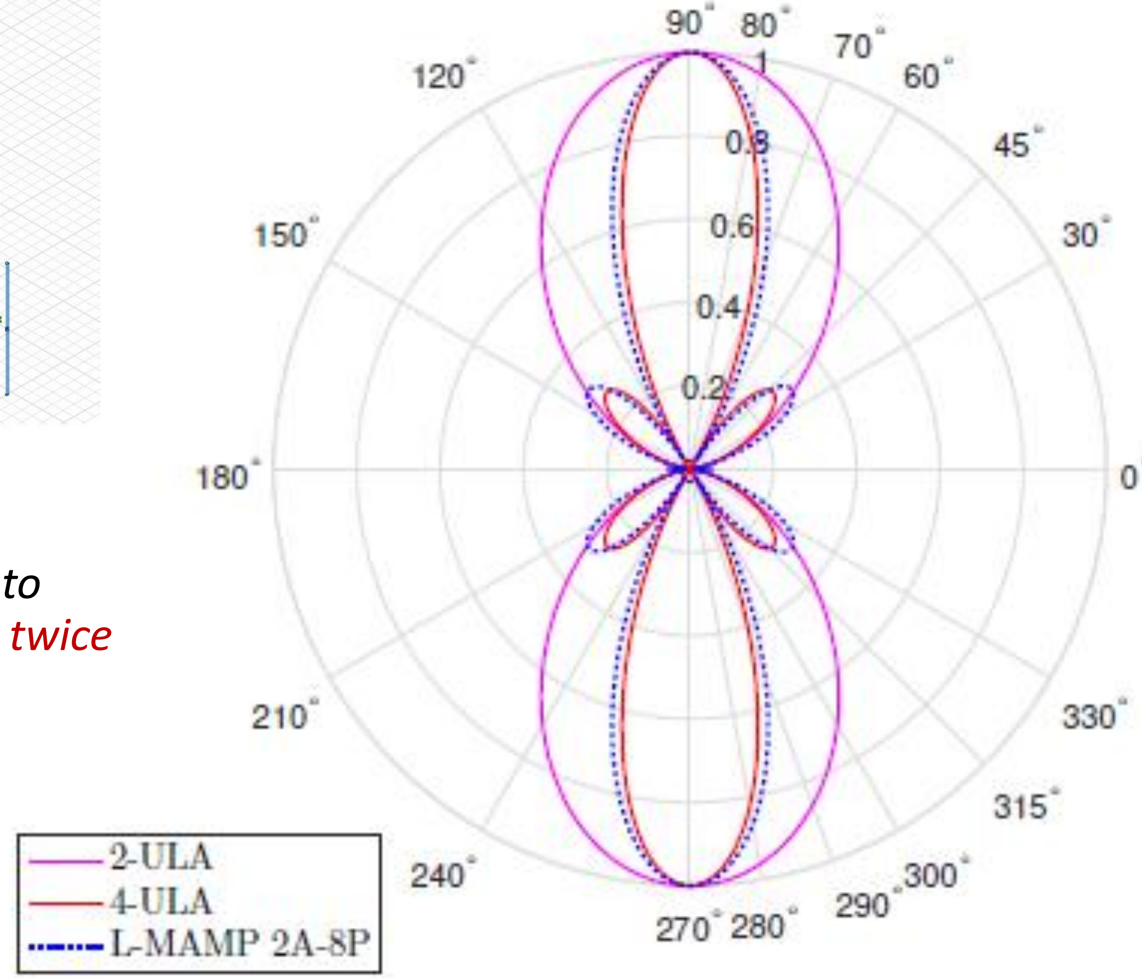
- Each vector x_i corresponds to the **loads** of the i-th column of the MAMP array with values:

$$x_i = [jx_i(1), \ldots, jx_i(N_P/2), R_a, jx_i(N_P/2+1), \ldots, jx_i(N_P)]^T,$$

for $i = 1, \ldots, Na$, where $R_a \in \mathbb{R}_+$ is the input impedance of the AE, and the other entries correspond to the PEs with imaginary **load values** (capacitors or inductors).

Example: Linear MAMP @ 2.5 GHz





- *Performance equivalent to that of active array with twice as many elements*

Results from paper submitted to IEEE SPAWC '2018

MAMP arrays towards the massive mmWave regime: 8 active / 80 parasitics at 19.25GHz

- **Directive towards the z-axis**
- **Gain of 13.2dBi**
- **Side lobes 12dB reduction**
- **Rotation of the main lobe can be achieved by altering the weights of the active elements**

EU Project

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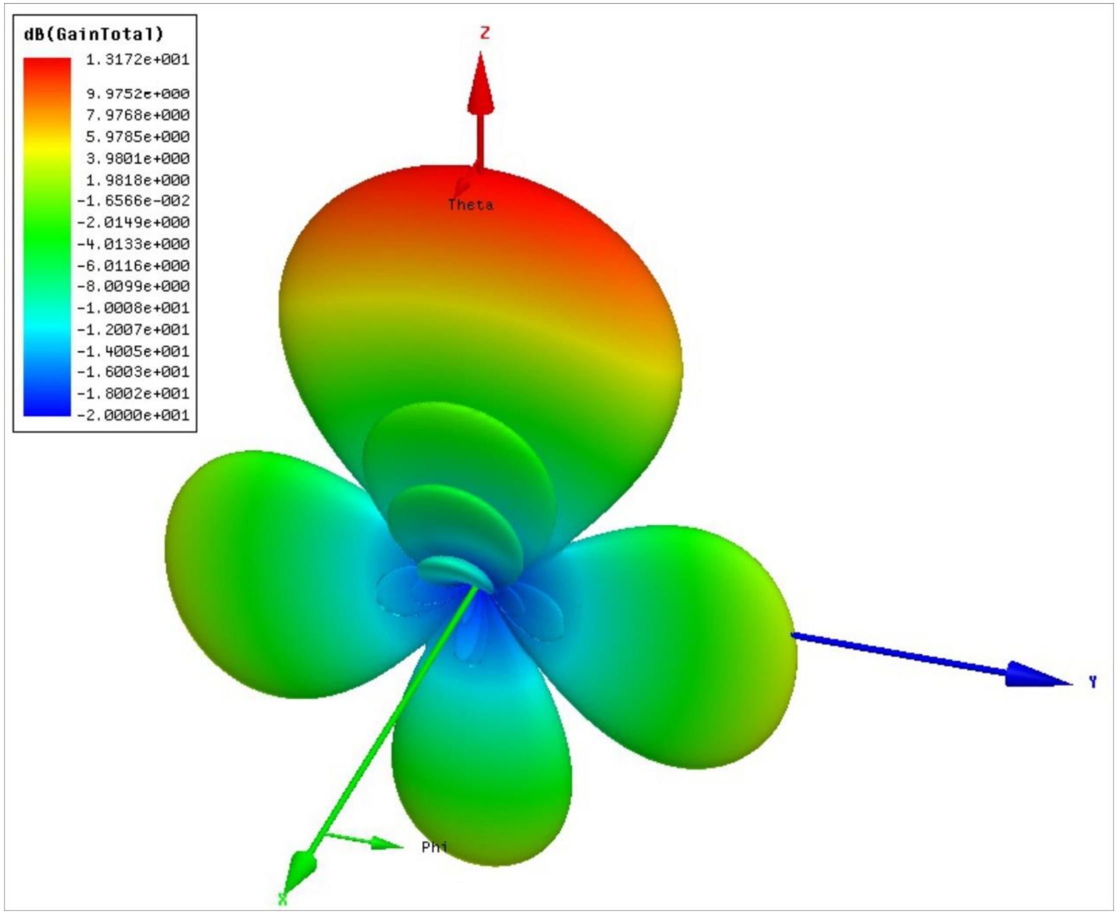
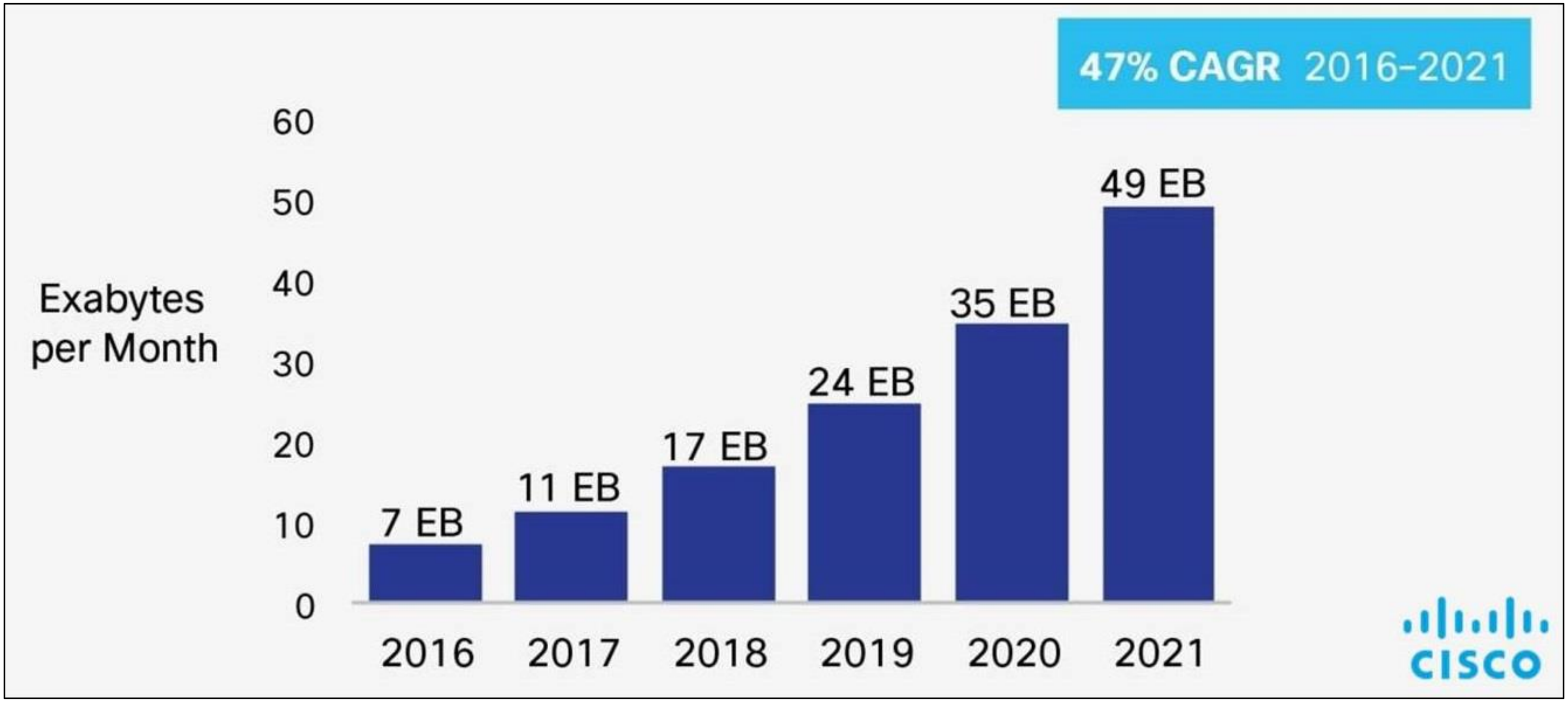


The regulatory perspective

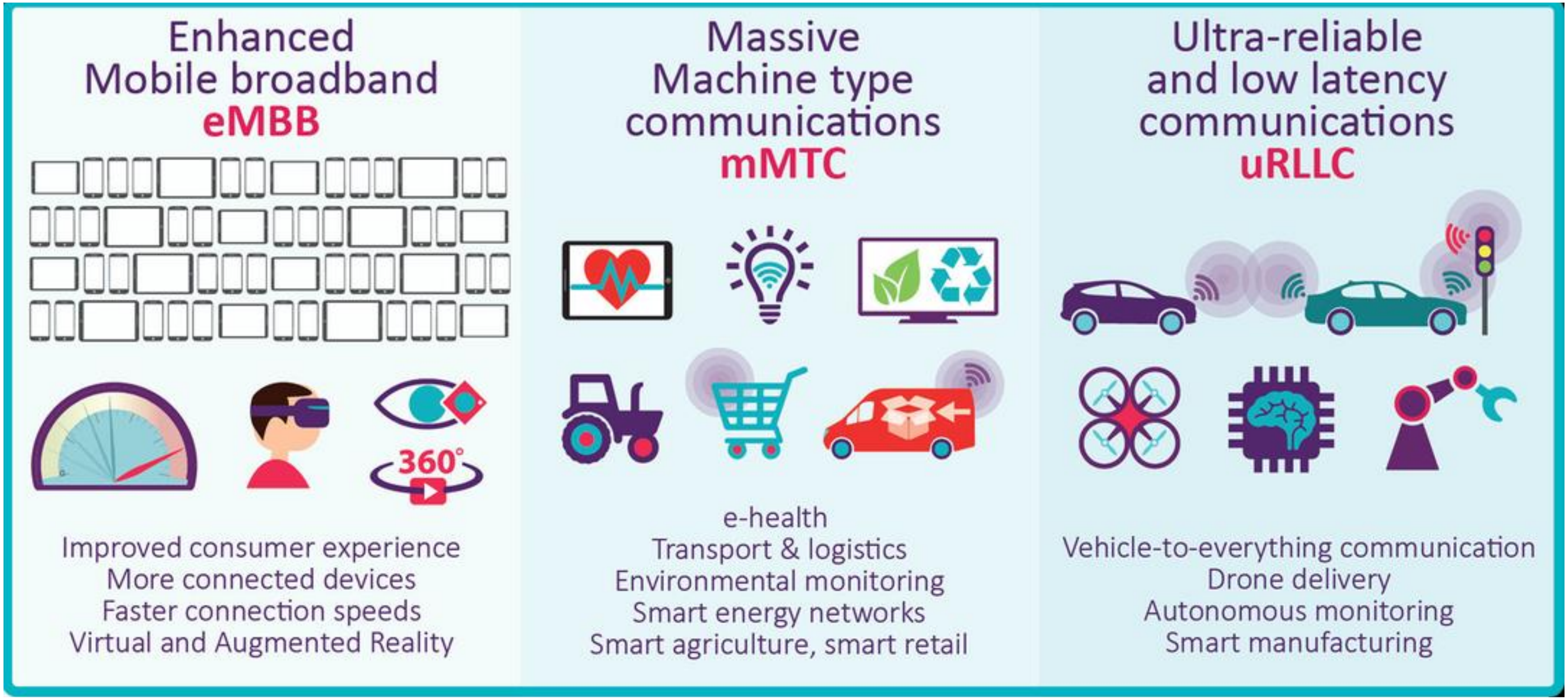
Behind it all..



Source: Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper.

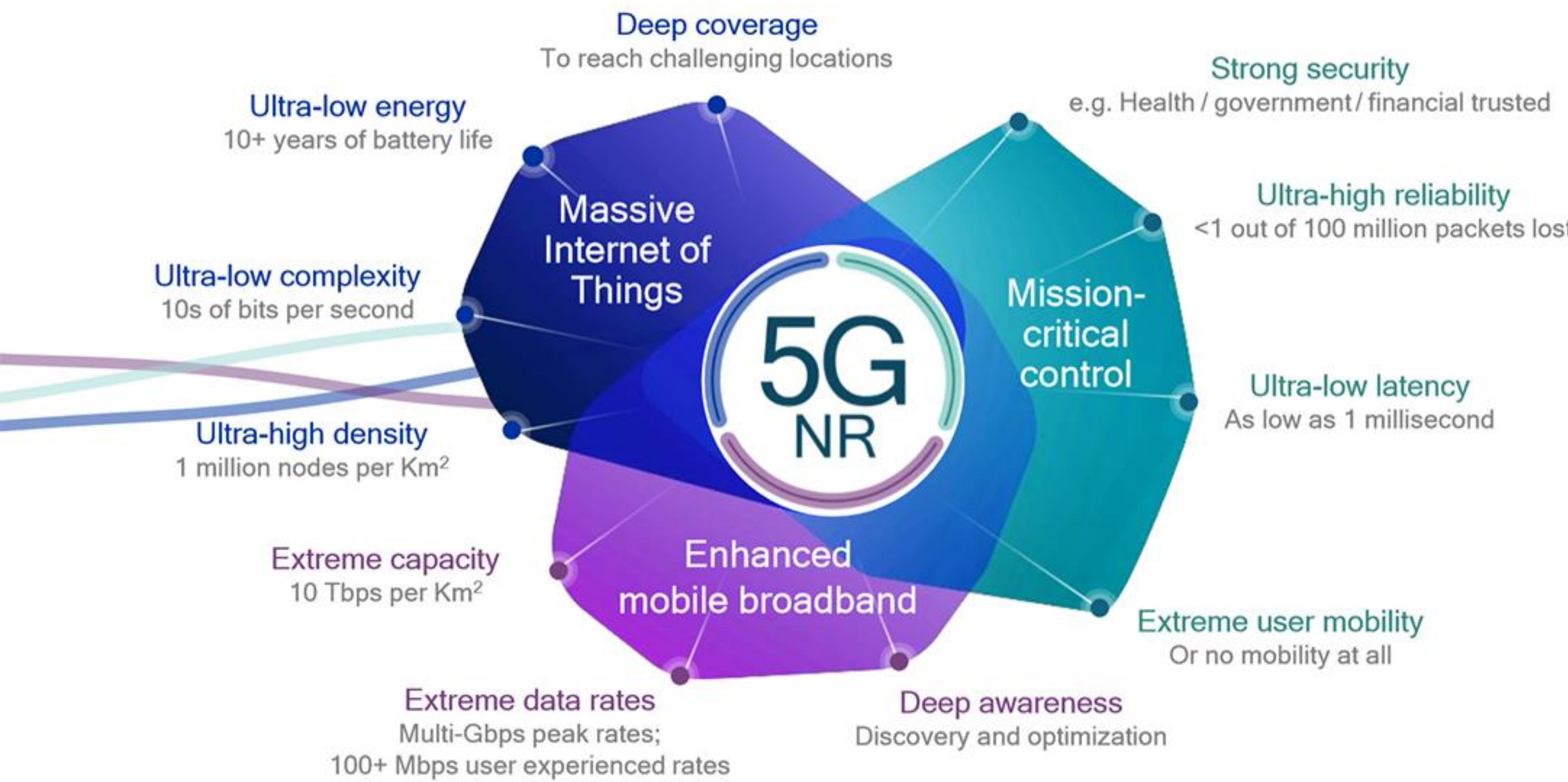
5G Use cases & Applications

- Three key use cases: eMBB, mMTC & uRLLC.
- A wide range of applications and industrial domains.



5G New Radio: Key Performance Indicators (KPIs)

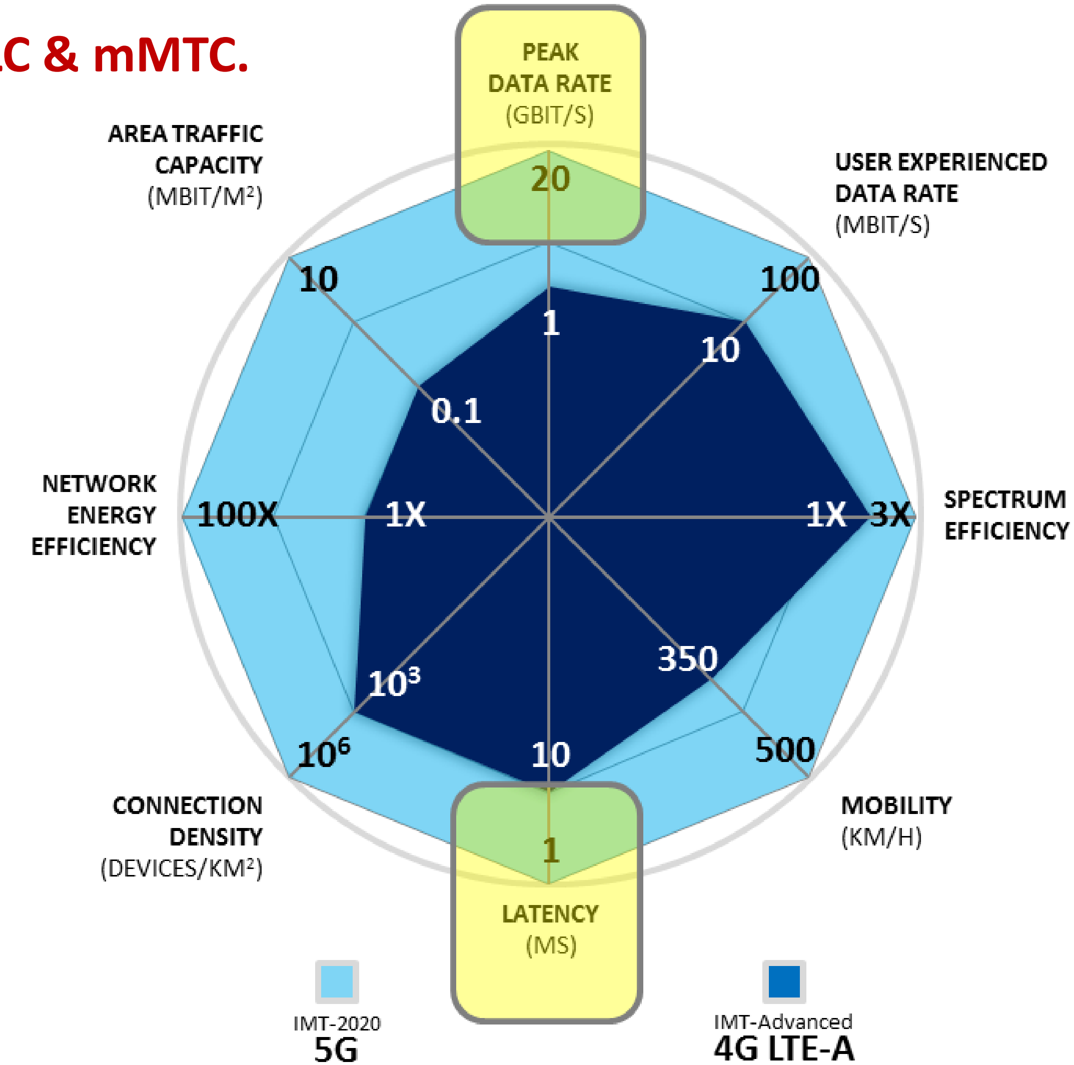
- **Challenging!**
- **Use case-dependent.**



https://www.qualcomm.com/documents/making-5g-nr-reality

Target improvements over 4G

- On-track for eMBB.
- Less so for uRLLC & mMTC.



Recommendation ITU-R M.2083-0, "IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Sept. 2015.

New spectrum allocations

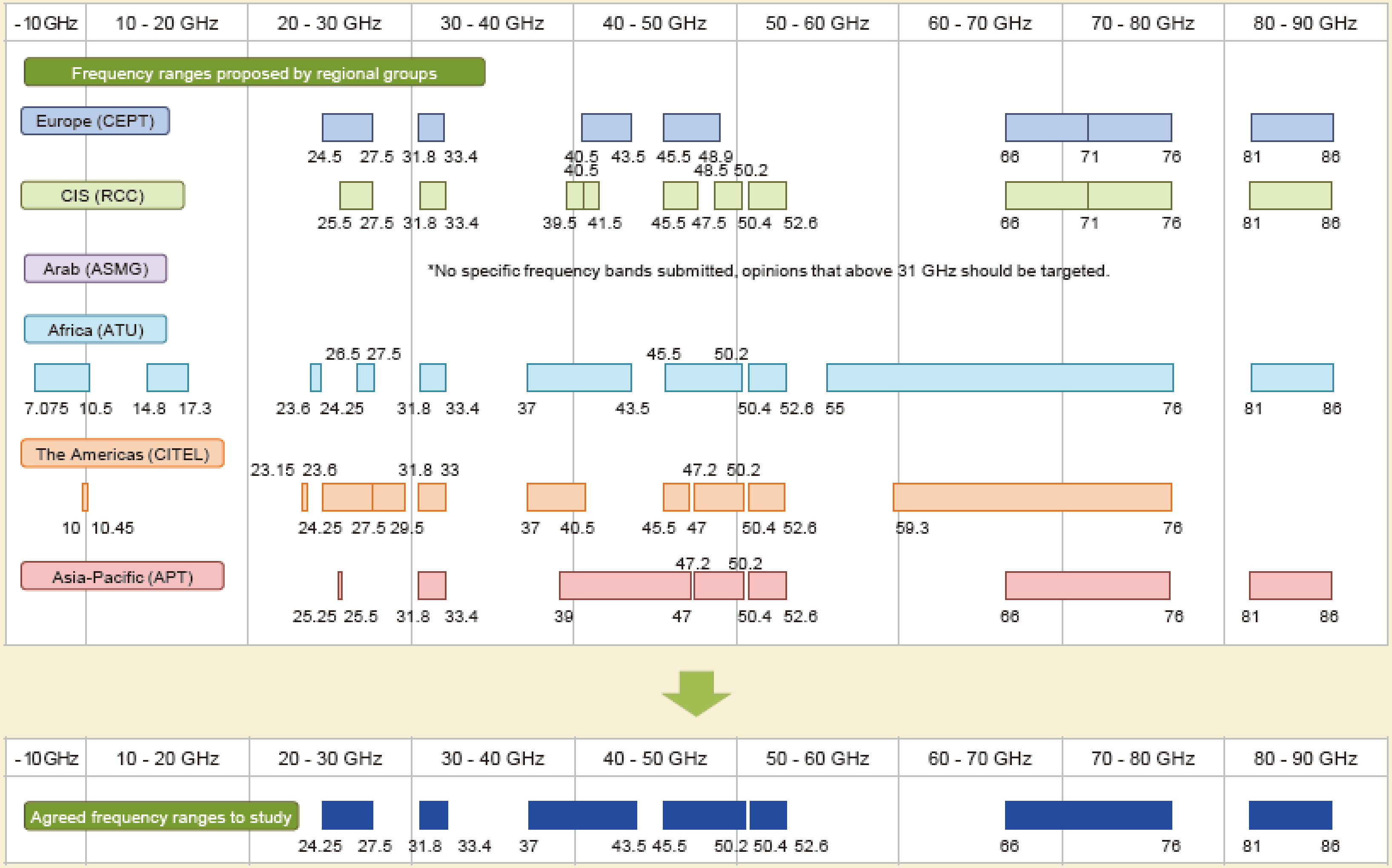


Figure 2 Frequency ranges to study for IMT identification in WRC-19

Some Examples of Antenna-aided Techniques and Results

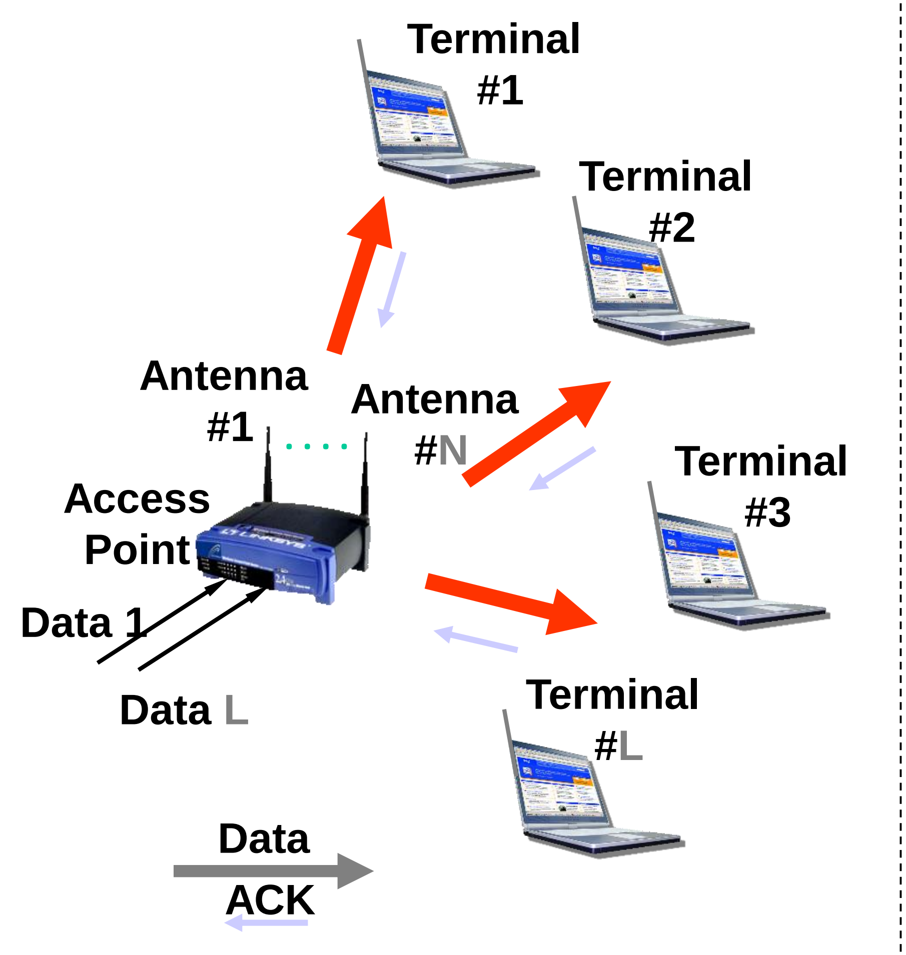
Co-existence of WiFi users

Objective:

- **Increase the 802.11 downlink throughput in an indoor scenario, so that more users can be served**

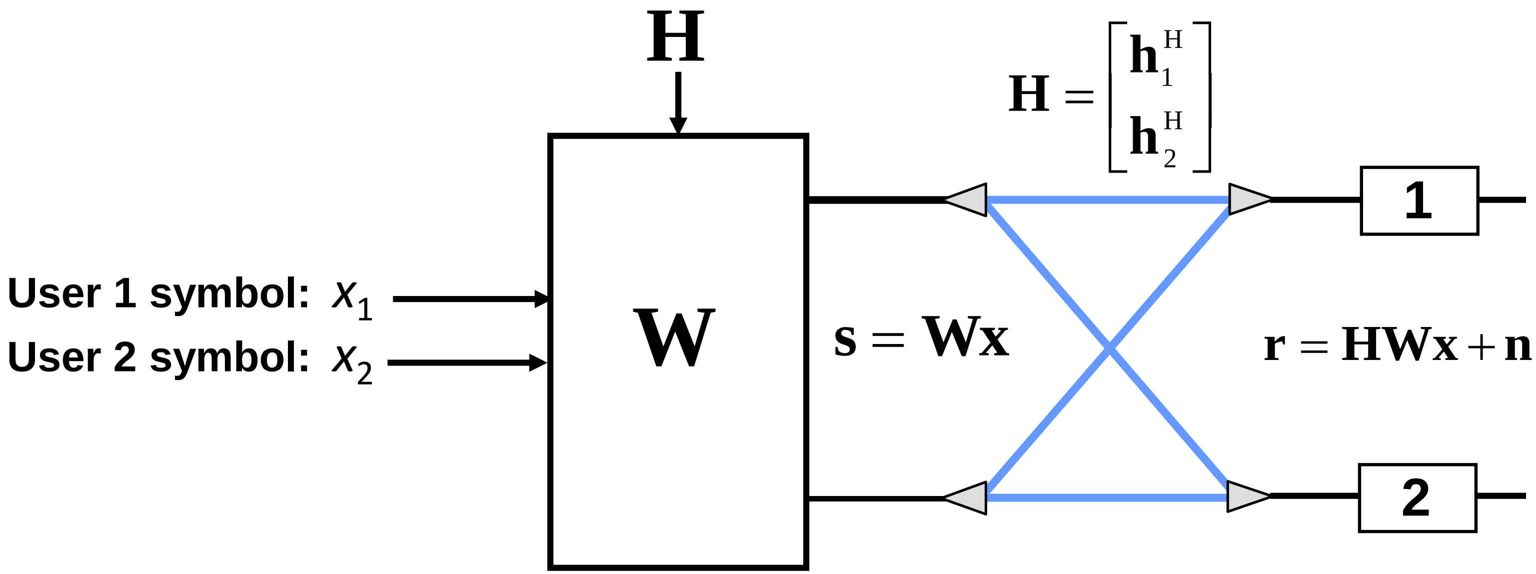
Backward compatibility:

- **Legacy terminals: no changes to IEEE 802.11a/g terminals are allowed**



Indoor Access Point sharing scenario

The solution: Spatial Division Multiple Access



$$\mathbf{W} = g\mathbf{H}^{\mathrm{H}}(\mathbf{H}\mathbf{H}^{\mathrm{H}} + \alpha\mathbf{I})^{-1}$$

$$r_1 = \mathbf{h}_1^{\mathrm{H}}\mathbf{s} + n_1 = \mathbf{h}_1^{\mathrm{H}}\mathbf{w}_1 x_1 + \underbrace{\mathbf{h}_1^{\mathrm{H}}\mathbf{w}_2 x_2}_{\sim 0} + n_1$$

$$r_2 = \mathbf{h}_2^{\mathrm{H}}\mathbf{s} + n_2 = \underbrace{\mathbf{h}_2^{\mathrm{H}}\mathbf{w}_1 x_1}_{\sim 0} + \mathbf{h}_2^{\mathrm{H}}\mathbf{w}_2 x_2 + n_2$$

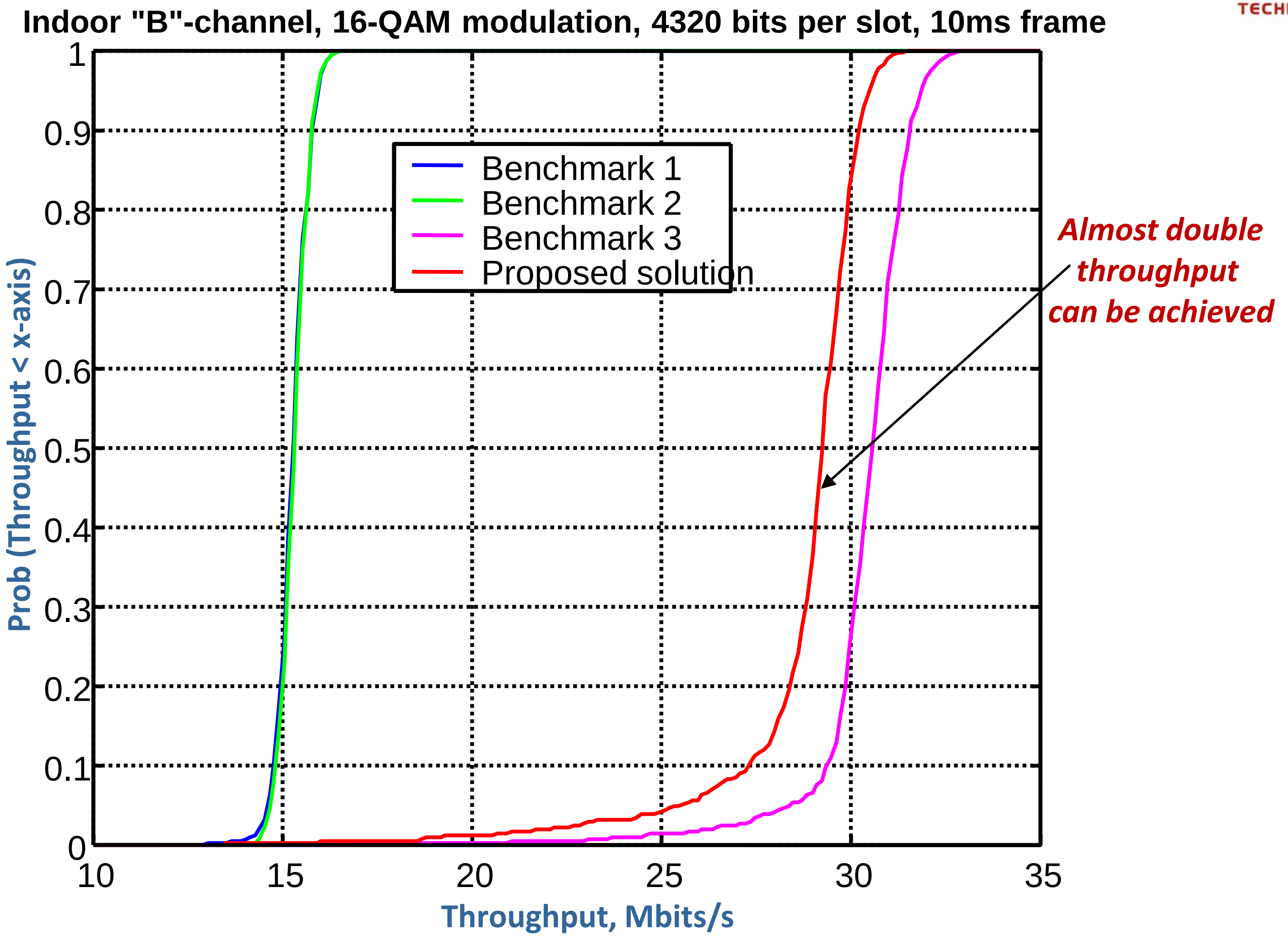
$\mathbf{x}$ is the $M \times T$ matrix of information symbols

$\mathbf{s}$ is the $N \times T$ transmitted signal

$\mathbf{r}$ is the $M \times T$ received signal

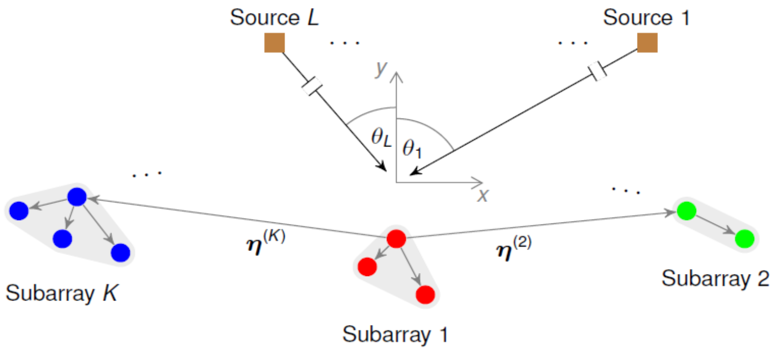
$\mathbf{H}$ is the $M \times N$ channel matrix

Results

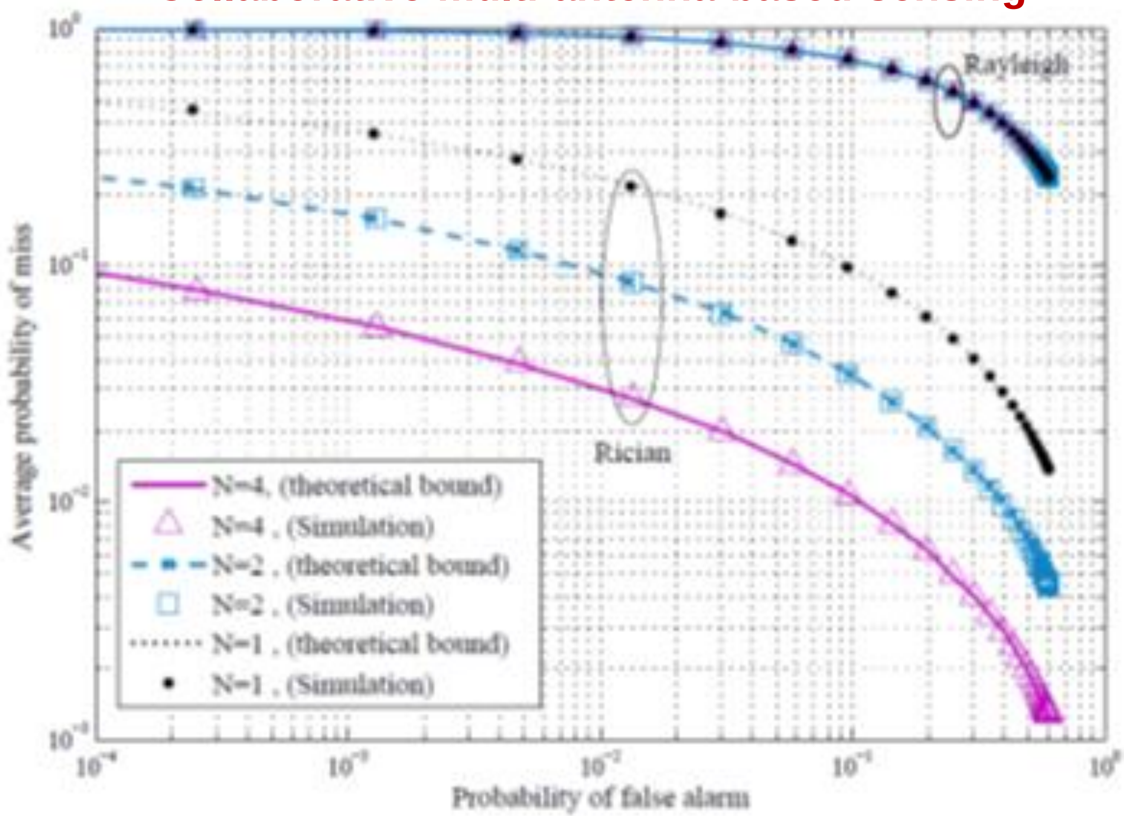


A. Kuzminskiy, H. Karimi, D. Morgan. C. Papadias, D. Avidor and J. Ling, "Downlink Throughput Enhancement of IEEE 802.11a/g Using SDMA with a Multi- Antenna Access Point," *EURASIP Signal Processing*, special issue on Advances in Signal Processing-assisted cross layer Designs, No. 86, Issue 2, pp. 1896-1910, Dec. 2005 (ISSN: 0165-1684).

Collaborative Sensing Techniques



Collaborative multi-antenna-based sensing



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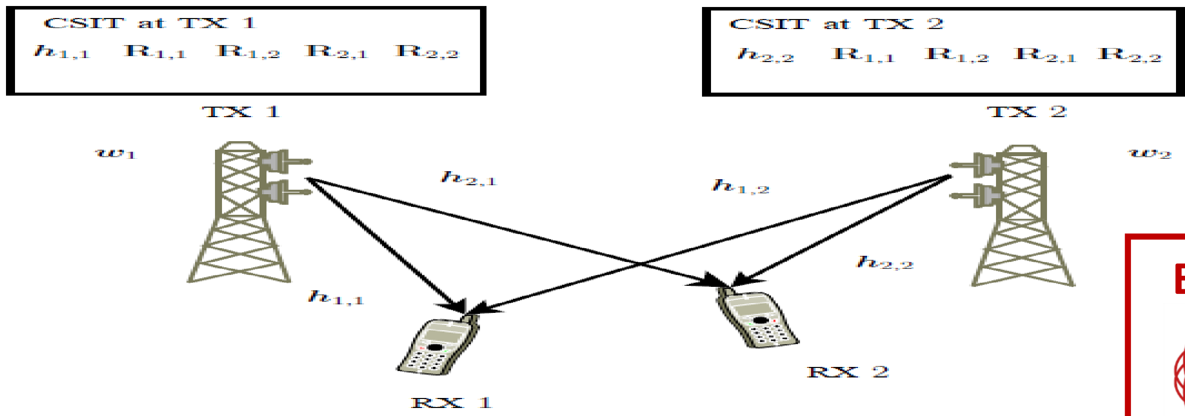
Cooperative Multi-Antenna Communication



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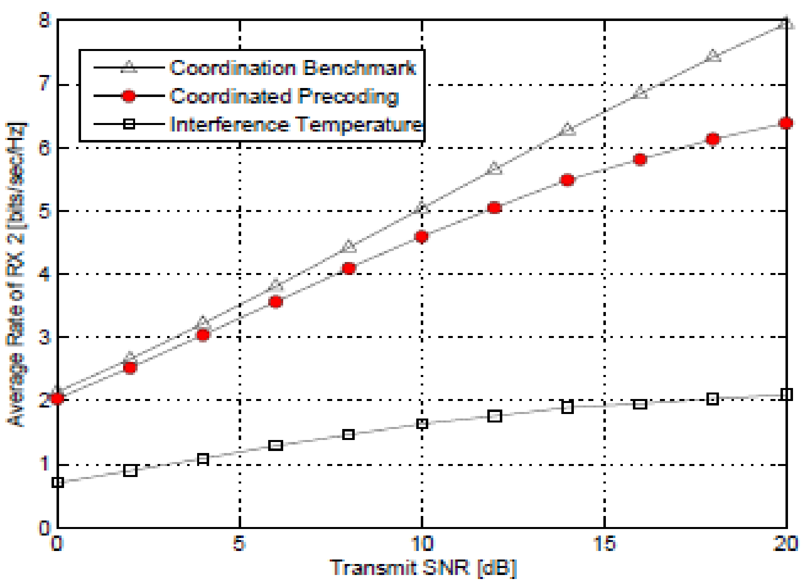
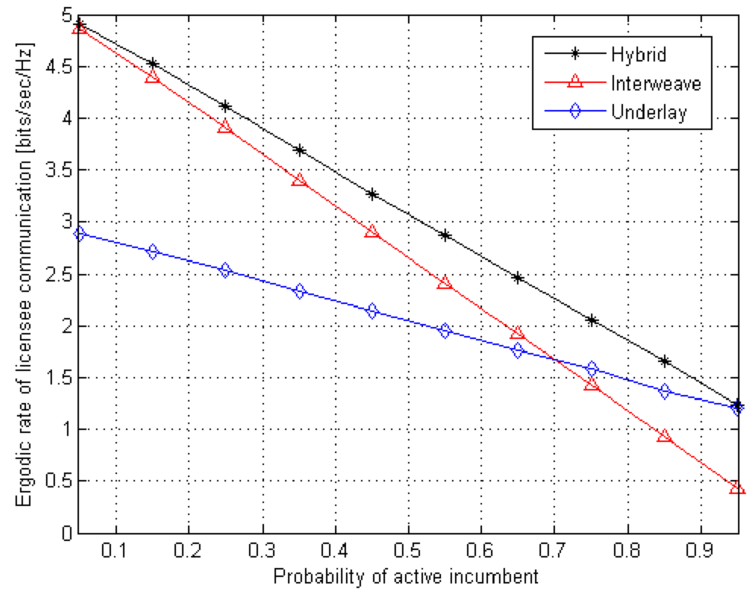
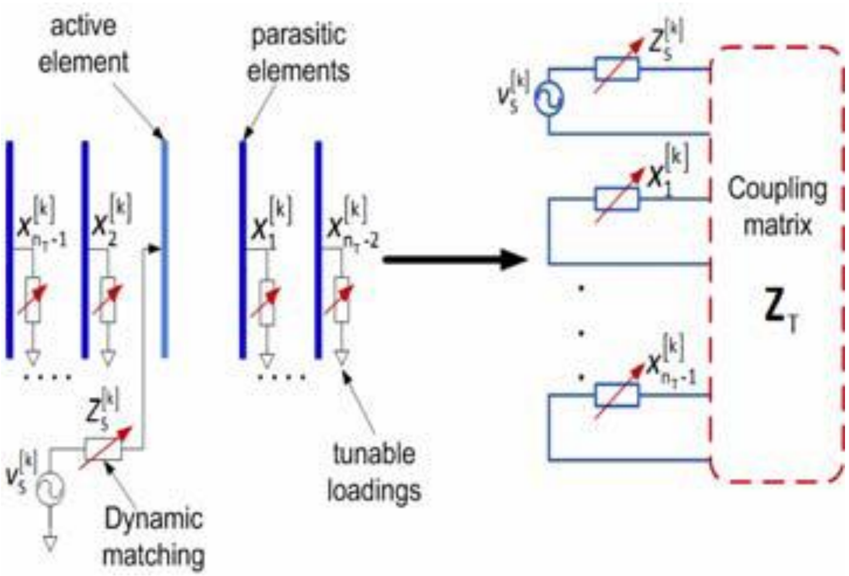
Downlink ergodic rates

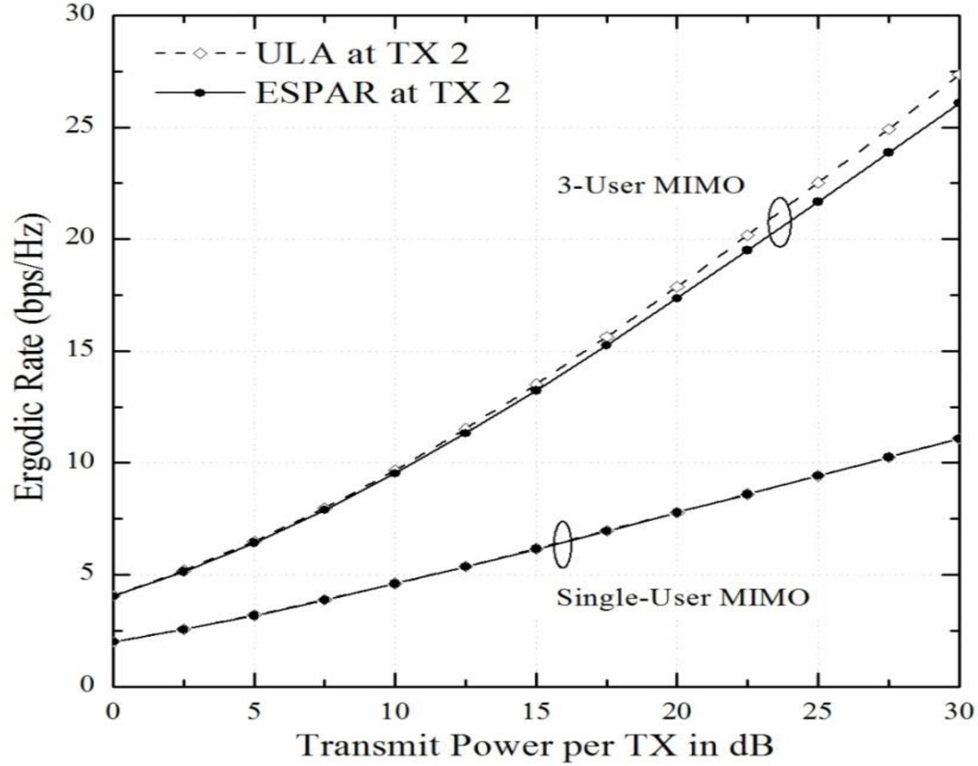


Uplink ergodic rates



Interference alignment with ESPARs





EU Project HiATUS

G. C. Alexandropoulos, V. I. Barousis, and C. B. Papadias, "Precoding for multiuser MIMO systems with single-fed parasitic antenna arrays," in Proc. GLOBECOM, Austin, USA, 8–12 December 2014.

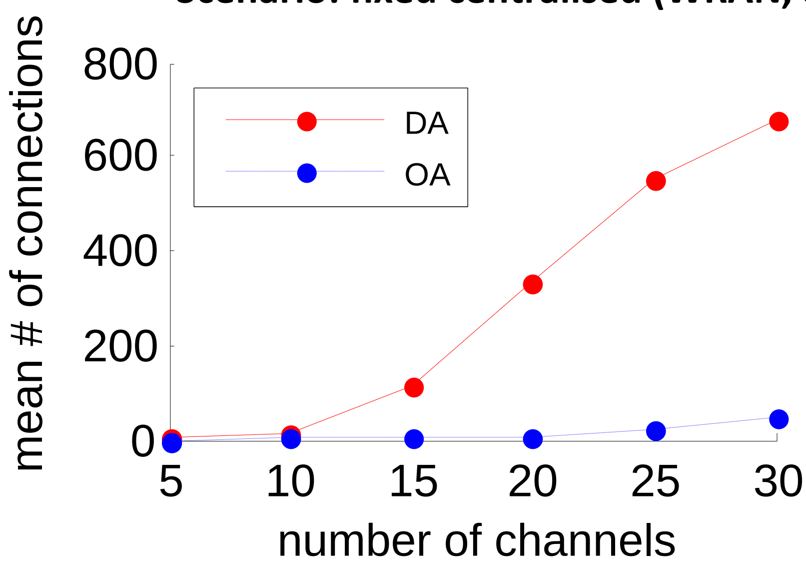
MAC protocol for CR with Directional Antennas

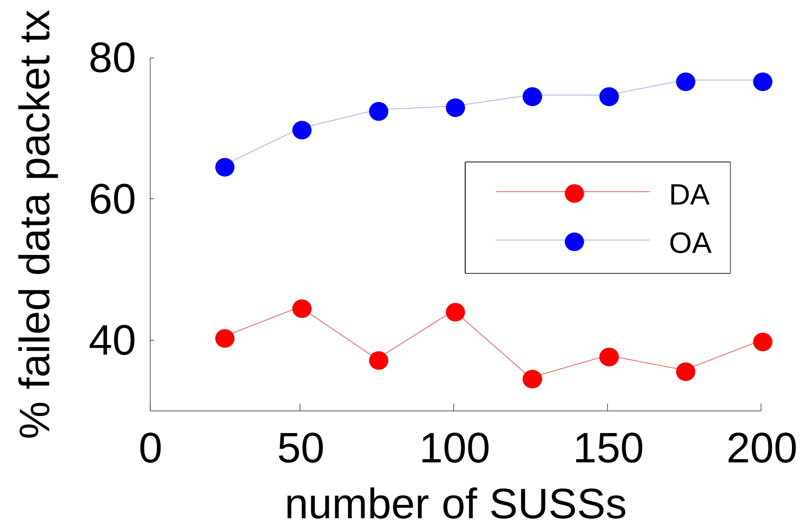
- CR-DMAC: to our best knowledge, the first Directional MAC for CR!
- Specifically designed to take advantage of interference mitigation and directional communication enabled by directional antennas
- Beams deployed at SU Base Station; CSMA/CA medium access

  sensing over quiet periods
- Scenario: fixed centralised (WRAN, 802.22)

EU Project

CROWN





- **One order of magnitude higher # of connections with 60º beams**
- **50% reduction in the number of failed packets**

Some Demos & Experimentation

Over the air tests with 2.6GHz MIMO Testbed

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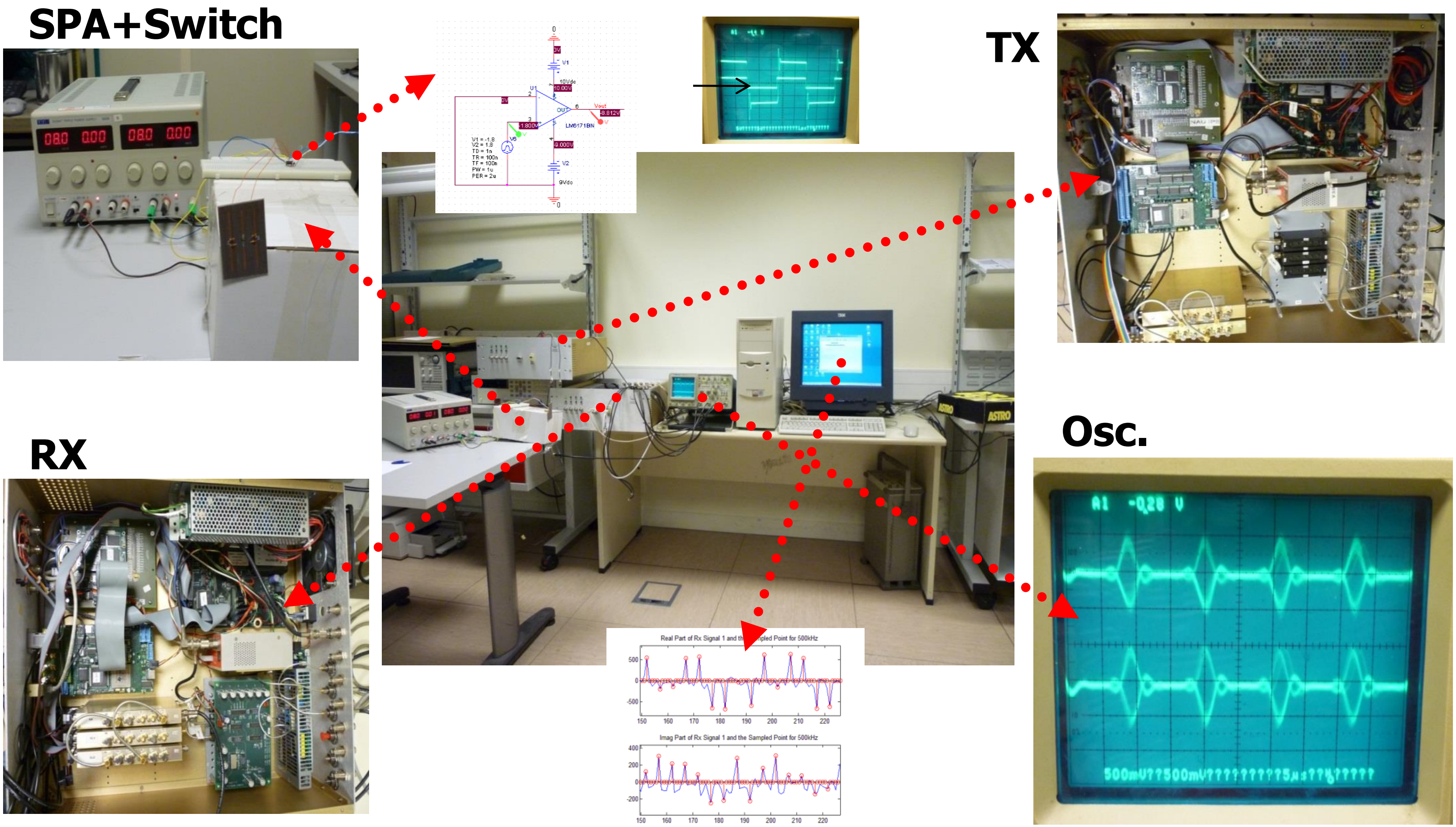

First ESPAR Spatial Multiplexing
(Spectrum sharing of data streams in the beamspace domain)
First Over-the-Air Proof-of-Concept Validation

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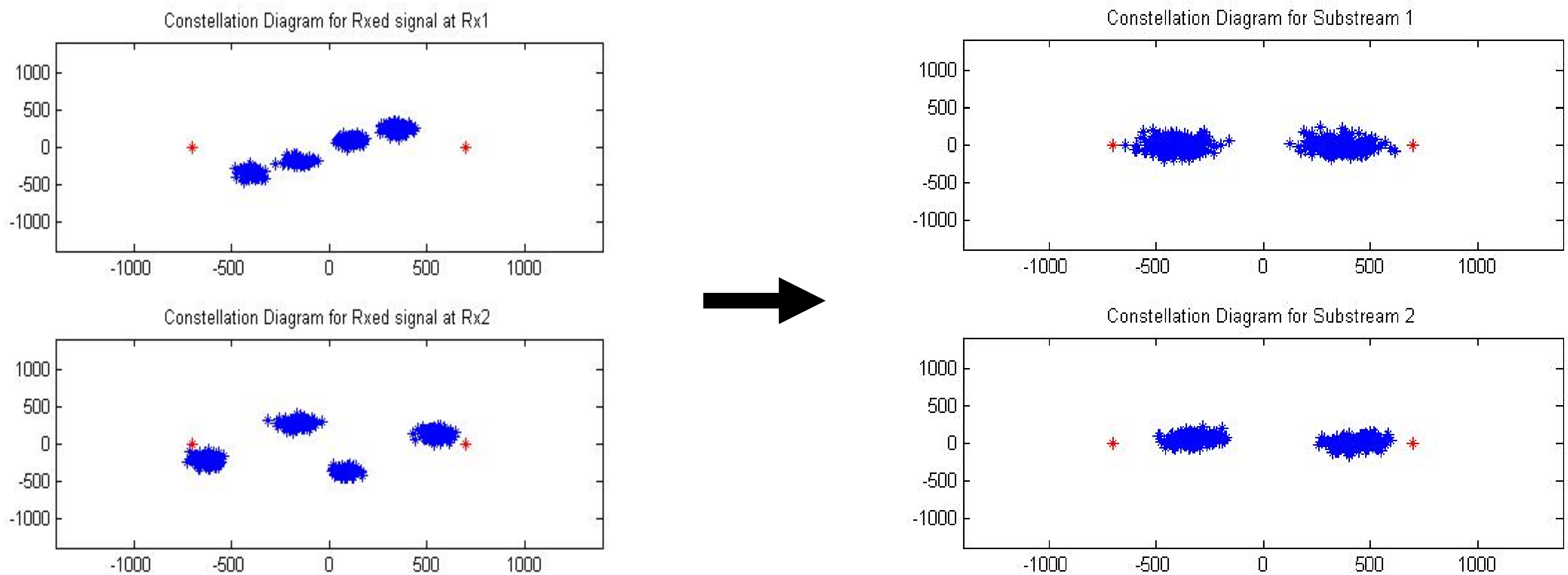
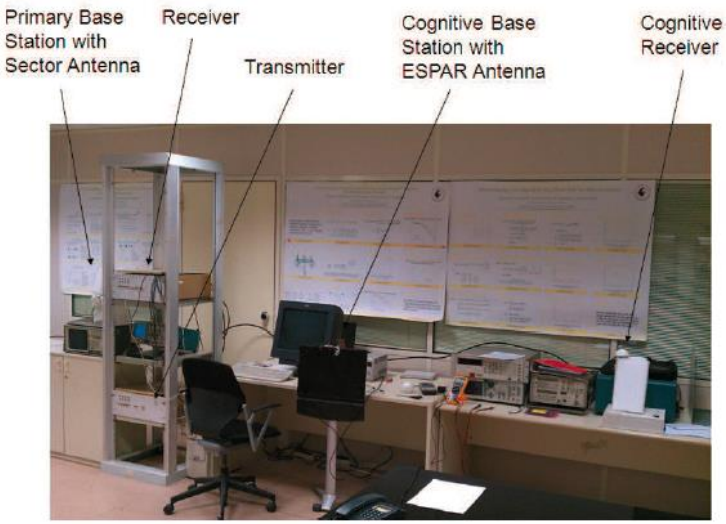
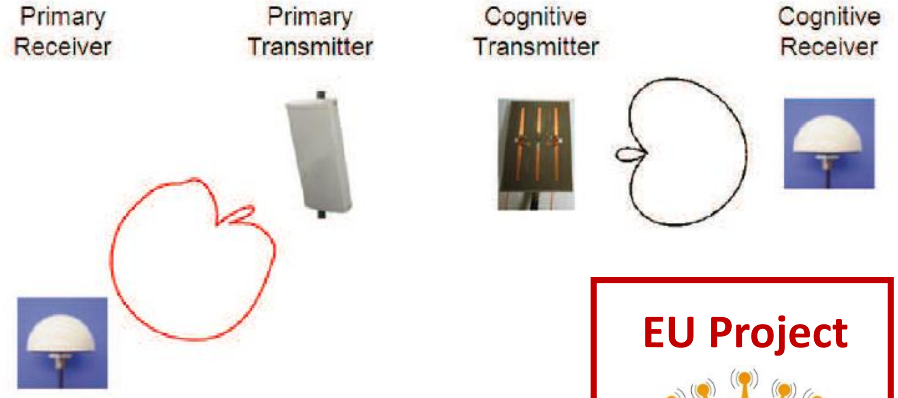


O. N. Alrabadi, C. Divarathne, P. Tragas, A. Kalis, N. Marchetti, C. B. Papadias, R. Prasad, "Spatial Multiplexing with a Single Radio: Proof-of-Concept Experiments in an Indoor Environment with a 2.6 GHz Prototype," IEEE Comm. Letters, vol. 15, No. 2, pp. 178-180, Feb. 2011.

Underlay spectrum sharing via parasitic arrays





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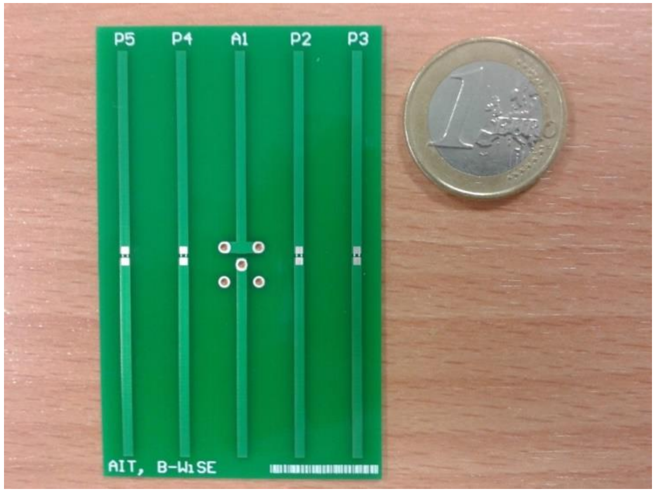
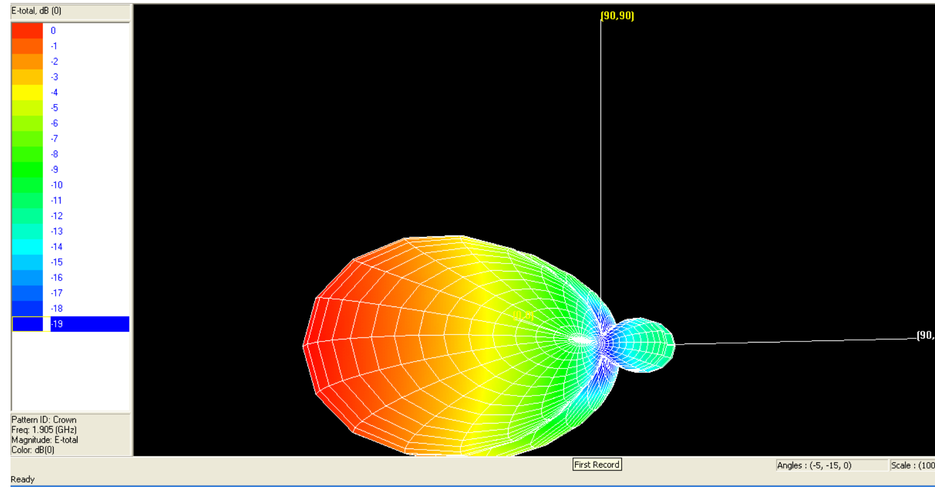
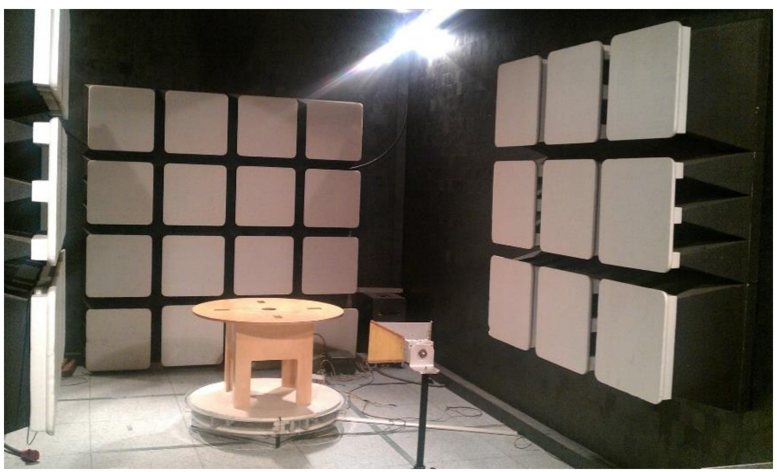
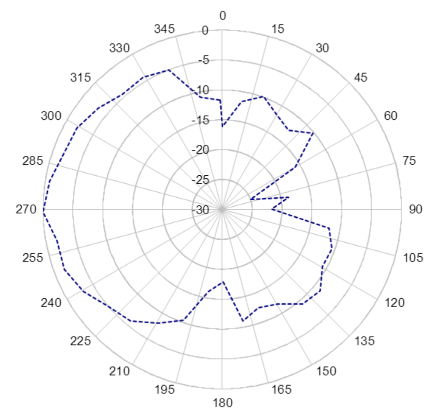
PBS	Transmit Power 12 dBm		Transmit Power 15 dBm	
Received Power (dBm)	Primary Receiver	Cognitive Receiver	Primary Receiver	Cognitive Receiver
CBS on	-52.27	-43.50	-52.27	-43.50
PBS ON	-43.94	-53.41	-39.93	-51.96
PBS & CBS, ON	-43.29	-43.01	-38.91	-42.72
PBS & CBS, OFF	-61.70	-61.58	-61.70	-61.58

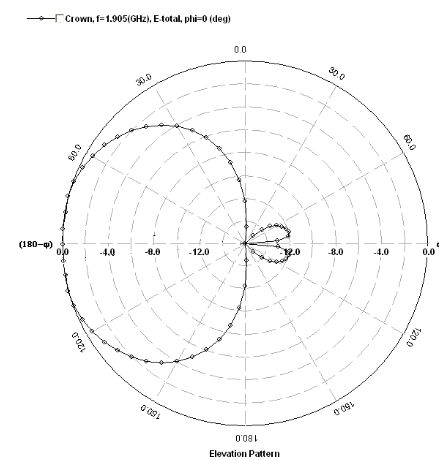
A 5-element (single-RF) prototype antenna for LTE





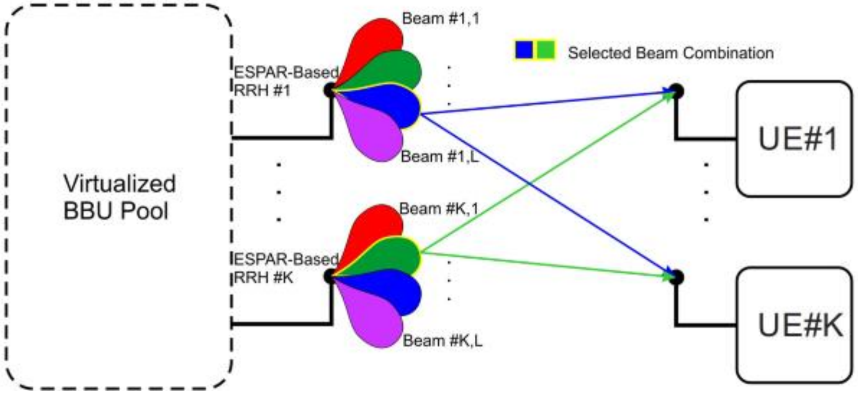






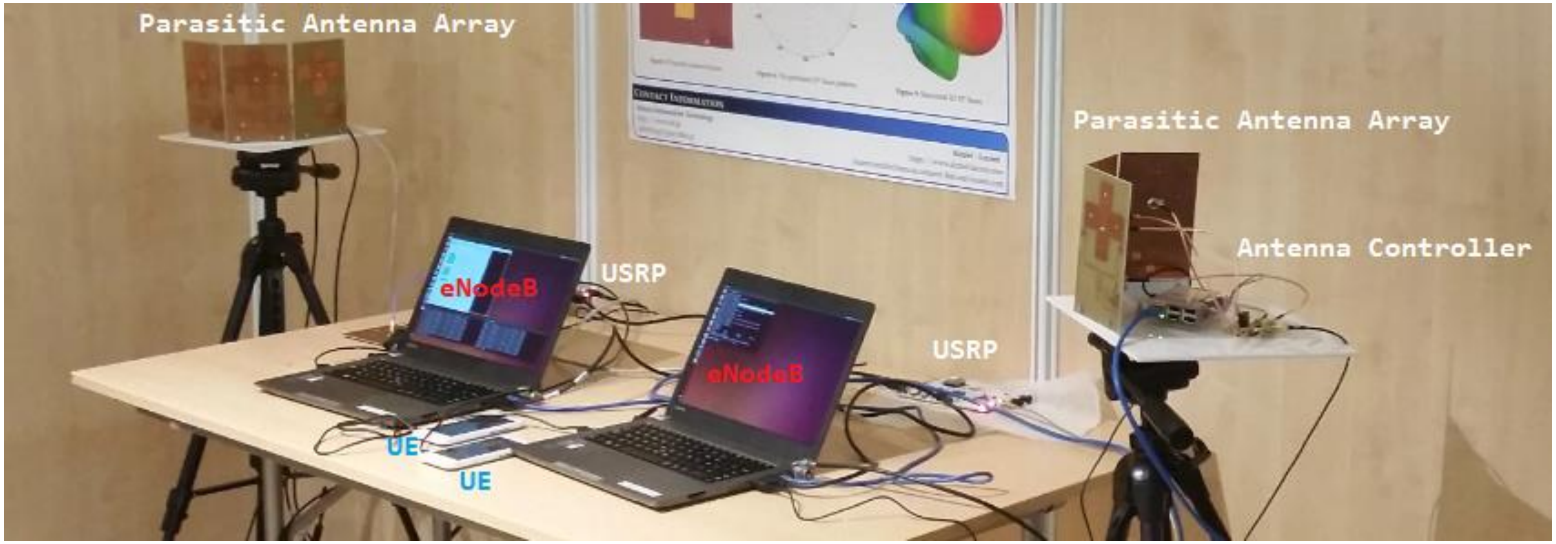
EU FP7 Project HARP: Spectrum sharing with Hybrid Antenna Arrays

Over-the-air demonstration



EU Project

HARP



HARP booth at EUCNC 2015

3 Active / 12 Passive Hybrid Antenna Array
Prototype built for Remote Radio Heads in EU Project HARP

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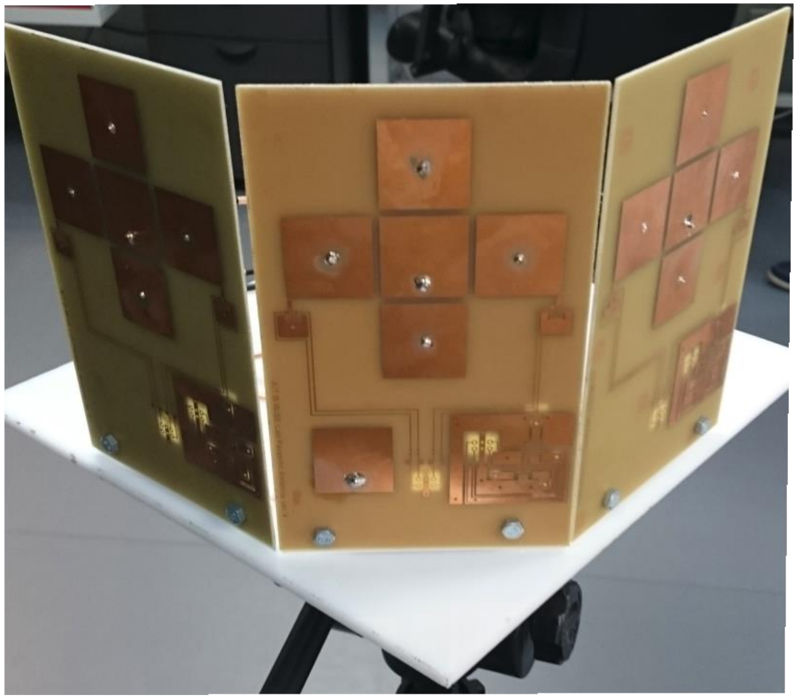
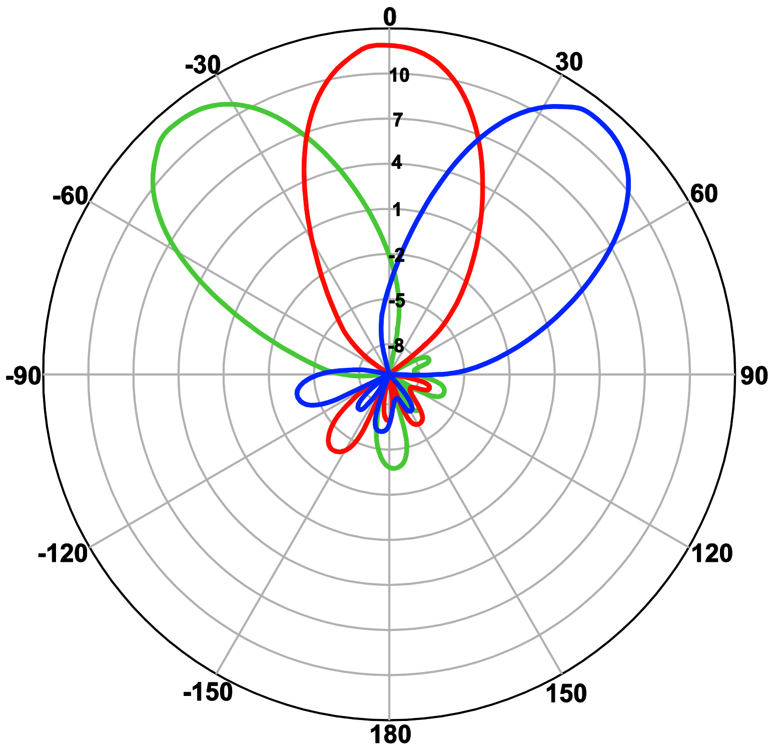


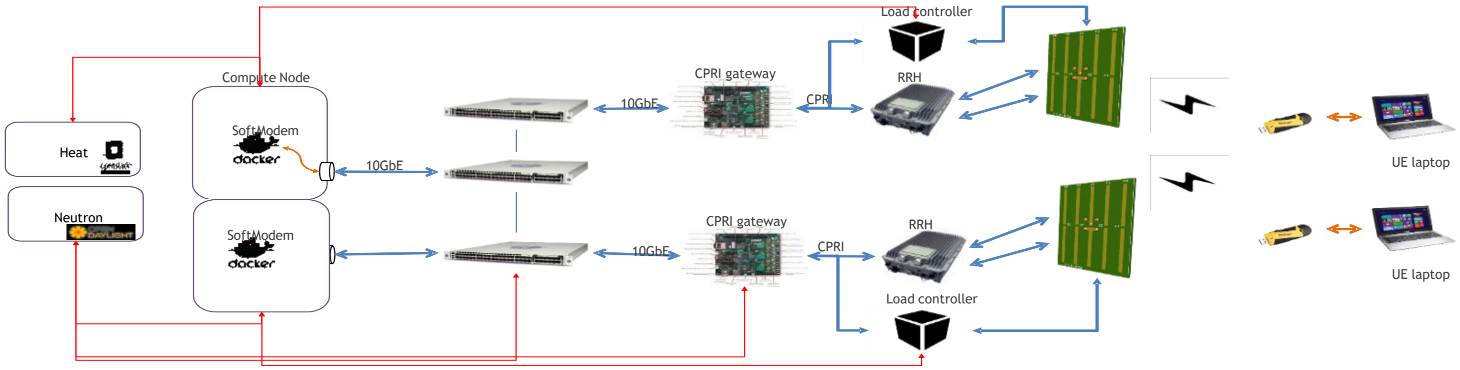
Final fabricated hybrid switchable antenna array



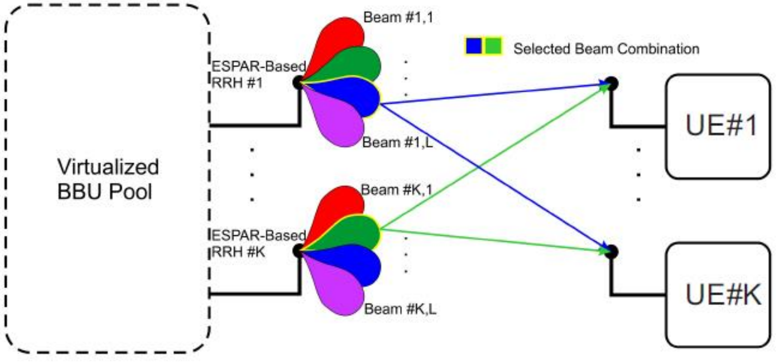
Employed mode of operation: Beam-switching

Cloud Radio in HARP

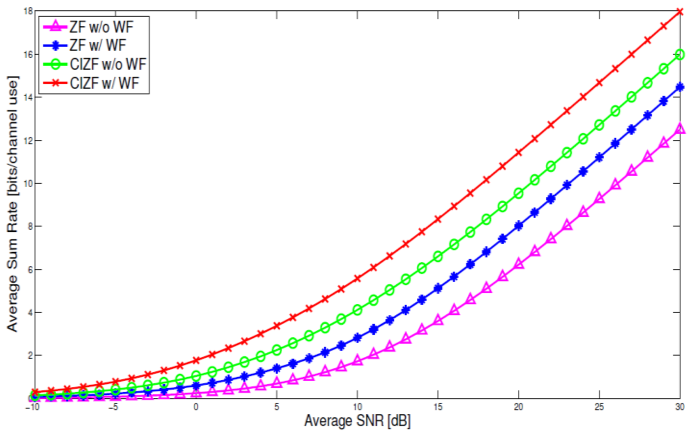
System setup



Switched-beam precoding



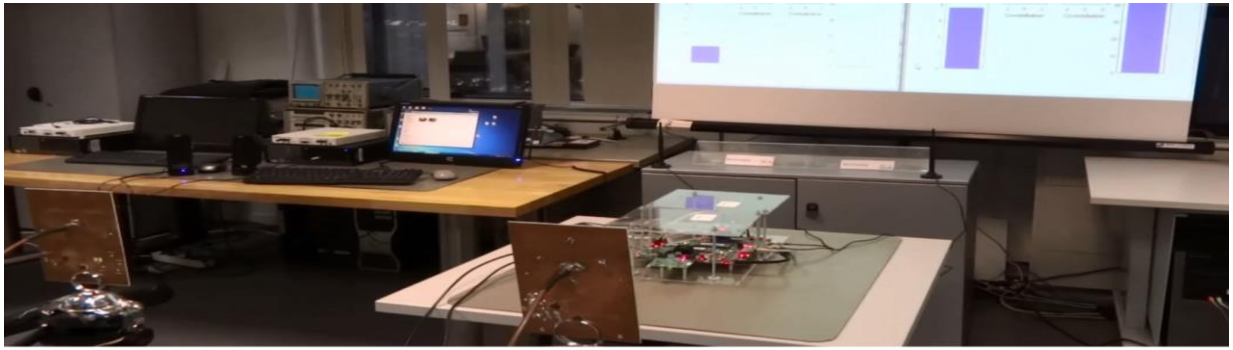
Sum-rate capacities

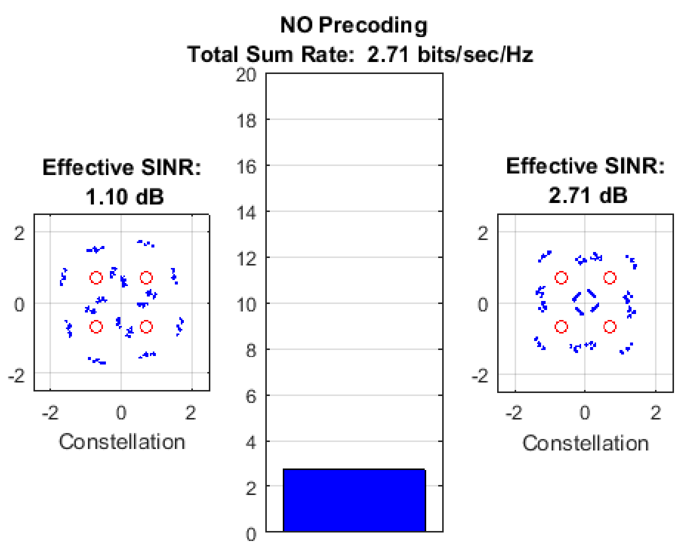


K. Ntougias, D. Ntaikos and C. B. Papadias, "Robust Low-Complexity Arbitrary User- and Symbol-Level Multi-Cell Precoding with Single-Fed Load-Controlled Parasitic Antenna Arrays," ICT 2016, Thessaloniki, Greece, May 16-18, 2016.

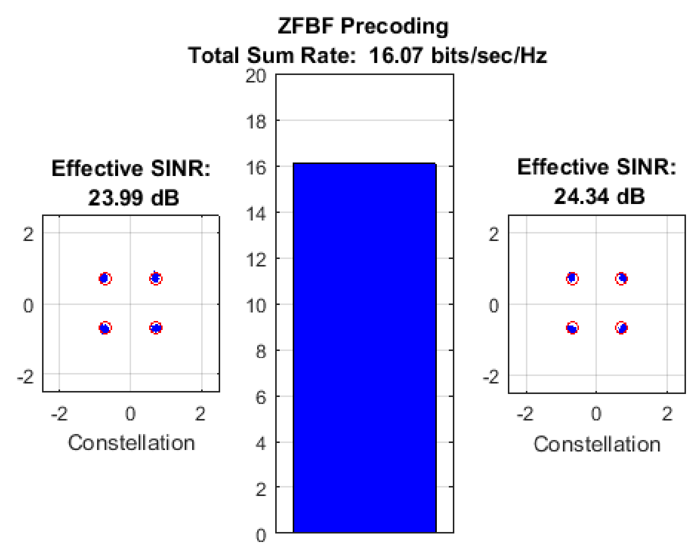
Indoor over-the air **hybrid array precoding** results

Real-time precoding



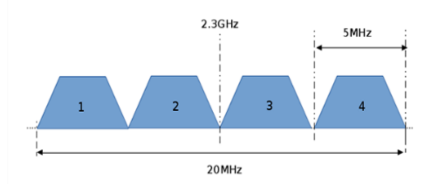


Without precoding



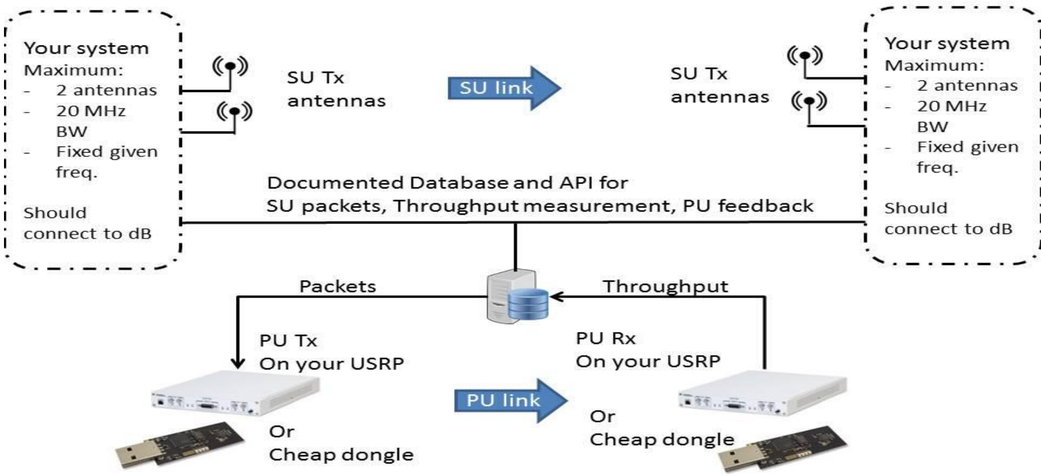
With precoding

Beam-assisted Spectrum Sharing

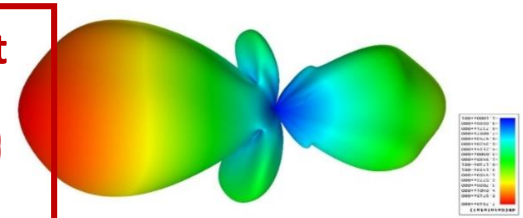


IEEE DYSPAN 2015 Spectrum Challenge:

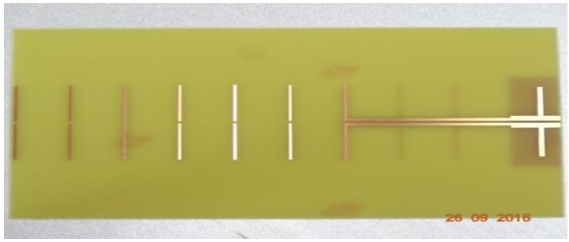
Our approach: Beamforming to improve the PU–SU isolation.



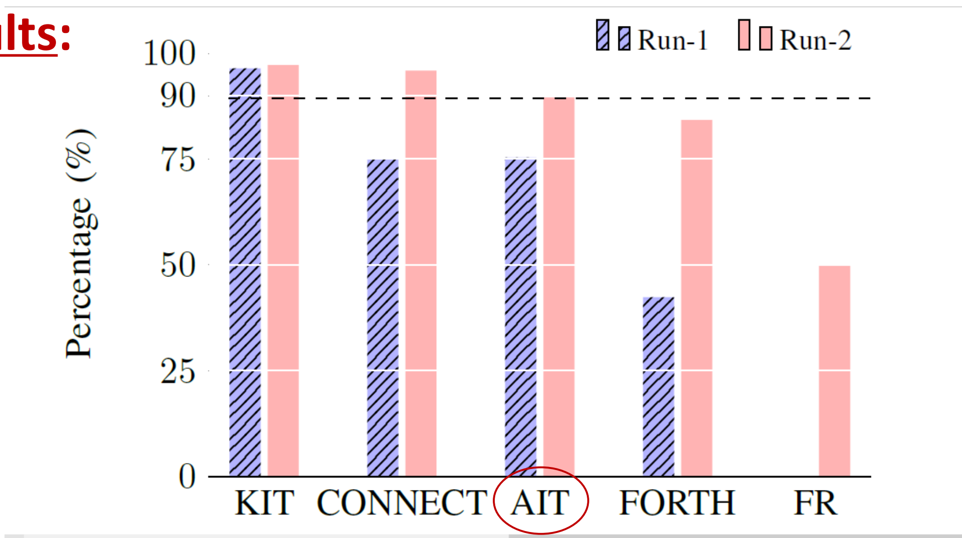
EU Project ADEL

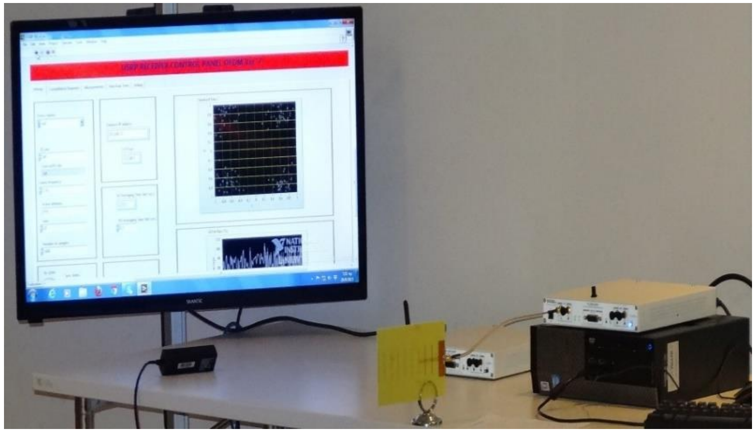


Printed Yagi-Uda array



Results:





ADEL LSA Proof-of-concept demo at EUCNC 2016

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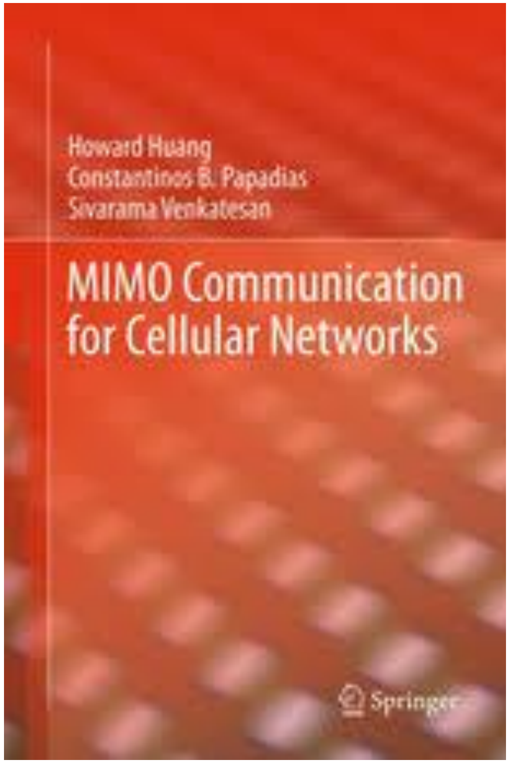
BROADNETS_2018_keynote_papadias_final

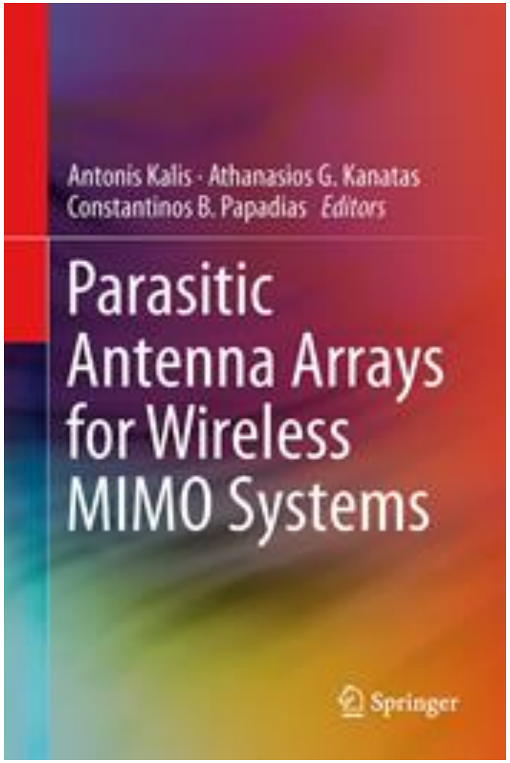
"ADEL Licensed Shared Access Proof-of-concept demonstration," Best Booth Award at the European Conference on Networks and Communications (EUCNC 2016), Athens, Greece, June 27-30, 2016.

Summary

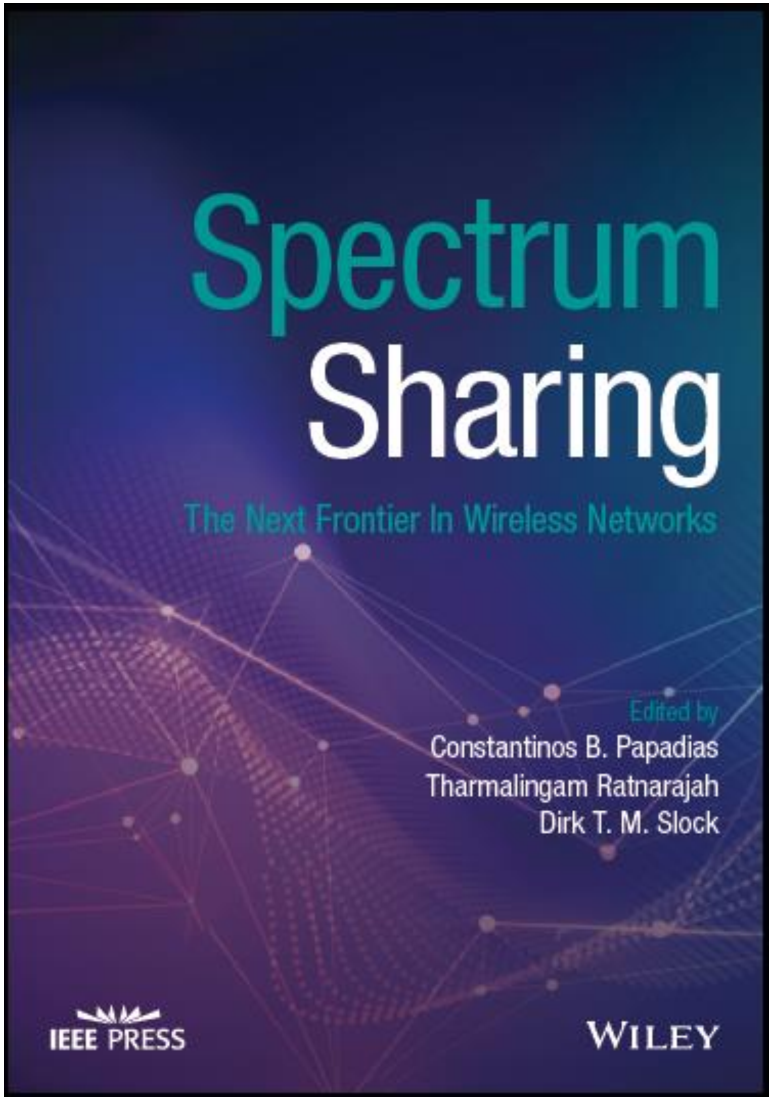
- **Antenna arrays are an important performance booster of wireless networks.**
- **From link-MIMO in 3G to cooperative MIMO in 4G to Massive MIMO in 5G, they keep and will likely keep playing a role in future generation wireless networks.**
- **mmWave spectrum is also becoming increasingly important for 5G networks and beyond.**
- **The combination of mmWave with Massive MIMO will be key to the success of wireless networks beyond 5G, in order to address the challenging KPIs in a number of applications, such as for the PAINLESS project's scenarios.**

For further reading..





.. and coming up soon!



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Thank you!