Massive MIMO
in
5G Wireless Networks

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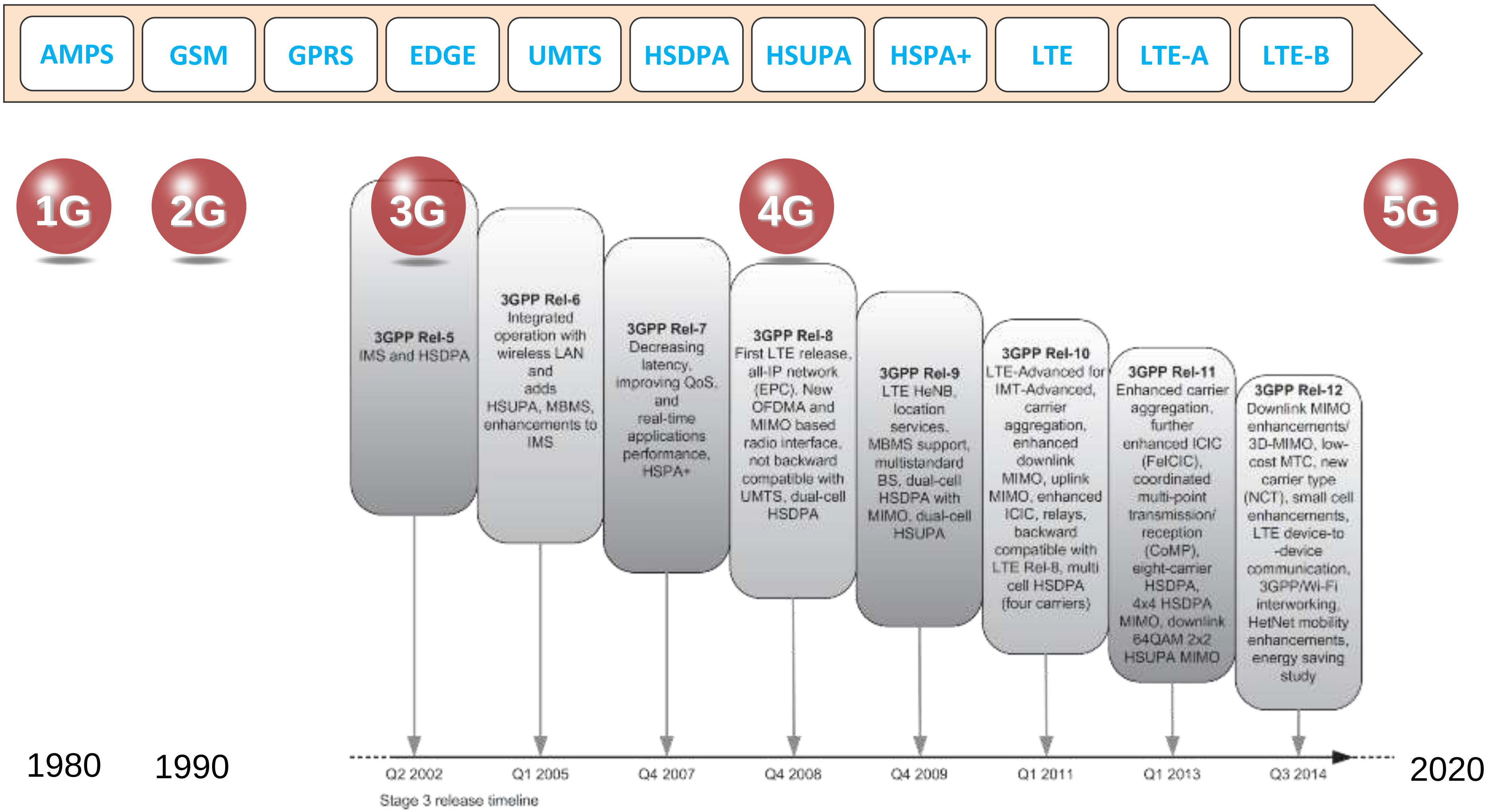
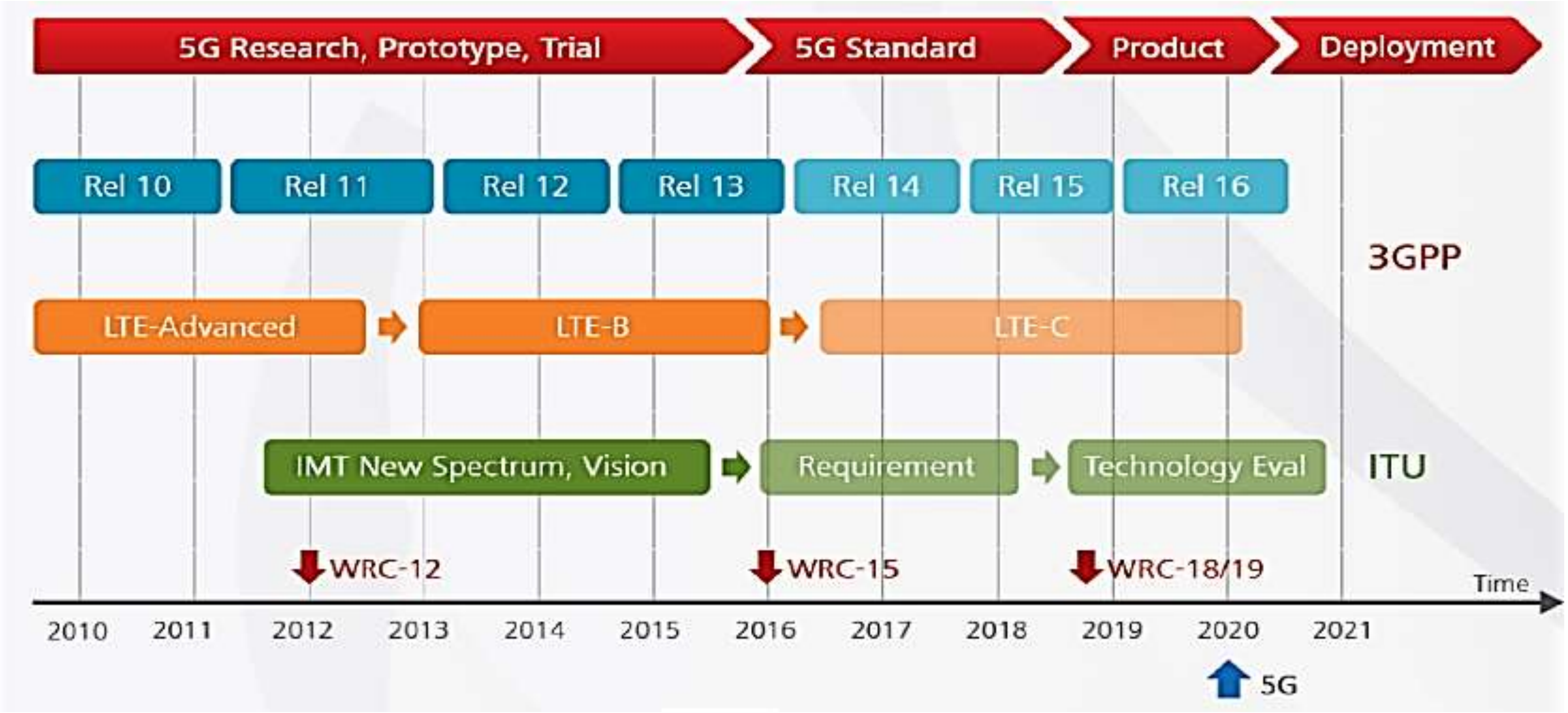
An Introduction to 5G

Evolution of Wireless Networks

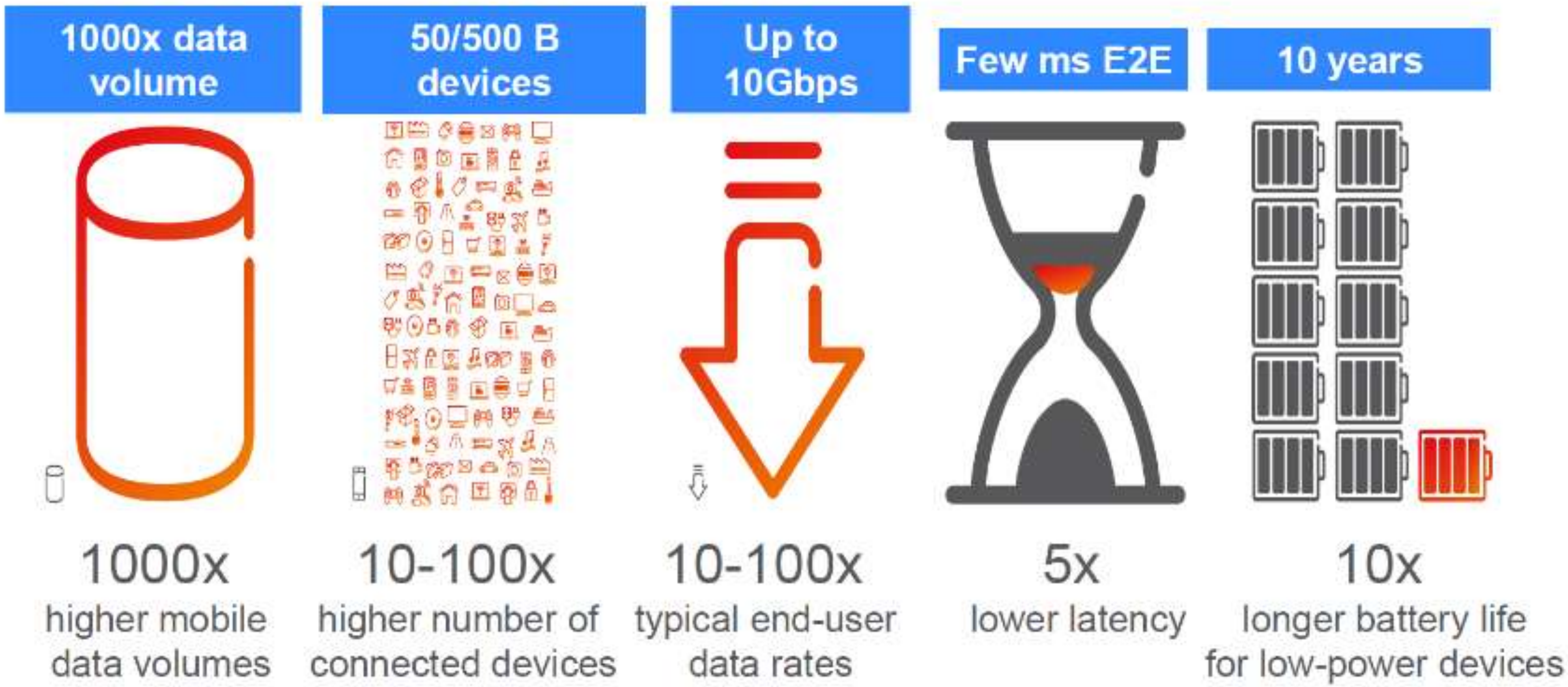


5G Timeline



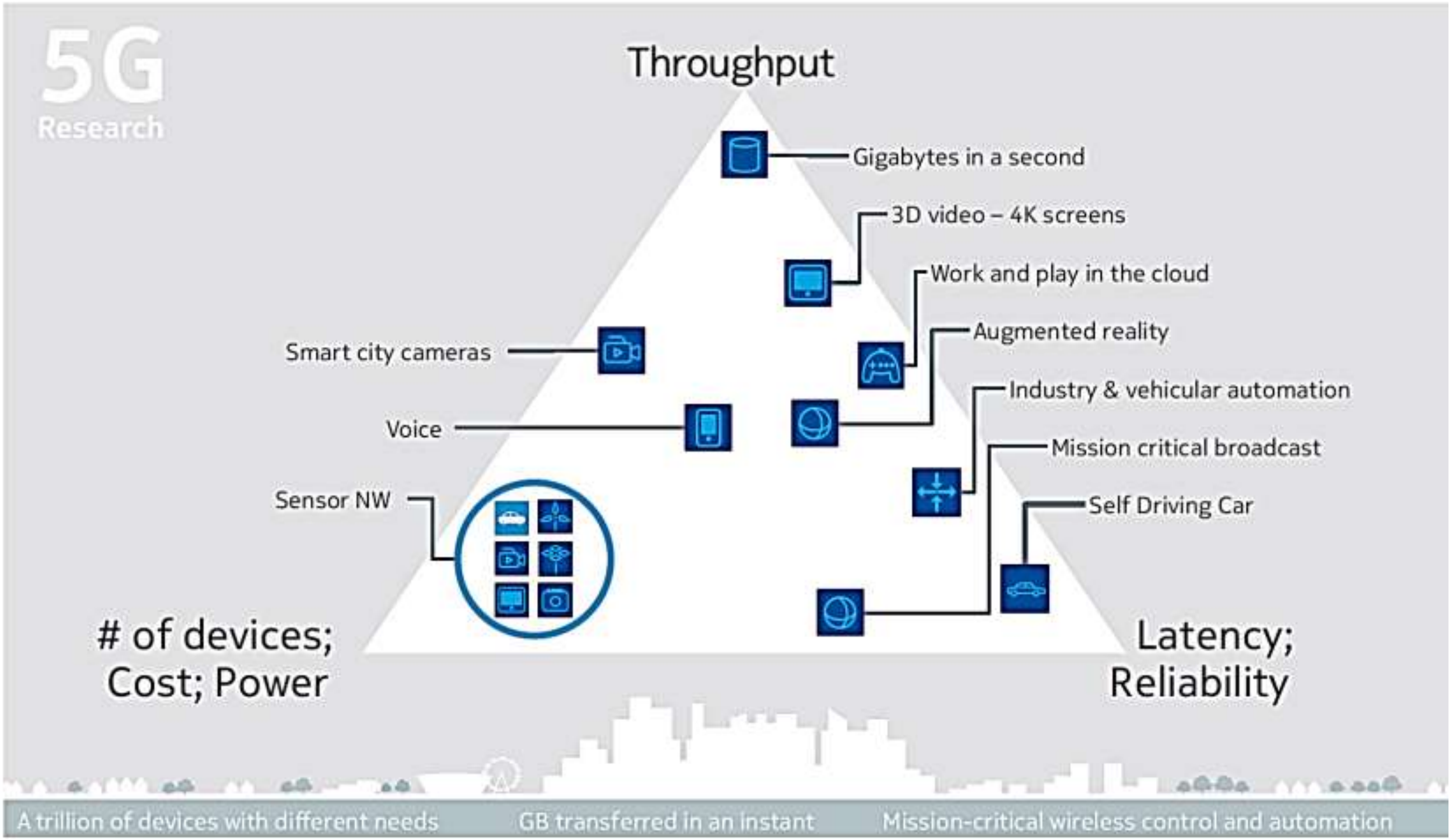
Ref: Huawei 2015

5G Objectives



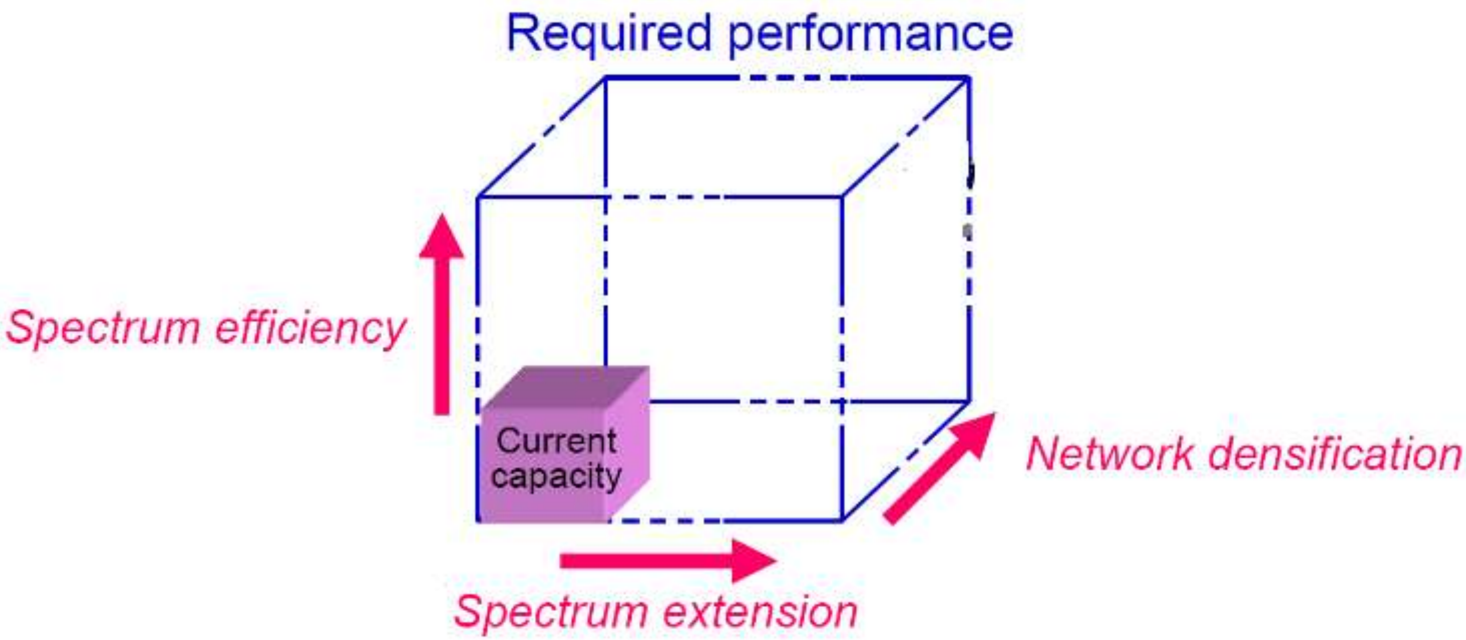
Ref: ITU

5G Use Cases



Ref: Nokia

5G Radio Access Solutions



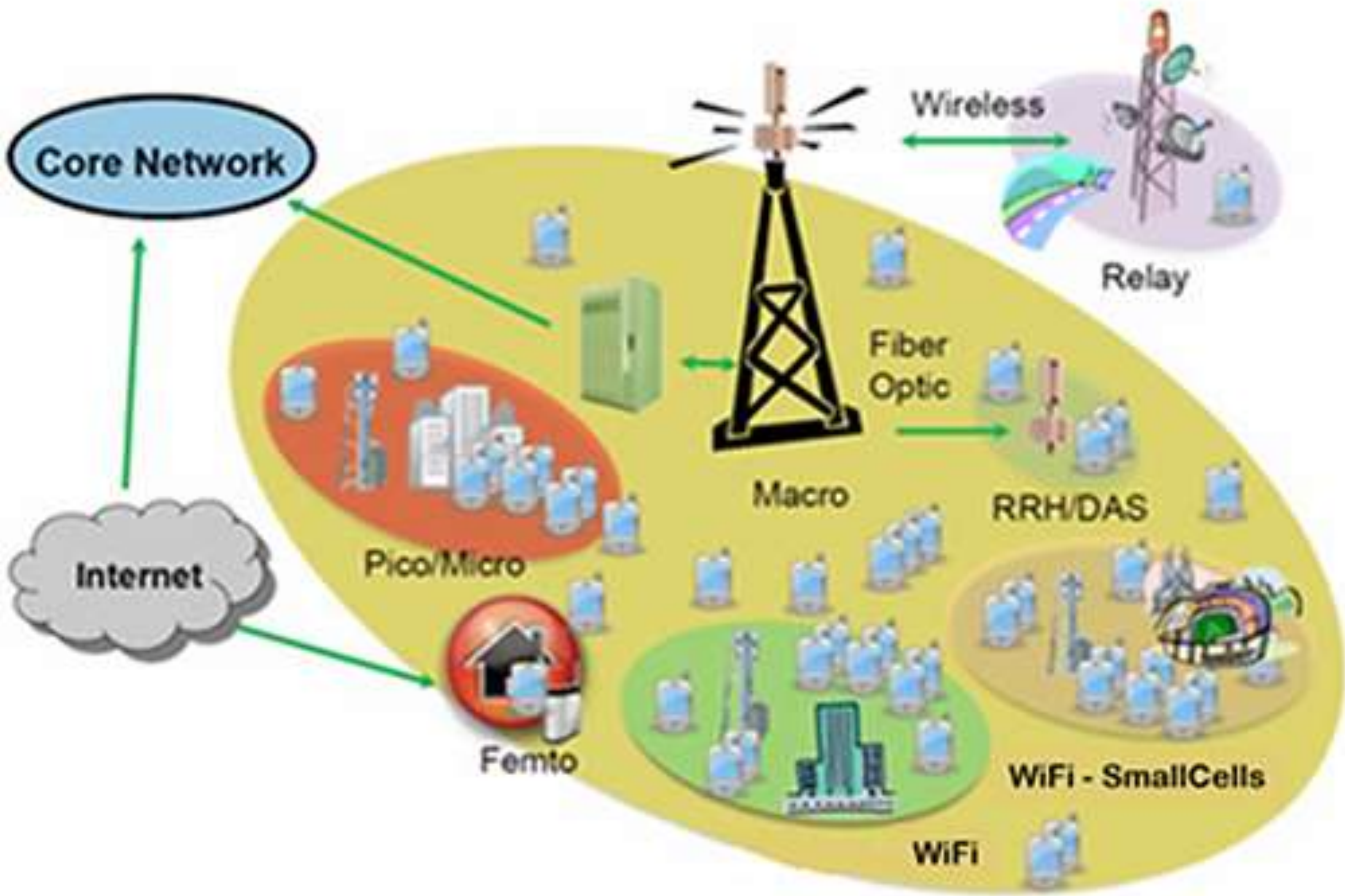
5G Radio Access Technologies

Spectrum Efficiency	×	Spectrum Extension/ Utilization	×	Network Efficiency/ Density	=	1000x Capacity
25 ✦		4		10		
10		10 ✦		10		
4		5		50		
2.5		4		100 ✦		

✦ High Challenge

Network densification

HetNet



Ref: **Tutorial @ ICC 2014**

Spectrum Extension

- Higher frequencies and millimeter waves
- New Regulations
- Unlicensed bands
- Spectrum Aggregation
- Spectrum Sharing
- Cognitive radio

mmWave

- 30 to 300 GHz
  - 23, 29, 38, 40, 46, 47, 49GHz, and E-band
- Already used in LAN, PAN, and VANET
  - backhaul in cellular networks

Frequency range	6-20 GHz	20-40 GHz	40-60 GHz	60-100 GHz
Specific bands identified	*10 GHz band* 10.125-10.225 GHz / 10.475-10.575 GHz	*32 GHz band* 31.8-33.4 GHz	*40 GHz band* 40.5-43.5 GHz *'45 GHz' band* 45.5-48.9 GHz	**66 GHz band** 66-71 GHz
Potential bandwidth	*2 x100 MHz*	*1.6 GHz*	*5.8 GHz total*	*5 GHz*

Ofcom

mmW

- Advantages
  - Higher BW
  - Multi-Gbps data rate
  - Less interference --> intra-tier and inter-tier
  - Dense spectrum re-use
  - Compact equipment
  - Spatial multiplexing

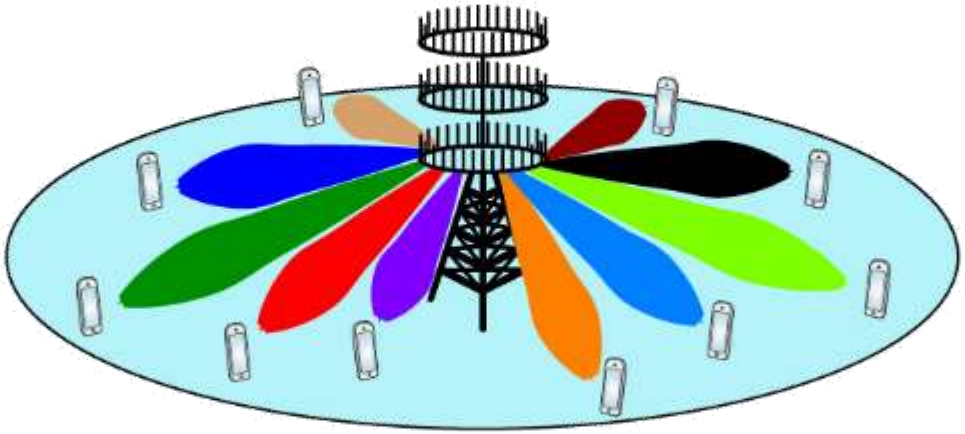
Other technologies in 5G

- Software based architecture (SDN and NFV)
- Radio Access Technologies:
- In-band full duplex
- Non-orthogonal multiple access (NOMA)
- Filter-bank multicarrier (FBMC)
- Three dimensional beamforming
- **Massive MIMO**

Massive MIMO

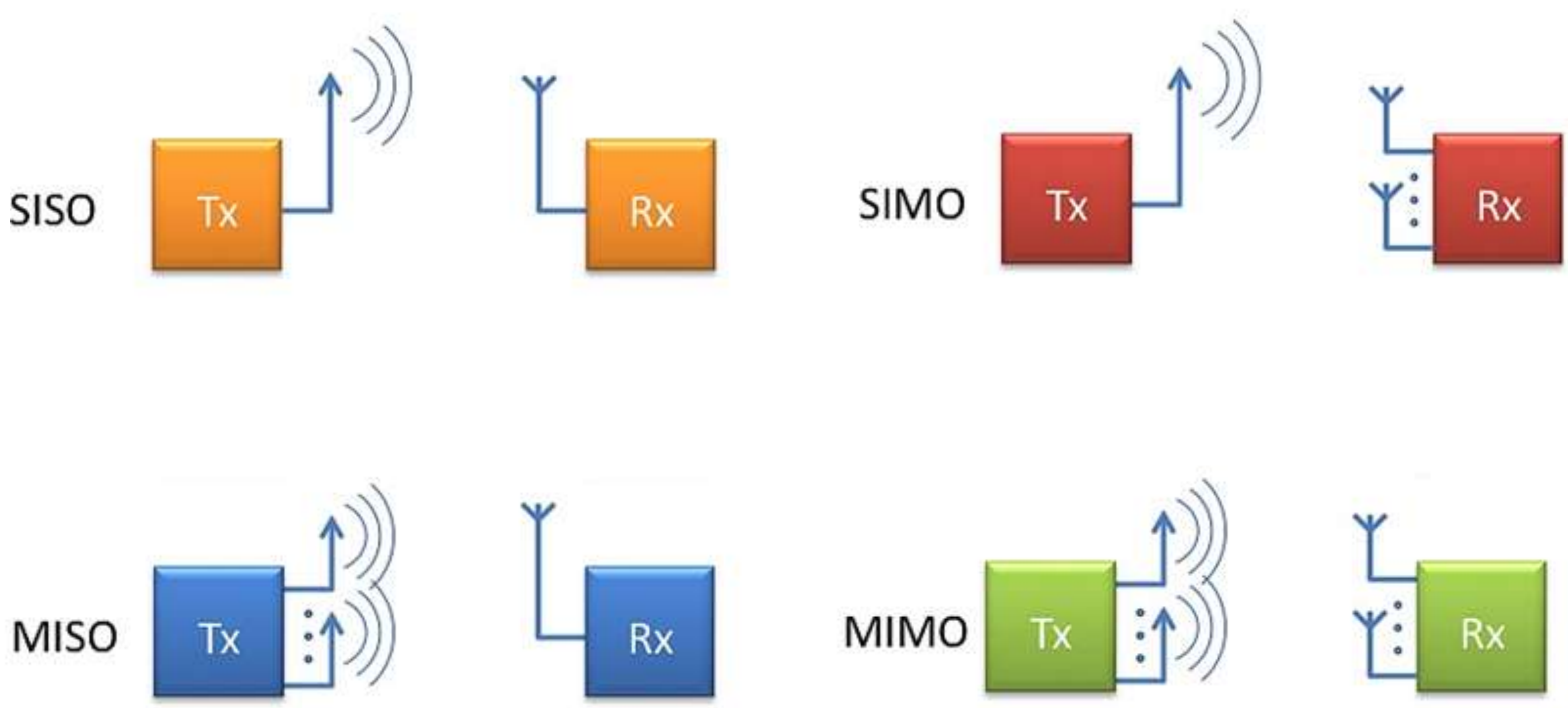
- Large-scale antenna systems
- Employing a large number of antennas at the BS

- High spectral efficiency
- High energy efficiency
- Simpler processing



Introduction to
Massive MIMO

Multiple Antenna Systems



Multiple Antenna Advantages

Spectral efficiency

Diversity and link reliability

Space-Time Coding

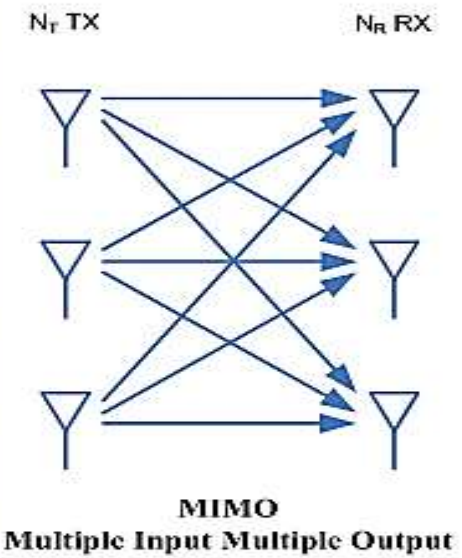
V-BLAST

Precoding (Beamforming)

Diversity Gain

Multiplexing Gain

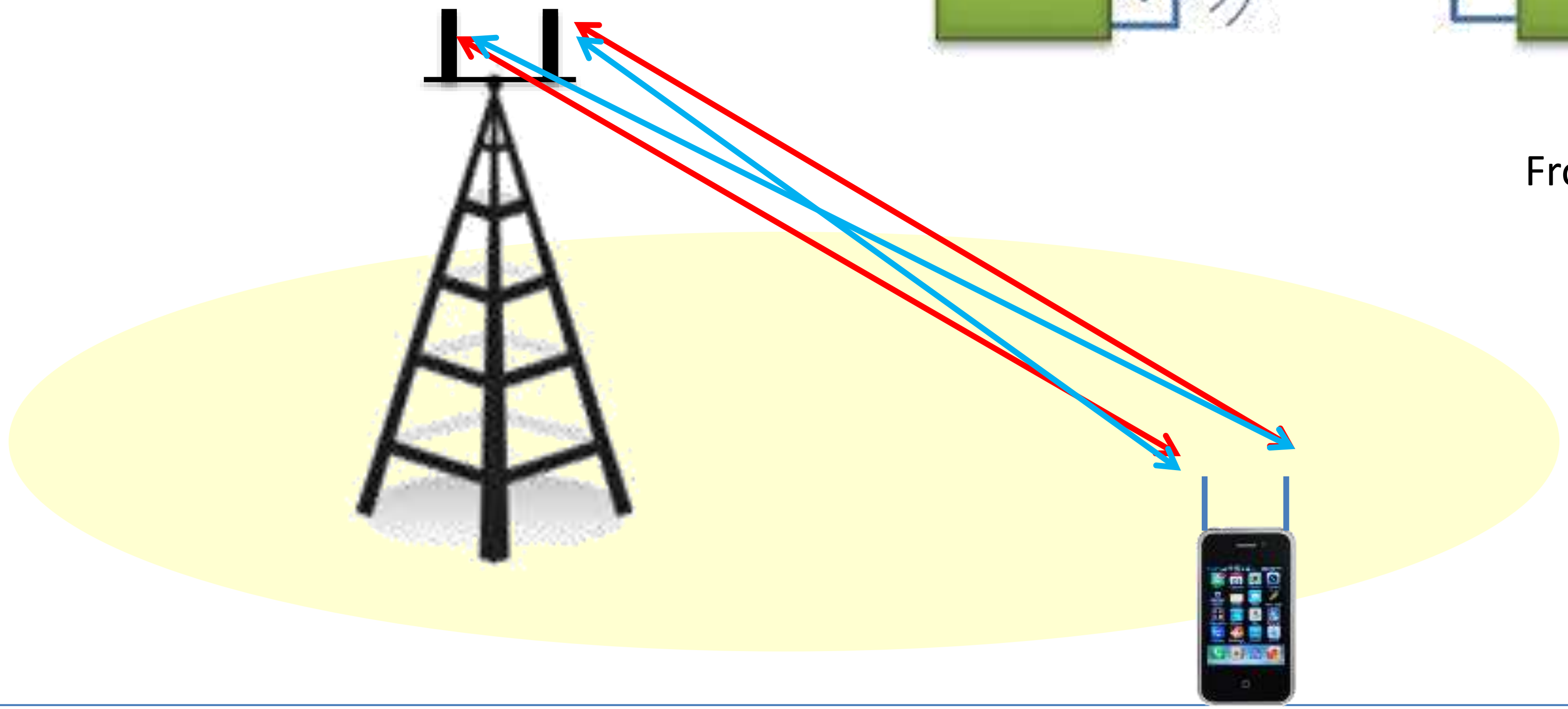
Array Gain



Single-User MIMO

- Point–to-Point MIMO

From 1993



Single-User MIMO

- $N_t \times N_r$ MIMO system
- Received signal

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{x} + \mathbf{n},$$

- Capacity (iid channels)

$$C = \log_2 \det \left(\mathbf{I} + \frac{\rho}{N_t} \mathbf{H}\mathbf{H}^{\mathrm{H}} \right)$$

Lu Lu, et.al, "An overview of massive MIMO: Benefits and challenges," IEEE J. Sel. Topics Signal Process., Oct. 2014.

Single-User MIMO

- With normalized channel

$$\mathrm{Tr}(\mathbf{H}\mathbf{H}^{\mathrm{H}}) \approx N_t N_r$$

- Upper and lower bound

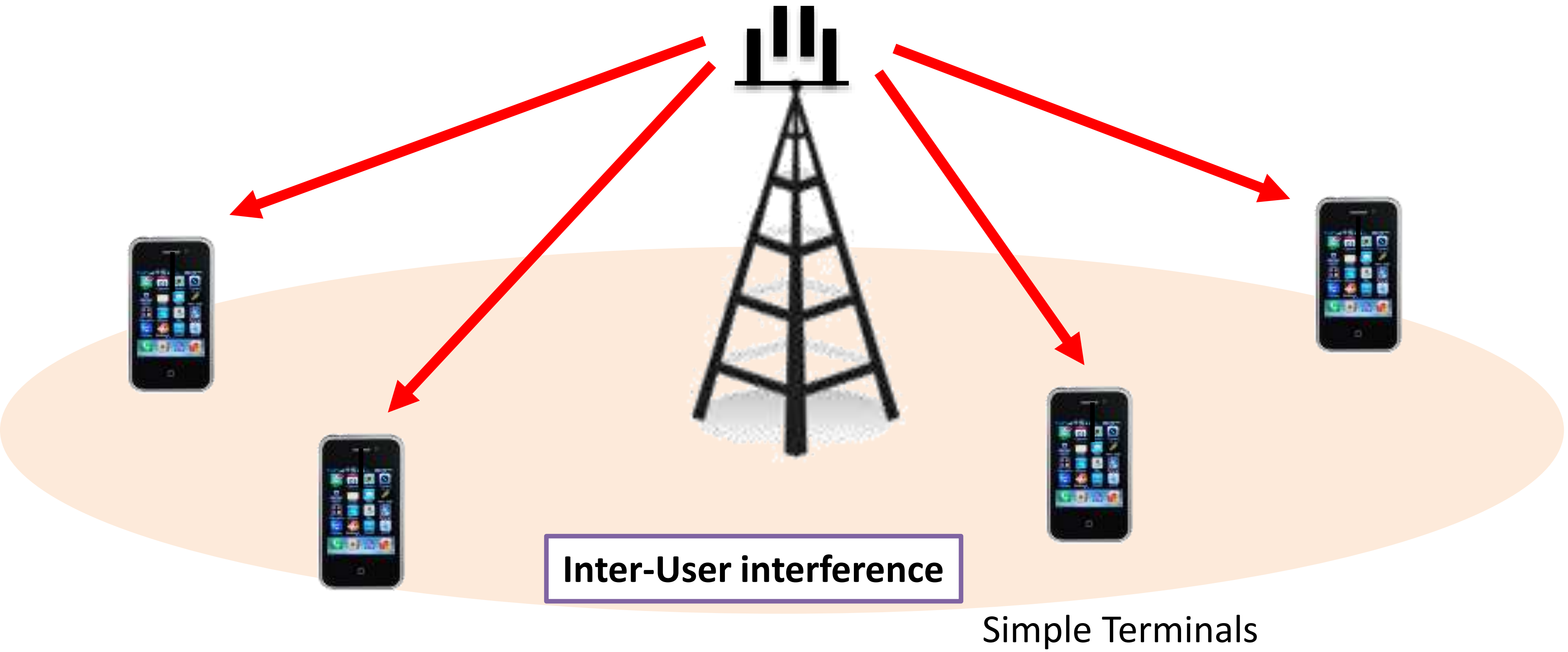
$$\log_2(1+\rho N_r) \le C \le \min(N_t, N_r)\log_2\left(1+\frac{\rho\max(N_t, N_r)}{N_t}\right)$$

- Problems of SU-MIMO:
  - Unfavorable propagations
  - Low multiplexing gain at cell edge

Lu Lu, et.al, "An overview of massive MIMO: Benefits and challenges," IEEE J. Sel. Topics Signal Process., Oct. 2014.

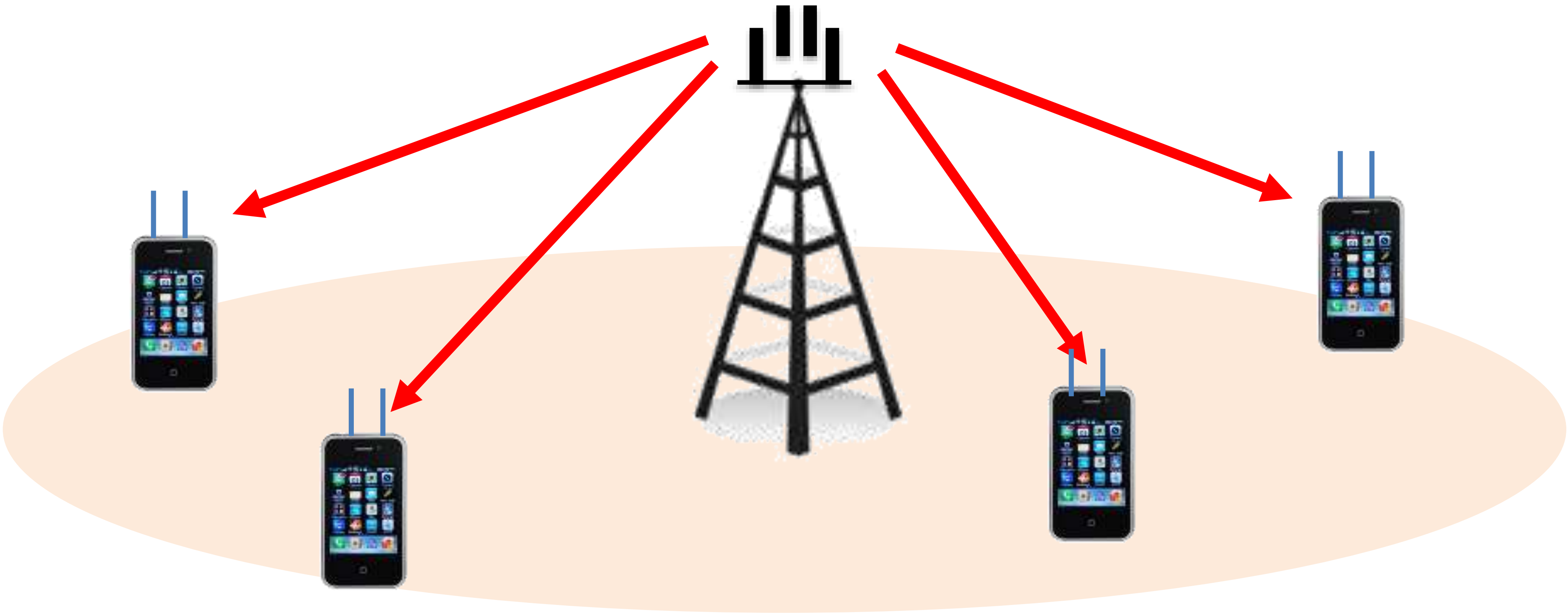
Multi-user MIMO

- multiple data streams to multiple single antenna users



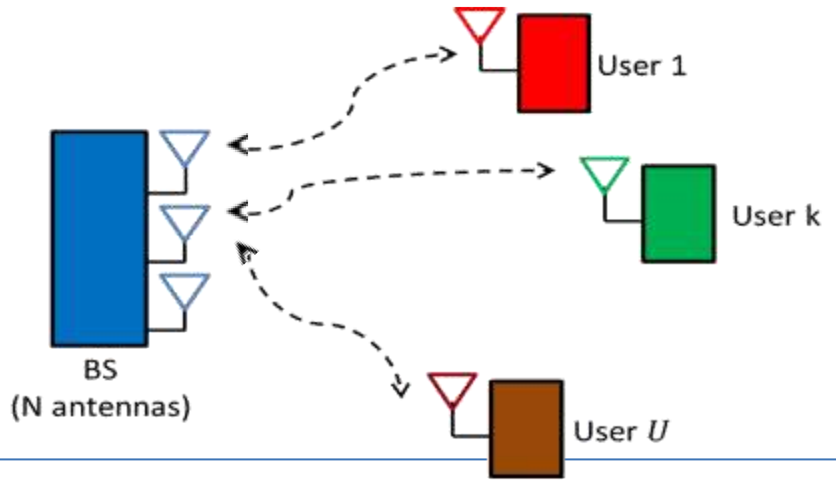
MU-MIMO

- Multiple Antenna Users



MU-MIMO

- MU-MIMO categories
  - MIMO broadcast channels (MIMO BC) – DL
    - Precoding: Linear and Non-Linear, ZF, MMSE, BD, DPC, THP, VP
  - MIMO multiple access channels (MIMO MAC) - UL
    - Decoding: Linear and Non-Linear, ZF, MMSE, ML

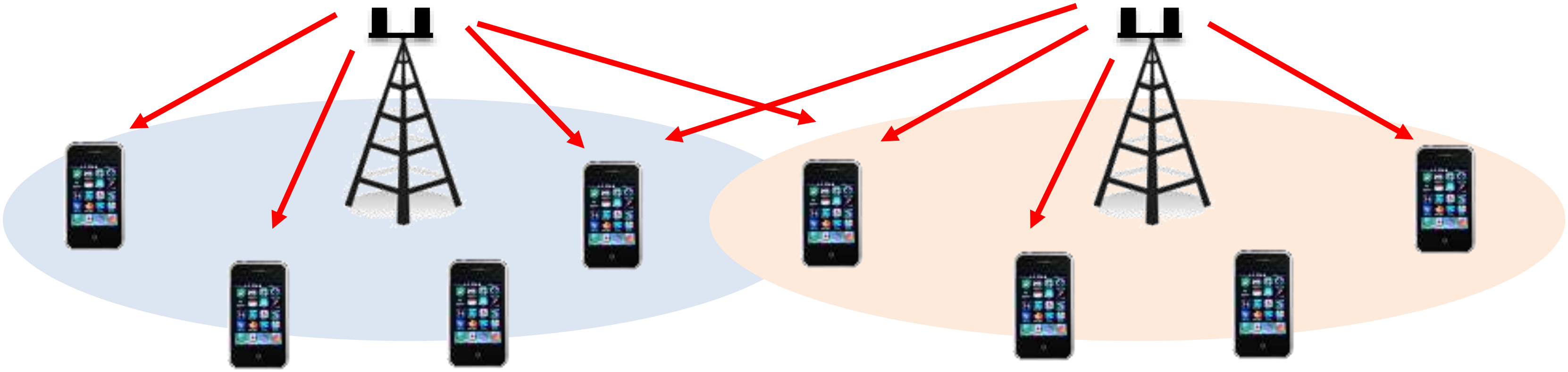


MU-MIMO

- More immune to most of propagation limitations
  - Channel rank loss or antenna correlation
  - Effect of the line-of-sight (LOS) propagation
- Development of small and cheap terminals
  - Single-antenna users
- Different techniques
  - SDMA, massive MIMO, coordinated multipoint (CoMP), Ad-hoc MIMO

MIMO Categories

- Multi-cell MIMO
  - Network MIMO



Inter-cell interference (ICI)

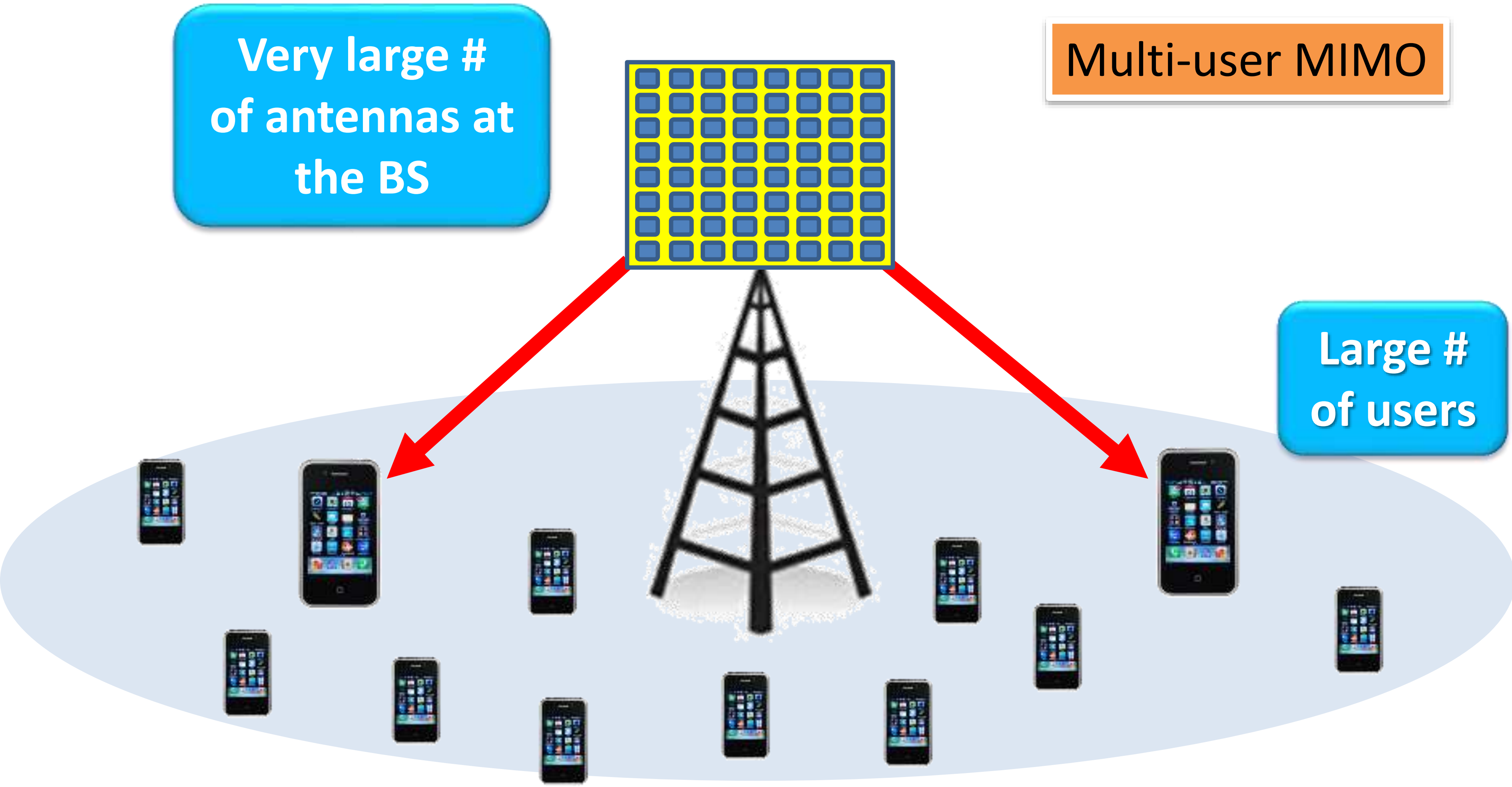
MU-MIMO

- **Challenges in the practice**
- Limited number of antennas at the BS (LTE-A)
- User scheduling
  - Selection of a group of users that will be served simultaneously
    - Max-rate techniques , Random user selection
- Channel state information at transmitter (CSIT) in DL
    - Vector quantization , Adaptive feedback , Statistical feedback
- Coordination of BSs

Conventional MIMO System

- Few # of Antenna at the BS
- Antenna ports – Antenna Elements
  - UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - LTE-A: 4-MIMO x 60 = 240 antennas
- 4x4 or 8x8
- SU-MIMO
- **AAS** – Active Antenna Systems

Massive MIMO



Massive MIMO

3590 IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 9, NO. 11, NOVEMBER 2010

Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Thomas L. Marzetta

Massive MIMO

- General assumptions:
  - CSI is only available at the BS
  - Linear precoding/decoding
  - No signal processing at users
- Benefits
  - Very narrow beams
  - Less Interference leakage
  - Simplicity
  - Higher Energy efficiency
  - Higher Spectral efficiency

Advantages of Massive MIMO

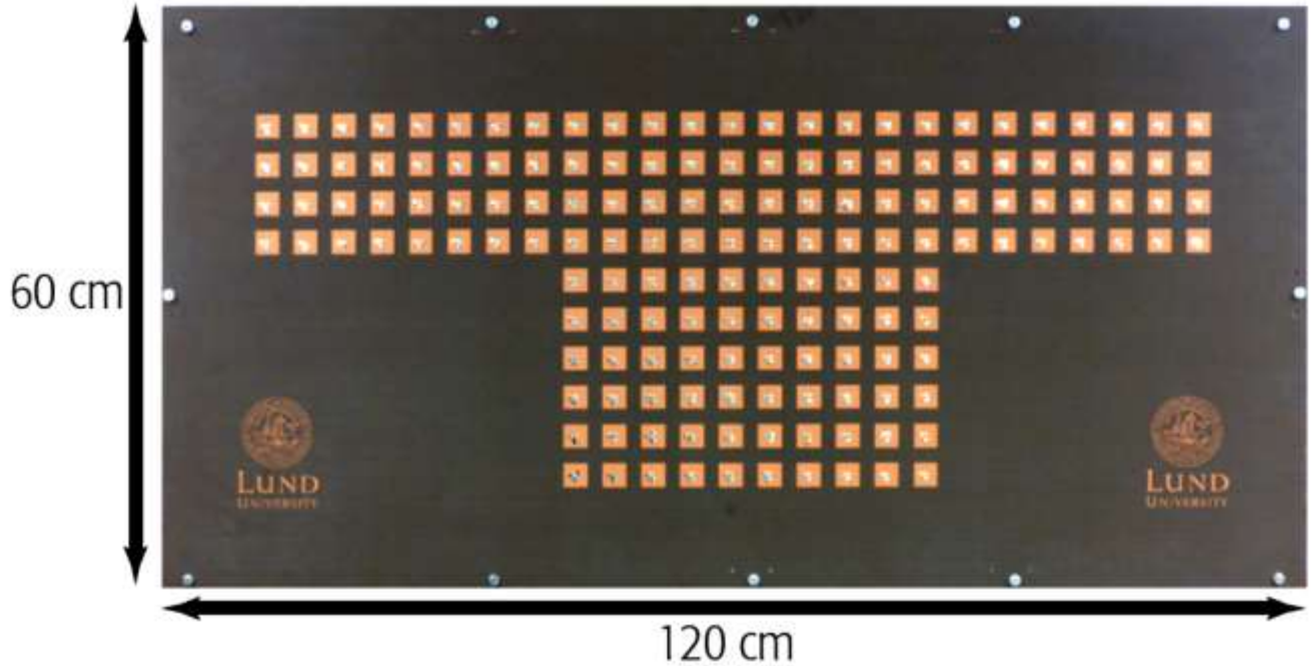
- High spectral efficiency
- Lower transmit power
- High energy efficiency
- Simple processing (MF)
- Higher capacity
- Extended Range
- Higher reliability
- More degrees of freedom (interference nulling)
- Simplified resource allocation and power control
- Better tradeoff Spectral – energy efficiency
- Good service for all users in the cell

Example

- Example (Marzeta'2010)
  - **MF**, non-cooperative
  - 42 users
  - 20 MHz BW
  - 17 Mbps for each user (both UL and DL)
  - Average 730 Mbps per cell
  - Overall Spectral efficiency : 36.5 bps/Hz

Example

- LuMaMi testbed, Lund University
- 160 antennas



- Many antenna ports

Asymptotic Analysis (single user)

- $N_t \gg N_r$ *and* $N_t \rightarrow \infty$

$$C = \log_2 \det \left(\mathbf{I} + \frac{\rho}{N_t} \mathbf{H}\mathbf{H}^{\mathrm{H}} \right)$$

$$\boxed{\frac{(\mathbf{H}\mathbf{H}^{\mathrm{H}})}{N_t} \approx \mathbf{I}_{N_r}}$$

- Achievable rate

$$C \approx N_r \log_2(1 + \rho)$$

- Upper bound is achieved

$$\min(N_t, N_r) \log_2 \left(1 + \frac{\rho \max(N_t, N_r)}{N_t} \right)$$

Asymptotic Analysis (single user)

- $N_r \gg N_t$ *and* $N_r \rightarrow \infty$

$$\frac{(\mathbf{H}\mathbf{H}^{\mathrm{H}})}{N_r} \approx \frac{N_r}{N_t} \mathbf{I}_{N_t}$$

- Achievable rate

$$C \approx N_t \log_2 \left(1 + \frac{\rho N_r}{N_t}\right)$$

- Upper bound is achieved $\min(N_t, N_r) \log_2 \left(1 + \frac{\rho \max(N_t, N_r)}{N_t}\right)$

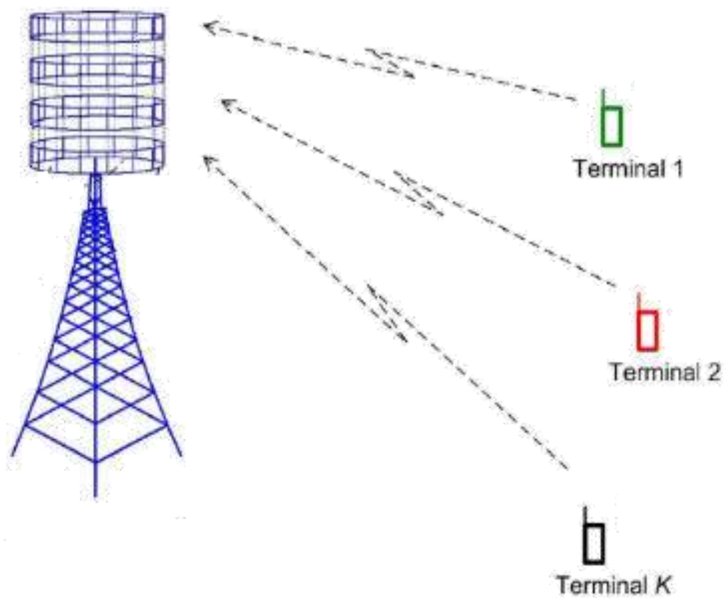
- Column or rows of H need to be orthogonal = not in LOS (favorable propagation)

Asymptotic Analysis (Multi-user)

- BS with N antennas and K users
- Uplink: received signal

$$\mathbf{y}_u = \sqrt{\rho_u}\mathbf{H}\mathbf{x}_u + \mathbf{n}_u$$

- Where $\mathbf{H} = \mathbf{G}\,\mathbf{D}^{1/2}$



Asymptotic Analysis (Multi-user)

- Independent fading channels for different users
- When $N \to \infty$

$$\mathbf{H}^{\mathrm{H}}\mathbf{H} = \mathbf{D}^{1/2}\mathbf{G}^{\mathrm{H}}\mathbf{G}\mathbf{D}^{1/2} \approx N\mathbf{D}^{1/2}\mathbf{I}_K\mathbf{D}^{1/2} = N\mathbf{D}$$

- Sum rate of the cell (network)

$$C = \log_2 \det(\mathbf{I} + \rho_u \mathbf{H}^{\mathrm{H}}\mathbf{H}) \approx \log_2 \det(\mathbf{I} + N\rho_u \mathbf{D})$$
$$= \sum_{k=1}^{K} \log_2(1 + N\rho_u d_k)$$

Asymptotic Analysis (Multi-user)

- Simple **MF** Processing (UL)

$$\mathbf{H}^{\mathrm{H}}\mathbf{y}_u = \mathbf{H}^{\mathrm{H}}(\sqrt{\rho_u}\mathbf{H}\mathbf{x}_u + \mathbf{n}_u) \approx N\sqrt{\rho_u}\mathbf{D}\mathbf{x}_u + \mathbf{H}^{\mathrm{H}}\mathbf{n}_u$$

White noise

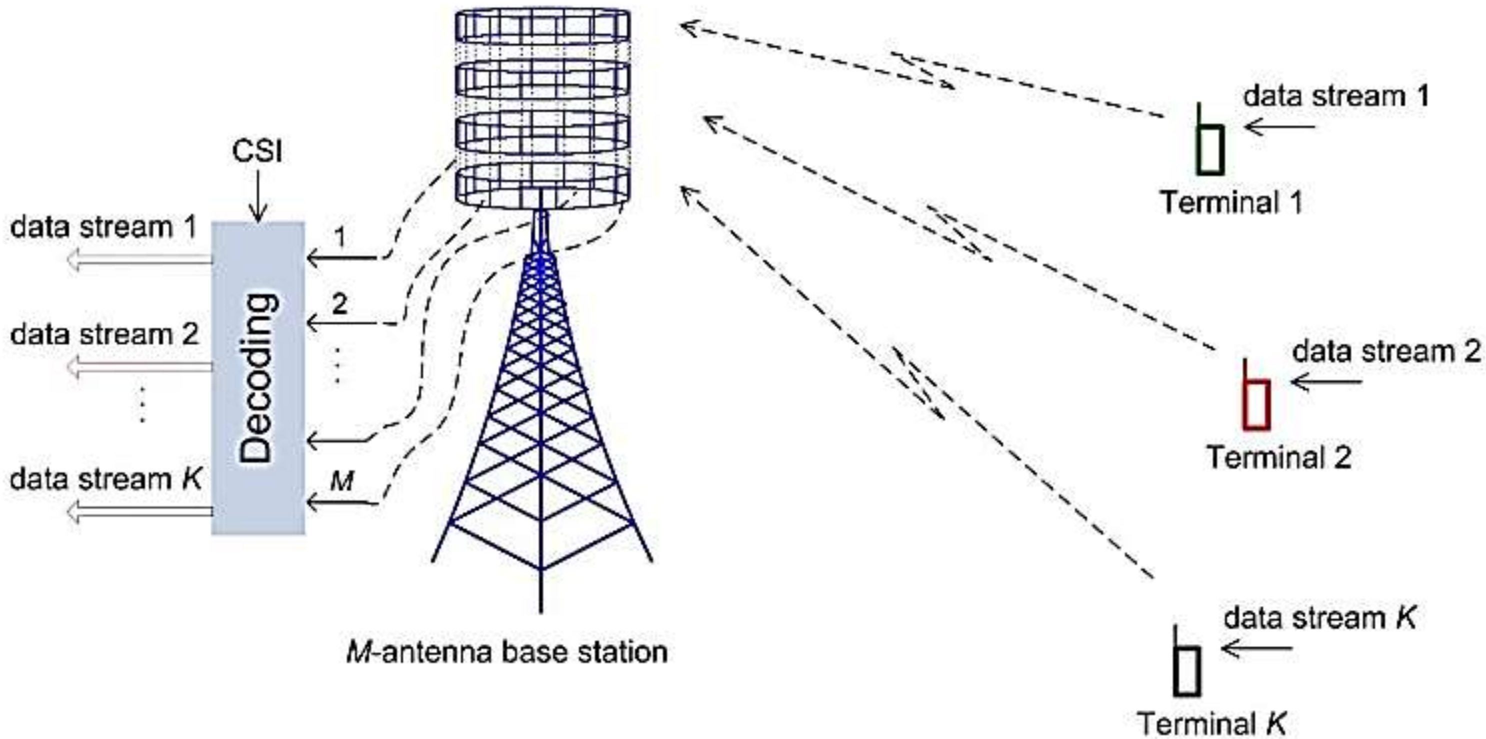
- No inter-user interference !
- Like a SISO channel
- SNR of each user $N\rho_u d_k$
- The capacity is achieved by MF

$$\sum_{k=1}^{K} \log_2(1 + N\rho_u d_k)$$

- MF is optimal !

Asymptotic Analysis (Multi-user)

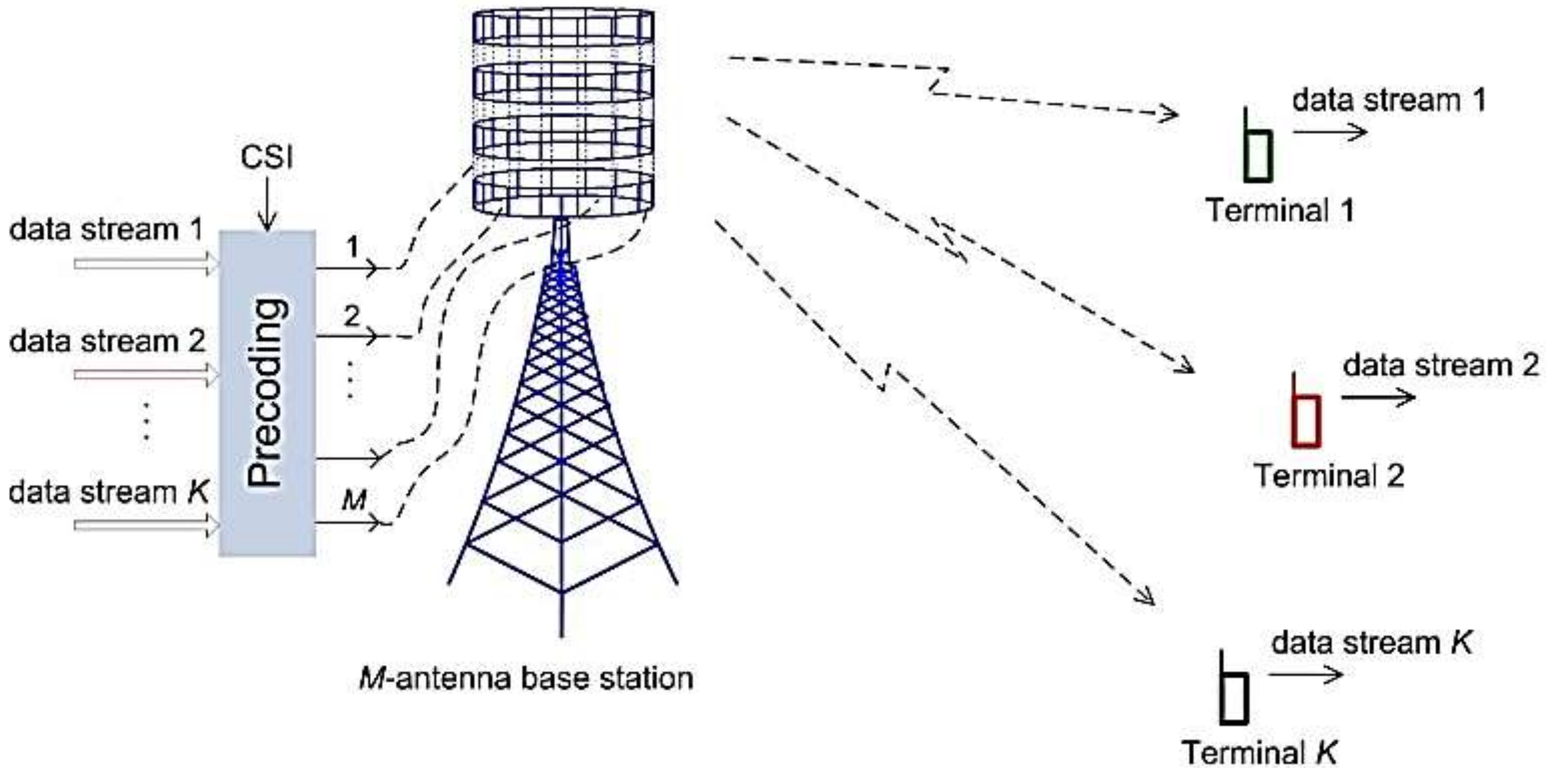
- Uplink



Thomas L. Marzetta“ MASSIVE MIMO: FUNDAMENTALS AND SYSTEM ISSUES” , Lund Circuit Design Workshop ,Sep. 2015

Asymptotic Analysis (Multi-user)

- Downlink



Thomas L. Marzetta“ MASSIVE MIMO: FUNDAMENTALS AND SYSTEM ISSUES” , Lund Circuit Design Workshop ,Sep. 2015

Asymptotic Analysis (Multi-user)

- Downlink:
- Received signal vector at all K users $\mathbf{y}_d = \sqrt{\rho_d}\mathbf{H}^{\mathrm{T}}\mathbf{x}_d + \mathbf{n}_d$
- TDD mode and CSI knowledge
- CSIT→ Power allocation can be used at the BS for max. rate

$$C = \max_{\mathbf{P}} \log_2 \det(\mathbf{I}_N + \rho_d \mathbf{H}\mathbf{P}\mathbf{H}^{\mathrm{H}}) \approx \max_{\mathbf{P}} \log_2 \det(\mathbf{I}_K + \rho_d N \mathbf{P}\mathbf{D})$$

- Power allocation matrix: $\mathbf{P} = diag(p_1, p_2, \dots, p_K)$, $\sum_1^K p_k = 1$

S. Vishwanath et.al., "Duality, achievable rates, and sum-rate capacity of Gaussian MIMO broadcast channels," IEEE Trans. Inf. Theory, Oct. 2003.

Lu Lu, et.al, "An overview of massive MIMO: Benefits and challenges," IEEE J. Sel. Topics Signal Process., Oct. 2014.

Asymptotic Analysis (Multi-user)

- Using MF precoder

$$\mathbf{x}_d = \mathbf{H}^* \mathbf{D}^{-1/2} \mathbf{P}^{1/2} \mathbf{s}_d$$

- The received vector

$$\mathbf{y}_d = \sqrt{\rho_d} \mathbf{H}^{\mathrm{T}} \mathbf{H}^* \mathbf{D}^{-1/2} \mathbf{P}^{1/2} \mathbf{s}_d + \mathbf{n}_d$$

- $N \rightarrow \infty$

$$\boxed{\mathbf{y}_d \approx \sqrt{\rho_d} N \mathbf{D}^{1/2} \mathbf{P}^{1/2} \mathbf{s}_d + \mathbf{n}_d}$$

- No inter-user interference !

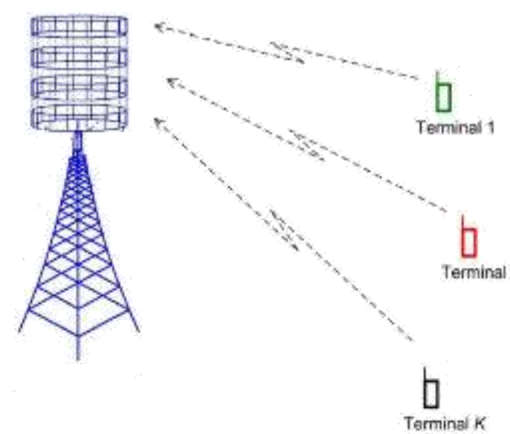
- **Capacity can be achieved by MF precoder** (Optimal powers)

Channel Estimation

- Need for CSI : multiuser precoding (DL) or detection (UL)
- Pilot based channel estimation
- Preamble

- In general, time and freq. resources required for estimation is proportional to the # of TR antennas

$\mathbf{H} \rightarrow \quad N \times K$



- Two modes of operation: **FDD** and **TDD**

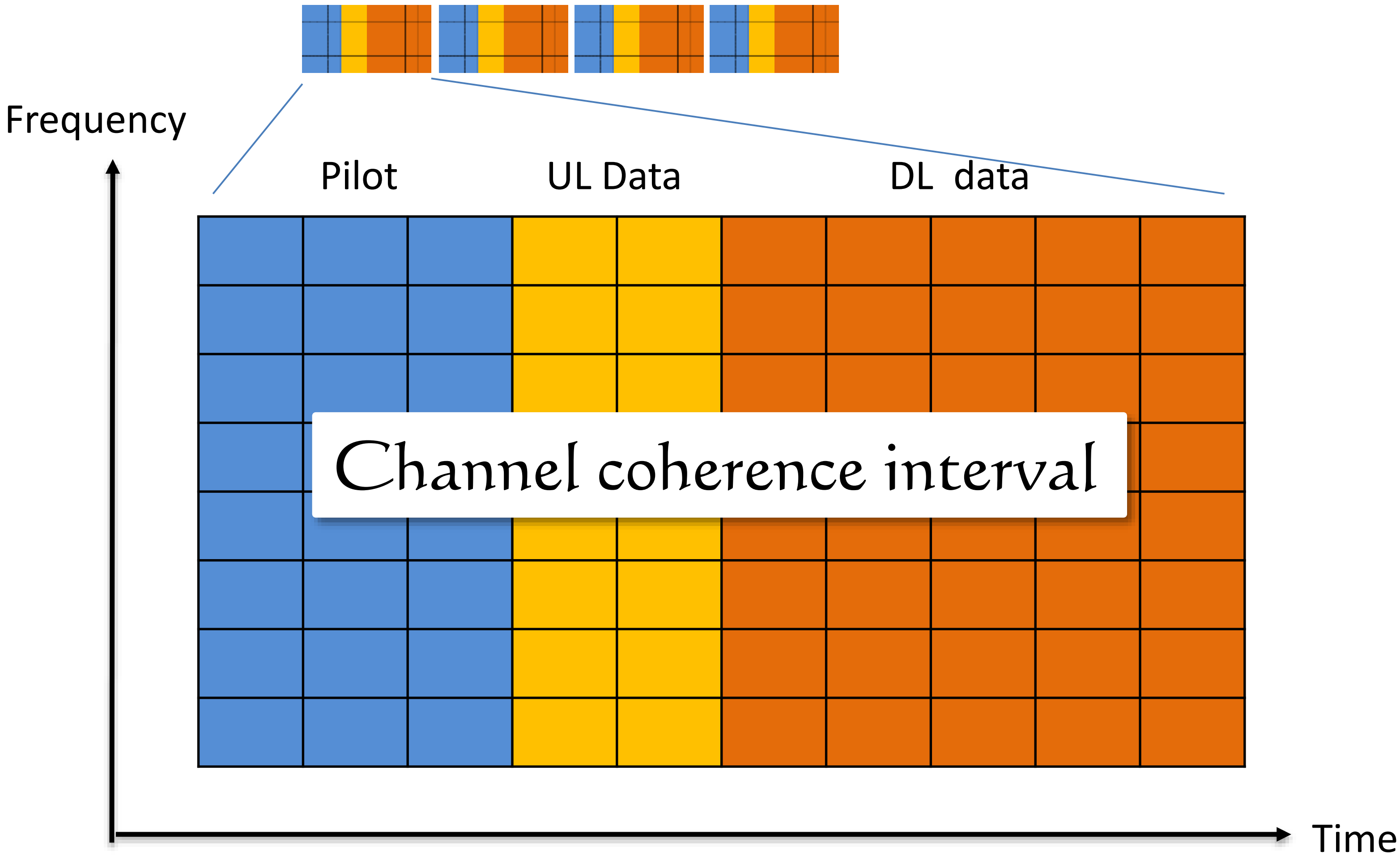
Channel Estimation

- **FDD**: Different CSI in UL and DL
  - no reciprocity in the channel
- Uplink → No problem
- Downlink → A big challenge
- BS transmits pilot symbols
- Channel estimation at the users
- Pilot length is proportional to the # of the BS antennas
- In large # of BS antenna (N) -> FDD is infeasible
  - Whole coherence interval is used for pilot transmission

Channel Estimation

- **TDD**
- Channel reciprocity
- Uplink pilot and channel estimation
- Pilot length is proportional to the # of the users (K)
  - Independent of N
  - $N \to \infty$

Channel Estimation



Pilot Contamination

- Pilot assignment in multi-cell networks
- Limitation in Pilots length ==> # of orthogonal pilots
- Pilot reusing
- Non-orthogonal pilots in neighbor cells
- Interference !

Pilot Contamination

- Error in channel estimation
  - a linear combination of the channels with the same pilots

MMSE estimation

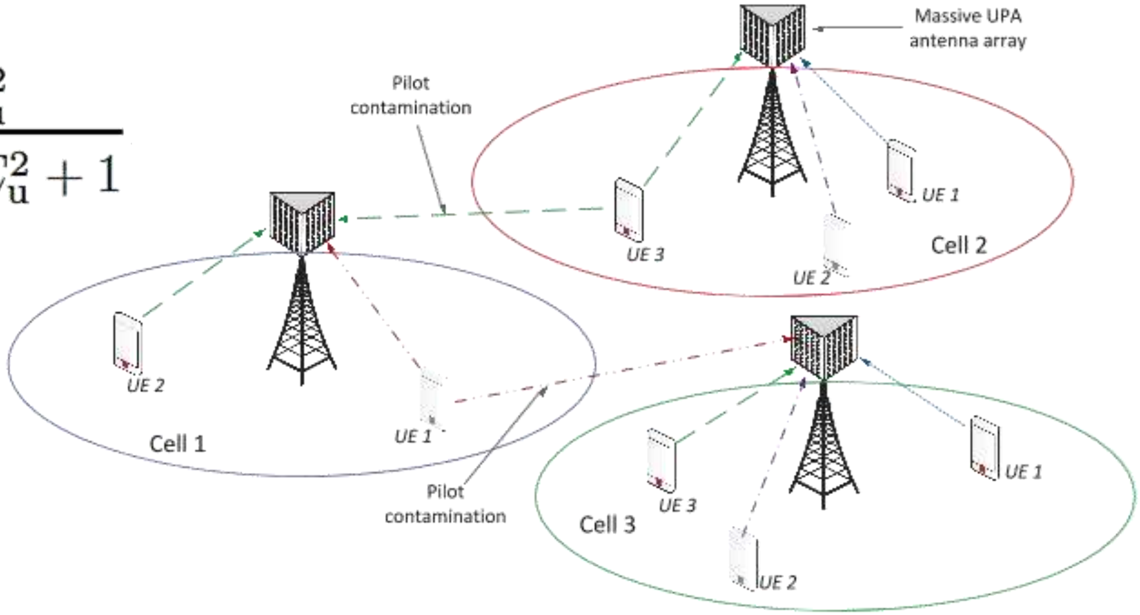
$$\hat{\mathbf{H}}_{jl} = \sqrt{p_r \tau}\mathbf{D}_{jl}^{\frac{1}{2}}\mathbf{\Psi}_j^{\dagger}\left(\mathbf{I} + p_r\tau\sum_{i=1}^{L}\mathbf{\Psi}_i\mathbf{D}_{il}\mathbf{\Psi}_i^{\dagger}\right)^{-1}\mathbf{Y}_l$$

$$\widehat{\mathbf{H}}_i = \mathbf{H}_i + \sum_{j=1\neq i}^{L}\mathbf{H}_{ij} + N$$

Pilot Contamination

- Beamforming to users in other cells
- Not cancelled as $N \to \infty$

$$\mathrm{SINR}_{l,k}^{\mathrm{IP}} \to \frac{\tau \beta_{llk}^2 E_{\mathrm{u}}^2}{\tau \sum_{i \neq l}^{L} \beta_{lik}^2 E_{\mathrm{u}}^2 + 1}$$



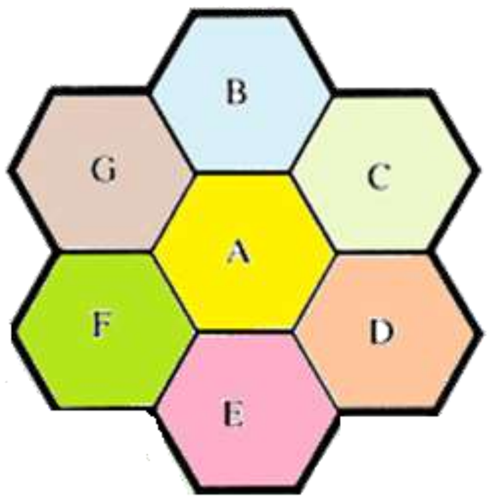
Pilot Contamination

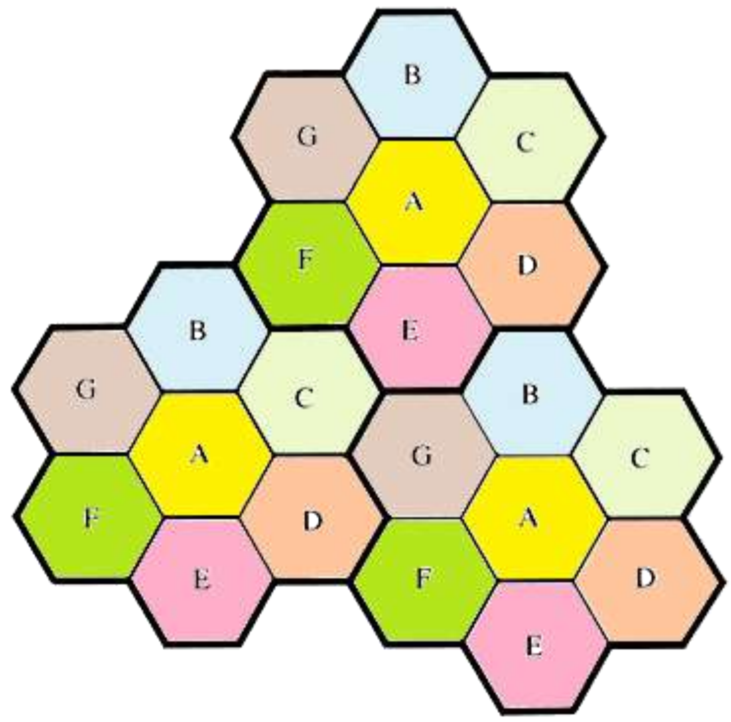
- Main sources of pilot contamination
  - Non-orthogonal pilots
  - Hardware impairment
  - Non-reciprocal transceivers
- The final result

$$\mathrm{SIR}_{rk} = \frac{\beta_{jkj}^2}{\sum_{\ell \neq j} \beta_{jk\ell}^2}$$

Mitigation of Pilot Contamination

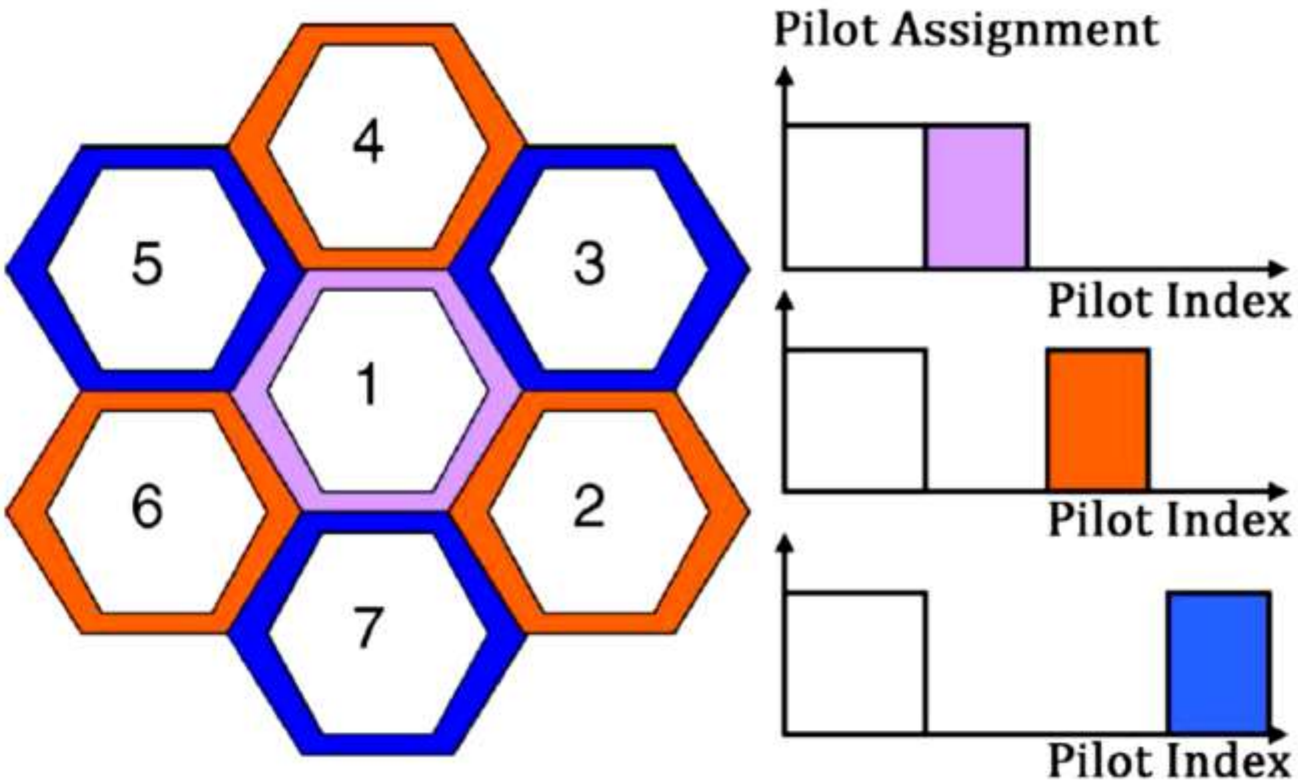
- Pilot partitioning and reusing





Mitigation of Pilot Contamination

- Soft pilot reuse (SPR)



Mitigation of Pilot Contamination

- Time shifted pilots

Mitigation of Pilot Contamination

- **Multi-cell cooperation based precoding**
  - Information exchange problem
  - In limited # of antennas
- **AoA-based methods**
- **Blind methods**
  - Sub-space partitioning
  - EVD-based estimation

Signal Detection

- Linear detectors are near optimal

$$\boldsymbol{A} = \begin{cases} \boldsymbol{G} & \text{for MF} \\ \boldsymbol{G}\left(\boldsymbol{G}^H\boldsymbol{G}\right)^{-1} & \text{for ZF} \\ \boldsymbol{G}\left(\boldsymbol{G}^H\boldsymbol{G} + \frac{1}{p_\mathrm{u}}\boldsymbol{I}_K\right)^{-1} & \text{for MMSE} \end{cases}$$

$$\boldsymbol{r} = \sqrt{p_\mathrm{u}}\boldsymbol{A}^H\boldsymbol{G}\boldsymbol{x} + \boldsymbol{A}^H\boldsymbol{n}$$

- ZF has better performance at high SNR
- Low complexity

Energy Efficeincy

- Spectral efficiency and Energy efficiency
- Power scaling law
  - Perfect CSI: proportional to N
  - Imperfect CSI: proportional to $\sqrt{N}$
  - $N \to \infty$ and same sum-rate as single antenna
- Range extension
- Spectral Efficiency $\times K$

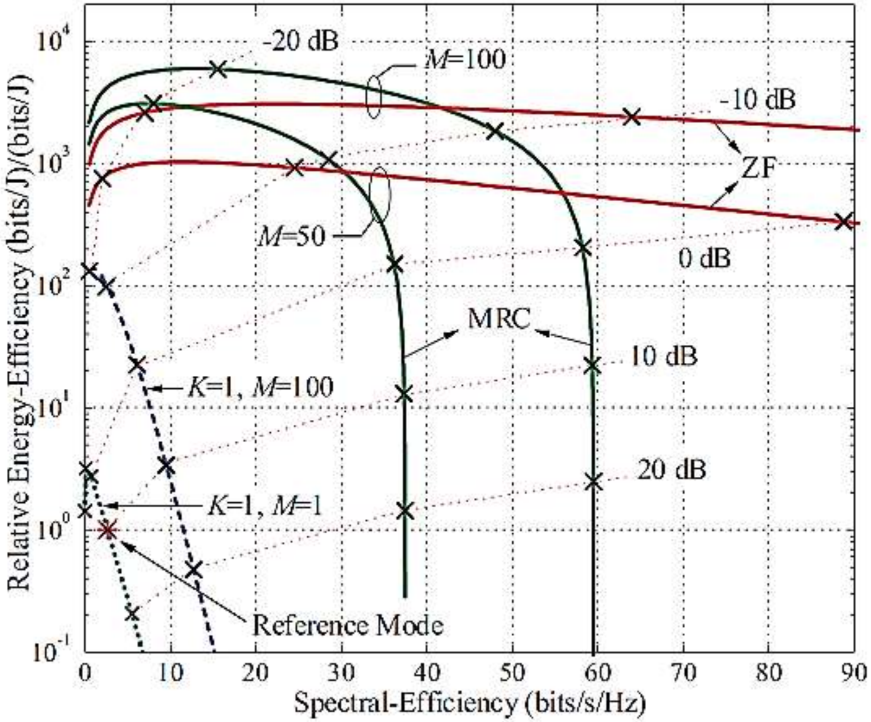
$$\mathrm{EE} = \frac{\sum_{k=1}^{K} \left(\mathbb{E}\left\{ R_k^{(\mathrm{ul})} \right\} + \mathbb{E}\left\{ R_k^{(\mathrm{dl})} \right\} \right)}{P_{\mathrm{TX}}^{(\mathrm{ul})} + P_{\mathrm{TX}}^{(\mathrm{dl})} + P_{\mathrm{CP}}}$$

$$\mathrm{SE} = \sum_{k=1}^{K} \left(1 - \frac{B}{T} \right) \log_2 (1 + \mathrm{SINR}_k)$$

H. Q.Ngo,E.G.Larsson, and T. L.Marzetta, “Energy and spectral efficiency of very large multiuser MIMO systems,” *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013

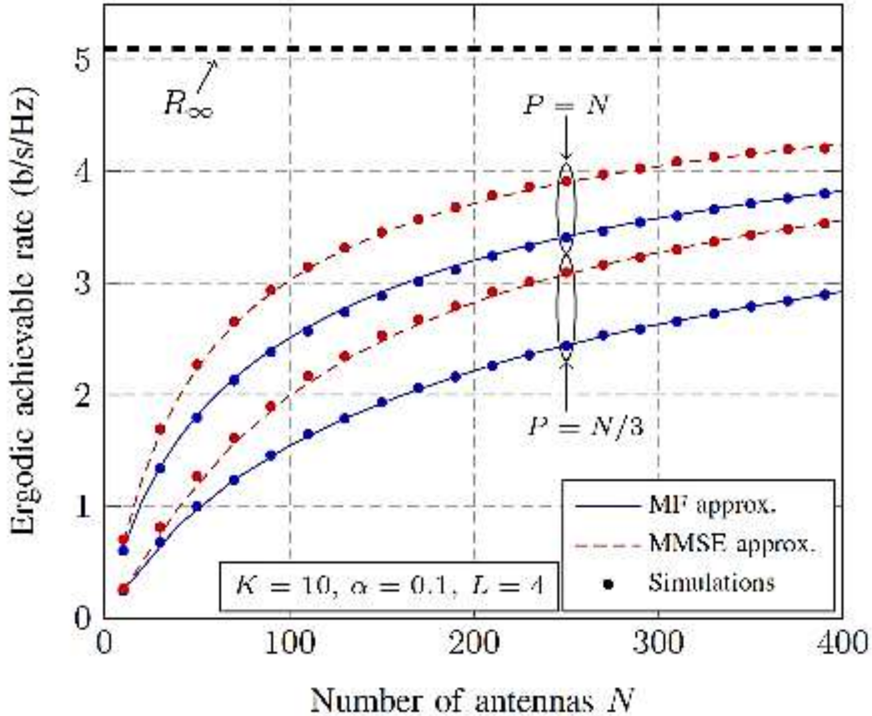
Energy Efficiency

- Tradeoff of two efficiencies
  - Good in low SNRs
  - MRC and ZF with imperfect CSI
- Circuit power consumption !



How many antennas do we need?

- In theory, more antenna ==> Better performance
- $N \to \infty$???



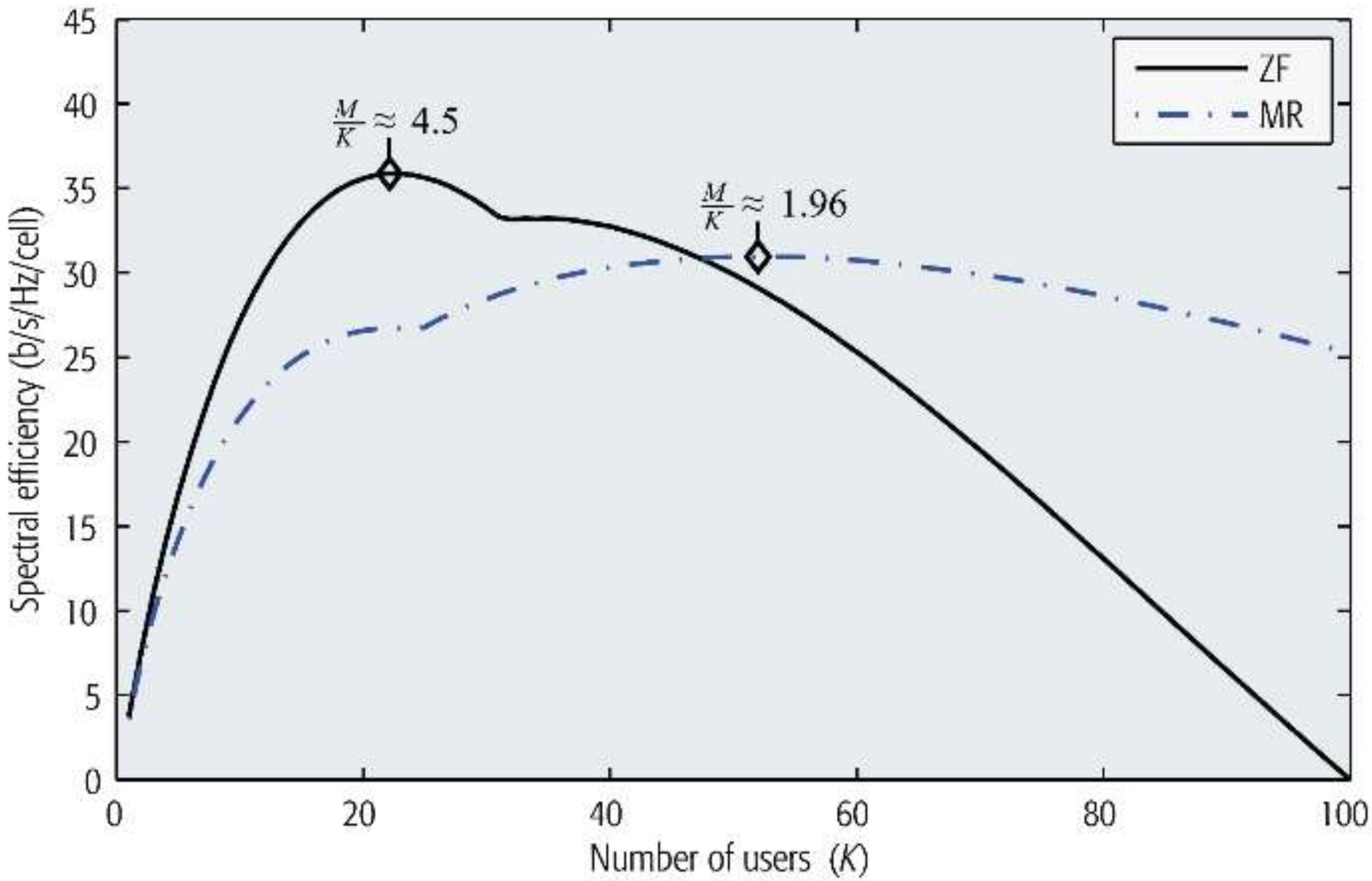
J. Hoydis et.al, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?" IEEE JSAC Feb. 2013.

How many users?

- Independent of # of antennas !
- Number of pilots
- Channel coherence time
- < Half of the frame (optimum rate)

- Coherence time? Small cell and indoor applications

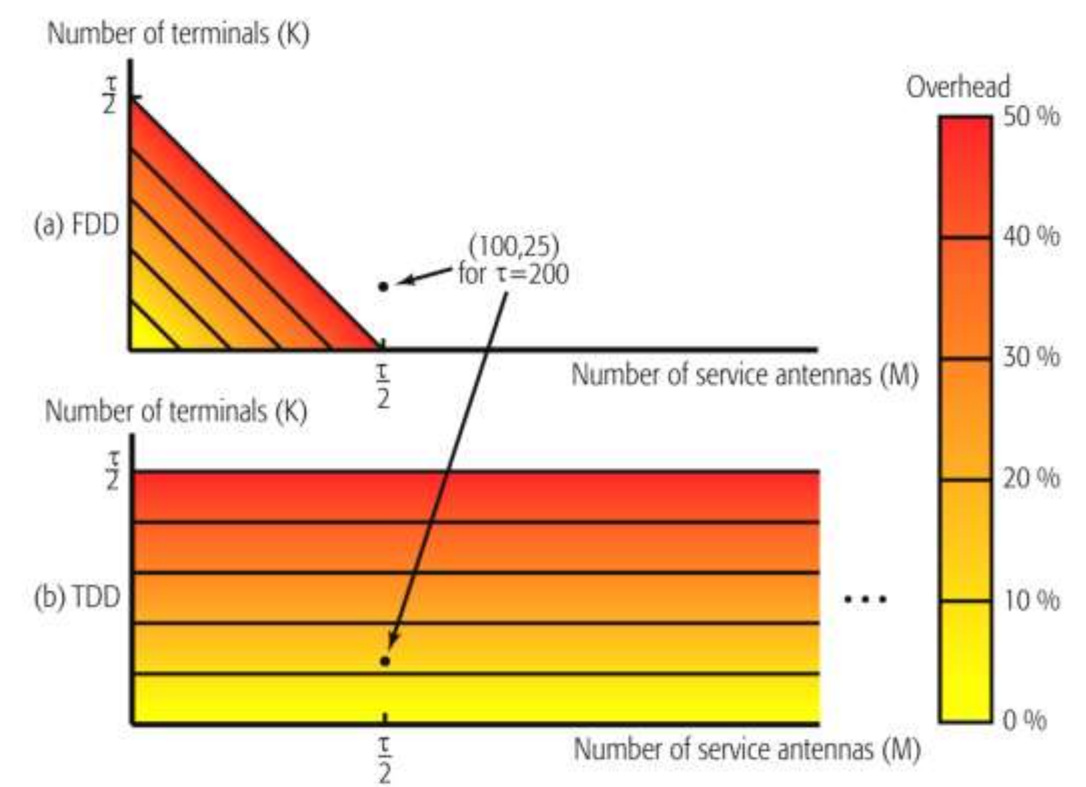
How many users ?



M= 100 Antennas

Emil Björnson, Erik G. Larsson, Thomas L. Marzetta, "Massive MIMO: Ten Myths and One Critical Question," IEEE Communications Magazine, vol. 54, no. 2, pp. 114-123, February 2016.

MaMIMO in FDD



FDD only in low-mobility and low-frequency scenarios

Emil Björnson, Erik G. Larsson, Thomas L. Marzetta, "Massive MIMO: Ten Myths and One Critical Question," IEEE Communications Magazine, vol. 54, no. 2, pp. 114-123, February 2016.

MaMIMO in FDD

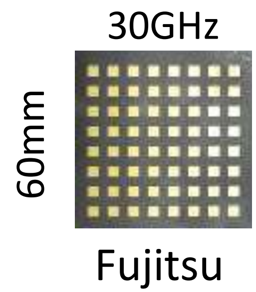
- Precoding based on partial CSI
  - Compresses Sensing
  - High correlation between antennas
  - No need for all CSI
  - Feedback only some CSI
- Channel reciprocity in FDD
  - Frequency correction algorithms
  - Based on DOA, Cov. Matrix , …

MaMIMO and Hetnets

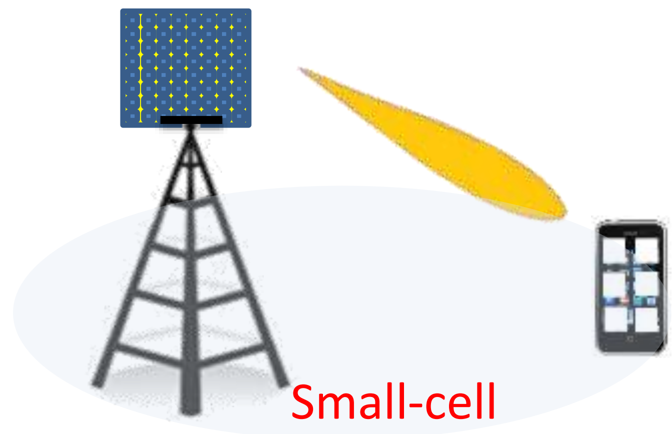
- Hetnet
- Improving spectral efficiency
- Energy efficiency
- Interference managements between MacroBS and Small BS
- Load balancing – user association
- Massive MIMO Backhauls for small cells

mmWave and MaMIMO

- mmWaves for massive MIMO
  - Shorter distances
  - Compact arrays



- Massive MIMO for mmWave
  - Compensating the path loss - Higher range

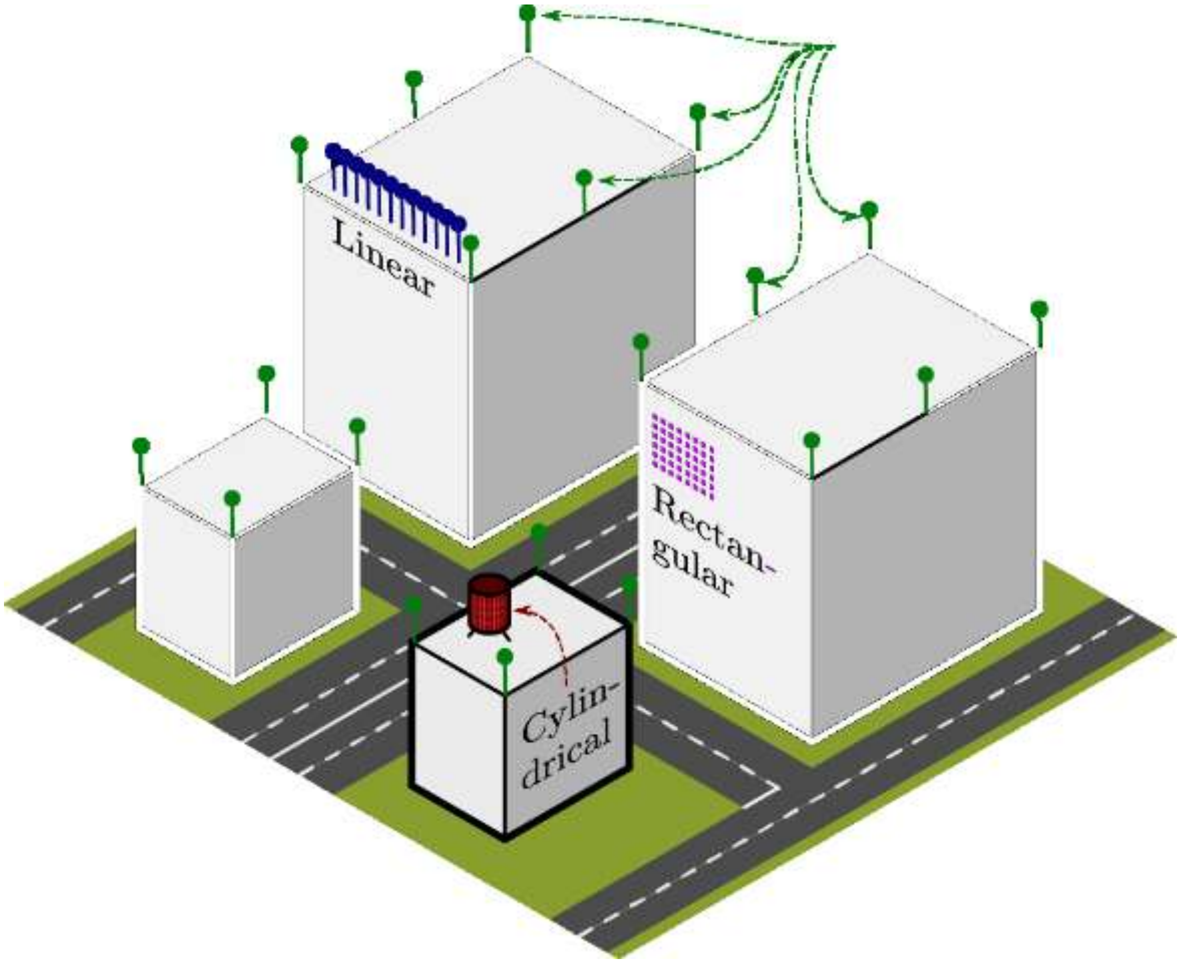


- LOS propagation and spatial multiplexing
- Higher Doppler shift and shorter coherence time

mmWave and MaMIMO

- mmWave is not necessary for MaMIMO
- f=2GHz (15cm)
- 400 dual-polarized antennas → in a 1.5 x 1.5 m array

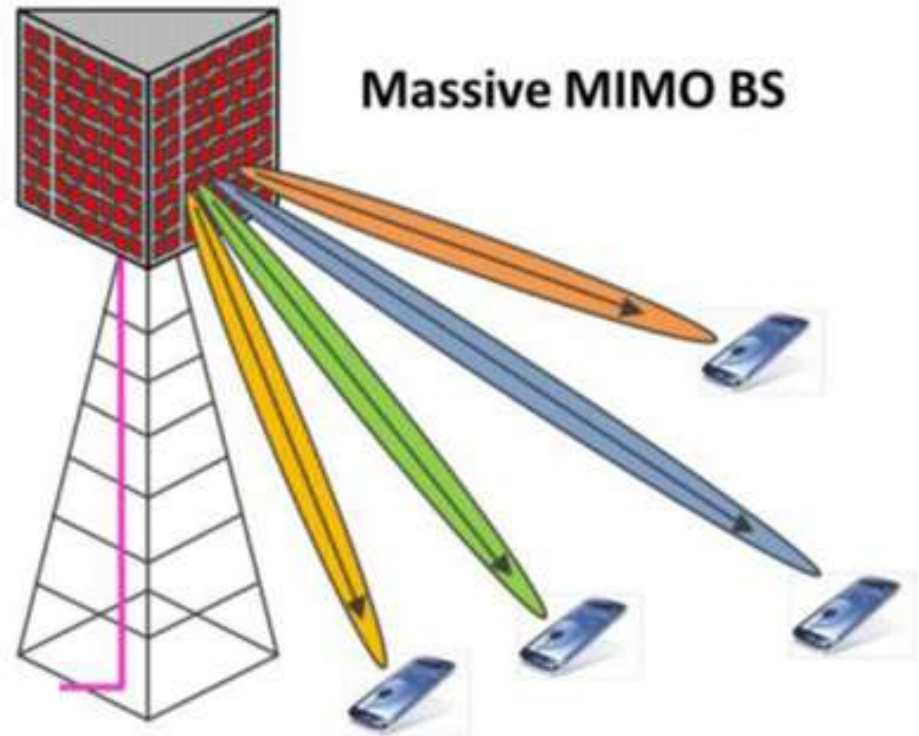
Massive MIMO Deployment



Emil Björnson, "Massive MIMO: Bringing the Magic of Asymptotic Analysis to Wireless Networks " , CAMAD, 2014

Full dimensional-MIMO and 3D Beamforming

- Two dimensional array - FD-MIMO
- Three dimensional beam-steering (elevation & azimuth): 3DBF
- Adaptive beamforming
- 3GPP Release 13 for LTE
- Massive MIMO
  - Very narrow beams
  - No inter-user Interference



Other Topics

- Non-orthogonal Multiple Access (NOMA)
- Filter Banks Multi-Carriers (FBMC)
- Full Duplex Communications
- Simultaneous Wireless Power and Information Transfer (SWIPT)
- Cognitive Radio

Massive MIMO Implementation and Testbeds

Practical Challenges

- Antenna array configuration
  - Mutual coupling
- Transceiver impairments
  - nonlinearities in amplifiers
  - Phase noise in local oscillators
  - quantization errors in analog-to-digital converters
  - I/Q imbalances in mixers
  - non-ideal analog filters

E. Bjornson *et al.*, "Massive MIMO Systems with Non-Ideal Hardware: Energy Efficiency, Estimation, and Capacity Limits," *IEEE Trans. Info. Theory*, vol. 60, no. 11, 2014.

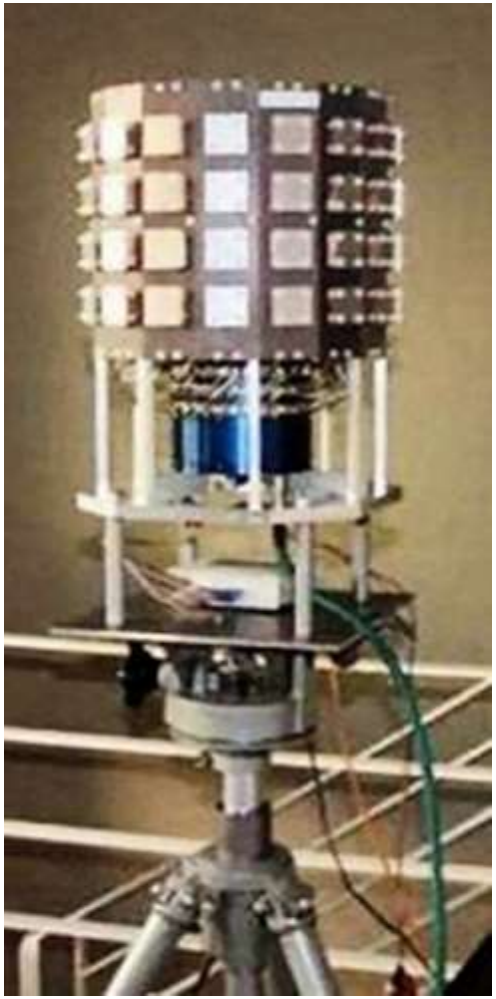
Practical Challenges

- High PAPR
- Low-cost power-efficient RF amplifiers
- Coherent processing
- Reciprocity calibration

E. Bjөrnson *et al.*, "Massive MIMO Systems with Non-Ideal Hardware: Energy Efficiency, Estimation, and Capacity Limits," *IEEE Trans. Info. Theory*, vol. 60, no. 11, 2014.

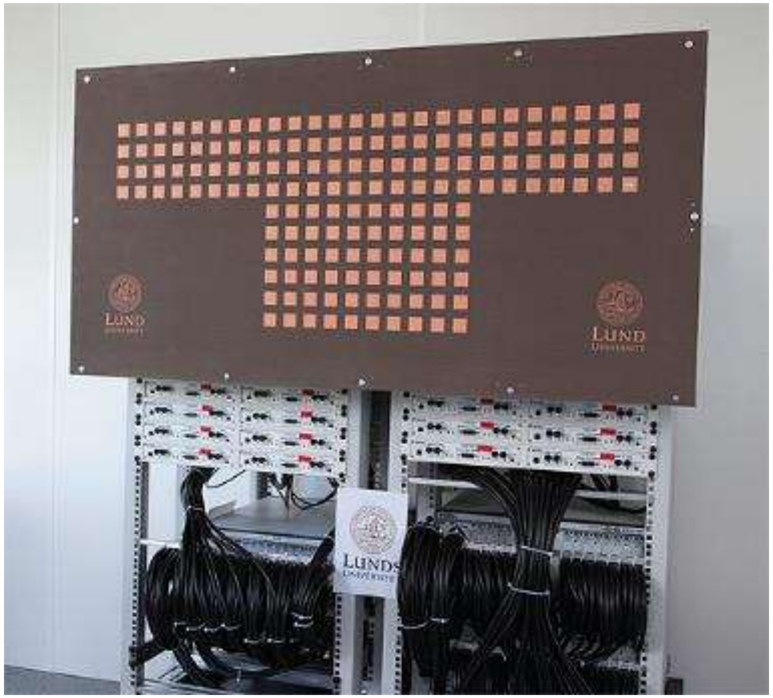
Experimental Results

- Cylindrical or linear antenna arrays
- 128 elements array
- 2.6 GHz and 50 MHz BW



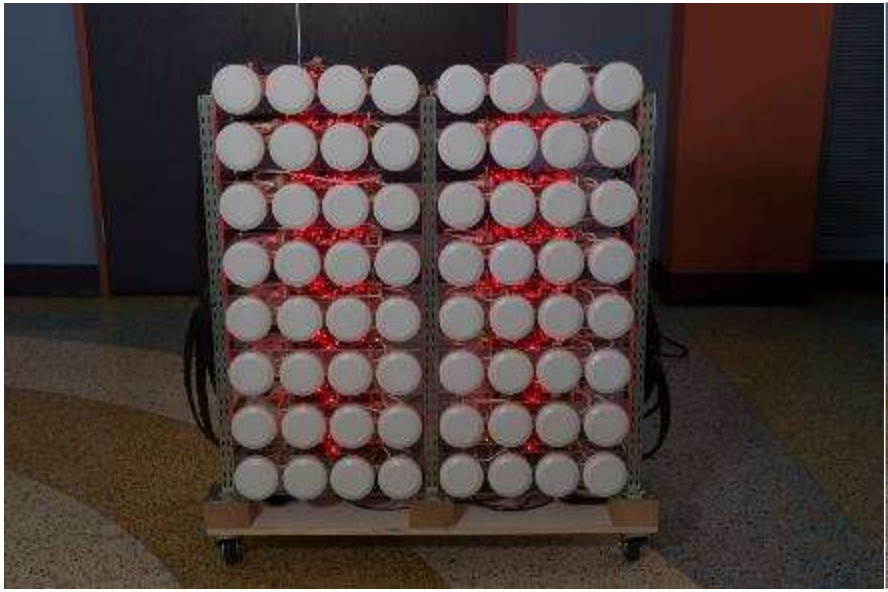
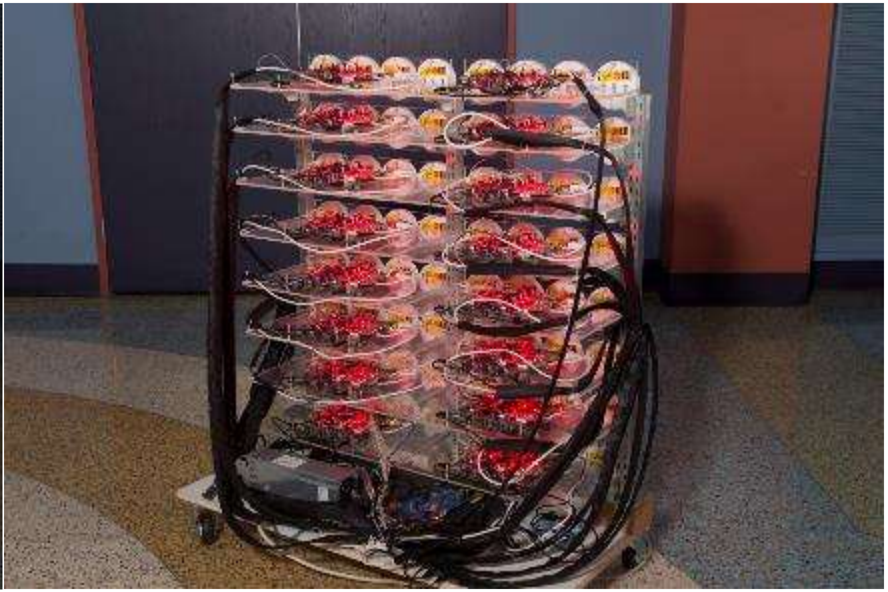
LuMaMI

- 160 dual-polarized patch antennas – 10 UEs
- 3.7 GHz, and the element spacing is 4 cm (half a wavelength)
- TDD



Argos

- Rice University

$2.4 million from the National Science Foundation (NSF)

Argos V2

- 96 Antennas (Scalable to 144 Antennas)
- TDD

C. Shepard, H. Yu, and L. Zhong, "ArgosV2: A flexible many-antenna research platform," in Proc. 2013 Annual International Conf. Mobile Comput. Netw.,2013.

Southeast University (SEU)

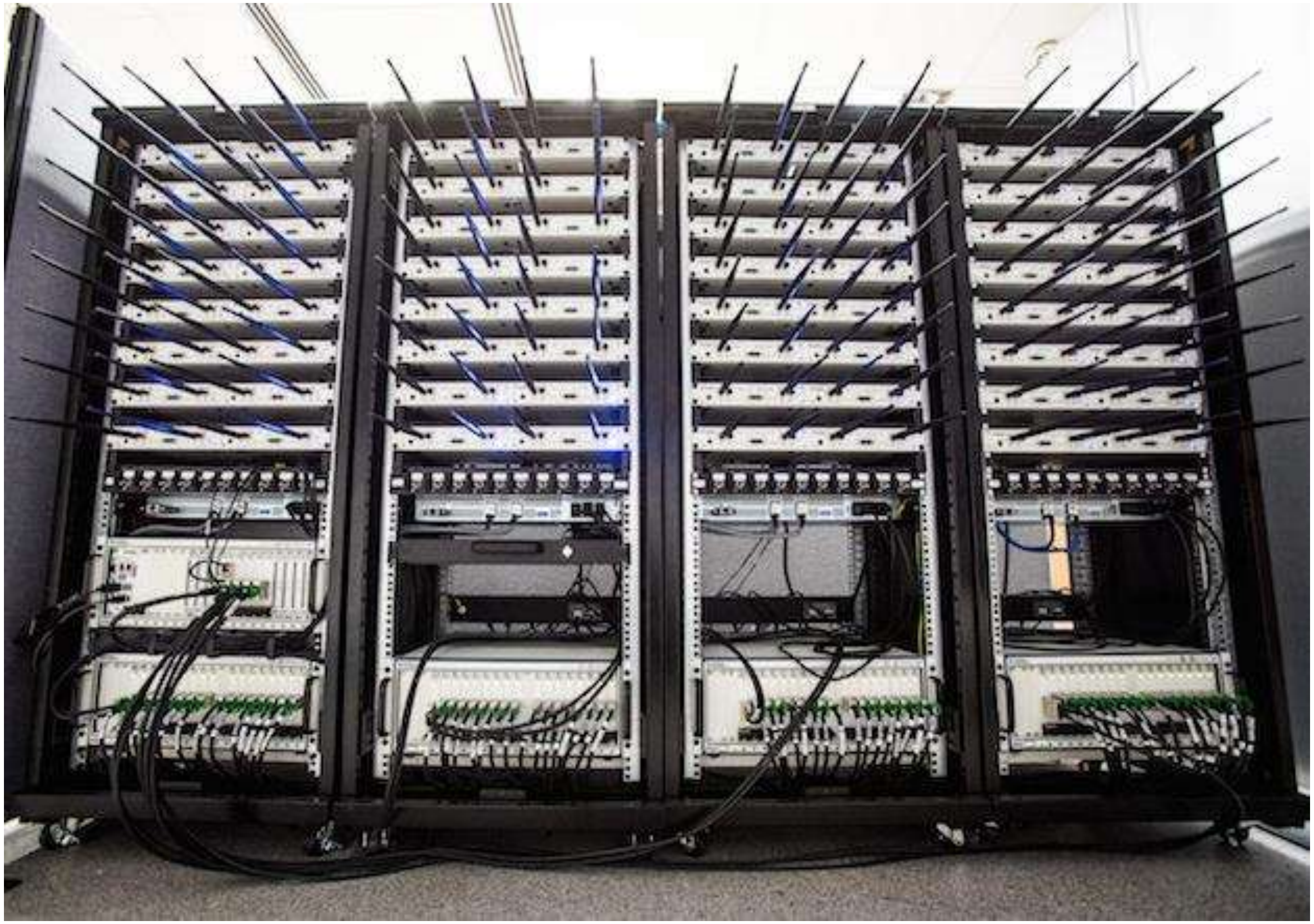
- 128 antenna base station
- 12 UEs
- 5.8 GHz
- 20 MHz

- The maximum spectral efficiency 80.64 bit/s/Hz
  - 12 single-antenna users with 256-QAM modulation
- 268.8 Mbps rate was achieved for eight single-antenna users using QPSK modulation

X. Yang , et.al. " Design and Implementation of a TDD-Based 128-Antenna Massive MIMO Prototyping System",2016

University of Bristol

- 128-antenna
- 12 UEs
- 3.5 GHz
- 20 MHz



OpenAirInterface Massive MIMO testbed

- Open source platform
- TDD based
- 64 elements
- 2.6GHz
- 5MHz bandwidth
- up to 4 commercial UEs

Massive MIMO, from Nokia and Mitsubishi

- 16X16

http://technical.ly/brooklyn/2015/04/10/wireless-future-demos-brooklyn-5g-summit/

Summary

- Challenges:
- Antenna array
- 3D channel modeling
- FDD operation
- Antenna calibration
- Pilot contamination
- Hardware and implementation challenges

Thank you

Questions?

www.mobilebroadband.ir