# Wireless Communications SSY135 – Lecture 11

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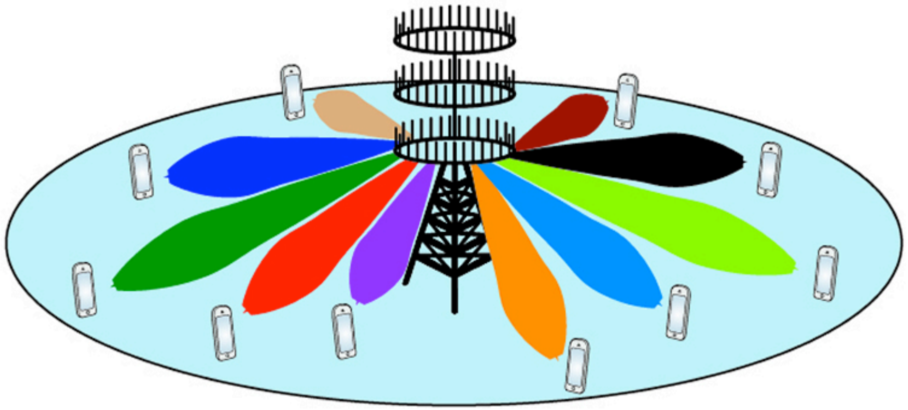


https://5g.co.uk/userfiles/images/massive-mimo.jpg

# Topics for today

- 5G key technologies
- MIMO capacity
- Multi-user MIMO
- Massive MIMO

5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice

Mansoor Shafi, *Life Fellow, IEEE*, Andreas F. Molisch, *Fellow, IEEE*, Peter J. Smith, *Fellow, IEEE*, Thomas Haustein, *Member, IEEE*, Peiying Zhu, *Senior Member, IEEE*, Prasan De Silva, *Member, IEEE*, Fredrik Tufvesson, *Fellow, IEEE*, Anass Benjebbour, *Senior Member, IEEE*, and Gerhard Wunder, *Senior Member, IEEE*

An Overview of Massive MIMO: Benefits and Challenges

Lu Lu, *Student Member, IEEE*, Geoffrey Ye Li, *Fellow, IEEE*, A. Lee Swindlehurst, *Fellow, IEEE*, Alexei Ashikhmin, *Senior Member, IEEE*, and Rui Zhang, *Member, IEEE*

Massive MIMO: Ten Myths and One Critical Question

Emil Björnson, Erik G. Larsson, and Thomas L. Marzetta

Suggested reading:
- Section 14.9
- The 3 listed papers

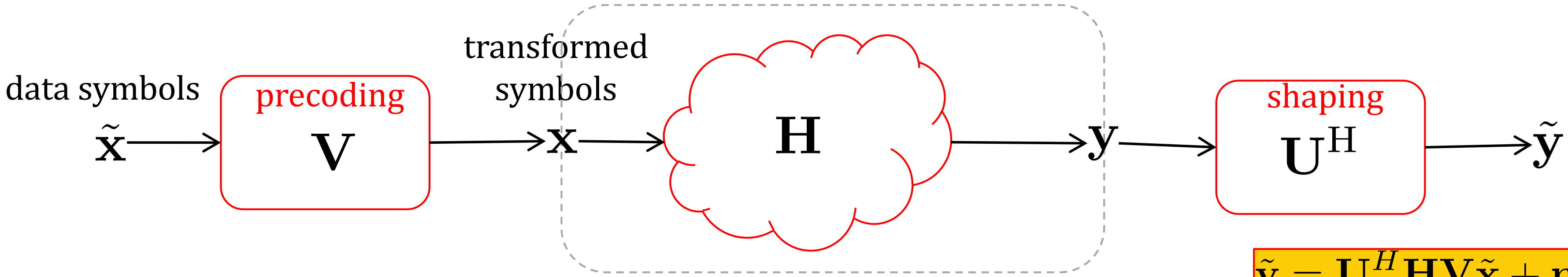
# Today's learning outcomes

At the end of this lecture, you must be able to

- Describe key characteristics of 5G
- Describe the difference between single-user MIMO and multi-user MIMO
- Express MU-MIMO in uplink and downlink as a standard MIMO
- Explain why in massive MIMO users have nearly orthogonal channels and why this is useful
- Describe what pilot contamination is

# Last time: Narrowband MIMO

- Observation model $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$
- **CSIR**: ML, ZF, MMSE
- **CSIT**: SVD creates spatial streams. You choose how many stream by zeroing entries in $\tilde{\mathbf{x}}$
- SVD: $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\mathrm{H}}$




$$\begin{aligned}\tilde{\mathbf{y}} &= \mathbf{U}^H\mathbf{H}\mathbf{V}\tilde{\mathbf{x}} + \mathbf{n}\\ &= \mathbf{U}^H\mathbf{U}\mathbf{\Sigma}\mathbf{V}^H\mathbf{V}\tilde{\mathbf{x}} + \mathbf{n}\end{aligned}$$

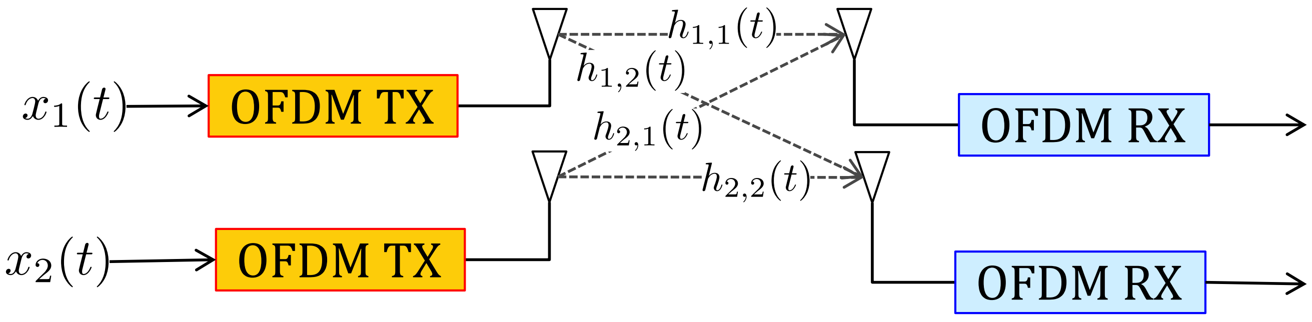
$$\mathbf{\Sigma} = \mathrm{diag}[\sigma_1, \sigma_2, \ldots, \sigma_{R_H}, 0, \ldots, 0]$$

$$\sigma_1 \geq \sigma_2 \ldots \geq \sigma_{R_H}$$

$$\tilde{y}_k = \sigma_k \tilde{x}_k + n_k, \sigma_k \geq 0, k \in \{1, \ldots, \min(M_t, M_r)\}$$

# Last time: Wideband MIMO

- MIMO can be combined with OFDM for frequency selective channels




- Narrowband MIMO model per subcarrier

$$\underbrace{\mathbf{z}_k}_{M_r \times 1} = \underbrace{\mathbf{H}_k}_{M_r \times M_t} \underbrace{\mathbf{x}_k}_{M_t \times 1} + \mathbf{n}_k$$

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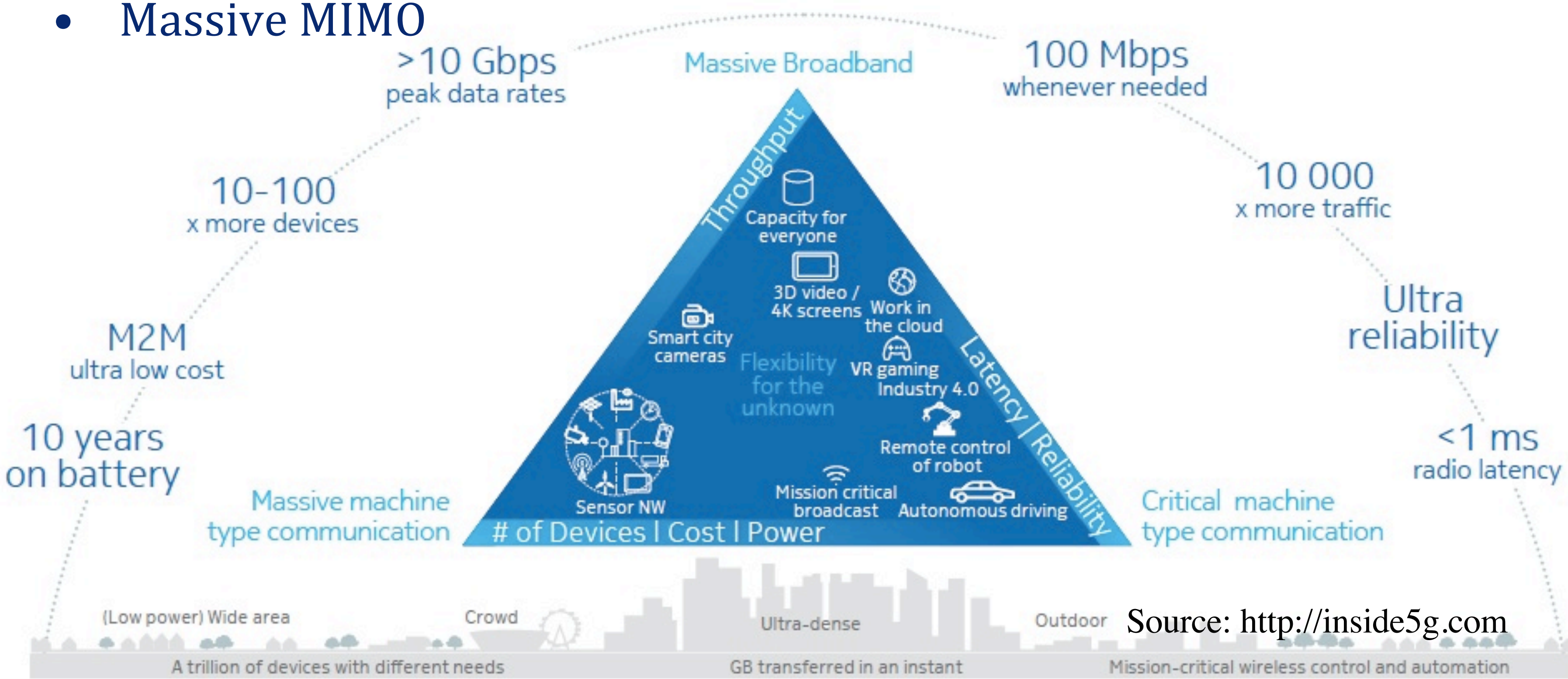


Source: http://inside5g.com

# 5G requirements and use cases

- **Use cases**: enhanced mobile broadband (eMBB), ultra reliable low latency communications (URLLC), massive machine type communications (MMTC)

MINIMUM TECHNICAL PERFORMANCE REQUIREMENTS OF IMT 2020

| KPI | Key Use Case | Values |
|---|---|---|
| Peak Data Rate | eMBB | DL: 20 Gbps, UL: 10 Gbps |
| Peak Spectral Efficiency | eMBB | DL: 30 bps/Hz, UL: 15 bps/Hz |
| User Experienced Data Rate | eMBB | DL: 100 Mbps, UL: 50 Mbps (Dense Urban) |
| 5% User Spectral Efficiency | eMBB | DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (Indoor Hotspot); DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (Dense Urban); DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (Rural) |
| Average Spectral Efficiency | eMBB | DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (Indoor Hotspot); DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (Dense Urban); DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (Rural) |
| Area Traffic Capacity | eMBB | DL: 10 Mbps/m$^2$ (Indoor Hotspot) |
| User Plane Latency | eMBB, URLLC | 4 ms for eMBB and 1 ms for URLLC |
| Control Plane Latency | eMBB, URLLC | 20 ms for eMBB and URLLC |
| Connection Density | mMTC | 1,000,000 devices/km$^2$ |
| Energy Efficiency | eMBB | Capability to support high sleep ratio and long sleep duration to enable low energy consumption when there is no data |
| Reliability | URLLC | $1–10^{-5}$ success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge |
| Mobility | eMBB | Up to 500 km/h |
| Mobility Interruption Time | eMBB, URLLC | 0 ms |
| Bandwidth | eMBB | At least 100 MHz; Up to 1 GHz for operation in higher frequency bands (e.g., above 6 GHz) |



Source: “5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice”

# 5G: how do we meet these requirements?

## Technological enablers

- **More bandwidth:** carriers above 24 GHz have > 1GHz bandwidth

Millimeter wave

- **More antennas:** equip base stations with 100s of antennas

Massive MIMO

- **More base stations:** shorter distance to user

Femtocells

- **New signals, new codes:** short packets

Polar codes

- Device to device communication, network slicing, …

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# Capacity of the MIMO channel

^Narrowband model, assumes OFDM
*CSIT = channel state information at transmitter

- Model $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \mathbb{E}\{\mathbf{x}\mathbf{x}^{\mathrm{H}}\} = \mathbf{R}_{\mathbf{x}}, \mathrm{tr}(\mathbf{R}_{\mathbf{x}}) = \rho, \mathbb{E}\{\mathbf{n}\mathbf{n}^{\mathrm{H}}\} = \mathbf{I}_{M_r}$
- Channel: $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\mathrm{H}}$ with $\mathbf{\Sigma} = \mathrm{diag}(\sigma_1, \sigma_2, \ldots, \sigma_{R_H}, 0, \ldots, 0)$
- Channel capacity for fixed channel (without proof)

$$C = \max_{\mathbf{R}_{\mathbf{x}}:\mathrm{Tr}(\mathbf{R}_{\mathbf{x}})=\rho} B \log_2 \det[\mathbf{I}_{M_r} + \mathbf{H}\mathbf{R}_{\mathbf{x}}\mathbf{H}^H],$$

- Channel unknown at the transmitter (no CSIT): $\mathbf{R}_{\mathbf{x}} = \rho/M_t \mathbf{I}_{M_t}$

$$\mathbf{H}\mathbf{H}^H = \mathbf{U}^H \Sigma \mathbf{V}^H \mathbf{V} \Sigma \mathbf{U} = \mathbf{U}^H \Sigma^2 \mathbf{U}$$

$$C = B \log_2 \det(\mathbf{I}_{M_r} + \frac{\rho}{M_t}\mathbf{U}^H \Sigma^2 \mathbf{U}) = B \log_2 \det(\mathbf{I}_{M_r} + \frac{\rho}{M_t}\Sigma^2)$$

$$= B \log_2 \left( \prod_{i=1}^{M_r} (1 + \frac{\rho}{M_t}\sigma_i^2) \right) = B \sum_{i=1}^{R_H} \log_2 (1 + \frac{\rho}{M_t}\sigma_i^2)$$

- Channel known at the transmitter (CSIT): waterfilling over parallel channels

$$C = \max_{\rho_i : \sum_i \rho_i \leq \rho} \sum_{i=1}^{R_{\mathbf{H}}} B \log_2 (1 + \sigma_i^2 \rho_i),$$

- Capacity for fading channel is random: average capacity / outage capacity.

# What is best possible and worst possible channel?

- General expression

$$C = B\sum_{i=1}^{R_H}\log_2\left(1+\frac{\rho\sigma_i^2}{M_t}\right)$$

- Suppose $\mathrm{trace}(\mathbf{\Sigma}^2) = M_r M_t$ (channel has fixed energy)
- **LOS:** 1 non-zero singular value with large energy. Capacity:

$$B\log_2\left(1+\rho M_r\right)$$

- **Rich NLOS:** Mr Mt equal singular values with small energy. Capacity:

$$B\min(M_r, M_t)\log_2\left(1+\frac{\rho\max(M_r, M_t)}{M_t}\right)$$

- General case:

$$B\log_2\left(1+\rho M_r\right) \leq C \leq B\boxed{\min(M_r, M_t)}\log_2\left(1+\frac{\rho\max(M_r, M_t)}{M_t}\right)$$

- Rich scattering is preferred: linear capacity scaling with number of antennas!

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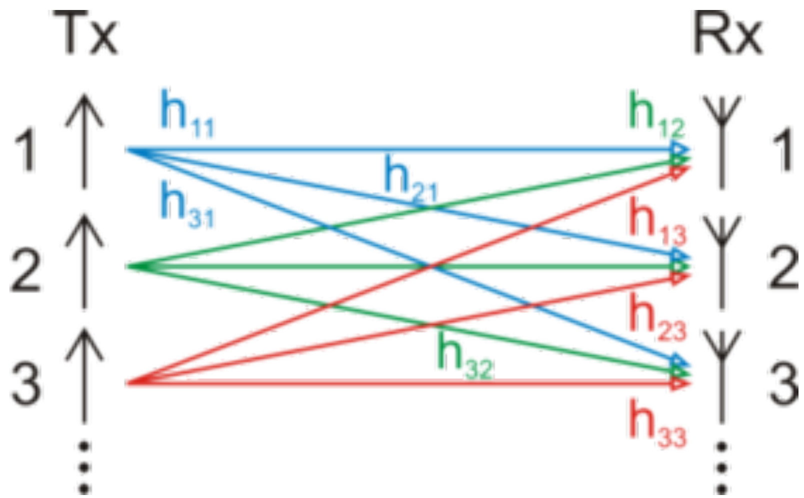




https://en.wikipedia.org/wiki/MIMO

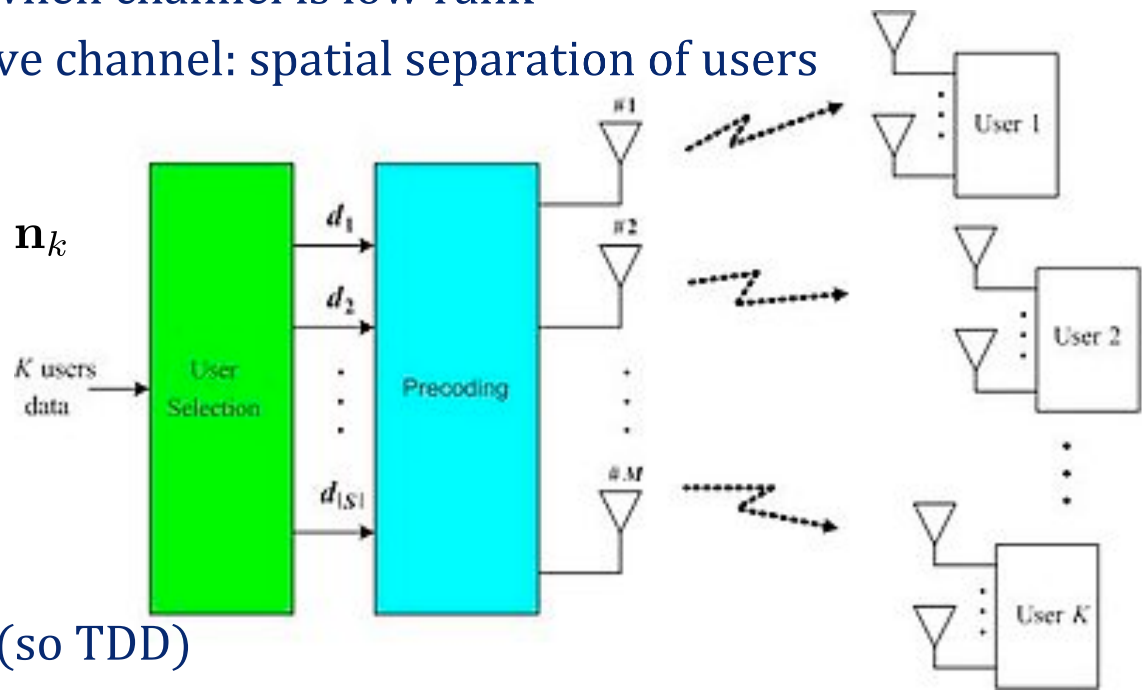
# Multi-user MIMO: creating rich channels

- Benefits from MIMO are low when channel is low rank
- MU-MIMO creates rich effective channel: spatial separation of users
- Downlink

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{H}_k \sum_{k' \neq k}^{K} \mathbf{x}_{k'} + \mathbf{n}_k$$

- Uplink

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{H}_k^T \mathbf{x}_k + \mathbf{n}$$




Source: wikipedia

- Assumes channel reciprocity (so TDD)
- Uplink is "standard MIMO": multiuser detector, no CSIT needed

$$\mathbf{y} = \underbrace{\left[\begin{array}{cccc} \mathbf{H}_1^T & \mathbf{H}_2^T & \ldots & \mathbf{H}_K^T \end{array}\right]}_{M_r \text{ x } (KM_t) \text{ matrix}} \left[\begin{array}{c} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \ldots \\ \mathbf{x}_K \end{array}\right] + \mathbf{n}$$

# Multi-user MIMO downlink

- Without CSIT: different users in different time slots ☹
- With CSIT: multi-user precoding. All the users at the same time ☺

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{H}_k \sum_{k' \neq k}^{K} \mathbf{x}_{k'} + \mathbf{n}_k = \mathbf{H}_k \mathbf{W}_k \mathbf{s}_k + \mathbf{H}_k \sum_{k' \neq k}^{K} \mathbf{W}_{k'} \mathbf{s}_{k'} + \mathbf{n}_k$$

- Consider a case with 1 antenna per user, so 1 stream per user

$$y_k = \mathbf{h}_k^T \mathbf{w}_k s_k + \mathbf{h}_k^T \sum_{k' \neq k}^{K} \mathbf{w}_{k'} s_{k'} + n_k$$

Data $s_k$, precoding matrix $W_k$ (here a $N_t$ x 1 vector)

- Considering all vectors for all users $\mathbf{y} = \mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{n}$

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_K \end{bmatrix} = \begin{bmatrix} \mathbf{h}_1^T \\ \mathbf{h}_2^T \\ \cdots \\ \mathbf{h}_K^T \end{bmatrix} \begin{bmatrix} \mathbf{w}_1 & \mathbf{w}_2 & \cdots & \mathbf{w}_K \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \cdots \\ s_K \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \cdots \\ n_K \end{bmatrix}$$

- W designed to optimize a performance criterion, e.g., MMSE, zero-forcing
- K and the best K users can be selected out of large set to have good **H** (user scheduling). Precoding also possible with statistical CSI.

# MU-MIMO precoding

- K users with 1 antenna, 1 BS with M antennas, channel **H**: K x M
- ZF precoding $\mathbf{W} = \mathbf{H}^{\dagger} = \mathbf{H}^H(\mathbf{H}\mathbf{H}^H)^{-1}$ may lead to too high TX power
- We want to enforce total power

$$\|\mathbf{W}\|^2 = \mathrm{trace}(\mathbf{W}^H\mathbf{W}) = P_{tot}$$

- Scale the entire precoding matrix: equal SNR per user

- Or simply scale each column to have fixed power (different SNR per user)
- Adjust power $\mathbf{H}^{\dagger}\underbrace{\mathrm{diag}[\sqrt{p_1},\ldots,\sqrt{p_K}]}_{\mathbf{D}_p^{1/2}}\mathbf{s}$

$$\max_{\mathbf{p}} \quad f(\mathbf{p})$$

$$s.t. \quad \sum_{k=1}^{K} p_k[(\mathbf{H}^{\dagger})^H\mathbf{H}^{\dagger}]_{k,k} = P_{tot}$$

Waterfilling!

- But: why does SVD not work?

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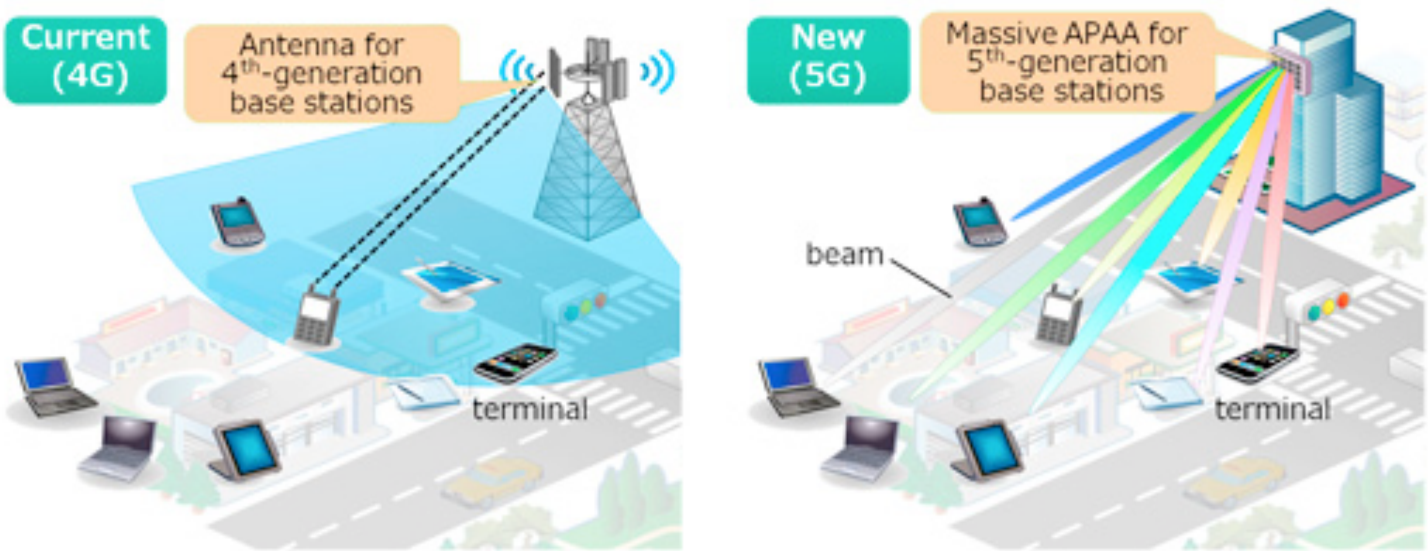
# MU-MIMO and massive MIMO

- MU-MIMO
  - Multiple antennas may be costly for user device
  - Gains are modest due to limited number of antennas (less than 10)
  - Signal processing is complex
- Massive MIMO
  - 1 antenna per user
  - 100s of antennas at the BS




Source: http://www.ni.com

# MIMO Capacity "favorable channels"

$$\mathbf{R_x} = \rho/M_t \mathbf{I}_{M_t}$$

$$C = \max_{\mathbf{R_x}:\mathrm{Tr}(\mathbf{R_x})=\rho} B \log_2 \det[\mathbf{I}_{M_r} + \mathbf{H}\mathbf{R_x}\mathbf{H}^H],$$

- Capacity bounds (no CSIT)

$$B \log_2 (1+\rho M_r) \leq C \leq B \min(M_r, M_t) \log_2 \left(1 + \frac{\rho \max(M_r, M_t)}{M_t}\right)$$

- Case 1: Very large number of *transmit* antennas, CN(0,1) entries

$\mathbf{H} =$ Almost orthogonal rows

$\mathbf{H}\mathbf{H}^H \approx M_t \mathbf{I}_{M_r}$ Small

"Number of users"

$$C = B \log_2 \det \left(\mathbf{I}_{M_r} + \frac{\rho}{M_t} \mathbf{I}_{M_r} M_t\right) = B M_r \log_2 (1+\rho)$$

- Case 2: Very large number of *receive* antennas, CN(0,1) entries

$\mathbf{H} =$ Almost orthogonal columns

$\mathbf{H}^H \mathbf{H} \approx M_r \mathbf{I}_{M_t}$ small

$$\det(I + \boldsymbol{A}\boldsymbol{A}^{\mathrm{H}}) = \det(I + \boldsymbol{A}^{\mathrm{H}}\boldsymbol{A}),$$

$$C = B M_t \log_2 (1 + \rho M_r / M_t)$$

"Number of users"

Massive MIMO can reach upper bound under orthogonal channels ("favorable propagation conditions")

# Massive MIMO – multi-user

- 1 base station with M antennas, K<<M users with 1 antenna
- Users should be sufficiently separated to have favorable prop. conditions
- MU-MIMO with channel reciprocity, nearly orthogonal channels
- **Uplink channel:** D is path loss

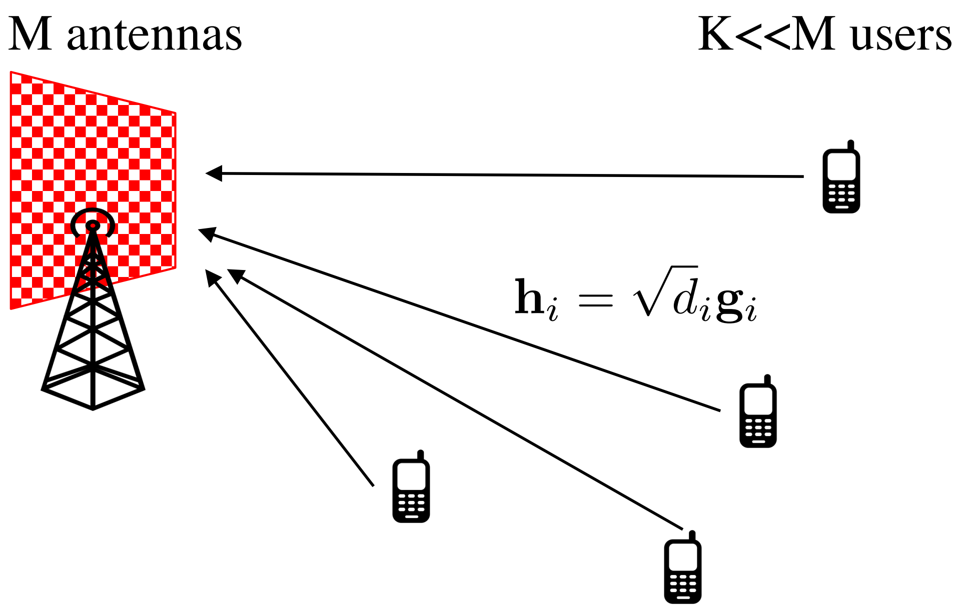
$$\mathbf{H} = \underbrace{\mathbf{G}}_{M\times K}\underbrace{\mathbf{D}^{1/2}}_{K\times K}$$

$$\mathbf{G}^H\mathbf{G} \approx M\mathbf{I}_K$$

- **Downlink channel:**

$$\mathbf{H}^T = \underbrace{\mathbf{D}^{1/2}}_{K\times K}\underbrace{\mathbf{G}^T}_{K\times M}$$

$$\mathbf{G}^T\mathbf{G}^* \approx M\mathbf{I}_K$$



# Massive MIMO – Uplink

- Observation model: $\mathbf{y} = \mathbf{Hx} + \mathbf{n} = \mathbf{GD}^{1/2}\mathbf{x} + \mathbf{n}$
- Property: $\mathbf{H}^H\mathbf{H} = \mathbf{D}^{1/2}\mathbf{G}^H\mathbf{G}\mathbf{D}^{1/2} = \mathbf{D}^{1/2}M\mathbf{I}_K\mathbf{D}^{1/2} = M\mathbf{D}$
- So base station can apply the following shaper / combiner

$$\mathbf{z} = \mathbf{H}^H\mathbf{y} = \mathbf{H}^H\mathbf{Hx} + \mathbf{H}^H\mathbf{n} = M\mathbf{Dx} + \mathbf{w}, \qquad \mathbf{w} \sim \mathcal{CN}(\mathbf{0}, N_0 M\mathbf{D})$$

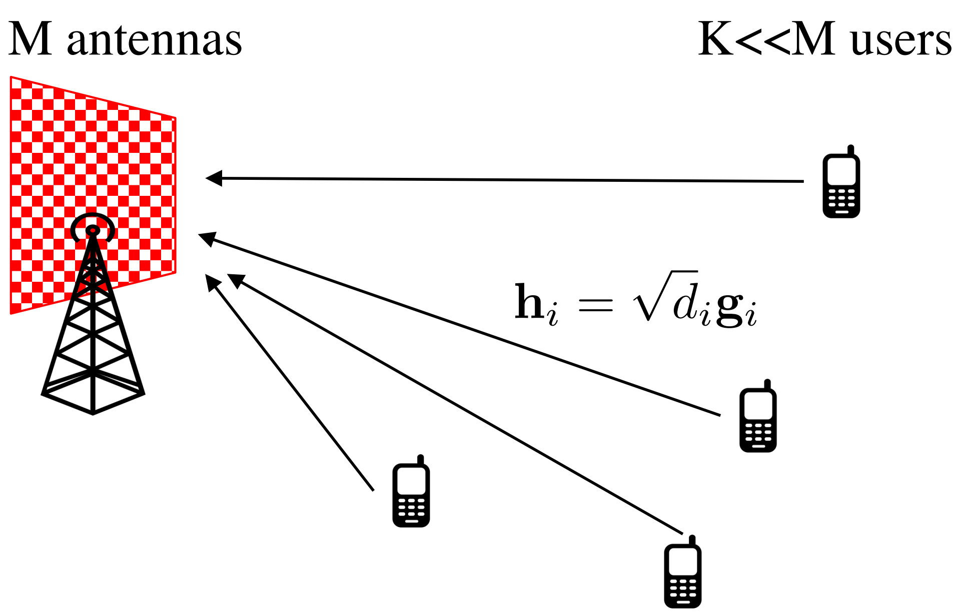
$$z_k = M d_k x_k + w_k, w_k \sim \mathcal{CN}(0, N_0 M d_k)$$

$$\mathrm{SNR}_k = M d_k E_x / N0$$

$$R_k = B \log_2\left(1 + \frac{M d_k E_x}{N_0}\right)$$

$$R_{\mathrm{sum}} = B \sum_{k=1}^{K} \log_2\left(1 + \frac{M d_k E_x}{N_0}\right)$$

Uplink: matched filter is asymptotically optimal!



# Massive MIMO – Downlink

- Observation model, with M x K precoding matrix $\mathbf{y} = \mathbf{H}^T\mathbf{W}\mathbf{s} + \mathbf{n}$
- We choose precoding of the form $\mathbf{W} = \mathbf{H}^*\mathbf{D}_p^{1/2}/\sqrt{M}$
- Power allocation $\mathbf{D}_p$ to ensure $\|\mathbf{W}\|^2 = \mathrm{trace}(\mathbf{W}^H\mathbf{W}) = P_{tot}$
- We find that $\mathbf{W}^H\mathbf{W} = \mathbf{D}_p^{1/2}\mathbf{H}^T\mathbf{H}^*\mathbf{D}_p^{1/2}/M = \mathbf{D}_p^{1/2}\mathbf{D}\mathbf{D}_p^{1/2} = \mathbf{D}_p\mathbf{D}$

- Observation

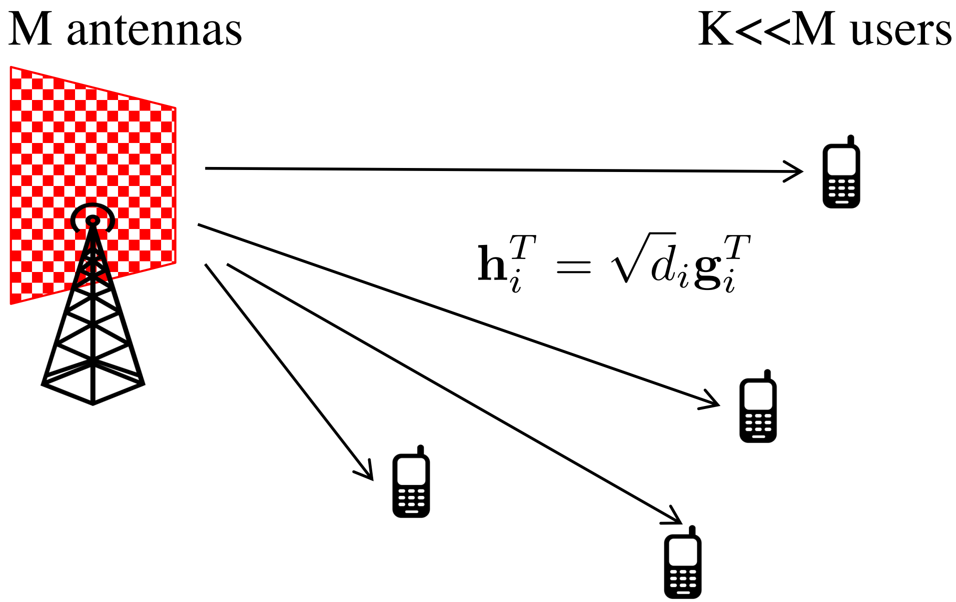
$$\begin{aligned}\mathbf{y} &= \mathbf{H}^T\mathbf{W}\mathbf{s} + \mathbf{n}\\ &= \mathbf{H}^T\mathbf{H}^*\mathbf{D}_p^{1/2}/\sqrt{M}\mathbf{s} + \mathbf{n}\\ &= \sqrt{M}\mathbf{D}^{1/2}\mathbf{D}_p^{1/2}\mathbf{s} + \mathbf{n}\end{aligned}$$

Diagonal with powers (see: MU-MIMO precoding)

- At user k:

$$y_k = \sqrt{Md_k}\sqrt{[\mathbf{D}_p]_{k,k}}s_k + n_k$$

$$\mathrm{SNR}_k = Md_k[\mathbf{D}_p]_{k,k}E_{s,k}/N_0$$




**Downlink: matched filter linear precoder is asymptotically optimal!**

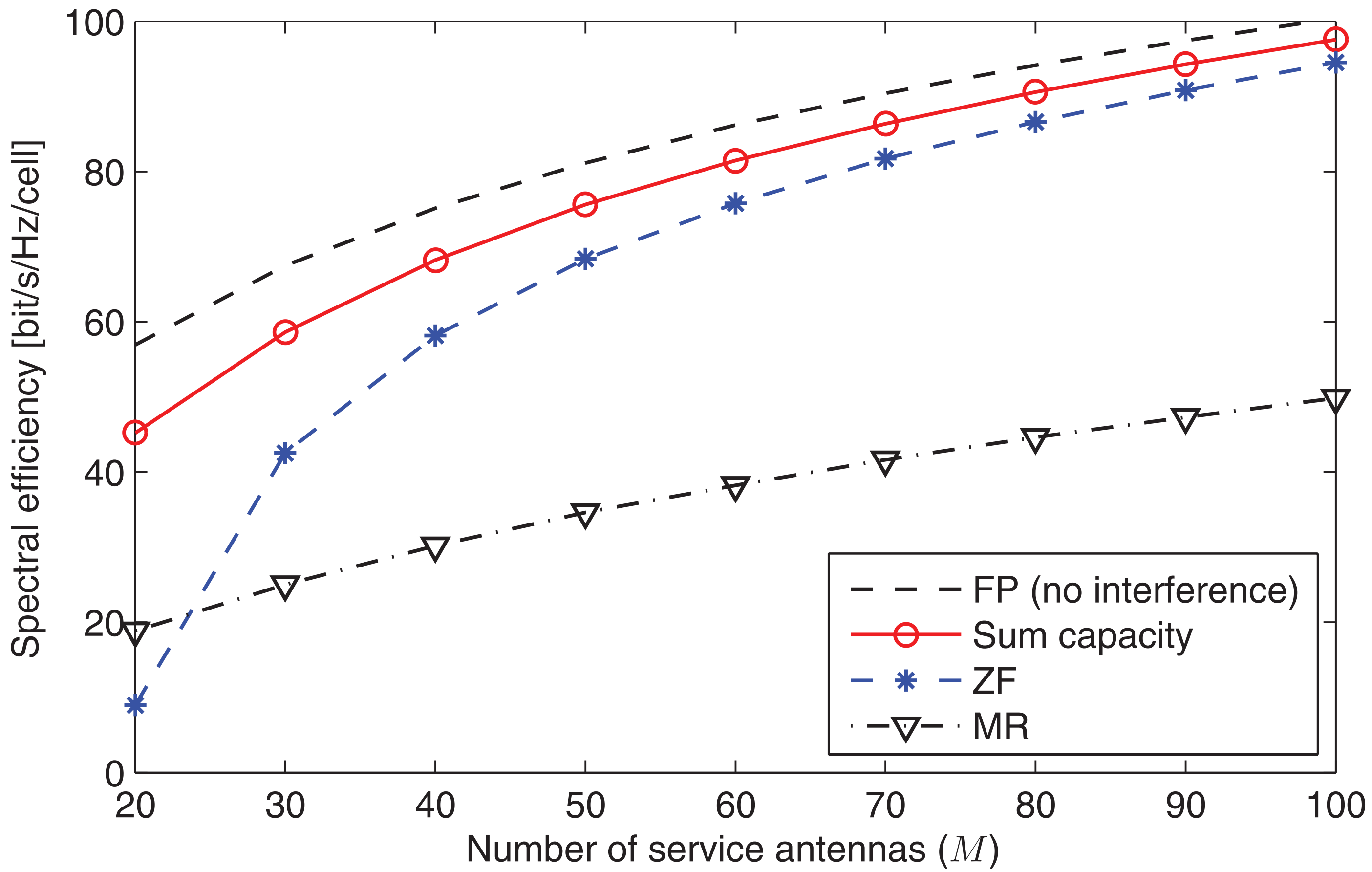
# Massive MIMO – multi-user

- **Uplink:** under favorable propagation conditions, no CSIT needed, linear combiner (in practice: maximum ratio, ZF, MMSE). Leads to optimal sum-rate, same as under full collaboration of the users. No inter-user interference.
- **Downlink:** under favorable propagation conditions, CSIT needed, simple precoder (in practice: maximum ratio, ZF, MMSE), leads to optimal sum-rate. No inter-user interference.

- Simple processing at user and base station
- Optimal in terms of sum-rate
- Interference vanishes
- Users served at the same time

- Hardware cost and power consumption at base station
- CSIT needed at base station
- Favorable propagation conditions required

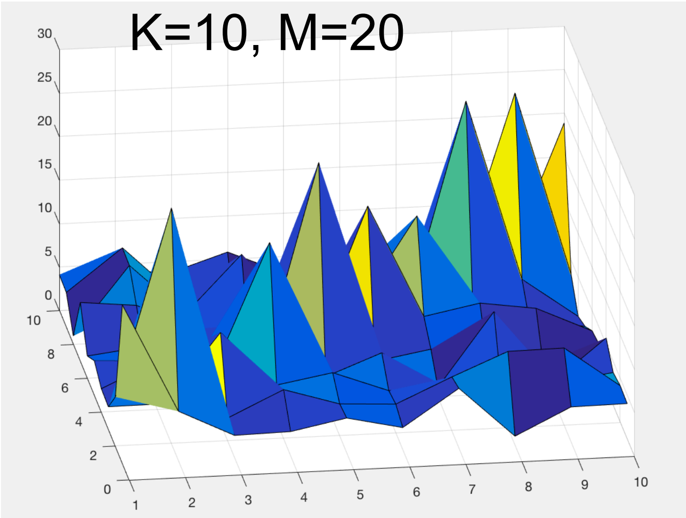
# Performance of massive MIMO

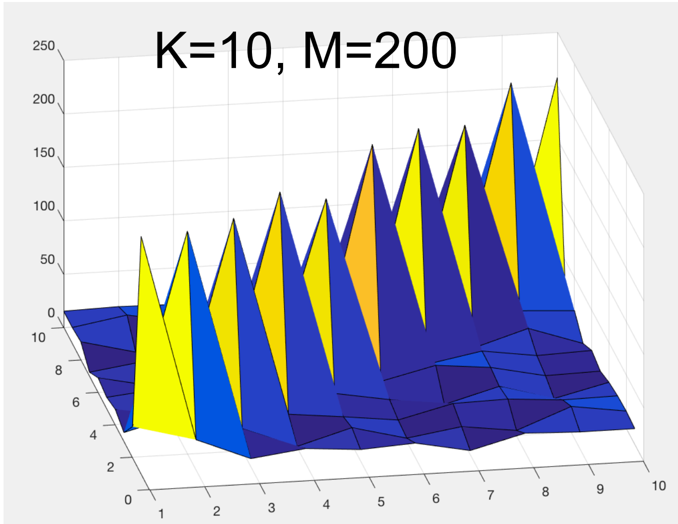



Source: Massive MIMO:
Ten Myths and One Critical Question

# Massive MIMO – "favorable propagation conditions" in NLOS

- We need orthogonal columns of uplink channel matrix $\mathbf{H}^H\mathbf{H} \approx M\mathbf{I}_K$
- Rayleigh fading: entries from CN(0,1)



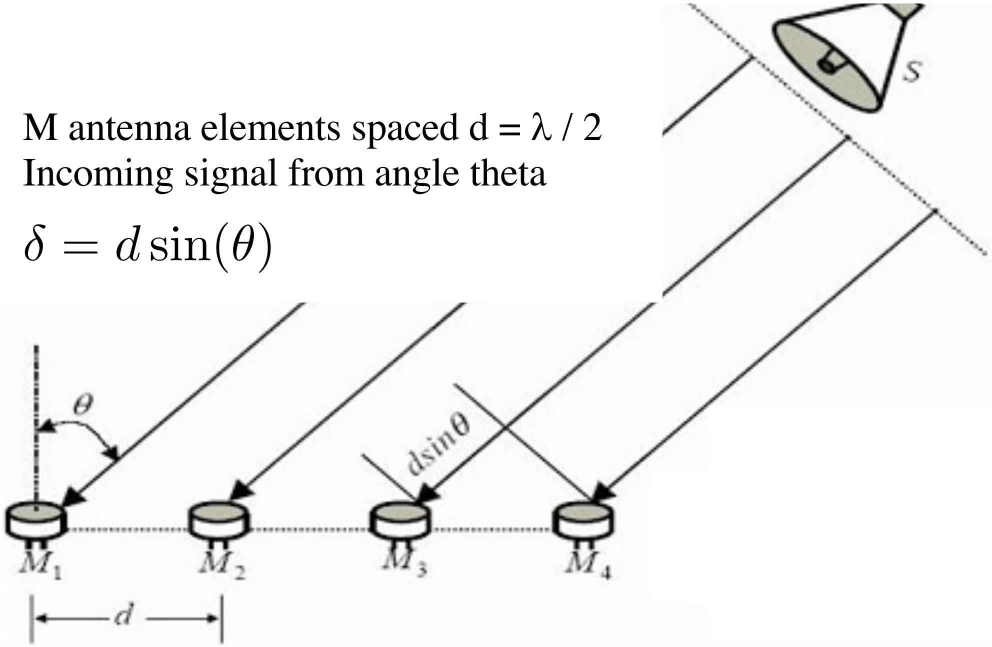

- Scaling of off-diagonal elements can be computed

# Massive MIMO – “favorable propagation conditions” in LOS

- Relies on geometry of the array, far field conditions

M antenna elements spaced d = λ / 2
Incoming signal from angle theta

$$\delta = d\sin(\theta)$$




Received passband signals:

$$\begin{aligned} r_0(t) &= \Re\{As(t-\tau)\exp(j2\pi f_c(t-\tau))\} \\ &= \Re\{gs(t)\exp(j2\pi f_c t)\} \\ r_1(t) &= \Re\{gs(t-\delta/c)\exp(j2\pi f_c(t-\delta/c))\} \\ &\approx \Re\{gs(t)\exp(j2\pi f_c t)\exp(-j2\pi f_c \delta/c)\} \end{aligned}$$

Received baseband signals:

$$y_m(t) = gs(t)\exp(-j2\pi\delta m/\lambda), m = 0, \ldots, M-1$$

$$\mathbf{y} = \mathbf{h}s + \mathbf{n}$$

- Channel (with $g_k$ being a complex number, same for all antenna elements)

$$\mathbf{h}_k = g_k[1 \; e^{-j2\pi d\sin(\theta_k)/\lambda} \; e^{-j4\pi d\sin(\theta_k)/\lambda} \ldots e^{-j2(M-1)\pi d\sin(\theta_k)/\lambda}]$$

$$\theta_l \neq \theta_k \Rightarrow \mathbf{h}_k^H \mathbf{h}_l \approx 0$$

- Allows beaming in specific directions (d = lambda / 2)

# LOS orthogonality

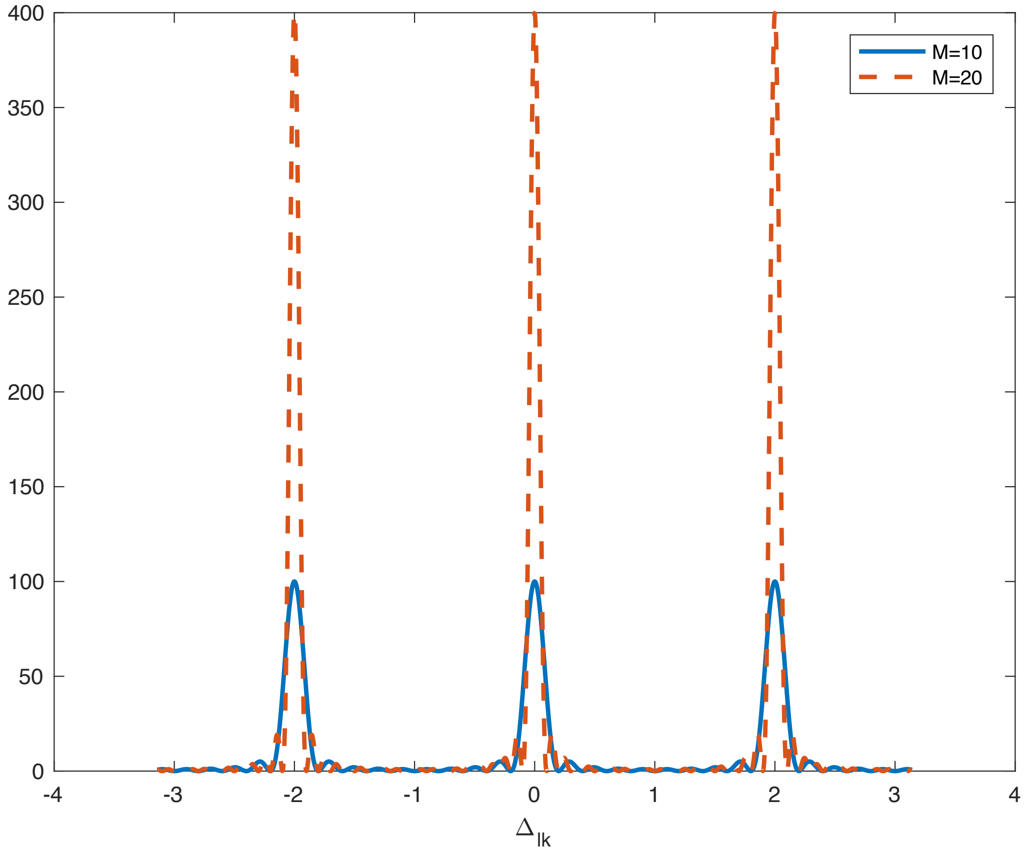
- Condition

$$|\mathbf{h}_k^H \mathbf{h}_l|^2 = |g_k^* g_l|^2 \left| \sum_{m=0}^{M-1} \exp(j\pi m \underbrace{(\sin\theta_l - \sin\theta_k)}_{\Delta_{lk}}) \right|^2$$

$$= |g_k^* g_l|^2 \left| \frac{1 - e^{j\pi M \Delta_{lk}}}{1 - e^{j\pi \Delta_{lk}}} \right|^2$$

$$= |g_k^* g_l|^2 \left| \frac{\sin(\pi M \Delta_{lk}/2)}{\sin(\pi \Delta_{lk}/2)} \right|^2$$

$$\approx 0, \Delta_{lk} > 2/M$$




- Massive array: users always orthogonal

# Massive MIMO – CSIT at the base station

- Processing in one coherence interval

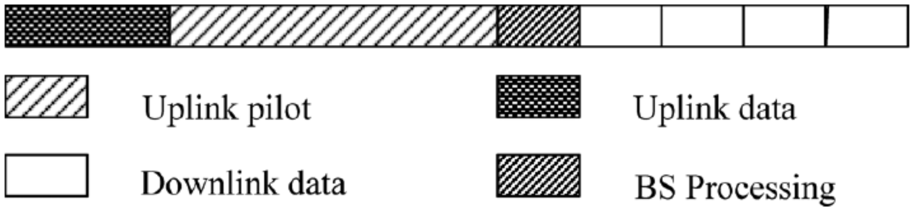



Fig. 2. Multi-User MIMO TDD protocol.

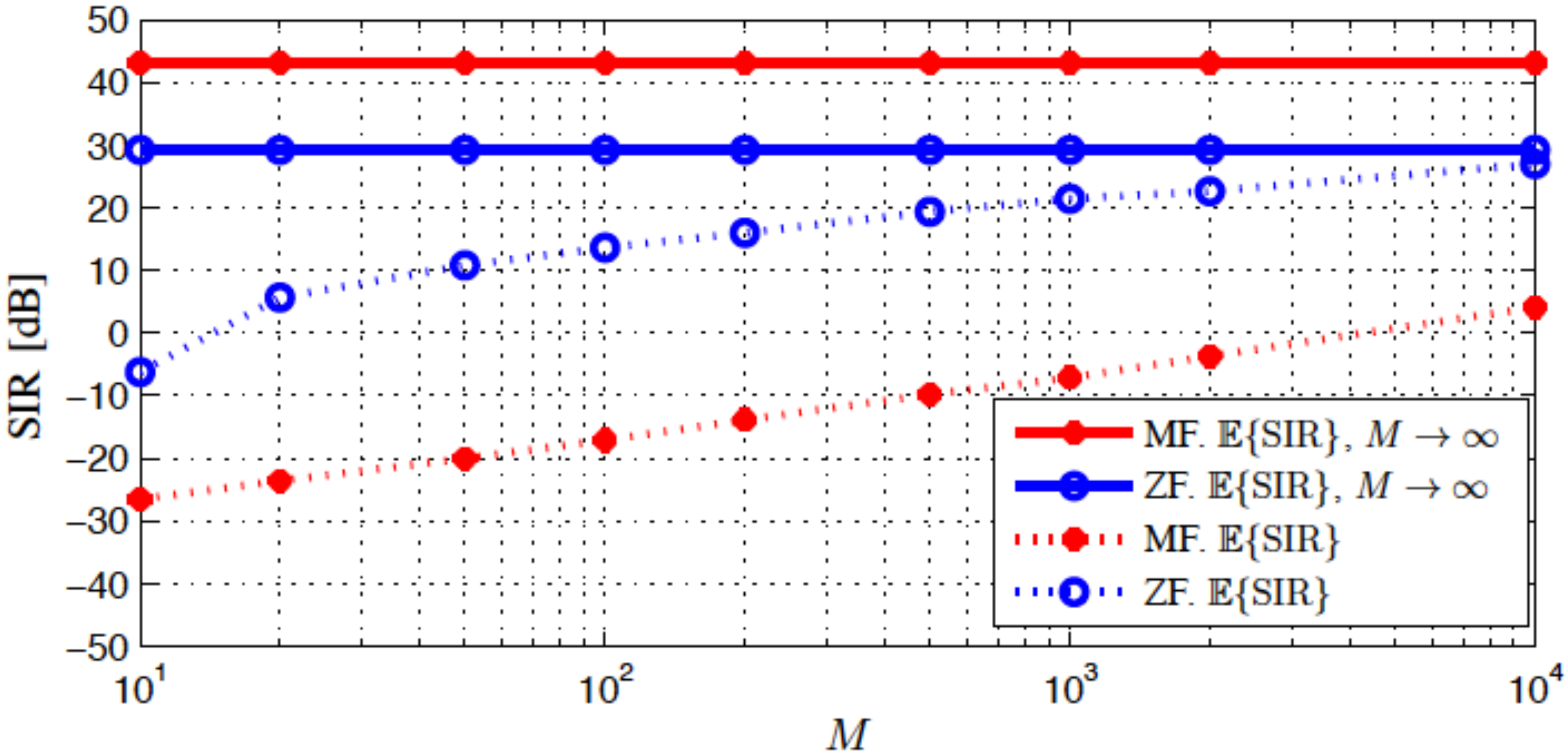
- Uplink training: coherence bandwidth $B_c$, coherence time $T_c$: we can send ($B_c$ *$T_c$) samples with a fixed channel. If we use a fraction *a* for pilots, then the rate becomes (1-*a)*max rate*.
- We want to have full spatial reuse, so some users will have same pilot
- Suppose 2 users have same pilot

$$\hat{\mathbf{h}}_k = \mathbf{h}_k + \mathbf{h}_l + \mathbf{w}_k$$

Noise depends on pilot length / power

- Leads to wrong precoder, loss in rate: SINR in uplink and downlink are interference-limited!
- This is called pilot contamination

# Pilot contamination






Source: Scaling up MIMO: Opportunities and Challenges with Very Large Arrays

# Today's learning outcomes

At the end of this lecture, you must be able to

- Describe key characteristics of 5G
- Describe the difference between single-user MIMO and multi-user MIMO
- Express MU-MIMO in uplink and downlink as a standard MIMO
- Explain why in massive MIMO users have nearly orthogonal channels and why this is useful
- Describe what pilot contamination is

# Other topics

- Research ethics
- Health effects of EM radiation
  - World Health Organization

Dr Christopher Wild, Director of IARC said: "An increased risk of brain cancer is not established from the data from Interphone. However, observations at the highest level of cumulative call time and the changing patterns of mobile phone use since the period studied by Interphone, particularly in young people, mean that further investigation of mobile phone use and brain cancer risk is merited."

  - Federal Communications Commission

Federal, state and local government agencies and other organizations have generally relied on RF exposure standards developed by expert non-government organizations such as the Institute of Electrical and Electronics Engineers (IEEE) and the National Council on Radiation Protection and Measurements (NCRP). Since 1996, the FCC has required that all wireless communications devices sold in the United States meet its minimum guidelines for safe human exposure to radiofrequency (RF) energy. The FCC's guidelines and rules regarding RF exposure are based upon standards developed by IEEE and NCRP and input from other federal agencies, such as those listed above. These guidelines specify exposure limits for hand-held wireless devices in terms of the Specific Absorption Rate (SAR). The SAR is a measure of the rate that RF energy is absorbed by the body. For exposure to RF energy from wireless devices, the allowable FCC SAR limit is 1.6 watts per kilogram (W/kg), as averaged over one gram of tissue.

All wireless devices sold in the US go through a formal FCC approval process to ensure that they do not exceed the maximum allowable SAR level when operating at the device's highest possible power level. If the FCC learns that a device does not confirm with the test report upon which FCC approval is based – in essence, if the device in stores is not the device the FCC approved – the FCC can withdraw its approval and pursue enforcement action against the appropriate party.