

# ELEC97094/ELEC97095 Wireless Communications

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# Course Objectives

- Course on wireless communication and communication theory
  - Fundamentals of wireless communications from a 4G and beyond perspective
  - At the cross-road between information theory, coding theory, signal processing and antenna/propagation theory
- Major focus of the course is on 1) fundamentals of wireless, 2) multi-antenna systems and 3) multi-user communications
  - Applications: everywhere in wireless communication networks: 4G, 5G, 6G, WiMAX(IEEE 802.16e, IEEE 802.16m), WiFi(IEEE 802.11n), satellite,...
- Valuable for those who want to either pursue a PhD in communication or a career in a high-tech telecom company (research centres, R&D branches of telecom manufacturers and operators,...).
- Skills
  - Some mathematical modelling and analysis of wireless communication systems
  - Design (transmitters and receivers) of wireless communication systems
  - Basic system design and performance evaluations

# Content

- **Part 1: Basics of Wireless**
  - The Wireless Channel
  - Fading and Diversity
  - Capacity of Wireless Channels
- **Part 2: MIMO systems**
  - Basics of MIMO
  - The MIMO Channel
  - Capacity of MIMO Wireless Channels
  - Transmission and Reception Strategies
  - Quantized Precoding
- **Part 3: Multiuser Communications**
  - Capacity of Multiuser (SISO and MIMO) Channels
  - Fairness, Scheduling and Precoding ... all the way to Massive MIMO
  - Multiuser Multicell Communications

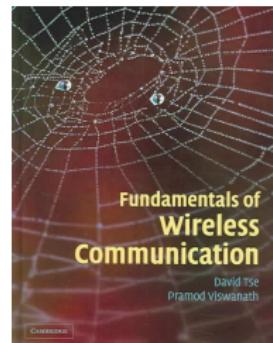
# Important Information

- Course material on blackboard
- Prerequisite: For Meng EE3-03 - Communication Systems
- No Exam
- 3 courseworks (using Matlab): 20%, 30%, 50%. 1) deadline: 7 February 2021, 2) deadline: 28 February 2021, 3) deadline: 23 March 2021. No oral for coursework 1 and 2, but oral for coursework 3 (to be scheduled on 25-26 March 2021).
- Participate to the lab sessions (7 sessions scheduled in week 3 to 9) with GTAs Longfei Yin and Yang Zhao. See the problem sheets on blackboard.

# Two reference books

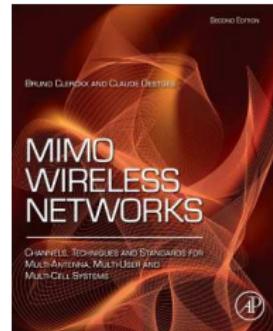
- Introductory

D. Tse and P. Viswanath, "Fundamentals of Wireless Communication," Cambridge University Press, May 2005



- More advanced and MIMO-focused

Bruno Clerckx and Claude Oestges, "MIMO Wireless Networks: Channels, Techniques and Standards for Multi-Antenna, Multi-User and Multi-Cell Systems," Academic Press (Elsevier), Oxford, UK, Jan 2013.



# Wireless Revolution



Marconi 1896

## Cellular systems

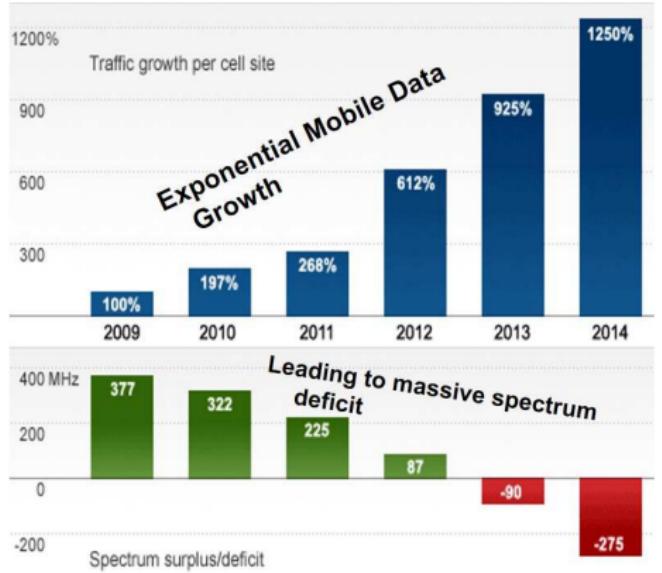
1G – 1980's

2G (GSM) – 1990's

3G (UMTS) – 2000's

4G (LTE) – 2010's

5G – 2020's



Source: FCC

## Other systems

WiFi, Satellite, Bluetooth, Zigbee, ...

# Challenges

## Network/Radio Challenges

- Data rates
- Scarce/limited spectrum
- Reliability and coverage
- Mobility
- Energy efficiency
- Latency
- Explosion of the number of devices

## Device/RF/Chip Challenges

- Performance
- Complexity
- Size, Power, Cost
- High frequencies/mmWave
- Multiple Antennas
- Multiradio Integration
- Coexistence

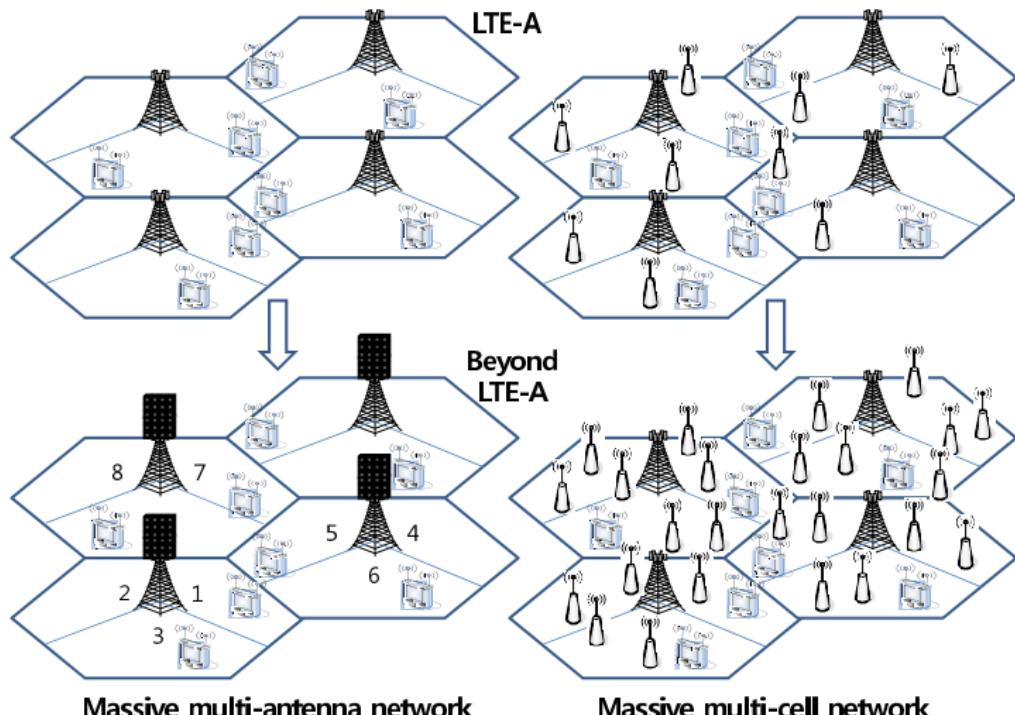
## Spectrum Regulation

- Spectrum limited
- Worldwide spectrum controlled by ITU-R
- Regulation/spectrum allocation needed

## Standards

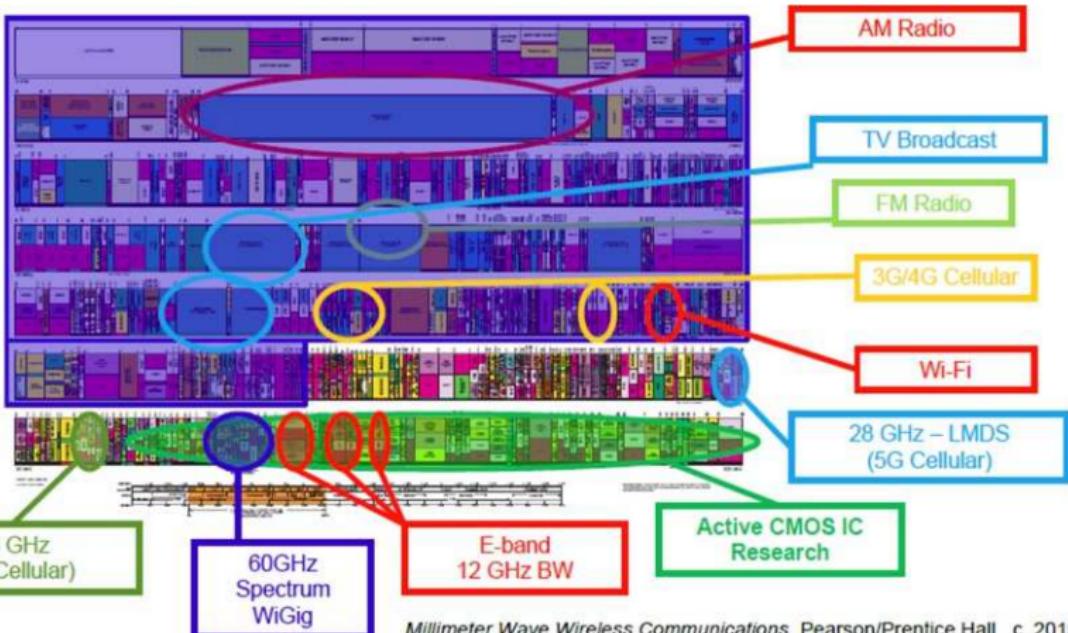
- Systems need to interact
- Companies want their systems adopted as standard
- Intellectual property (patents)
- IEEE, 3GPP

# 5G: more antennas, more cells



# 5G: higher frequencies and larger bandwidth

## UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



# Future Wireless Networks

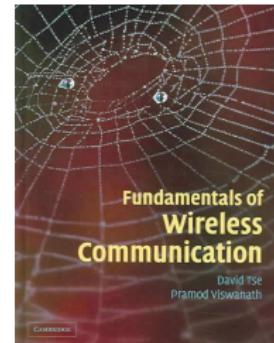
- Next-Gen Cellular/WiFi (5G and beyond)
- Smart Homes/Spaces
- Smart Cities
- Internet of Things
- Autonomous Cars
- Body-Area Networks
- Satellite
- Drones/UAV
- Chemical/Molecular Communications
- Applications of Communications in Health, Bio-medicine, and Neuroscience
- Energy harvesting and transfer
- integrated sensing and communications
- new/intelligent material and surfaces
- new algorithms, optimization, learning mechanisms
- ...

# Part 1: Basics of Wireless

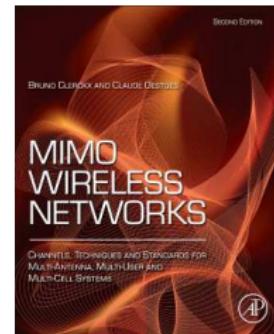
- Discrete Time Representation
- The Wireless Channel
- Fading and Diversity
- Capacity of Wireless Channels

# Reference Book

Chapter 5 - Sections 5.2.1, 5.3.1, 5.3.2,  
5.4.1, 5.4.2, 5.4.3, 5.4.5.



Chapter 1 - Sections 1.2, 1.3, 1.4, 1.5.



# Discrete Time Representation

# Discrete Time Representation

- *channel*: the impulse response of the linear time-varying communication system between one (or more) transmitter(s) and one (or more) receiver(s).
- Assume a SISO transmission where the digital signal is defined in discrete-time by the complex time series  $\{c_l\}_{l \in \mathbb{Z}}$  and is transmitted at the symbol rate  $T_s$ .
- The transmitted signal is then represented by

$$c(t) = \sum_{l=-\infty}^{\infty} \sqrt{E_s} c_l \delta(t - lT_s),$$

where  $E_s$  is the transmitted symbol energy, assuming that the average energy constellation is normalized to unity.

- Define a function  $h_B(t, \tau)$  as the time-varying (along variable  $t$ ) impulse response of the channel (along  $\tau$ ) over the system bandwidth  $B = 1/T_s$ , i.e.  $h_B(t, \tau)$  is the response at time  $t$  to an impulse at time  $t - \tau$ .
- The received signal  $y(t)$  is given by

$$\begin{aligned} y(t) &= h_B(t, \tau) * c(t) + n(t) \\ &= \int_0^{\tau_{max}} h_B(t, \tau) c(t - \tau) d\tau + n(t) \end{aligned}$$

where  $*$  denotes the convolution product,  $n(t)$  is the additive noise of the system and  $\tau_{max}$  is the maximal length of the impulse response.

# Discrete Time Representation

- $h_B$  is a scalar quantity, which can be further decomposed into three main terms,

$$h_B(t, \tau) = f_r * h(t, \tau) * f_t,$$

where

- $f_t$  is the pulse-shaping filter,
- $h(t, \tau)$  is the electromagnetic propagation channel (including the transmit and receive antennas) at time  $t$ ,
- $f_r$  is the receive filter.

- Nyquist criterion: the cascade  $f = f_r * f_t$  does not create inter-symbol interference when  $y(t)$  is sampled at rate  $T_s$ .
- In practice,
  - difficult to model  $h(t, \tau)$  (infinite bandwidth is required).
  - $h_B(t, \tau)$  is usually the modeled quantity, but is written as  $h(t, \tau)$  (abuse of notation).
  - Same notational approximation: the channel impulse response writes as  $h(t, \tau)$  or  $h_t[\tau]$ .
- The input-output relationship reads thereby as

$$y(t) = h(t, \tau) * c(t) + n(t) = \sum_{l=-\infty}^{\infty} \sqrt{E_s} c_l h_t[t - lT_s] + n(t).$$

# Discrete Time Representation

- Sampling the received signal at the symbol rate  $T_s$  ( $y_k = y(t_0 + kT_s)$ , using the epoch  $t_0$ ) yields

$$\begin{aligned}y_k &= \sum_{l=-\infty}^{\infty} \sqrt{E_s} c_l h_{t_0+kT_s}[t_0 + (k-l)T_s] + n(t_0 + kT_s) \\&= \sum_{l=-\infty}^{\infty} \sqrt{E_s} c_l h_k[k-l] + n_k\end{aligned}$$

## Example

At time  $k = 0$ , the channel has two taps:  $h_0[0]$ ,  $h_0[1]$

$$y_0 = \sqrt{E_s} [c_0 h_0[0] + c_{-1} h_0[1]] + n_0$$

- If  $T_s \gg \tau_{max}$ ,
  - $h_B(t, \tau)$  is modeled by a single dependence on  $t$ : write simply as  $h_B(t)$  (or  $h(t)$  using the same abuse of notation). In the sampled domain,  $h_k = h(t_0 + kT_s)$ .
  - the channel is then said to be *flat fading* or narrowband

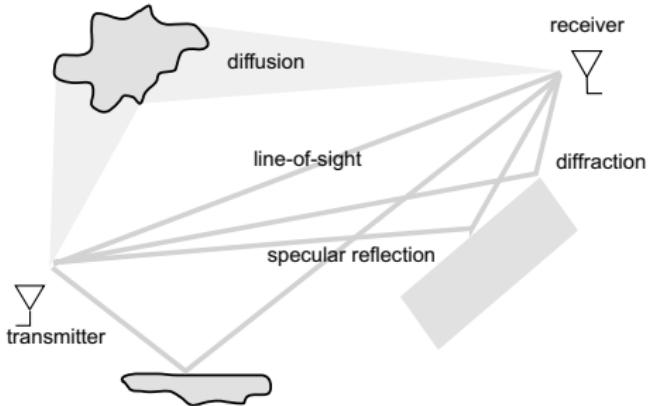
$$y_k = \sqrt{E_s} h_k c_k + n_k$$

- Otherwise the channel is said to be *frequency selective*.

# The Wireless Channel

# The Wireless Channel

- Multipath



- Wireless channel varies:
  - Long time scale: Large Scale Fading (Path-Loss and Shadowing)
  - Short time scale: Small Scale Fading

# Large Scale Fading: Path-Loss and Shadowing

- Time constants associated with variations are very long as the mobile moves.
  - many seconds or minutes
- Important for cell site planning and rough estimate of network performance.
- Modeling:
  - Maxwell's equations: complex and impractical
  - Free space and 2-path models: (too) simple
  - Ray tracing models: requires site-specific information
  - Simplified power falloff models: good for high-level analysis
  - Empirical and Standards-based Models: not accurate, used to assess different designs

# Free space model

- Path loss for unobstructed LOS path: distance  $R$  between Tx and Rx
- Friis equation: received power attenuates like  $1/R^2$

$$P_r = P_t D_t D_r \left( \frac{\lambda}{4\pi R} \right)^2$$

$$P_r|_{\text{dB}} = P_t|_{\text{dB}} + D_t|_{\text{dB}} + D_r|_{\text{dB}} + 20 \log_{10} \left( \frac{\lambda}{4\pi R} \right)$$

- $|_{\text{dB}}$  indicates the conversion to dB
  - $D_t, D_r$  the transmit and receive antenna directivities
  - $R \gg \lambda$  the wavelength
- Path Loss:  $\Lambda_0|_{\text{dB}} = 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right)$

## 2-path model

- Path loss for one LOS path and 1 ground (or reflected) bounce
- Ground bounce approximately cancels LOS path above critical distance
- Received power
  - Inversely proportional to  $R^2$  ( $\text{small } R$ )
  - Inversely proportional to  $R^4$  ( $R > R_c$ )
- Important in rural areas where base stations are placed on roads

# Simplified Path Loss Model

- Used extensively in system design
- A real-valued deterministic attenuation term modeled as  $\Lambda_0 \propto R^\eta$

$$P_r = P_t K \left( \frac{R_0}{R} \right)^\eta$$

- Important parameter: the path loss exponent  $\eta$ 
  - Determined empirically:  $2 \leq \eta \leq 8$ .
- Path Loss:  $\Lambda_0|_{\text{dB}} = L_0|_{\text{dB}} + 10\eta \log_{10} \left( \frac{R}{R_0} \right)$ 
  - $L_0$  is the deterministic path-loss at a reference distance  $R_0$
- What about at higher frequencies? mmWave?
  - Much less mature, on-going characterization
  - Path loss large due to frequency, rain, and oxygen
  - Limited to short range or would need massive MIMO

# Shadowing

- Models attenuation from obstructions/obstacles
- Random due to random number and type of obstructions
- Modeled as a lognormal random variable  $S$ 
  - $S|_{\text{dB}} = 10 \log_{10}(S)$  is a zero-mean normal variable of given standard deviation  $\sigma_S$ , i.e.  $S|_{\text{dB}} \sim \mathcal{N}(0, \sigma_S^2)$ .
  - zero mean as mean captured in path loss
  - $4 < \sigma_S < 12$
  - Central Limit Theorem used to explain this model
- Path loss + shadowing

$$\Lambda|_{\text{dB}} = \Lambda_0|_{\text{dB}} + S|_{\text{dB}} = L_0|_{\text{dB}} + 10\eta \log_{10} \left( \frac{R}{R_0} \right) + S|_{\text{dB}},$$

$$P_r|_{\text{dB}} = P_t|_{\text{dB}} + K|_{\text{dB}} - 10\eta \log_{10} \left( \frac{R}{R_0} \right) - S|_{\text{dB}}$$

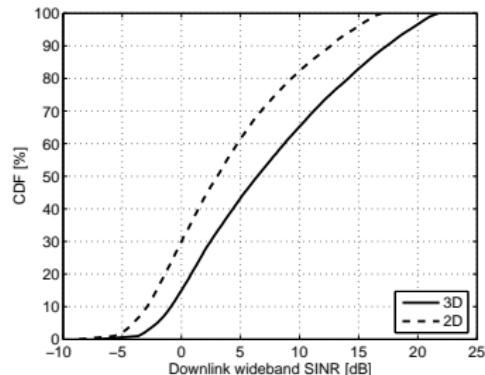
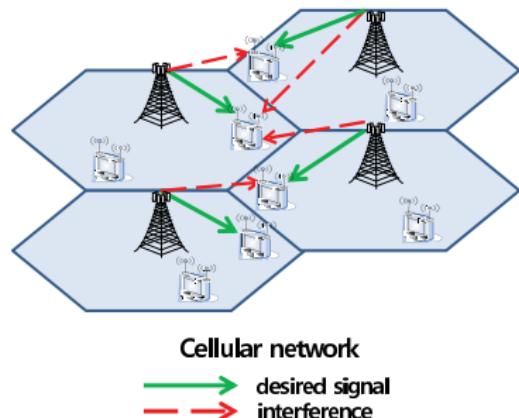
- $\Lambda$  is sometimes simply known as the path-loss.

# Large Scale Fading and Network Performance

- For user  $q$  in cell  $i$ , the *wideband/long-term SINR*

$$SINR_{w,q} = \frac{\Lambda_{q,i}^{-1} E_{s,i}}{\sigma_{n,q}^2 + \sum_{j \neq i} \Lambda_{q,j}^{-1} E_{s,j}}.$$

- Function of major propagation mechanisms (path loss, shadowing, antenna radiation patterns,...), base stations deployment and user distribution.
- CDF of  $SINR_{w,q}$  in a frequency reuse 1 network (cells share the same frequency band) with 2D and 3D antenna patterns in urban macro deployment.



# Integrating Large Scale and Small Scale Fading

- Assuming narrowband channels and given specific Tx and Rx locations,  $h_k$  is modeled as

$$h_k = \frac{1}{\sqrt{\Lambda_0 S}} h_k,$$

where

- path-loss*  $\Lambda_0$ :  $\Lambda_0 \propto R^\eta$  where  $\eta$ .
- shadowing*  $S$ : Lognormal random variable,  $S|_{\text{dB}} \sim \mathcal{N}(0, \sigma_S^2)$ .
- fading*  $h_k$ : caused by the combination of non coherent multipaths. By definition of  $\Lambda_0$  and  $S$ ,  $\mathcal{E}\{|h|^2\} = 1$ .

- Alternatively,  $h_k = \Lambda^{-1/2} h_k$  with  $\Lambda$  modeled on a logarithm scale

$$\Lambda|_{\text{dB}} = \Lambda_0|_{\text{dB}} + S|_{\text{dB}} = L_0|_{\text{dB}} + 10\eta \log_{10} \left( \frac{R}{R_0} \right) + S|_{\text{dB}},$$

# Reminder: Gaussian Random Variable

- Real Gaussian random variable  $x$  with mean  $\mu = \mathcal{E}\{x\}$  and variance  $\sigma^2$

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right).$$

Standard Gaussian random variable:  $\mu = 0$  and  $\sigma^2 = 1$

- Complex Gaussian random variable  $x = x_r + jx_i$ :  $[x_r, x_i]^T$  is a real Gaussian random vector.
- Important case:  $x = x_r + jx_i$  is such that its real and imaginary parts are i.i.d. zero mean Gaussian variables of variance  $\sigma^2$  (circularly symmetric complex Gaussian random variable).
- $s = |x| = \sqrt{x_r^2 + x_i^2}$  is Rayleigh distributed

$$p(s) = \frac{s}{\sigma^2} \exp\left(-\frac{s^2}{2\sigma^2}\right).$$

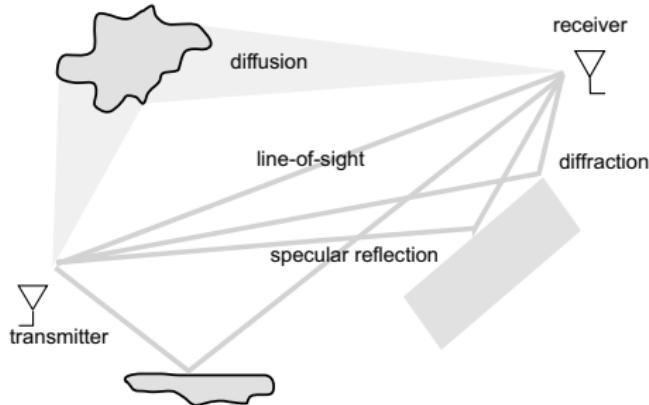
- $y = s^2 = |x|^2 = x_r^2 + x_i^2$  is  $\chi_2^2$  (i.e. exponentially) distributed (with two degrees of freedom)

$$p_y(y) = \frac{1}{2\sigma^2} \exp\left(-\frac{y}{2\sigma^2}\right).$$

Hence,  $\mu = \mathcal{E}\{y\} = 2\sigma^2$ .

# Small Scale Fading (or simply Fading)

- Multipaths



- Assuming that the signal reaches the receiver via a large number of paths of similar energy,
  - Central Limit Theorem used to explain this model
  - $h$  is modeled such that its real and imaginary parts are i.i.d. zero mean Gaussian variables of variance  $\sigma^2$  (circularly symmetric complex Gaussian variable).
  - Recall  $\mathcal{E}\{|h|^2\} = 2\sigma^2 = 1$ .

# Small Scale Fading (or simply Fading)

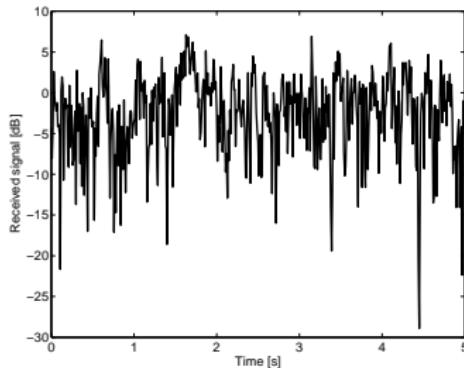
- The channel *amplitude*  $s \triangleq |h|$  follows a *Rayleigh* distribution,

$$p_s(s) = \frac{s}{\sigma^2} \exp\left(-\frac{s^2}{2\sigma^2}\right),$$

whose first two moments are

$$\mathcal{E}\{s\} = \sigma \sqrt{\frac{\pi}{2}}, \quad \mathcal{E}\{s^2\} = 2\sigma^2 = \mathcal{E}\{|h|^2\} = 1.$$

- The *phase* of  $h$  is uniformly distributed over  $[0, 2\pi)$
- Typical received signal strength of a Rayleigh fading channel



## Fading and Diversity

# System Model

- Path loss models are identical for both single- and multi-antenna systems.
- For point to point systems, it is common to discard the path loss and shadowing and only investigate the effect due to fading, i.e. the classical model for narrowband channels

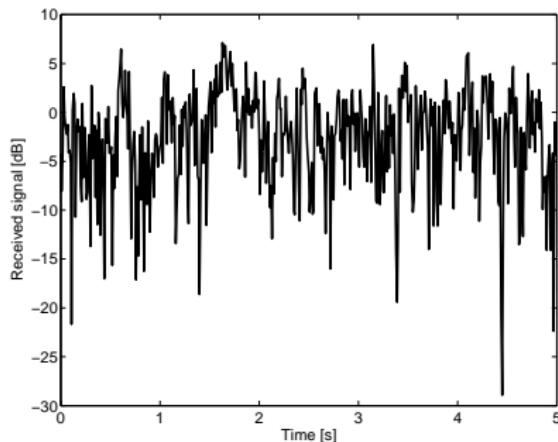
$$y = \sqrt{E_s} h c + n,$$

where the time index is removed for better legibility and  $n$  is usually taken as white Gaussian distributed,  $\mathcal{E}\{n_k n_l^*\} = \sigma_n^2 \delta(k - l)$ .

- $E_s$  can then be seen as an average received symbol energy.
- The *average SNR* is defined as  $\rho \triangleq E_s / \sigma_n^2$ .
- The *instantaneous SNR* is  $E_s |h|^2 / \sigma_n^2 = \rho |h|^2$ .

# Fading and Diversity

- The signal level randomly fluctuates, with some sharp declines of power and instantaneous received SNR known as *fades*.



- When the channel is in a deep fade, a reliable decoding of the transmitted signal may not be possible anymore, resulting in an error.
- How to recover the signal? Use of diversity techniques

# Maximum Likelihood Detection

- Decision rule: choose the hypothesis that maximizes the conditional density

$$\arg \max_x p(y|x) = \arg \max_x \log p(y|x)$$

- If real AWGN  $y = x + n$  with  $n \sim N(0, \sigma_n^2)$ ,

$$p(y|x) = \frac{1}{\sqrt{2\pi\sigma_n^2}} \exp\left(-\frac{(y-x)^2}{2\sigma_n^2}\right)$$

and

$$\arg \max_x p(y|x) = \arg \min_x (y-x)^2$$

- If  $y = \sqrt{E_s}hc + n$ , the ML decision rule becomes

$$\arg \min_c |y - \sqrt{E_s}hc|^2$$

# Impact of Fading

- What is the impact of fading on system performance?
- Consider the simple case of BPSK transmission through an AWGN channel and a SISO Rayleigh fading channel:
  - In the absence of fading ( $h = 1$ ), the symbol-error rate (SER) in an additive white Gaussian noise (AWGN) channel is given by

$$\bar{P} = \mathcal{Q}\left(\sqrt{\frac{2E_s}{\sigma_n^2}}\right) = \mathcal{Q}(\sqrt{2\rho}),$$

where  $\mathcal{Q}(x)$  is the Gaussian  $\mathcal{Q}$ -function defined as

$$\mathcal{Q}(x) \triangleq P(y \geq x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{y^2}{2}\right) dy.$$

- In the presence of (Rayleigh) fading, the received signal level fluctuates as  $s\sqrt{E_s}$ , and the SNR varies as  $\rho s^2$ . As a result, the SER

$$\begin{aligned}\bar{P} &= \int_0^\infty \mathcal{Q}(\sqrt{2\rho s}) p_s(s) ds \\ &= \frac{1}{2} \left(1 - \sqrt{\frac{\rho}{1+\rho}}\right) \\ &\stackrel{(\rho \nearrow)}{\approx} \frac{1}{4\rho}\end{aligned}$$

although the average SNR  $\bar{\rho} = \int_0^\infty \rho s^2 p_s(s) ds$  remains equal to  $\rho$ .

# Diversity in Multiple Antennas Wireless Systems

- How to combat the impact of fading? Use diversity techniques
- The principle of diversity is to provide the receiver with multiple versions (called diversity branch) of the same transmitted signal.
  - Independent fading conditions across branches needed.
  - Diversity stabilizes the link through channel hardening which leads to better error rate.
  - Multiple domains: time (coding and interleaving), frequency (equalization and multi-carrier modulations) and space (multiple antennas/polarizations).
- *Array Gain*: increase in average output SNR (i.e., at the input of the detector) relative to the single-branch average SNR  $\rho$

$$g_a \triangleq \frac{\bar{\rho}_{out}}{\bar{\rho}} = \frac{\bar{\rho}_{out}}{\rho}$$

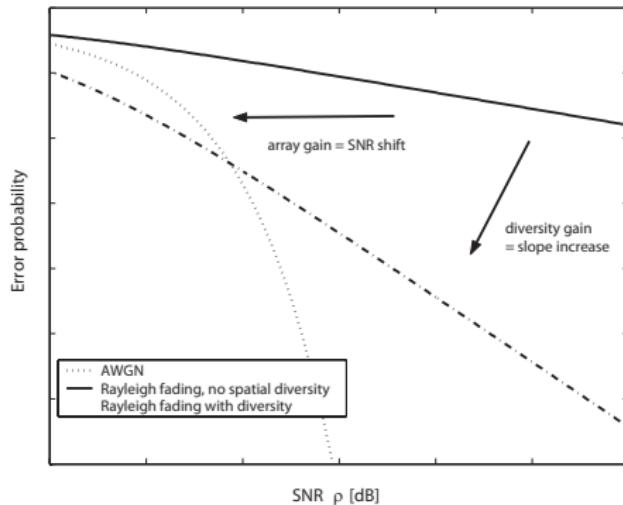
- *Diversity Gain*: increase in the error rate slope as a function of the SNR. Defined as the negative slope of the log-log plot of the average error probability  $\bar{P}$  versus SNR

$$g_d^o(\rho) \triangleq -\frac{\log_2 (\bar{P})}{\log_2 (\rho)}.$$

The diversity gain is commonly taken as the asymptotic slope, i.e., for  $\rho \rightarrow \infty$ .

# Diversity in Multiple Antennas Wireless Systems

- Illustration of diversity and array gains



Careful that the curves have been plotted against the single-branch average SNR  $\bar{\rho} = \rho$  !  
If plotted against the output average SNR  $\bar{\rho}_{out}$ , the array gain disappears.

- Coding Gain*: a shift of the error curve (error rate vs. SNR) to the left, similarly to the array gain.
  - If the error rate vs. the average receive SNR  $\bar{\rho}_{out}$ , any variation of the array gain is invisible but any variation of the coding gain is visible: for a given SNR level  $\bar{\rho}_{out}$  at the input of the detector, the error rates will differ.

# SIMO Systems

- Receive diversity may be implemented via two rather different combining methods:
  - *selection combining*: the combiner selects the branch with the highest SNR among the  $n_r$  receive signals, which is then used for detection,
  - *gain combining*: the signal used for detection is a linear combination of all branches,  $z = \mathbf{g}y$ , where  $\mathbf{g} = [g_1, \dots, g_{n_r}]$  is the combining vector.
    - ① Equal Gain Combining
    - ② Maximal Ratio Combining
    - ③ Minimum Mean Square Error Combining
- Space antennas sufficiently far apart from each other so as to experience independent fading on each branch.
- We assume that the receiver is able to acquire the perfect knowledge of the channel.

# Receive Diversity via Selection Combining

- Assume that the  $n_r$  channels are independent and identically Rayleigh distributed (i.i.d.) with unit energy and that the noise levels are equal on each antenna.
- Choose the branch with the largest amplitude  $s_{max} = \max\{s_1, \dots, s_{n_r}\}$ .
- The probability that  $s$  falls below a certain level  $S$  is given by its CDF

$$P[s < S] = 1 - e^{-S^2/2\sigma^2}.$$

- The probability that  $s_{max}$  falls below a certain level  $S$  is given by

$$P[s_{max} < S] = P[s_1, \dots, s_{n_r} \leq S] = [1 - e^{-S^2}]^{n_r}.$$

- The PDF of  $s_{max}$  is then obtained by derivation of its CDF

$$p_{s_{max}}(s) = n_r 2s e^{-s^2} [1 - e^{-s^2}]^{n_r-1}.$$

- The average SNR at the output of the combiner  $\bar{\rho}_{out}$  is eventually given by

$$\bar{\rho}_{out} = \int_0^\infty \rho s^2 p_{s_{max}}(s) ds = \rho \sum_{n=1}^{n_r} \frac{1}{n} \stackrel{n_r \rightarrow \infty}{\approx} \rho \left[ \gamma + \log(n_r) + \frac{1}{2n_r} \right].$$

where  $\gamma \approx 0.57721566$  is Euler's constant. We observe that the array gain  $g_a$  is of the order of  $\log(n_r)$ .

# Receive Diversity via Selection Combining

- For BPSK and a two-branch diversity, the SER as a function of the average SNR per channel  $\rho$  writes as

$$\begin{aligned}\bar{P} &= \int_0^{\infty} Q(\sqrt{2\rho s}) p_{s_{max}}(s) ds \\ &= \frac{1}{2} - \sqrt{\frac{\rho}{1+\rho}} + \frac{1}{2} \sqrt{\frac{\rho}{2+\rho}} \\ &\stackrel{\rho \nearrow}{\cong} \frac{3}{8\rho^2}.\end{aligned}$$

The slope of the bit error rate curve is equal to 2.

- In general, the diversity gain  $g_d^o$  of a  $n_r$ -branch selection diversity scheme is equal to  $n_r$ . Selection diversity extracts all the possible diversity out of the channel.

# Receive Diversity via Gain Combining

- In gain combining, the signal  $z$  used for detection is a linear combination of all branches,

$$z = \mathbf{g}\mathbf{y} = \sum_{n=1}^{n_r} g_n y_n = \sqrt{E_s} \mathbf{g} \mathbf{h} c + \mathbf{g} \mathbf{n}$$

where

- $g_n$ 's are the combining weights and  $\mathbf{g} \triangleq [g_1, \dots, g_{n_r}]$
- the data symbol  $c$  is sent through the channel and received by  $n_r$  antennas
- $\mathbf{h} \triangleq [h_1, \dots, h_{n_r}]^T$

- Assume Rayleigh distributed channels  $h_n = |h_n| e^{j\phi_n}$ ,  $n = 1, \dots, n_r$ , with unit energy, all the channels being independent.
- Equal Gain Combining*: fixes the weights as  $g_n = e^{-j\phi_n}$ .
  - Mean value of the output SNR  $\bar{\rho}_{out}$  (averaged over the Rayleigh fading):

$$\bar{\rho}_{out} = \frac{\mathcal{E} \left\{ \left[ \sum_{n=1}^{n_r} \sqrt{E_s} |h_n| \right]^2 \right\}}{n_r \sigma_n^2} = \dots = \rho \left[ 1 + (n_r - 1) \frac{\pi}{4} \right],$$

where the expectation is taken over the channel statistics. The array gain grows linearly with  $n_r$ , and is therefore larger than the array gain of selection combining.

- The diversity gain of equal gain combining is equal to  $n_r$  analogous to selection.

## Reminder: Chi-Square Distribution and MGF

- $\chi_n^2$  is the sum of the square of  $n$  i.i.d. zero-mean Gaussian random variables.
- Assume  $n$  i.i.d. zero mean complex Gaussian variables  $h_1, \dots, h_n$  (real and imaginary parts with variance  $\sigma^2$ ). Defining  $u = \sum_{k=1}^n |h_k|^2$ , the MGF of  $u$  is given by

$$\mathcal{M}_u(\tau) = \mathcal{E}\{e^{\tau u}\} = \left[ \frac{1}{1 - 2\sigma^2\tau} \right]^n,$$

# Receive Diversity via Gain Combining

- *Maximal Ratio Combining*: the weights are chosen as  $g_n = h_n^*$ .
  - It maximizes the average output SNR  $\bar{\rho}_{out}$

$$\bar{\rho}_{out} = \frac{E_s}{\sigma_n^2} \mathcal{E} \left\{ \frac{\|\mathbf{h}\|^4}{\|\mathbf{h}\|^2} \right\} = \rho \mathcal{E} \left\{ \|\mathbf{h}\|^2 \right\} = \rho n_r.$$

The array gain  $g_a$  is thus always equal to  $n_r$ , or equivalently, the output SNR is the sum of the SNR levels of all branches (holds true irrespective of the correlation between the branches).

- For BPSK transmission, the symbol error rate reads as

$$\bar{P} = \int_0^\infty \mathcal{Q}(\sqrt{2\rho u}) p_u(u) du$$

where  $u = \|\mathbf{h}\|^2$  is  $\chi^2$  distribution with  $2n_r$  degrees of freedom when the different channels are i.i.d. Rayleigh

$$p_u(u) = \frac{1}{(n_r - 1)!} u^{n_r - 1} e^{-u}.$$

At high SNR,  $\bar{P}$  becomes

$$\bar{P} = (4\rho)^{-n_r} \binom{2n_r - 1}{n_r}.$$

The diversity gain is again equal to  $n_r$ .

# Receive Diversity via Gain Combining

- For alternative constellations, the error probability is given, assuming ML detection, by

$$\begin{aligned}\bar{P} &\approx \int_0^\infty \bar{N}_e \mathcal{Q}\left(d_{min} \sqrt{\frac{\rho u}{2}}\right) p_u(u) du, \\ &\leq \bar{N}_e \mathcal{E}\left\{e^{-\frac{d_{min}^2 \rho u}{4}}\right\} \quad (\text{using Chernoff bound } \mathcal{Q}(x) \leq \exp\left(-\frac{x^2}{2}\right))\end{aligned}$$

where  $\bar{N}_e$  and  $d_{min}$  are respectively the number of nearest neighbors and minimum distance of separation of the underlying constellation.

Since  $u$  is a  $\chi^2$  variable with  $2n_r$  degrees of freedom, the above average upper-bound is given by

$$\begin{aligned}\bar{P} &\leq \bar{N}_e \left(\frac{1}{1 + \rho d_{min}^2 / 4}\right)^{n_r} \\ &\stackrel{\rho \nearrow}{\leq} \bar{N}_e \left(\frac{\rho d_{min}^2}{4}\right)^{-n_r}.\end{aligned}$$

The diversity gain  $g_d^o$  is equal to the number of receive branches in i.i.d. Rayleigh channels.

# Receive Diversity via Gain Combining

- *Minimum Mean Square Error Combining*

- So far noise was white Gaussian. When the noise (and interference) is colored, MRC is not optimal anymore.
- Let us denote the combined noise plus interference signal as  $\mathbf{n}_i$  such that  $\mathbf{y} = \sqrt{E_s} \mathbf{h} c + \mathbf{n}_i$ .
- An optimal gain combining technique is the minimum mean square error (MMSE) combining, where the weights are chosen in order to minimize the mean square error between the transmitted symbol  $c$  and the combiner output  $z$ , i.e.,

$$\mathbf{g}^* = \arg \min_{\mathbf{g}} \mathcal{E}\{ |\mathbf{g}\mathbf{y} - c|^2 \}.$$

- The optimal weight vector  $\mathbf{g}^*$  is given by

$$\mathbf{g}^* = \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1},$$

where  $\mathbf{R}_{\mathbf{n}_i} = \mathcal{E}\{\mathbf{n}_i \mathbf{n}_i^H\}$  is the correlation matrix of the combined noise plus interference signal  $\mathbf{n}_i$ .

- Such combiner can be thought of as first whitening the noise plus interference by multiplying  $\mathbf{y}$  by  $\mathbf{R}_{\mathbf{n}_i}^{-1/2}$  and then match filter the effective channel  $\mathbf{R}_{\mathbf{n}_i}^{-1/2} \mathbf{h}$  using  $\mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-H/2}$ .
- The Signal to Interference plus Noise Ratio (SINR) at the output of the MMSE combiner simply writes as

$$\rho_{out} = E_s \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h}.$$

- In the absence of interference and the presence of white noise, MMSE combiner reduces to MRC filter up to a scaling factor.

# Receive Diversity via Gain Combining

## Example

*Question:* Assume a transmission of a signal  $c$  from a single antenna transmitter to a multi-antenna receiver through a SIMO channel  $\mathbf{h}$ . The transmission is subject to the interference from another transmitter sending signal  $x$  through the interfering SIMO channel  $\mathbf{h}_i$ .

The received signal model writes as

$$\mathbf{y} = \mathbf{h}c + \mathbf{h}_i x + \mathbf{n}$$

where  $\mathbf{n}$  is the zero mean complex additive white Gaussian noise (AWGN) vector with  $\mathcal{E}\{\mathbf{n}\mathbf{n}^H\} = \sigma_n^2 \mathbf{I}_{n_r}$ .

We apply a combiner  $\mathbf{g}$  at the receiver to obtain the observation  $z = \mathbf{g}\mathbf{y}$ . Derive the expression of the MMSE combiner and the SINR at the output of the combiner.

# Receive Diversity via Gain Combining

## Example

Answer: The MMSE combiner  $\mathbf{g}$  is given by

$$\mathbf{g} = \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1}$$

where  $\mathbf{R}_{\mathbf{n}_i} = \mathcal{E}\{\mathbf{n}_i \mathbf{n}_i^H\}$  with  $\mathbf{n}_i = \mathbf{h}_i x + \mathbf{n}$ .

Hence  $\mathbf{R}_{\mathbf{n}_i} = \mathbf{h}_i P_x \mathbf{h}_i^H + \sigma_n^2 \mathbf{I}_{n_r}$  with  $P_x = \mathcal{E}\{|x|^2\}$ , the power of the interfering signal.

Hence,

$$\mathbf{g} = \mathbf{h}^H \left( \mathbf{h}_i P_x \mathbf{h}_i^H + \sigma_n^2 \mathbf{I}_{n_r} \right)^{-1}.$$

At the receiver, we obtain

$$z = \mathbf{g} \mathbf{y} = \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} c + \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{n}_i.$$

# Receive Diversity via Gain Combining

## Example

Answer: The output SINR writes

$$\begin{aligned}\rho_{out} &= \frac{\left| \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} \right|^2 P_c}{\mathcal{E} \left\{ \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{n}_i (\mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{n}_i)^H \right\}} \\ &= \frac{\left| \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} \right|^2 P_c}{\mathcal{E} \left\{ \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{n}_i \mathbf{n}_i^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} \right\}} \\ &= \frac{\left| \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} \right|^2 P_c}{\mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h}} \\ &= \mathbf{h}^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{h} P_c \\ &= P_c \mathbf{h}^H \left( \mathbf{h}_i P_x \mathbf{h}_i^H + \sigma_n^2 \mathbf{I}_{n_r} \right)^{-1} \mathbf{h} \\ &= \text{SNR} \mathbf{h}^H \left( \text{INR} \mathbf{h}_i \mathbf{h}_i^H + \mathbf{I}_{n_r} \right)^{-1} \mathbf{h}\end{aligned}$$

with  $P_c = \mathcal{E} \{ |c|^2 \}$ ,  $\text{SNR} = P_c / \sigma_n^2$  (the average SNR),  $\text{INR} = P_x / \sigma_n^2$  (the average INR - Interference to Noise Ratio).



# MISO Systems

- MISO systems exploit diversity at the transmitter through the use of  $n_t$  transmit antennas in combination with pre-processing or precoding.
- A significant difference with receive diversity is that the transmitter might not have the knowledge of the MISO channel.
  - At the receiver, the channel is easily estimated.
  - At the transmit side, feedback from the receiver is required to inform the transmitter.
- There are basically two different ways of achieving *direct transmit diversity*:
  - when Tx has a *perfect channel knowledge*, beamforming can be performed to achieve both diversity and array gains,
  - when Tx has a *partial or no channel knowledge of the channel*, space-time coding is used to achieve a diversity gain (but no array gain in the absence of any channel knowledge).
- *Indirect transmit diversity* techniques convert spatial diversity to time or frequency diversity.

# Transmit Diversity via Matched Beamforming

- The actual transmitted signal is a vector  $\mathbf{c}'$  that results from the multiplication of the signal  $c$  by a weight vector  $\mathbf{w}$ .
- At the receiver, the signal reads as

$$y = \sqrt{E_s} \mathbf{h} \mathbf{c}' + n = \sqrt{E_s} \mathbf{h} \mathbf{w} c + n,$$

where  $\mathbf{h} \triangleq [h_1, \dots, h_{n_t}]$  represents the MISO channel vector, and  $\mathbf{w}$  is also known as the precoder.

- The choice that maximizes the receive SNR is given by

$$\mathbf{w} = \frac{\mathbf{h}^H}{\|\mathbf{h}\|}.$$

- Transmit along the direction of the matched channel. Hence also known as *matched beamforming* or *transmit MRC* or *maximum ratio transmission (MRT)*.
- The array gain is equal to the number of transmit antennas, i.e.  $\bar{\rho}_{out} = n_t \rho$ .
- The diversity gain equal to  $n_t$  as the symbol error rate is upper-bounded at high SNR by

$$\bar{P} \leq \bar{N}_e \left( \frac{\rho d_{min}^2}{4} \right)^{-n_t}.$$

- Matched beamforming presents the same performance as receive MRC, but *requires a perfect transmit channel knowledge*.

# Transmit Diversity via Space-Time Coding

- *Alamouti scheme* is an ingenious transmit diversity scheme for two transmit antennas which does not require transmit channel knowledge.
  - Assume that the flat fading channel remains constant over the two successive symbol periods, and is denoted by  $\mathbf{h} = [h_1 \ h_2]$ .
  - Two symbols  $c_1$  and  $c_2$  are transmitted simultaneously from antennas 1 and 2 during the first symbol period, followed by symbols  $-c_2^*$  and  $c_1^*$ , transmitted from antennas 1 and 2 during the next symbol period:

$$y_1 = \sqrt{E_s} h_1 \frac{c_1}{\sqrt{2}} + \sqrt{E_s} h_2 \frac{c_2}{\sqrt{2}} + n_1, \quad (\text{first symbol period})$$

$$y_2 = -\sqrt{E_s} h_1 \frac{c_2^*}{\sqrt{2}} + \sqrt{E_s} h_2 \frac{c_1^*}{\sqrt{2}} + n_2. \quad (\text{second symbol period})$$

The two symbols are spread over two antennas and over two symbol periods.

- Equivalently

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \sqrt{E_s} \underbrace{\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}_{\mathbf{H}_{eff}} \underbrace{\begin{bmatrix} c_1/\sqrt{2} \\ c_2/\sqrt{2} \end{bmatrix}}_{\mathbf{c}} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}.$$

- Applying the matched filter  $\mathbf{H}_{eff}^H$  to the received vector  $\mathbf{y}$  effectively decouples the transmitted symbols as shown below

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \mathbf{H}_{eff}^H \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \sqrt{E_s} \left[ |h_1|^2 + |h_2|^2 \right] \mathbf{I}_2 \begin{bmatrix} c_1/\sqrt{2} \\ c_2/\sqrt{2} \end{bmatrix} + \mathbf{H}_{eff}^H \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}$$

# Transmit Diversity via Space-Time Coding

- The mean output SNR (averaged over the channel statistics) is thus equal to

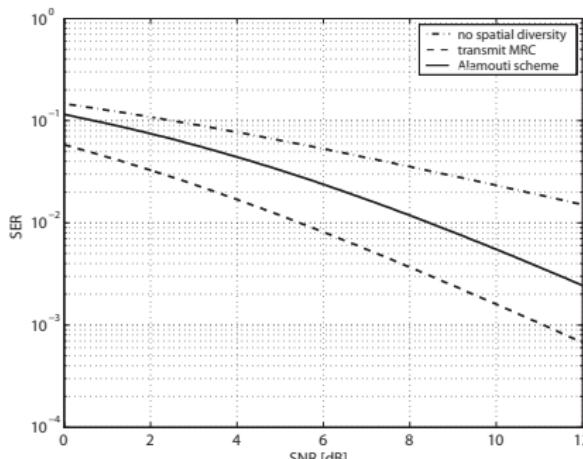
$$\bar{\rho}_{out} = \frac{E_s}{\sigma_n^2} \mathcal{E} \left\{ \frac{[\|\mathbf{h}\|^2]^2}{2 \|\mathbf{h}\|^2} \right\} = \rho.$$

No array gain owing to the lack of transmit channel knowledge.

- The average symbol error rate at high SNR can be upper-bounded according to

$$\bar{P} \leq \bar{N}_e \left( \frac{\rho d_{min}^2}{8} \right)^{-2}.$$

The diversity gain is equal to  $n_t = 2$  despite the lack of transmit channel knowledge.



Transmit MRC vs. Alamouti with 2 transmit antennas in i.i.d. Rayleigh fading channels (BPSK).

## Observations:

- At high SNR, any increase in the SNR by 10dB leads to a decrease of SER by  $10^{-n}$  for diversity order  $n$ .
  - Alamouti, transmit MRC: 2
  - No spatial diversity: 1
- Transmit MRC has 3 dB gain over Alamouti

# Indirect Transmit Diversity

- It is also possible to convert spatial diversity to time or frequency diversity, which are then exploited using well-known SISO techniques.
- Assume that  $n_t = 2$  and that the signal on the second transmit branch is
  - either delayed by one symbol period: the spatial diversity is converted into *frequency diversity* (delay diversity)
  - either phase-rotated: the spatial diversity is converted into *time diversity*
  - The effective SISO channel resulting from the addition of the two branches seen by the receiver now fades over frequency or time. This selective fading can be exploited by conventional diversity techniques, e.g. FEC/interleaving.

# Capacity of Wireless Channels

# System Model

- A single-user SISO system with one transmit and one receive antennas over a frequency flat-fading channel.
- The transmit and received signals are related by

$$y_k = \sqrt{E_s} h_k c_k + n_k$$

where

- $y_k$  is the received signal,
- $h_k$  is the complex channel,
- $n_k$  is a zero mean complex additive white Gaussian noise (AWGN)  $\mathcal{CN}(0, \sigma_n^2)$ , with  $\mathbb{E}\{n_k n_l\} = \sigma_n^2$  if  $k = l$  and 0 otherwise.
- $\rho = E_s / \sigma_n^2$  represents the average SNR.
- Power constraint:  $\mathbb{E}\{|c_k|^2\} \leq 1$ .
- Channel time variation:  $T_{coh}$  coherence time
  - *slow fading*:  $T_{coh}$  is so long that coding is performed over a single channel realization.
  - *fast fading*:  $T_{coh}$  is so short that coding over multiple channel realizations is possible.

# Capacity of Deterministic SISO Channel

## Definition

The capacity of an AWGN channel is

$$C = \log_2 (1 + SNR) \quad [\text{bits}/\text{s}/H].$$

## Definition

The capacity of a deterministic (time-invariant) SISO channel  $h$  is

$$C = \log_2 (1 + \rho|h|^2) \quad [\text{bits}/\text{s}/H].$$

Instantaneous SNR is  $\rho|h|^2$ .

# Capacity of Deterministic SISO Channel

- Low SNR:  $\log_2(1 + x) \approx x \log_2(e)$  for  $x$  small

$$C \approx \rho |h|^2 \log_2(e).$$

- $C$  grows linearly with SNR at low SNR.
  - Double SNR and  $C$  is doubled.

- High SNR:  $\log_2(1 + x) \approx \log_2(x)$  for  $x$  large

$$C \approx \log_2(\rho |h|^2) = \log_2(\rho) + \log_2(|h|^2).$$

- $C$  grows logarithmically with SNR (or linearly with SNR in dB) at high SNR.
  - Double SNR (or 3dB increase) and  $C$  is increased by 1 bits/s/Hz.

# Capacity of Deterministic SIMO Channel

- System model

$$\mathbf{y}_k = \sqrt{E_s} \mathbf{h}_k c_k + n_k$$

- $\mathbf{y}_k$ ,  $\mathbf{h}_k$   $n_r$ -dimensional vectors

- MRC combining

$$\mathbf{h}_k^H \mathbf{y}_k = \sqrt{E_s} \mathbf{h}_k^H \mathbf{h}_k c_k + \mathbf{h}_k^H n_k$$

Instantaneous SNR  $\rho \|\mathbf{h}_k\|^2$ .

## Definition

The capacity of a deterministic (time-invariant) SIMO channel  $\mathbf{h}$  is

$$C = \log_2 (1 + \rho \|\mathbf{h}\|^2) \quad [\text{bits/s/H}].$$

# Capacity of Deterministic MISO Channel

- System model

$$y_k = \sqrt{E_s} \mathbf{h}_k \mathbf{c}_k + n_k$$

- $\mathbf{h}_k$ ,  $\mathbf{c}_k$   $n_t$ -dimensional vectors
- MRT  $\mathbf{c}_k = \mathbf{w}_k c_k$  with  $\mathbf{w}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$

$$y_k = \sqrt{E_s} \mathbf{h}_k \mathbf{w}_k c_k + n_k$$

Instantaneous SNR  $\rho \|\mathbf{h}_k\|^2$ .

## Definition

The capacity of a deterministic (time-invariant) MISO channel  $\mathbf{h}$  is

$$C = \log_2 (1 + \rho \|\mathbf{h}\|^2) \quad [\text{bits/s/H}]$$

With perfect transmit channel knowledge!

# Ergodic Capacity of Fast Fading Channels

- Fast fading:
  - Doppler frequency sufficiently high to allow for coding over many channel realizations/coherence time periods
  - The transmission capability is represented by a single quantity known as the ergodic capacity
- Rate of information flow between Tx and Rx at time instant  $k$  over channels  $h_k$

$$\log_2 (1 + \rho|h_k|^2).$$

Such a rate varies over time according to the channel fluctuations. The average rate of information flow over a time duration  $T \gg T_{coh}$  is

$$\frac{1}{T} \sum_{k=0}^{T-1} \log_2 (1 + \rho|h_k|^2).$$

## Definition

The ergodic capacity of fast-fading channel is given by

$$\bar{C} = \mathcal{E} \left\{ \log_2 (1 + \rho|h|^2) \right\}.$$

# Impact on Coding Strategy

- Perfect Transmit Channel Knowledge
  - Use a variable-rate code (family of codes of different rates) adapted as a function of the channel state.
  - Code for state  $h$  achieves the capacity  $\log_2 (1 + \rho|h|^2)$ .
  - Average throughput  $\mathcal{E} \{\log_2 (1 + \rho|h|^2)\}$ .
  - No need for the codeword to span many coherence time periods.
  - Code average out the effect of noise
- Partial Transmit Channel Knowledge (only channel distribution known)
  - Same average throughput  $\mathcal{E} \{\log_2 (1 + \rho|h|^2)\}$  achievable.
  - Encoding requires a fixed-rate code (whose rate is given by the ergodic capacity) with encoding spanning many channel realizations.
  - Code length large enough  $T \gg T_c$  to average out both the noise and channel fluctuations.

# Ergodic Capacity of Fast Fading Channels

- Low SNR:

$$\bar{C} \approx \rho \mathcal{E}\{|h|^2\} \log_2(e) = \rho \log_2(e) = C_{AWGN}$$

Same as AWGN

- High SNR:

$$\bar{C} \approx \log_2(\rho) + \mathcal{E}\{\log_2(|h|^2)\} = \log_2(\rho) - 0.83 = C_{AWGN} - 0.83$$

Fading detrimental: 2.5 dB more power needed in the fading case to achieve the same capacity as in AWGN.

# Outage Capacity and Probability in Slow Fading Channels

- In slow fading, the encoding still averages out the randomness of the noise but cannot fully average out the randomness of the channel.
- For a given channel realization  $h$  and a target rate  $R$ , reliable transmission if

$$\log_2 (1 + \rho|h|^2) > R$$

If not met, an outage occurs and the decoding error probability is strictly non-zero.

- Look at the tail probability of  $\log_2 (1 + \rho|h|^2)$ , not its average!

## Definition

The outage probability  $P_{out}(R)$  of a wireless channel with a target rate  $R$  is given by

$$P_{out}(R) = P(\log_2 (1 + \rho|h|^2) < R).$$

- More meaningful in the absence of CSI knowledge at the transmitter: the transmitter cannot adjust its transmit strategy → hopes the channel is good enough

# Diversity-Multiplexing Trade-Off in Slow Fading Channels

- For a given  $R$ , how does  $P_{out}$  behave as a function of the SNR  $\rho$ ?

## Definition

A diversity gain  $g_d^*(g_s, \infty)$  is achieved at multiplexing gain  $g_s$  at *infinite SNR* if

$$\lim_{\rho \rightarrow \infty} \frac{R(\rho)}{\log_2(\rho)} = g_s$$
$$\lim_{\rho \rightarrow \infty} \frac{\log_2(P_{out}(R))}{\log_2(\rho)} = -g_d^*(g_s, \infty)$$

The curve  $g_d^*(g_s, \infty)$  as function of  $g_s$  is known as the asymptotic diversity-multiplexing trade-off of the channel.

- The multiplexing gain indicates how fast the transmission rate increases with the SNR.
- The diversity gain represents how fast the outage probability decays with the SNR.

# Diversity-Multiplexing Trade-Off in Slow Fading Channels

- Determine for a transmission rate  $R$  scaling with  $\rho$  as  $g_s \log_2(\rho)$ , the rate at which the outage probability decreases with  $\rho$  as  $\rho$  increases.
- Outage probability

$$\begin{aligned} P_{\text{out}} &= P(\log_2 [1 + \rho |h|^2] < g_s \log_2(\rho)) \\ &= P(1 + \rho |h|^2 < \rho^{g_s}) \end{aligned}$$

- At high SNR,

$$P_{\text{out}} \approx P(|h|^2 \leq \rho^{-(1-g_s)})$$

- Since  $|h|^2$  is exponentially distributed, i.e.,  $P(|h|^2 \leq \epsilon) \approx \epsilon$  for small  $\epsilon$

$$P_{\text{out}} \approx \rho^{-(1-g_s)}$$

An outage occurs at high SNR when  $|h|^2 \leq \rho^{-(1-g_s)}$  with a probability  $\rho^{-(1-g_s)}$ .

- DMT for the scalar Rayleigh fading channel  $g_d^*(g_s, \infty) = 1 - g_s$  for  $g_s \in [0, 1]$ .

# Impact on Coding Strategy

- $g_s = 0$  (constant rate):  $P_{\text{out}} \approx 1/\rho$ 
  - Error probability of uncoded transmission also decays as  $1/\rho$ .
  - Coding cannot further improve the slope in slow fading.
  - Coding can average out the noise but cannot average out the channel fade.
- $g_s = 1$  (rate scales with SNR):  $P_{\text{out}} \approx \text{constant}$ 
  - $P_{\text{out}}$  does not decrease with SNR.

## Careful

- AWGN: Send data at rate  $R < C$  and error probability as small as desired.
- Slow fading: Cannot be done if the probability of having a deep fade is non-zero.
  - Impossible to code over a large number of independent channel realizations  $\rightarrow$  outage as soon as the channel is in deep fade.
  - Capacity of the slow fading channel in the strict sense is zero.
  - $\epsilon$ -outage capacity  $C_\epsilon$ : largest rate of transmission  $R$  such that  $P_{\text{out}}(R) \leq \epsilon$ .

# Outage Capacity and Probability in MISO/SIMO Channels

- $P_{out}(R)$  of a SIMO wireless channel with a target rate  $R$

$$P_{out}(R) = P \left( \log_2 \left( 1 + \rho \|\mathbf{h}\|^2 \right) < R \right).$$

- Use receive diversity based on MRC.
  - $g_s = 0$  (constant rate):  $P_{out} \approx 1/\rho^{n_r}$ .

- $P_{out}(R)$  of a MISO wireless channel with a target rate  $R$

$$P_{out}(R) = P \left( \log_2 \left( 1 + \frac{\rho}{n_t} \|\mathbf{h}\|^2 \right) < R \right).$$

- Use transmit diversity based on Alamouti for 2Tx.
  - $g_s = 0$  (constant rate):  $P_{out} \approx 1/\rho^{n_t}$ .

## Part 2: MIMO Systems

Basics of MIMO

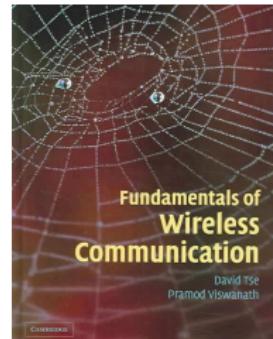
The MIMO Channel

Capacity of MIMO Channels

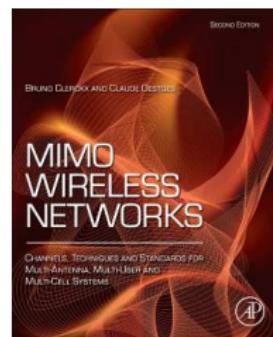
Tx and Rx Strategies: Space-Time Coding and Processing

Quantized Precoding

# Reference Book



- Chapter 1 - Sections 1.2.4, 1.3.2, 1.6
- Chapter 2 - Sections 2.2.1, 2.3.1
- Chapter 3 - Sections 3.2.1, 3.4.1
- Chapter 5 - Sections 5.2, 5.3, 5.4.2, 5.5.1, 5.7, 5.8.1
- Chapter 6 - Sections 6.1, 6.2, 6.3.1, 6.5.2, 6.5.4, 6.5.8



## Basics of MIMO

# Previous Lectures

- Discrete Time Representation
  - SISO:  $y = \sqrt{E_s}hc + n$
  - SIMO:  $\mathbf{y} = \sqrt{E_s}\mathbf{h}\mathbf{c} + \mathbf{n}$
  - MISO (with perfect CSIT):  $y = \sqrt{E_s}\mathbf{h}\mathbf{w}\mathbf{c} + n$
- $h$  is fading
  - amplitude Rayleigh distributed
  - phase uniformly distributed
- Diversity
  - Diversity gain:  $g_d^o(\rho) \triangleq -\frac{\log_2(\bar{P})}{\log_2(\rho)}$
  - Array gain:  $g_a \triangleq \frac{\bar{\rho}_{out}}{\bar{\rho}} = \frac{\bar{\rho}_{out}}{\rho}$
- SIMO
  - selection combining
  - gain combining
- MISO
  - with perfect channel knowledge at Tx: Matched Beamforming
  - without channel knowledge at Tx: Space-Time Coding (Alamouti Scheme), indirect (time, frequency) transmit diversity

# MIMO Systems

- In MIMO systems, the fading channel between each transmit-receive antenna pair can be modeled as a SISO channel.
- For uni-polarized antennas and small inter-element spacings (of the order of the wavelength), path loss and shadowing of all SISO channels are identical.
- Stacking all inputs and outputs in vectors  $\mathbf{c}_k = [c_{1,k}, \dots, c_{n_t,k}]^T$  and  $\mathbf{y}_k = [y_{1,k}, \dots, y_{n_r,k}]^T$ , the input-output relationship at any given time instant  $k$  reads as

$$\mathbf{y}_k = \sqrt{E_s} \mathbf{H}_k \mathbf{c}'_k + \mathbf{n}_k,$$

where

- $\mathbf{c}'_k$  is a precoded version of  $\mathbf{c}_k$  that depends on the channel knowledge at the Tx.
- $\mathbf{H}_k$  is defined as the  $n_r \times n_t$  MIMO channel matrix,  $\mathbf{H}_k(n, m) = h_{nm,k}$ , with  $h_{nm}$  denoting the narrowband channel between transmit antenna  $m$  ( $m = 1, \dots, n_t$ ) and receive antenna  $n$  ( $n = 1, \dots, n_r$ ),
- $\mathbf{n}_k = [n_{1,k}, \dots, n_{n_r,k}]^T$  is the sampled noise vector, containing the noise contribution at each receive antenna, such that the noise is white in both time and spatial dimensions,  $\mathcal{E}\{\mathbf{n}_k \mathbf{n}_l^H\} = \sigma_n^2 \mathbf{I}_{n_r} \delta(k - l)$ .
- Using the same channels normalization as for SISO channels,  $\mathcal{E}\{\|\mathbf{H}\|_F^2\} = n_t n_r$ .
- when Tx has a *perfect channel knowledge*: (dominant and multiple) eigenmode transmission
- when Tx has *no knowledge of the channel*: space-time coding (with  $\mathbf{c}'_k = \mathbf{c}_k$ )

# Reminder: Linear Algebra

- *Vector Orthogonality*:  $\mathbf{a}^H \mathbf{b} = 0$  ( $^H$  stands for Hermitian, i.e. conjugate transpose)
- *Hermitian matrix*:  $\mathbf{A} = \mathbf{A}^H$
- *Unitary matrix*:  $\mathbf{A}^H \mathbf{A} = \mathbf{I}$
- *Singular Value Decomposition (SVD)* of a matrix  $\mathbf{H}$  [ $n_r \times n_t$ ]:  $\mathbf{H} = \mathbf{U} \Sigma \mathbf{V}^H$ 
  - $\mathbf{U}$  [ $n_r \times r(\mathbf{H})$ ]: unitary matrix of left singular vectors
  - $\Sigma = \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_{r(\mathbf{H})}\}$ : diagonal matrix containing the singular values of  $\mathbf{H}$
  - $\mathbf{V}$  [ $n_t \times r(\mathbf{H})$ ]: unitary matrix of right singular vectors
  - $r(\mathbf{H})$ : the rank of  $\mathbf{H}$

We will often look at Hermitian matrices of the form  $\mathbf{A} = \mathbf{H}^H \mathbf{H}$  whose *Eigenvalue Value Decomposition (EVD)* writes as  $\mathbf{A} = \mathbf{V} \Lambda \mathbf{V}^H$  with  $\Lambda = \Sigma^2$ .

- $\mathbf{A} = \mathbf{H}^H \mathbf{H}$  is a positive-semidefinite matrix ( $\geq 0$ ), i.e. all eigenvalues of  $\mathbf{A}$  are nonnegative.
- *Trace of a matrix  $\mathbf{A}$* :  $\text{Tr}\{\mathbf{A}\} = \sum_i \mathbf{A}(i, i)$ .
- *Frobenius norm of a matrix  $\mathbf{A}$* :  $\|\mathbf{A}\|_F^2 = \sum_i \sum_j |A(i, j)|^2$
- $\|\mathbf{A}\|_F^2 = \text{Tr}\{\mathbf{A} \mathbf{A}^H\} = \text{Tr}\{\mathbf{A}^H \mathbf{A}\}$
- $\text{Tr}\{\mathbf{AB}\} = \text{Tr}\{\mathbf{BA}\}$
- $\det(\mathbf{I} + \mathbf{AB}) = \det(\mathbf{I} + \mathbf{BA})$

# Reminder: Linear Algebra and Matrix Properties

- Kronecker product:  $\mathbf{A} \otimes \mathbf{B} = \begin{bmatrix} \mathbf{A}(1,1)\mathbf{B} & \dots & \mathbf{A}(1,n)\mathbf{B} \\ \vdots & \dots & \vdots \\ \mathbf{A}(m,1)\mathbf{B} & \dots & \mathbf{A}(m,n)\mathbf{B} \end{bmatrix}$
- $(\mathbf{A} \otimes \mathbf{B}) \otimes \mathbf{C} = \mathbf{A} \otimes (\mathbf{B} \otimes \mathbf{C})$
- $(\mathbf{A} \otimes \mathbf{B})^H = \mathbf{A}^H \otimes \mathbf{B}^H$
- $(\mathbf{A} \otimes \mathbf{B})(\mathbf{C} \otimes \mathbf{D}) = (\mathbf{AC} \otimes \mathbf{BD})$
- $(\mathbf{A} \otimes \mathbf{B})^{-1} = \mathbf{A}^{-1} \otimes \mathbf{B}^{-1}$  if  $\mathbf{A}, \mathbf{B}$  square and non singular.
- $\det(\mathbf{A}_{m \times m} \otimes \mathbf{B}_{n \times n}) = \det(\mathbf{A})^n \det(\mathbf{B})^m$
- $\text{Tr}\{\mathbf{A} \otimes \mathbf{B}\} = \text{Tr}\{\mathbf{A}\} \text{Tr}\{\mathbf{B}\}$
- $\text{vec}(\mathbf{A})$  converts  $[m \times n]$  matrix into  $mn \times 1$  vector by stacking the columns of  $\mathbf{A}$  on top of one another.
  - $\text{vec}(\mathbf{ABC}) = (\mathbf{C}^T \otimes \mathbf{A}) \text{vec}(\mathbf{B})$
- $\text{Tr}\{\mathbf{ABB}^H \mathbf{A}^H\} = \text{vec}(\mathbf{A}^H)^H (\mathbf{I} \otimes \mathbf{BB}^H) \text{vec}(\mathbf{A}^H)$
- $\det(\mathbf{I} + \epsilon \mathbf{A}) = 1 + \epsilon \text{Tr}\{\mathbf{A}\}$  if  $\epsilon \ll 1$

# Space-Time Coding

- MIMO without Transmit Channel Knowledge
- Array/diversity/coding gains are exploitable in SIMO, MISO and ... MIMO
- *Alamouti scheme* can easily be applied to  $2 \times 2$  MIMO channels

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

- Received signal vector (make sure the channel remains constant over two symbol periods!)

$$\mathbf{y}_1 = \sqrt{E_s} \mathbf{H} \begin{bmatrix} c_1/\sqrt{2} \\ c_2/\sqrt{2} \end{bmatrix} + \mathbf{n}_1, \quad (\text{first symbol period})$$

$$\mathbf{y}_2 = \sqrt{E_s} \mathbf{H} \begin{bmatrix} -c_2^*/\sqrt{2} \\ c_1^*/\sqrt{2} \end{bmatrix} + \mathbf{n}_2. \quad (\text{second symbol period})$$

- Equivalently

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2^* \end{bmatrix} = \sqrt{E_s} \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix}}_{{\mathbf{H}_{eff}}} \underbrace{\begin{bmatrix} c_1/\sqrt{2} \\ c_2/\sqrt{2} \end{bmatrix}}_{{\mathbf{c}}} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2^* \end{bmatrix}.$$

# Space-Time Coding

- Apply the matched filter  $\mathbf{H}_{eff}^H$  to  $\mathbf{y}$  ( $\mathbf{H}_{eff}^H \mathbf{H}_{eff} = \|\mathbf{H}\|_F^2 \mathbf{I}_2$ )

$$\mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \sqrt{E_s} \mathbf{H}_{eff}^H \mathbf{y} = \sqrt{E_s} \|\mathbf{H}\|_F^2 \mathbf{I}_2 \mathbf{c} + \mathbf{n}'$$

where  $\mathbf{n}'$  is such that  $\mathcal{E}\{\mathbf{n}'\} = \mathbf{0}_{2 \times 1}$  and  $\mathcal{E}\{\mathbf{n}' \mathbf{n}'^H\} = \|\mathbf{H}\|_F^2 \sigma_n^2 \mathbf{I}_2$ .

- Average output SNR

$$\bar{\rho}_{out} = \frac{E_s}{\sigma_n^2} \mathcal{E} \left\{ \frac{[\|\mathbf{H}\|_F^2]^2}{2 \|\mathbf{H}\|_F^2} \right\} = 2\rho,$$

Receive array gain ( $g_a = n_r = 2$ ) but no transmit array gain!

- Average symbol error rate

$$\bar{P} \leq \bar{N}_e \left( \frac{\rho d_{min}^2}{8} \right)^{-4}.$$

Full diversity ( $g_d^o = n_t n_r = 4$ )

# Dominant Eigenmode Transmission

- MIMO with Perfect Transmit Channel Knowledge
- Extension of Matched Beamforming to MIMO

$$\mathbf{y} = \sqrt{E_s} \mathbf{H} \mathbf{c}' + \mathbf{n} = \sqrt{E_s} \mathbf{H} \mathbf{w} c + \mathbf{n},$$
$$z = \mathbf{g} \mathbf{y} = \sqrt{E_s} \mathbf{g} \mathbf{H} \mathbf{w} c + \mathbf{g} \mathbf{n}.$$

- Decompose

$$\mathbf{H} = \mathbf{U}_{\mathbf{H}} \boldsymbol{\Sigma}_{\mathbf{H}} \mathbf{V}_{\mathbf{H}}^H,$$
$$\boldsymbol{\Sigma}_{\mathbf{H}} = \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_{r(\mathbf{H})}\}.$$

- Received SNR is maximized by matched filtering, leading to

$$\mathbf{w} = \mathbf{v}_{max}$$
$$\mathbf{g} = \mathbf{u}_{max}^H$$

where  $\mathbf{v}_{max}$  and  $\mathbf{u}_{max}$  are respectively the right and left singular vectors corresponding to the maximum singular value of  $\mathbf{H}$ ,  $\sigma_{max} = \max\{\sigma_1, \sigma_2, \dots, \sigma_{r(\mathbf{H})}\}$ . Note the generalization of matched beamforming (MISO) and MRC (SIMO)!

- Equivalent channel:  $z = \sqrt{E_s} \sigma_{max} c + \tilde{n}$  where  $\tilde{n} = \mathbf{g} \mathbf{n}$  has a variance equal to  $\sigma_n^2$ .

# Dominant Eigenmode Transmission

- Array gain:  $\mathcal{E}\{\sigma_{max}^2\} = \mathcal{E}\{\lambda_{max}\}$  where  $\lambda_{max}$  is the largest eigenvalue of  $\mathbf{H}\mathbf{H}^H$ . Commonly,  $\max\{n_t, n_r\} \leq g_a \leq n_t n_r$ .
- Diversity gain: the dominant eigenmode transmission extracts a full diversity gain of  $n_t n_r$  in i.i.d. Rayleigh channels.

# Dominant Eigenmode Transmission

## Example

*Question:* Show that the optimum (in the sense of SNR maximization) transmit precoder and combiner in dominant eigenmode transmission is given by the dominant right and left singular vector of the channel matrix, respectively.

*Answer:* Let us write

$$\mathbf{y} = \sqrt{E_s} \mathbf{H} \mathbf{c}' + \mathbf{n} = \sqrt{E_s} \mathbf{H} \mathbf{w} \mathbf{c} + \mathbf{n},$$

$$z = \mathbf{g} \mathbf{y} = \sqrt{E_s} \mathbf{g} \mathbf{H} \mathbf{w} \mathbf{c} + \mathbf{g} \mathbf{n}.$$

where  $\|\mathbf{w}\|^2 = 1$  (power constraint). We decompose

$$\mathbf{H} = \mathbf{U}_\mathbf{H} \boldsymbol{\Sigma}_\mathbf{H} \mathbf{V}_\mathbf{H}^H, \quad \boldsymbol{\Sigma}_\mathbf{H} = \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_{r(\mathbf{H})}\}.$$

In order to maximize the SNR, we choose  $\mathbf{g}$  as a matched filter, i.e.  
 $\mathbf{g} = (\mathbf{H} \mathbf{w})^H$  such that

$$\mathbf{g} \mathbf{H} \mathbf{w} = \mathbf{w}^H \mathbf{H}^H \mathbf{H} \mathbf{w} = \mathbf{w}^H \mathbf{V}_\mathbf{H} \boldsymbol{\Sigma}_\mathbf{H}^2 \mathbf{V}_\mathbf{H}^H \mathbf{w} = \sum_{i=1}^{r(\mathbf{H})} \sigma_i^2 \left| \mathbf{v}_i^H \mathbf{w} \right|^2 \leq \sigma_{max}^2$$

where  $\mathbf{v}_i$  is the  $i$  column of  $\mathbf{V}_\mathbf{H}$  and  $\sigma_{max} = \max_{i=1, \dots, r(\mathbf{H})} \sigma_i$ .

# Dominant Eigenmode Transmission

## Example

*Answer:* The inequality is replaced by an equality if  $\mathbf{w} = \mathbf{v}_{max}$ . By choosing  $\mathbf{w} = \mathbf{v}_{max}$ ,

$$\begin{aligned}\mathbf{g} &= \mathbf{w}^H \mathbf{H}^H = \mathbf{v}_{max}^H \mathbf{V}_\mathbf{H} \boldsymbol{\Sigma}_\mathbf{H} \mathbf{U}_\mathbf{H}^H \\ &= \sigma_{max} \mathbf{u}_{max}^H\end{aligned}$$

where  $\mathbf{u}_{max}$  is the column of  $\mathbf{U}_\mathbf{H}$  corresponding to the dominant singular value  $\sigma_{max}$  of  $\mathbf{H}$ . If we normalize  $\mathbf{g}$  such that  $\|\mathbf{g}\|^2 = 1$ , we can write  $\mathbf{g} = \mathbf{u}_{max}$ .  $\square$

# Multiple Eigenmode Transmission

- Assume  $n_r \geq n_t$  and that  $r(\mathbf{H}) = n_t$ , i.e.  $n_t$  singular values in  $\mathbf{H}$ . Hence, what about spreading symbols over all non-zero eigenmodes of the channel:
  - Tx side: multiply the input vector  $\mathbf{c}$  ( $n_t \times 1$ ) using  $\mathbf{V}_\mathbf{H}$ , i.e.  $\mathbf{c}' = \mathbf{V}_\mathbf{H}\mathbf{c}$ .
  - Rx side: multiply the received vector  $\mathbf{y}$  by  $\mathbf{G} = \mathbf{U}_\mathbf{H}^H$ .
  - Overall,

$$\begin{aligned}\mathbf{z} &= \sqrt{E_s} \mathbf{G} \mathbf{H} \mathbf{c}' + \mathbf{G} \mathbf{n} \\ &= \sqrt{E_s} \mathbf{U}_\mathbf{H}^H \mathbf{H} \mathbf{V}_\mathbf{H} \mathbf{c} + \mathbf{U}_\mathbf{H}^H \mathbf{n} \\ &= \sqrt{E_s} \boldsymbol{\Sigma}_\mathbf{H} \mathbf{c} + \tilde{\mathbf{n}}.\end{aligned}$$

The channel has been decomposed into  $n_t$  parallel SISO channels given by  $\{\sigma_1, \dots, \sigma_{n_t}\}$ .

- The rate achievable in the MIMO channel is the sum of the SISO channel capacities

$$R = \sum_{k=1}^{n_t} \log_2(1 + \rho s_k \sigma_k^2),$$

where  $\{s_1, \dots, s_{n_t}\}$  is the power allocation on each of the channel eigenmodes.

- The rate scales linearly in  $n_t$ .
- In general, the rate scales linearly with the rank of  $\mathbf{H}$ .

# Multiple Eigenmode Transmission

## Example

*Question:* Is the rate achievable in a MIMO channel with multiple eigenmode transmission and uniform power allocation across modes always larger than that achievable with dominant eigenmode transmission?

*Answer:* No! The achievable rate with multiple eigenmode transmission in the MIMO channel is the sum of the SISO channel achievable rates

$$R = \sum_{k=1}^{r(\mathbf{H})} \log_2(1 + \rho s_k \sigma_k^2),$$

where  $\{s_1, \dots, s_{r(\mathbf{H})}\}$  is the power allocation on each of the channel eigenmodes.

Two strategies (for a total power constraint  $\sum_{k=1}^{r(\mathbf{H})} s_k = 1$ ):

- Uniform power allocation:  $R_u = \sum_{k=1}^{r(\mathbf{H})} \log_2(1 + \rho 1/r(\mathbf{H}) \sigma_k^2)$
- Dominant eigenmode transmission:  $R_d = \log_2(1 + \rho \sigma_{max}^2)$

$R_u$  could be either greater or smaller than  $R_d$ . For instance, if  $\sigma_1 \gg 0$  and  $\sigma_k \approx \epsilon$  for  $k > 1$ ,  $R_u \approx \log_2(1 + \rho \sigma_1^2 / r(\mathbf{H})) \leq R_d$  for small values of  $\rho$ . At very high SNR, despite the little contributions of  $\sigma_k \approx \epsilon$ ,  $R_u$  will become higher than  $R_d$ .



# Multiplexing gain

- Array/diversity/coding gains are exploitable in SIMO, MISO and MIMO but MIMO can offer much more than MISO and SIMO.
- MIMO channels offer *multiplexing gain*: measure of the number of independent streams that can be transmitted in parallel in the MIMO channel. Defined as

$$g_s \triangleq \lim_{\rho \rightarrow \infty} \frac{R(\rho)}{\log_2(\rho)}$$

where  $R(\rho)$  is the transmission rate.

- The multiplexing gain is the pre-log factor of the rate at high SNR, i.e.

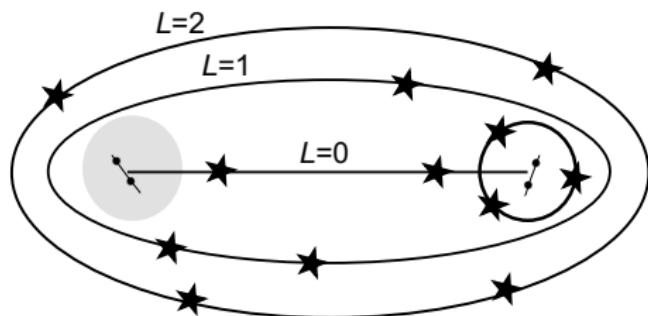
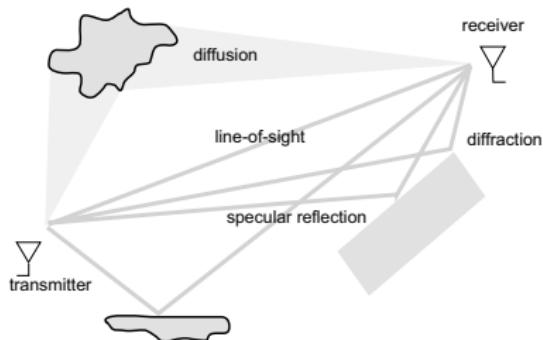
$$R \approx g_s \log_2(\rho)$$

- Modeling only the individual SISO channels from one Tx antenna to one Rx antenna not enough:
  - MIMO performance depends on the channel matrix properties
  - characterize all statistical correlations between all matrix elements necessary!

# The MIMO Channel

# Double-Directional Channel Modeling

- Space comes as an additional dimension
  - *directional*: model the angular distribution of the energy at the antennas
  - *double*: there are multiple antennas at transmit and receive sides
- Spatial distribution of scatterers matters
  - delay-spread  $\iff$  channel frequency selectivity
  - angle-spread  $\iff$  channel spatial selectivity



# The MIMO Channel Matrix

- $n_r \times n_t$  narrowband MIMO channel (the channel is not frequency selective)

$$\mathbf{H}(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \dots & h_{1n_t}(t) \\ h_{21}(t) & h_{22}(t) & \dots & h_{2n_t}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_r 1}(t) & h_{n_r 2}(t) & \dots & h_{n_r n_t}(t) \end{bmatrix},$$

# Statistical Properties of the MIMO Channel Matrix

- Assume narrowband channels, the spatial correlation matrix of the MIMO channel

$$\mathbf{R} = \mathcal{E}\{\text{vec}(\mathbf{H}^H)\text{vec}(\mathbf{H}^H)^H\}$$

This is a  $n_t n_r \times n_t n_r$  positive semi-definite Hermitian matrix.

- It describes the correlation between all pairs of transmit-receive channels:

- $\mathcal{E}\{\mathbf{H}(n, m)\mathbf{H}^*(n, m)\}$ : the average energy of the channel between antenna  $m$  and antenna  $n$ ,
- $r_m^{(nq)} = \mathcal{E}\{\mathbf{H}(n, m)\mathbf{H}^*(q, m)\}$ : the receive correlation between channels originating from transmit antenna  $m$  and impinging upon receive antennas  $n$  and  $q$ ,
- $t_n^{(mp)} = \mathcal{E}\{\mathbf{H}(n, m)\mathbf{H}^*(n, p)\}$ : the transmit correlation between channels originating from transmit antennas  $m$  and  $p$  and arriving at receive antenna  $n$ ,
- $\mathcal{E}\{\mathbf{H}(n, m)\mathbf{H}^*(q, p)\}$ : the cross-channel correlation between channels  $(m, n)$  and  $(q, p)$ .

## Example

2x2 MIMO

$$\mathbf{R} = \begin{bmatrix} 1 & t_1^* & r_1^* & s_1^* \\ t_1 & 1 & s_2^* & r_2^* \\ r_1 & s_2 & 1 & t_2^* \\ s_1 & r_2 & t_2 & 1 \end{bmatrix} \quad \begin{aligned} t_1 &= \mathcal{E}\{\mathbf{H}(1, 1)\mathbf{H}^*(1, 2)\} \\ r_1 &= \mathcal{E}\{\mathbf{H}(1, 1)\mathbf{H}^*(2, 1)\} \end{aligned}$$



# Spatial Correlation

- When the energy spreading is very large at both sides and  $d_t/d_r$  are sufficiently large, elements of  $\mathbf{H}$  become uncorrelated, and  $\mathbf{R}$  becomes diagonal.

## Example

Consider two transmit antennas spaced by  $d_t$ .

- *isotropic scattering*: very rich scattering environment around the transmitter with a uniform distribution of the energy.

$$t = J_0 \left( 2\pi \frac{d_t}{\lambda} \right).$$

The transmit correlation only depends on the spacing between the two antennas.

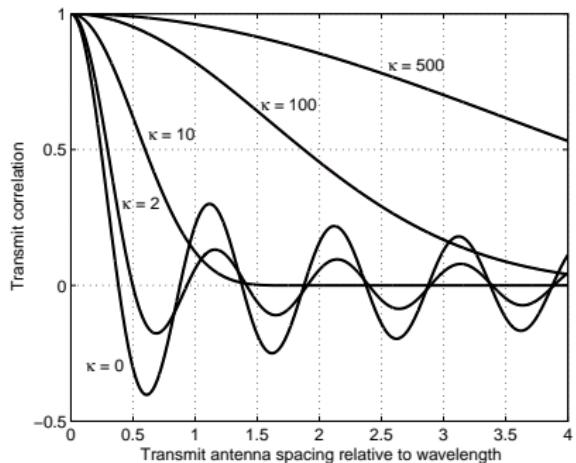
- *highly directional scattering*: scatterers around the transmit array are concentrated along a narrow direction  $\theta_{t,0}$ , i.e.,  $\mathcal{A}_t(\theta_t) \rightarrow \delta(\theta_t - \theta_{t,0})$

$$t \rightarrow e^{j\varphi_t(\theta_{t,0})} = e^{j2\pi(d_t/\lambda) \cos \theta_{t,0}}.$$

Very high transmit correlation approaching one. The scattering direction is directly related to the phase of the transmit correlation.

# Spatial Correlation

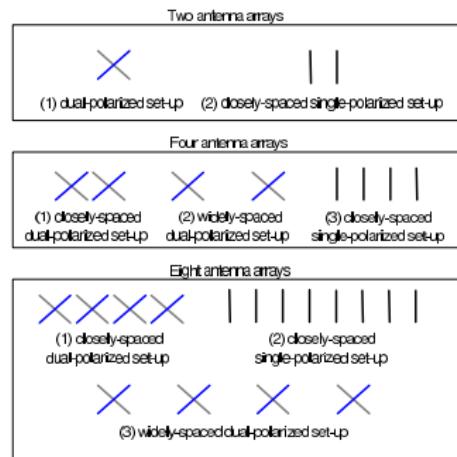
## Example



- $\mathcal{A}_t(\theta_t)$  in real-world channels: neither uniform nor a delta.
- isotropic scattering ( $\kappa = 0$ ): first minimum for  $d_t = 0.38\lambda$
- directional scattering ( $\kappa = \infty$ ): correlation never reaches 0
- in practice, decorrelation in rich scattering is reached for  $d_t \approx 0.5\lambda$
- The more directional the azimuthal dispersion (i.e. for  $\kappa$  increasing), the larger the antenna spacing required to obtain a null correlation.

# Analytical Representation of Rayleigh MIMO Channels

- Independent and Identically Distributed (I.I.D.) Rayleigh fading
  - $\mathbf{R} = \mathbf{I}_{n_t n_r}$
  - $\mathbf{H} = \mathbf{H}_w$  is a random fading matrix with unit variance and i.i.d. circularly symmetric complex Gaussian entries.
- Realistic in practice only if both conditions are satisfied:
  - the antenna spacings and/or the angle spreads at Tx and Rx are large enough,
  - all individual channels characterized by the same average power (i.e., balanced array).
- What about real-world channels? Sometimes significantly deviate from this ideal channel:
  - *limited angular spread and/or reduced array sizes* cause the channels to become *correlated* (channels are not independent anymore)
  - a *coherent contribution* may induce the channel statistics to become *Ricean* (channels are not Rayleigh distributed anymore),
  - the use of multiple *polarizations* creates gain imbalances between the various elements of the channel matrix (channel are not identically distributed anymore).



# Correlated Rayleigh Fading Channels

- For identically distributed Gaussian channels,  $\mathbf{R}$  constitutes a sufficient description of the stochastic behavior of the MIMO channel.
- Any channel realization is obtained by

$$\text{vec}(\mathbf{H}^H) = \mathbf{R}^{1/2} \text{vec}(\mathbf{H}_w),$$

where  $\mathbf{H}_w$  is one realization of an i.i.d. channel matrix.

- Complicated to use because
  - cross-channel correlation not intuitive and not easily tractable
  - Too many parameters: dimensions of  $\mathbf{R}$  rapidly become large as the array sizes increase
  - vec operation complicated for performance analysis
- Kronecker model: use a separability assumption

$$\mathbf{R} = \mathbf{R}_r \otimes \mathbf{R}_t,$$

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2}$$

where  $\mathbf{R}_t$  and  $\mathbf{R}_r$  are respectively the transmit and receive correlation matrices.

- Strictly valid only if  $r_1 = r_2 = r$  and  $t_1 = t_2 = t$  and  $s_1 = rt$  and  $s_2 = rt^*$  (for  $2 \times 2$ )

$$\mathbf{R} = \begin{bmatrix} 1 & t_1^* & r_1^* & s_1^* \\ t_1 & 1 & s_2^* & r_2^* \\ r_1 & s_2 & 1 & t_2^* \\ s_1 & r_2 & t_2 & 1 \end{bmatrix} = \begin{bmatrix} 1 & t^* & r^* & r^*t^* \\ t & 1 & r^*t & r^* \\ r & rt^* & 1 & t^* \\ rt & r & t & 1 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & r^* \\ r & 1 \end{bmatrix}}_{\mathbf{R}_r} \otimes \underbrace{\begin{bmatrix} 1 & t^* \\ t & 1 \end{bmatrix}}_{\mathbf{R}_t}$$

# Capacity of MIMO Channels

# Previous Lectures

- Transmission strategies
  - Space-Time Coding when no Tx channel knowledge
  - Multiple (including dominant) eigenmode transmission when Tx channel knowledge

$$\begin{aligned}\mathbf{z} &= \sqrt{E_s} \mathbf{G} \mathbf{H} \mathbf{c}' + \mathbf{G} \mathbf{n} \\ &= \sqrt{E_s} \mathbf{U}_\mathbf{H}^H \mathbf{H} \mathbf{V}_\mathbf{H} \mathbf{c} + \mathbf{U}^H \mathbf{n} \\ &= \sqrt{E_s} \boldsymbol{\Sigma}_\mathbf{H} \mathbf{c} + \tilde{\mathbf{n}}.\end{aligned}$$

Multiple parallel data pipes → Spatial multiplexing gain!

- Performance highly depends on the channel matrix properties
  - Angle spread and inter-element spacing
  - Spatial Correlation: spread antennas far apart to decrease spatial correlation
  - Rayleigh and Ricean distribution

# System Model

- A single-user MIMO system with  $n_t$  transmit and  $n_r$  receive antennas over a frequency flat-fading channel.
- The transmit and received signals in a MIMO channel are related by

$$\mathbf{y}_k = \sqrt{E_s} \mathbf{H}_k \mathbf{c}'_k + \mathbf{n}_k$$

where

- $\mathbf{y}_k$  is the  $n_r \times 1$  received signal vector,
- $\mathbf{H}_k$  is the  $n_r \times n_t$  channel matrix
- $\mathbf{n}_k$  is a  $n_r \times 1$  zero mean complex additive white Gaussian noise (AWGN) vector with  $\mathcal{E}\{\mathbf{n}_k \mathbf{n}_l^H\} = \sigma_n^2 \mathbf{I}_{n_r} \delta(k-l)$ .
- $\rho = E_s / \sigma_n^2$  represents the SNR.
- The input covariance matrix is defined as the covariance matrix of the transmit signal  $\mathbf{c}'$  (we drop the time index) and writes as  $\mathbf{Q} = \mathcal{E}\{\mathbf{c}' \mathbf{c}'^H\}$ .
- Power constraint:  $\text{Tr}\{\mathbf{Q}\} \leq 1$ .
- Channel time variation:  $T_{coh}$  coherence time
  - *slow fading*:  $T_{coh}$  is so long that coding is performed over a single channel realization.
  - *fast fading*:  $T_{coh}$  is so short that coding over multiple channel realizations is possible.

# Capacity of Deterministic MIMO Channels

## Proposition

For a deterministic MIMO channel  $\mathbf{H}$ , the mutual information  $\mathcal{I}$  is written as

$$\mathcal{I}(\mathbf{H}, \mathbf{Q}) = \log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right]$$

where  $\mathbf{Q}$  is the input covariance matrix whose trace is normalized to unity.

## Definition

The capacity of a deterministic  $n_r \times n_t$  MIMO channel with perfect channel state information at the transmitter is

$$C(\mathbf{H}) = \max_{\mathbf{Q} \geq 0: \text{Tr}\{\mathbf{Q}\}=1} \log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right].$$

Note the difference with SISO capacity.

# Capacity and Water-Filling Algorithm

- What is the best transmission strategy, i.e. the optimum input covariance matrix  $\mathbf{Q}$ ?
- First, create  $n = \min\{n_t, n_r\}$  parallel data pipes (Multiple Eigenmode Transmission)
  - Decouple the channel along the individual channel modes (in the directions of the singular vectors of the channel matrix  $\mathbf{H}$  at both the transmitter and the receiver)

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

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

- Optimum input covariance matrix  $\mathbf{Q}^*$  writes as

$$\mathbf{Q}^* = \mathbf{V}_\mathbf{H} \text{diag} \{s_1^*, \dots, s_n^*\} \mathbf{V}_\mathbf{H}^H,$$

- Second, allocate power to data pipes

- $\boldsymbol{\Sigma}_\mathbf{H} = \text{diag} \{\sigma_1, \dots, \sigma_n\}$ , and  $\sigma_k^2 \triangleq \lambda_k$

- Capacity:  $C(\mathbf{H}) = \max_{\{s_k\}_{k=1}^n} \sum_{k=1}^n \log_2 [1 + \rho s_k \lambda_k] = \sum_{k=1}^n \log_2 [1 + \rho s_k^* \lambda_k]$

## Proposition

The power allocation strategy  $\{s_1, \dots, s_n\} = \{s_1^*, \dots, s_n^*\}$  that maximizes  $\sum_{k=1}^n \log_2 (1 + \rho \lambda_k s_k)$  under the power constraint  $\sum_{k=1}^n s_k = 1$ , is given by the water-filling solution,

$$s_k^* = \left( \mu - \frac{1}{\rho \lambda_k} \right)^+, \quad k = 1, \dots, n$$

where  $\mu$  is chosen so as to satisfy the power constraint  $\sum_{k=1}^n s_k^* = 1$ .



# Water-Filling Algorithm

- Iterative power allocation
  - Order eigenvalues  $\lambda_k$  in decreasing order of magnitude
  - At iteration  $i$ , evaluate the constant  $\mu$  from the power constraint

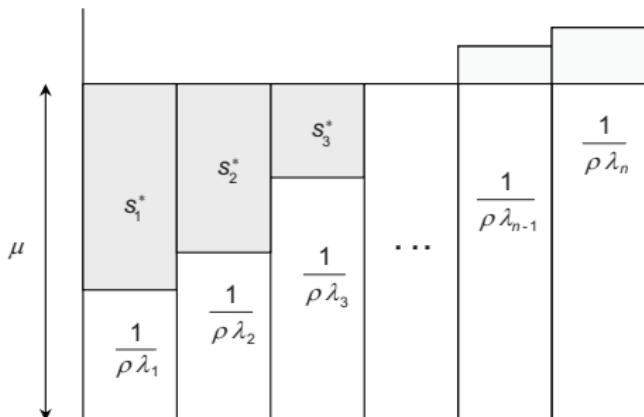
$$\mu(i) = \frac{1}{n-i+1} \left( 1 + \sum_{k=1}^{n-i+1} \frac{1}{\rho \lambda_k} \right)$$

- Calculate power

$$s_k(i) = \mu(i) - \frac{1}{\rho \lambda_k}, \quad k = 1, \dots, n-i+1.$$

If  $s_{n-i+1} < 0$ , set to 0

- Iterate till the power allocated on each mode is non negative.



# Water-Filling Algorithm

## Example

*Question:* Consider the transmission  $\mathbf{y} = \mathbf{H}\mathbf{c}' + \mathbf{n}$  with perfect CSIT over a deterministic point to point MIMO channel whose matrix is given by

$$\mathbf{H} = \begin{bmatrix} a & 0 & a & 0 \\ 0 & b & 0 & b \end{bmatrix}$$

where  $a$  and  $b$  are complex scalars with  $|a| \geq |b|$ . The input covariance matrix is given by  $\mathbf{Q} = \mathcal{E}\{\mathbf{c}'\mathbf{c}'^H\}$  and is subject to the transmit power constraint  $\text{Tr}\{\mathbf{Q}\} \leq P$ .

- ① Compute the capacity with perfect CSIT of that deterministic channel.  
Particularize to the case  $a = b$ . Explain your reasoning.
- ② Explain how to achieve that capacity.
- ③ In which deployment scenario, could such channel matrix structure be encountered?

# Water-Filling Algorithm

## Example

Answer:

- ① Let us write  $\mathbf{Q} = \mathbf{V}\mathbf{P}\mathbf{V}^H$  with the diagonal element of  $\mathbf{P}$ , denoted as  $P_k$  (satisfying  $\sum_{k=1}^{n_t} P_k = P$ ), refers to the power allocated to stream  $k$ . The capacity with perfect CSIT over the deterministic channel  $\mathbf{H}$  is given by

$$C(\mathbf{H}) = \max_{P_1, \dots, P_k} \sum_{k=1}^{\min\{2,4\}} \log_2 \left( 1 + \frac{P_k}{\sigma_n^2} \lambda_k \right)$$

where  $\lambda_k$  refers the non-zero eigenvalue of  $\mathbf{H}^H \mathbf{H}$ , respectively equal to  $2|a|^2$  and  $2|b|^2$ . Hence,

$$C(\mathbf{H}) = \max_{P_1, P_2} \left( \log_2 \left( 1 + \frac{P_1}{\sigma_n^2} 2|a|^2 \right) + \log_2 \left( 1 + \frac{P_2}{\sigma_n^2} 2|b|^2 \right) \right).$$

The optimal power allocation is given by the water-filling solution

$$P_1^* = \left( \mu - \frac{\sigma_n^2}{2|a|^2} \right)^+, \quad P_2^* = \left( \mu - \frac{\sigma_n^2}{2|b|^2} \right)^+$$

with  $\mu$  computed such that  $P_1^* + P_2^* \equiv P$ .



# Water-Filling Algorithm

## Example

Answer:

Assuming  $P_1^*$  and  $P_2^*$  are positive,  $\mu = \frac{P}{2} + \frac{\sigma_n^2}{4} \left( \frac{1}{|a|^2} + \frac{1}{|b|^2} \right)$ . If  $\mu - \frac{\sigma_n^2}{2|b|^2} \leq 0$ , i.e.  $\frac{P}{2} + \frac{\sigma_n^2}{4|a|^2} - \frac{\sigma_n^2}{4|b|^2} \leq 0$ ,  $P_2^* = 0$  and  $P_1^* = P$ . The capacity writes as

$$C(\mathbf{H}) = \log_2 \left( 1 + \frac{P}{\sigma_n^2} 2 |a|^2 \right).$$

If  $\frac{P}{2} + \frac{\sigma_n^2}{4|a|^2} - \frac{\sigma_n^2}{4|b|^2} > 0$ ,  $P_1^* = \frac{P}{2} - \frac{\sigma_n^2}{4|a|^2} + \frac{\sigma_n^2}{4|b|^2}$  and  $P_2^* = \frac{P}{2} + \frac{\sigma_n^2}{4|a|^2} - \frac{\sigma_n^2}{4|b|^2}$ .

The capacity writes as

$$C(\mathbf{H}) = \log_2 \left( 1 + \frac{P_1^*}{\sigma_n^2} 2 |a|^2 \right) + \log_2 \left( 1 + \frac{P_2^*}{\sigma_n^2} 2 |b|^2 \right).$$

In the particular case where  $a = b$ , uniform power allocation  $P_1^* = P_2^* = \frac{P}{2}$  is optimal and

$$C(\mathbf{H}) = 2 \log_2 \left( 1 + \frac{P}{\sigma_n^2} |a|^2 \right).$$

# Water-Filling Algorithm

## Example

Answer:

- ② Transmit along  $\mathbf{V}$ , given by the two dominant eigenvector of  $\mathbf{H}^H \mathbf{H}$ . They are easily computed given the orthogonality of the channel matrix  $\mathbf{H}$  as

$$\mathbf{V} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

The power allocated to the two streams is given by  $P_1^*$  and  $P_2^*$ . At the receiver, the precoded channel is already decoupled and no further combiner is necessary. Each stream can be decoded using the corresponding SISO decoder.

- ③ Dual-polarized antenna deployment (e.g. VH/VH-VH) with LoS and good antenna XPD.



# Capacity Bounds and Suboptimal Power Allocations

- Low SNR: power allocated to the dominant eigenmode

$$C(\mathbf{H}) \xrightarrow{\rho \rightarrow 0} \log_2(1 + \rho \lambda_{max}).$$

- High SNR: power is uniformly allocated among the non-zero modes

$$C(\mathbf{H}) \xrightarrow{\rho \rightarrow \infty} \sum_{k=1}^n \log_2 \left(1 + \frac{\rho}{n} \lambda_k\right) \cong n \log_2 \left(\frac{\rho}{n}\right) + \sum_{k=1}^n \log_2(\lambda_k).$$

**Observations:**  $C(\mathbf{H})$  scales linearly with  $n$ . The spatial multiplexing gain is  $g_s = n$ . MISO fading channels do not offer any multiplexing gain.

- At any SNR

$$C(\mathbf{H}) \geq \log_2(1 + \rho \lambda_{max}),$$

$$C(\mathbf{H}) \geq \sum_{k=1}^n \log_2 \left(1 + \frac{\rho}{n} \lambda_k\right).$$

# Impact on Coding Architecture

- Transmit independent streams in the directions of the eigenvectors of the channel matrix  $\mathbf{H}$ .
- For a total transmission rate  $R$ , each stream  $k$  can then be encoded using a capacity-achieving Gaussian code with rate  $R_k$  such that  $\sum_{k=1}^n R_k = R$ , ascribed a power  $\lambda_k$  and be decoded independently of the other streams.
- The optimal power allocation based on the water-filling allocation strategy.

# Ergodic Capacity of Fast Fading Channels

- Fast fading:
  - Doppler frequency sufficiently high to allow for coding over many channel realizations/coherence time periods
  - The transmission capability is represented by a single quantity known as the ergodic capacity
- With Perfect Transmit Channel Knowledge, similar to deterministic channels
- Focus on Partial Transmit Channel Knowledge

# MIMO Capacity with Partial Transmit Channel Knowledge

- $\mathbf{H}$  is not known to the transmitter  $\rightarrow$  we cannot adapt  $\mathbf{Q}$  at all time instants
- Rate of information flow between Tx and Rx at time instant  $k$  over channels  $\mathbf{H}_k$

$$\log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H}_k \mathbf{Q} \mathbf{H}_k^H \right].$$

Such a rate varies over time according to the channel fluctuations. The average rate of information flow over a time duration  $T \gg T_{coh}$  is

$$\frac{1}{T} \sum_{k=0}^{T-1} \log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H}_k \mathbf{Q} \mathbf{H}_k^H \right].$$

## Definition

The ergodic capacity of a  $n_r \times n_t$  MIMO channel with channel distribution information at the transmitter (CDIT) is given by

$$\bar{C}_{CDIT} \triangleq \bar{C} = \max_{\mathbf{Q} \geq 0: \text{Tr}\{\mathbf{Q}\}=1} \mathcal{E} \left\{ \log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right] \right\},$$

where  $\mathbf{Q}$  is the input covariance matrix optimized as to maximize the ergodic mutual information.

- $T \gg T_c$  to average out the noise and the channel fluctuations

# I.I.D. Rayleigh Fast Fading Channels: Partial Transmit Channel Knowledge

- Optimal covariance matrix

## Proposition

In i.i.d. Rayleigh fading channels, the ergodic capacity with CDIT is achieved under an equal power allocation scheme  $\mathbf{Q} = \mathbf{I}_{n_t}/n_t$ , i.e.,

$$\bar{C}_{CDIT} = \bar{\mathcal{I}}_e = \mathcal{E} \left\{ \log_2 \det \left[ \mathbf{I}_{n_r} + \frac{\rho}{n_t} \mathbf{H}_w \mathbf{H}_w^H \right] \right\} = \mathcal{E} \left\{ \sum_{k=1}^n \log_2 \left[ 1 + \frac{\rho}{n_t} \lambda_k \right] \right\}.$$

Encoding requires a fixed-rate code (whose rate is given by the ergodic capacity) with encoding spanning many channel realizations.

- Low SNR:

$$\bar{C}_{CDIT} \geq \mathcal{E} \left\{ \log_2 \left[ 1 + \frac{\rho}{n_t} \|\mathbf{H}_w\|_F^2 \right] \right\} \approx \frac{\rho}{n_t} \mathcal{E} \left\{ \|\mathbf{H}_w\|_F^2 \right\} \log_2(e) = n_r \rho \log_2(e)$$

## Observations:

- $\bar{C}_{CDIT}$  is only determined by the energy of the channel.
- A MIMO channel only yields a  $n_r$  gain over a SISO channel. Increasing the number of transmit antennas is not useful (contrary to perfect CSIT). SIMO and MIMO channels reach the same capacity for a given  $n_r$ .

# I.I.D. Rayleigh Fast Fading Channels: Partial Transmit Channel Knowledge

- High SNR:

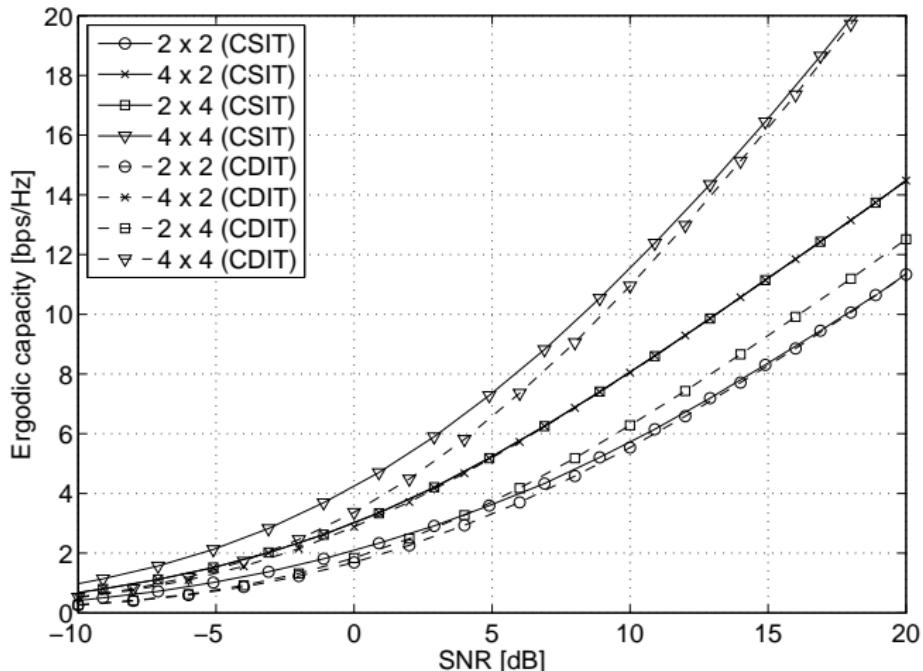
$$\bar{C}_{CDIT} \approx \mathcal{E} \left\{ \sum_{k=1}^n \log_2 \left[ \frac{\rho}{n_t} \lambda_k \right] \right\} = n \log_2 \left( \frac{\rho}{n_t} \right) + \mathcal{E} \left\{ \sum_{k=1}^n \log_2 (\lambda_k) \right\}$$

## Observations:

- $\bar{C}_{CDIT}$  at high SNR scales linearly with  $n$  (by contrast to the low SNR regime).
- The multiplexing gain  $g_s$  is equal to  $n$ , similarly to the CSIT case.
- $\bar{C}_{CDIT}$  and  $\bar{C}_{CSIT}$  are not equal: constant gap equal to  $n \log_2(n_t/n)$  at high SNR.
- Expressions can be particularized to SISO, SIMO, MISO cases. At high SNR,
  - SISO ( $N = n = 1$ ):
$$\bar{C}_{CDIT} \approx \log_2(\rho) + \mathcal{E} \left\{ \log_2 \left( |h|^2 \right) \right\} = \log_2(\rho) - 0.83 = C_{AWGN} - 0.83$$
  - SIMO ( $n_t = n = 1, n_r = N$ ):
$$\bar{C}_{CDIT} \approx \log_2(n_r \rho)$$
  - MISO ( $n_r = n = 1, n_t = N$ ):
$$\bar{C}_{CDIT} \approx \log_2(\rho) + \mathcal{E} \left\{ \log_2 \left( \|h\|^2 / n_t \right) \right\} \xrightarrow{n_t \rightarrow \infty} \log_2(\rho) = C_{AWGN}$$

# I.I.D. Rayleigh Fast Fading Channels

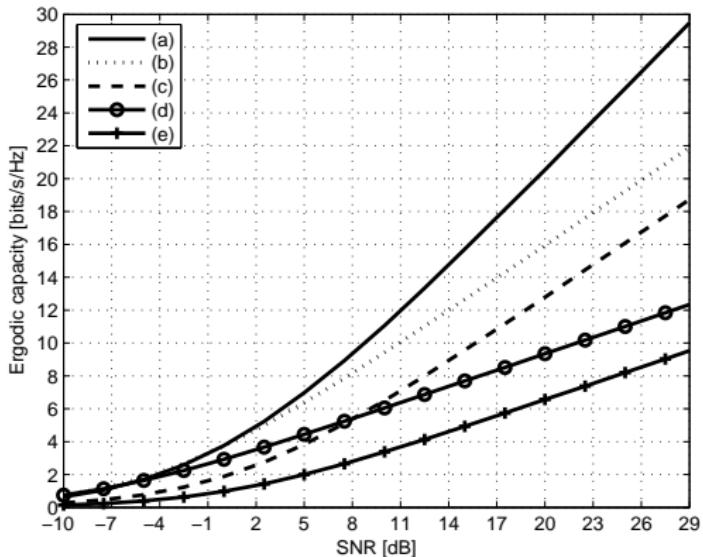
- Ergodic capacity of various  $n_r \times n_t$  i.i.d. Rayleigh channels with full (CSIT) and partial (CDIT) channel knowledge at the transmitter.



# I.I.D. Rayleigh Fast Fading Channels

## Example

**Question:** Here is the ergodic capacity of point-to-point i.i.d. Rayleigh fast fading channels with Channel Distribution Information at the Transmitter (CDIT) for five antenna ( $n_r \times n_t$ ) configurations (denoted as (a) to (e)) with  $n_t + n_r = 8$ .



# I.I.D. Rayleigh Fast Fading Channels

## Example

**Question:** What is the achievable (spatial) multiplexing gain (at high SNR) for cases (a), (b), (c), (d) and (e)? Provide your reasoning.

**Answer:** The multiplexing gain is the pre-log factor of the ergodic capacity at high SNR, i.e.  $g_s = \lim_{\rho \rightarrow \infty} \frac{\bar{C}_{CDIT}}{\log_2(\rho)}$ . Hence by increasing the SNR by 3dB (e.g. from 17dB to 20dB), the ergodic capacity increases by  $g_s$  bits/s/Hz.

- (a)  $g_s = 3$ .
- (b)  $g_s = 2$ .
- (c)  $g_s = 2$ .
- (d)  $g_s = 1$ .
- (e)  $g_s = 1$ .

# I.I.D. Rayleigh Fast Fading Channels

## Example

**Question:** For (a), (b), (c), (d) and (e), identify an antenna configuration, i.e.  $n_t$  and  $n_r$ , satisfying  $n_t + n_r = 8$  that achieves such multiplexing gain. Provide your reasoning.

**Answer:** There are several possible configurations that satisfy to  $n_r + n_t = 8$ , namely  $5 \times 3$ ,  $3 \times 5$ ,  $6 \times 2$ ,  $2 \times 6$ ,  $7 \times 1$  and  $1 \times 7$ ,  $4 \times 4$ . The matching between curves and antenna configurations is easily identified by using the following two arguments: 1) The multiplexing gain with CDIT at high SNR is given by  $\min\{n_t, n_r\}$ . 2) With CDIT only, the input covariance matrix in i.i.d. channel is  $\mathbf{Q} = 1/n_t \mathbf{I}_{n_t}$ . This implies that  $6 \times 2$  and  $7 \times 1$  outperform  $2 \times 6$  and  $1 \times 7$ , respectively.

- (a)  $n_r \times n_t = 5 \times 3$  or  $3 \times 5$
- (b)  $n_r \times n_t = 6 \times 2$
- (c)  $n_r \times n_t = 2 \times 6$
- (d)  $n_r \times n_t = 7 \times 1$
- (e)  $n_r \times n_t = 1 \times 7$

# Impact on Coding Architecture

- When the channel is i.i.d. Rayleigh fading,  $\mathbf{Q} = (1/n_t) \mathbf{I}_{n_t}$ .
- Transmission of independent information symbols may be performed in parallel over  $n$  virtual spatial channels.
- The transmitter is very similar to the CSIT case except that all eigenmodes now receive the same amount of power.
- Transmit with uniform power allocation over  $n_t$  independent streams, each stream using an AWGN capacity-achieving code and perform joint ML decoding (independent decoding of all streams is clearly suboptimal due to interference between streams).

# Outage Capacity and Probability in Slow Fading Channels

- In slow fading, the encoding still averages out the randomness of the noise but cannot fully average out the randomness of the channel.
- For a given channel realization  $\mathbf{H}$  and a target rate  $R$ , reliable transmission if

$$\log_2 \det \left( \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right) > R$$

If not met with any  $\mathbf{Q}$ , an outage occurs and the decoding error probability is strictly non-zero.

- Look at the tail probability of  $\log_2 \det \left( \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right)$ , not its average!

## Definition

The outage probability  $P_{out}(R)$  of a  $n_r \times n_t$  MIMO channel with a target rate  $R$  is given by

$$P_{out}(R) = \min_{\mathbf{Q} \geq 0: \text{Tr}\{\mathbf{Q}\} \leq 1} P \left( \log_2 \det \left( \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right) < R \right),$$

where  $\mathbf{Q}$  is the input covariance matrix optimized as to minimize the outage probability.

- More meaningful in the absence of CSI knowledge at the transmitter: the transmitter cannot adjust its transmit strategy → hopes the channel is good enough

# Diversity-Multiplexing Trade-Off in Slow Fading Channels

- For a given  $R$ , how does  $P_{out}$  behave as a function of the SNR  $\rho$ ?

## Definition

A diversity gain  $g_d^*(g_s, \infty)$  is achieved at multiplexing gain  $g_s$  at *infinite SNR* if

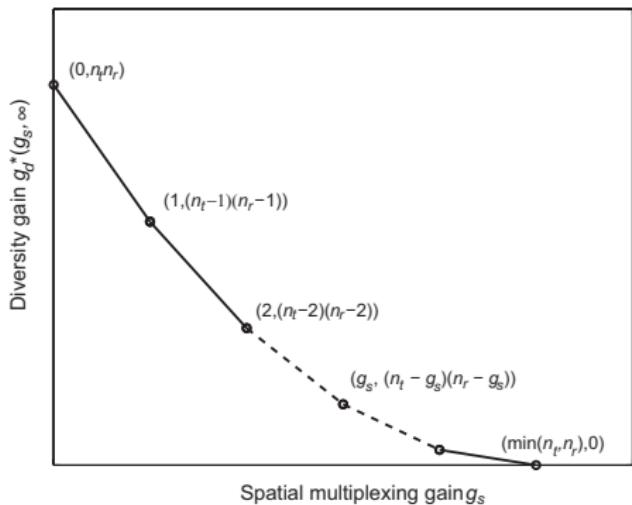
$$\lim_{\rho \rightarrow \infty} \frac{R(\rho)}{\log_2(\rho)} = g_s$$
$$\lim_{\rho \rightarrow \infty} \frac{\log_2(P_{out}(R))}{\log_2(\rho)} = -g_d^*(g_s, \infty)$$

The curve  $g_d^*(g_s, \infty)$  as function of  $g_s$  is known as the asymptotic diversity-multiplexing trade-off of the channel.

- The multiplexing gain indicates how fast the transmission rate increases with the SNR.
- The diversity gain represents how fast the outage probability decays with the SNR.

# Diversity-Multiplexing Trade-Off in I.I.D. Rayleigh Slow Fading Channels

- Point  $(0, n_t n_r)$ : for a spatial multiplexing gain of zero (i.e.,  $R$  is fixed), the maximal diversity gain achievable is  $n_t n_r$ .
- Point  $(\min \{n_t, n_r\}, 0)$ : transmitting at diversity gain  $g_d^* =$  (i.e.,  $P_{out}$  is kept fixed) allows the data rate to increase with SNR as  $n = \min \{n_t, n_r\}$ .
- Intermediate points: possible to transmit at non-zero diversity and multiplexing gains but that any increase of one of those quantities leads to a decrease of the other quantity.



# Diversity-Multiplexing Trade-Off in I.I.D. Rayleigh Slow Fading Channels

- For fixed rates  $R = 2, 4, \dots, 40$  bits/s/Hz,
  - The asymptotic slope of each curve is four and matches the maximum diversity gain  $g_d^*(0, \infty)$ .
  - The horizontal separation is 2 bits/s/Hz per 3 dB, which corresponds to the maximum multiplexing gain equal to  $n (= 2)$ .
- As the rate increases more rapidly with SNR (i.e., as the multiplexing gain  $g_s$  increases), the slope of the outage probability curve (given by the diversity gain  $g_d^*$ ) vanishes.

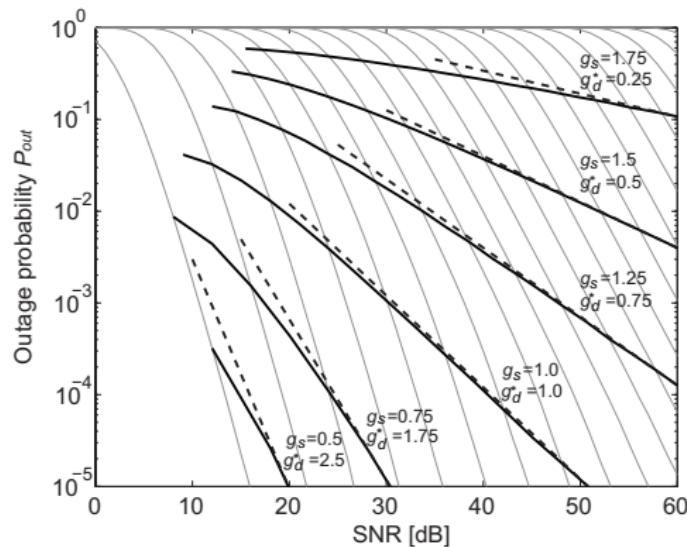


Figure:  $2 \times 2$  MIMO i.i.d. Rayleigh fading channels

# Impact on Coding Architecture

- Impossible to code over a large number of independent channel realizations → separate coding leads to an outage as soon as one of the subchannels is in deep fade.
- Joint coding across all subchannels necessary in the absence of transmit channel knowledge!

# Tx and Rx Strategies: Space-Time Coding and Processing

# Previous Lectures

- Previous lecture

- Capacity of deterministic MIMO channels

$$C(\mathbf{H}) = \max_{\mathbf{Q} \geq 0: \text{Tr}\{\mathbf{Q}\}=1} \log_2 \det \left[ \mathbf{I}_{n_r} + \rho \mathbf{H} \mathbf{Q} \mathbf{H}^H \right].$$

- Ergodic capacity of fast fading channels
  - Outage capacity and probability of slow fading channels

- MIMO provides huge gains in terms of reliability and transmission rate

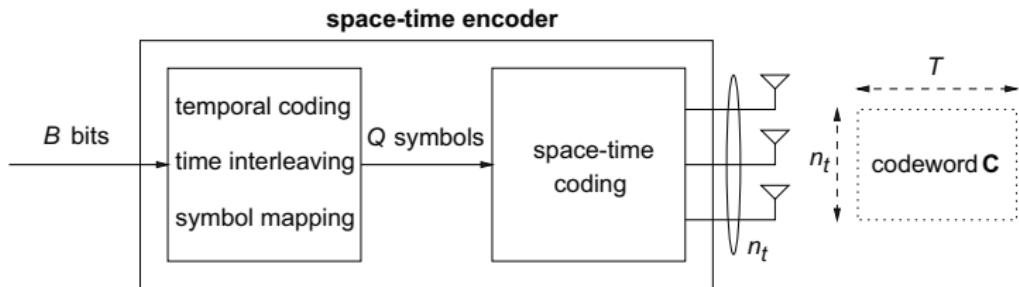
- diversity gain, array gain, coding gain, spatial multiplexing gain, interference management

- What we further need

- practical methodologies to achieve these gains?
  - how to code across space and time?
  - Some preliminary answers: multimode eigenmode transmission when channel knowledge available at the Tx, Alamouti scheme when no channel knowledge available at the Tx

# Overview of a Space-Time Encoder

- Space-time encoder: sequence of two black boxes



- First black box: combat the randomness created by the noise at the receiver.
- Second black box: spatial interleaver which spreads symbols over several antennas in order to mitigate the spatial selective fading.
- The ratio  $B/T$  is the signaling rate of the transmission.
- The ratio  $Q/T$  is defined as the spatial multiplexing rate (representative of how many symbols are packed within a codeword per unit of time).

# System Model

- MIMO system with  $n_t$  transmit and  $n_r$  receive antennas over a frequency flat-fading channel
- Transmit a codeword  $\mathbf{C} = [\mathbf{c}_0 \dots \mathbf{c}_{T-1}]$  [ $n_t \times T$ ] contained in the codebook  $\mathcal{C}$
- At the  $k^{\text{th}}$  time instant, the transmitted and received signals are related by

$$\mathbf{y}_k = \sqrt{E_s} \mathbf{H}_k \mathbf{c}_k + \mathbf{n}_k$$

where

- $\mathbf{y}_k$  is the  $n_r \times 1$  received signal vector,
- $\mathbf{H}_k$  is the  $n_r \times n_t$  channel matrix,
- $\mathbf{n}_k$  is a  $n_r \times 1$  zero mean complex AWGN vector with  $\mathcal{E}\{\mathbf{n}_k \mathbf{n}_l^H\} = \sigma_n^2 \mathbf{I}_{n_r} \delta(k - l)$ ,
- The parameter  $E_s$  is the energy normalization factor. SNR  $\rho = E_s / \sigma_n^2$ .
- No transmit channel knowledge but we know it is i.i.d. Rayleigh fading.
- Codeword average transmit power  $\mathcal{E}\{\text{Tr}\{\mathbf{C}\mathbf{C}^H\}\} = T$ . Assume  $\mathcal{E}\{\|\mathbf{H}\|_F^2\} = n_t n_r$ .
- Channel time variation:
  - *slow fading*:  $T_{coh} >> T$  and  $\{\mathbf{H}_k = \mathbf{H}_w\}_{k=0}^{T-1}$ , with  $\mathbf{H}_w$  denoting an i.i.d. random fading matrix with unit variance circularly symmetric complex Gaussian entries.
  - *fast fading*:  $T \geq T_{coh}$  and  $\mathbf{H}_k = \mathbf{H}_{k,w}$ , where  $\{\mathbf{H}_{k,w}\}_{k=0}^{T-1}$  are uncorrelated matrices, each  $\{\mathbf{H}_{k,w}\}$  being an i.i.d. random fading matrix with unit variance circularly symmetric complex Gaussian entries.

# Error Probability Motivated Design Methodology

- With instantaneous channel realizations perfectly known at the receive side, the ML decoder computes an estimate of the transmitted codeword according to

$$\hat{\mathbf{C}} = \arg \min_{\mathbf{C}} \sum_{k=0}^{T-1} \left\| \mathbf{y}_k - \sqrt{E_s} \mathbf{H}_k \mathbf{c}_k \right\|^2$$

where the minimization is performed over all possible codeword vectors  $\mathbf{C}$ .

- Pairwise Error Probability (PEP): probability that the ML decoder decodes the codeword  $\mathbf{E} = [\mathbf{e}_0 \dots \mathbf{e}_{T-1}]$  instead of the transmitted codeword  $\mathbf{C}$ .
- When the PEP is conditioned on the channel realizations  $\{\mathbf{H}_k\}_{k=0}^{T-1}$ , it is defined as the conditional PEP,

$$P(\mathbf{C} \rightarrow \mathbf{E} | \{\mathbf{H}_k\}_{k=0}^{T-1}) = \mathcal{Q}\left(\sqrt{\frac{\rho}{2} \sum_{k=0}^{T-1} \|\mathbf{H}_k (\mathbf{c}_k - \mathbf{e}_k)\|_F^2}\right)$$

where  $\mathcal{Q}(x)$  is the Gaussian  $\mathcal{Q}$ -function.

- The average PEP,  $P(\mathbf{C} \rightarrow \mathbf{E})$ , obtained by averaging the conditional PEP over the probability distribution of the channel gains.
- System performance dominated at high SNR by the couples of codewords that lead to the worst PEP.

# Diversity Gain and Coding Gain

- Assume a fixed rate transmission, i.e., spatial multiplexing gain  $g_s = 0$ .

## Definition

The **diversity gain**  $g_d^o(\rho)$  achieved by a pair of codewords  $\{\mathbf{C}, \mathbf{E}\} \in \mathcal{C}$  is defined as the slope of  $P(\mathbf{C} \rightarrow \mathbf{E})$  as a function of the SNR  $\rho$  on a log-log scale, usually evaluated at very high SNR, i.e.,

$$g_d^o(\infty) = \lim_{\rho \rightarrow \infty} g_d^o(\rho) = - \lim_{\rho \rightarrow \infty} \frac{\log_2 (P(\mathbf{C} \rightarrow \mathbf{E}))}{\log_2 \rho}.$$

PS:  $g_d^o(\infty) \leftrightarrow P(\mathbf{C} \rightarrow \mathbf{E})$ ,  $g_d^*(0, \infty) \leftrightarrow P_{out}$ .

## Definition

The **coding gain** achieved by a pair of codewords  $\{\mathbf{C}, \mathbf{E}\} \in \mathcal{C}$  is defined as the magnitude of the left shift of the  $P(\mathbf{C} \rightarrow \mathbf{E})$  vs.  $\rho$  curve evaluated at very high SNR.

- If  $P(\mathbf{C} \rightarrow \mathbf{E})$  is well approximated at high SNR by

$$P(\mathbf{C} \rightarrow \mathbf{E}) \approx c (g_c \rho)^{-g_d^o(\infty)}$$

with  $c$  being a constant,  $g_c$  is identified as the coding gain.

# Derivation of the Average PEP

- Conditional PEP

$$P \left( \mathbf{C} \rightarrow \mathbf{E} \mid \{\mathbf{H}_k\}_{k=0}^{T-1} \right) = \mathcal{Q} \left( \sqrt{\frac{\rho}{2} \sum_{k=0}^{T-1} \|\mathbf{H}_k (\mathbf{c}_k - \mathbf{e}_k)\|_F^2} \right)$$

where  $\mathcal{Q}(x)$  is the Gaussian  $\mathcal{Q}$ -function defined as

$$\mathcal{Q}(x) \triangleq P(y \geq x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{y^2}{2}\right) dy.$$

- Average PEP

$$P(\mathbf{C} \rightarrow \mathbf{E}) = \mathcal{E}_{\mathbf{H}_k} \left\{ P \left( \mathbf{C} \rightarrow \mathbf{E} \mid \{\mathbf{H}_k\}_{k=0}^{T-1} \right) \right\}.$$

- This integration is sometimes difficult to calculate. Use Chernoff bound

$$\mathcal{Q}(x) \leq \exp\left(-\frac{x^2}{2}\right).$$

- Average PEP

$$P(\mathbf{C} \rightarrow \mathbf{E}) = \mathcal{E}_{\mathbf{H}_k} \left\{ P \left( \mathbf{C} \rightarrow \mathbf{E} \mid \{\mathbf{H}_k\}_{k=0}^{T-1} \right) \right\}$$

- Computable using moment generating function (MGF), e.g. see in SISO

# Slow Fading MIMO Channels

- The conditional PEP writes as

$$P(\mathbf{C} \rightarrow \mathbf{E} | \mathbf{H}) = \mathcal{Q}\left(\sqrt{\frac{\rho}{2} \|\mathbf{H}(\mathbf{C} - \mathbf{E})\|_F^2}\right).$$

- The average PEP over Rayleigh slow fading channels is

$$P(\mathbf{C} \rightarrow \mathbf{E}) = \mathcal{E}_{\mathbf{H}} \{P(\mathbf{C} \rightarrow \mathbf{E} | \mathbf{H})\}$$

- Using MGF and Chernoff bound

$$P(\mathbf{C} \rightarrow \mathbf{E}) \leq \left[ \det \left( \mathbf{I}_{n_t} + \frac{\rho}{4} \tilde{\mathbf{E}} \right) \right]^{-n_r} = \prod_{i=1}^{r(\tilde{\mathbf{E}})} \left( 1 + \frac{\rho}{4} \lambda_i(\tilde{\mathbf{E}}) \right)^{-n_r}$$

with  $r(\tilde{\mathbf{E}})$  denotes the rank of the error matrix  $\tilde{\mathbf{E}} = (\mathbf{C} - \mathbf{E})(\mathbf{C} - \mathbf{E})^H$  and  $\{\lambda_i(\tilde{\mathbf{E}})\}$  for  $i = 1, \dots, r(\tilde{\mathbf{E}})$  the set of its non-zero eigenvalues.

- At high SNR,  $\frac{\rho}{4} \lambda_i(\tilde{\mathbf{E}}) \gg 1$

$$P(\mathbf{C} \rightarrow \mathbf{E}) \leq \left( \frac{\rho}{4} \right)^{-n_r r(\tilde{\mathbf{E}})} \prod_{i=1}^{r(\tilde{\mathbf{E}})} \lambda_i^{-n_r}(\tilde{\mathbf{E}})$$

- diversity gain:  $n_r r(\tilde{\mathbf{E}})$ , coding gain:  $\prod_{i=1}^{r(\tilde{\mathbf{E}})} \lambda_i(\tilde{\mathbf{E}})$ .

# The Rank-Determinant Criterion

## Design Criterion

(Rank-determinant criterion) Over i.i.d. Rayleigh slow fading channels,

- ① **rank criterion:** maximize the minimum rank  $r_{min}$  of  $\tilde{\mathbf{E}}$  over all pairs of codewords  $\{\mathbf{C}, \mathbf{E}\}$  with  $\mathbf{C} \neq \mathbf{E}$

$$r_{min} = \min_{\substack{\mathbf{C}, \mathbf{E} \\ \mathbf{C} \neq \mathbf{E}}} r(\tilde{\mathbf{E}})$$

- ② **determinant criterion:** over all pairs of codewords  $\{\mathbf{C}, \mathbf{E}\}$  with  $\mathbf{C} \neq \mathbf{E}$ , maximize the minimum of the product  $d_\lambda$  of the non-zero eigenvalues of  $\tilde{\mathbf{E}}$ ,

$$d_\lambda = \min_{\substack{\mathbf{C}, \mathbf{E} \\ \mathbf{C} \neq \mathbf{E}}} \prod_{i=1}^{r(\tilde{\mathbf{E}})} \lambda_i(\tilde{\mathbf{E}}).$$

If  $r_{min} = n_t$ , the determinant criterion comes to maximize the minimum determinant of the error matrix over all pairs of codewords  $\{\mathbf{C}, \mathbf{E}\}$  with  $\mathbf{C} \neq \mathbf{E}$

$$d_\lambda = \min_{\substack{\mathbf{C}, \mathbf{E} \\ \mathbf{C} \neq \mathbf{E}}} \det(\tilde{\mathbf{E}}).$$

# The Rank-Determinant Criterion

## Definition

A full-rank (a.k.a. full-diversity) code is characterized by  $r_{min} = n_t$ . A rank-deficient code is characterized by  $r_{min} < n_t$ .

## Example

Rank-deficient and full-rank codes for  $n_t = 2$

- Rank-deficient code

$$\mathbf{C} = \frac{1}{\sqrt{2}} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}, \mathbf{E} = \frac{1}{\sqrt{2}} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

- Full-rank code

$$\mathbf{C} = \frac{1}{\sqrt{2}} \begin{bmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{bmatrix}, \mathbf{E} = \frac{1}{\sqrt{2}} \begin{bmatrix} e_1 & -e_2^* \\ e_2 & e_1^* \end{bmatrix}$$

$$(\mathbf{C} - \mathbf{E})(\mathbf{C} - \mathbf{E})^H = \frac{1}{2} \begin{bmatrix} |c_1 - e_1|^2 + |c_2 - e_2|^2 & 0 \\ 0 & |c_1 - e_1|^2 + |c_2 - e_2|^2 \end{bmatrix}$$

# The Rank-Determinant Criterion

## Example

**Question:** Assume that  $c_1, c_2, c_3$  and  $c_4$  are constellation symbols taken from a unit average energy QAM constellation. Consider the Linear Space-Time Block Code, characterized by codewords

$$\mathbf{C} = \frac{1}{2} \begin{bmatrix} c_1 + c_3 & c_2 + c_4 \\ c_2 - c_4 & c_1 - c_3 \end{bmatrix}.$$

What is the diversity gain achieved by this code over slow Rayleigh fading channels?

**Answer:** Check the rank of its error matrix

$$\mathbf{C} - \mathbf{E} = \frac{1}{2} \begin{bmatrix} d_1 + d_3 & d_2 + d_4 \\ d_2 - d_4 & d_1 - d_3 \end{bmatrix}$$

where  $d_k = c_k - e_k$  for  $k = 1, \dots, 4$ . This code is rank deficient. It is easily seen that by taking two codewords  $\mathbf{C}$  and  $\mathbf{E}$  such that  $d_3 = d_4 = 0$  and  $d_1 = d_2 = d$  (which is encountered for any constellations),  $r(\mathbf{C} - \mathbf{E}) = 1$ . Hence diversity gain of  $n_r$ .

# Space-Time Block Coding (STBC)

- STBCs can be seen as a mapping of  $Q$  symbols (complex or real) onto a codeword  $\mathbf{C}$  of size  $n_t \times T$ .
- Codewords are uncoded in the sense that no error correcting code is contained in the STBC.
- Linear STBCs are by far the most widely used
  - Spread information symbols in space and time in order to improve either the diversity gain, either the spatial multiplexing rate ( $r_s = \frac{Q}{T}$ ) or both the diversity gain and the spatial multiplexing rate.
  - Pack more symbols into a given codeword, i.e., increase  $Q$ , to increase the data rate.

## Example

Alamouti code:  $n_t = 2$ ,  $Q = 2$ ,  $T = 2$ ,  $r_s = 1$

$$\mathbf{C} = \frac{1}{\sqrt{2}} \begin{bmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{bmatrix}.$$

# Spatial Multiplexing/V-BLAST/D-BLAST

- Spatial Multiplexing (SM), also called V-BLAST, is a full rate code ( $r_s = n_t$ ) that consists in transmitting independent data streams on each transmit antenna.
- In uncoded transmissions, we assume one symbol duration ( $T = 1$ ) and codeword  $\mathbf{C}$  is a symbol vector of size  $n_t \times 1$ .

## Example

$$\mathbf{C} = \frac{1}{\sqrt{n_t}} \begin{bmatrix} c_1 & \dots & c_{n_t} \end{bmatrix}^T.$$

Each element  $c_q$  is a symbol chosen from a given constellation.

# ML decoding

- Error probability

$$P(\mathbf{C} \rightarrow \mathbf{E}) \leq \left( \frac{\rho}{4n_t} \right)^{-n_r} \left( \sum_{q=1}^{n_t} |c_q - e_q|^2 \right)^{-n_r}$$

The SNR exponent is equal to  $n_r$ . Due to the lack of coding across transmit antennas, no transmit diversity is achieved and only receive diversity is exploited.

- Over fast fading channels, we know that it is not necessary to code across antennas to achieve the ergodic capacity.

## Proposition

*Spatial Multiplexing with ML decoding and equal power allocation achieves the ergodic capacity of i.i.d. Rayleigh fast fading channels.*

# Zero-Forcing (ZF) Linear Receiver

- MIMO ZF receiver acts similarly to a ZF equalizer in frequency selective channels.
- ZF filtering effectively decouples the channel into  $n_t$  parallel channels
  - interference from other transmitted symbols is suppressed
  - scalar decoding may be performed on each of these channels
- The complexity of ZF decoding similar to SISO ML decoding, but the inversion step is responsible for the noise enhancement (especially at low SNR).
- Assuming that a symbol vector  $\mathbf{C} = 1/\sqrt{n_t} [ c_1 \dots c_{n_t} ]^T$  is transmitted, the output of the ZF filter  $\mathbf{G}_{ZF}$  is given by

$$\mathbf{z} = \mathbf{G}_{ZF}\mathbf{y} = [ c_1 \dots c_{n_t} ]^T + \mathbf{G}_{ZF}\mathbf{n}$$

where  $\mathbf{G}_{ZF}$  inverts the channel,

$$\mathbf{G}_{ZF} = \sqrt{\frac{n_t}{E_s}} \mathbf{H}^\dagger$$

with  $\mathbf{H}^\dagger = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H$  denoting the Moore-Penrose pseudo inverse.

# Zero-Forcing (ZF) Linear Receiver

- Covariance matrix of the noise at the output of the ZF filter

$$\mathcal{E} \left\{ \mathbf{G}_{ZF} \mathbf{n} (\mathbf{G}_{ZF} \mathbf{n})^H \right\} = \frac{n_t}{\rho} \mathbf{H}^\dagger \left( \mathbf{H}^\dagger \right)^H = \frac{n_t}{\rho} \left( \mathbf{H}^H \mathbf{H} \right)^{-1}.$$

- The output SNR on the  $q^{\text{th}}$  subchannel is thus given by

$$\rho_q = \frac{\rho}{n_t} \frac{1}{(\mathbf{H}^H \mathbf{H})^{-1}(q, q)}, \quad q = 1, \dots, n_t.$$

- Inversion leads to noise enhancement. Severe degradation at low SNR.
- Assuming that the channel is i.i.d. Rayleigh distributed,  $\rho_q$  is a  $\chi^2$  random variable with  $2(n_r - n_t + 1)$  degrees of freedom, denoted as  $\chi_{2(n_r - n_t + 1)}^2$ . The average PEP on the  $q^{\text{th}}$  subchannel is thus upper-bounded by

$$P(c_q \rightarrow e_q) \leq \left( \frac{\rho}{4n_t} \right)^{-(n_r - n_t + 1)} |c_q - e_q|^{-2(n_r - n_t + 1)}.$$

The lower complexity of the ZF receiver comes at the price of a diversity gain limited to  $n_r - n_t + 1$ . Clearly, the system is undetermined if  $n_t > n_r$ .

# Zero-Forcing (ZF) Linear Receiver

- In fast fading channels, the average maximum achievable rate  $\bar{C}_{ZF}$  is equal to the sum of the maximum rates achievable by all layers

$$\begin{aligned}\bar{C}_{ZF} &= \sum_{q=1}^{\min\{n_t, n_r\}} \mathcal{E} \left\{ \log_2 (1 + \rho_q) \right\} \\ &\stackrel{(\rho \nearrow)}{\approx} \min \{n_t, n_r\} \log_2 \left( \frac{\rho}{n_t} \right) + \min \{n_t, n_r\} \mathcal{E} \left\{ \log_2 (\chi^2_{2(n_r - n_t + 1)}) \right\}.\end{aligned}$$

Spatial Multiplexing in combination with a ZF decoder allows for transmitting over  $n = \min \{n_t, n_r\}$  independent data pipes.

# Zero-Forcing (ZF) Linear Receiver

- ZF receiver maximizes the SNR under the constraint that the interferences from all other layers are nulled out.
  - For a given layer  $q$ , the ZF combiner  $\mathbf{g}_q$  is such that this layer is detected through a projection of the output vector  $\mathbf{y}$  onto the direction closest to  $\mathbf{H}(:, q)$  within the subspace orthogonal to the one spanned by the set of vectors  $\mathbf{H}(:, p)$ ,  $p \neq q$ .
- Assume the following system model with  $n_r \geq n_t$

$$\begin{aligned}\mathbf{y} &= \mathbf{H}\mathbf{c} + \mathbf{n}, \\ &= \mathbf{h}_q c_q + \sum_{p \neq q} \mathbf{h}_p c_p + \mathbf{n}\end{aligned}$$

where  $\mathbf{h}_q$  is the  $q^{th}$  column of  $\mathbf{H}$ .

- Let us build the following  $n_r \times (n_t - 1)$  matrix by collecting all  $h_p$  with  $p \neq q$ :

$$\begin{aligned}\mathbf{H}_{-q} &= [\dots \quad \mathbf{h}_p \quad \dots]_{p \neq q}, \\ &= [\mathbf{U}' \quad \tilde{\mathbf{U}}] \mathbf{\Lambda} \mathbf{V}^H\end{aligned}$$

where  $\tilde{\mathbf{U}}$  is the matrix containing the left singular vectors corresponding to the null singular values. Similarly we define

$$\mathbf{c}_{-q} = [\dots \quad c_p \quad \dots]_{p \neq q}^T.$$

# Zero-Forcing (ZF) Linear Receiver

- By multiplying by  $\tilde{\mathbf{U}}^H$ , we project the output vector onto the subspace orthogonal to the one spanned by the columns of  $\mathbf{H}_{-q}$

$$\begin{aligned}\tilde{\mathbf{U}}^H \mathbf{y} &= \tilde{\mathbf{U}}^H \mathbf{h}_q c_q + \tilde{\mathbf{U}}^H \mathbf{H}_{-q} \mathbf{c}_{-q} + \tilde{\mathbf{U}}^H \mathbf{n} \\ &= \tilde{\mathbf{U}}^H \mathbf{h}_q c_q + \tilde{\mathbf{U}}^H \mathbf{n}.\end{aligned}$$

- To maximize the SNR, noting the noise is still white, we match to the effective channel  $\tilde{\mathbf{U}}^H \mathbf{h}_q$  such that

$$z = \left( \tilde{\mathbf{U}}^H \mathbf{h}_q \right)^H \tilde{\mathbf{U}}^H \mathbf{h}_q c_q + \left( \tilde{\mathbf{U}}^H \mathbf{h}_q \right)^H \tilde{\mathbf{U}}^H \mathbf{n}$$

and the ZF combiner is  $g_q = \left( \tilde{\mathbf{U}}^H \mathbf{h}_q \right)^H \tilde{\mathbf{U}}^H = \mathbf{h}_q^H \tilde{\mathbf{U}} \tilde{\mathbf{U}}^H$ .

# Minimum Mean Squared Error (MMSE) Linear Receiver

- Filter maximizing the SINR. Minimize the total resulting noise: find  $\mathbf{G}$  such that  $\mathcal{E}\{\|\mathbf{Gy} - [c_1 \dots c_{n_t}]^T\|^2\}$  is minimum.
- The combined noise plus interference signal  $\mathbf{n}_{i,q}$  when estimating symbol  $c_q$  writes as

$$\mathbf{n}_{i,q} = \sum_{p \neq q} \sqrt{\frac{E_s}{n_t}} \mathbf{h}_p c_p + \mathbf{n}.$$

The covariance matrix of  $\mathbf{n}_{i,q}$  reads as

$$\mathbf{R}_{\mathbf{n}_{i,q}} = \mathcal{E}\left\{\mathbf{n}_{i,q} \mathbf{n}_{i,q}^H\right\} = \sigma_n^2 \mathbf{I}_{n_r} + \sum_{p \neq q} \frac{E_s}{n_t} \mathbf{h}_p \mathbf{h}_p^H$$

and the MMSE combiner for stream  $q$  is given by

$$\mathbf{g}_{MMSE,q} = \sqrt{\frac{E_s}{n_t}} \mathbf{h}_q^H \left( \sigma_n^2 \mathbf{I}_{n_r} + \sum_{p \neq q} \frac{E_s}{n_t} \mathbf{h}_p \mathbf{h}_p^H \right)^{-1}.$$

- An alternative and popular representation of the MMSE filter can also be written as

$$\mathbf{G}_{MMSE} = \sqrt{\frac{n_t}{E_s}} \left( \mathbf{H}^H \mathbf{H} + \frac{n_t}{\rho} \mathbf{I}_{n_t} \right)^{-1} \mathbf{H}^H = \sqrt{\frac{n_t}{E_s}} \mathbf{H}^H \left( \mathbf{H} \mathbf{H}^H + \frac{n_t}{\rho} \mathbf{I}_{n_r} \right)^{-1}$$

- Bridge between matched filtering at low SNR and ZF at high SNR.

# Minimum Mean Squared Error (MMSE) Linear Receiver

- The output SINR on the  $q^{\text{th}}$  subchannel (stream) is given by

$$\rho_q = \frac{E_s}{n_t} \mathbf{h}_q^H \left( \sigma_n^2 \mathbf{I}_{n_r} + \sum_{p \neq q} \frac{E_s}{n_t} \mathbf{h}_p \mathbf{h}_p^H \right)^{-1} \mathbf{h}_q.$$

- At high SNR, the MMSE filter is practically equivalent to ZF and the diversity achievable is thus limited to  $n_r - n_t + 1$ .

# Successive Interference Canceler

- Successively decode one symbol (or more generally one layer/stream) and cancel the effect of this symbol from the received signal.
  - Decoding order based on the SINR of each symbol/layer: the symbol/layer with the highest SINR is decoded first at each iteration.
  - SM with (ordered) SIC is generally known as V-BLAST, and ZF and MMSE  
V-BLAST refer to SM with respectively ZF-SIC and MMSE-SIC receivers.
- 
- The diversity order experienced by the decoded layer is increased by one at each iteration. Therefore, the symbol/layer detected at iteration  $i$  will achieve a diversity of  $n_r - n_t + i$ .
  - Major issue: error propagation
    - The error performance is mostly dominated by the weakest stream.
    - Non-ordered SIC: diversity order approximately  $n_r - n_t + 1$ .
    - Ordered SIC: performance improved by reducing the error propagation caused by the first decoded stream. The diversity order remains lower than  $n_r$ .

# Successive Interference Canceler

① *Initialization:*  $i \leftarrow 1$ ,  $\mathbf{y}^{(1)} = \mathbf{y}$ ,  $\mathbf{G}^{(1)} = \mathbf{G}_{ZF}(\mathbf{H})$ ,  $q_1 \stackrel{(*)}{=} \arg \min_j \|\mathbf{G}^{(1)}(j, :) \|^2$   
where  $\mathbf{G}_{ZF}(\mathbf{H})$  is defined as the ZF filter of the matrix  $\mathbf{H}$ .

② *Recursion:*

① *step 1:* extract the  $q_i^{\text{th}}$  transmitted symbol from the received signal  $\mathbf{y}^{(i)}$

$$\tilde{c}_{q_i} = \mathbf{G}^{(i)}(q_i, :) \mathbf{y}^{(i)}$$

where  $\mathbf{G}^{(i)}(q_i, :)$  is the  $q_i^{\text{th}}$  row of  $\mathbf{G}^{(i)}$ ;

② *step 2:* slice  $\tilde{c}_{q_i}$  to obtain the estimated transmitted symbol  $\hat{c}_{q_i}$ ;

③ *step 3:* assume that  $\hat{c}_{q_i} = c_{q_i}$  and construct the received signal

$$\begin{aligned}\mathbf{y}^{(i+1)} &= \mathbf{y}^{(i)} - \sqrt{\frac{E_s}{n_t}} \mathbf{H}(:, q_i) \hat{c}_{q_i} \\ \mathbf{G}^{(i+1)} &= \mathbf{G}_{ZF}(\mathbf{H}_{\overline{q_i}}) \\ i &\leftarrow i + 1 \\ q_{i+1} &\stackrel{(*)}{=} \arg \min_{j \notin \{q_1, \dots, q_i\}} \|\mathbf{G}^{(i+1)}(j, :) \|^2\end{aligned}$$

where  $\mathbf{H}_{\overline{q_i}}$  is the matrix obtained by zeroing columns  $q_1, \dots, q_i$  of  $\mathbf{H}$ . Here  $\mathbf{G}_{ZF}(\mathbf{H}_{\overline{q_i}})$  denotes the ZF filter applied to  $\mathbf{H}_{\overline{q_i}}$ .

# Successive Interference Canceler

- In fast fading channels, the maximum rate achievable with ZF-SIC

$$\begin{aligned}\bar{C}_{ZF-SIC} &= \sum_{q=1}^{\min\{n_t, n_r\}} \mathcal{E}\{\log_2(1 + \rho_q)\} \\ &\stackrel{(\rho \nearrow)}{\approx} \min\{n_t, n_r\} \log_2 \left( \frac{\rho}{n_t} \right) + \sum_{q=1}^{\min\{n_t, n_r\}} \mathcal{E}\{\log_2(\chi^2_{2(n_r - n_t + q)})\} = \bar{C}_{CDIT}\end{aligned}$$

The loss that was observed with ZF filtering is now compensated because the successive interference cancellation improves the SNR of each decoded layer.

## Proposition

*Spatial Multiplexing with ZF-SIC (ZF V-BLAST) and equal power allocation achieves the ergodic capacity of i.i.d. Rayleigh fast fading MIMO channels at asymptotically high SNR.*

This only holds true when error propagation is neglected.

# Successive Interference Canceler

- MMSE-SIC does better for any SNR

$$\bar{C}_{MMSE-SIC} = \sum_{q=1}^{\min\{n_t, n_r\}} \mathcal{E}\{\log_2(1 + \rho_q)\} = \mathcal{E}\left\{\log_2 \det\left(\mathbf{I}_{n_r} + \frac{\rho}{n_t} \mathbf{H} \mathbf{H}^H\right)\right\} = \bar{\mathcal{I}}_e,$$

## Proposition

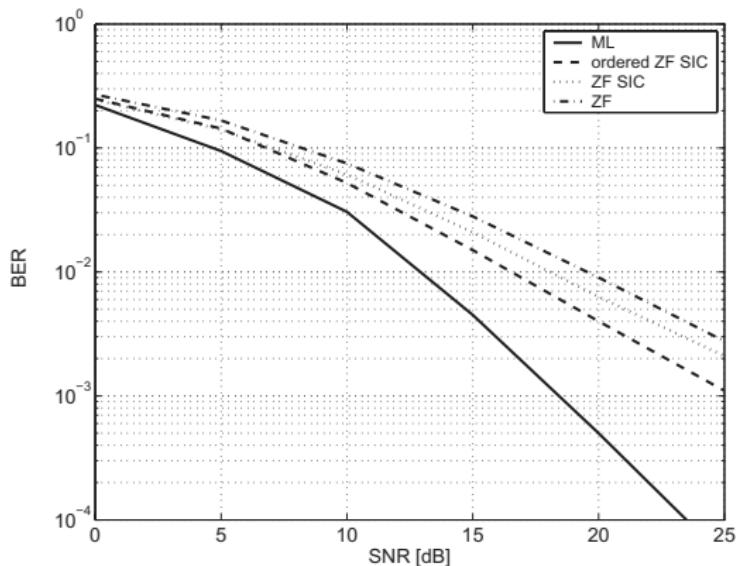
*Spatial Multiplexing with MMSE-SIC (MMSE V-BLAST) and equal power allocation achieves the ergodic capacity for all SNR in i.i.d. Rayleigh fast fading MIMO channels.*

Result also valid for a deterministic channel.

- Diversity achieved similar to that of ZF/MMSE receiver. This comes from the fact that the first layer dominates the error probability since its error exponent is the smallest.

# Impact of Decoding Strategy on Error Probability

- SM with ML, ordered and non ordered ZF SIC (with perfect cancellation) and simple ZF decoding in  $2 \times 2$  i.i.d. Rayleigh fading channels for 4 bits/s/Hz.



The slope of the ML curve approaches 2. ZF only achieves a diversity order of  $n_r - n_t + 1 = 1$ .

# Orthogonal Space-Time Block Codes

- O-STBC vs. SM
  - Remarkable properties which make them extremely easy to decode: MIMO ML decoding decouples into several SIMO ML decoding
  - Achieve a full-diversity of  $n_t n_r$ .
  - Much smaller spatial multiplexing rate than SM.
- Linear STBC characterized by the two following properties

$$\mathbf{C}\mathbf{C}^H = \frac{T}{Qn_t} \left[ \sum_{q=1}^Q |c_q|^2 \right] \mathbf{I}_{n_t}.$$

- Complex O-STBCs with  $r_s = 1$  only exist for  $n_t = 2$ . For larger  $n_t$ , codes exist with  $r_s \leq 1/2$ . For some particular values of  $n_t > 2$ , complex O-STBCs with  $1/2 < r_s < 1$  have been developed. This is the case for  $n_t = 3$  and  $n_t = 4$  with  $r_s = 3/4$ .

# Orthogonal Space-Time Block Codes

## Example

Alamouti code: complex O-STBC for  $n_t = 2$  with a spatial multiplexing rate  $r_s = 1$

$$\mathbf{C} = \frac{1}{\sqrt{2}} \begin{bmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{bmatrix}.$$

- $\mathbf{CC}^H = \frac{1}{2} [ |c_1|^2 + |c_2|^2 ] \mathbf{I}_2$ .
- $r_s = 1$  since two symbols are transmitted over two symbol durations.

## Example

For  $n_t = 3$ , a complex O-STBC expanding on four symbol durations ( $T = 4$ ) and transmitting three symbols on each block ( $Q = 3$ )

$$\mathbf{C} = \frac{2}{3} \begin{bmatrix} c_1 & -c_2^* & c_3^* & 0 \\ c_2 & c_1^* & 0 & c_3^* \\ c_3 & 0 & -c_1^* & -c_2^* \end{bmatrix}.$$

The spatial multiplexing rate  $r_s$  is equal to  $3/4$ .

# Orthogonal Space-Time Block Codes

- Error Probability

$$P(\mathbf{C} \rightarrow \mathbf{E}) \stackrel{(\rho \nearrow)}{\leq} \left( \frac{\rho}{4} \frac{T}{Qn_t} \right)^{-n_r n_t} \left( \sum_{q=1}^Q |c_q - e_q|^2 \right)^{-n_r n_t}.$$

Full diversity gain of  $n_t n_r$ .

# Orthogonal Space-Time Block Codes

- O-STBCs are not capacity efficient  $\mathcal{I}_{O-STBC}(\mathbf{H}) \leq \mathcal{I}_e(\mathbf{H})$ 
  - mutual information of MIMO channel

$$\mathcal{I}_e(\mathbf{H}) = \log_2 \left( 1 + \frac{\rho}{n_t} \|\mathbf{H}\|_F^2 + \dots + \left( \frac{\rho}{n_t} \right)^{r(\mathbf{H})} \prod_{k=1}^{r(\mathbf{H})} \lambda_k(\mathbf{H}\mathbf{H}^H) \right).$$

- rate achieved by the O-STBC

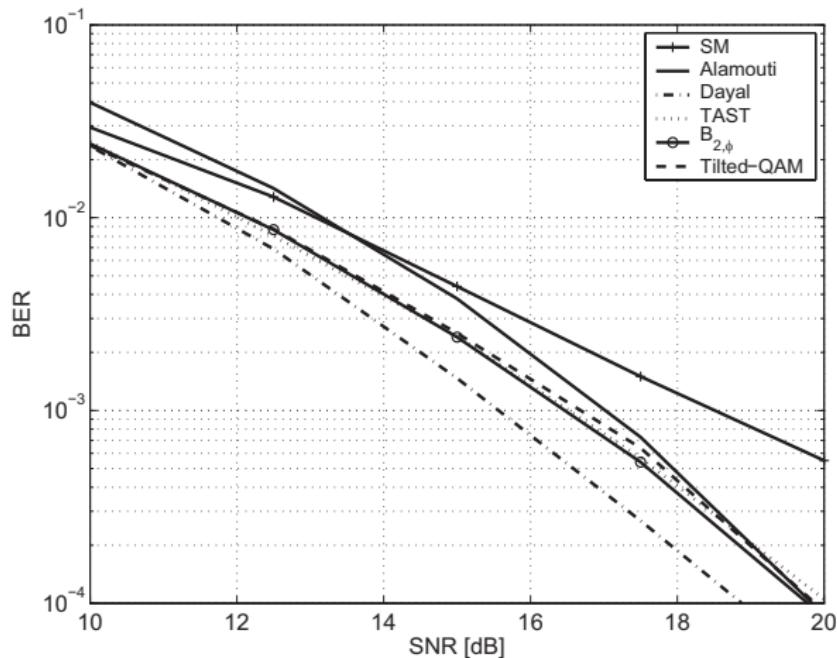
$$\mathcal{I}_{O-STBC}(\mathbf{H}) = \frac{Q}{T} \log_2 \left( 1 + \frac{\rho T}{Q n_t} \|\mathbf{H}\|_F^2 \right).$$

## Proposition

*The Alamouti scheme is optimal with respect to the mutual information when used with only one receive antenna.*

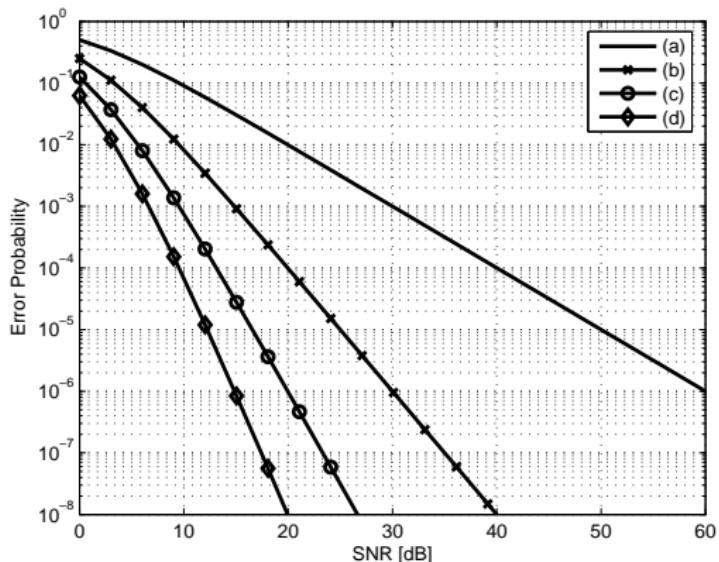
# Global Performance Comparison

- Bit error rate (BER) of several space-time block codes in i.i.d. slow Rayleigh fading channels with  $n_t = 2$  and  $n_r = 2$  in a 4-bit/s/Hz transmission. ML decoding is used.



## Example

*Question:* Here is the average Error Probability of one scheme (i.e., one transmission and reception strategy) vs. SNR for point-to-point channels with i.i.d. Rayleigh slow fading and four different antenna configurations (a) to (d). The CSI is unknown to the transmitter.



## Example

*Question:* What is the diversity gain (at high SNR) achieved by that scheme in each antenna configuration? Provide your reasoning.

*Answer:* The diversity gain is the slope at high SNR of the error curve vs. the SNR on a log-log scale, i.e.  $-\lim_{\rho \rightarrow \infty} \frac{\log(P_e(\rho))}{\log(\rho)}$  with  $\rho$  being the SNR.

For (a), the diversity gain is 1 as the error rate decreases by  $10^{-1}$  when the SNR is increased from 50dB to 60dB.

For (b), the diversity gain is 2 as the error rate decreases by  $10^{-2}$  when the SNR is increased from 30dB to 40dB.

For (c), the diversity gain is 3 as the error rate decreases by  $10^{-3}$  when the SNR is increased from roughly 26dB to 36dB.

For (d), the diversity gain is 4 as the error rate decreases by  $10^{-4}$  when the SNR is increased from 10dB to 20dB.

## Example

**Question:** For each scenario (a) to (d), identify an antenna configuration (i.e.,  $n_t$  and  $n_r$ ) and the corresponding transmission/reception strategy that can achieve such diversity gain. Provide your reasoning.

**Answer:** The simplest approach is to perform

for (a), receive matched filter with  $n_r = 1, n_t = 1$

for (b), receive matched filter with  $n_r = 2, n_t = 1$

for (c), receive matched filter with  $n_r = 3, n_t = 1$

for (d), receive matched filter with  $n_r = 4, n_t = 1$

Alternative strategies are possible, for instance selection combining at the receiver for all 4 cases. We could also perform transmit diversity based on space-time coding and use O-STBC for (b),(c),(d) to achieve diversity order of 2 with  $n_t = 2$  and  $n_r = 1$ , 3 with  $n_t = 3$  and  $n_r = 1$ , 4 with  $n_t = 4$  and  $n_r = 1$ , respectively. Alternatively, we could as well use Spatial Multiplexing with ZF receiver and transmit two streams over two transmit antennas and use 2,3,4,5 receive antennas for a,b,c,d respectively.

# Quantized Precoding

# Limited Feedback

- full CSIT
  - array and diversity gain
  - lower system complexity (parallel virtual transmissions)
  - hardly achievable (especially when the channel varies rapidly), costly in terms of feedback
- Exploiting a Limited Amount of Feedback at the Transmitter
  - codebook of precoding matrices, i.e., a finite set of precoders, designed off-line and known to both the transmitter and receiver.
  - The receiver estimates the best precoder as a function of the current channel and feeds back only the index of this best precoder in the codebook.

# Quantized Precoding: Dominant Eigenmode Transmission

- Assume dominant eigenmode transmission (i.e. beamforming)

$$\begin{aligned}\mathbf{y} &= \sqrt{E_s} \mathbf{H} \mathbf{w} c + \mathbf{n}, \\ z &= \mathbf{g}^H \mathbf{y}, \\ &= \sqrt{E_s} \mathbf{g}^H \mathbf{H} \mathbf{w} c + \mathbf{g}^H \mathbf{n}\end{aligned}$$

where  $\mathbf{g}$  and  $\mathbf{w}$  are respectively  $n_r \times 1$  and  $n_t \times 1$  vectors.

- Assuming MRC, the optimal beamforming vector  $\mathbf{w}$  that maximizes the SNR is given by

$$\mathbf{w}^* = \arg \max_{\mathbf{w} \in \mathcal{C}_w} \|\mathbf{H} \mathbf{w}\|^2$$

with  $\mathcal{C}_w$  set of unit-norm vectors. The best precoder is the dominant right singular vector of  $\mathbf{H}$ .

- Reduce the number of feedback bits: limit the space  $\mathcal{C}_w$  over which  $\mathbf{w}$  can be chosen to a codebook called  $\mathcal{W}$ . The receiver evaluates the best precoder  $\mathbf{w}^*$  among all unit-norm precoders  $\mathbf{w}_i \in \mathcal{W}$  (with  $i = 1, \dots, n_p$ ) such that

$$\mathbf{w}^* = \arg \max_{\substack{1 \leq i \leq n_p \\ \mathbf{w}_i \in \mathcal{W}}} \|\mathbf{H} \mathbf{w}_i\|^2.$$

# Quantized Precoding: Some Extensions

- Extension to other kinds of channel models (e.g. spatial/time correlation, polarization), transmission strategies (e.g. O-STBCs, SM), reception strategies (e.g. MRC, ZF, MMSE, ML), criteria (e.g. error rate or transmission rate)
- Quantized precoding for SM with rank adaptation and rate maximization

$$\mathbf{W}^* = \arg \max_{n_e} \max_{\mathbf{W}_i^{(n_e)} \in \mathcal{W}_{n_e}} R.$$

The codebooks  $\mathcal{W}_{n_e}$  are defined for ranks  $n_e = 1, \dots, \min\{n_t, n_r\}$ . Rate is computed on the equivalent precoded channel  $\mathbf{H}\mathbf{W}_i^{(n_e)}$ .

- Uniform power allocation and joint ML decoding

$$R = \log_2 \det \left[ \mathbf{I}_{n_e} + \frac{\rho}{n_e} \left( \mathbf{W}_i^{(n_e)} \right)^H \mathbf{H}^H \mathbf{H} \mathbf{W}_i^{(n_e)} \right].$$

- With other types of receivers/combiner

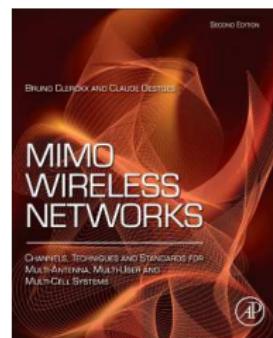
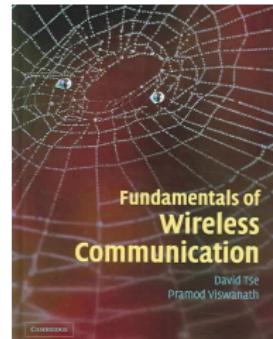
$$R = \sum_{q=1}^{n_e} \log_2 \left( 1 + \rho_q \left( \mathbf{H}\mathbf{W}_i^{(n_e)} \right) \right).$$

where  $\rho_q$  is the SINR of stream  $q$  on at the output of the combiner for the equivalent channel  $\mathbf{H}\mathbf{W}_i^{(n_e)}$ .

## Part 3: Multiuser Communications

Capacity of Multiuser (SISO and MIMO) Channels  
Fairness, Scheduling and Precoding ... all the way to Massive MIMO  
Multiuser Multicell Communications

# Reference Book

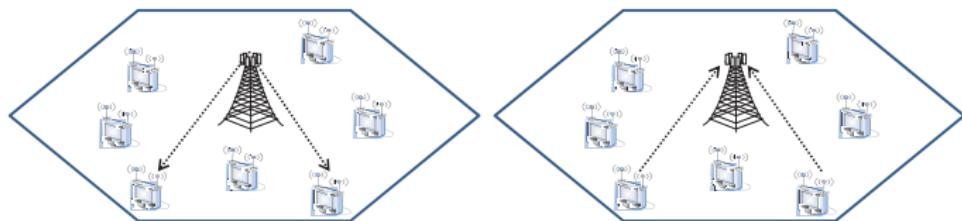


Chapter 12 - Sections  
12.1, 12.2.1, 12.3.1, 12.5.1,  
12.6.2, 12.8.1, 12.8.2, 12.8.10  
Chapter 13 - Section 13.2

# Capacity of Multiuser (SISO and MIMO) Channels

# BC vs MAC

- So far, we looked at a single link/user. Most systems are multi-user!
- How to deal with multiple users?
- Broadcast Channel (BC) and Multiple Access Channel(MAC)



(a) Broadcast Channel - Downlink

(b) Multiple Access Channel - Uplink

Differences between BC and MAC:

- there are multiple independent receivers (and therefore multiple independent additive noises) in BC while there is a single receiver (and therefore a single noise term) in MAC.
- there is a single transmitter (and therefore a single transmit power constraint) in BC while there are multiple transmitters (and therefore multiple transmit power constraints) in MAC.
- the desired signal and the interference (originating from the co-scheduled signals) propagate through the same channel in the BC while they propagate through different channels in the MAC.

# Capacity Region

- In a multi-user setup, given that all users share the same spectrum, the rate achievable by a given user  $q$ , denoted as  $R_q$ , will depend on the rate of the other users  $R_p$ ,  $p \neq q \rightarrow$  Trade-off between rates achievable by different users!
- The capacity region  $\mathcal{C}$  formulates this trade-off by expressing the set of all user rates  $(R_1, \dots, R_K)$  that are simultaneously achievable.

## Definition

The capacity region  $\mathcal{C}$  of a channel  $\mathbf{H}_{ul}$  is the set of all rate vectors  $(R_1, \dots, R_K)$  such that simultaneously user 1 to user  $K$  can reliably communicate at rate  $R_1$  to rate  $R_K$ , respectively.

Any rate vector not in the capacity region is not achievable (i.e. transmission at those rates will lead to errors).

## Definition

The sum-rate capacity  $C$  of a capacity region  $\mathcal{C}$  is the maximum achievable sum of rates

$$C = \max_{(R_1, \dots, R_K) \in \mathcal{C}} \sum_{q=1}^K R_q.$$



# SISO MAC System Model

- Uplink multi-user SISO transmission
  - total number of  $K$  users ( $\mathcal{K} = \{1, \dots, K\}$ ) distributed in a cell,
  - 1 transmit antennas at each mobile terminal
  - 1 receive antenna at the base station
- Received signal (we drop the time dimension)

$$y_{ul} = \sum_{q=1}^K \Lambda_q^{-1/2} h_{ul,q} c'_{ul,q} + n_{ul}$$

where

- $h_{ul,q}$  models the small scale time-varying fading process and  $\Lambda_q^{-1}$  refers to the large-scale fading accounting for path loss and shadowing
  - $n_{ul}$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_n^2)$ .
- Power constraint:  $\mathcal{E}\{|c'_{ul,q}|^2\} \leq E_{s,q}$ .

# SISO MAC System Model

- By stacking up the transmit signal vectors and the channel matrices of all  $K$  users,

$$\mathbf{c}'_{ul} = \left[ c'_{ul,1}, \dots, c'_{ul,K} \right]^T, \\ \mathbf{h}_{ul} = \left[ \Lambda_1^{-1/2} h_{ul,1}, \dots, \Lambda_K^{-1/2} h_{ul,K} \right],$$

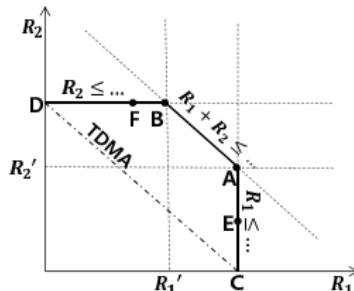
the system model also writes as

$$y_{ul} = \mathbf{h}_{ul} \mathbf{c}'_{ul} + n_{ul}.$$

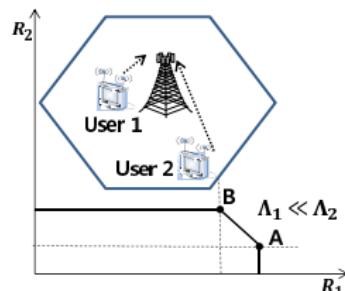
- Long term SNR of user  $q$  defined as  $\eta_q = E_{s,q} \Lambda_q^{-1} / \sigma_n^2$ .
- Note on the notations: the dependence on the path loss and shadowing is made explicit in order to stress that the co-scheduled users experience different path losses and shadowings and therefore receive power.
- The receiver (i.e. the BS in a UL scenario) has always perfect knowledge of the CSI.

# Capacity Region of a Two-User SISO MAC

- The capacity region is a pentagon with two corner points A and B.



(a) Two-user MIMO MAC rate region for fixed  $Q_{ul,1}$  and  $Q_{ul,2}$



(b) Rate regions with various path losses

- $\mathcal{C}_{MAC}$  is the set of all rates pair  $(R_1, R_2)$  satisfying to

$$R_q \leq \log_2 (1 + \eta_q |h_{ul,q}|^2), q = 1, 2$$

$$R_1 + R_2 \leq \log_2 (1 + \eta_1 |h_{ul,1}|^2 + \eta_2 |h_{ul,2}|^2).$$

- Remarkably, at point A, user 1 can transmit at a rate equal to its single-link SISO rate and user 2 can simultaneously transmit at a rate  $R'_2 > 0$  equal to

$$\begin{aligned} R'_2 &= \log_2 (1 + \eta_1 |h_{ul,1}|^2 + \eta_2 |h_{ul,2}|^2) - \log_2 (1 + \eta_1 |h_{ul,1}|^2) \\ &= \log_2 \left( 1 + \frac{\eta_2 |h_{ul,2}|^2}{1 + \eta_1 |h_{ul,1}|^2} \right) = \log_2 \left( 1 + \frac{\Lambda_2^{-1} |h_{ul,2}|^2 E_{s,2}}{\sigma_n^2 + \Lambda_1^{-1} |h_{ul,1}|^2 E_{s,1}} \right). \end{aligned}$$

# Capacity Region of SISO MAC

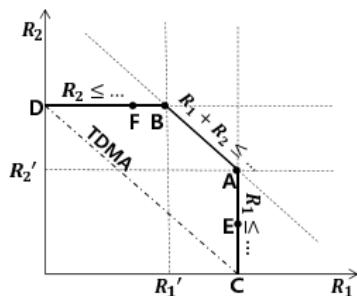
## Proposition

$$\mathcal{C}_{MAC} = \left\{ (R_1, \dots, R_K) : \sum_{q \in S} R_q \leq \log_2 \left( 1 + \sum_{q \in S} \eta_q |h_{ul,q}|^2 \right), \forall S \subseteq \mathcal{K} \right\}$$

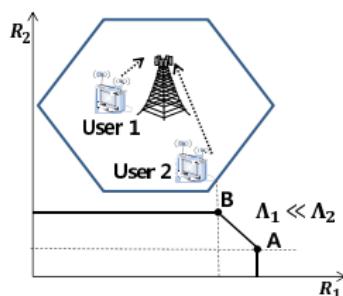
where  $\eta_q = \Lambda_q^{-1} E_{s,q} / \sigma_n^2$ .

# Achievability of the Capacity Region

- SIC is optimal for achieving the corner points of the SISO MAC rate region.
- The exact corner point that is achieved on the capacity region depends on the stream cancellation ordering:
  - Point A, user 2 is canceled first (i.e. all streams from user 2) such that user 1 is left with the Gaussian noise and can achieve a rate equal to the single-link bound.
  - Assuming  $n_t = 1$ ,  $R'_2 = \log_2(1 + \rho_q)$  where  $\rho_q$  is the SINR of the receiver for user 2's stream treating user 1's stream as Gaussian interference.



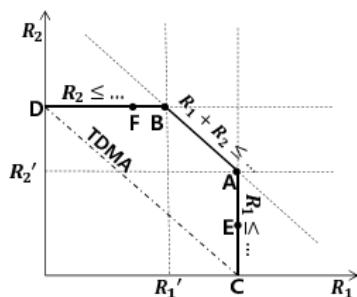
(a) Two-user MIMO MAC rate region for fixed  $Q_{u1,1}$  and  $Q_{u1,2}$



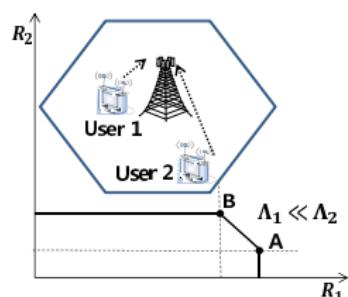
(b) Rate regions with various path losses

# Comparisons with TDMA

- TDMA allocates the time resources in an orthogonal manner such that users are never transmitting at the same time (line D-C in the rate region).
- TDMA rate region is strictly smaller than the one achievable with SIC.



(a) Two-user MIMO MAC rate region for fixed  $Q_{4,1}$  and  $Q_{4,2}$



(b) Rate regions with various path losses

# SISO BC System Model

- Downlink multi-user SISO transmission
  - total number of  $K$  users ( $\mathcal{K} = \{1, \dots, K\}$ ) distributed in a cell,
  - 1 receive antenna at each mobile terminal
  - 1 transmit antenna at the base station
- Received signal (we drop the time dimension)

$$y_q = \Lambda_q^{-1/2} h_q c' + n_q$$

where

- $h_q$  models the small scale time-varying fading process and  $\Lambda_q^{-1}$  refers to the large-scale fading accounting for path loss and shadowing
- $n_q$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_{n,q}^2)$ .

- Transmit power constraint:  $\mathcal{E}\{|c'|^2\} = E_s$ .

# SISO BC System Model

- By stacking up the received signal vectors, the noise vectors and the channel matrices of all  $K$  users,

$$\mathbf{y} = [y_1, \dots, y_K]^T,$$

$$\mathbf{n} = [n_1, \dots, n_K]^T,$$

$$\mathbf{h} = \left[ \Lambda_1^{-1/2} h_1, \dots, \Lambda_K^{-1/2} h_K \right]^T,$$

the system model also writes as

$$\mathbf{y} = \mathbf{h}c' + \mathbf{n}.$$

- SNR of user  $q$  defined as  $\eta_q = E_s \Lambda_q^{-1} / \sigma_{n,q}^2$ .
- Perfect instantaneous channel state information (CSI) at the Tx and all Rx.
- Generally speaking,  $c'$  is written as the superposition of statistically independent signals  $c'_q$

$$c' = \sum_{q=1}^K c'_q.$$

# Capacity Region of two-user Deterministic SISO BC

- In *two-user SISO MAC*, point  $A$  was obtained by canceling user 2's signal first such that user 1 is left with Gaussian noise.
- Let us apply the same philosophy to the SISO BC:
  - transmit  $c' = c'_1 + c'_2$ , with power of  $c'_q$  denoted as  $s_q$
  - user 1 cancels user 2's signal  $c'_2$  so as to be left with its own Gaussian noise
  - user 2 decodes its signal by treating user 1's signal  $c'_1$  as Gaussian noise.
- Achievable rates of such strategy (with sum-power constraint  $s_1 + s_2 = E_s$ )

$$R_1 = \log_2 \left( 1 + \frac{\Lambda_1^{-1} s_1}{\sigma_{n,1}^2} |h_1|^2 \right)$$

$$R_2 = \log_2 \left( 1 + \frac{\Lambda_2^{-1} |h_2|^2 s_2}{\sigma_{n,2}^2 + \Lambda_2^{-1} |h_2|^2 s_1} \right).$$

- *Careful!* For user 1 to be able to correctly cancel user 2's signal, user 1's channel has to be good enough to support  $R_2$ , i.e.

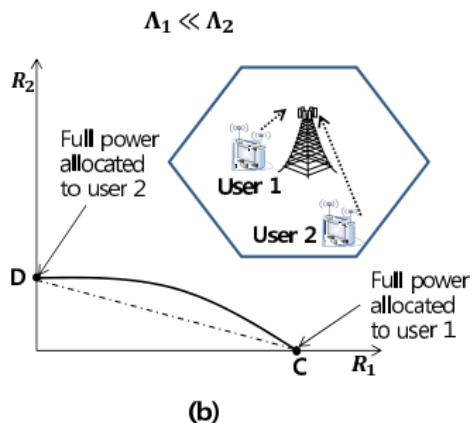
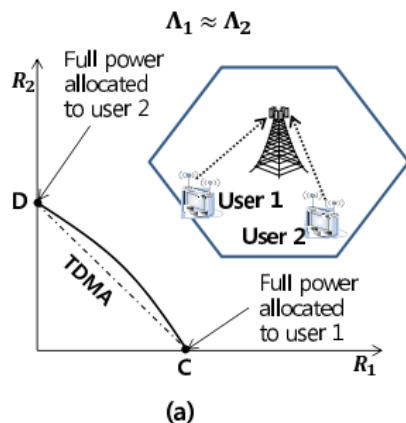
$$R_2 \leq \log_2 \left( 1 + \frac{\Lambda_1^{-1} |h_1|^2 s_2}{\sigma_{n,1}^2 + \Lambda_1^{-1} |h_1|^2 s_1} \right).$$

- The channel gains normalized w.r.t. their respective noise power should be ordered

$$\frac{\Lambda_2^{-1} |h_2|^2}{\sigma_{n,2}^2} \leq \frac{\Lambda_1^{-1} |h_1|^2}{\sigma_{n,1}^2}.$$

# Capacity Region of two-user SISO Deterministic BC

- If the ordering condition is satisfied, the above strategy achieves the boundary of the capacity region of the two-user SISO BC for any power allocation  $s_1$  and  $s_2$  satisfying  $s_1 + s_2 = E_s$ .
- The capacity region is given by the union of all rate pairs  $(R_1, R_2)$  over all power allocations  $s_1$  and  $s_2$  satisfying  $s_1 + s_2 = E_s$ .



# Capacity Region of K-user Deterministic SISO BC

- Define  $\mathbf{h}_q = \Lambda_q^{-1/2} \mathbf{h}_q / \sigma_{n,q}$ . Assume  $|\mathbf{h}_1|^2 \geq |\mathbf{h}_2|^2 \geq \dots \geq |\mathbf{h}_K|^2$ .

## Proposition

With the ordering  $|\mathbf{h}_1|^2 \geq |\mathbf{h}_2|^2 \geq \dots \geq |\mathbf{h}_K|^2$ , the capacity region  $\mathcal{C}_{BC}$  of the Gaussian SISO BC is the set of all achievable rate vectors  $(R_1, \dots, R_K)$  given by

$$\bigcup_{s_q : \sum_{q=1}^K s_q = E_s} \left\{ (R_1, \dots, R_K) : R_q \leq \log_2 \left( 1 + \frac{|\mathbf{h}_q|^2 s_q}{1 + |\mathbf{h}_q|^2 \left[ \sum_{p=1}^{q-1} s_p \right]} \right), \forall q \right\}.$$

## Proposition

The sum-rate capacity of the SISO BC is achieved by allocating the transmit power to the strongest user

$$C_{BC} = \log_2 \left( 1 + E_s \max_{q=1, \dots, K} |\mathbf{h}_q|^2 \right) = \log_2 \left( 1 + \max_{q=1, \dots, K} \eta_q |\mathbf{h}_q|^2 \right).$$

Recall that the MAC sum-rate capacity is obtained with all users simultaneously transmitting at their respective full power.

# Achievability of the SISO BC Capacity Region

- *Superposition coding with SIC and appropriate ordering*
- User ordering: decode and cancel out weaker users signals before decoding their own signal.
- The weakest user decodes only the coarsest constellation. The strongest user decodes and subtracts all constellation points in order to decode the finest constellation.

# Achievability of the SISO BC Capacity Region

## Proposition

*With the appropriate cancellation/encoding ordering, Superposition Coding with SIC is optimal for achieving the SISO BC capacity region.*

## Proposition

*The SISO BC sum-rate capacity is achievable with dynamic TDMA (to the strongest user) and Superposition Coding with SIC (with the appropriate cancellation ordering).*

## Comparisons with TDMA

- Similarly to MAC, TDMA rate region is contained in the BC capacity region.
- The gap between the BC capacity region and the TDMA rate region increases proportionally with the asymmetry between users normalized channel gains.
- TDMA achieves the sum-rate capacity of SISO BC.

# MIMO MAC System Model

- Uplink multi-user MIMO (MU-MIMO) transmission
  - total number of  $K$  users ( $\mathcal{K} = \{1, \dots, K\}$ ) distributed in a cell,
  - $n_{t,q}$  transmit antennas at mobile terminal  $q$  (we simply drop the index  $q$  and write  $n_t$  if  $n_{t,q} = n_t \forall q$ )
  - $n_r$  receive antenna at the base station
- Received signal (we drop the time dimension)

$$\mathbf{y}_{ul} = \sum_{q=1}^K \Lambda_q^{-1/2} \mathbf{H}_{ul,q} \mathbf{c}'_{ul,q} + \mathbf{n}_{ul}$$

where

- $\mathbf{y}_{ul}$  [ $n_r \times 1$ ]
- $\mathbf{H}_{ul,q}$  [ $n_r \times n_{t,q}$ ] models the small scale time-varying fading process and  $\Lambda_q^{-1}$  refers to the large-scale fading accounting for path loss and shadowing
- $\mathbf{n}_{ul}$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_n^2 \mathbf{I}_{n_r})$ .

- User  $q$ 's input covariance matrix is defined as the covariance matrix of the transmit signal of user  $q$  as  $\mathbf{Q}_{ul,q} = \mathcal{E}\{\mathbf{c}'_{ul,q} \mathbf{c}_{ul,q}^H\}$ .
- Power constraint:  $\text{Tr}\{\mathbf{Q}_{ul,q}\} \leq E_{s,q}$ .

# MIMO MAC System Model

- By stacking up the transmit signal vectors and the channel matrices of all  $K$  users,

$$\begin{aligned}\mathbf{c}'_{ul} &= \left[ \mathbf{c}_{ul,1}^{'T}, \dots, \mathbf{c}_{ul,K}^{'T} \right]^T, \\ \mathbf{H}_{ul} &= \left[ \Lambda_1^{-1/2} \mathbf{H}_{ul,1}, \dots, \Lambda_K^{-1/2} \mathbf{H}_{ul,K} \right], \\ \mathbf{y}_{ul} &= \mathbf{H}_{ul} \mathbf{c}'_{ul} + \mathbf{n}_{ul},\end{aligned}$$

$\mathbf{H}_{ul}$  is assumed to be full-rank as it would be the case in a typical user deployment.

- Long term SNR of user  $q$  defined as  $\eta_q = E_{s,q} \Lambda_q^{-1} / \sigma_n^2$ .
- Note on the notations: the dependence on the path loss and shadowing is made explicit in order to stress that the co-scheduled users experience different path losses and shadowings and therefore receive power.
- We assume that the receiver (i.e. the BS in a UL scenario) has always perfect knowledge of the CSI, but we will consider strategies where the transmitters have perfect or partial knowledge of the CSI.
- Capacity region of MIMO MAC can be characterized.

# Capacity Region of SIMO MAC

## Corollary

$$\mathcal{C}_{MAC} = \left\{ \begin{array}{l} (R_1, \dots, R_K) : \sum_{q \in S} R_q \leq \\ \log_2 \det \left[ \mathbf{I}_{n_r} + \sum_{q \in S} \eta_q \mathbf{h}_{ul,q} \mathbf{h}_{ul,q}^H \right], \forall S \subseteq \mathcal{K} \end{array} \right\}$$

where  $\eta_q = \Lambda_q^{-1} E_{s,q} / \sigma_n^2$ .

## Example

Two-user SIMO:  $\mathcal{C}_{MAC}$  is the set of all rates pair  $(R_1, R_2)$  satisfying to

$$R_q \leq \log_2 (1 + \eta_q \|\mathbf{h}_{ul,q}\|^2) = \log_2 \det \left( \mathbf{I}_{n_r} + \eta_q \mathbf{h}_{ul,q} \mathbf{h}_{ul,q}^H \right), q = 1, 2$$

$$R_1 + R_2 \leq \log_2 \det \left( \mathbf{I}_{n_r} + \eta_1 \mathbf{h}_{ul,1} \mathbf{h}_{ul,1}^H + \eta_2 \mathbf{h}_{ul,2} \mathbf{h}_{ul,2}^H \right).$$

$$\begin{aligned} R'_2 &= \log_2 \det \left( \mathbf{I}_{n_r} + \eta_1 \mathbf{h}_{ul,1} \mathbf{h}_{ul,1}^H + \eta_2 \mathbf{h}_{ul,2} \mathbf{h}_{ul,2}^H \right) - \log_2 \det \left( \mathbf{I}_{n_r} + \eta_1 \mathbf{h}_{ul,1} \mathbf{h}_{ul,1}^H \right) \\ &= \log_2 \det \left( \mathbf{I}_{n_r} + \eta_2 \mathbf{h}_{ul,2} \mathbf{h}_{ul,2}^H \left( \mathbf{I}_{n_r} + \eta_1 \mathbf{h}_{ul,1} \mathbf{h}_{ul,1}^H \right)^{-1} \right) \\ &= \log_2 \left( 1 + \eta_2 \mathbf{h}_{ul,2}^H \left( \mathbf{I}_{n_r} + \eta_1 \mathbf{h}_{ul,1} \mathbf{h}_{ul,1}^H \right)^{-1} \mathbf{h}_{ul,2} \right) \end{aligned}$$

# Achievability of the SIMO MAC Capacity Region

- For  $n_t = 1$ , the SIMO MAC architecture is reminiscent of the Spatial Multiplexing architecture discussed for a single-link MIMO channel.
- We can therefore fully reuse the various receiver architectures derived for single-link MIMO.
- Recall the optimality of the MMSE V-BLAST (also called Spatial Multiplexing with MMSE-SIC receiver)

## Proposition

*MMSE-SIC is optimal for achieving the corner points of the MIMO MAC rate region.*

- The exact corner point that is achieved on the rate region depends on the stream cancellation ordering:
  - Point A, user 2 is canceled first (i.e. all streams from user 2) such that user 1 is left with the Gaussian noise and can achieve a rate equal to the single-link bound.
  - Assuming  $n_t = 1$ ,  $R'_2 = \log_2(1 + \rho_q)$  where  $\rho_q$  is the SINR of the MMSE receiver for user 2's stream treating user 1's stream as colored Gaussian interference.

# Comparisons with TDMA

- TDMA allocates the time resources in an orthogonal manner such that users are never transmitting at the same time (line D-C in the rate region).
- SISO: both TDMA and SIC exploit a single degree of freedom but TDMA rate region is strictly smaller than the one achievable with SIC.
- SIMO: TDMA incurs a big loss compared to SIMO MAC (with MMSE-SIC) as it only exploits a single degree of freedom despite the presence of  $\min\{n_r, K\}$  degrees of freedom achievable with SIMO MAC at high SNR.
- MIMO: As  $n_t$  increases, the gap between the TDMA and MIMO MAC rate regions decreases.

# MIMO BC System Model

- Downlink multi-user MIMO (MU-MIMO) transmission
  - total number of  $K$  users ( $\mathcal{K} = \{1, \dots, K\}$ ) distributed in a cell,
  - $n_{r,q}$  receive antennas at mobile terminal  $q$  (we simply drop the index  $q$  and write  $n_r$  if  $n_{r,q} = n_r \forall q$ )
  - $n_t$  transmit antenna at the base station
- Received signal (we drop the time dimension)

$$\mathbf{y}_q = \Lambda_q^{-1/2} \mathbf{H}_q \mathbf{c}' + \mathbf{n}_q$$

where

- $\mathbf{y}_q[n_{r,q} \times 1]$
  - $\mathbf{H}_q [n_{r,q} \times n_t]$  models the small scale time-varying fading process and  $\Lambda_q^{-1}$  refers to the large-scale fading accounting for path loss and shadowing
  - $\mathbf{n}_q$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_{n,q}^2 \mathbf{I}_{n_{r,q}})$ .
- The input covariance matrix is defined as the covariance matrix of the transmit signal as  $\mathbf{Q} = \mathcal{E}\{\mathbf{c}'\mathbf{c}'^H\}$ .
  - Power constraint:  $\text{Tr}\{\mathbf{Q}\} \leq E_s$ .

# MIMO BC System Model

- By stacking up the received signal vectors, the noise vectors and the channel matrices of all  $K$  users,

$$\mathbf{y} = \left[ \mathbf{y}_1^T, \dots, \mathbf{y}_K^T \right]^T,$$

$$\mathbf{n} = \left[ \mathbf{n}_1^T, \dots, \mathbf{n}_K^T \right]^T,$$

$$\mathbf{H} = \left[ \Lambda_1^{-1/2} \mathbf{H}_1^T, \dots, \Lambda_K^{-1/2} \mathbf{H}_K^T \right]^T,$$

$$\mathbf{y} = \mathbf{H}\mathbf{c}' + \mathbf{n},$$

$\mathbf{H}$  is assumed to be full-rank as it would be the case in a typical user deployment.

- SNR of user  $q$  defined as  $\eta_q = E_s \Lambda_q^{-1} / \sigma_{n,q}^2$ .
- Perfect instantaneous channel state information (CSI) at the Tx and all Rx.
- Capacity region of MIMO BC can be characterized (more complicated than MIMO BC, some more insights on this later on).
- Dirty Paper Coding (DPC) is capacity achieving.

Fairness, Scheduling and Precoding ... all the  
way to Massive MIMO

# Multi-User Diversity

- In single-link systems, channel fading is viewed as a source of unreliability mitigated through diversity techniques (e.g. space-time coding).
- In multi-user communications, fading is viewed as a source of randomization that can be exploited!
- Multi-User (MU) diversity is a form of selection diversity among users provided by independent time-varying channels across the different users.
- Provided that the BS is able to track the user channel fluctuations (based on feedback), it can schedule transmissions to the users with favorable channel fading conditions, i.e. near their peaks, to improve the total cell throughput.
- Recall that MU diversity was already identified as part of the sum-rate maximization in SISO BC.

# Multi-User Diversity Gain

- Assume that the fading distribution of the  $K$  users are independent and identically ( $\Lambda_q^{-1} = \Lambda^{-1}$  and channel gains  $h_q$  are drawn from the same) Rayleigh distributed and that users experience the same average SNR  $\eta_q = \eta$  ( $\sigma_{n,q}^2 = \sigma_n^2$ )  $\forall q$ :

$$\mathbf{y}_q = \Lambda^{-1/2} h_q \mathbf{c}' + \mathbf{n}_q.$$

- Assume MU-SISO where one user is scheduled at a time in a TDMA manner: select the user with the largest channel gain.
- Mathematically same as antenna selection diversity.
- Average SNR gain

- Average SNR after user selection  $\bar{\rho}_{out}$

$$\bar{\rho}_{out} = \mathcal{E} \left\{ \eta \max_{q=1,\dots,K} |h_q|^2 \right\} = \eta \sum_{q=1}^K \frac{1}{q}.$$

- SNR gain provided by MU diversity  $g_m$

$$g_m = \frac{\bar{\rho}_{out}}{\eta} = \sum_{q=1}^K \frac{1}{q} \stackrel{K \rightarrow \infty}{\cong} \log(K).$$

$g_m$  is of the order of  $\log(K)$  and hence the gain of the strongest user grows as  $\log(K)!$

- Heavily relies on CSIT (partial or imperfect feedback impacts the performance) and independent user fading distributions (correlated fading or LOS are not good for MU diversity)

# Multi-User Diversity Gain

- Sum-rate capacity

$$\bar{C}_{TDMA} = \mathcal{E}\{C_{TDMA}\} = \mathcal{E}\left\{\log_2\left(1 + \eta \max_{q=1,\dots,K} |h_q|^2\right)\right\}.$$

- low SNR

$$\bar{C}_{TDMA} \approx \mathcal{E}\left\{\max_{q=1,\dots,K} |h_q|^2\right\} \eta \log_2(e) \approx g_m C_{awgn}.$$

**Observations:** capacity of the fading channel  $\log(K)$  times larger than the AWGN capacity.

- high SNR (Use Jensen's inequality:  $\mathcal{E}_x\{\mathcal{F}(x)\} \leq \mathcal{F}(\mathcal{E}_x\{x\})$  if  $\mathcal{F}$  concave)

$$\begin{aligned}\bar{C}_{TDMA} &\approx \log_2(\eta) + \mathcal{E}\left\{\log_2\left(\max_{q=1,\dots,K} |h_q|^2\right)\right\}, \\ &\approx C_{awgn} + \mathcal{E}\left\{\log_2\left(\max_{q=1,\dots,K} |h_q|^2\right)\right\}, \\ &\stackrel{(a)}{\leq} C_{awgn} + \log_2\left(\mathcal{E}\left\{\max_{q=1,\dots,K} |h_q|^2\right\}\right), \\ &= C_{awgn} + \log_2(g_m).\end{aligned}$$

**Observations:** capacity of a fading channel is larger than the AWGN capacity by a factor roughly equal to  $\log_2(g_m) \approx \log \log(K)$ .

- Fading channels are significantly more useful in a multi-user setting than in a single-user setting

# Multi-User Diversity

- Few fundamental differences with classical spatial/time/frequency diversity:
  - Diversity techniques, like space-time coding, mainly focus on improving reliability by decreasing the outage probability in slow fading channels. MU diversity on the other hand increases the data rate over time-varying channels.
  - Classical diversity techniques mitigate fading while MU diversity exploits fading.
  - MU diversity takes a system-level view while classical diversity approaches focus on a single-link. This system-level view becomes increasingly important as we shift from single-cell to multi-cell scenarios.

# Fairness and Scheduling

- Sum-rate maximization in SISO BC: pick the strongest user. Is that fair?
- An appropriate scheduler should allocate resources (time, frequency, spatial, power) to the users in a fair manner while exploiting the MU diversity gain.
- Goal of the resource allocation strategy at the scheduler: maximize the utility metric  $\mathcal{U}$ .

$$q^* = \arg \max_{q \in \mathcal{K}} \mathcal{U}$$

where  $q^*$  refers to the optimum user (or more generally subset of users) to be scheduled.

- Two major kinds of resource allocation strategies:
  - *rate-maximization policy*: maximizes the sum-rate - no fairness among users
  - *fairness oriented policy*, commonly relying on a *proportional fair* (PF) metric: maximizes a weighted sum-rate and guarantees fairness among users.
- Those two strategies can be addressed by using two different utility metrics:

$$q^* = \arg \max_{q \in \mathcal{K}} w_q R_q$$

where

- rate-maximization approach:  $w_q = 1$
- proportional fair approach:  $w_q = \frac{\gamma_q}{\bar{R}_q}$  ( $\bar{R}_q$  is the long-term average rate of user  $q$  and  $\gamma_q$  is the Quality of Service (QoS) of each user).

# Practical Proportional Fair Scheduling

- The long-term average rate  $\bar{R}_q$  of user  $q$  is updated using an exponentially weighted low-pass filter such that the estimate of  $\bar{R}_q$  at time  $k+1$ , denoted as  $\bar{R}_q(k+1)$ , is function of the long-term average rate  $\bar{R}_q(k)$  and of the current rate  $R_q(k)$  at current time instant  $k$  as outlined by

$$\bar{R}_q(k+1) = \begin{cases} (1 - 1/t_c) \bar{R}_q(k) + 1/t_c R_q(k), & q \text{ scheduled at time } k \\ (1 - 1/t_c) \bar{R}_q(k), & q \text{ not scheduled at time } k \end{cases}$$

where  $t_c$  is the scheduling time scale. User to be scheduled at time instant  $k$  is

$$q^* = \arg \max_q \gamma_q \frac{R_q(k)}{\bar{R}_q(k)}.$$

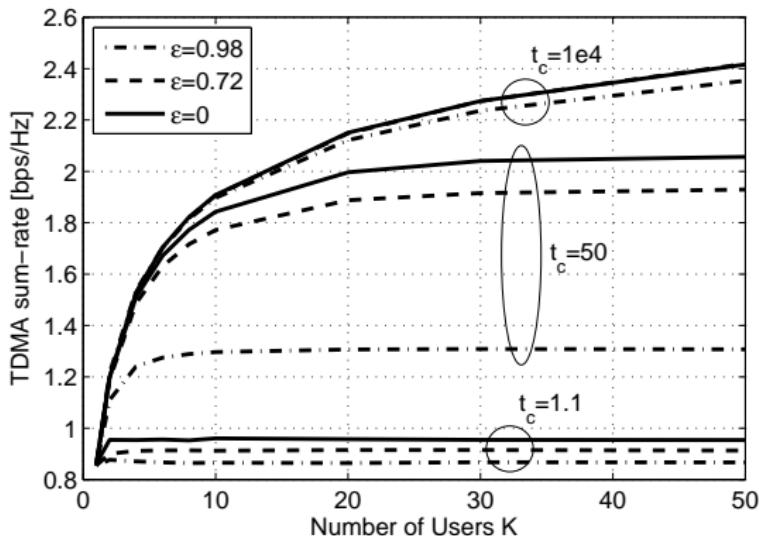
- The scheduling time scale  $t_c$  is a design parameter of the system that highly influences the user fairness and the performance
  - Very large  $t_c$ : assuming all users experience identical fading statistics and have the same QoS, the PF scheduler is equivalent to the rate-maximization scheduler, i.e. users contributing to the highest sum-rate are selected.
  - Small  $t_c$ : assuming all users have the same QoS, the scheduler divides the available resources equally among users (*Round-Robin* scheduling). No MU diversity is exploited.

# Proportional Fair Scheduling

- Sum-rate of SISO TDMA with PF scheduling at SNR=0 dB as a function of the number of users  $K$ , the scheduling time scale  $t_c$  and the channel model

$$h_k = \epsilon h_{k-1} + \sqrt{1 - \epsilon^2} n_k$$

with  $\epsilon$  the channel time correlation coefficient.



# Precoding

- Downlink multi-user MIMO (MU-MIMO) transmission
  - total number of  $K$  users ( $\mathcal{K} = \{1, \dots, K\}$ ) distributed in a cell,
  - $n_{r,q}$  receive antennas at mobile terminal  $q$  (we simply drop the index  $q$  and write  $n_r$  if  $n_{r,q} = n_r \forall q$ )
  - $n_t$  transmit antenna at the base station
- Received signal (we drop the time dimension)

$$\mathbf{y}_q = \Lambda_q^{-1/2} \mathbf{H}_q \mathbf{c}' + \mathbf{n}_q$$

where

- $\mathbf{y}_q \in \mathbb{C}^{n_{r,q}}$
- $\mathbf{H}_q \in \mathbb{C}^{n_{r,q} \times n_t}$  models the small scale time-varying fading process and  $\Lambda_q^{-1}$  refers to the large-scale fading accounting for path loss and shadowing
- $\mathbf{n}_q$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_{n,q}^2 \mathbf{I}_{n_{r,q}})$ .
- Long term SNR of user  $q$  defined as  $\eta_q = E_s \Lambda_q^{-1} / \sigma_{n,q}^2$ .
- Generally speaking,  $\mathbf{c}'$  is written as the superposition of statistically independent signals  $\mathbf{c}'_q$

$$\mathbf{c}' = \sum_{q=1}^K \mathbf{c}'_q.$$

- Power constraint:  $\text{Tr}\{\mathbf{Q}\} \leq E_s$  with  $\mathbf{Q} = \mathcal{E}\{\mathbf{c}' \mathbf{c}'^H\}$ .

# Precoding

- *scheduled user set*, denoted as  $\mathbf{K} \subset \mathcal{K}$ , is the set of users who are actually scheduled (with a non-zero transmit power) by the transmitter at the time instant of interest.
- The transmitter serves users belonging to  $\mathbf{K}$  with  $n_e$  data streams and user  $q \in \mathbf{K}$  is served with  $n_{u,q}$  data streams ( $n_{u,q} \leq n_e$ ). Hence,  $n_e = \sum_{q \in \mathbf{K}} n_{u,q}$ .
- Linear Precoding

$$\mathbf{c}' = \mathbf{P}\mathbf{c} = \mathbf{W}\mathbf{S}^{1/2}\mathbf{c} = \sum_{q \in \mathbf{K}} \mathbf{P}_q \mathbf{c}_q = \sum_{q \in \mathbf{K}} \mathbf{W}_q \mathbf{S}_q^{1/2} \mathbf{c}_q$$

where

- $\mathbf{c}$  is the symbol vector made of  $n_e$  unit-energy independent symbols.
- $\mathbf{P} \in \mathbb{C}^{n_t \times n_e}$  is the precoder subject to  $\text{Tr}\{\mathbf{P}\mathbf{P}^H\} \leq E_s$ , made of two matrices: a power control diagonal matrix denoted as  $\mathbf{S} \in \mathbb{R}^{n_e \times n_e}$  and a transmit beamforming matrix  $\mathbf{W} \in \mathbb{C}^{n_t \times n_e}$ .
- $\mathbf{P}_q \in \mathbb{C}^{n_t \times n_{u,q}}$ ,  $\mathbf{W}_q \in \mathbb{C}^{n_t \times n_{u,q}}$ ,  $\mathbf{S}_q \in \mathbb{R}^{n_{u,q} \times n_{u,q}}$ , and  $\mathbf{c}_q \in \mathbb{C}^{n_{u,q}}$  are user  $q$ 's sub-matrices and sub-vector of  $\mathbf{P}$ ,  $\mathbf{W}$ ,  $\mathbf{S}$ , and  $\mathbf{c}$ , respectively.
- The received signal  $\mathbf{y}_q \in \mathbb{C}^{n_r, q}$  is shaped by  $\mathbf{G}_q \in \mathbb{C}^{n_{u,q} \times n_r, q}$  and the filtered received signal  $\mathbf{z}_q \in \mathbb{C}^{n_{u,q}}$  at user  $q$  writes as

$$\begin{aligned} \mathbf{z}_q &= \mathbf{G}_q \mathbf{y}_q, \\ &= \Lambda_q^{-1/2} \mathbf{G}_q \mathbf{H}_q \mathbf{W}_q \mathbf{S}_q^{1/2} \mathbf{c}_q + \sum_{p \in \mathbf{K}, p \neq q} \Lambda_q^{-1/2} \mathbf{G}_q \mathbf{H}_q \mathbf{W}_p \mathbf{S}_p^{1/2} \mathbf{c}_p + \mathbf{G}_q \mathbf{n}_q. \end{aligned}$$

# Achievable Rate

- Maximum rate achievable by user  $q$  with linear precoding is

$$R_q = \sum_{l=1}^{n_{u,q}} \log_2 (1 + \rho_{q,l})$$

where  $\rho_{q,l}$  denotes the SINR experienced by stream  $l$  of user  $q$

$$\rho_{q,l} = \frac{\Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{p}_{q,l}|^2}{I_l + I_c + \|\mathbf{g}_{q,l}\|^2 \sigma_{n,q}^2} = \frac{\Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{w}_{q,l}|^2 s_{q,l}}{I_l + I_c + \|\mathbf{g}_{q,l}\|^2 \sigma_{n,q}^2}$$

with  $\mathbf{p}_{q,l} = \mathbf{w}_{q,l} s_{q,l}$  (resp.  $\mathbf{g}_{q,l}$ ) the precoder (resp. combiner) attached to stream  $l$  of user  $q$ ,  $I_l$  the inter-stream interference and  $I_c$  the intra-cell interference (also called multi-user interference)

$$I_l = \sum_{m \neq l} \Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{p}_{q,m}|^2 = \sum_{m \neq l} \Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{w}_{q,m}|^2 s_{q,m},$$

$$I_c = \sum_{\substack{p \in \mathbf{K} \\ p \neq q}} \sum_{m=1}^{n_{u,p}} \Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{p}_{p,m}|^2 = \sum_{\substack{p \in \mathbf{K} \\ p \neq q}} \sum_{m=1}^{n_{u,p}} \Lambda_q^{-1} |\mathbf{g}_{q,l} \mathbf{H}_q \mathbf{w}_{p,m}|^2 s_{p,m}.$$

- If  $n_r = 1$ , the SINR of user  $q$  simply reads as  $\rho_q = \frac{\Lambda_q^{-1} |\mathbf{h}_q \mathbf{w}_q|^2 s_q}{\sum_{\substack{p \in \mathbf{K} \\ p \neq q}} \Lambda_q^{-1} |\mathbf{h}_q \mathbf{w}_p|^2 s_p + \sigma_{n,q}^2}.$
- Various designs: MBF/MRT, ZFBF, R-ZFBF, BD, ...

# Zero-Forcing Beamforming (ZFBF)

- Most popular MU-MIMO precoder. Assume single receive antenna per user.
- Channel Direction Information (CDI) of user  $q$ :  $\bar{\mathbf{h}}_q = \mathbf{h}_q / \|\mathbf{h}_q\|$ .
- Idea is to force the intra-cell interference  $I_c$  to zero: the precoder of a user  $q$ ,  $\mathbf{w}_q$ , is chosen such that  $\mathbf{h}_p \mathbf{w}_q = 0 \forall p \in \mathbf{K} \setminus q$ . Only possible if  $n_e \leq n_t$ !
- Define

$$\mathbf{H} = \left[ \Lambda_i^{-1/2} \mathbf{h}_i^T, \dots, \Lambda_j^{-1/2} \mathbf{h}_j^T \right]_{i,j \in \mathbf{K}}^T = \mathbf{D} \bar{\mathbf{H}}$$

with

$$\mathbf{D} = \text{diag} \left\{ \Lambda_i^{-1/2} \|\mathbf{h}_i\|, \dots, \Lambda_j^{-1/2} \|\mathbf{h}_j\| \right\}_{i,j \in \mathbf{K}},$$

$$\bar{\mathbf{H}} = \left[ \bar{\mathbf{h}}_i^T, \dots, \bar{\mathbf{h}}_j^T \right]_{i,j \in \mathbf{K}}^T.$$

The ZFBF aims at designing  $\mathbf{W} = [\mathbf{w}_i, \dots, \mathbf{w}_j]_{i,j \in \mathbf{K}}$  such that  $\mathbf{HW}$  is diagonal.

- Assuming  $n_e \leq n_t$  and  $\bar{\mathbf{H}}$  is full rank, the precoders can be chosen as the normalized columns of the right pseudo inverse of  $\mathbf{H}$

$$\mathbf{F} = \mathbf{H}^H \left( \mathbf{H} \mathbf{H}^H \right)^{-1} = \bar{\mathbf{H}} \mathbf{D}^{-1} = \bar{\mathbf{H}}^H \left( \bar{\mathbf{H}} \bar{\mathbf{H}}^H \right)^{-1} \mathbf{D}^{-1}.$$

Transmit precoder  $\mathbf{w}_q$  for user  $q \in \mathbf{K}$ :  $\mathbf{w}_q = \mathbf{F}(:, q) / \|\mathbf{F}(:, q)\| = \bar{\mathbf{H}}(:, q) / \|\bar{\mathbf{H}}(:, q)\|$  where  $\mathbf{F}(:, q)$  is to be viewed as the column of  $\mathbf{F}$  corresponding to user  $q$ .

# Zero-Forcing Beamforming (ZFBF)

- Assuming that  $\mathbf{c} = [c_i, \dots, c_j]^T_{i,j \in \mathbf{K}}$ , the received signal of user  $q \in \mathbf{K}$  is

$$\mathbf{y}_q = \Lambda_q^{-1/2} \mathbf{h}_q \mathbf{w}_q s_q^{1/2} c_q + n_q = d_q c_q + n_q,$$

with  $d_q = \Lambda_q^{-1/2} \mathbf{h}_q \mathbf{w}_q s_q^{1/2} = \Lambda_q^{-1/2} \frac{\|\mathbf{h}_q\|}{\|\mathbf{F}(:,q)\|} s_q^{1/2}$ .

**Observations:** MU-MIMO channel with ZFBF is split into  $n_e$  parallel (non-interfering) channels.

- The rate achievable by user  $q$  is given by

$$R_q = \log_2 (1 + d_q^2 / \sigma_{n,q}^2).$$

$d_q^2$  is low if  $\mathbf{H}$  is badly conditioned but would get larger if users' CDI are orthogonal or quasi-orthogonal.

– reminiscent of the loss caused by noise enhancement incurred by the linear ZF

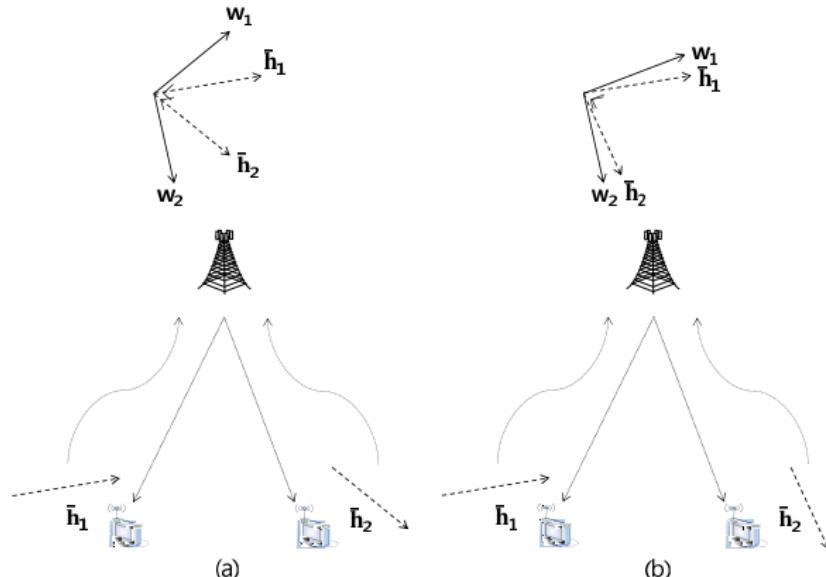
- For large  $K$ , better conditioning of matrix  $\mathbf{H}$  through the use of user grouping.
- By uniformly allocating the power across user streams  $s_q = E_s / n_e$  and by choosing  $n_e = \tilde{n} = \min \{n_t, K\}$ ,  $d_q^2 / \sigma_{n,q}^2 = \alpha_q^2 \eta_q / n_e$  with  $\alpha_q^2 = |\mathbf{h}_q \mathbf{w}_q|^2 = \|\mathbf{h}_q\|^2 / \|\bar{\mathbf{F}}(:,q)\|^2$

$$C_{BF}(\mathbf{H}) = \sum_{q=1}^{\min\{n_t, K\}} \log_2 \left( 1 + \alpha_q^2 \frac{\eta_q}{\tilde{n}} \right).$$

At high SNR with  $\eta_q = \eta$ ,  $C_{BF}(\mathbf{H}) \approx \min \{n_t, K\} \log_2 (\eta_q)$ . The multiplexing gain  $\min \{n_t, K\}$  is achieved (same as with DPC).

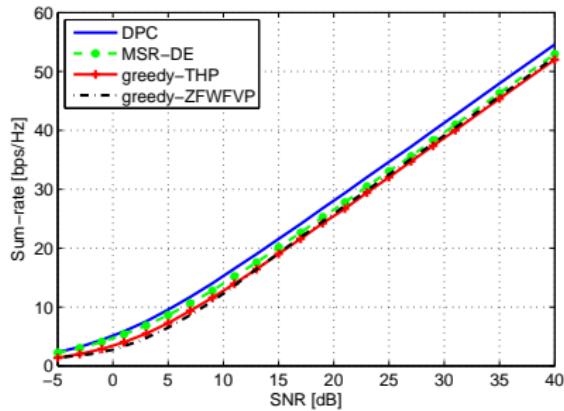
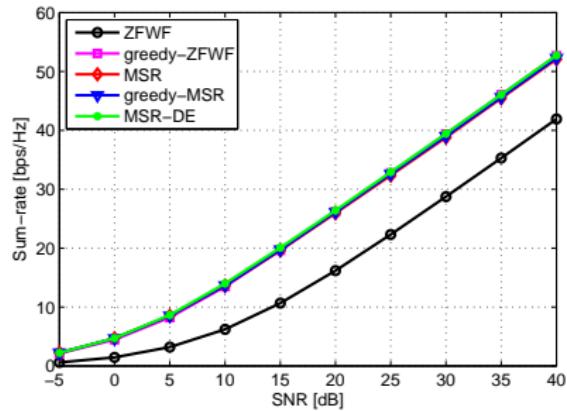
# Zero-Forcing Beamforming (ZFBF)

- Illustration of ZFBF precoding for a two-user scenario: (a) non-orthogonal user set, (b) quasi-orthogonal user set.



# Global Performance Comparison

- Sum-rate of linear (left) and non-linear (right) MU-MIMO precoders vs SNR in  $n_t = 4, K = 20$  i.i.d. Rayleigh fading channels

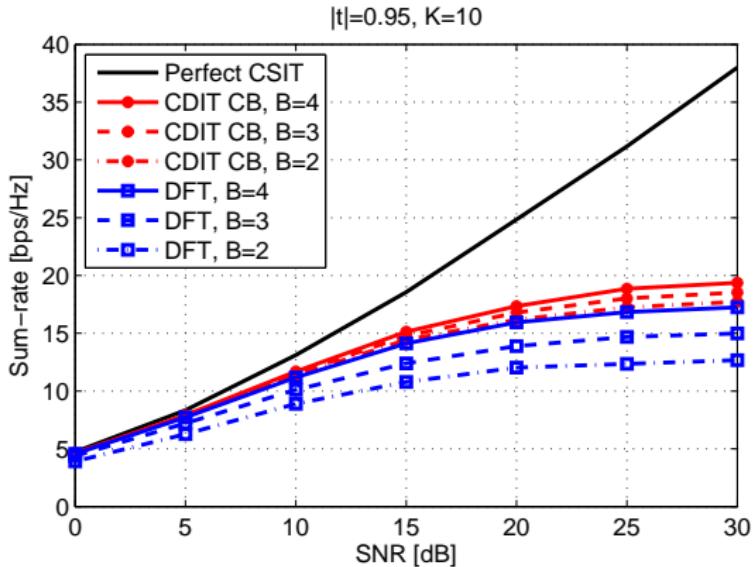


**Observations:** ZFBF without user selection (ZFWF) performs poorly. ZFBF with user selection (greedy-ZFWF) is a competitive strategy for MU-MIMO broadcast channels, in terms of both performance and complexity.

Keep in mind the assumptions: perfect CSIT, the same average SNR for all users and a max-rate scheduler (i.e. there is no fairness issue involved here).

# Precoding with Partial Transmit Channel Knowledge

- If imperfect CSIT (e.g. quantized feedback), residual interference term in the SINR does not vanish with SNR, therefore inducing a ceiling effect as SNR increases.
- Performance of channel statistics-based codebook (CDIT-CB) and DFT codebook with Greedy user selection for  $B = 2, 3, 4$ ,  $n_t = 4$ ,  $|t| = 0.95$  and  $K = 10$ .



# Massive MIMO

- Very large number of transmit antennas  $n_t$  in the downlink (MISO/MIMO BC) or receive antennas  $n_r$  in the uplink (SIMO/MIMO MAC).
- Narrow beams: large beamforming gain and low multi-user interference.
- Simple precoder design sufficient.
- Simultaneously serve many users in the same resource block, simplified scheduling.
- Massive demand for CSIT.

# Massive MIMO: Intuition

- Assume independent and identically Rayleigh fading (across antennas and independent across users). By the law of large numbers, channels become mutually orthogonal as  $n_t$  becomes large (decorrelation effect),

$$\lim_{n_t \rightarrow \infty} \frac{1}{n_t} \mathbf{H}_l \mathbf{H}_p^H = \mathbf{I}_{n_r} \delta_{lp}, \quad \forall l, p = 1, \dots, K,$$

for MIMO,

$$\lim_{n_t \rightarrow \infty} \frac{1}{n_t} \mathbf{h}_l \mathbf{h}_p^H = \delta_{lp}, \quad \forall l, p = 1, \dots, K,$$

for MISO ( $\delta_{lp} = 0$  if  $l \neq p$ , 1 if  $l = p$ ).

# Massive MIMO: Matched Beamforming (MBF)

- As  $n_t$  increases, with perfect CSIT, the channel of user  $q$  becomes orthogonal to co-scheduled users ( $s \neq q$ ) channels. Hence, the multi-user interference is naturally eliminated by matching user  $q$  precoder to user  $q$  channel.
- Massive MIMO is spectrally and energy efficient:
  - Assume a single receive antenna for simplicity, and transmit with a MBF/MRT precoder  $\mathbf{w}_s = \bar{\mathbf{h}}_s^H = \mathbf{h}_s^H / \|\mathbf{h}_s\|$  and a transmit power  $s_s = E_s/n_t \forall s = 1, \dots, K$
  - For large  $n_t$ , the SINR  $\rho_q$  of user  $q$  simplifies as

$$\rho_q = \frac{\Lambda_q^{-1} |\mathbf{h}_q \mathbf{w}_q|^2 E_s/n_t}{\sum_{\substack{p \in \mathbf{K} \\ p \neq q}} \Lambda_q^{-1} |\mathbf{h}_q \mathbf{w}_p|^2 E_s/n_t + \sigma_{n,q}^2} \xrightarrow{n_t \nearrow} \frac{\Lambda_q^{-1} \|\mathbf{h}_q\|^2 E_s/n_t}{\sigma_{n,q}^2} \approx \frac{\Lambda_q^{-1} E_s}{\sigma_{n,q}^2} = \eta_q$$

and the sum-rate is equal to

$$C_{BF}(\mathbf{H}) \approx \bar{C}_{BF} \approx \sum_{q=1}^K \log_2(1 + \eta_q)$$

for a total transmit power  $K E_s/n_t$ .

- By MBF with a power  $E_s/n_t$  per user in a large MISO system (i.e. the transmit power is scaled down proportionally to  $1/n_t$ ), each of the  $K$  users gets the same rate as if it were scheduled on a SISO AWGN channel with a transmit power  $E_s$  (and received SNR  $\eta_q$ ) without any intra-cell interference and without any fading.
- Assuming  $\eta_q = \eta \forall q$ , the total achievable sum-rate writes as  $K$  times the SISO AWGN rate.
- The transmit power is scaled down proportionally to  $1/n_t$  and the multiplexing gain increased proportional to  $K$ .

# Massive MIMO: Zero-Forcing Beamforming

- ZFBF precoding:  $\mathbf{w}_q$  for user  $q \in \mathbf{K}$  writes as

$$\mathbf{w}_q = \mathbf{F}(:, q) / \|\mathbf{F}(:, q)\| = \bar{\mathbf{F}}(:, q) / \|\bar{\mathbf{F}}(:, q)\|$$

with

$$\begin{aligned}\mathbf{F} &= \mathbf{H}^H \left( \mathbf{H} \mathbf{H}^H \right)^{-1}, \\ &= \underbrace{\bar{\mathbf{H}}^H \left( \bar{\mathbf{H}} \bar{\mathbf{H}}^H \right)^{-1}}_{\bar{\mathbf{F}}} \mathbf{D}^{-1}.\end{aligned}$$

- Massive MIMO effect also benefits ZFBF:

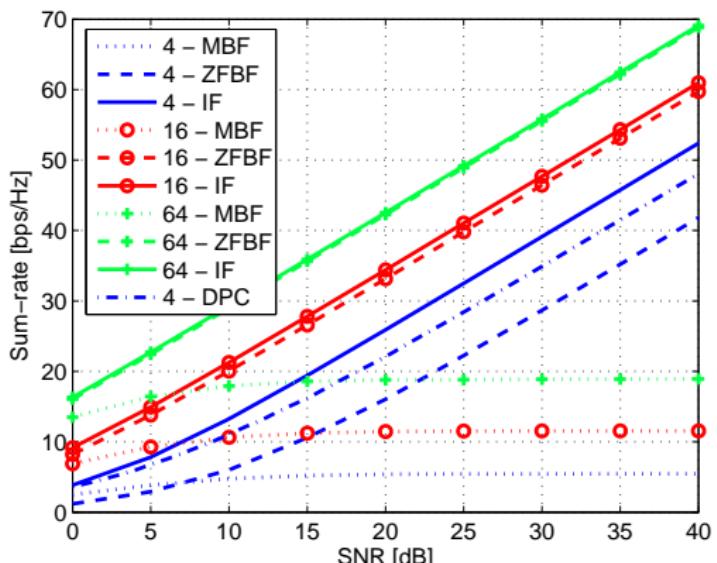
- As  $n_t$  grows,  $\mathbf{H} \mathbf{H}^H$  and  $\bar{\mathbf{H}} \bar{\mathbf{H}}^H$  become better conditioned, thereby simplifying the computation of the matrix inverse.
  - In the limit where user channels are orthogonal,  $\mathbf{H} \mathbf{H}^H$  and  $\bar{\mathbf{H}} \bar{\mathbf{H}}^H$  are diagonal and ZFBF boils down to MBF.

# Massive MIMO: Channel Hardening and Scheduling

- The transmit (and also receive) beamforming gain approximates as  $n_t$  for large  $n_t$ . As  $n_t$  increases, the value of  $\|\mathbf{h}_q\|^2$ , being a  $\chi^2_{2n_t}$  distributed random variable, concentrates indeed more and more around its mean (channel hardening).
- The SINR and the sum-rates become exclusively a function of  $\Lambda_q$  and not of the fading (that is so useful to benefit from MU diversity).
- Transmit/Receive beamforming and MU diversity are somehow not complementary. A large  $n_t$  benefits the array gain and multiplexing gain but restricts the MU diversity gain.
- In general, any transmission scheme that exploits spatial diversity reduces the multi-user diversity gain because of the channel hardening effect.
- Scheduling in Massive MIMO becomes much simpler.

# Sum-Rate Evaluations

- Performance of MBF, ZFBF, DPC, IF in  $n_t = 4, 16, 64$  and  $K = 4$  i.i.d. Rayleigh fading channels.
  - IF stands for interference free and is the upper bound on the performance obtained assuming perfect matched beamforming, no intra-cell interference and an uniform power allocation across the four users, leading to a sum-rate of  $\sum_{q=1}^K \log_2 (1 + \eta_q/K \| \mathbf{h}_q \|^2)$ .



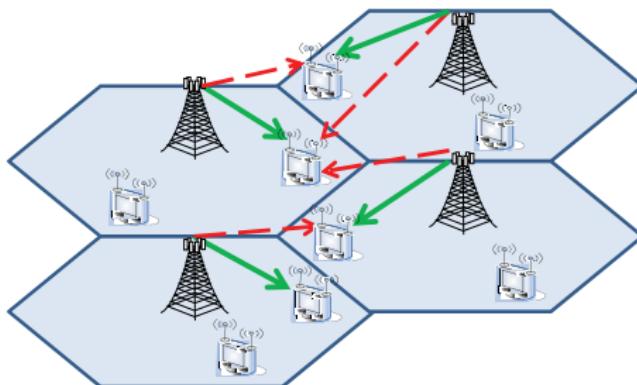
# Sum-Rate Evaluations

- As  $n_t$  grows, the gap between IF and ZFBF shrinks significantly:
  - Severe gap exists in the four transmit antenna case between IF, DPC and ZFBF,
  - The gap completely vanishes with 64 transmit antennas with ZFBF performing as well as an IF system.
  - Hence the performance gain of advanced precoding techniques does not justify the complexity increase.
- MBF on the other hand performs relatively poorly (except at low SNR)
  - sum-rate performance fundamentally limited by intra-cell interference and his SINR is limited at high SNR by the ratio  $\alpha = n_t/K$ .
  - MBF requires a much larger number of antennas to reach the same performance as ZFBF.
- In summary, for  $K \gg n_t$  (with scheduling) and  $n_t \gg K$ , simple linear precoding schemes provide very competitive alternatives to more complex (non-linear) strategies.

# Multiuser Multicell Communications

# Interference

- Current wireless networks primarily operate using a frequency reuse 1 (or close to 1), i.e. all cells share the same frequency band
- Interference is not only made of intra-cell (i.e. multi-user interference), but also of inter-cell (i.e. multi-cell) interference.
- Cell edge performance is primarily affected by the inter-cell interference.



Cellular network

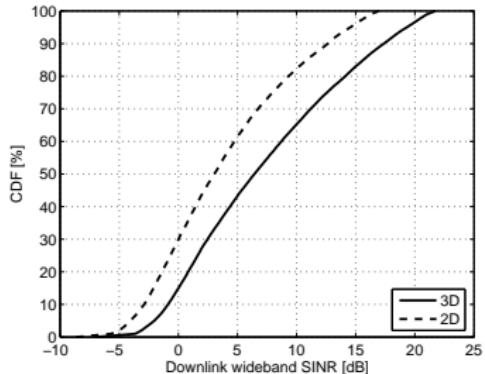
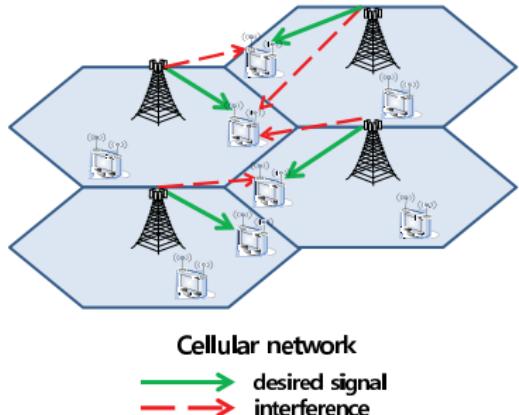
→ desired signal  
→ interference

# Wideband/long-term SINR

- For user  $q$  in cell  $i$ , the wideband/long-term SINR is commonly evaluated by ignoring the effect of fading but only account for path loss and shadowing

$$SINR_{w,q} = \frac{\Lambda_{q,i}^{-1} E_{s,i}}{\sigma_{n,q}^2 + \sum_{j \neq i} \Lambda_{q,j}^{-1} E_{s,j}}.$$

- Provides a rough estimate of the network performance. Function of major propagation mechanisms (path loss, shadowing, antenna radiation patterns,...), base stations deployment and user distribution.
- CDF of  $SINR_{w,q}$  in a frequency reuse 1 network (cells share the same frequency band) with 2D and 3D antenna patterns in urban macro deployment.



# Multi-User Multi-Cell Network

- General downlink multi-cell multi-user MIMO network with a total number of  $K_T$  users distributed in  $n_c$  cells.
- $K_i$  users in every cell  $i$ ,  $n_{t,i}$  transmit antennas at BS  $i$ ,  $n_{r,q}$  receive antennas at mobile terminal  $q$ .
- The received signal of a given user  $q$  in cell  $i$  is

$$\mathbf{y}_q = \Lambda_{q,i}^{-1/2} \mathbf{H}_{q,i} \mathbf{c}'_i + \underbrace{\sum_{j \neq i} \Lambda_{q,j}^{-1/2} \mathbf{H}_{q,j} \mathbf{c}'_j}_{\text{inter-cell interference}} + \mathbf{n}_q$$

where

- $\mathbf{y}_q \in \mathbb{C}^{n_{r,q}}$ ,
- $\mathbf{n}_q$  is a complex Gaussian noise  $\mathcal{CN}(0, \sigma_{n,q}^2 \mathbf{I}_{n_{r,q}})$ ,
- $\Lambda_{q,i}^{-1}$  refers to the path-loss and shadowing between transmitter  $i$  and user  $q$ ,
- $\mathbf{H}_{q,i} \in \mathbb{C}^{n_{r,q} \times n_{t,i}}$  models the MIMO fading channel between transmitter  $i$  and user  $q$ .

# Linear Precoding

- *scheduled user set* of cell  $i$ , denoted as  $\mathbf{K}_i$ , as the set of users who are actually scheduled by BS  $i$  at the time instant of interest
- Transmit  $n_{e,i}$  streams in each cell  $i$  using MU-MIMO linear precoding

$$\mathbf{c}'_i = \mathbf{P}_i \mathbf{c}_i = \mathbf{W}_i \mathbf{S}_i^{1/2} \mathbf{c}_i = \sum_{q \in \mathbf{K}_i} \mathbf{P}_{q,i} \mathbf{c}_{q,i} = \sum_{q \in \mathbf{K}_i} \mathbf{W}_{q,i} \mathbf{S}_{q,i}^{1/2} \mathbf{c}_{q,i}$$

where

- $\mathbf{c}_i$  is the symbol vector made of  $n_{e,i}$  unit-energy independent symbols
- $\mathbf{P}_i \in \mathbb{C}^{n_{t,i} \times n_{e,i}}$  is the precoder made of two matrices, namely a power control diagonal matrix denoted as  $\mathbf{S}_i \in \mathbb{R}^{n_{e,i} \times n_{e,i}}$  and a transmit beamforming matrix  $\mathbf{W}_i \in \mathbb{C}^{n_{t,i} \times n_{e,i}}$ .
- $\mathbf{P}_{q,i} \in \mathbb{C}^{n_{t,i} \times n_{u,q}}$ ,  $\mathbf{W}_{q,i} \in \mathbb{C}^{n_{t,i} \times n_{u,q}}$ ,  $\mathbf{S}_{q,i} \in \mathbb{R}^{n_{u,q} \times n_{u,q}}$ , and  $\mathbf{c}_{q,i} \in \mathbb{C}^{n_{u,q}}$  are user  $q$ 's sub-matrices and sub-vector of  $\mathbf{P}_i$ ,  $\mathbf{W}_i$ ,  $\mathbf{S}_i$ , and  $\mathbf{c}_i$ , respectively.
- The input covariance matrix at cell  $i$  is  $\mathbf{Q}_i = \mathcal{E}\{\mathbf{c}'_i \mathbf{c}'_i^H\}$  subject to the transmit power constraint  $\text{Tr}\{\mathbf{Q}_i\} \leq E_{s,i}$ .

# Linear Precoding

- The received signal  $\mathbf{y}_q \in \mathbb{C}^{n_{r,q}}$  of user  $q \in \mathbf{K}_i$

$$\mathbf{y}_q = \Lambda_{q,i}^{-1/2} \mathbf{H}_{q,i} \mathbf{P}_{q,i} \mathbf{c}_{q,i} + \underbrace{\sum_{p \in \mathbf{K}_i, p \neq q} \Lambda_{q,i}^{-1/2} \mathbf{H}_{q,i} \mathbf{P}_{p,i} \mathbf{c}_{p,i}}_{\text{intra-cell (multi-user) interference}} \\ + \underbrace{\sum_{j \neq i} \sum_{l \in \mathbf{K}_j} \Lambda_{q,j}^{-1/2} \mathbf{H}_{q,j} \mathbf{P}_{l,j} \mathbf{c}_{l,j}}_{\text{inter-cell interference}} + \mathbf{n}_q.$$

- Apply a receive combiner to stream  $l$  of user  $q$  in cell  $i$

$$z_{q,l} = \mathbf{g}_{q,l} \mathbf{y}_q = \Lambda_{q,i}^{-1/2} \mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{q,i,l} c_{q,i,l} + \underbrace{\sum_{m \neq l} \Lambda_{q,i}^{-1/2} \mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{q,i,m} c_{q,i,m}}_{\text{inter-stream interference}} \\ + \underbrace{\sum_{p \in \mathbf{K}_i, p \neq q} \Lambda_{q,i}^{-1/2} \mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{P}_{p,i} \mathbf{c}_{p,i}}_{\text{intra-cell (multi-user) interference}} + \underbrace{\sum_{j \neq i} \sum_{l \in \mathbf{K}_j} \Lambda_{q,j}^{-1/2} \mathbf{g}_{q,l} \mathbf{H}_{q,j} \mathbf{P}_{l,j} \mathbf{c}_{l,j}}_{\text{inter-cell interference}} + \mathbf{g}_{q,l} \mathbf{n}_q.$$

# Achievable Rate

- By treating all interference as noise, the maximum rate achievable by user  $q$  in cell  $i$  with linear precoding is

$$R_{q,i} = \sum_{l=1}^{n_{u,q}} \log_2 (1 + \rho_{q,l}).$$

- The quantity  $\rho_{q,l}$  denotes the SINR experienced by stream  $l$  of user- $q$  and writes as

$$\rho_{q,l} = \frac{S}{I_l + I_c + I_o + \|\mathbf{g}_{q,l}\|^2 \sigma_{n,q}^2}.$$

where  $S$  refers to the received signal power of the intended stream,  $I_l$  the inter-stream interference,  $I_c$  the intra-cell interference (i.e. interference from co-scheduled users) and  $I_o$  the inter-cell interference and they write as

$$S = \Lambda_{q,i}^{-1} |\mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{q,i,l}|^2,$$

$$I_l = \sum_{m \neq l} \Lambda_{q,i}^{-1} |\mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{q,i,m}|^2,$$

$$I_c = \sum_{p \in \mathbf{K}_i, p \neq q} \sum_{m=1}^{n_{u,p}} \Lambda_{q,i}^{-1} |\mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{p,i,m}|^2,$$

$$I_o = \sum_{j \neq i} \Lambda_{q,j}^{-1} \|\mathbf{g}_{q,l} \mathbf{H}_{q,j} \mathbf{P}_j\|^2.$$

# Achievable Rate

## Example

Given the precoders in all cells, what is the SINR of stream  $l$  of user- $q$  in cell  $i$ ?

- Noise plus interference:  $I_l + I_c + I_o + \|\mathbf{g}_{q,l}\|^2 \sigma_{n,q}^2 = \mathbf{g}_{q,l} \mathbf{R}_{\mathbf{n}_i} \mathbf{g}_{q,l}^H$  where

$$\begin{aligned}\mathbf{R}_{\mathbf{n}_i} = & \sum_{m \neq l} \Lambda_{q,i}^{-1} \mathbf{H}_{q,i} \mathbf{p}_{q,i,m} (\mathbf{H}_{q,i} \mathbf{p}_{q,i,m})^H \\ & + \sum_{p \in \mathbf{K}_i, p \neq q} \sum_{m=1}^{n_u,p} \Lambda_{q,i}^{-1} \mathbf{H}_{q,i} \mathbf{p}_{p,i,m} (\mathbf{H}_{q,i} \mathbf{p}_{p,i,m})^H \\ & + \sum_{j \neq i} \Lambda_{q,j}^{-1} \mathbf{H}_{q,j} \mathbf{P}_j (\mathbf{H}_{q,j} \mathbf{P}_j)^H + \sigma_{n,q}^2 \mathbf{I}_{n_r,q}\end{aligned}$$

is the covariance matrix of the noise plus interference.

- MMSE combiner for stream  $l$ :  $\mathbf{g}_{q,l} = \Lambda_{q,i}^{-1/2} (\mathbf{H}_{q,i} \mathbf{p}_{q,i,l})^H \mathbf{R}_{\mathbf{n}_i}^{-1}$
- SINR  $\rho_{q,l}$  experienced by stream  $l$  of user- $q$

$$\rho_{q,l} = \frac{\Lambda_{q,i}^{-1} |\mathbf{g}_{q,l} \mathbf{H}_{q,i} \mathbf{p}_{q,i,l}|^2}{\mathbf{g}_{q,l} \mathbf{R}_{\mathbf{n}_i} \mathbf{g}_{q,l}^H} = \Lambda_{q,i}^{-1} (\mathbf{H}_{q,i} \mathbf{p}_{q,i,l})^H \mathbf{R}_{\mathbf{n}_i}^{-1} \mathbf{H}_{q,i} \mathbf{p}_{q,i,l}.$$



# Future of Wireless

# Wireless is More than just Communications

**Radio waves carry both energy and information**

Wireless Power Transmission  
(WPT)



Tesla 1901

**0G**

Wireless Information Transmission  
(WIT)

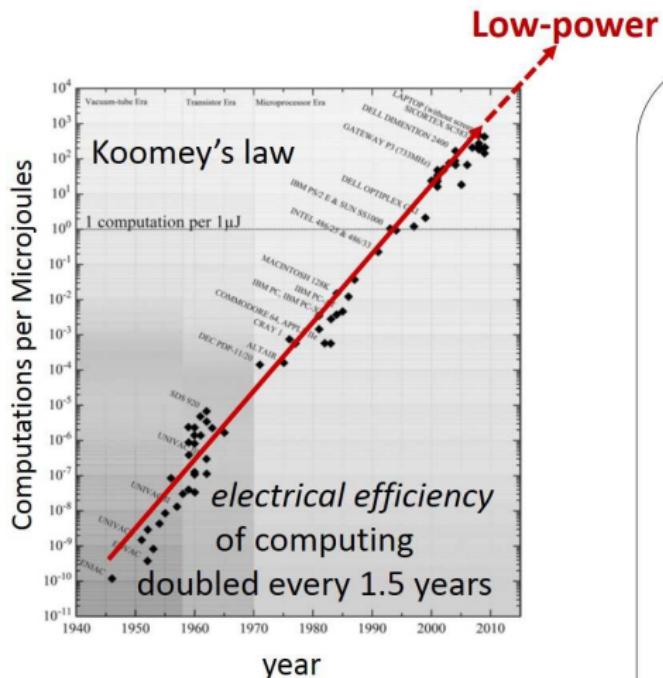


Marconi 1896

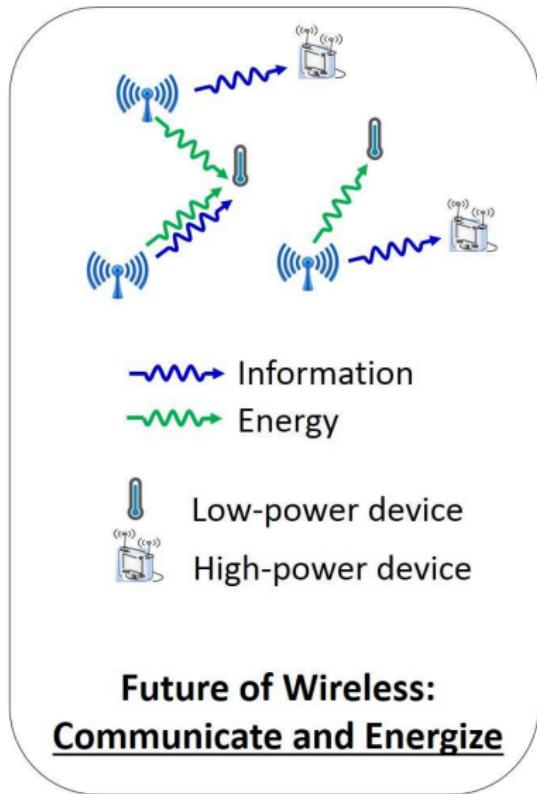
**5G**

**Unified Wireless Information and Power Transmission  
(WIPT)**

# In 20 Years from Now ... Trillions of Low-Power Devices



2017: 5 Billions phones  
2035: **Trillions** IoT devices



# A Missing Signal Theory of Wireless Transmission

## Wireless Power Transmission

RF Theory



Signal Theory



## Wireless Information Transmission

RF Theory



Signal Theory  
(Shannon, ...)

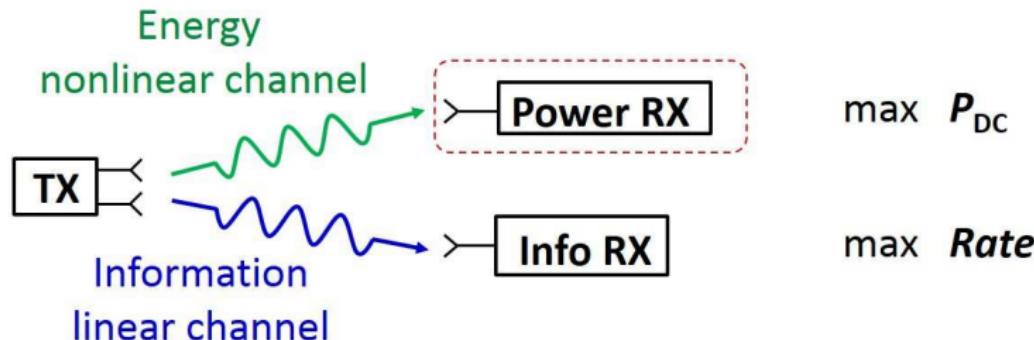


## Wireless Information and Power Transmission

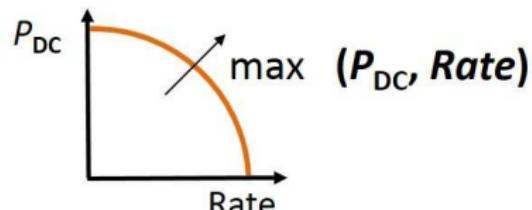
Unified Signal Theory



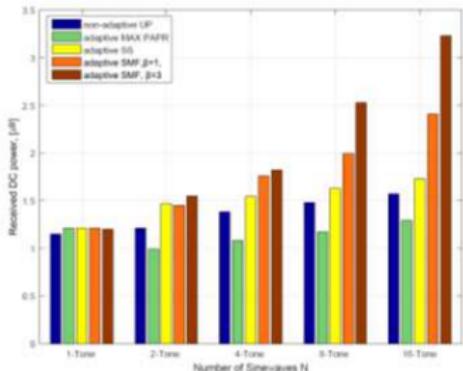
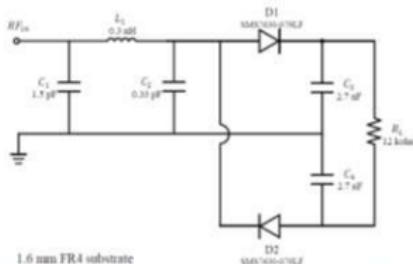
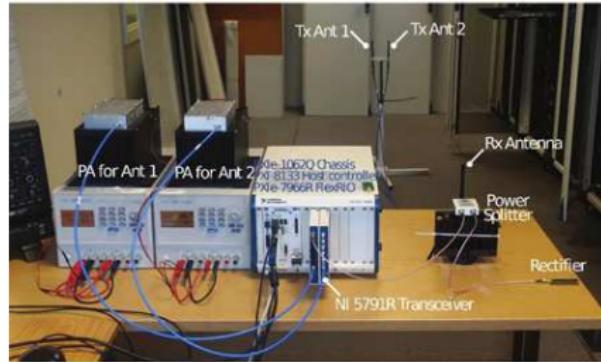
# Signal Theory and Design



- New communications and signal design for WPT
- Novel and unified signal theory and design for WIPT
- Fundamental tradeoff

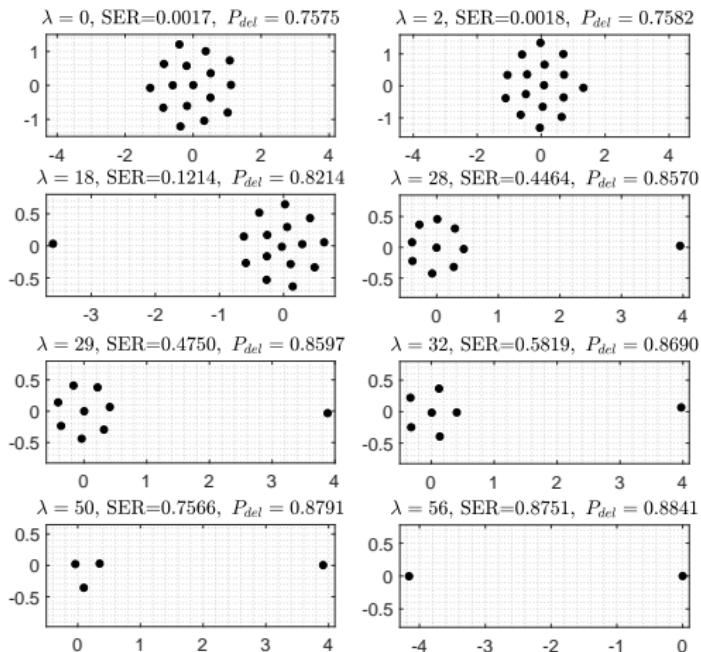


# System Design, Prototyping and Experimentation



# Machine learning for Wireless Communications and Power Transfer

16-symbols modulation for different values of energy



Many on-going research activities:

- enhanced eMBB, enhanced URLLC, enhanced mMTC
- new services: integrated sensing (radar, localization, ...) and communication
- new materials and surfaces
- new multi-antenna techniques (beyond massive MIMO)
- ...