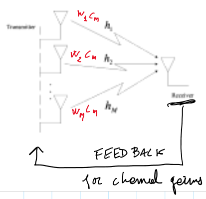
MISO channel: transmit diversity

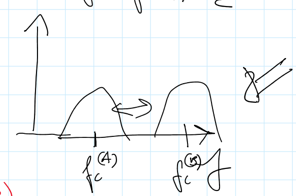


- $M > 1$ antennas at the transmitter and $N = 1$ at the receiver
- Spatial precoding: the signals are precoded at the transmitter.
- The signal at the j-th transmit antenna is $y_j(m) = w_j c_m$
- The transmitted energy depends also on the precoding weights.
- The received signal is
$$x(m) = h_1 y_1 + \cdots + h_M y_M$$

$$h = [h_1, h_2, \dots, h_M]$$

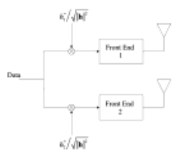
$$\begin{cases} w_1 = h_1^* \\ w_2 = h_2^* \end{cases}$$

$$f_c^{(B)} - f_c^{(A)} \gg B_c$$



Maximal ratio transmit (MRT) combining

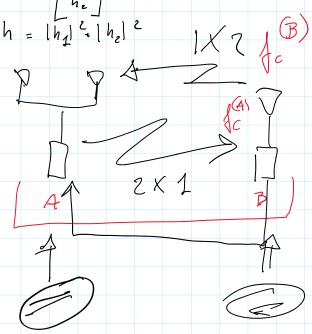
- The optimal precoding weight for the j-th transmit antenna is
$$w_j = h_j^* / \|\mathbf{h}\|$$
so that the overall transmitted energy per symbol is still $E_s = A/2$.
- At the receiver
$$x(m) = \left(\frac{h_1 h_1^*}{\|\mathbf{h}\|} + \frac{h_2 h_2^*}{\|\mathbf{h}\|}\right) c_m + n(m)$$
- The signal to noise is
$$SNR = (|h_1|^2 + |h_2|^2)\frac{A}{\sigma^2}$$

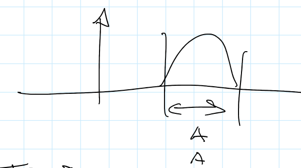


$M = 2$

$$E_s = |w_1|^2 A + |w_2|^2 A = (|w_1|^2 + |w_2|^2) A = \left(\frac{|h_1|^2}{\|h\|^2} + \frac{|h_2|^2}{\|h\|^2}\right) A$$
$$= \frac{|h_1|^2 + |h_2|^2}{\|h\|^2} = 1$$

$$h = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \qquad \|h\|^2 = h^H h = |h_1|^2 + |h_2|^2$$





TDD

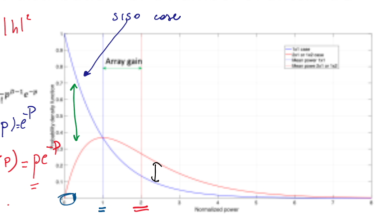
FDD

Power distribution for a number of antenna D

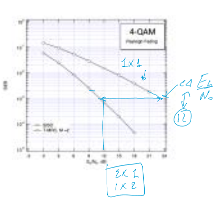
$$f_D(p) = \frac{1}{(D-1)!} p^{D-1} e^{-p}$$

$D = 1 \Rightarrow f_{D=1}(p) = e^{-p}$

$D = 2 \Rightarrow f_{D=2}(p) = p e^{-p}$



Maximal ratio combining



- Advantages
  - Diversity gain
  - Array gain
  - MRT: No additional processing at the receiver
- Disadvantage
  - MRT: Requires channel knowledge at the transmitter
  - MRC: requires some extra processing at the receiver.

Singular Value Decomposition

$$H = \begin{bmatrix} & & \\ & h_{i,j} & \\ & & \end{bmatrix} \quad (N \times M,\ i: \text{Rx},\ j: \text{Tx})$$

$$y = H x$$

$$H = U \Sigma V^H$$

Unitary

Diagonal

$$H_{2\times 2} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} = U \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} V^H$$

MIMO: spatial multiplexing

- The channel is a (N, M)-dimensional matrix
- The optimal technique is called *spatial multiplexing* based on the *singular value decomposition* (SVD) of the channel matrix $\boldsymbol{H}$.
- By employing SVD and coordinating the precoding weights at the transmitter with the combiner weights at the receiver it is possible to create a certain number of independent orthogonal channels.
- Assuming that $M = N$, spatial multiplexing creates N independent spatial channels.

V is the precoder

U^H is the combiner

if V is the precoder

$x = V b$

$$y = Hx \ ; \quad z = U^H y = U^H H x = U^H H V b$$
$$= \underbrace{U^H U}_{I_{2\times 2}} \Sigma \underbrace{V^H V}_{I_{2\times 2}} b = \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\boxed{z_1 = \sigma_1 b_1} \ ; \ \boxed{z_2 = \sigma_2 b_2}$$

LTE

Physical layer LTE

- Long Term Evolution (LTE) is the 4th wireless communication standard
  - 1G: various national analog FDMA-based systems
  - 2G: GSM. First digital standard. Maximum data rate supported $R = 9.6$ kb/s
  - 3G: UMTS CDMA
  - 4G: LTE OFDM (JUST AS WIFI)

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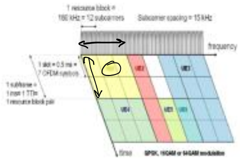
  - 3G: UMTS CDMA
  - 4G: LTE OFDM (JUST AS WIFI)
  - 5G: NR (currently deployed now)
- LTE is a very flexible communication system mainly used for data transmissions

Pyhysical layer LTE

Numerology

$\Delta f = 325$ KHz

- LTE is based on OFDM
- The sampling time is
  $$f_s = 30.72 \text{ MHz}$$
- FFT size is $N = \underline{2048}$
- Subcarrier's bandwidth is
  $$\Delta f = \frac{30.72}{2048} = 15 \text{ kHz}$$
- A single slot groups 7 OFDM blocks and has a duration of 0.5 ms



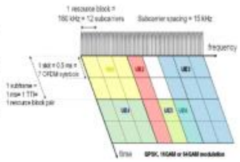
OFDM block (symbol) is composed by $(N + N_{cp})$ samples

Pyhysical layer LTE

$B_c > 12 \cdot 15 = 180$ KHz

$T_c > 7$ OFDM symb. $= 0.5$ ms

- Multiple access technique is OFDMA: groups of subcarriers are allocated to the user.
- The minimum allocation unit is a resource block (RB). A RB contains 12 subcarriers and spans 180 kHz for the duration of a slot.



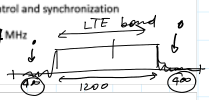
Orthogonal Frequency Division Multiple Access

Pyhysical layer LTE: peak data rate

- Most recent phones fall in the 19-20 category list.
- Raw Bandwidth:

  Of the 2048 available subcarriers only 1200 (100 RB) are used the remaining 848 are 0-level guard subcarrier. The maximum available bandwidth for data transmission is
  $$B_{raw} = 1200x15 \text{ kHz} = 18 \text{ MHz}$$
- Available bandwidth

  Approximately 4 MHz are spent for sending control and synchronization information
  $$B_{av} = B_{raw} - 4 \text{ MHz} = 14 \text{ MHz}$$



Theoretically was $\underline{30.72}$ MHz

In practice is $\underline{20}$ MHz

1 RB = 12 subcarriers

1200 subcarriers are 100 RB

$B_{RAW} = 1200 \times 15 \text{ KHz} = \underline{\underline{18 \text{ MHz}}}$ bandw

100 RB

50 RB

25 RB

20, 10, 5, 3, 1.5 } channelization

Pyhysical layer LTE: peak data rate

- Modulation and coding

  In LTE coding rate ranges in the interval 0.0762 - 0.9258. The modulation used are 4-QAM to 256-QAM. Modulation order and coding rate are based on the radio link quality.

  Radio link quality is estimated based on CQI (Channel Quality Indicator), which is measured by the terminal and fed back to the base station. The highest coding rate (including CRC) is $R = 0.9258$ and the largest modulation order is $M = 256$ (8 bits per symbol).

  The maximum bit rate per SISO channel is is
  $$R_{1x1} = 0.9258x8x14 \text{ MHz} \approx 100 \text{ Mb/s}$$

Pyhysical layer LTE: peak data rate

- MIMO

  In LTE various configurations are supported (1x1,2x1,1x2,2x2,4x4) depending on
    - the user equipment capabilities (number of anttennas)
    - The eNode-B capabilities: cell traffic, hardware limits.
    - The channel conditions
  - Most performing scheme is spatial multiplexing 4x4 , which creates 4 parallel channels. With 4x4 MIMO spatial multiplexing the peak data rate is
    $$R_{4x4} = 4xR_{1x1} = 400 \text{ Mb/s}$$
- Carrier aggregation
  - Most advanced terminals can aggregate several 20 MHz bandwidth together
  - Iphone 11 pro: 3 with 4x4 MIMO and 2 with 2x2 MIMO
    $$R_I = 3x400 + 2x200 = 1.6 \text{ Gb/s}$$
  - Samsung S20+
    $$R_s = 5x400 = 2 \text{ Gb/s}$$