TTH4A3
Komunikasi Akses Wireless

Bahan Kajian 2c:

MULTIPLE ANTENNA

Team Dosen

Telkom University

Pertemuan ke-7

Outline

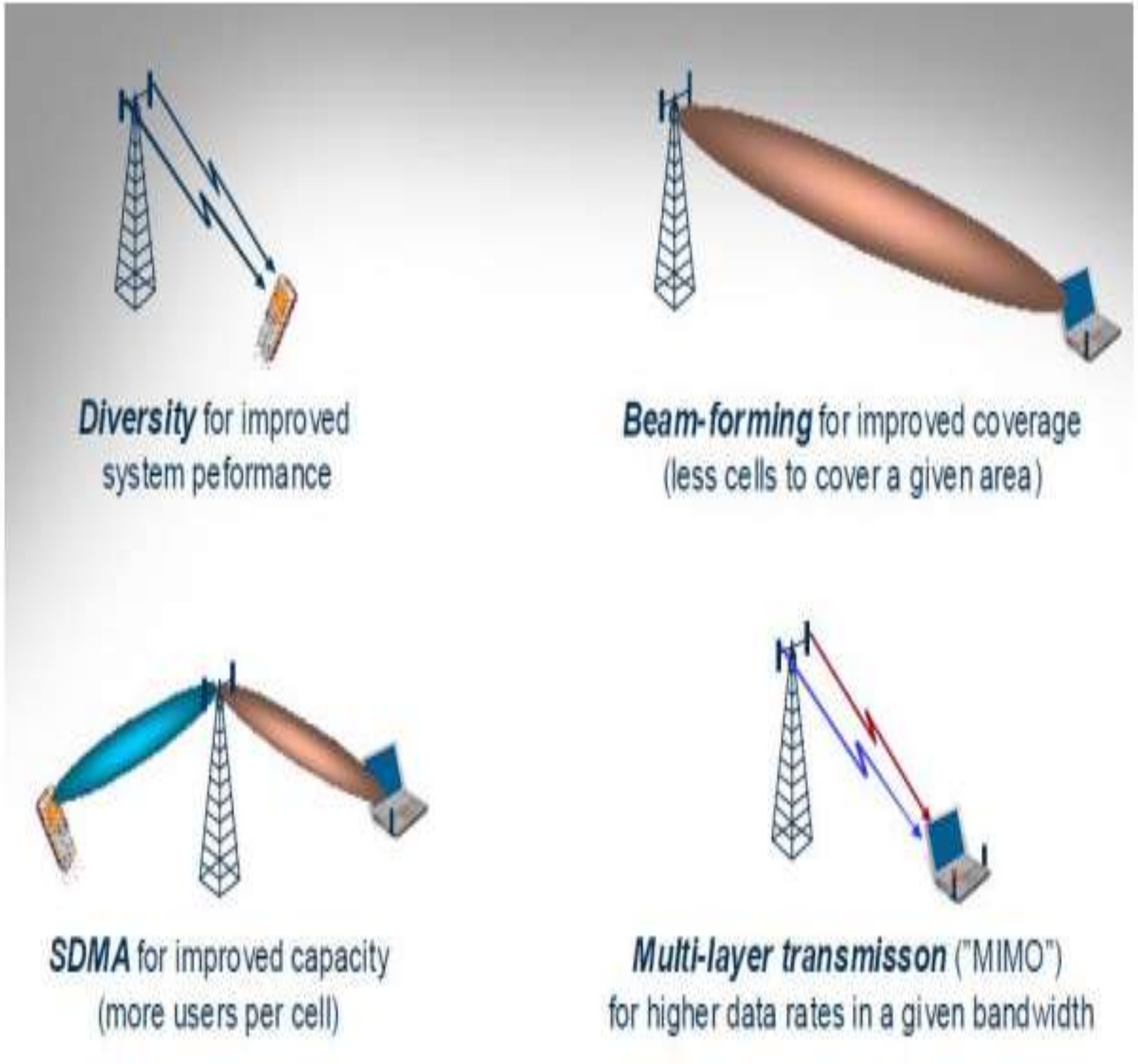
Multiple Antenna Systems

- SISO
- SIMO
- MISO
- MIMO

Why MIMO

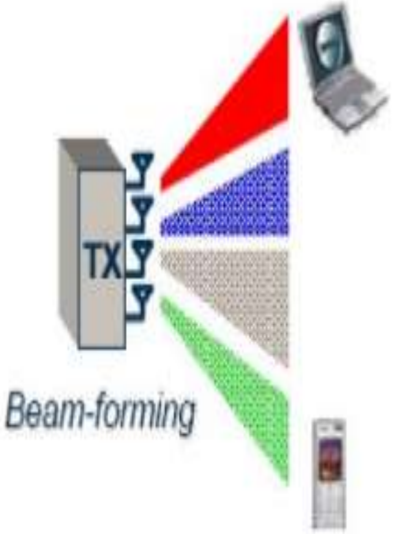
- Motivation: current wireless systems
  - Capacity constrained networks
  - Issues related to quality and coverage
- MIMO exploits the *space* dimension to improve wireless systems capacity, range and reliability
- MIMO-OFDM – the corner stone of future broadband wireless access
  - WiFi – 802.11n
  - WiMAX – 802.16e (a.k.a 802.16-2005)
  - 3G / 4G

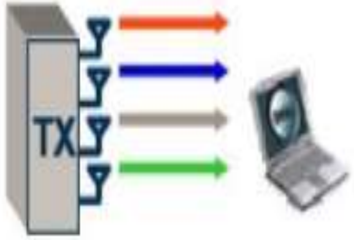
MIMO and Others



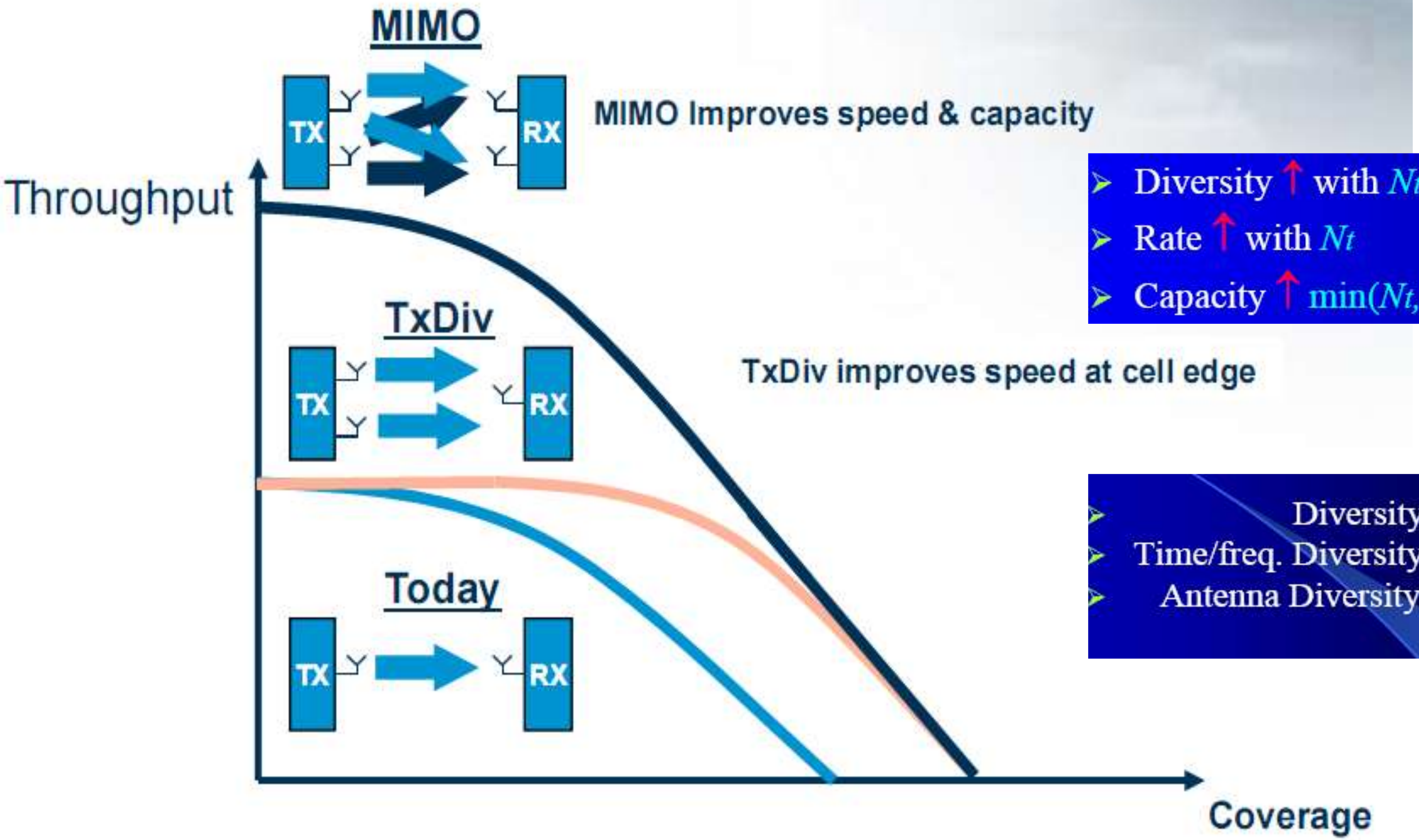
Teknik Advanced Antenna

- Single data stream / user
- Beam-forming
  - Coverage, longer battery life
- Spatial Division Multiple Access (SDMA)
  - Multiple user pada sumberdaya radio yang sama
- Multiple data stream / user Diversity
  - Link robustness
- Spatial multiplexing
  - Spectral efficiency, high data rate support





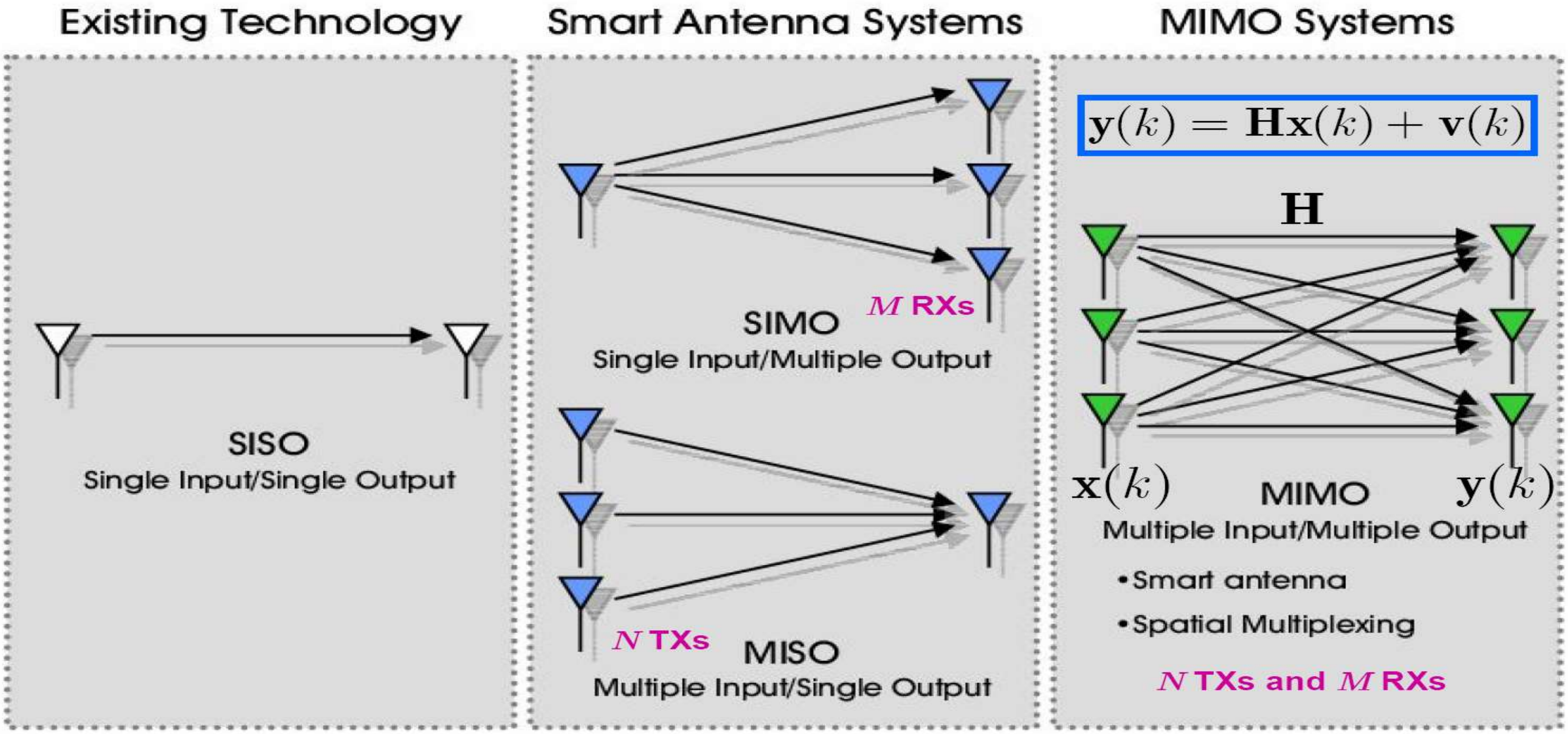
Multi-layer transmission ("MIMO")



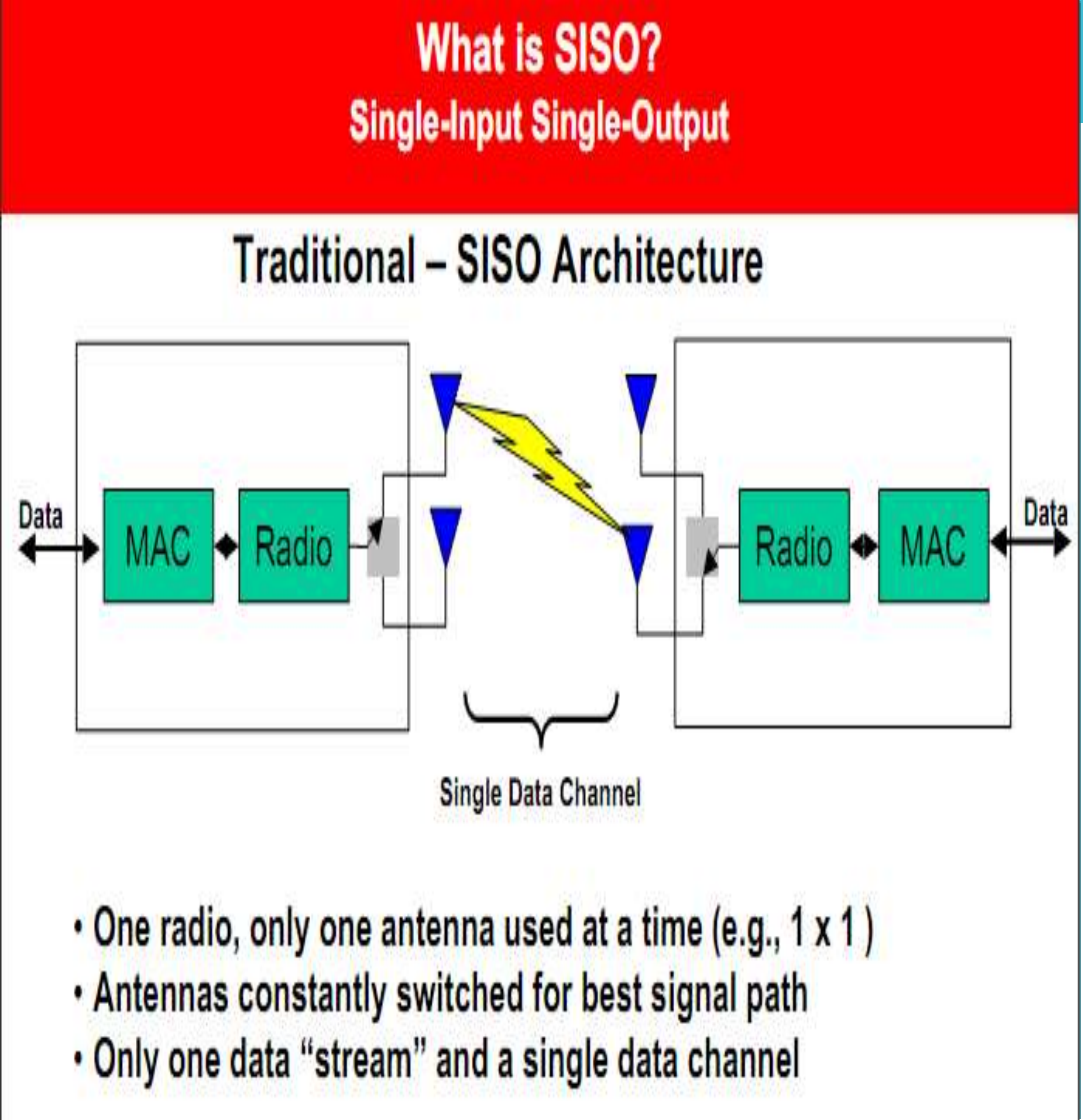
- Diversity ↑ with *NtNr*
- Rate ↑ with *Nt*
- Capacity ↑ min(*Nt*, *Nr*) [Foschini'98]

- Diversity → multiple copies
- Time/freq. Diversity → BW expansion
- Antenna Diversity → cost, but no BW expansion

Multiple Antenna Technique: Four Basic Models

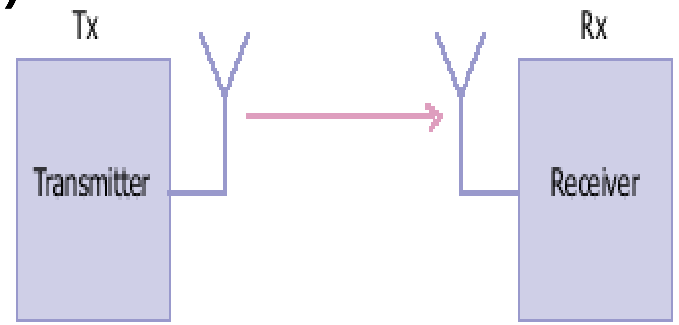


SISO



Radio transmissions traditionally use one antenna at the transmitter and one antenna at the receiver.
This system is termed Single Input Single Output (SISO).

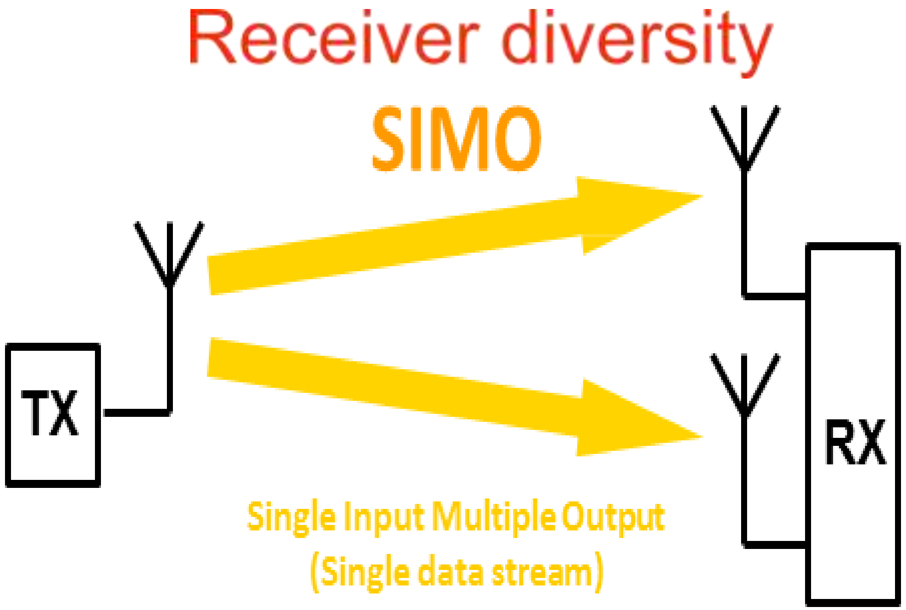
Both the transmitter and the receiver have one RF chain (that's coder and modulator). SISO is relatively simple and cheap to implement and it has been used age long since the birth of radio technology.
It is used in radio and TV broadcast and our personal wireless technologies (e.g. Wi-Fi and Bluetooth).



Picture. Single Input Single Output (SISO)
One antenna at both the transmitter and the receiver.
Employs no diversity technique.

SIMO

To improve performance, a multiple antenna technique has been developed. A system which uses a single antenna at the transmitter and multiple antennas at the receiver is named Single Input Multiple Output (SIMO). The receiver can either choose the best antenna to receive a stronger signal or combine signals from all antennas in such a way that maximizes SNR (Signal to Noise Ratio). The first technique is known as switched diversity or selection diversity. The latter is known as maximal ratio combining (MRC).



- Receiver coherently combines signals received by multiple antennas

- Asymptotic gain: Increasing SNR proportionally to Nr (#of receive antennas)

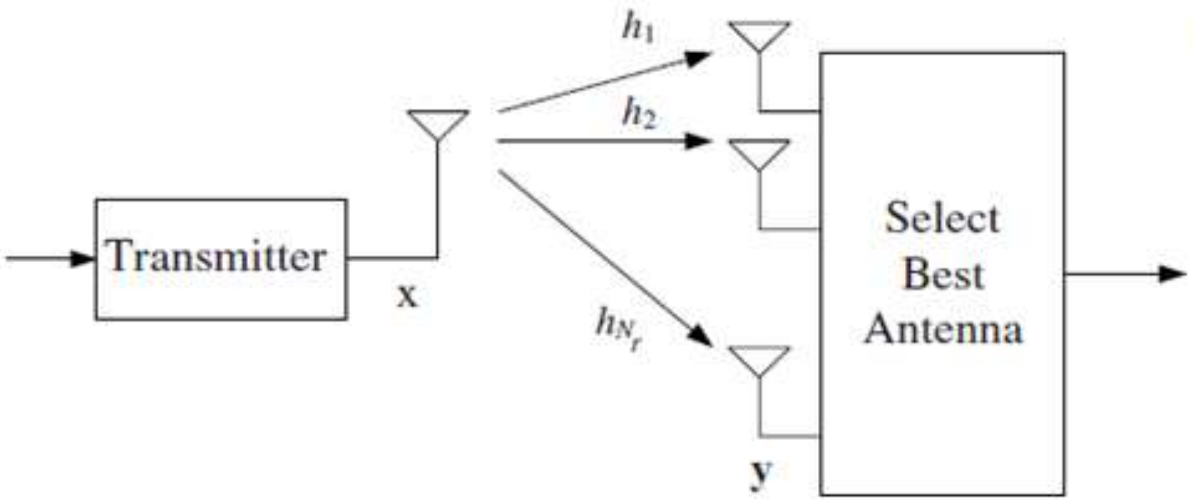
* Intuition: received signal power adds up

- What's the capacity gain?

*Logarithmically, according to Shannon's equation: C=B log(1+SNR)

*When SNR is low, $\log(1+SNR) \approx SNR$, so gain is almost linear w.r.t. Nr

Picture. Single Input Multiple Output (SIMO), 1x2
One antenna at the transmitter, two antennas the receiver.
Employs a receive diversity technique.

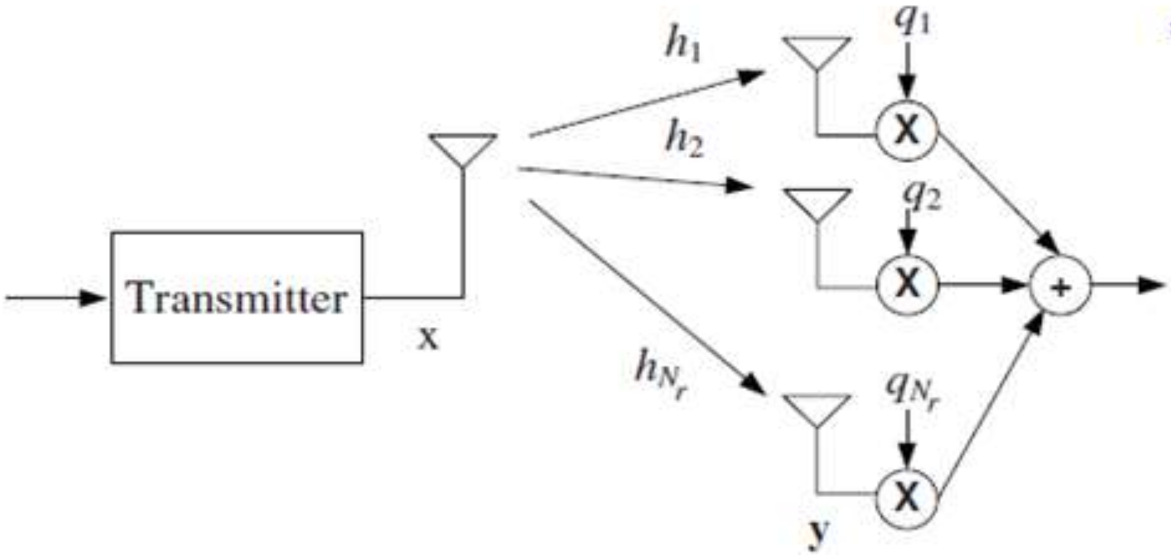


* Selection combining

Improves SNR to

$$avgSNR\cdot(1+\frac{1}{2}+\ldots+\frac{1}{N_r})$$

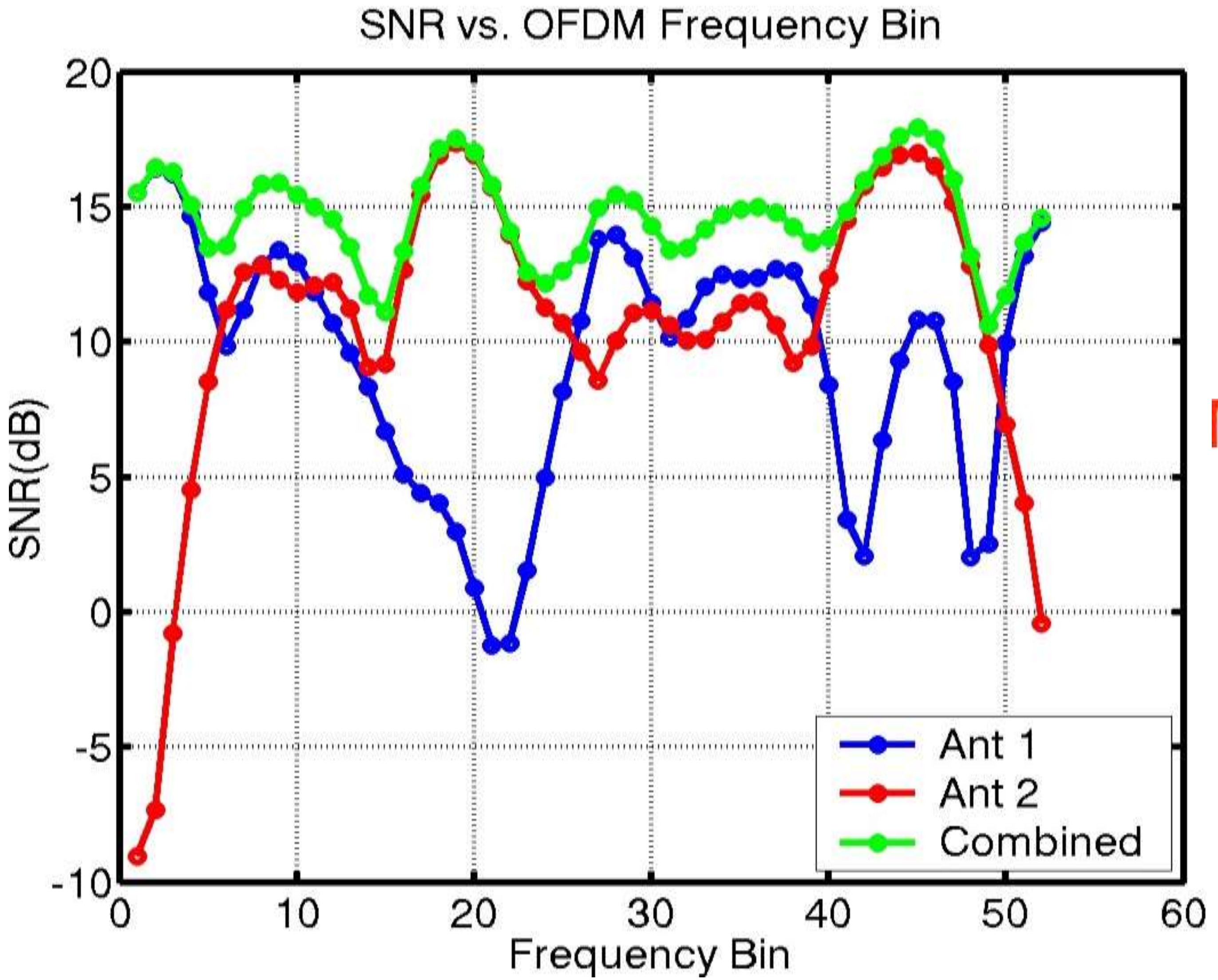
Implementing receiver diversity



* Maximum Ratio combining

Improves SNR to

$$\sum_{i=1}^{N_r} SNR_i$$

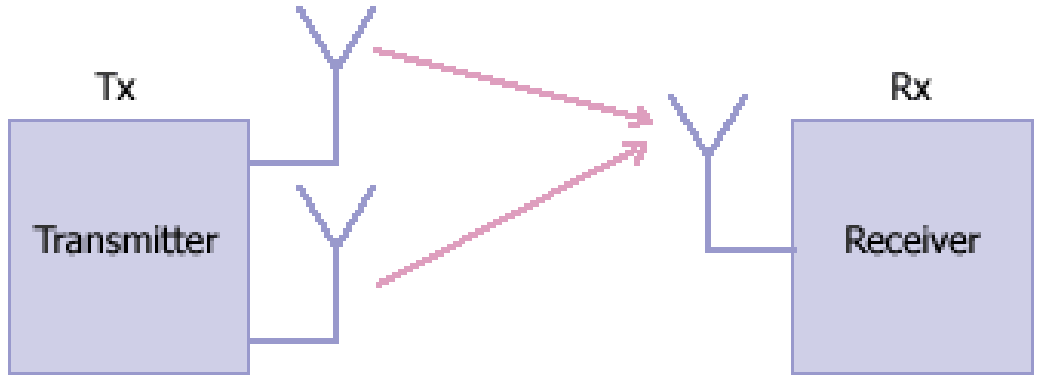


Mitigating fading with receiver diversity

Multiple receive antennas allow compensation of by non- notches in the other

MISO

- **A system using multiple antennas at the transmitter and a single antenna at the receiver is named Multiple Input Single Output (MISO).**
- **A technique known as Alamouti STC (Space Time Coding) is employed at the transmitter with two antennas.**
- **STC allows the transmitter to transmit signals (information) both in time and space, meaning the information is transmitted by two antennas at two different times consecutively.**



Picture. Multiple Input Single Output (MISO), 2x1
Two antennas at the transmitter, one antenna at the receiver.
Employs a transmit diversity technique

Transmitter sends multiple versions of the same signal, through multiple antennas

Two modes of transmit diversity

* **Open-loop transmit diversity**

* **Closed-loop transmit diversity**

Open-Loop Transmit Diversity

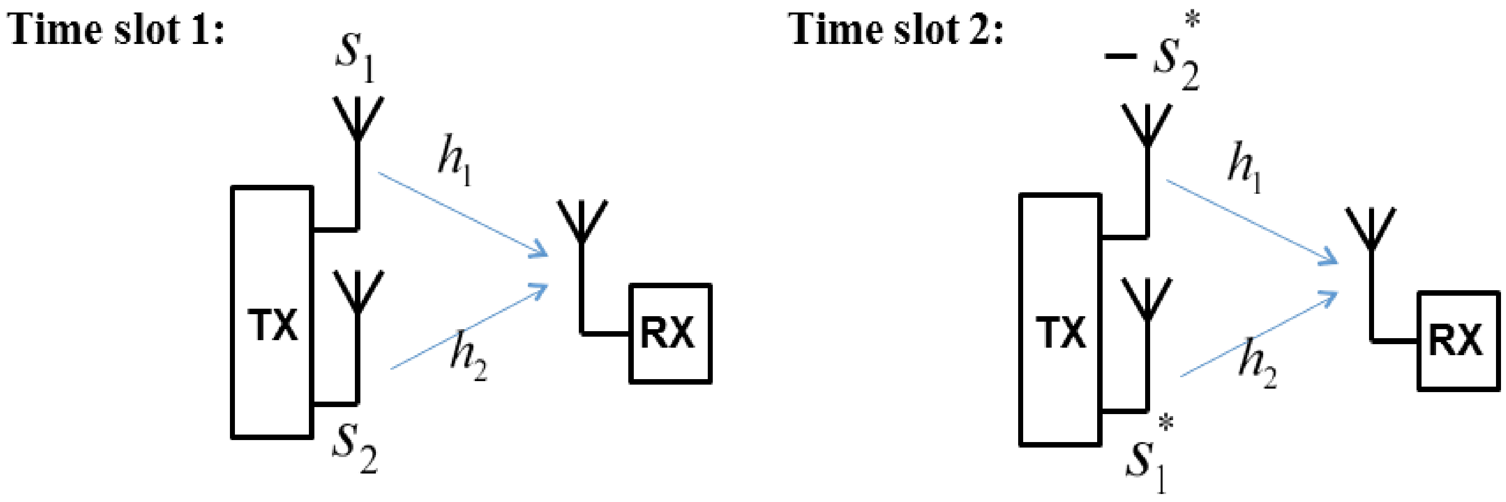
Principle :

*** Send redundant versions of the same signal (symbol), over multiple time slots, and through multiple antennas**

*** Encode the symbols differently for different time slots and TX antennas**

- **Space-Time Block Code (STBC)**

- Example: 2 TX antenna STBC
  - Send two data symbols, s_1 and s_2



  - Received signals:

$$r(t_1) = h_1 s_1 + h_2 s_2$$

$$r(t_2) = -h_1 s_2^* + h_2 s_1^*$$

Open-Loop Transmit Diversity

- Example: 2 TX antenna STBC
  - Diversity combining

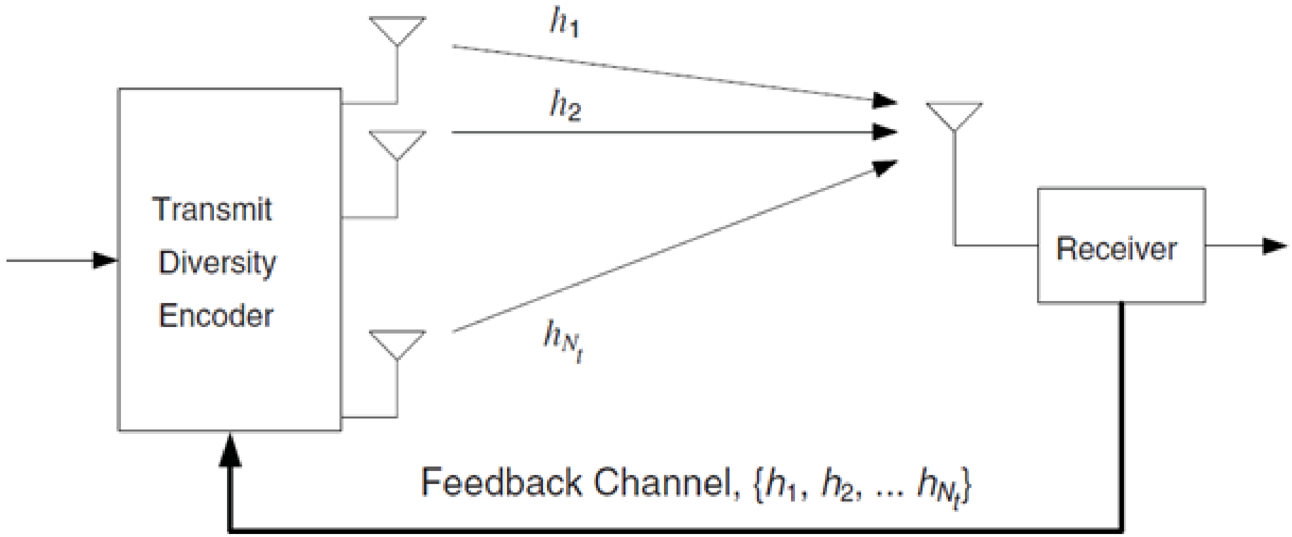
$$y_1 = h_1^* r(t_1) + h_2 r(t_2) = (|h_1|^2 + |h_2|^2) s_1$$

  - i.e., signal power is boosted from $|h_1|^2$ to $|h_1|^2 + |h_2|^2$
  - Open-loop transmit diversity gain:

    In general, open-loop transmit diversity increases SNR **linearly** with the number of transmit antennas
  - What's the capacity gain?

Closed-Loop Transmit Diversity

- Principle
  - Send redundant versions of the same signal (symbol), over the same time slot
  - Encode the symbols differently for different TX antennas
    - i.e., weight the symbols on different antennas, following a precoding algorithm
    - Precoding design requires feedback of channel state information (CSI)

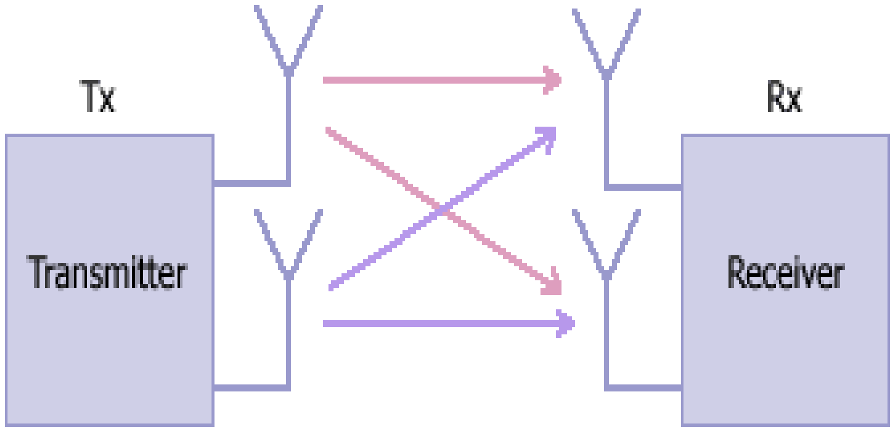


Closed-Loop Transmit Diversity

- Asymptotic gain from closed-loop transmit diversity
  - Signal level combining, also called transmit beamforming
    * Suppose we have 2 transmit antennas, then instead of x, we receive: x+x=2x, received power becomes $4|x|^2$, SNR increases to 4 times!
    * More generally, with N_t TX antennas, SNR increases to N_t^2
    * What's the capacity gain?

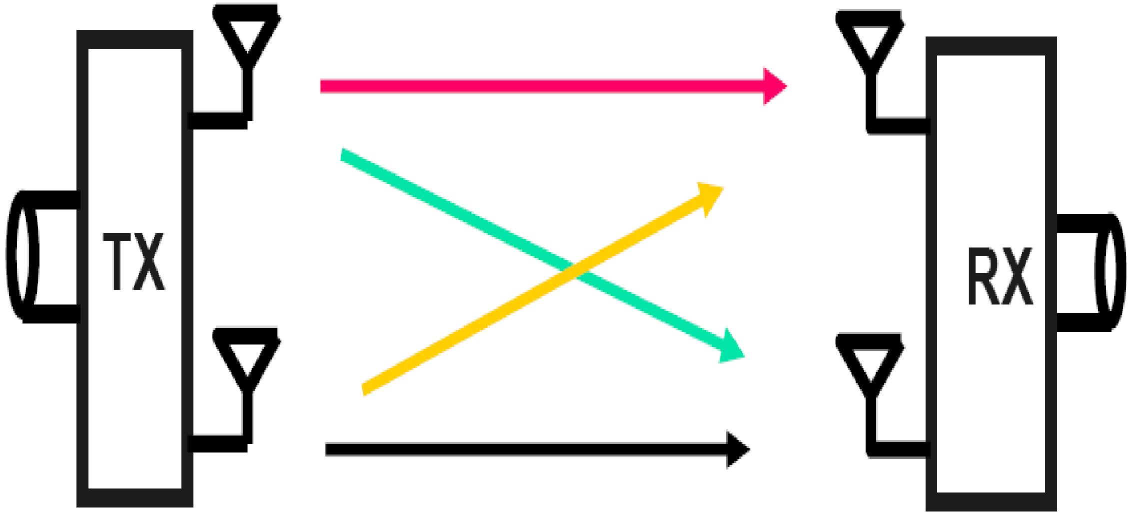
MIMO

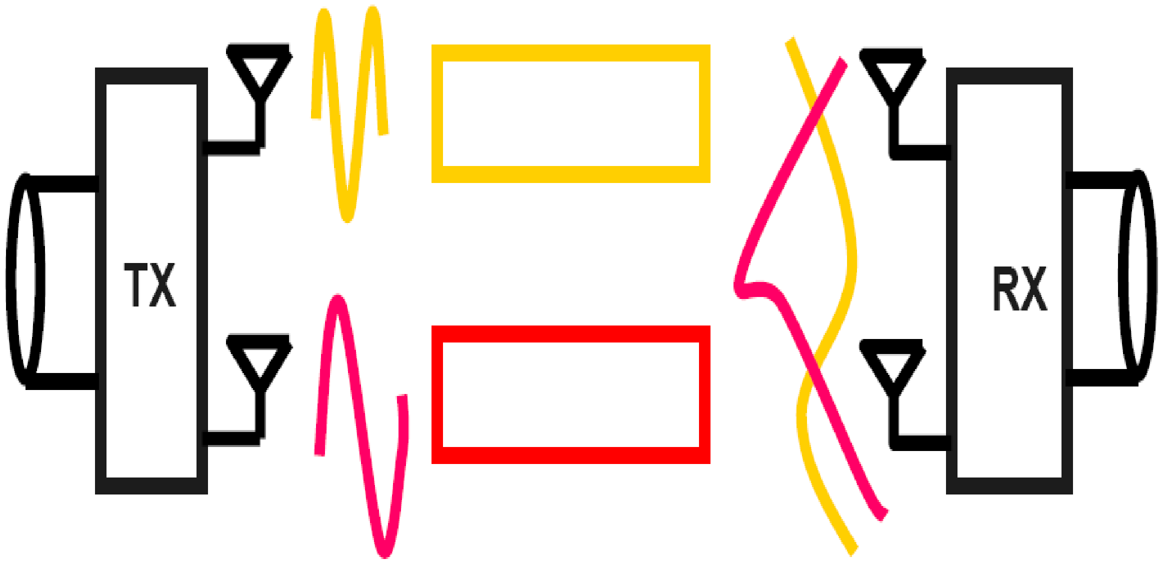
- **To multiply throughput of a radio link, multiple antennas (and multiple RF chains accordingly) are put at both the transmitter and the receiver.**
- **This system is referred to as Multiple Input Multiple Output (MIMO).**
- **A MIMO system with similar count of antennas at both the transmitter and the receiver in a point-to-point (PTP) link is able to multiply the system throughput linearly with every additional antenna.**
- **For example, a 2x2 MIMO will (approximate) double the throughput.**



Multiple Antenna Technique

Two popular techniques in MIMO wireless systems:





Spatial Diversity: Increased SNR

- **Receive and transmit diversity mitigates fading and improves link quality**

Spatial Multiplexing: Increased rate

- **Spatial multiplexing yields substantial increase spectral efficiency**

Spatial Diversity and Spatial Multiplexing

Spatial Diversity :

- Signal copies are transferred from multiple antennas or received at more than one antenna.

- Redundancy is provided by employing an array of antennas, with a minimum separation of λ/2 between neighbouring antennas.

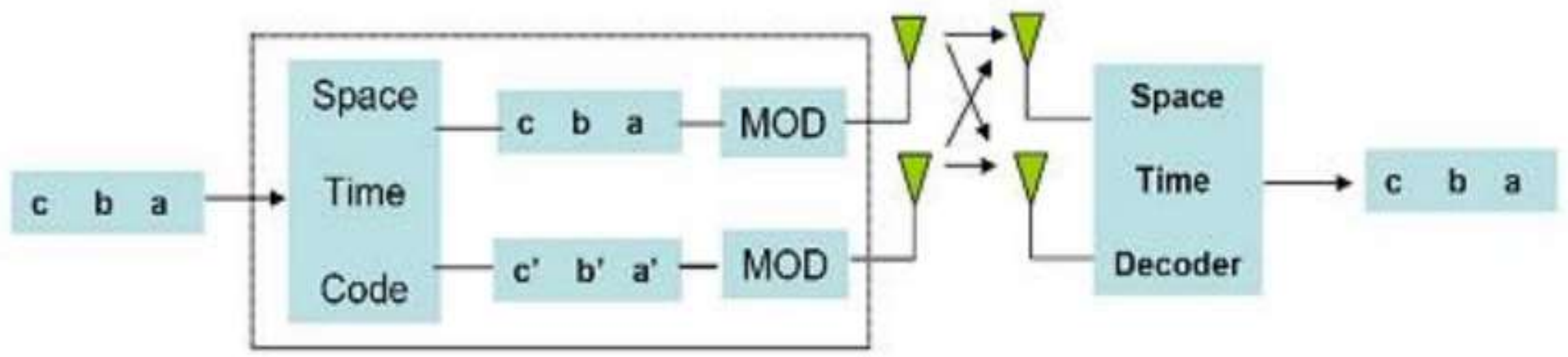
- Improves the signal quality and achieves a higher SNR at the receiver-side.

- Principle of diversity relies on the transmission of structured redundancy.

Spatial Multiplexing :

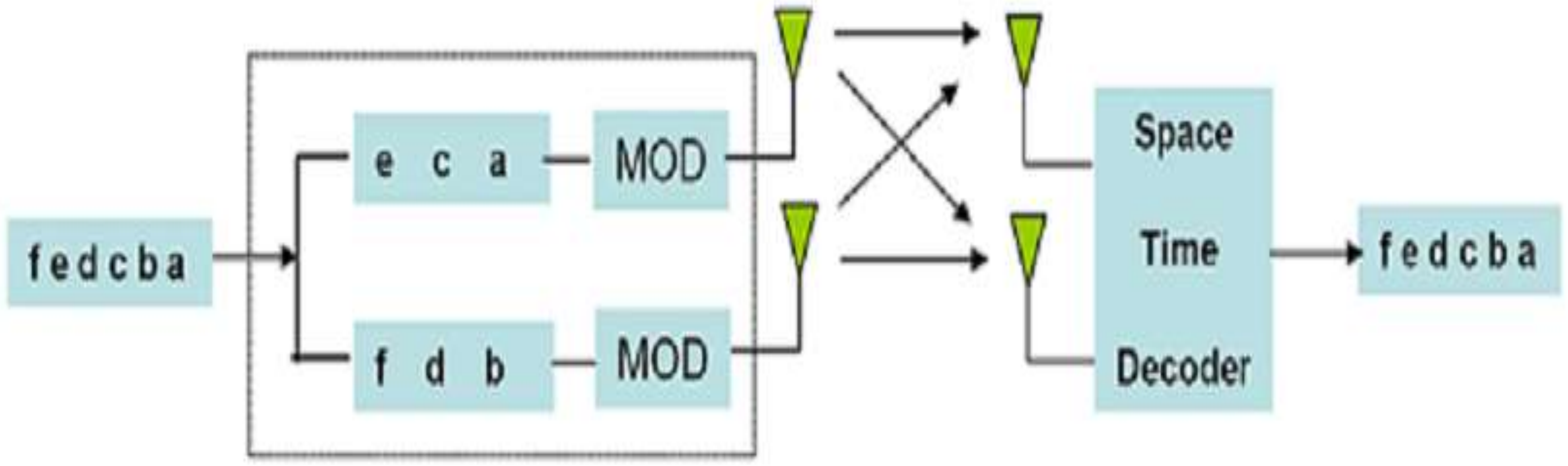
- The system is able to carry more than one data stream over one frequency, simultaneously.

Spatial Diversity



- Beberapa replika sinyal informasi dikirim dari beberapa antenna yang berbeda (data informasi yang dikirim yaitu data info asli dan replika).
- Tujuan *Spatial Diversity* yaitu untuk meningkatkan *SNR* dengan cara mengurangi *fading* dan meningkatkan kualitas *link* antara pengirim dengan penerima.

Spatial Multiplexing

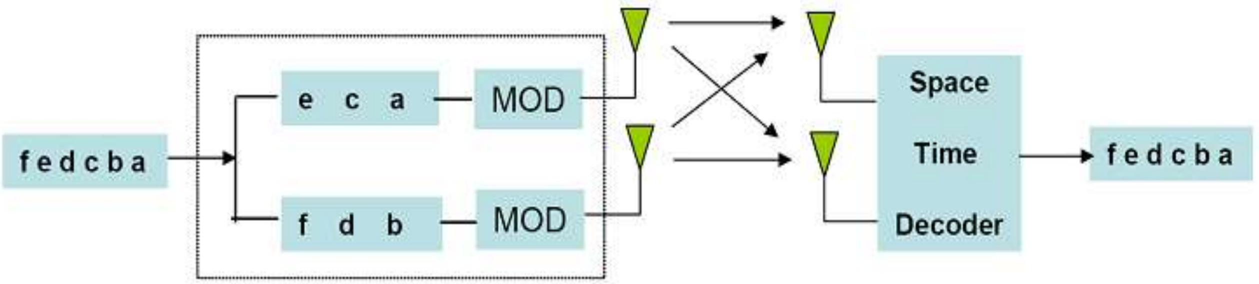


- **Spatial multiplexing bertujuan untuk meningkatkan kapasitas dengan cara mengirimkan beberapa aliran data secara paralel pada waktu yang bersamaan.**
- **Prinsip kerja dari *spatial multiplexing* adalah mengirim sinyal dari dua atau lebih antenna yang berbeda dengan beberapa aliran data dan aliran data dipisahkan dipenerima dengan proses *signal processing*, oleh karena itu peningkatan *bit rate* berdasarkan konfigurasi antenna mimo (2 untuk antenna mimo 2 by 2 and 4 untuk antena mimo 4 by 4).**

Spatial Multiplexing

Spatial Multiplexing Concept :

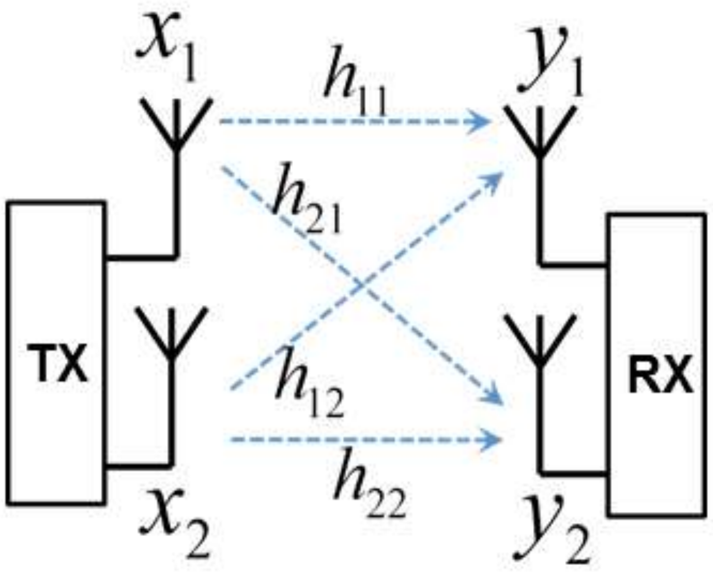
- Data is not redundant – less diversity, less repetition.
- Provides multiplexing gain to increase data-rate.
- Low (no) diversity compared to STC.
- Form multiple independent links (on the same spectrum band) between TX and RX, and send data in parallel through them.
- Unfortunately, there is cross-talk between antennas
- Cross-talk must be removed by digital signal processing algorithms



$$\text{Capacity:} \quad C_{MIMO} = \log\det(\mathbf{I} + \frac{SNR}{N_t}(\mathbf{H}'\mathbf{H})) \simeq min(N_t, N_r)C_{SISO}$$

Spatial Multiplexing : Signal Processing

- Example 2x2 MIMO spatial multiplexing
  - Data to be sent over two TX antennas: x_1, x_2
  - Data received on two RX antennas:



$$y_1 = h_{11}x_1 + h_{12}x_2$$
$$y_2 = h_{21}x_1 + h_{22}x_2$$

  - Channel distortions: h_{**} can be estimated by the receiver
  - Only two unknowns: x_1, x_2, easily obtained by solving the equations!

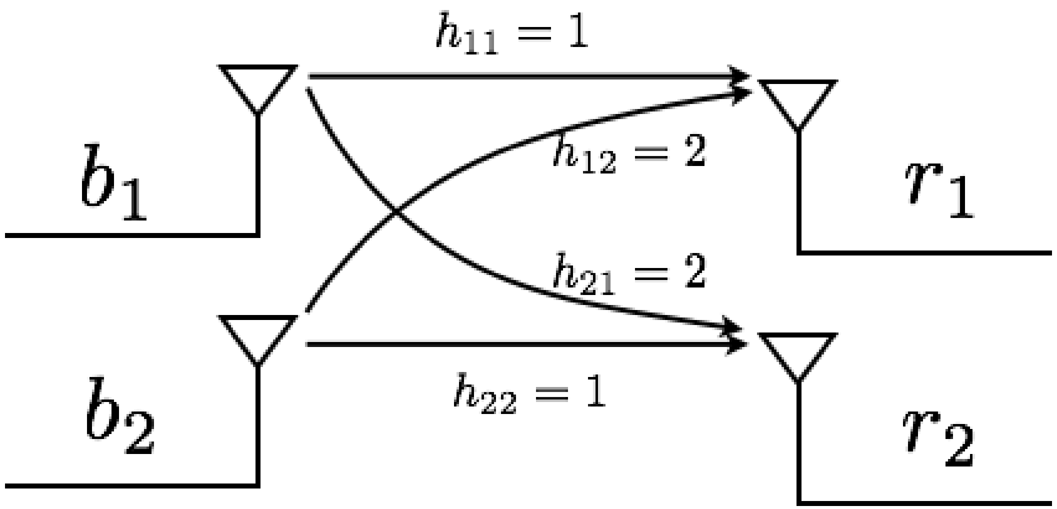
Spatial Multiplexing Gain

- Asymptotic gain
  - In general, capacity gain from spatial multiplexing scales linearly with

$$\min(N_t, N_r)$$

- In practice
  - Spatial multiplexing gain also depends on channel "condition"
    - If the channels between different antennas are *correlated*, e.g., h_{**} are all the same, then you can't solve the equations. Spatial multiplexing becomes infeasible!
    - Channel condition can be profiled using "condition number" (see reference)
  - Practical wireless devices' multiple antennas are separated sufficiently far (further than half-wavelength), so the channel is usually uncorrelated

Contoh MIMO



a. Tuliskan matrix untuk MIMO channel tersebut.
b. Carilah singular value untuk MIMO channel tersebut.
c. Untuk Sistem dengan Bandwidth B MHz dan modulasi BPSK, menjadi berapakah kenaikannya dengan menggunakan MIMO ?

Jawab (a)

a. Tuliskan matrix untuk MIMO channel tersebut.

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

Channel matrix untuk MIMO tersebut adalah

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

Dengan n_1 dan n_2 adalah noise yang masing-masing terdapat pada antenna 1 dan antenna 2.

Jawab (b)

b. Carilah singular value untuk MIMO channel tersebut.
Singular value didapat dengan mencari eigenvalue dari matrix MIMO berikut

$$\mathbf{HH}^T = \begin{bmatrix} 1 & 2 \\ 2 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 2 & 1 \end{bmatrix} = \begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix} \qquad \begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \lambda \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Dikelompokkan menjadi

$$\begin{bmatrix} (5-\lambda) & 4 \\ 4 & (5-\lambda) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = 0$$

Dengan membuat determinan *ad-bc=0*, didapat

$$(5-\lambda)^2 - 16 = 0 \qquad \lambda^2 - 10\lambda + 9 = 0 \qquad \lambda_1 = 9, \lambda_2 = 1$$

Sehingga diperoleh singular value $d_1 = \sqrt{\lambda_1} = 3, d_2 = \sqrt{\lambda_2} = 1$

Jawab (b)

Dengan MATLAB, kita juga dapat menghitung nilai singular value sebagai berikut

```
>> H=[1 2; 2 1]

H =
     1     2
     2     1

>> svd(H)
ans =

    3.0000
    1.0000
```

Jawab (c)

c. Untuk Sistem dengan Bandwidth B MHz dan modulasi BPSK, menjadi berapakah kenaikannya dengan menggunakan MIMO ?

$$C = \sum_{i=1}^{n} B \log_2(1 + |d_i|^2 \frac{S}{N})$$

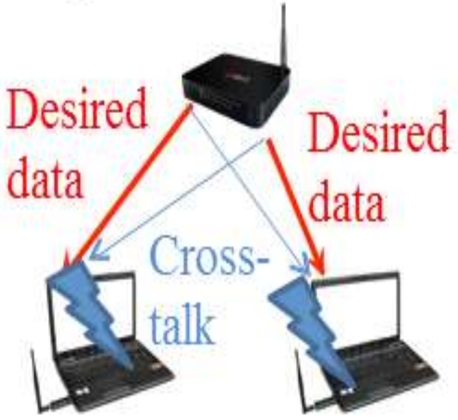
$$= B \log_2(1+|3|^2 \frac{S}{N}) + B \log_2(1+|1|^2 \frac{S}{N})$$

$$= B \log_2(1 + \frac{9S}{N}) + B \log_2(1 + \frac{S}{N})$$

Dua buah singular value d_1 dan d_2 menjadikan kapasitas lebih besar hampir dua kali.

Multi User MIMO : How It works

- Concept of Multi-User MIMO (MU-MIMO)
  - Single-antenna network

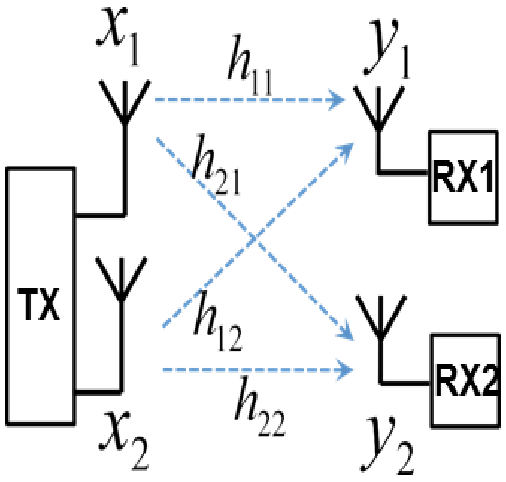


  - Multi-user MIMO

  - MU-MIMO enables multiple streams of data to be sent to differe users in parallel, without cross-talk interference

- MU-MIMO differs from traditional MIMO
  - Data to be sent over two TX antennas: x_1, x_2
  - Data received on two RX nodes:

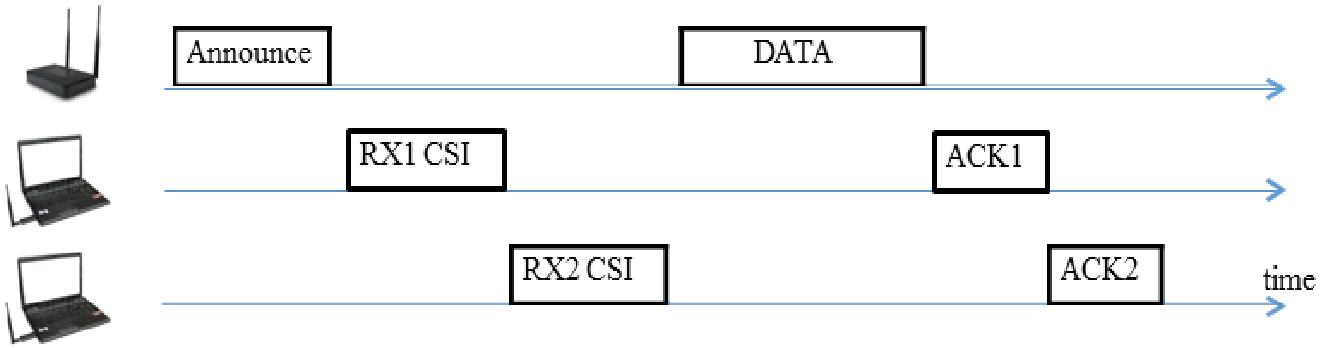
$$y_1 = h_{11}x_1 + h_{12}x_2$$
$$y_2 = h_{21}x_1 + h_{22}x_2$$



  - Each RX only has one equation, but two variables; no way to solve it directly
    - x2 causes cross-talk interference to x1, and vice versa

Multi User MIMO : How It works

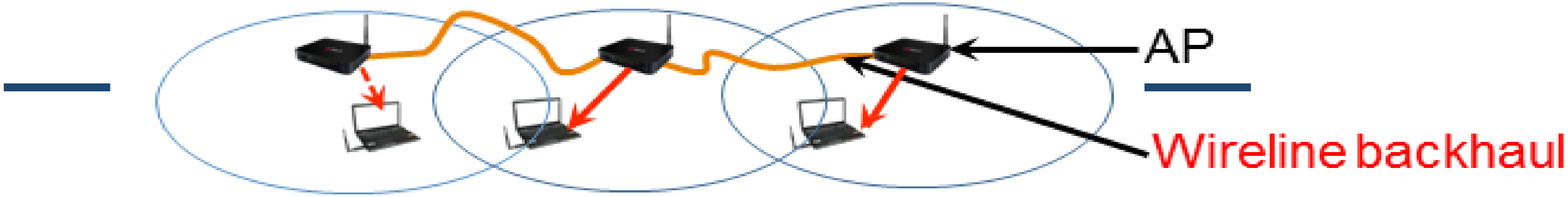
- MU-MIMO precoding
  - TX can obtain h_{11}, h_{12} from RXs' feedback, so it can tune w_{12}, w_{22} to satisfy $(h_{11}w_{12} + h_{12}w_{22}) = 0$
    - This cancels the cross-talk interference from x2 to x1
    - Similarly, we can cancel that from x1 to x2
    - This is called Zero-Forcing Beamforming (ZFBF)
- How does TX obtain channel state information h_{**}
    - Simplest approach in 802.11ac: CSI feedback scheduling



- Asymptotic capacity gain
  - If the transmitter has N_t antennas, then it can send N_t streams of data simultaneously to N_t users, increasing capacity to N_t times compared with single-antenna transmitter
- Limitation
  - MU-MIMO is essentially a form of spatial multiplexing
  - So the channel must be well-conditioned

Network MIMO

- A **giant-MIMO** comprised of many APs



  - APs are tightly synchronized and share data
  - Mutual interference can be cancelled
  - Asymptotic gain: Network capacity scales **linearly** with the number of APs, theoretically

End