MOB 9-2: Radio Communications – III: Autumn 2004

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Lecture-1	09-09-2004; 12.30-14.15; A5-006	FF
Lecture-2	30-09-2004; 12.30-14.15; A5-006	FF
Lecture-3	07-10-2004; 12.30-14.15; A5-006	FF
Lecture-4	14-10-2004; 12.30-14.15; A5-006	IMR
Lecture-5	**21-10-2004; 12.30-14.15; A5-006**	**IMR**
Lecture-6	28-10-2004; 12.30-14.15; A5-006	IMR
Lecture-7	04-11-2004; 12.30-14.15; A5-006	FF

Lecture notes can be downloaded at
http://kom.aau.dk/~imr/RadioCommIII/

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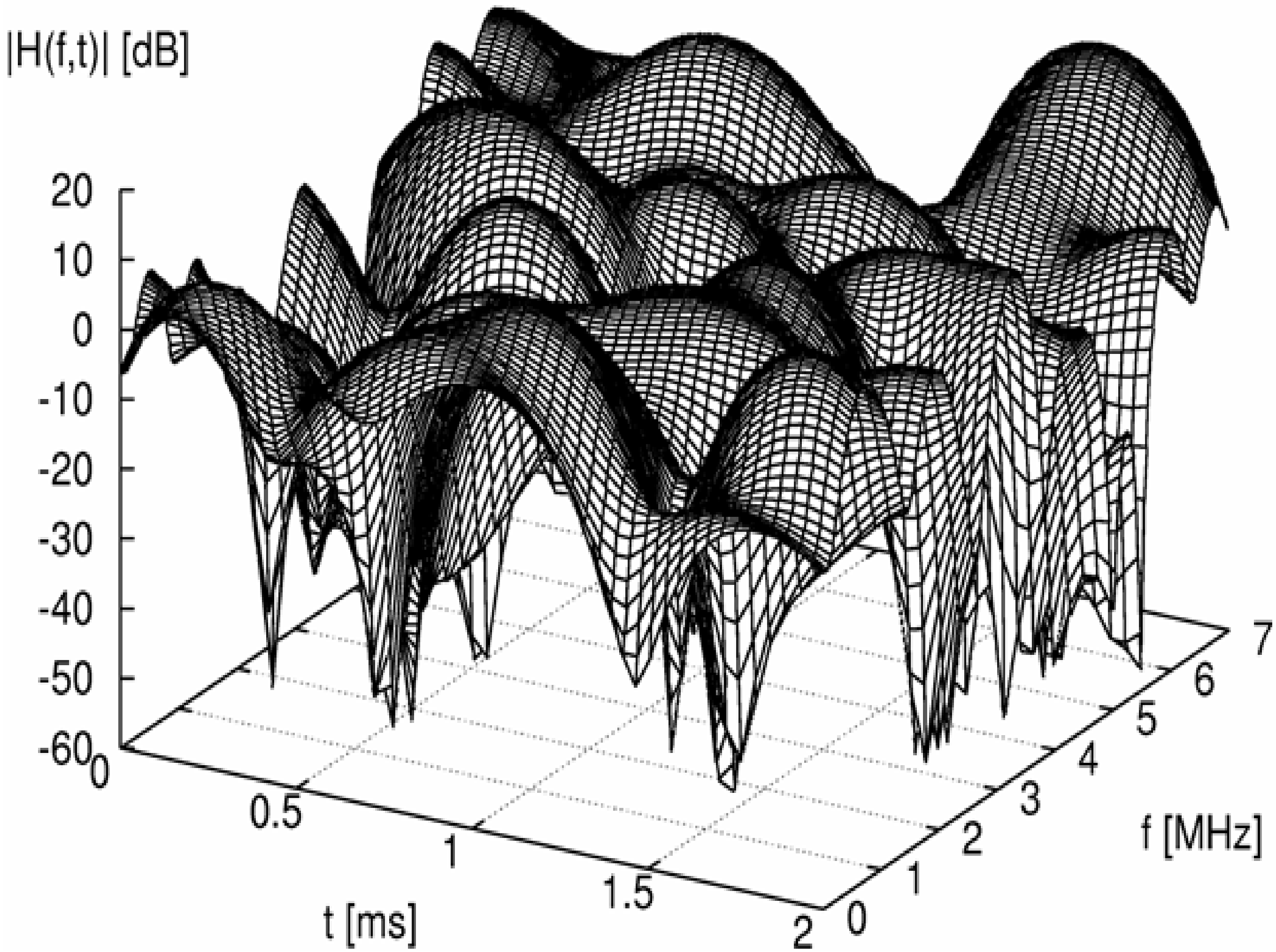
Lecture-5: Multi- Antenna OFDM Systems

1. **Diversity Techniques in OFDM**
2. Receive Diversity in OFDM Systems
3. Transmit Diversity in OFDM Systems
4. Spatial Multiplexing (MIMO-OFDM)
5. Smart Antenna Technique: Beamforming

Wireless Channel Scenario



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Mitigation Techniques

- **Equalization:** DSP technique used to compensate for ISI created by multipath fading within time-dispersive channels

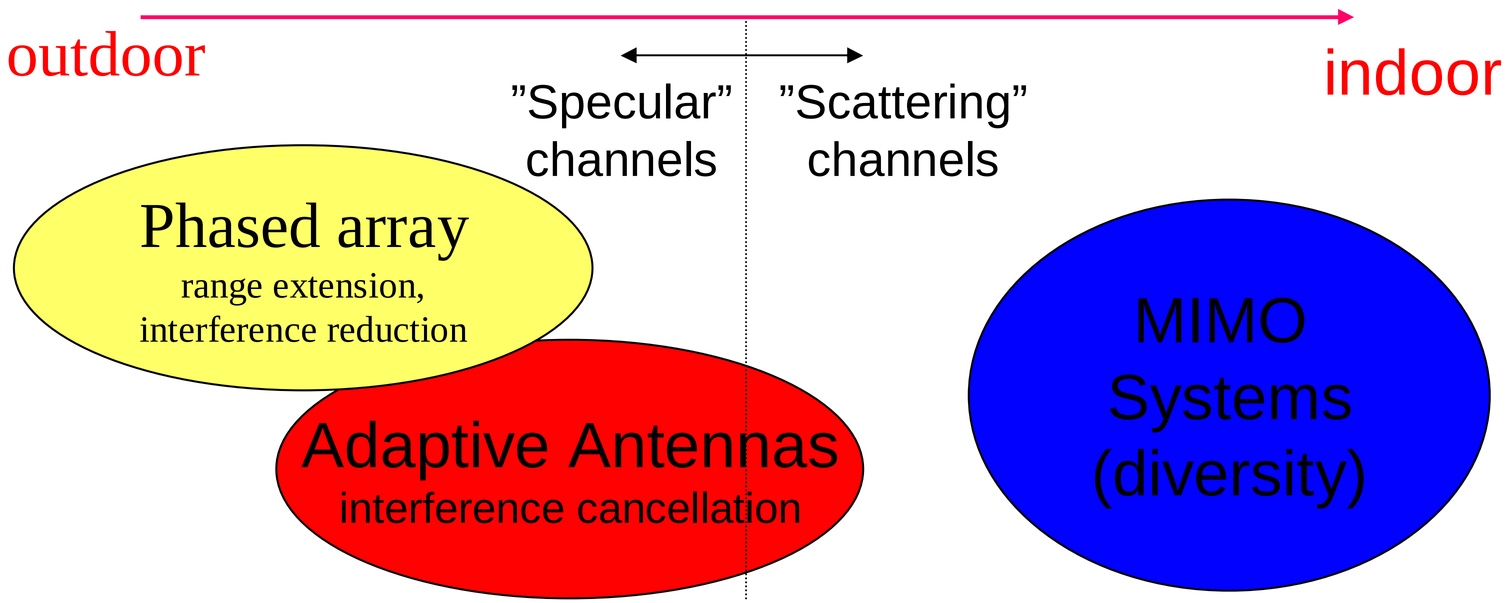
- **Channel Coding**: To improve mobile communication link performance by including redundant bits in the transmitted message

- **Diversity**: To reduce the depth and duration of fades experienced by a receiver in a frequency or time selective channel

Why Multiple Antennas???

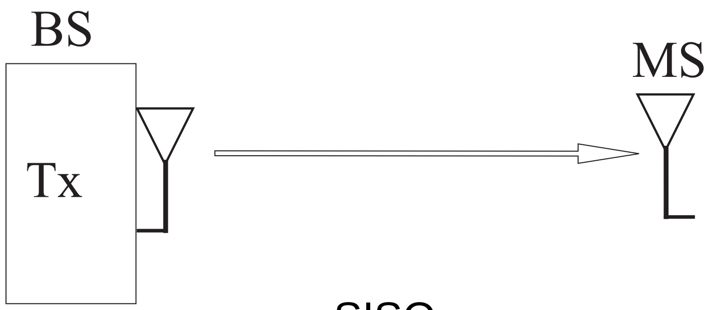
• Frequency and time processing are at limits

• Space processing is interesting because it does not increase bandwidth

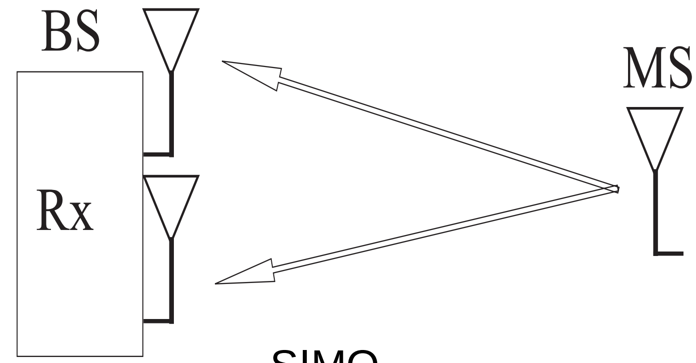


Source: Uppdala University, Sweden

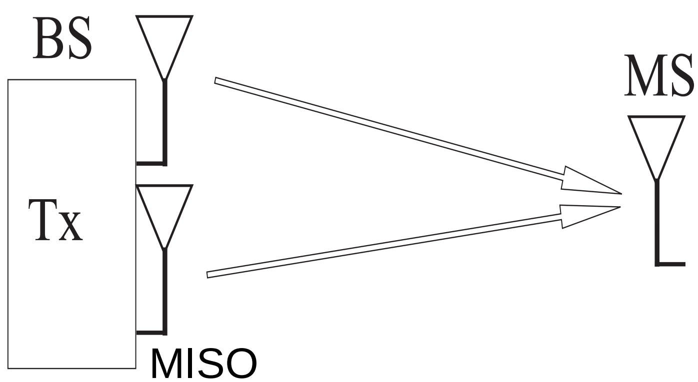
Multiple Antenna Configurations



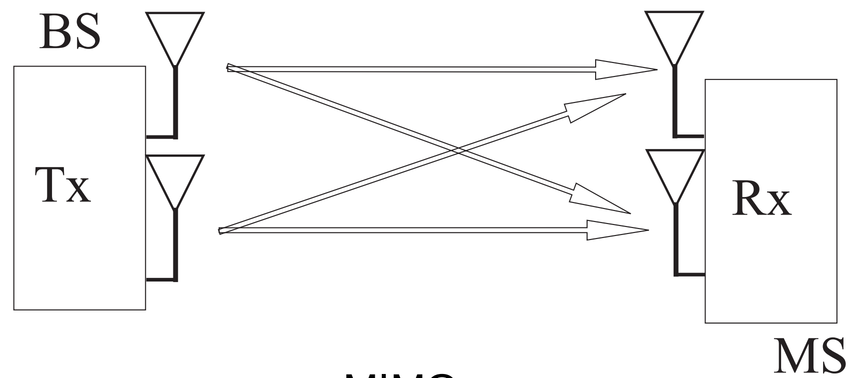
SISO
(Single-Input-Single-Output)



SIMO
(Single-Input-Multiple-Output)



MISO
(Multiple-Input-Single-Output)



MIMO
(Multiple-Input-Multiple-Output)

Advantages of Multi-Antenna Techniques

Performance improvements achieved by Multi-antenna systems are mainly due to:

- Array gain
  - Increase power
  - beamforming
- Diversity gain
  - Mitigate fading
  - Space-time coding
- Spatial multiplexing gain
  - Multiply data rates
  - Spatially orthogonal channels
- Interference reduction
  - Aggressive frequency reuse
  - Users spatial signatures

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What is Diversity?

• Diversity schemes provide two or more inputs at the mobile reception unit such that the fading phenomenon among these inputs are uncorrelated.

• If one radio path undergoes a deep fade at a particular point in time, another independent (or at least highly uncorrelated) path may have a strong signal at that point.

• By having more than one path to select from, both the instaneous and average SNR's at the receiver may be proved often as much as by 20 to 30dB.

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Diversity Techniques (1/2)

- **Space diversity** (Antenna Diversity)**:**
  Transmission from/to several base stations
- **Frequency Diversity:**
  Transmission of same signal at different frequencies
- **Time Diversity**: Transmission of same signal sequence at different time
- **Multipath Diversity**: Delay and Doppler discrimination
- **Polarization Diversity:**
  Two polarized diversity branches available
- **Field Component Diversity** (Antenna pattern Diversity)
- **Angle Diversity** (Direction Diversity): Angle discrimination

Diversity Techniques (2/2)

- **Space –Time (S-T) diversity:**

  Utilization of spatial and temporal domain for obtaining diversity

- **Space-Frequency (S-F) Diversity:**

  OFDM system specific diversity technique by exploiting OFDM sub-carriers and spatial domain.

- **Space-Time-Frequency (S-T-F) Diversity:**

  Another OFDM system specific diversity technique

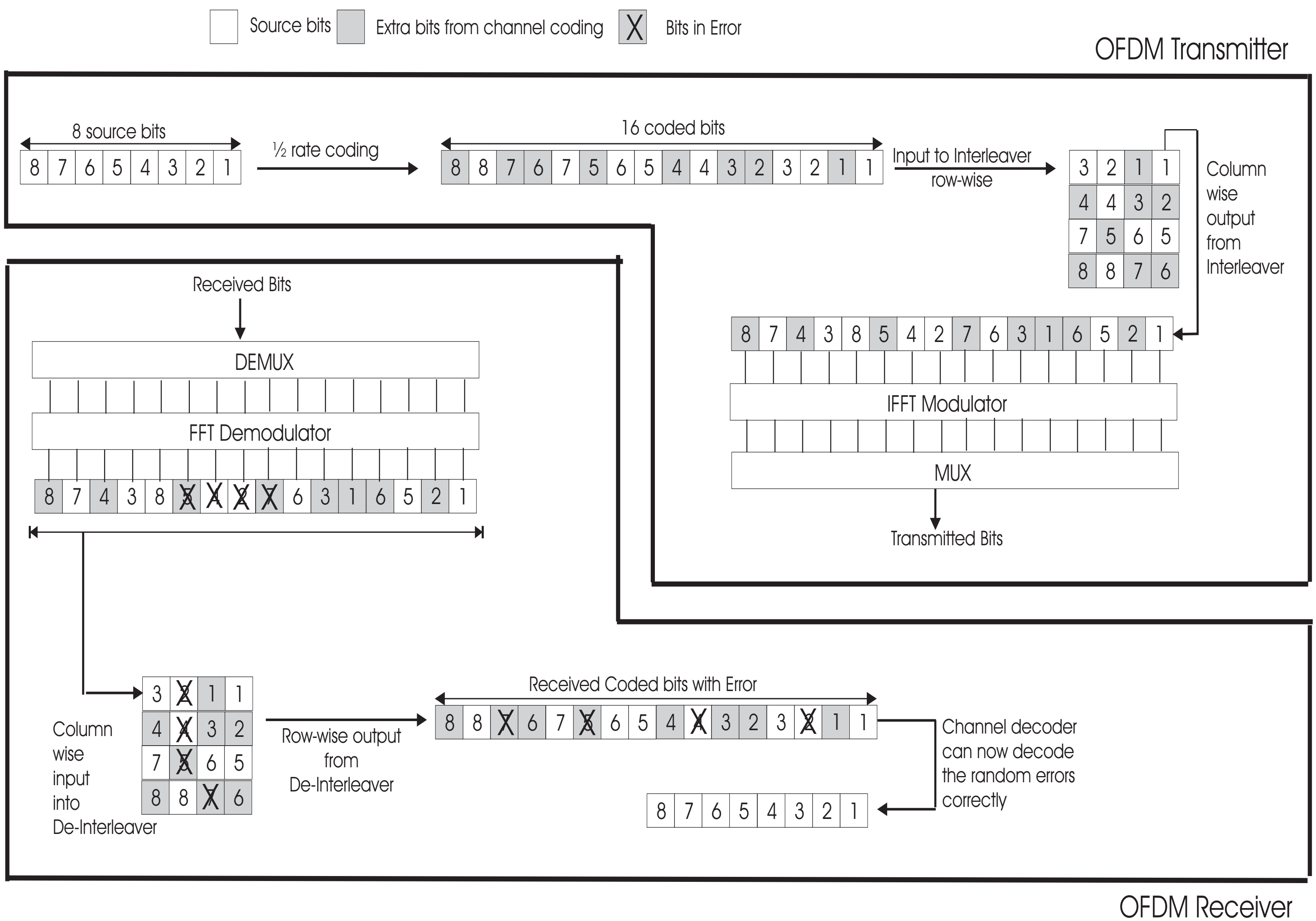
Frequency Diversity via COFDM & Interleaving

- Time and/or frequency diversity may be viewed as a form of repetition(block) coding of the information sequence. So, coding provides an efficient mean of obtaining diversity on a fading channel.

- Channel coding cannot handle burst errors effectively in fading situations, so interleaving is used to spread the errors in time and/or frequency domain

- It is the function of the interleaver to spread these bits out in time, so that if there is a deep fade or noise burst, the important bits from a block of source data are not corrupted at the same time.

Frequency Diversity via COFDM & Interleaving



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Time Diversity in OFDM Systems

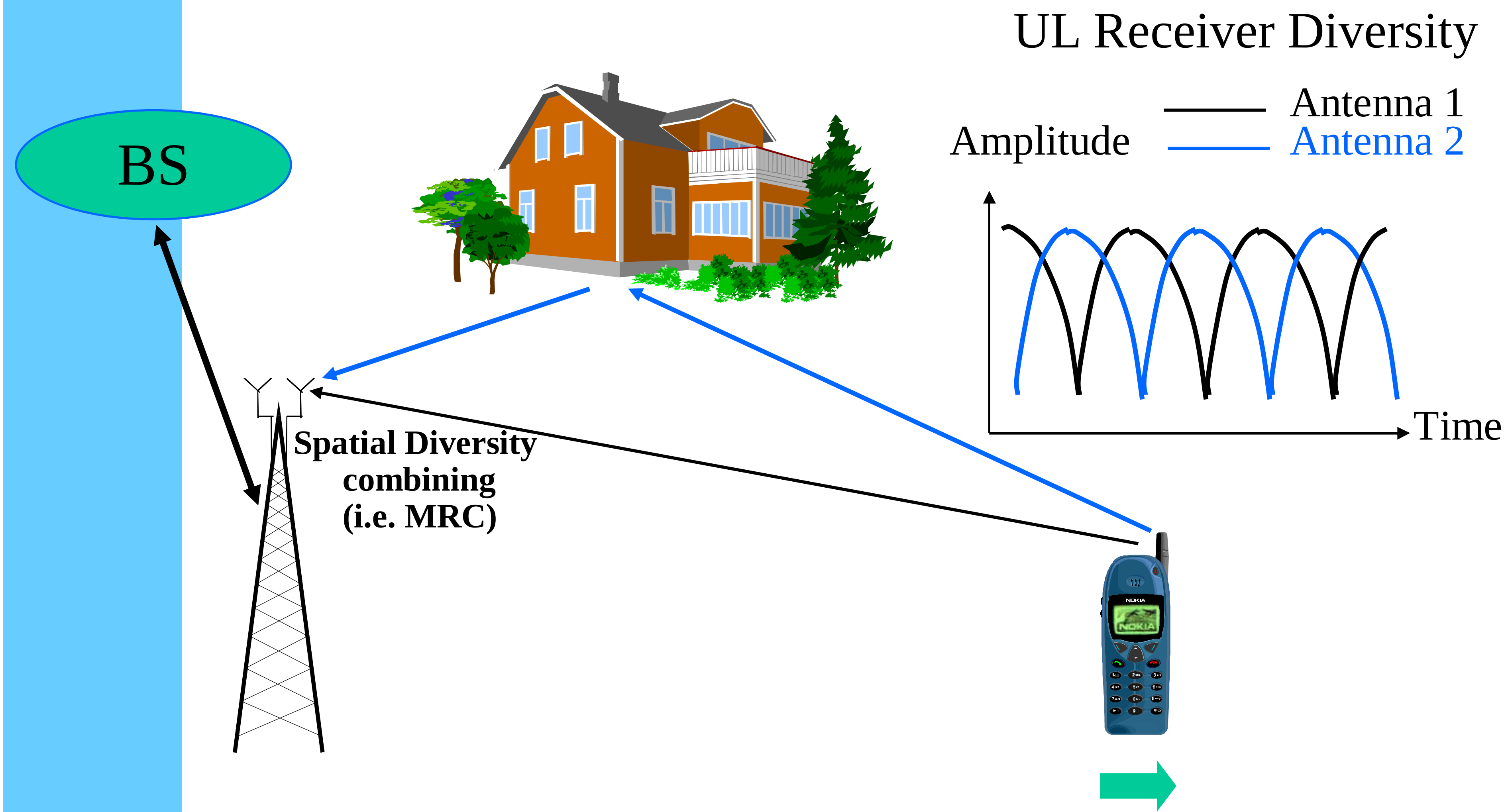
•Delay Diversity (DD):

➔Transmit the original signal from the first antenna and use delayed signals in the subsequent antennas

➔ Constraint: Inserted delay must be smaller than RMS delay spread

➔ Not a good scheme, especially when channel has higher delay spread. In those cases, the affectivity of CP is reduced and the performance may be worse in certain scenario.

Space Diversity in OFDM Systems



Space Diversity in OFDM Systems

- **Combining techniques for Space Diversity:**

  Post-DFT Maximum Ratio Combining
  Post-DFT Equal Gain Combining
  Post-DFT Subcarrier Selection Combing
  Pre-DFT Maximum Average Ratio Combining with CDD
  Pre-DFT Equal Average Ratio Combining with CDD
  Pre-DFT Antenna Selection Combining

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Diversity Techniques Based on Locations

- **Receiver Diversity (SIMO):**

  Usually space diversity

- **Transmitter Diversity (MISO) :**

  Time diversity (Delay diversity)

  S-T Diversity

  S-F Diversity

  S-T-F Diversity

- **Transmit-Receive Diversity (MIMO-Diversity)**:

  S-T diversity at the transmitter and space diversity at the receiver

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Post-DFT MRC/EGC

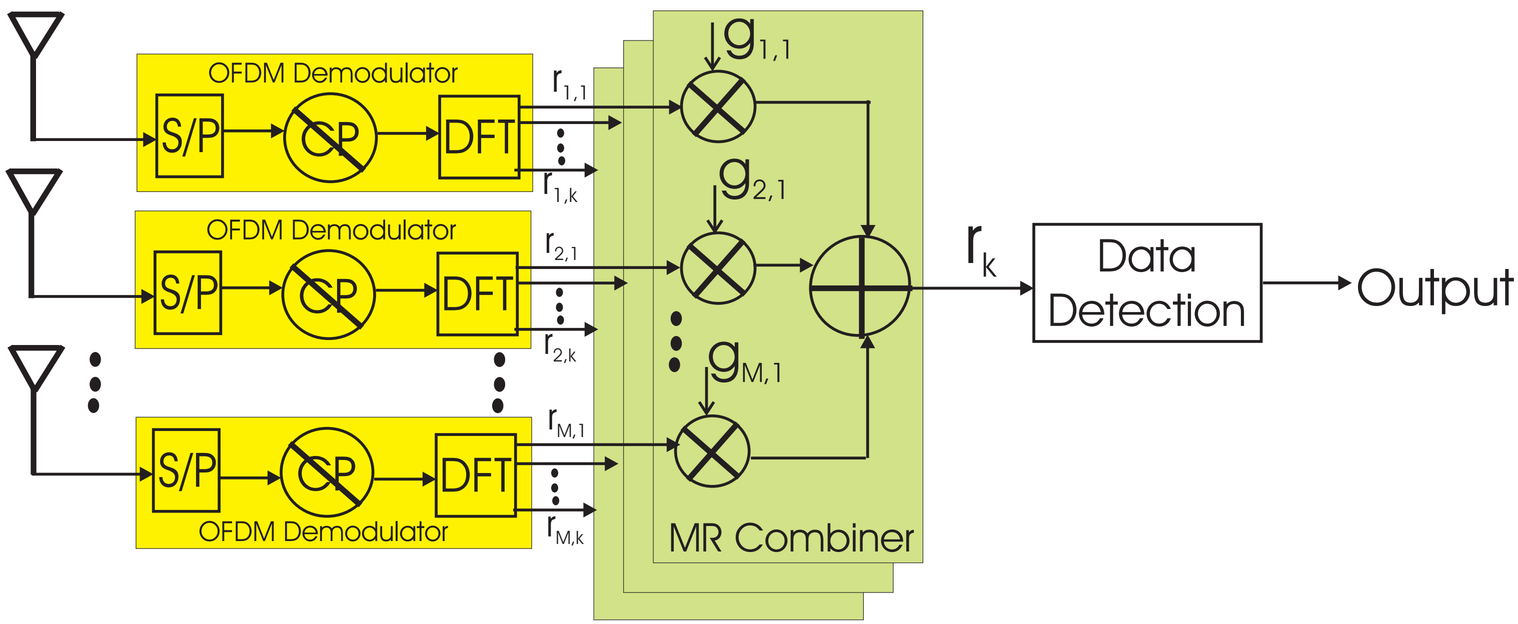
M number of receive antennas

Separate OFDM demodulation and co-phasing on Rx signals

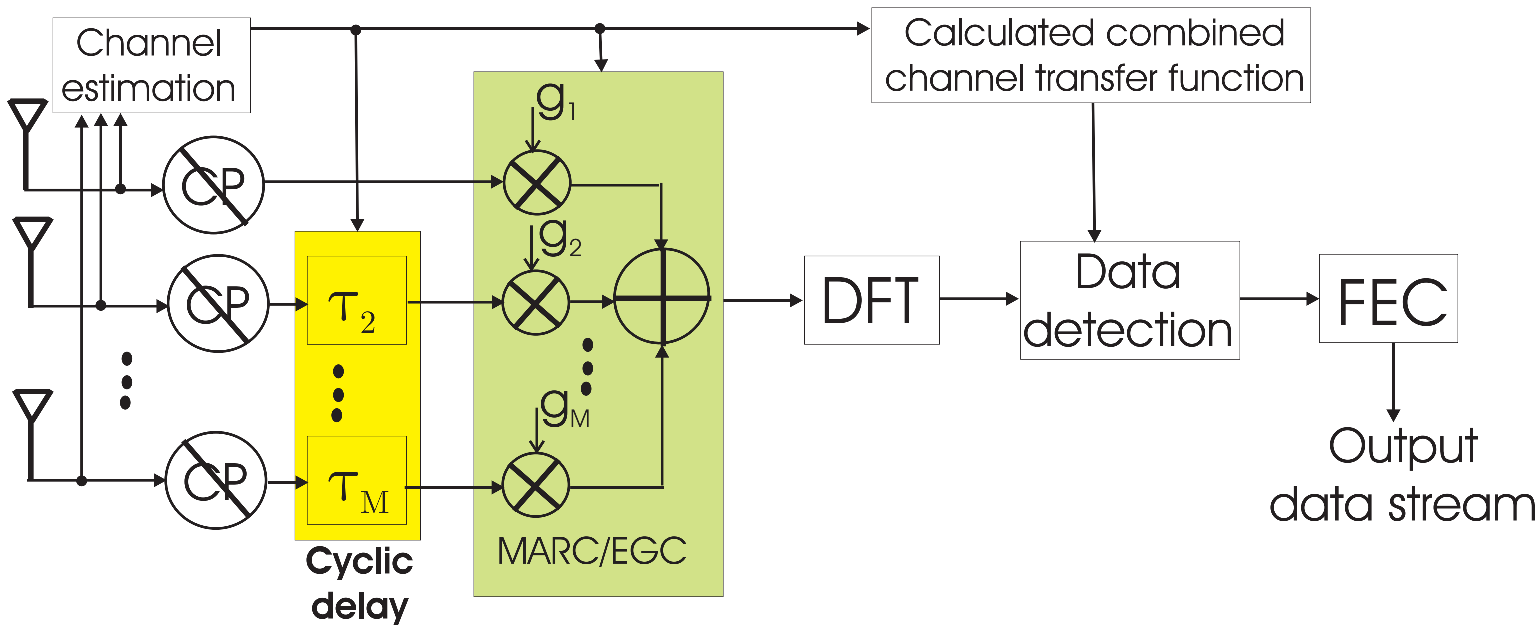
Important: Knowledge of CSI is required.

Combining at subcarrier level

Antenna weight factors are decided based on the instantaneous SC signal power.



Pre-DFT MARC/EAGC



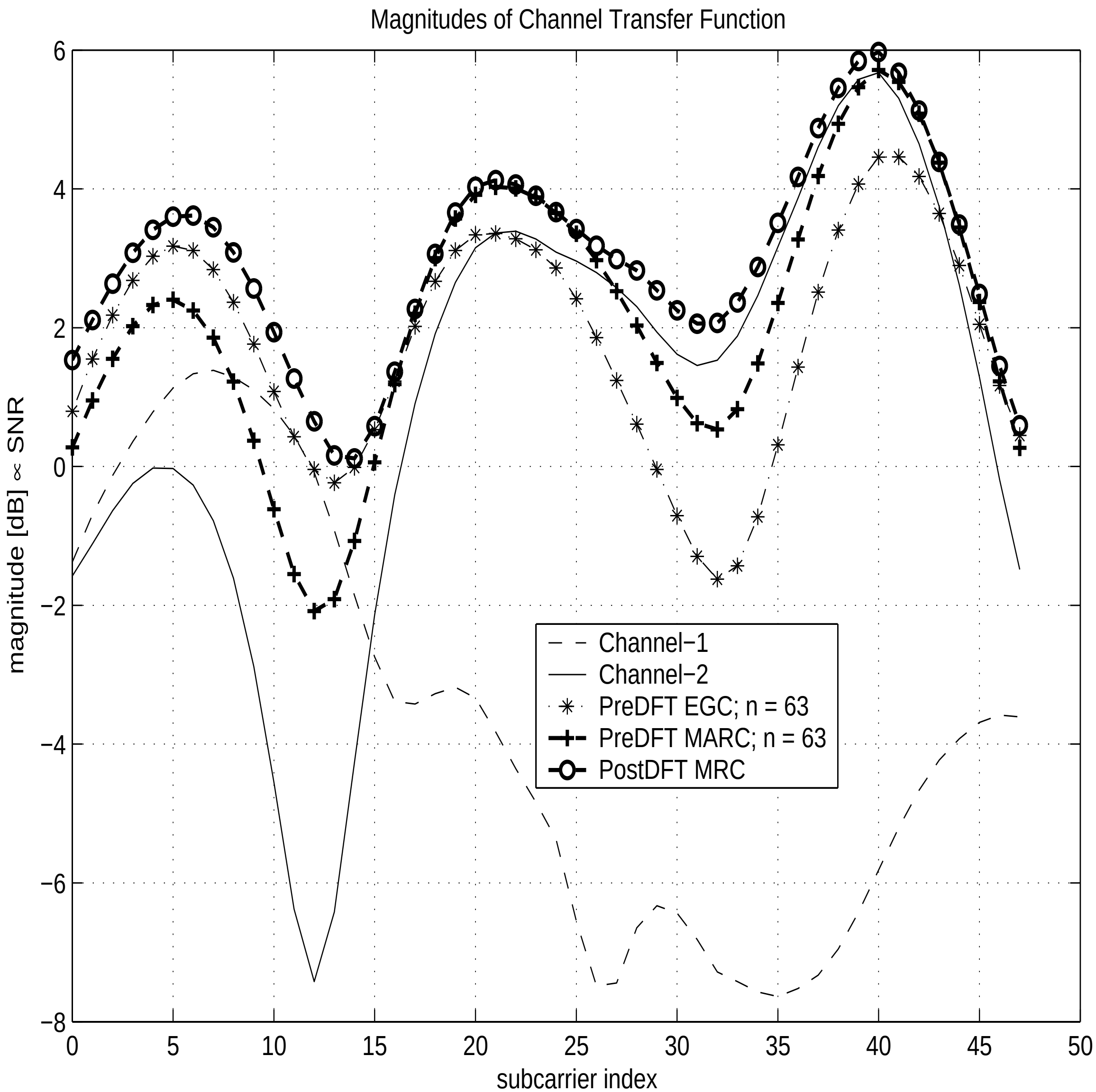
M receive antennas are available.

CSI estimated to determine delay and gain factor

optimized g and τ by using instantaneous SNR averaged over all OFDM SC

Combining prior to DFT

Channel Response After Combining



Post-DFT MRC shows better channel responses, though Pre-DFT MARC and Pre-DFT EGC is also very close.

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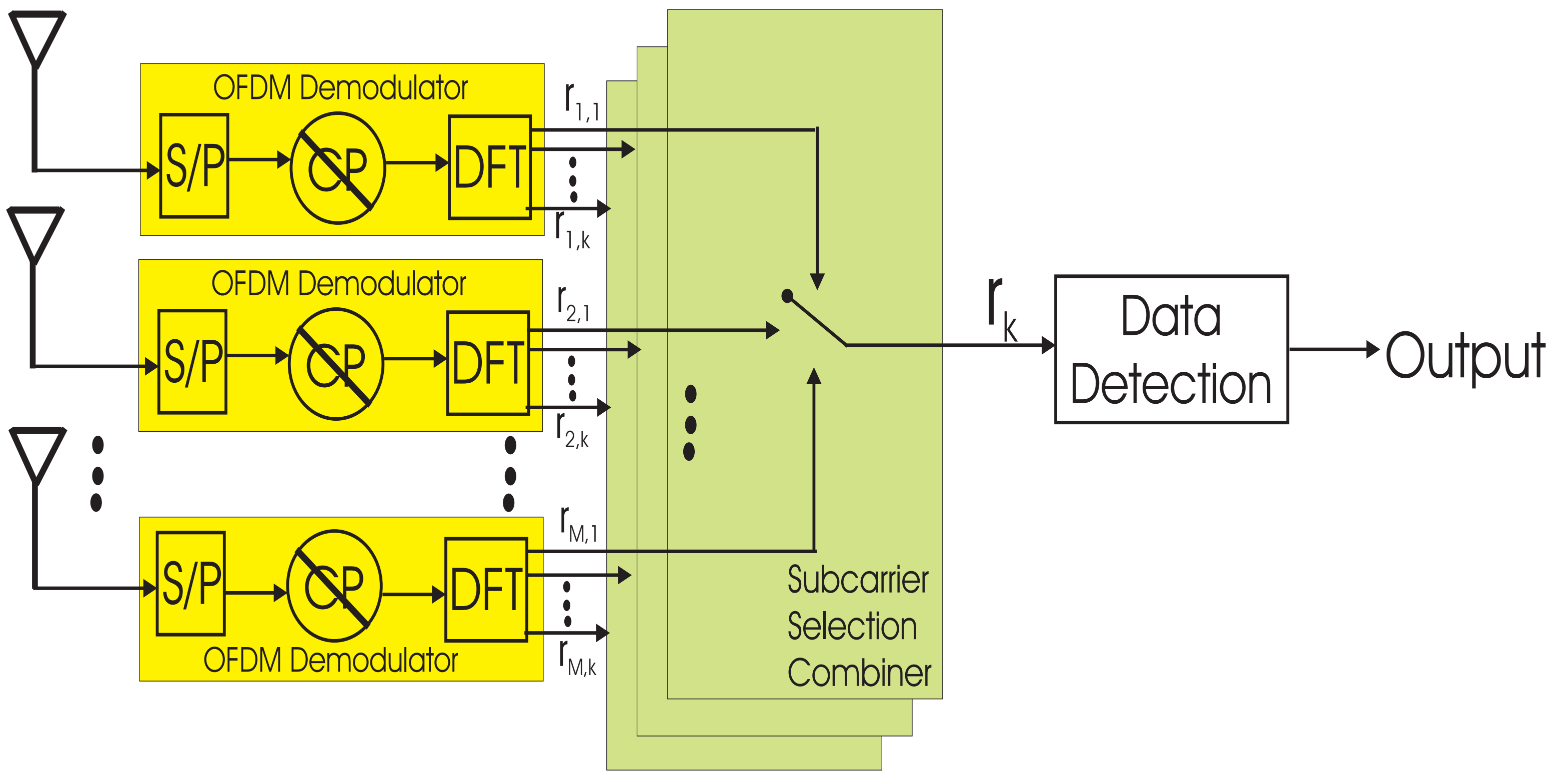
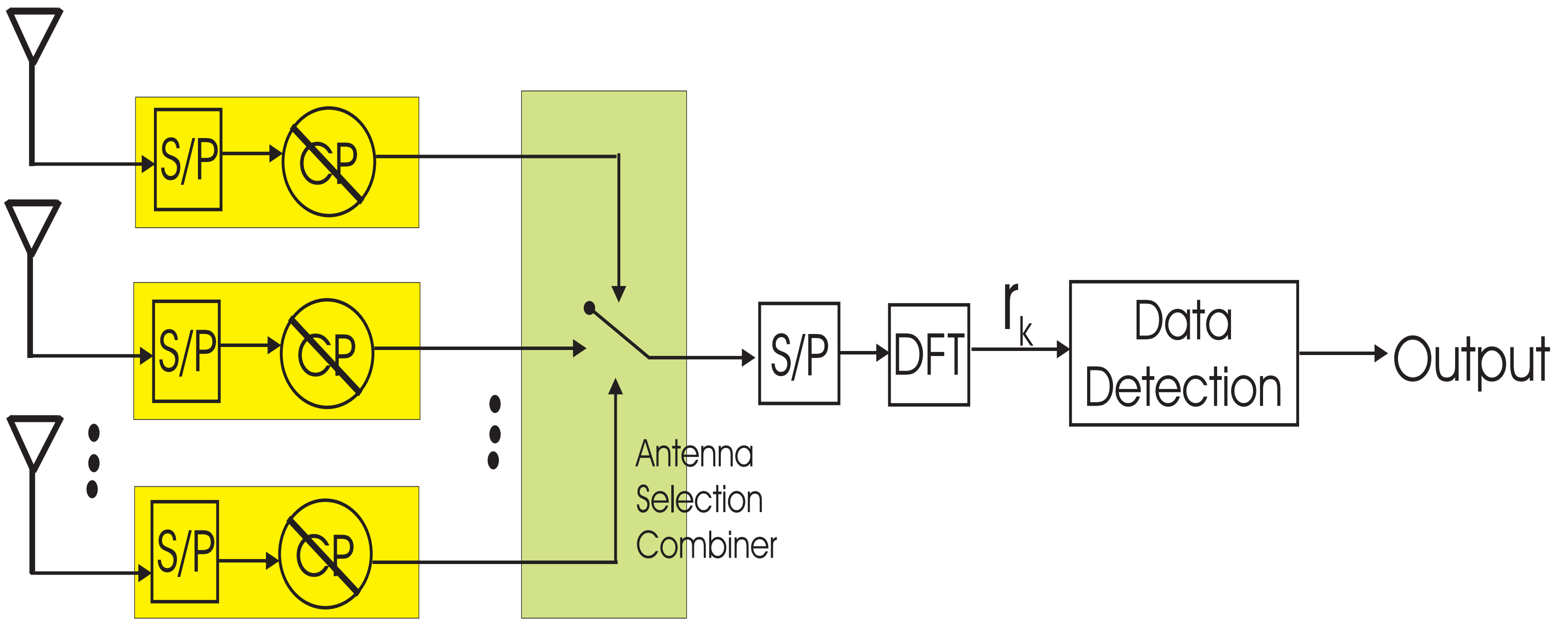
Post-DFT Subcarrier Selection Combining



Pre-DFT Antenna Selection Combining



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Transmit Diversity

Time diversity → Delay diversity

S-T Diversity → STBC, STTC

S-F Diversity → SFBC, SFTC

S-T-F Diversity → STFBC

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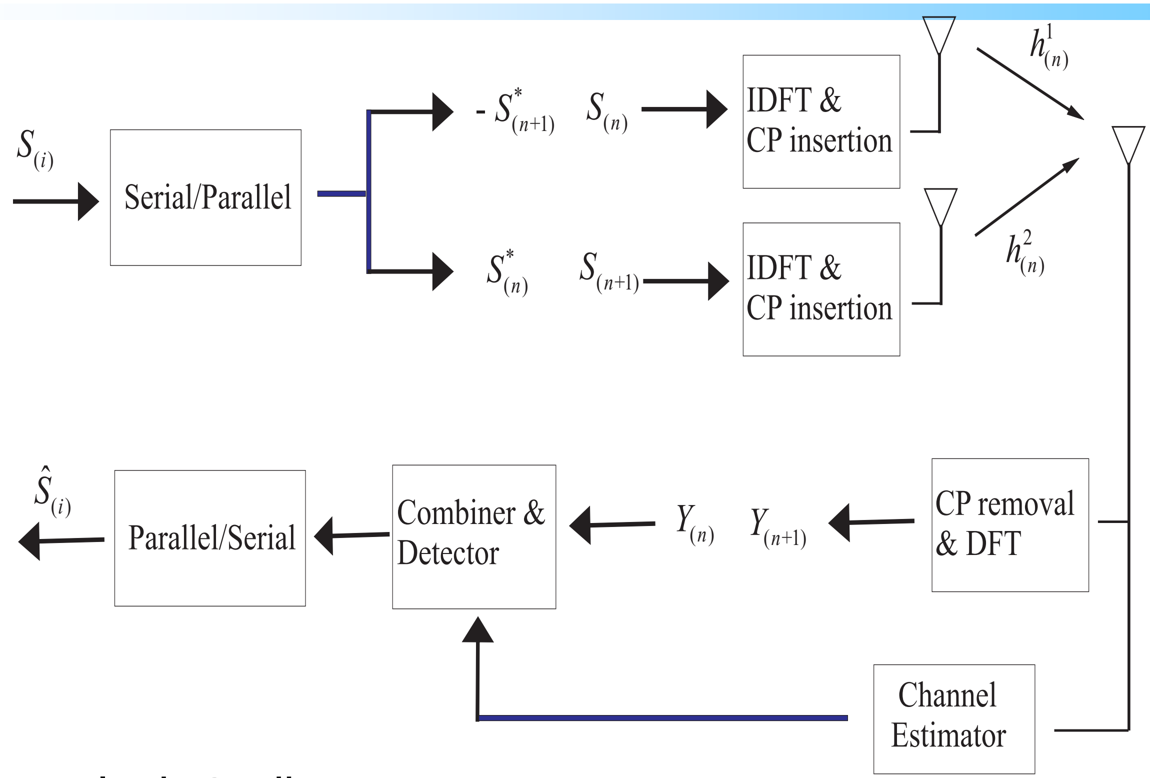
STBC-OFDM Systems



Space-Time Block Coding

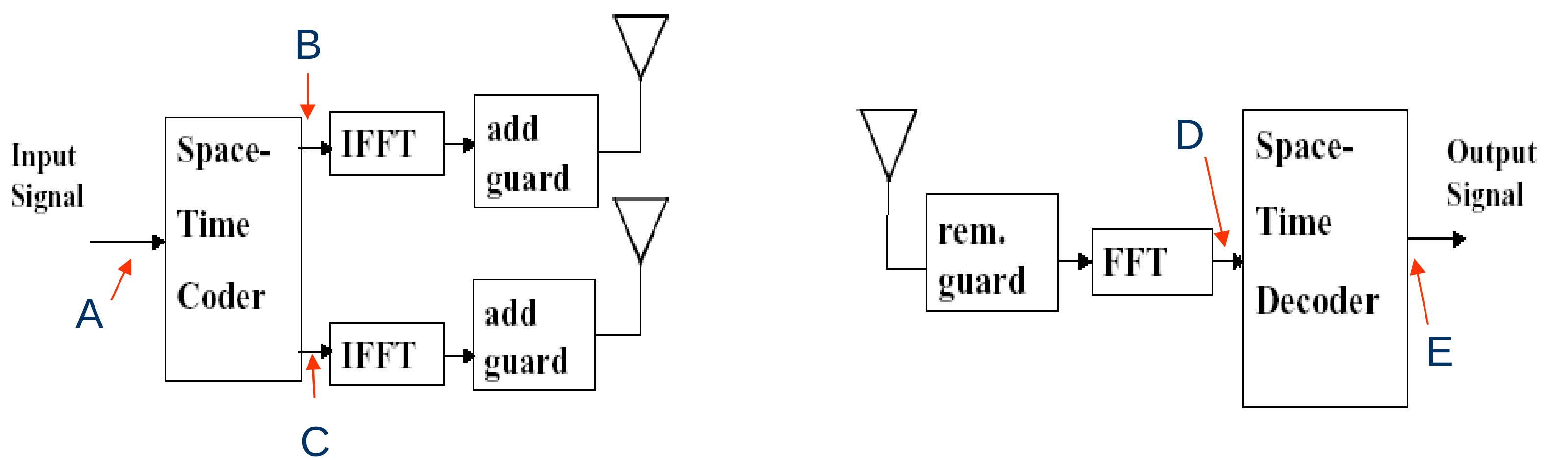
- Input: stream of modulated symbols
- Encoder operates on a block of length K, producing a codeword (n_T x T)
- Alamouti scheme (K=2)

$$\mathbf{y}=\mathbf{H}\mathbf{x}+\mathbf{n}$$

$$\begin{bmatrix} y_1 & y_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} + \begin{bmatrix} n_1 & n_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}$$

ST(F)BC Decoding



	Time/Tone index	
	i	i+1
A	s_1	s_2
B	s_1	$-s_2^*$
C	s_2	s_1^*
D	$h_1 s_1 + h_2 s_2$	$-h_1 s_2^* + h_2 s_1^*$
E	$\|\|H[k]\|\|^2 s_1$	$\|\|H[k]\|\|^2 s_2$

[Paulraj 03]

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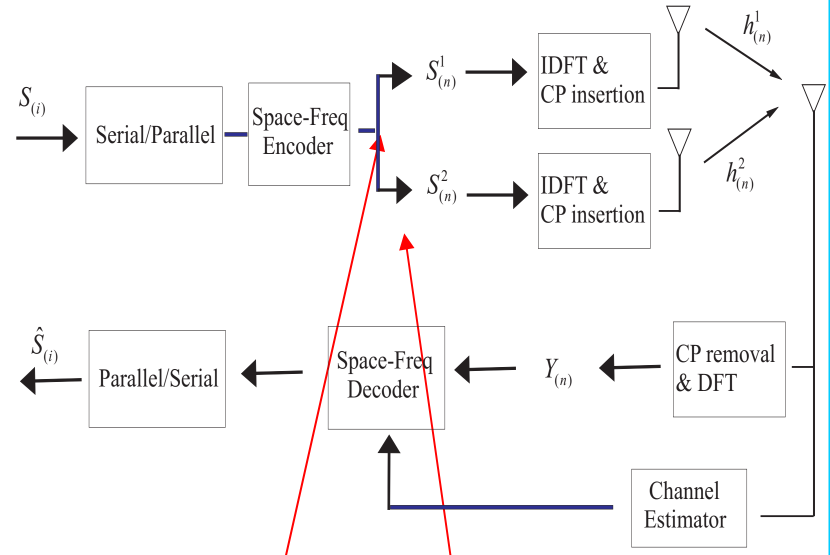
SFBC-OFDM

Space-Frequency Block Coding

- The same concept already explained for STBC can be applied to OFDM subcarriers level
- Coding within a single OFDM symbol
- Two consecutive subcarriers are used as



$$S_n^1 = \begin{bmatrix} s_{n_1} \\ -s_{n_2}^* \end{bmatrix} \qquad S_n^2 = \begin{bmatrix} s_{n_2} \\ s_{n_1}^* \end{bmatrix}$$

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What is a MIMO System??

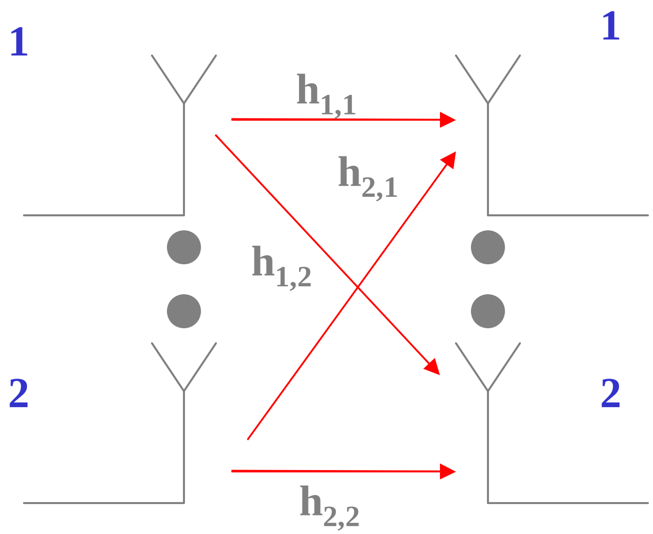
- What are MIMO systems ?

A MIMO system consists of several antenna elements, plus adaptive signal processing, at both transmitter and receiver, the combination of which exploits the spatial dimension of the mobile radio channel.

Benefits

- higher capacity (bits/s/Hz):
  - spectrum is expensive; number of BS is limited
- better transmission quality
- Increased coverage
- Improved user position estimation

Narrowband MIMO Channel Model



- Frequency flat channel model

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix}$$

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Wideband MIMO Channel Model

- Channel measurements typically show large delay spreads.
- Insufficient antenna spacing or lack of scattering cause individual antennas to be correlated.
- Geometry of Ricean component has a direct bearing on multiplexing gain.

- Broadband channel is frequency selective :

$$H(\tau) = \begin{bmatrix} h_{1,1}(\tau) & h_{1,2}(\tau) & \ldots & h_{1,N_T}(\tau) \\ h_{2,1}(\tau) & h_{2,2}(\tau) & \ldots & h_{2,N_T}(\tau) \\ \mathrm{M} & \mathrm{M} & \mathrm{M} & \mathrm{M} \\ h_{N_R,1}(\tau) & h_{N_R,2}(\tau) & \ldots & h_{N_R,N_T}(\tau) \end{bmatrix}$$

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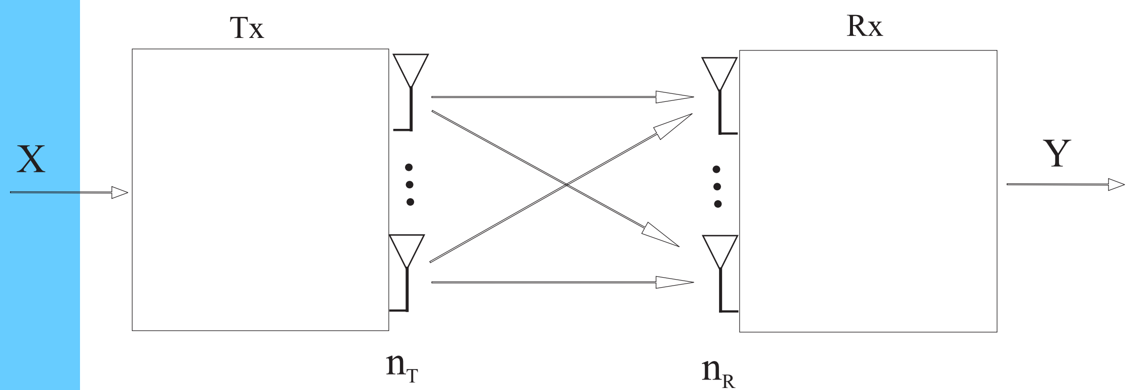
MIMO System Model



AWGN

$$\mathbf{y} = \mathbf{H}x + \mathbf{n}$$

with

$$r = \begin{bmatrix} r_1 & r_2 & \dots & r_{N_R} \end{bmatrix}^T \quad \dots\ N_R \times 1 \text{ receive signal vector}$$

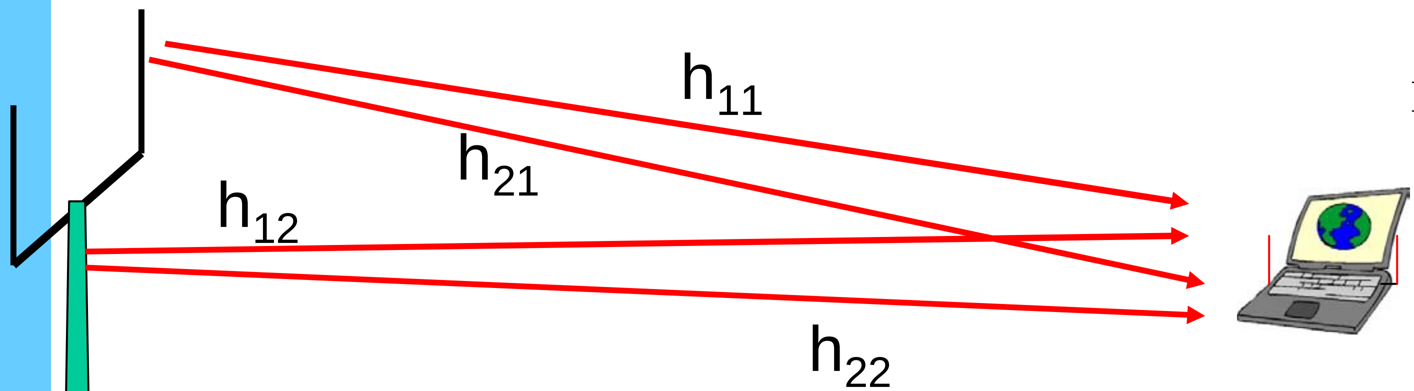
$$x = \begin{bmatrix} x_1 & x_2 & \dots & x_{N_T} \end{bmatrix}^T \quad \dots\ N_T \times 1 \text{ transmit signal vector}$$

$$n = \begin{bmatrix} n_1 & n_2 & \dots & n_{N_R} \end{bmatrix}^T \quad \dots\ N_R \times 1 \text{ noise vector}$$

$$\mathrm{H} \ \dots\ N_R \times N_T \text{ channel transfer matrix}$$

$$\text{Noise: } n_i : \ \mathcal{CN}\left(0, \sigma_R^2\right) \text{ with } \mathrm{E}\left\{ n n^H \right\} = \sigma_R^2 I_{M_R}$$

Capacity of MIMO System



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

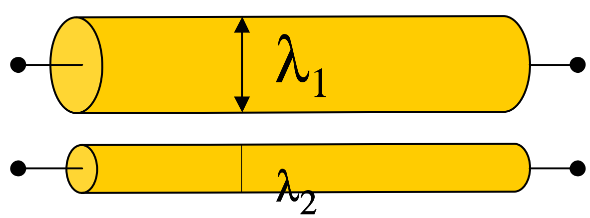
$$C_{diversity} = \log_2 \det[\mathbf{I} + (P_T/2\sigma^2)\cdot \mathbf{HH}^\dagger] =$$

$$= \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_1\right] + \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_2\right]$$

Where the λ_i are the eigenvalues to $\mathbf{HH}^\dagger$

Interpretation:

Transmitter



Receiver

m=min(N_R, N_T) parallel channels, equal power allocated to each ”pipe”

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Capacity of MIMO System

H unknown at TX

$$C = \log_2 \det\left[I + \frac{P_T}{\sigma^2 N_T} HH^* \right] =$$

$$= \sum_{i=1}^{m} \log_2 \left[1 + \frac{P_T}{\sigma^2 N_T} \lambda_i \right]$$

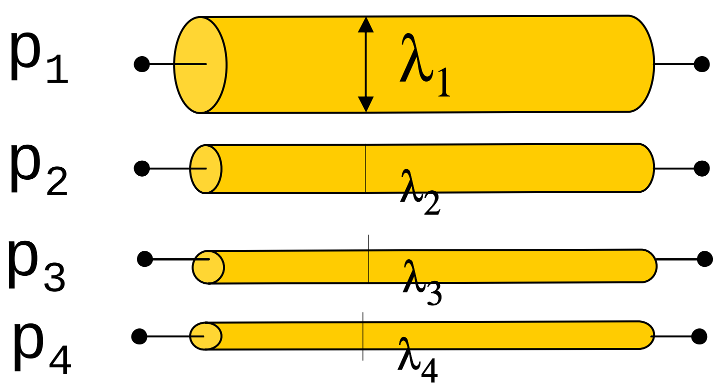
$$m = \min(N_R, N_T)$$

H known at TX

$$C = \sum_{i=1}^{m} \log_2 \left[1 + \frac{p_i \lambda_i}{\sigma^2} \right]$$

Where the power distribution over ”pipes” are given by a water filling solution

$$P_T = \sum_{i=1}^{m} p_i = \sum_{i=1}^{m} \left(\nu - \frac{1}{\lambda_i} \right)^+$$



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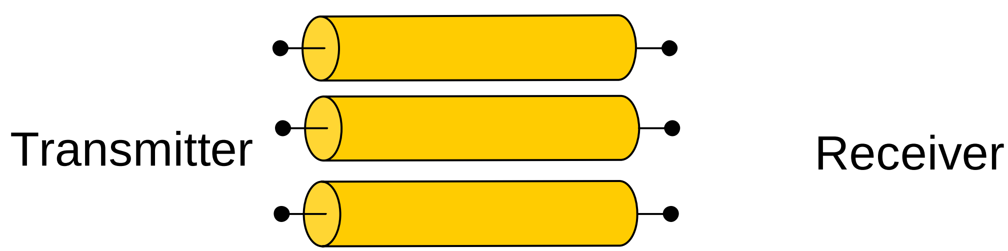
Channel Eigen Values

Orthogonal channels $\mathbf{HH}^{\dagger} = \mathbf{I}$, $\lambda_1 = \lambda_2 = \ldots = \lambda_m = 1$

$$C_{\textbf{diversity}} = \sum_{i=1}^{m} \log_2\left[1 + \frac{P_T}{\sigma^2 n_t}\lambda_i\right] = \min(n_t, n_r)\cdot\log_2(1 + P_T/\sigma^2 n_t)$$

- Capacity increases linearly with $\min(n_r, n_t)$
- An equal amount of power P_T/n_t is allocated to each "pipe"



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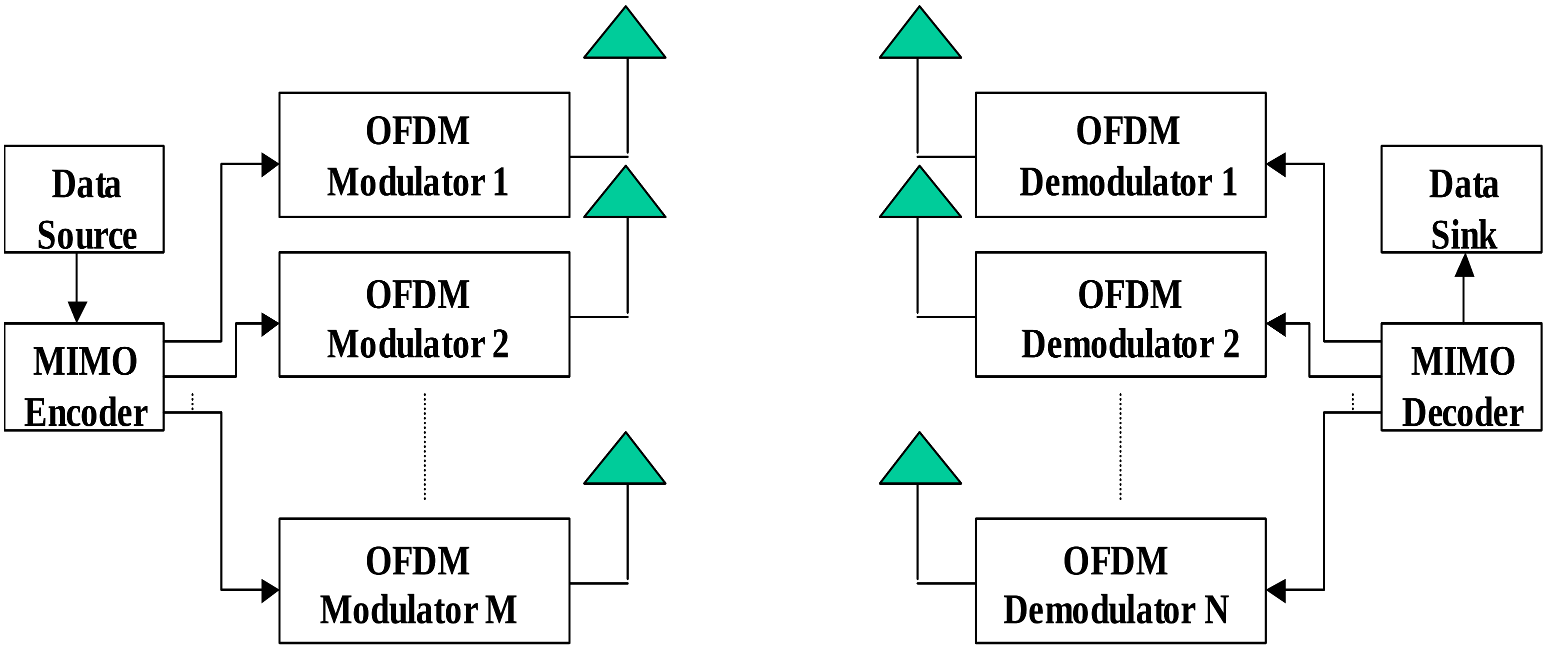
MIMO-OFDM System Model



OFDM turns a frequency-selective MIMO fading channel into a set of parallel frequency-flat MIMO fading channels

MIMO-OFDM drastically simplifies equalization in frequency-selective environments

Spatial Multiplexing - BLAST

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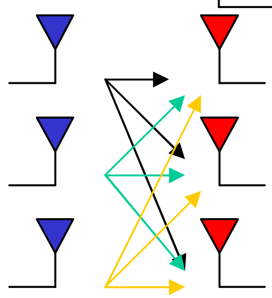
Bell Labs Layered Space Time Architecture



Time →

Antenna ↓

V-BLAST

s1	s1	s1	s1	s1	s1
s2	s2	s2	s2	s2	s2
s3	s3	s3	s3	s3	s3

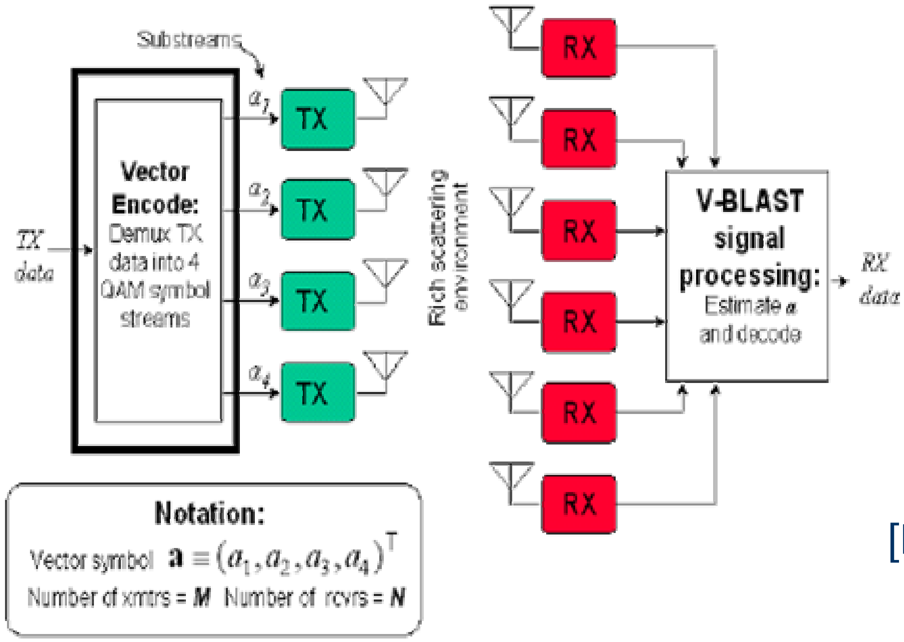
D-BLAST

s0	s1	s2	s0	s1	s2
	s0	s1	s2	s0	s1
		s0	s1	s2	s0

- $N_R \geq N_T$ required
- Symbol by symbol detection. Using nulling and symbol cancellation
- V-BLAST implemented -98 by Bell Labs (40 bps/Hz)
- If one ”pipe” is bad in BLAST we get errors ...

{G.J.Foschini, Bell Labs Technical Journal 1996 }

V-BLAST



[Bell Labs]

V-BLAST detection

- Use of linear combinatorial nulling techniques (such as ZF or MMSE) or non-linear methods like symbol cancellation
- Turn by turn each substream is considered to be the desired signal and all the others are interferers
- Nulling is obtained by linearly weighting the received signals

Comments about BLAST System

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- Requires multiple antennas at both ends of radio link.
- Increase data rate by transmitting independent information streams on different antennas.
- No channel knowledge required at transmitter.
- Orthogonal H maximizes capacity.
- In the presence of rich scattering several data pipes are created within the same bandwidth.
- Multiplexing gain comes at no extra bandwidth or power.

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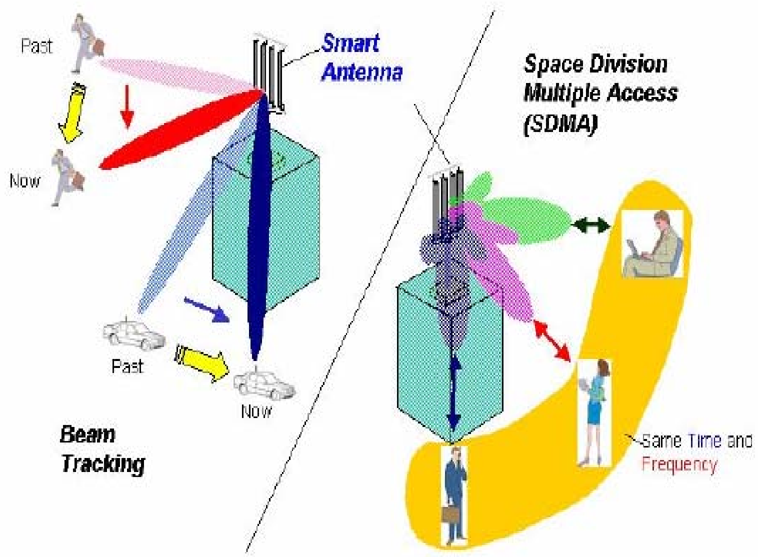
Smart Antennas

Feature	Benefit
Signal gain	Extended coverage
Reduced interference	Increased capacity
Spatial diversity	Multipath rejection
Power efficiency	Reduced expenses

[Adapted from iec.org]



Smart Antenna Technology

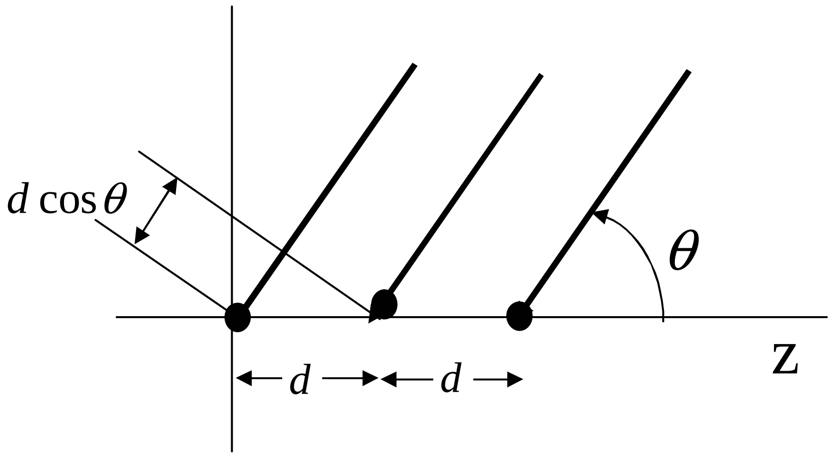
[Ref. ntt.co.jp]

Antenna Arrays

Equally spaced linear arrays

- Excitation coefficients

$$I_n = A_n e^{jn\delta} \qquad n = 0,\dots,N\text{-}1$$



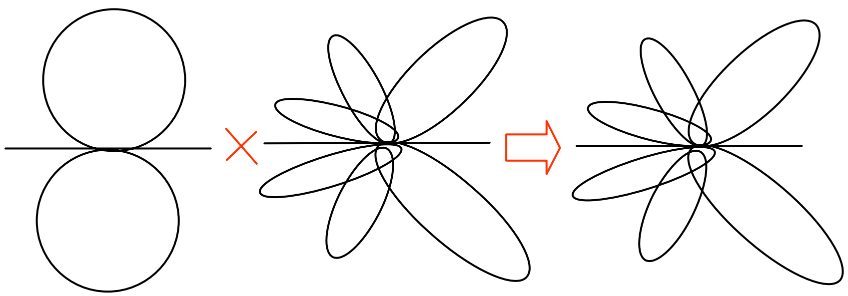
- Array factor:

$$AF = \sum_{n=0}^{N-1} A_n e^{jn(\beta d \cos\theta + \delta)}$$

Antenna Arrays

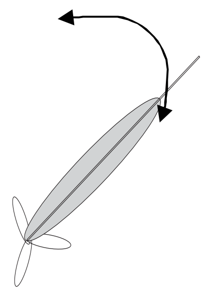
Radiation pattern

- The final pattern is obtained multiplying AF by element pattern
- As number of antennas increases, the main beam narrows and more sidelobes appear



Phased Arrays

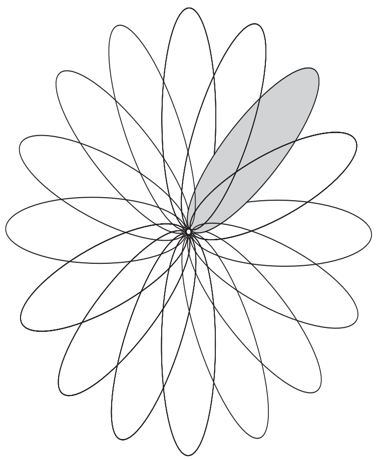
- By modifying the phases of the signals at the antennas, leaving unchanged their amplitude, the beam is steered



Beamforming

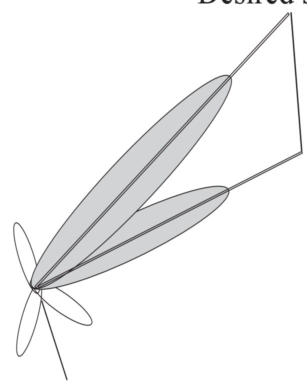
Switched Beam Systems

- A bank of weight vectors is used to form M beams out of M antenna elements
- At the receiver side, a switch is used to select the best beam



Adaptive Antennas Systems

- A weight vector is determined to establish a beam in the direction of the user and possibly using also multipath signals
- Interference can be reduced by placing the nulls of the radiation pattern in the direction of interferers



[Ref. Liberti 99]

Weighting Algorithms

Optimum Algorithms

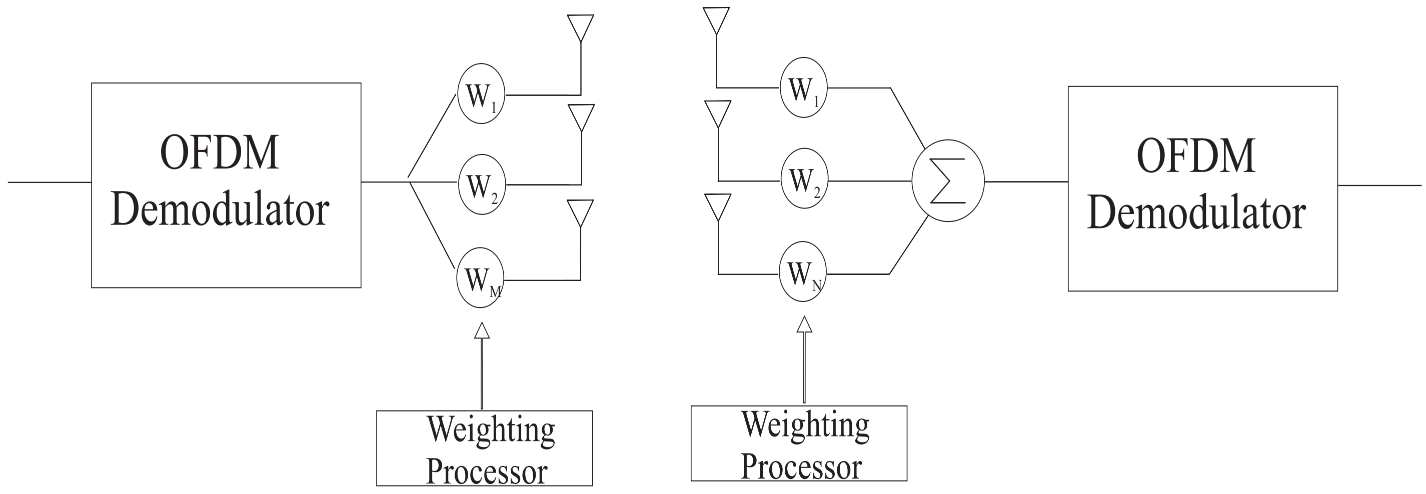
- Maximum Signal-to-Noise Ratio (MSNR)
- Minimum Mean Square Error (MMSE)
- Least Squares (LS)

Adaptive Algorithms

- Least Mean Square (LMS)
- Recursive Least Square (RLS)
- Linearly Constrained Minimum Variance (LCMV)

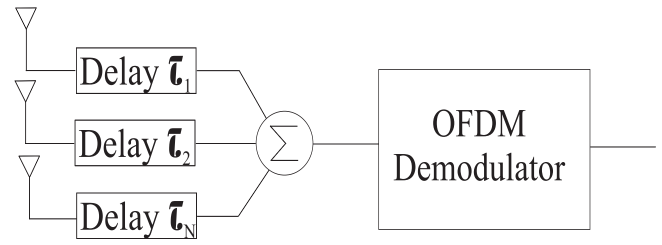
Beamforming

Beamforming



Delay-and-sum

- Another way of achieving beamforming



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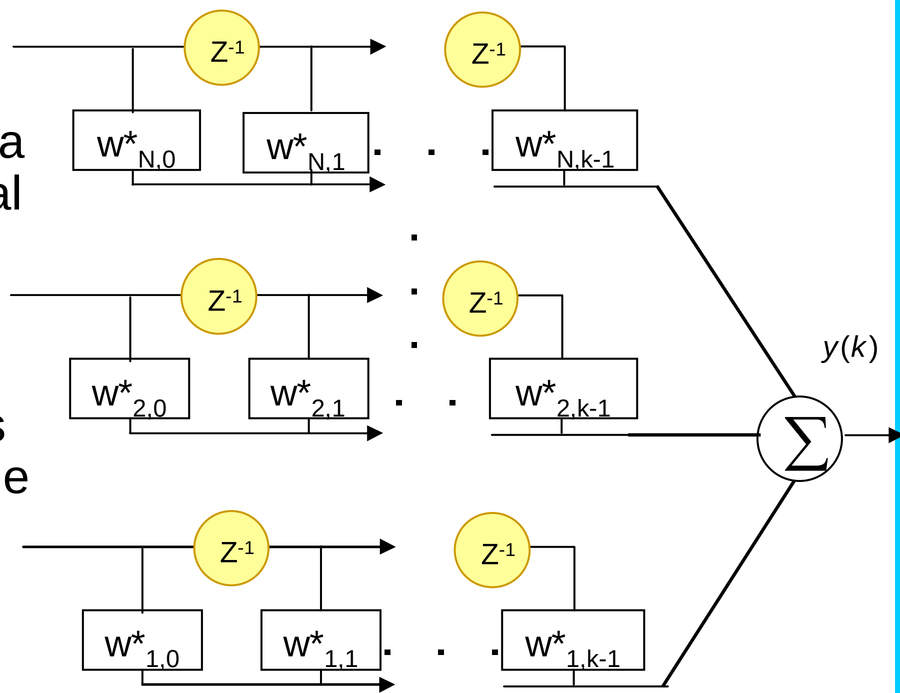
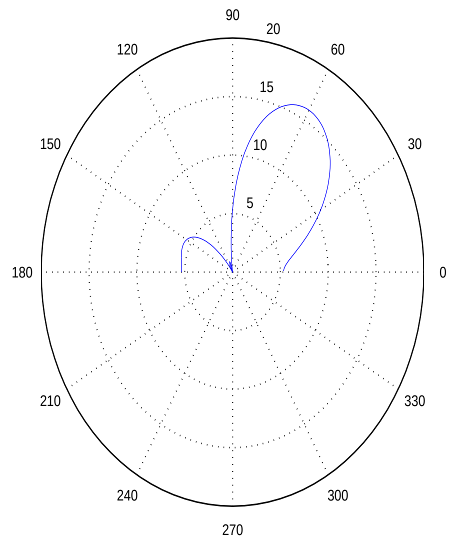
Wideband Beamformer

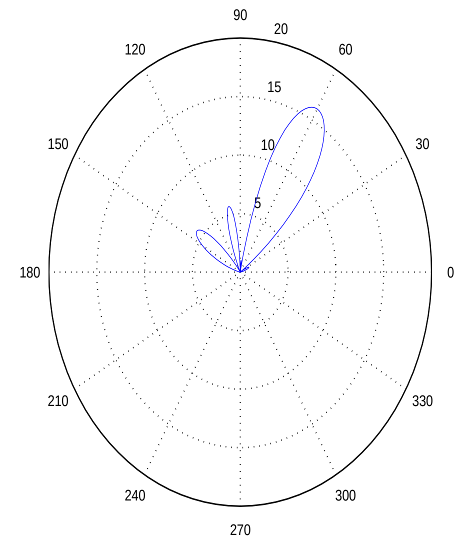
- In order to compensate the phase variation with frequency, a wideband array combines spatial filtering with temporal filtering
- Hence, in each branch of the array considered in the previous configuration, a tapped-delay line is added



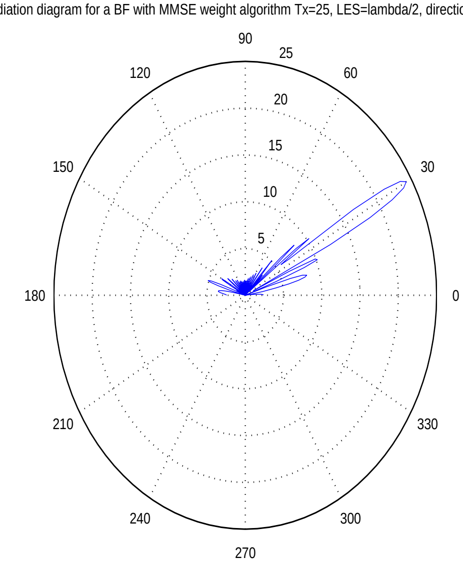
[Ref. Liberti 99]

Radiation Patterns





- Obtaining radiation patterns with MMSE algorithm with DoA previously known
- 4 Tx antennas, d=λ/4
- 4 Tx antennas, d=λ/2
- 25 Tx antennas, d=λ/2 (just for comparison)



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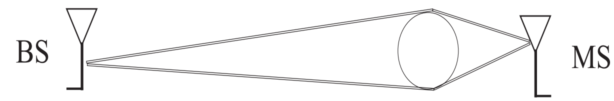
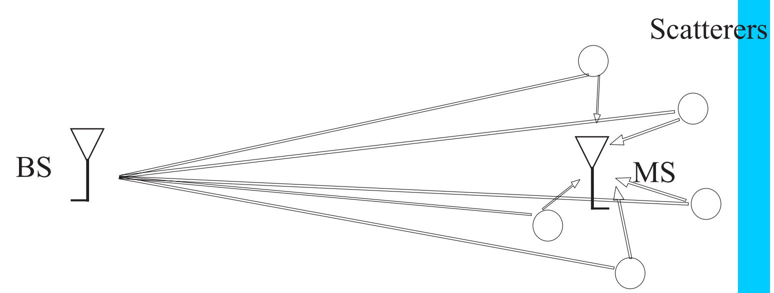
Angular Spread and Environments





Signal Correlation

- Diversity can only be exploited if the signals are sufficiently uncorrelated

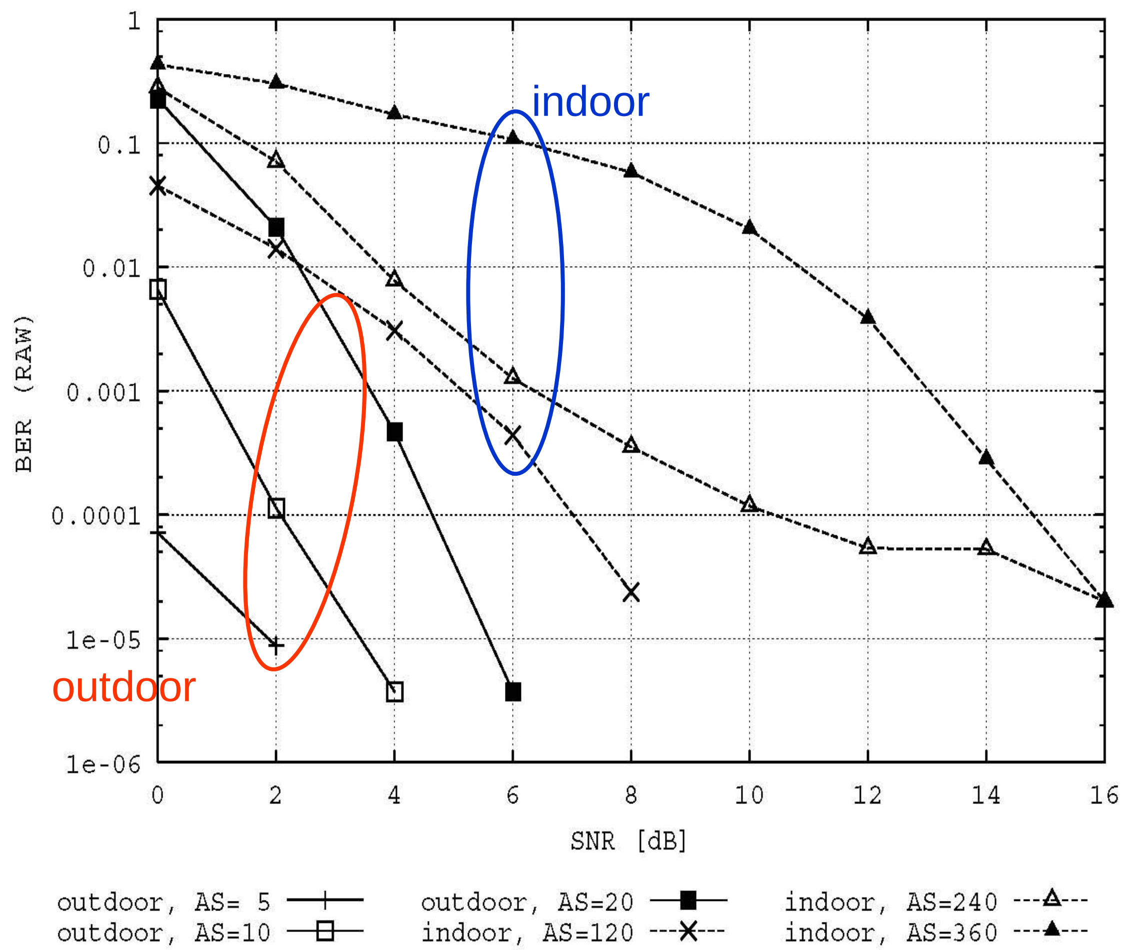
Angular Spread (AS)

- Signals arriving with different DoA have different phases
- The bigger the DoA difference between arriving signals is, the lower the correlation between them gets
- A broader AS allows an effective angle diversity exploitation, since the multipath signals have low correlation between them (especially in Indoors)

Environment	**Angle spread**
Flat rural (Macro)	1 deg
Urban (Macro)	20 deg
Hilly (Macro)	30 deg
Microcell (Mall)	120 deg
Picocell (Indoors)	360 deg

[Ref. Paulraj, IEEE, Nov97]

BER Performance for Beamforming for Different AS



[Ref. D. Figueiredo, WPMC'04]

Conclusions

Outdoor environments (low AS)

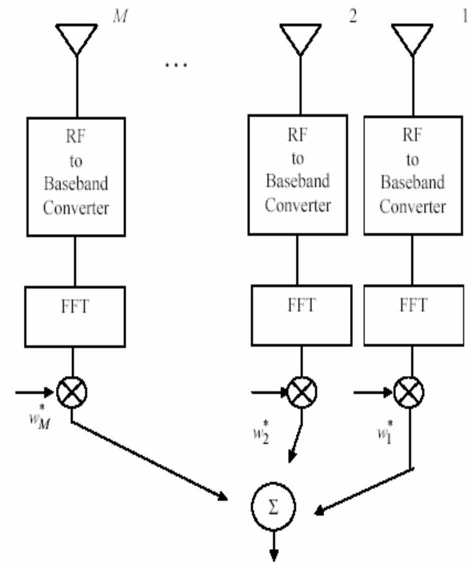
- Beamforming always performs better and may compensate the increase in complexity

Indoor environments (high AS)

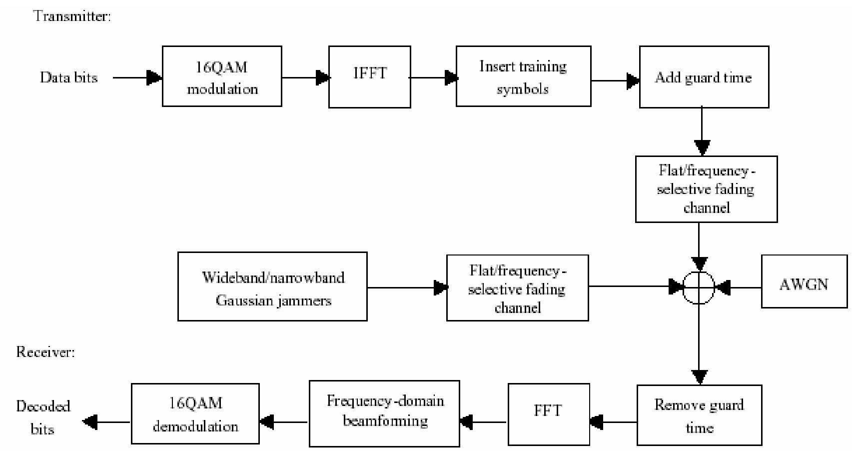
- Transmit diversity is more suitable due to its simplicity when compared to beamforming implementation (even if in some cases is outperformed by beamforming)

Beamforming for OFDM

Frequency domain beamforming
- Receiving: after FFT
- Transmitting: before IFFT
- Water filling power allocation
- Fast adaptive algorithms may be used, like RLS



Sub-band beamforming
- a beamformer for a smaller set of subcarriers
- Weights can track the channel variations across frequency

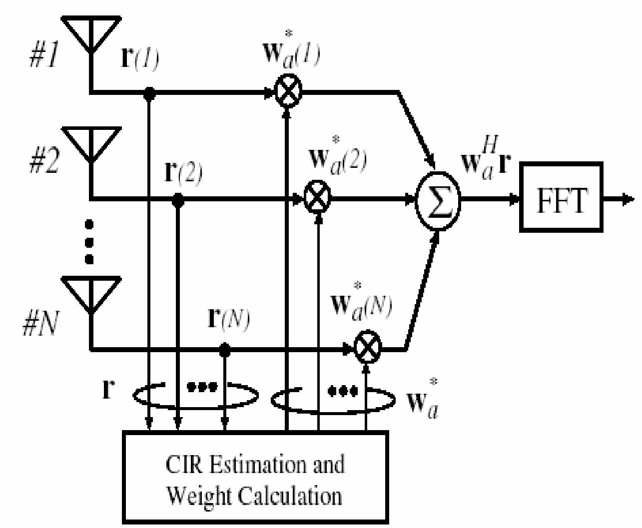


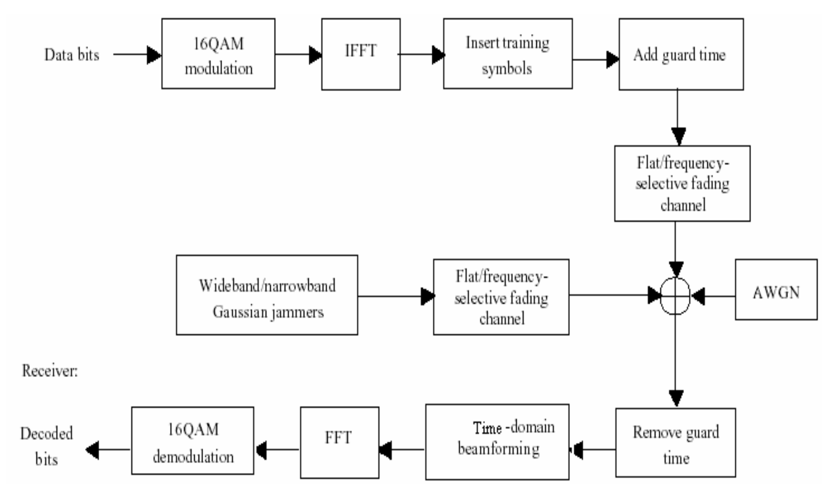
[Ref. Alam 02]

Beamforming for OFDM

Time domain beamforming

- Receiving: before FFT
- Transmitting: after IFFT
- Adaptive algorithms





[Ref. Alam 02]

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Comparison of Techniques

Beamforming

- Higher SINR due to a narrow beam focusing the target and nulling interferers
- Array gain
- Signal variability remains unchanged
- Not effective in scattered environments
- Requires channel knowledge (CSI), like DoA/DoD
- Effective when DOF ≥ N_{path}

Diversity

- Uses independent paths
- Diversity gain
- Most effective in scattered environment
- Average SNR improves
- Variability of the signal is reduced
- Not effective when low fading
- Available in time, frequency, space, etc.

Technique	LOS	NLOS	Strong interference
Beamforming	Effective	Not effective	Effective
Diversity	Not effective	Effective	Not effective

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Conclusions

- The goal is to give a overview about multi-antenna techniques that can be applied to OFDM systems
- The more interested students are suggested to study appropriate reference materials.
- MIMO-OFDM is an exciting area for research. If you are interested in it, please contact us.

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Thank you for your attention!

Any question or discussion or new ideas?

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