UNIT V

MULTIPLE ANTENNA TECHNIQUES

MIMO systems – spatial multiplexing -System model -Pre-coding – Beam forming – transmitter diversity, receiver diversity- Channel state information-capacity in fading and non-fading channels.

Introduction

MIMO or Multiple Input Multiple Output can be referred to as the communication channel created with multiple transmitters and receivers of an antenna to improve communication's performance. Since their initial development in the year 1990, MIMO Wireless Communications have become integral part of the most forthcoming commercial and next generation wireless data communication systems. MIMO is one among the several types of Smart Antenna Technologies. Nowadays MIMO techniques are used in different technologies such as WI-FI and LTE (long term evolution).

MIMO achieves space measurements to improve wireless systems' capacity, range and reliability. It offers increase in the data throughput and link range without any additional bandwidth or transmitting power. MIMO antenna technology achieves this objective by spreading the same total transmit power over the antennas to accomplish an array gain that recovers the spectral efficiency (more bits per second per Hertz of bandwidth) or to achieve a diversity gain that increases the link reliability (reduced fading).

MIMO technology makes advantage of a natural radio wave phenomenon called multipath. MIMO uses multiple antennas to transfer multiple parallel data signals from a transmitter. In any urban areas, this multi path will bounce off trees, ceilings and other commercial buildings. The signals can reach their destination on their own at the receiver end in different directions.

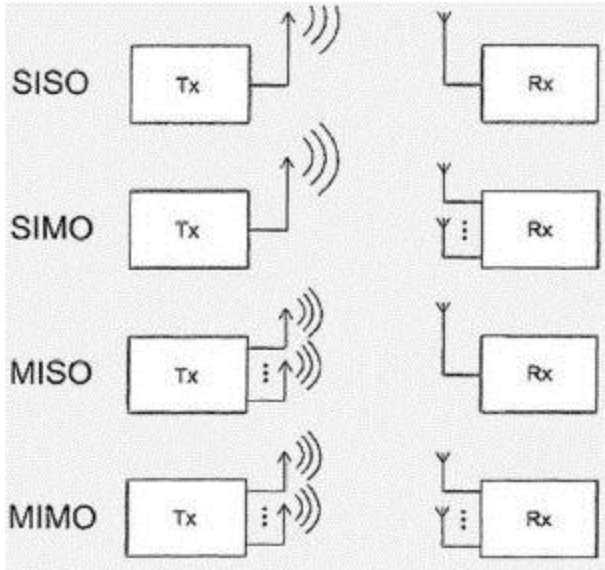
There are different multi-antenna types that require different number of antennas, and also different levels of complexity. These types can be balanced to provide optimum solution for any kind of application.

SISO: It is also named as Single-Input Single-Output which means that the transmitter and receiver of the radio system have only one antenna. SISO is a simple single variable control system which is less complex than the MIMO systems. This system doesn't require any additional processing or diversity.

SIMO: The SIMO or Single-Input Multiple-Outputs means the transmitter has single antenna and the receiver has multiple antennas. This is also known as receiving diversity, and it is applicable in many applications.

MISO: The MISO or Multiple-Inputs Single-Output is also termed as transmit diversity. This transmitter has multiple antennas, and the receiver has only one antenna. The advantage with this system is that it has multiple antennas and the redundancy coding is moved from the receiver to the transmitter. It also creates a positive impact based on the size, price and life of the battery.

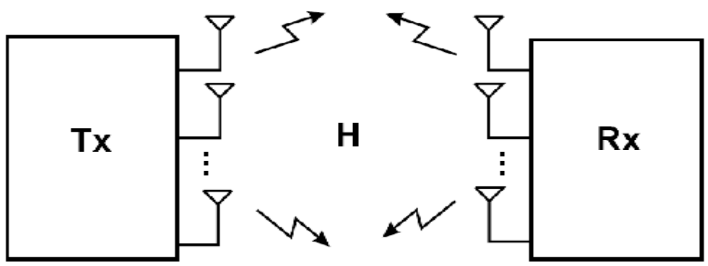
MIMO: MIMO is also termed as Multiple-Inputs Multiple-Outputs. MIMO is also used to provide improvement in both channel robustness and as well as channel throughput. MIMO means both transmitter and receiver have multiple antennas.



Multi Antenna Types

MIMO Systems:

- use multiple inputs and multiple outputs from a single channel
- are defined by Spatial Diversity and Spatial Multiplexing



Why MIMO?

- There is always a need for increase in performance in wireless systems
  - Significant increase in spectral efficiency and data rates
  - High Quality of Service (QoS)
  - Wide coverage, etc.
- Wireless channel that we are using is very unfriendly
  - Suffers from Co–channel interference and signal level fading
  - It provides a limited bandwidth
  - power falls off with distance
- By using Multiple Output Multiple Input (MIMO) systems
  - Diversity gain mitigates the fading and increases coverage and improves QoS

- Multiplexing gain increases capacity and spectral efficiency with no additional power or bandwidth expenditure
- Array gain results in an increase in average receive SNR.

- Spatial Diversity and Spatial Multiplexing can be conflicting goals

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

Spatial Multiplexing
- the system is able to carry more than one data stream over one frequency, simultaneously

Advantages and Application of MIMO

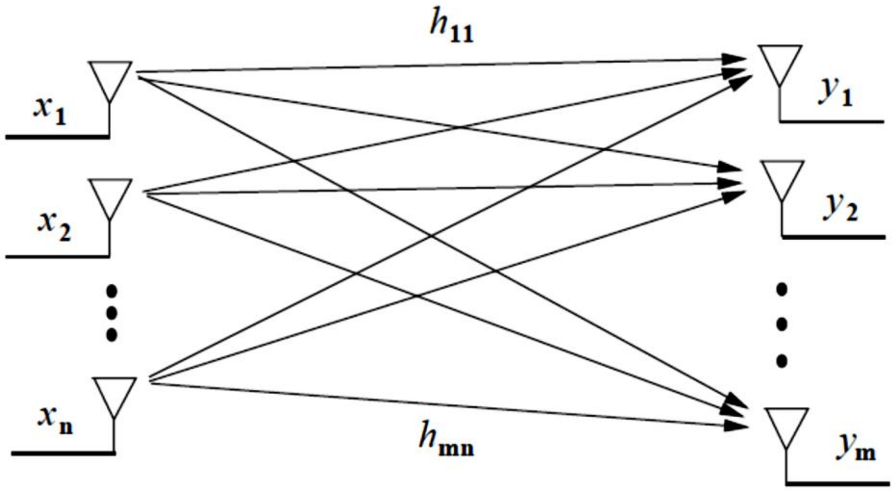
Advantages:
- Higher channel capacity
- Better spectral efficiency
- Increased coverage
- Improved user position estimation
- Lower power consumption
- Minimize the errors
- Faster speeds
- Higher data rate

Challenges:
- The cost of this increased rate is the added cost of deploying multiple antennas
- The space requirements of these extra antennas (especially on small handheld units)
- The added complexity required for multi-dimensional signal processing.
- Circuit power requirements

Applications:
- MIMO is currently being used within the telecommunications and networking industries that is cellular WMAN, WWAN and so forth
- MIMO is used largely in cellular towers
- It is used in modern wireless standards including in 3GPP LTE and mobile WiMAX system
- MIMO OFDM is considered a key technology in emerging high data rate systems such as 4G, IEEE 802.16 and IEEE 802.11n

The Narrowband Multiple Antenna System Model (MIMO System Model)

A narrowband (flat-fading) point to point communication system employing n transmit and m receive antennas is shown in Figure



This system can be represented by the following discrete time model:

$$\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} N_1 \\ \vdots \\ N_m \end{bmatrix}$$

or simply as $y = Hx + N$.

Here *x* represents the *n*-dimensional transmitted symbol,
N is the *m* dimensional additive white Gaussian noise (AWGN) vector,
and the channel matrix *H* consists of zero mean (Rayleigh Fading) complex circular Gaussian random variables
hij representing the channel gain from transmit antenna *j* to receive antenna *i*.

Without loss of generality we normalize the noise so that the noise covariance matrix is an identity matrix.

Note that although the dependence on time is suppressed here, *x*, *y*, *N* and *H* are all stochastic processes.

Channel matrix *H* consists of zero mean (Rayleigh Fading) complex circular Gaussian random variables. So power spectral density of the channel noise is calculated by $\sigma^2 I_m$.

$$\sigma^2 \equiv E[{n_i}^2] = \frac{N_o}{2}$$

The average SNR per receive antenna under unity channel gain,

$$\frac{P}{\sigma^2} = \rho$$

Where p – Power, σ^2 – Noise power Unity

We assume that the receiver is able to estimate the channel state *H* perfectly. So at each instant *H* is known at the receiver.

The transmit power constraint is given as

$$\sum_{i=1}^{n} \mathrm{E}[x_i x_i^*] = P,$$

(or) $T_r\ (R_x) = \rho$

(or) $R_x = E\ [\ x\ x^*]$

Important parameters in MIMO system:

CSIT – Channel Side Information at the Transmitter
CSIR – Channel Side Information at the Receiver

In wireless communication, channel state information (CSI) simply represents the properties of a communication link between the transmitter and receiver.

The CSI describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading and power decay with distance etc.,

To know more about channel H, Different Assumption need to be considered

For Static Channel

- CSIR is assumed
- Pilot sequence used for channel Estimation

If feedback path is available:

- CSIR sends feedback to CSIT

If CSIT may be available in Bidirectional system without feedback

- When reciprocal properties
- Propagation are exploited

If channel not known to Transmitter and Receiver

Some distribution on the channel matrix gain must be assumed.
Common Model: Zero Mean Spatially White Model (ZMSW)

- **Parameters of Zero Mean Spatially White Model (ZMSW):**
  H assumed to be Independent
  Identically Distributed
  Zero Mean
  Unit Variance
  Complex circularly symmetric Gaussian random variables

- **Alternate Distribution model**
  Circularly symmetric Gaussian random variables with a non-zero mean
  Covariance matrix not equal to identify matrix

Different Assumption of Channel Side information's are
Different Channel Capacity
Different Approach to space – time signaling

Maximum Likelihood Demodulation provides optimal decoding of received signals and cross coupling between transmitted symbols. In general matrix, if transmitter does not known about channel it will be more complicated even for small antennas.

PARALLEL DECOMPOSITION OF THE MIMO MODEL

When transmitter and receiver consist of multiple antennas Diversity gain, Performance gain and multiplexing gain will be increased.

The multiplexing gain of a MIMO system results from the fact that a MIMO channel can be decomposed into a number R of parallel independent channels.

By multiplexing independent data onto these independent channels, we got an R fold increase in data rate in comparison to a system with just one antenna at the transmitter and receiver. This increased data rate is called the **Multiplexing Gain.**

Consider $M_r * M_t$ MIMO channel

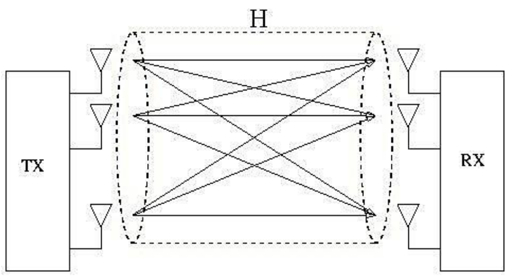
Let us consider the case of perfect Channel State Information at the Transmitter (CSIT). In other words, both the transmitter and the receiver know *H* at each instant.

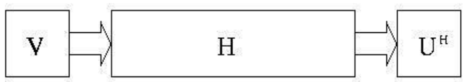
Further let the instantaneous channel matrix have **singular value decomposition (SVD)**

$$\boldsymbol{H} = \boldsymbol{U} \in \boldsymbol{V}^{\boldsymbol{H}}$$

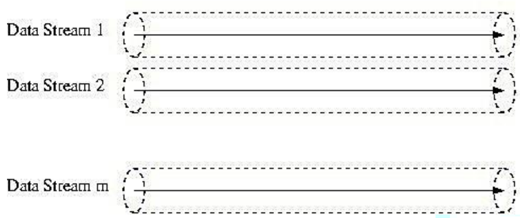
Where,

U - $M_r * M_r$ and V - $M_t * M_t$ are Unitary Matrices
$\in - Mr * Mt$ Diagonal Matrix of singular Values σ_i of H





$H = U \Sigma V^H$



Properties of Singular Values

$$\sigma_i = \sqrt{\lambda_i}$$

Where, λ_i - i^{th} largest Eigen values of HH^H

Rank of Matrix (R_H) is a Non Zero Value, cannot exceed the number of Colum's and Rows of H

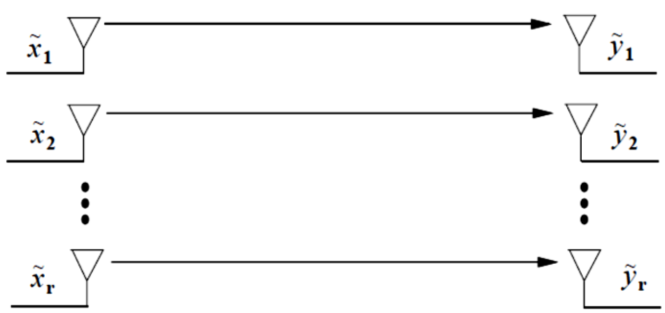
$$R_H \leq \min(M_t, M_r)$$

If channel has full Rank then channel is called as Rich Scattering Environment

$$R_H = \min(M_t, M_r)$$

For low Rank channel, H may have rank 1 with high correlation

The parallel decomposition of the channel is obtained by transformation on the channel input and output x and y via transmit precoding and receiver reshaping.



Parallel Decomposition of the MIMO Channel

Transmit Precoding and Receiver Shaping

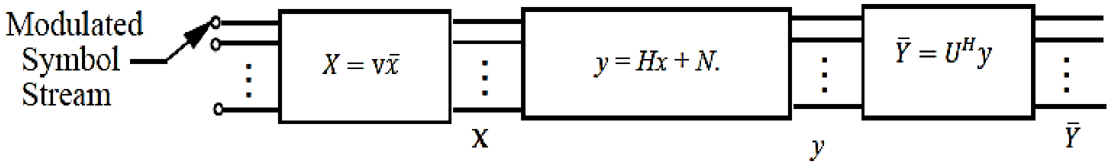
In general an *R* symbols/s input data stream can be split into *r* parallel, independent data streams, producing *r*-tuples $\bar{x}$ at a rate *R/r* symbols/s.

In transmit precoding the input x to the antennas is generated by linear transformation on input vector $\bar{x}$

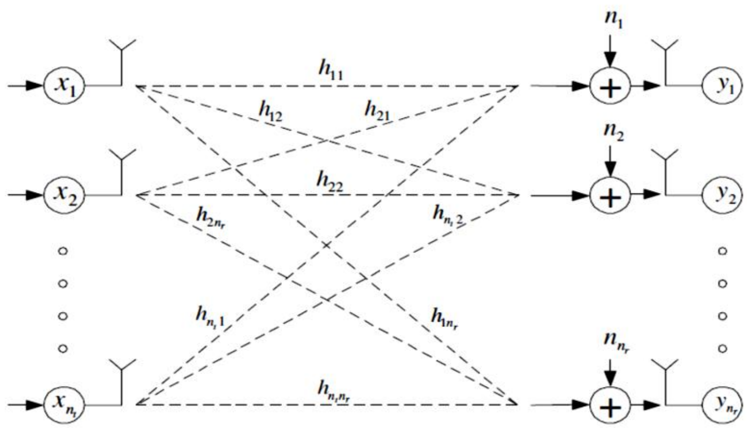
$$X = v\bar{x}$$

This operation is sometimes called transmit precoding. A similar operation, called receiver shaping, can be performed at the receiver by multiplying the channel output

$$\bar{Y} = U^H y$$



The transmit precoding and receiver shaping transform the MIMO channel into R_H parallel SISO channels with input $\bar{x}$ and output $\bar{y}$.



$$\bar{Y} = U^H y$$

$$\bar{Y} = U^H \left(\boldsymbol{Hx} + \boldsymbol{n} \right)$$

$$\bar{Y} = U^H \left(\left(\boldsymbol{U} \ \in \boldsymbol{V^H} \right) x + n \right)$$

$$\bar{Y} = U^H \left(\left(U \ \in V^H \right) V \, \bar{\boldsymbol{x}} + n \right)$$

$$\bar{Y} = \boldsymbol{U^H U} \ \in \boldsymbol{V^H} \, \boldsymbol{V} \ \bar{x} + \boldsymbol{U^H} n$$

$$\bar{Y} = \in \bar{x} + \boldsymbol{U^H} n$$

$$\boxed{\bar{\boldsymbol{Y}} = \in \bar{\boldsymbol{x}} + \bar{\boldsymbol{n}}} \qquad \text{Where } \bar{\boldsymbol{n}} = \ \boldsymbol{U^H} n$$

Where ∈ is the matrix of singular values of H with σ_i.

Note: Multiplication by unitary matrix does not change the distribution of the noise. Because n and $\bar{n}$ are identically distributed.

In MIMO channel, if we apply transmit precoding and receiver shaping channel will be convert into parallel independent channel.

Where i^{th} channel has

$\bar{x_i}$ – Input, $\bar{y_i}$ – Output, $\bar{n_i}$ – Noise and $\bar{\sigma_i}$ – Channel gain

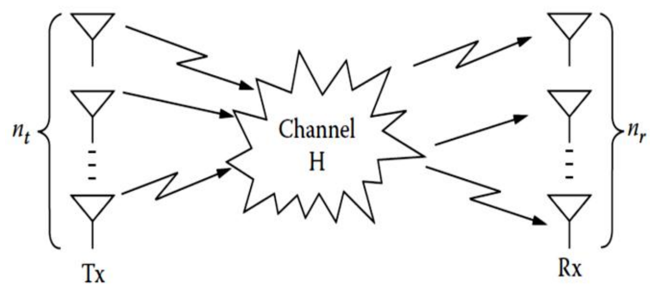
Since the parallel channels do not interface with each other the optimal Maximum Likelihood demodulation complexity is linear. In R_H the number of independent paths that need to be demodulated.
MIMO channel supports R_H times the data rate of a system with just one transmit and receive antenna.

Capacity of Wireless Channel

Shannon's Capacity Formula (1940)

When wireless communication demands increases, capacity play important parameter and error probability should be decrease.

Shannon coding theorem proved that, high data rate close to capacity with less BER.



Shannon's capacity formula approximated theoretically the maximum achievable transmission rate for a given channel with bandwidth B, transmitted signal power P and single side noise spectrum No, based on the assumption that the channel is white Gaussian (i.e., fading and interference effects are not considered explicitly).

$$\mathbf{C = B\ \log_2\left(1 + \frac{P}{N_0 B}\right)}$$

In practice, this is considered to be a SISO scenario (single input, single output) and Equation gives an upper limit for the achieved error-free SISO transmission rate.

If the transmission rate is less than *C* bits/sec (bps), then an appropriate coding scheme exists that could lead to reliable and error-free transmission. On the contrary, if the transmission rate is more than *C* bps, then the received signal, regardless of the robustness of the employed code, will involve bit errors.

Capacity of the channel may be time varying or time variant. Many coding techniques used to achieve high data rate and less BER. Optimal Power Allocation method (Water Filling) used for this purpose ie., channel information known to the both transmitter and receiver.

If channel is time invariant, Additive White Gaussian Noise (AWGN) formula used to calculate the capacity.

If channel is unknown to transmitter/receiver and time varying channel frequency selective fading or flat fading may occurs. To avoid the fading effects channel may approximated by set of parallel channels.

The sum of capabilities on each channel with power optimally allocating among the channel is called as capacity achieving power allocation.

Capacity in AWGN:

Y [i] = X [i] + n [i]

Where

n [i] – White Gaussian Noise Random Process

Receiver SNR is calculated by,

$$\gamma = \frac{P}{N_0 B}$$

Where, P – Power, B - Bandwidth

$\frac{N_0}{2}$ – Power Spectral Density of the Noise

Capacity of this channel by Shannon,

$$\mathbf{C = B\ \log_2(1+\gamma)}$$

Mutual Information between input and output is calculated by

$$I(X:Y) = \sum_{x\in X\ y\in Y} P(x,y)\log\left(\frac{P(x,y)}{P(x)P(y)}\right)$$

Mutual Information interms of Entropy is calculated by

$$I(X:Y) = H(Y) - H\left(\frac{Y}{X}\right)$$

$$H(Y) = -\sum_{y\in Y} P\ (y)\log P(y)$$

$$H\left(\frac{Y}{X}\right) = -\sum_{x\in X\, y\in Y} P(x,y)\log\, P\left(\frac{y}{x}\right)$$

Capacity of the channel interms of mutual information

$$\text{C} = \max_{p(x)}\, I(X\!:Y) = \max_{p(x)} \sum_{x,y} P(x,y)\log\left(\frac{P(x,y)}{P(x)P(y)}\right)$$

MIMO Channel Capacity / Capacity in Flat Fading and Non fading Channels

Shannon capacity of a MIMO channel, which equals the maximum data rate that can be transmitted over the channel will arbitrary small error probability.

STATIC CHANNEL

Condition: Channel unknown at transmitter

By Shannon capacity for SISO channel,

$$\mathbf{C = B\ \log_2(1+\gamma)}$$

$$\gamma = \frac{P}{N_0 B}$$

Entropy Output

$$I(X\!:Y) = H(Y) - H\left(\frac{Y}{X}\right)$$

For MIMO, static channel estimated by CSIR. The capacity is given interms of the mutual information between the channel input vector x and output vector y

$$\text{C} = \max_{p(x)}\, I(X\!:Y)$$

$$\text{C} = \max_{p(x)}\left[H(Y) - H\left(\frac{Y}{X}\right)\right]$$

$H(Y)$ & $H\left(\frac{Y}{X}\right)$ is the entropy of y and y/x

$$H\left(\frac{Y}{X}\right) = H(n) \text{ Entropy is the Noise}$$

The output covariance matrix Ry associated with MIMO channel output y.

$$R_y = E\,[YY^H] = I_{mr} + HR_xH^H$$

Maximum Entropy in y will increase

When,

Maximum mutual information increases &
Y is Zero Mean Circularly Symmetric Complex Gaussian (ZMCSCG)

y is ZMCSCG when x is ZMCSCG. This is called **Optimal Distribution**.

$$T_r\ (R_{x)} = \ \rho \text{ Power constraints}$$

$$\text{H}\ (y) = B\ \log_2 \det[\pi_c R_y]$$

$$\text{H}\ (n) = B\ \log_2 \det[\pi_e I_{mr}]$$

Mutual information for multi antenna

$$I(X\colon Y) = \ B\ \log_2 \det[I_{mr} + HR_x H^H]$$

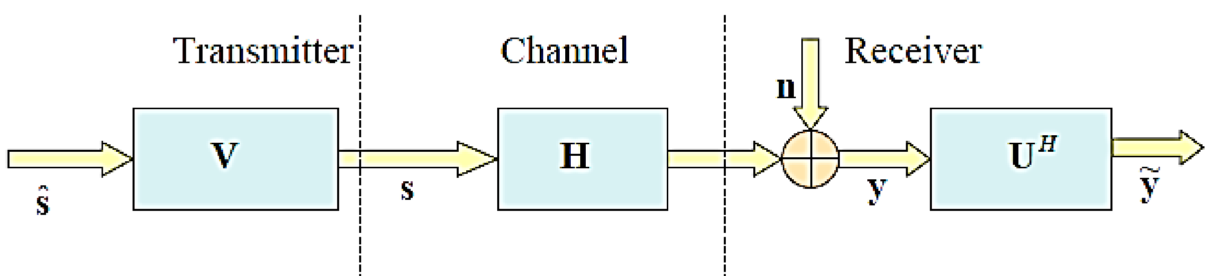
MIMO capacity is achieved by increasing mutual information

$$\text{C} = {}_{p(x)}^{max}\ B\ \log_2 \det[I_{mr} + HR_x H^H]$$

$\det[A]$ – Determinant of the matrix A

Optimization related to the receiver based on transmitter is known to the (H) channel or not.

Optimizations under different assumption are
- Channel known at transmitter
- Channel unknown at transmitter



Transmitter with Channel Knowledge

CHANNEL KNOWN AT TRANSMITTER – WATTER FILLING METHOD

Condition: Channel (H) known to the both transmitter and receiver

To maximize the capacity formula we need to optimize the input covariance

MIMO capacity with CSIT and CSIR is calculated by

$$C = \max_{\rho_i : \varepsilon_i \rho_i \leq \rho} \sum_{i=1}^{R_H} B \ \log_2 \det[1 + {\sigma_i}^2 p_i \,]$$

R_H is the number of non-zero singular values ${\sigma_i}^2$of H

The MIMO channel decomposes into R_H parallel channel, we can say that it has R_H degrees of freedom.

$$C = \max_{\rho_i : \varepsilon_i \rho_i \leq \rho} \sum_{i=1}^{R_H} B \ \log_2 \left(1 + \frac{{\sigma_i}^2 p_i}{\sigma^2}\right)$$

$$C = \max_{\rho_i : \varepsilon_i \rho_i \leq \rho} \sum_{i=1}^{R_H} B \ \log_2 \left(1 + \frac{\gamma_i p_i}{p}\right)$$

Where, $\gamma_i - SNR$ $\gamma_i = \frac{{\sigma_i}^2 p_i}{\sigma^2}$

At High SNR, channel capacity increases linearly with the number of degree of freedom in the channel

At Low SNR, all power will be allocated to the parallel channel with the largest SNR.

The capacity formula is similar to **flat fading & frequency selective fading**

When both the receiver and transmitter knows the channel perfectly, then it is not necessary to distribute power uniformly between the different transmit antennas but assign it based on the channe state.

Optimally allocating the power to several parallel channels is difficult because each has different SNR. This issue can be overcome by using **Water Filling Method.**

$$\frac{p_i}{p} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_i} & \gamma_i \geq \gamma_0 \\ 0 & \gamma_i < \gamma_0 \end{cases}$$

$$C = \sum_{i:\ \gamma_i \geq \gamma_0} B \log\left(\frac{\gamma_i}{\gamma_0}\right) \quad where, \gamma_0 - cutoff\ value$$

Capacity under perfect CSIT & CSIR will produce diversity & array gain from the multiple antenna but no multiplexing gain.

If both transmitter and receiver knows H

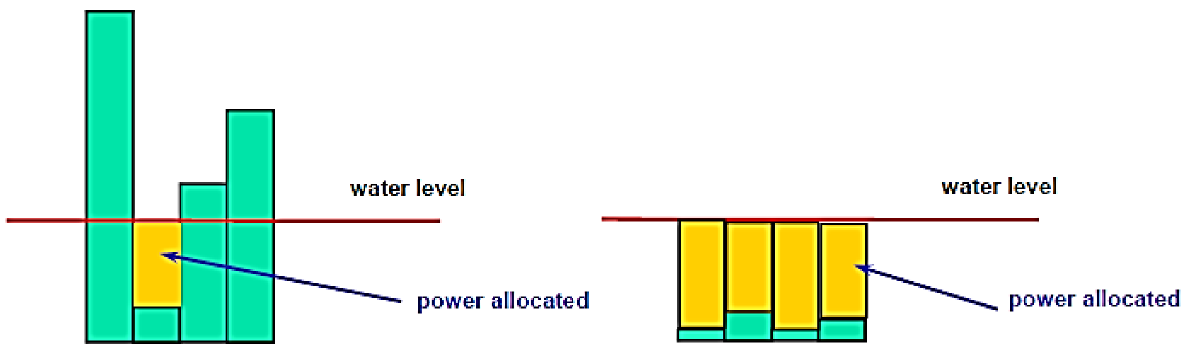
SISO with max SNR

$$C = B \ \log_2 \left(1 + \rho \ ||h||^2\right)$$

Channel matrix H is reduced to a vector h of channel gain.
The optimal weight vector

$$C = \frac{h^H}{||h||}$$

$$\rho = \frac{p}{\sigma^2}$$



Case I: Low SNR   Case II: High SNR

CHANNEL UNKNOWN AT TRANSMITTER UNIFORM POWER ALLOCATION

Condition:

- Receiver knows H
- Transmitter does not knows H

Transmitter cannot optimize its power allocation and input covariance structure.

If H follows ZMSW there is no bias interms of Mean/ covariance

Input covariance matrix equal to identical matrix

$$R_x = \left(\frac{\rho}{M_t}\right) IM_t$$

M_t – Transmit Antenna M_r – Receive Antenna

Mutual Information

$$I(X\!:Y) = \ B \ \log_2 \det\left[IM_t + H\frac{\rho}{M_t}H^H\right]$$

Using Singular Value Decomposition (SVD)

$$I(X{:}Y) = \sum_{i=1}^{R_H} B \ \log_2\left(1 + \frac{\gamma_i}{M_t}\right)$$

$$\gamma_i = \ \sigma^2\rho = \frac{{\sigma_i}^2\rho}{\sigma^2}$$

Mutual information of the MIMO channel depends on the specific realization of the matrix H in a particular its singular values σ_i.

In fading channel, transmit at a rate equal to average mutual information at receiver.

In channel information does not known to the transmitter, transmitter don't know what rate it want to transmit to reach receiver. This is called as **channel outage.**

For this case transmitter fix the data rate R with probability

Probability includes: may be reached, not reached and average or equally reached.

$$P_{out} = P\ \left(H\ :\ B\ \log_2 \det\left[IM_t + H\frac{\rho}{M_t}H^H\right] < R\ \right)$$

Probability is determine by HH^H

Eigen values are the squares of the singular values of H.

If number of transmitter & receiver antenna grows large random matrix theory provide a central limit theorem for the distribution of singular values of H.

By ZMSW Model,

$$IM_r = \lim_{M\to\infty}\frac{1}{M_t}\ HH^H$$

Large M_r equal to

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

$$M = Min\ (M_t, M_r)$$

When absence of CSIT

$$C = M\, B\ \log_2(1 +\ \rho)$$

Similarly SNR grows linearly and capacity also grows linearly with $M = Min\ (M_t, M_r)$

For M_t, M_r value ZMSW MIMO channel has

$$R_H = M = Min\ (M_t, M_r)$$

For this channel, Capacity in the absence of CSIT at high SNR and large number of antennas increases linearly with the number of degrees of freedom in the channel.

Even if the channel realization is not known at the receiver, the capacity of ZMSW MIMO channels still grow linearly with the minimum number of transmitter and receiver antennas as long as the channel can be accurately estimated at the receiver.

Thus MIMO channel can provide high data rate without requiring increased signal power/ Bandwidth.

Note:

The two types of capacity possible in flat fading MIMO systems are
1. Ergodic (Shannon Capacity
2. Outage Capacity

Ergodic (Shannon Capacity

It is the expected value of the capacity taken over all realization of the channel. This quality assumes an infinitely long code that extends over all the different channel realizations.

Outage Capacity:
This is minimum transmission rate that is achieved over a certain fraction of time.

SMART ANTENNA TECHNOLOGY

A smart antenna consists of several antenna elements, whose signal is processed adaptively in order to exploit the spatial domain of the mobile radio channel. The smart antenna technology can significantly improve wireless system performance and economics for a range of potential users. It enables operators of PC's cellular and wireless local loop networks to realize significant increase in signal quality, network capacity and coverage.

In actual, antennas are not Smart Antenna, systems are smart. Generally co-located with a base station, a smart antenna system combines an antenna array with a digital signal-processing capability to transmit and receive in an adaptive, spatially sensitive manner. In other words, such a system can automatically change the directionality of its radiation patterns in response to its signal environment. This can dramatically increase the performance characteristics (such as capacity) of a wireless system.

This is a new and promising technology in the field of wireless and mobile communications in which capacity and performance are usually limited by two major impairments multipath and co-channel interference. Multipath is a condition that arises when a transmitted signal undergoes reflection from various obstacles in the environment. This gives rise to multiple signals arriving from different directions at the receiver.

Smart antennas (also known as adaptive array antennas and multiple antennas) are antenna arrays with smart signal processing algorithms to identify spatial signal signature such as the **Direction of arrival (DOA)** of the signal and use it to calculate beam forming vectors, to track and locate the antenna beam on the mobile targets. The antenna could optionally be any sensor. Smart antenna techniques are used notably in acoustic signal processing, track and scan Radar, Radio astronomy and Radio Telescopes and mostly in Cellular Systems like W-CDMA and UMTS.

A smart antenna is a digital wireless communications antenna system that takes advantage of diversity effect at the source (transmitter), the destination (receiver) or both. Diversity effect involves the transmission and/or reception of multiple radio frequency (RF) waves to increase data speed and reduce the error rate. The result is bad signal quality at the receiver due to phase mismatch. Co-channel interference is interference between two signals that operate at the same frequency. A smart antenna enables a higher capacity in wireless networks by effectively reducing multipath and co-channel interference. This is achieved by focusing the radiation only in the desired direction and adjusting itself to changing traffic conditions or signal environments. Smart antennas employ a set of radiating elements arranged in the form of an array.

TYPES OF SMART ANTENNA SYSTEMS

Two of the main types of smart antennas include switched beam smart antennas and adaptive array smart antennas. Switched beam systems have several available fixed beam patterns. A decision is made as to which beam to access, at any given point of time, based upon the requirements of the system. Adaptive arrays allow the antenna to steer the beam to any direction of interest while simultaneously nullifying interfering signals. Beam direction can be estimated using the so-called **Direction-of-Arrival (DOA)** estimation methods.

Switched Beam Antennas:

Switched beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choose from one of several predetermined, fixed beams and switch from one beam to another as the mobile moves throughout the sector. Instead of shaping the directional antenna pattern with the metallic properties and physical design of a single element, switched beam systems combine the outputs of multiple antennas in such a way as to form finely directional beams with more spatial selectivity than can be achieved with conventional, single-element approaches.

Adaptive Array Antennas:

Adaptive antenna technology represents the most advanced smart antenna approach as on date. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception. Both systems attempt to increase gain according to the location of the user, however, only the adaptive system provides optimal gain while simultaneously identifying, tracking and minimizing interfering signals.

COMPARISON BETWEEN SWITCHED BEAM AND ADAPTIVE ARRAY SYSTEMS

Switched Beam System:

(a) It uses multiple fixed directional beams with narrow beam widths.

(b) The required phase shifts are provided by simple fixed phase shifting networks like the butler matrix.

(c) They do not require complex algorithms; simple algorithms are used for beam selection.

(d) It requires only moderate interaction between mobile unit and base station as compared to adaptive array system.

(e) Since low technology is used, it has lesser cost and complexity.

(f) Integration into existing cellular system is easy and cheap.

(g) It provides significant increase in coverage and capacity compared to conventional antenna based systems.

(h) Since, multiple narrow beams are used, frequent intra-cell hand-offs between beams have to be handled as mobile moves from one beam to another.

(j) It cannot distinguish between direct signal and interfering and/or multipath signals, this leads to undesired enhancement of the interfering signal more than the desired signal.

(k) Since, there is no null steering involved, switched beam systems offer limited co-channel interference suppression as compared to the adaptive array systems.

Adaptive Array System.

(a) A complete adaptive system; steers the beam towards desired signal of interest and places nulls at the interfering signal directions.

(b) It requires implementation of DSP technology.

(c) It requires complicated adaptive algorithms to steer the beam and the nulls.

(d) It has better interference rejection capability compared to Switched beam systems.

(e) It is not easy to implement in existing systems i.e. up-gradation is difficult and expensive.

(f) Since, continuous steering of the beam is required as the mobile moves; high interaction between mobile unit and base station is required.

(g) Since, the beam continuously follows the user; intra-cell hand-offs are less.

(h) It provides better coverage and increased capacity because of improved interference rejection as compared to the Switched beam systems.

(j) It can either reject multipath components or add them by correcting the delays to enhance.

BENEFITS OF SMART ANTENNA TECHNOLOGY

There are large number of benefits of Smart Antennas, some of them are enumerated below as:

(a) **Reduction in Co-Channel Interference.** Smart antennas have a property of spatial filtering to focus radiated energy in the form of narrow beams only in the direction of the desired mobile user and no other direction. In addition, they also have nulls in their radiation pattern in the direction of other mobile users in the vicinity. Therefore, there is often negligible co-channel interference.

(b) **Range Improvement.** Since, smart antennas employs collection of individual elements in the form of an array they give rise to narrow beam with increased gain when compared to conventional antennas using the same power. The increase in gain leads to increase in range and the coverage of the system. Therefore, fewer base stations are required to cover a given area.

(c) **Increase in Capacity.** Smart antennas enable reduction in co-channel interference which leads to increase in the frequency reuse factor means smart antennas allow more users to use the same frequency spectrum at the same time bringing about tremendous increase in capacity.

(d) **Reduction in Transmitted Power.** Ordinary antennas radiate energy in all directions leading to a waste of power. Comparatively, smart antennas radiate energy only in the desired direction. Therefore, less power is required for radiation at the base station. Reduction in transmitted power also implies reduction in interference towards other users.

(e) **Reduction in Handoff.** To improve the capacity in a crowded cellular network, congested cells are further broken into micro cells to enable increase in the frequency reuse factor. This results in frequent handoffs as the cell size is smaller. Using smart antennas at the base station, there is no need to split the cells as the capacity is increased by using independent spot beams.

MIMO CHANNEL WITH BEAMFORMING

Consider the case when the transmitter does not know the instantaneous channel. It is no longer possible to transform the MIMO channel into non-interfering SISO channels. Since the decoding complexity is exponential in r, we can keep the complexity low by keeping r small. Of particular interest is the case where $r = 1$.

A transmit strategy where the input covariance matrix has unit rank is called ***beamforming.***

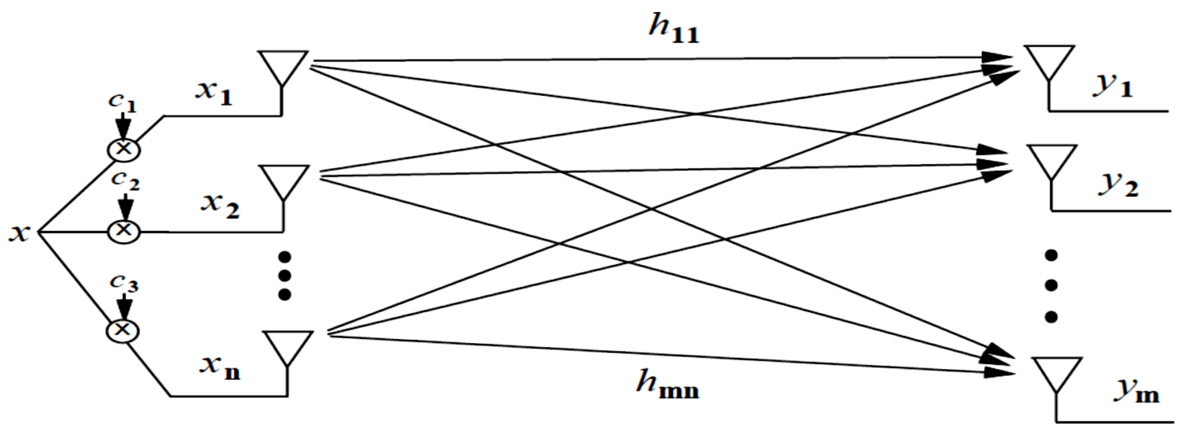
Multiple antennas at transmitter and receiver can be used to obtain array gain and diversity gain instead of capacity gain.

In beamforming method, same symbol weighted by a complex scale factor is sending over each Transmit antenna to that the input covariance matrix has unit rank.

Beamforming techniques can be used in any antenna system, particularly in MIMO system in order to create a certain required antenna directive pattern to give the required performance under the given conditions.

Beamforming is the combination of radio signals from a set of small non-directional antennas in order to simulate a large directional antenna. Aligning the transmit signal in the direction of the transmit antenna array pattern is called **transmit beamforming.** It takes advantages of an interference to change the directionality of the antenna.

Beamforming strategy is similar to precoding and shaping matrices.



Column vector V = v and U = u

In MIMO channel, if we apply transmit precoding and receiver shaping channel will be convert into parallel independent channel.

Where i[th] channel has

$\bar{x}_i$ – Input, $\bar{y}_i$ – Output, $\bar{n}_i$ – Noise, $\bar{\sigma}_i$ – Channel gain and γ_i- Weight

$$||u|| = ||v|| = 1$$

$$\bar{Y} = U^H H x + U^H n$$

Where, $n = n_1, n_2, \dots \dots \dots . n_{mr}$

Beamforming provides diversity and array gain via coherent combining of the multiple signal paths.

If H known to the transmitter

H based on singular value

$$\sigma_i = \sigma_{max}$$

$$where\ \sigma_{max} - Largest\ Singular\ value$$

$$SNR = \gamma = \sigma_{max}{}^2 \rho$$

Capacity similar to SISO:

$$C = B\ \log_2(1 + \sigma_{max}{}^2 \rho\ )$$

Power gain = $\sigma_{max}{}^2$

Array gain of beam diversity max (M_t, M_r)

If H not known to Transmitter

Alamouti scheme used

For M_t = 2 maximum diversity gain 2 M_r

For M_t > 2 full diversity gain using space time block code

Demodulation technique very simple in beamforming order of |X| instead of $|X|^{RH}$

Advantages of Beamforming Antenna:
Increase SNR and support higher user densities.

Spatial Multiplexing Techniques

Spatial Multiplexing defines the system is able to carry more than one data stream over one frequency, simultaneously.

Spatial multiplexing needs MIMO antenna configuration. In spatial multiplexing, a signal placed at high rate splits into lower rate streams in multiples and each stream is transferred from different transmitting antennas in a similar frequency channel. If this transmitted signal reaches the receiver antenna array with different spatial signatures, the receiver can discrete these streams parallel into channels. Spatial multiplexing is a very influential method used for increasing channel capacity at higher signal-to-noise ratios (SNR).

The maximum number of spatial streams is limited by the lesser number of antennas placed at both the transmitter and receiver ends. This multiplexing technique can be used with or without any transmitting knowledge of the channel. Spatial multiplexing can also be used for transmission of data to multiple receivers simultaneously; this method is also known as Space Division Multiple Accessing.

Goal: Increased data rates compared to single-antenna system

Capacity of MIMO systems grows **linearly** with min {M,N}

At the **transmitter**, the data sequence is split into M sub-sequences that are transmitted simultaneously using the same frequency band

Data rate increased by factor M (**multiplexing gain**)

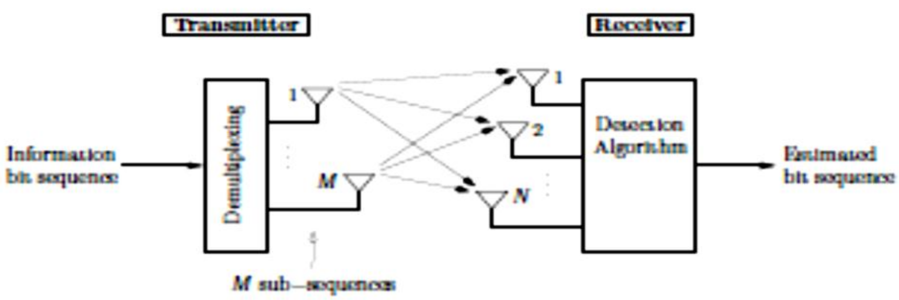
At the **receiver**, the sub-sequences are separated by means of **interference cancellation** algorithm used

e.g., linear zero-forcing (ZF)/ minimum-mean squared-error (MMSE) detector,maximum-likelihood (ML) detector, successive interference cancellation (SIC) detector

Typically, channel knowledge required **solely** at the receiver

For a good error **performance**, typically N ≥M required

Intensive **research** started at the end of the 1990's



Spatial Diversity Techniques

- 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

Goal: Decreased error rates compared to single-antenna system

Send/ receive multiple **redundant** versions of the same data sequence and perform appropriate **combining** (in baseband domain)

If the redundant signals undergo statistically **independent** fading, it is unlikely that all signals simultaneously experience a deep fade

Spatial **diversity gain** (typically, small antenna spacing sufficient)

Receive diversity:

In receiver diversity, one transmitting antenna and many receiving antennas are used. Here the desired message is transmitted by using single transmitting antenna and received by multiple antennas. Nr different antennas appropriately separated are deployed at the receiver to combine the uncorrelated fading signals. It is also called space diversity.

Types of Space Diversity:

1. Selection Diversity
2. Feedback Diversity
3. Maximal Ratio Combining
4. Equal Gain Diversity

SIMO system with N receive antennas and linear combining of the received signals

Various **combining strategies**, e.g., equal-gain combining (EGC), selection combining (SC), maximum-ratio combining (MRC) etc.,

Well-established since the 1950's

Transmit diversity:

In transmitter diversity, multiple antenna elements are required at the transmitter and one antenna element at the receiver end and provide better performance. The transmit power is divided among these antennas.

Types of Transmitter Diversity:

1. Transmitter Diversity with Channel state Information (Closed loop Transmit Diversity)
2. Transmitter Diversity without Channel state information (Open Loop Transmit Diversity)

MISO system with M transmit antennas – Appropriate **pre-processing** of transmitted redundant signals to enable **coherent** combining at receiver (space-time encoder/ decoder)

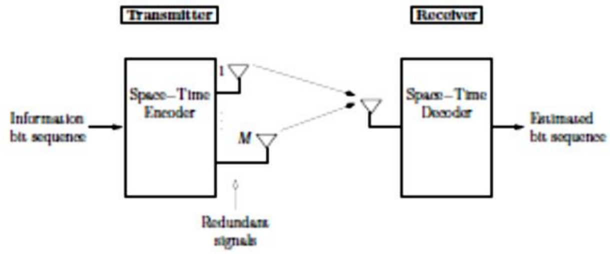
Optionally, N >1 receive antennas for enhanced performance

Typically, channel knowledge required **solely** at the receiver

Intensive **research** started at the end of the 1990's

Well-known techniques are **Alamouti's scheme** for M = 2 transmit antennas, **space-time trellis codes**, and **orthogonal space-time block codes**

An **abundance** of transmitter/ receiver structures has been proposed (some offer additional **coding gain**)



Maximum Ratio Transmission:

An optimum transmission scheme linearly weights the signals send from the various antenna elements with the complex conjugates of the channel transfer functions from the transmit antenna elements to the single receive antenna. This approach is known as Maximum Ratio Transmission. Here the choice of antenna weights will maximize the received SNR.

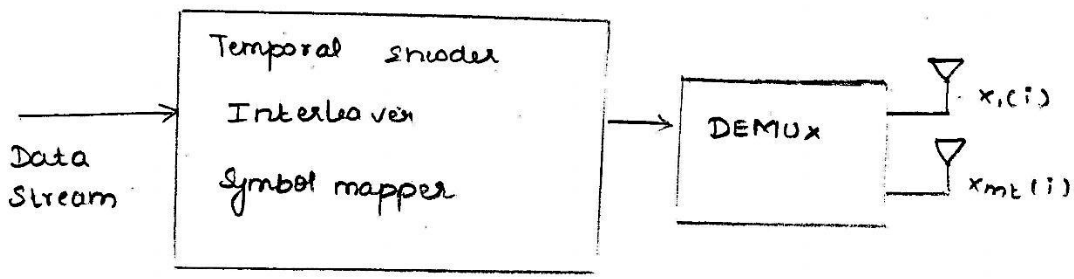
Delay Diversity

The transmit data streams with the delay of one symbol duration from each of the transmit antennas.

SPATIAL MULTIPLEXING AND BLAST ARCHITECTURE

Premise of multiplexing is to send m_t independent symbols per symbol period using the dimensions of space & time

To obtain full diversity order encoder bit stream must be transmitted over all m_t transmit antennas This can be done through a serial encoding.



Serial encoding the bit stream → Temporally Encoded → Channel Block Length T → code word $[x_1 \ldots x_T]$

→ Interleaved & mapped to constellation point → DEMUX → Different antenna

m_t Symbol → Transmitted from m_t antenna → Over first symbol time → Next m_t symbol → Next symbol time

→ continuous upto enter codeword has been transmitted

Symbol sent over the k^{th} antenna at time i } $x_k[i]$

code word sufficiently Long → full diversity in Tx & Rxer.

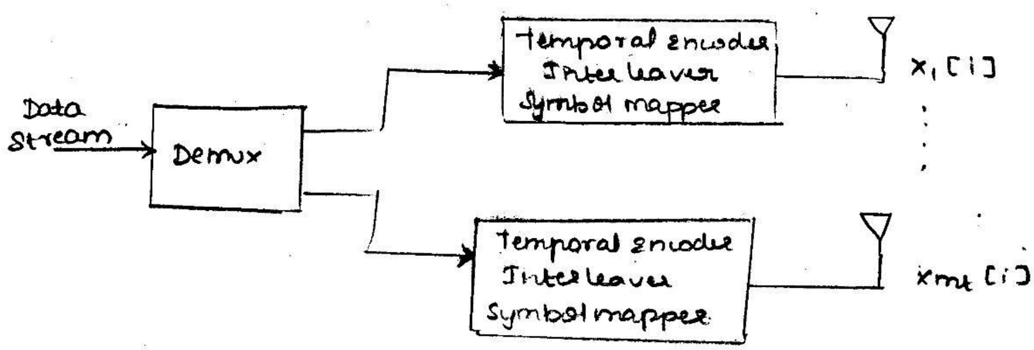
→ code Length Required to achieve full diversity $m_t m_r T$

→ Decoding complexity grows exponentially with this codeword length.

→ High level of complexity makes serial Encoding impractical.

Simple method for spatial multiplexing → Bell Lab

Bell Labs Layered space time (BLAST) Architecture.



Parallel encoding

Parallel Encoding Data stream → Demux → m_t Independent Stream → Sub Streams

→ SISO Temporal Encoder Block Length T → Transmitted over its corresponding Tx antenna.

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K^th SISO Encoder generates codeword

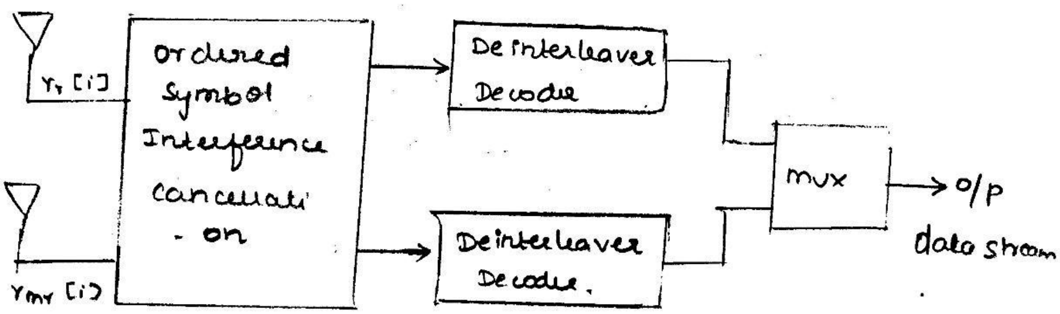
$X_k[i]$, i = 1 .... T Transmitted sequentially over Kth antenna.

This process consider as

Encoding of serial data → vertical vector → vertical Encoding V-BLAST

Decreased complexity in Txed antennas.

The Receiver complexity can be significantly reduced through symbol Interference cancellation.



→ Received SNR for Txed Signal → highest SNR → Others noise – subtract

Next SNR → Removing Noise → Subtract

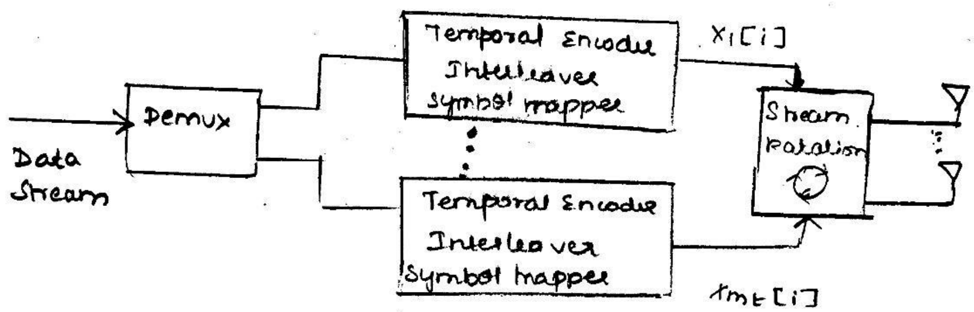
After cancelling out Interfering symbol → Each Txed antenna Individually decoded → Data Rate – Reasonable Error rate

20–40bps/Hz

Serial Encoding + parallel encoding → Diagonal encoding
D- BLAST

datastream → parallel encoding → codeword symbol Rotated across antenna

→ Txed by all m_t antennas.



i_{th} Encoder generates codeword.

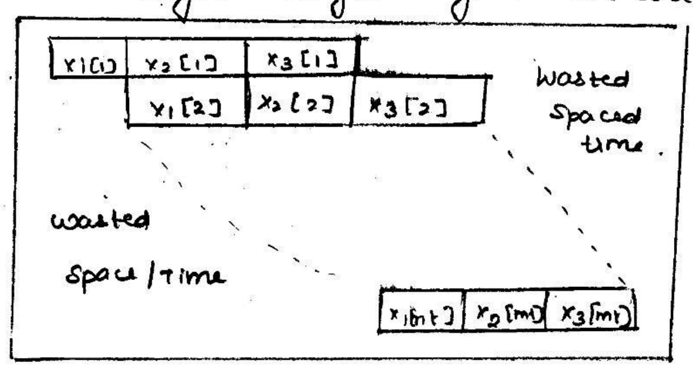
$$X_i = [x_i[1] \dots x_i[r]]$$

$x_i[1]$ is sent to antenna 1 over symbol time i

$x_i[2]$ is sent to antenna 2 over symbol time i+1

If code block length $T > m_t$

rotation begin length again on antenna 1.



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D- Blast → max capacity → wasted space/time neglected

complexity of Rx ↓

η Loss wasted space time dimension can be large

If the form size is not appropirately choosen