Chapter 10 Multiantenna Syatem

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10.1. Diversity –Introduction

- **In wireless communications, diversity techniques are based on the notion that errors occur in reception when the channel is in a deep fade.**
- **If we can supply to the receiver several replicas of the same information signal transmitted over independently fading channels , then there is a good likelihood that at least one of the received signals will not be severely degraded by fading . That is, the probability that all the signal components will fade simultaneously is reduced considerably.**

- **Space Diversity :**

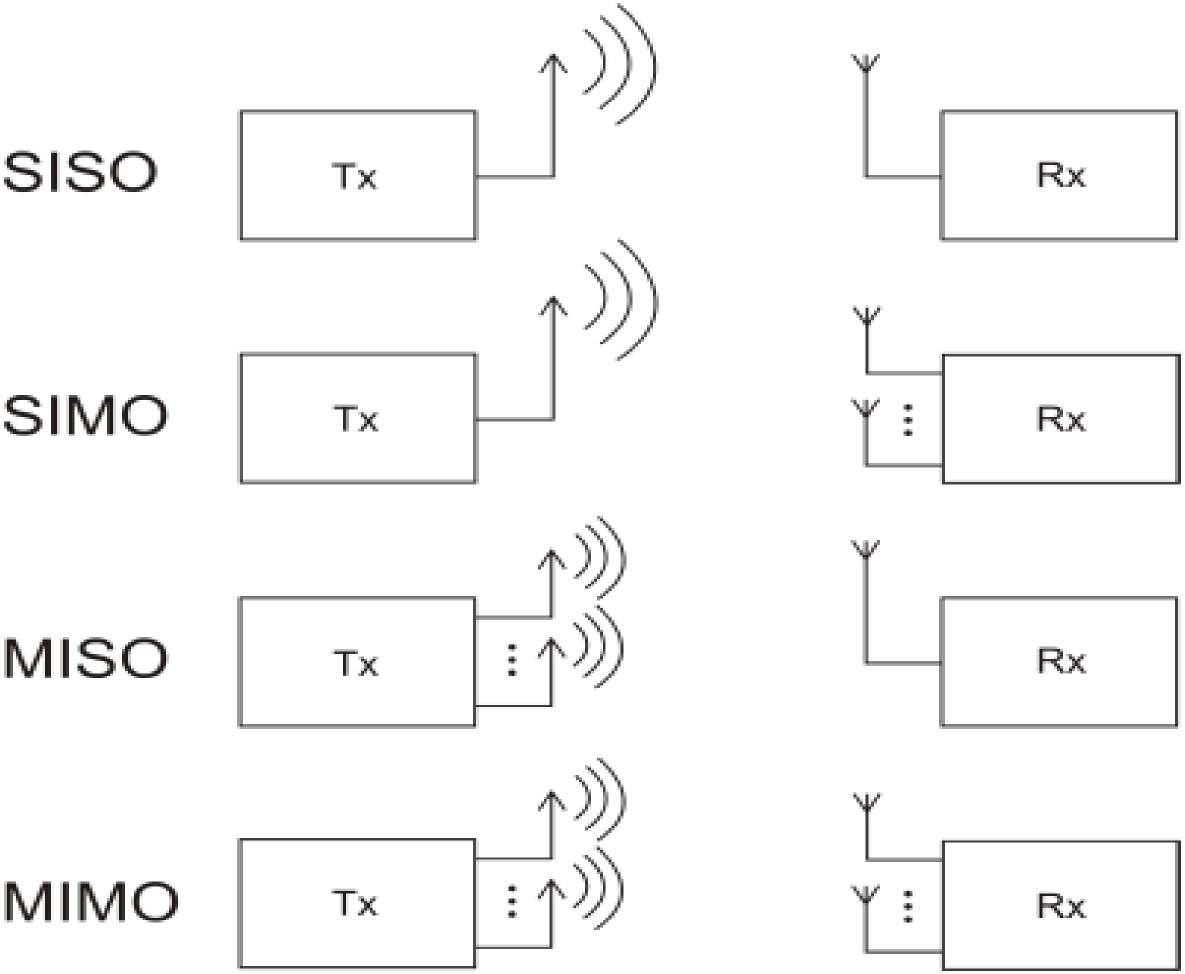
--- Multiple transmit or receive antennas, or both, are used , with the spacing between adjacent antennas being chosen so as to ensure the independence of possible fading events occurring in the channel.

--- Depending on which end of the wireless link is equipped with multiple antennas , we may identify three different forms of space diversity :

receive diversity, transmit diversity, and diversity on both transmit and receive.

--- To ensure independence, antennas at the mobile stations are separated half wavelength or more ; at base station , antenna spacing need to be several tens of wavelengths.

Fig.10.1 Multiantenna systems



- **MIMO :**

  --- A wireless channel using multiple antennas at both (transmit and receive) ends is commonly referred to as a *multiple-input multiple- output* (MIMO) channel , Fig.10.1 .

  --- Given fixed values of transmit power and channel bandwidth , MIMO technology offers a sophisticated approach to exchanging increased system complexity for boosting the channel capacity.

10.2. Space Diversity on Receive

(Receive Diversity)

- In “ space diversity on receive “ , multiple receiving antennas are used , with the spacing between adjacent antennas chosen so that their respective outputs are essentially independent of each other.
- The requirement may be satisfied by spacing the adjacent receiving antennas by as much as 10 to 20 radio wavelengths or less apart from each other.
- There are several methods of combining the outputs of these statistically independent fading channels in accordance with a criterion to provide improved receiver performance :

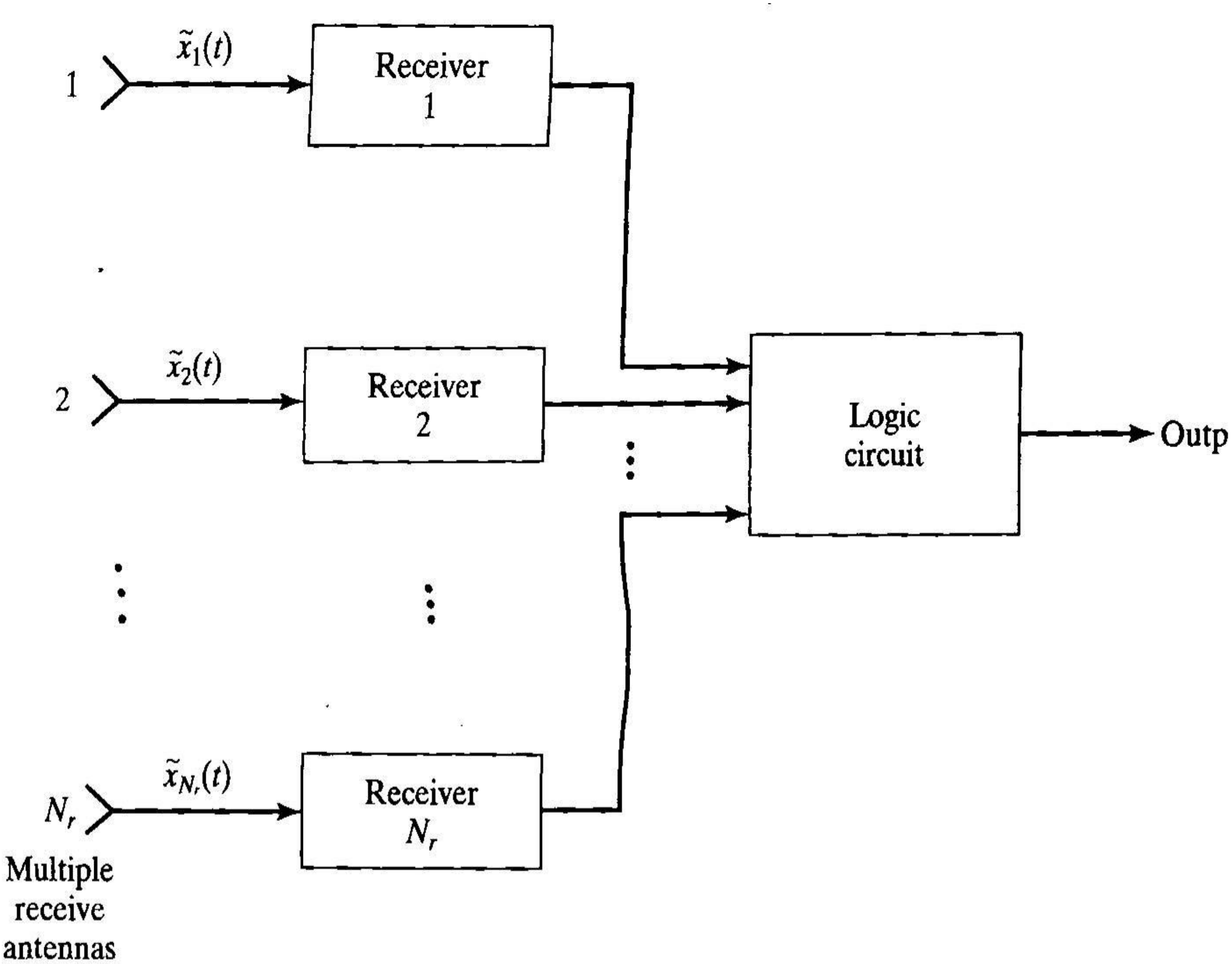
  selection combining, maximal-ratio combining ,

  equal-gain combining

10.2.1 Selection Combining (SC)

- Selection combining is the simplest type of combining. It simply estimates the instantaneous strengths of each of the N_r streams and selects the highest one, as shown in Fig.10.2 .
- The communication channel assumed is a frequency-flat, slowly fading Rayleigh channel.
- With SC, the path output from the combiner has an SNR equal to the maximum SNR of all the branches.
- Since only one branch output is used , co-phasing or multiple branches is not required ; this technique can be used with either coherent or differential modulation.

Fig.10.2 Selection Combiner



- Assuming that the wireless communication channel is described by a frequency-flat, slowly fading Rayleigh channel, let *s(t)* denote the complex envelope of the modulated signal transmitted during the symbol interval $0 \leq t \leq T$.
- Then the complex envelope of the received signal of the *k-th* diversity branch is defined by

$$x_k(t) = \alpha_k \exp(j\theta_k)\, s(t) + w_k(t)$$

$$0 \leq t \leq T,\ k = 1,2, \ldots N_r \qquad (10.1)$$

where w_k is additive channel noise. The fading is represented by the multiplicative term $\alpha_k \exp(j\theta_k)$.

- With the fading assumed to be slowly varying in the symbol duration T, we should be able to estimate and then remove the unknown phase shift $\exp(j\theta_k)$ at each diversity branch.

Eq.(6.1) can be simplified to

$$x_k(t) = \alpha_k\, s(t) + w_k \qquad (10.2)$$

$$0 \leq t \leq T,\ k = 1,2, \ldots N_r$$

- The instantaneous signal-to- noise ratio measured at the output of the *kth* receiver during the transmission of a given interval is expressed by

  $\gamma_k = (E_s / N_0) \alpha_k^2 \qquad k = 1,2, \ldots N_r \qquad (10.3)$

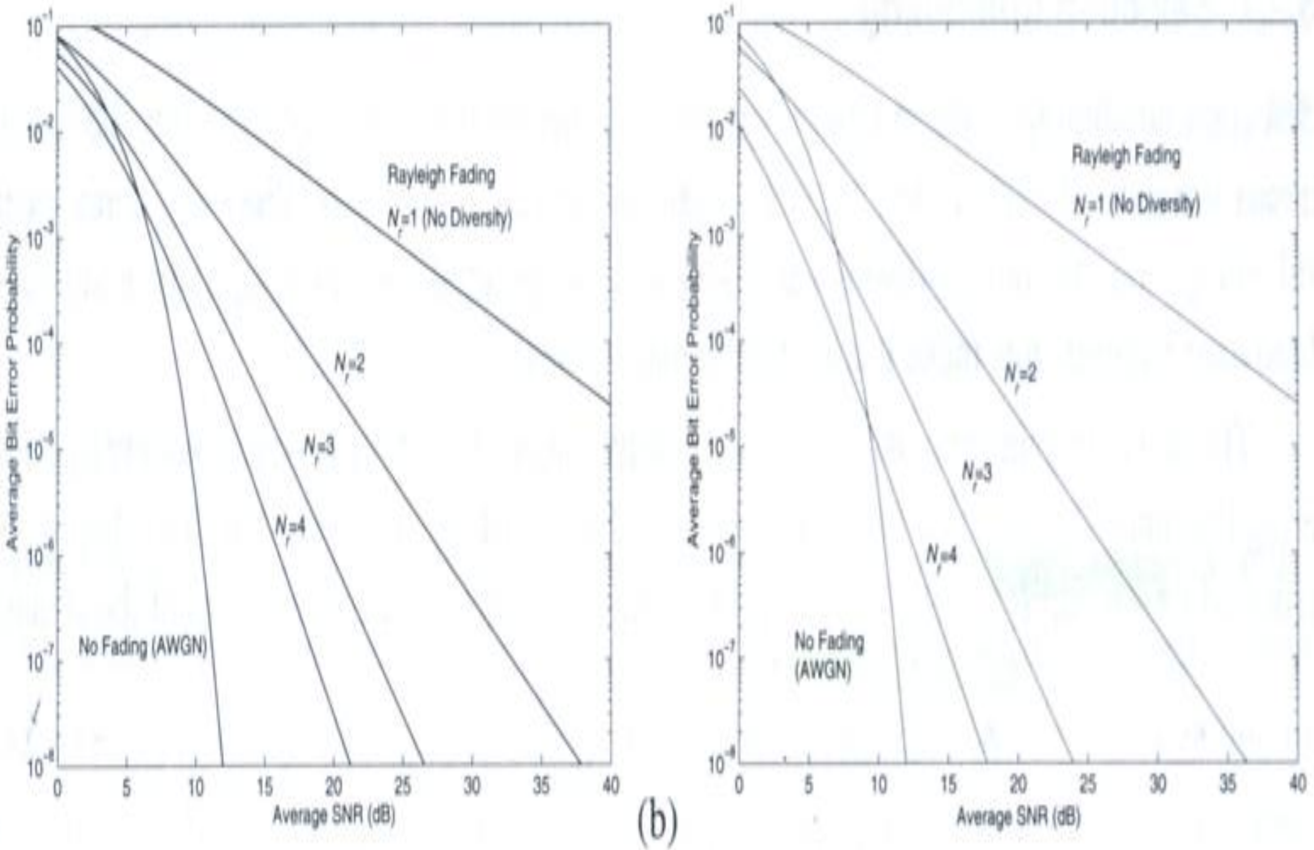
  where E_s *is the symbol energy ,* N_0 *is one-sided noise spectral density .*

  The SNR after selection diversity is

  $\gamma_{sc} = \max \{\gamma_1 , \gamma_2 , \ldots, \gamma_N \} \qquad (10.4)$

- The average bit error probability (BEP) can be derived by averaging (intergrating) the appropriate BEP expression in AWGN against the exponential distribution Fig.10.3(a) shows average bit error probability for several number of diversity branches of selection combining

Fig.10.3



(a) (b)

Figure 5.4 Average bit error probability for (a) selection combining and (b) maximal ratio combinings using coherent BPSK. Owing to its array gain, MRC typically achieves a few dB better SNR than does SC.

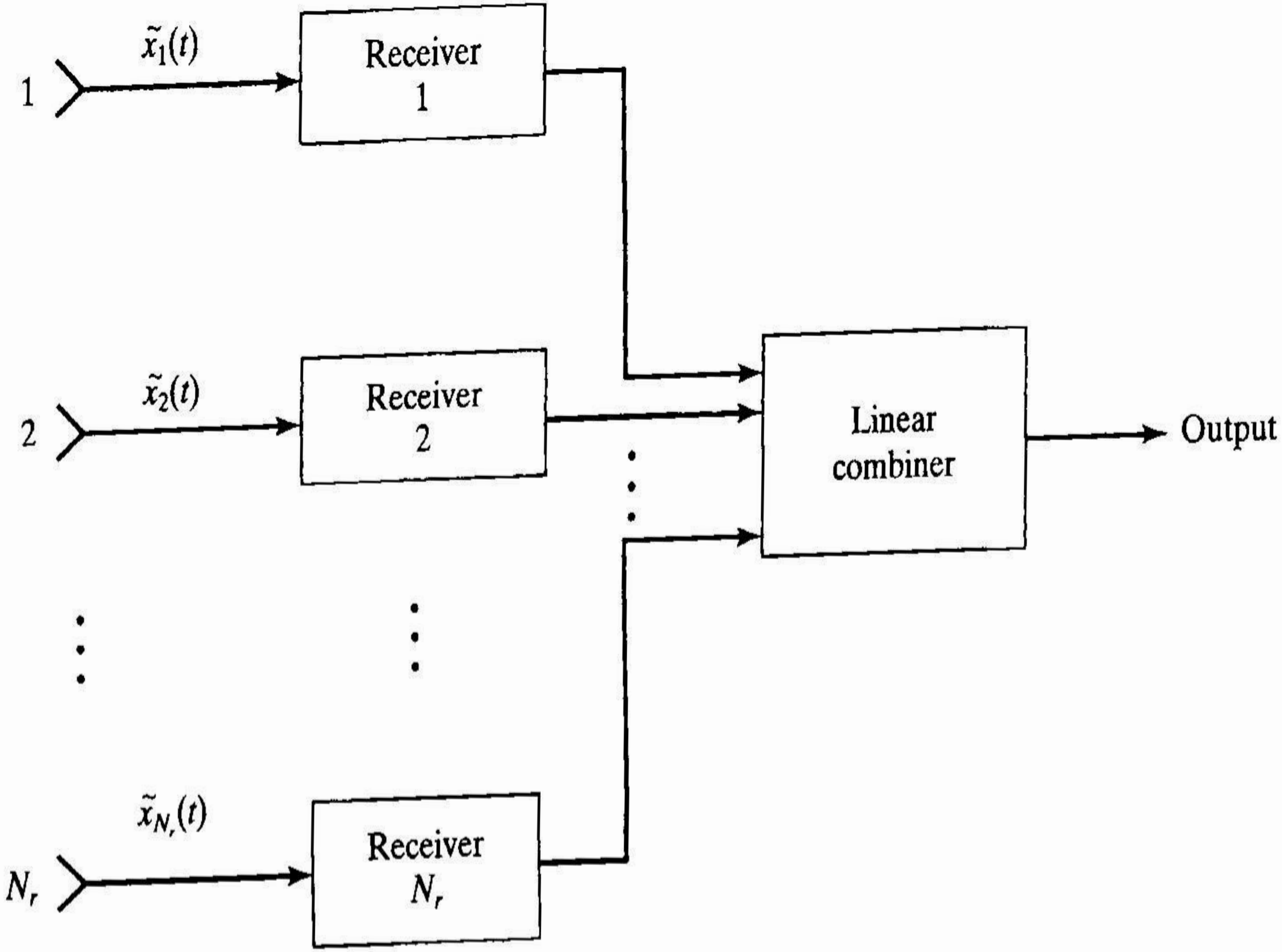
10.2.2 Maximal-Ratio Combining (MRC)

- The SC is relatively straightforward to implement. However, it is not optimum from a performance point of view because it ignores the information available from all the diversity branches except the particular branch that produces the largest instantaneous SNR .
- In maximal-ratio combining (MRC), the output is a weighted sum of all branches , as shown in Fig.10.4 .
- The maximal-ratio combiner consists of N_r linear receivers , followed by a linear combiner.
- The complex envelope of the linear combiner output is defined by

$$Y(t) = \Sigma\, a_k\, x_k\,(t) \qquad (10.5)$$

where a_k are complex weighting parameters that characterize the linear combiner.

Fig.10.4 Maximal-ratio combiner



- Let γ_c denote the instantaneous output signal-to-noise ratio of the linear combiner, the with some mathematical manipulations, we may write

$$\gamma_c = (E_s / N_0) \frac{\left| \Sigma a_k \alpha_k \exp(j \theta_k) \right|^2}{\Sigma \left| \alpha_k \right|^2} \qquad (10.6)$$

The requirement is to maximize γ_c with respect to the a_k .

- The instantaneous output SNR of MRC is found to be

$$\gamma_{mrc} = (E_s / N_0) \Sigma \alpha_k^2 = \Sigma \gamma_k \qquad (10.7)$$

with the optimal weighting factor a_k given by

$$a_k = c \, \alpha_k \exp(-j \theta_k) \qquad (10.8)$$

- Hence, the maximal-ratio combiner produces an instantaneous output SNR that is the sum of the instantaneous SNR of the individual branches.
- Fig.10.3 (b)plots the average bit error probability of the maximal-ratio combiner with the N_r as a running parameter.
- Significant instrumentation is needed to adjust the complex weighting parameters of the MRC to their exact values , in accordance with Eq. (10.8) .
- Diversity gain :

  The diversity gain , defined as the saving in E/N_0 at a given bit error rate, provides a measure of the effectiveness of a diversity technique on an outage probability basis.

10.2.3 Equal Gain Combining

- Equal- Gain combining (EGC), which corrects only the phase and assumes equal gain of each branch, i.e. ,

  $a_k = \quad c \exp(-j\,\theta_k) = 1/\sqrt{N_r}\exp(-j\,\theta_k) \qquad \text{for all } k$

  Then the instantaneous SNR is given by

  $$\gamma_{EGC} = (1/N_r)\,(E_s/N_0)\,\left|\,\Sigma\,\alpha_k\,\right|^2 \qquad (10.9)$$

  where α_k is the fading factor of *k-th* branch .

- EGC scheme is useful for modulation techniques having equal energy symbol , e.g., MPSK.
- For an interference-limited cellular system , such as WiMAX , MRC would be strongly preferred to either EGC or SC , despite the fact that the latter techniques are somewhat simpler.

10.3 Transmit Diversity and Alamouti Code

10.3.1 Transmit Diversity

- **Transmit diversity is a newer phenomenon than receive diversity and has become widely implemented only in the early 2000s.**
- **Because the signals sent from different transmit antennas interfere with one another , processing is required at both the transmitter and the receiver in order to achieve diversity while removing or at least attenuating the spatial interference.**
- **Transmit diversity is particularly attractive for the down link of infrastructure-base systems such as WiMAX , since it shifts the burden for multiple antennas to the transmitter , which in this case is a base station , thus greatly benefiting mobile stations that have severe power, size , and cost constraints.**

- Transmit diversity can be categorized as either open loop or closed loop.
- Open- loop systems do not require knowledge of the channel at the transmitter.
- On the contrary, closed-loop systems require channel knowledge at the transmitter , thus necessitating either channel reciprocity ,i.e. same uplink and downlink channel possible in TDD , or more commonly a feedback channel from the receiver to the transmitter.
- The most popular open-loop transmit diversity scheme is space-time coding , whereby a code known to the receiver is applied at the transmitter.
- Space-time coding was first suggested in the early 1990s before generating intense interest in the late 1990s.

- Of many types of space-time cods , we focus only on space-time block codes (STBCs), which lends themselves to easy implementation and are defined for transmit diversity in WiMAX systems.

10.3.2 Alamouti Codes

- The **Alamouti code,** after its inventor , is a two-by-one orthogonal block code . It uses two transmit antennas and a single receive antenna , as shown in Fig. 10.5.
- Let s_1 and s_2 denote the baseband equivalent complex signal to be transmitted over the wireless channel.
- Signal transmission over the channel proceeds as follows :

1. **At some arbitrary time t, antenna 1 transmits s_1, antenna 2 transmits s_2 .**
2. **At time $t + T$, where T is the symbol duration , signal transmission is switched , with $-s_2^*$ transmitted by antenna 1 and s_1^* simultaneously transmitted by antenna 2 .**

- **The two-by-two space-time block code is formally written in matrix form as**

$$S = \begin{matrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{matrix} \tag{10.10}$$

- **The transmission matrix S is a complex-orthogonal matrix , in that it satisfies the condition**

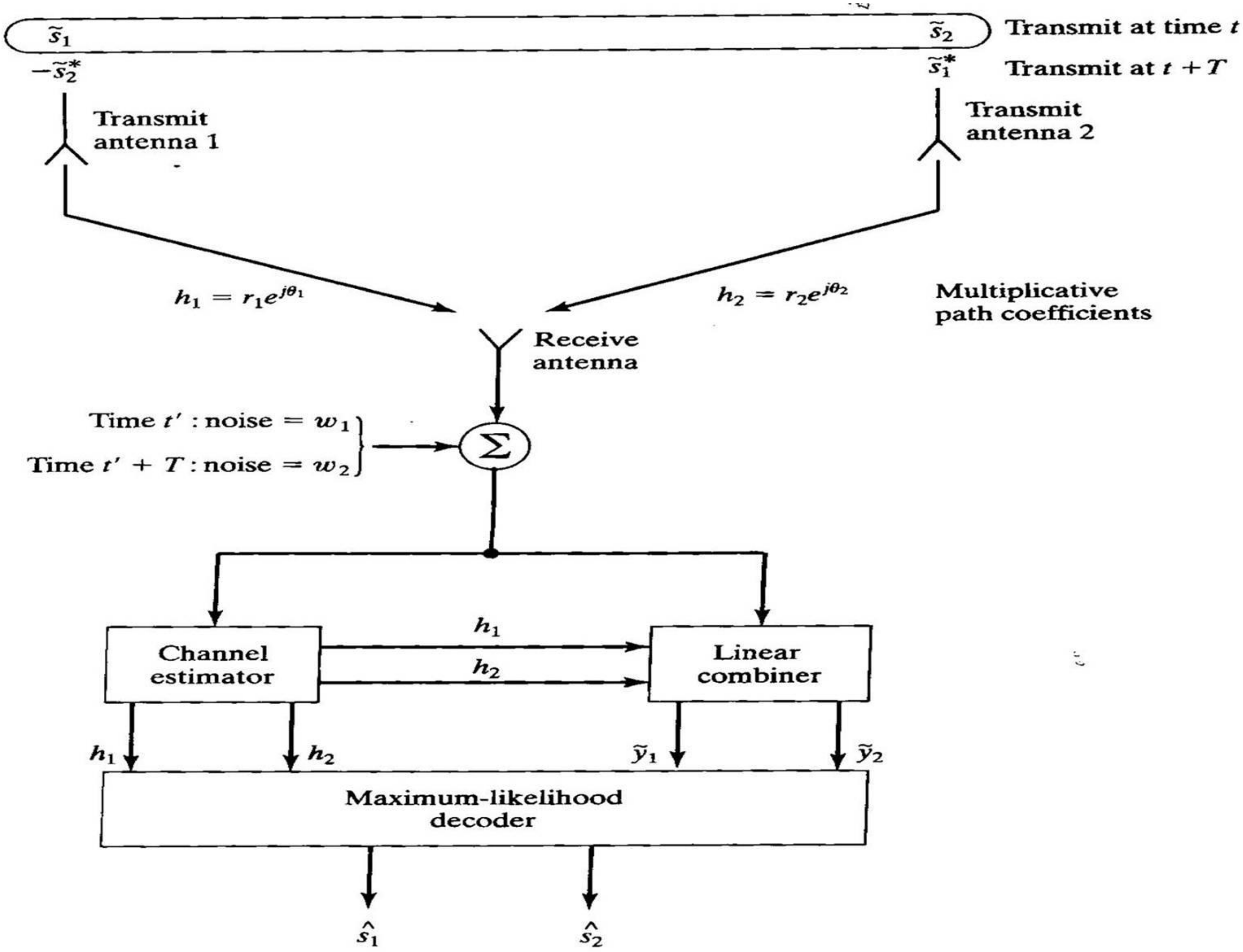
  for orthogonality in spatial and temporal sense.

- Note :

Orthogonal matrices are matrices whose columns constitute a set of orthonormal vectors.

If A is an orthogonal matrix then $AA^+ = A^+A = I$

Fig. 10.5 Transceiver for the Alamouti code



- Assuming a flat fading channel, $h_1(t)$ is the complex channel gain from antenna 1 to the receive antenna , and $h_2(t)$ is from antenna 2 .

An additional assumption is that the channel is constant over two symbol times, or equivalently,

$f_D T << 1$. The complex multiplicative distortion introduced by the channel is denoted by $\alpha_k e^{j\theta}$, where $k = 1,2$

- The received signal can be written as

$$x_1 = \alpha_1 e^{j\theta} s_1 + \alpha_2 e^{j\theta} s_2 + w_1 \quad \text{at time } t$$

and $$x_2 = -\alpha_1 e^{j\theta} s_2^* + \alpha_2 e^{j\theta} s_1^* + w_2 \quad \text{at time } t+T$$

- **If the linear combiner in Fig.10.5 can be expressed by the weighting matrix , assuming that the channel is known at the receiver :**

$$\begin{matrix} \alpha_1 e^{-j\theta} & \alpha_2 e^{j\theta} \\ \alpha_2 e^{-j\theta} & -\alpha_1 e^{j\theta} \end{matrix}$$

The two complex outputs computed by the linear combiner in terms of x_1 and x_2 are expressed as

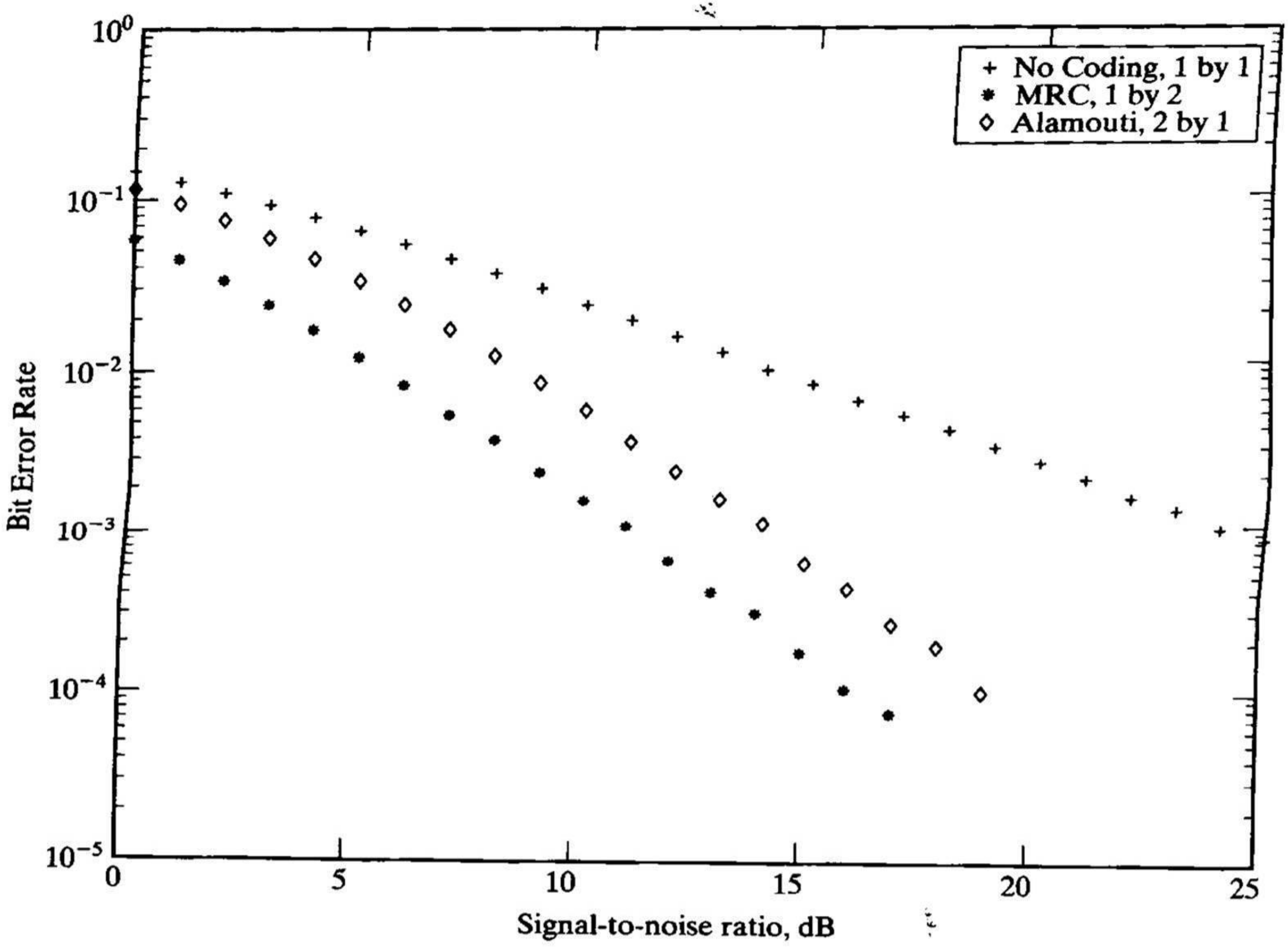
$$\begin{matrix} y_1 \\ y_2 \end{matrix} = \begin{matrix} \alpha_1 e^{-j\theta} & \alpha_2 e^{j\theta} \\ \alpha_2 e^{-j\theta} & -\alpha_1 e^{j\theta} \end{matrix} \begin{matrix} x_1 \\ x_2 \end{matrix} \qquad (10.11)$$

- **The resulting SNR at the detector output is given by**

$$\gamma = (\alpha_1^{\,2} + \alpha_2^{\,2})\, E_s \,/\, 2\sigma^2 \qquad (10.12)$$

- **We can see that the gain in SNR of the Alamouti code system is similar to the gain from MRC .**
- **However, in order to keep the transmit power the same in the MRC case , each transmit antenna must halve its transmit power so that the total energy per actual data symbol is E_s for both cases.**
- **Fig.10.6 presents a computer simulation comparing the bit error rate performance of coherent BPSK over an uncorrelated Rayleigh-fading channel for different schemes : no diversity, MRC (receiver diversity with 2 receive antennas) , Alamouti code.**

Fig. 10.6 BER performance of BPSK over flat fading Rayleigh channel for (a) no diversity (b) MRC (c) Alamouti code



10.4. Space-Division Multiple Access (SDMA)

- In cellular systems, a few channels are broadcast by the base station or shared by all users on the uplink. The majority of the traffic –bearing channels are point-to-point , between a base station and a single user terminal, In which case the communications is directional in nature.
- The recognition that user terminals can be spatially separated by virtue of their angular directions is the basis of space-division multiple access (SDMA), a technique that relies on the use of directional antennas to distinguish among users.

Fig.10.7 Space-division multiple access

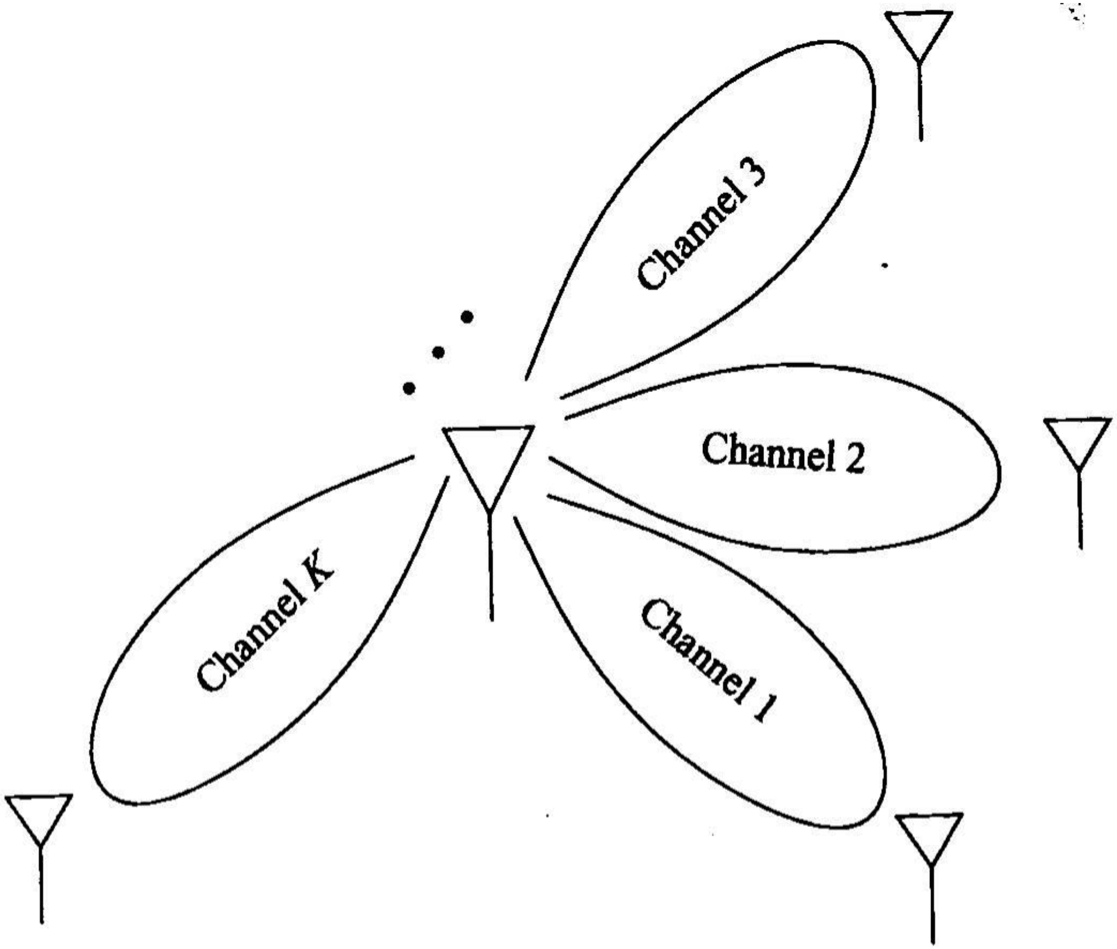
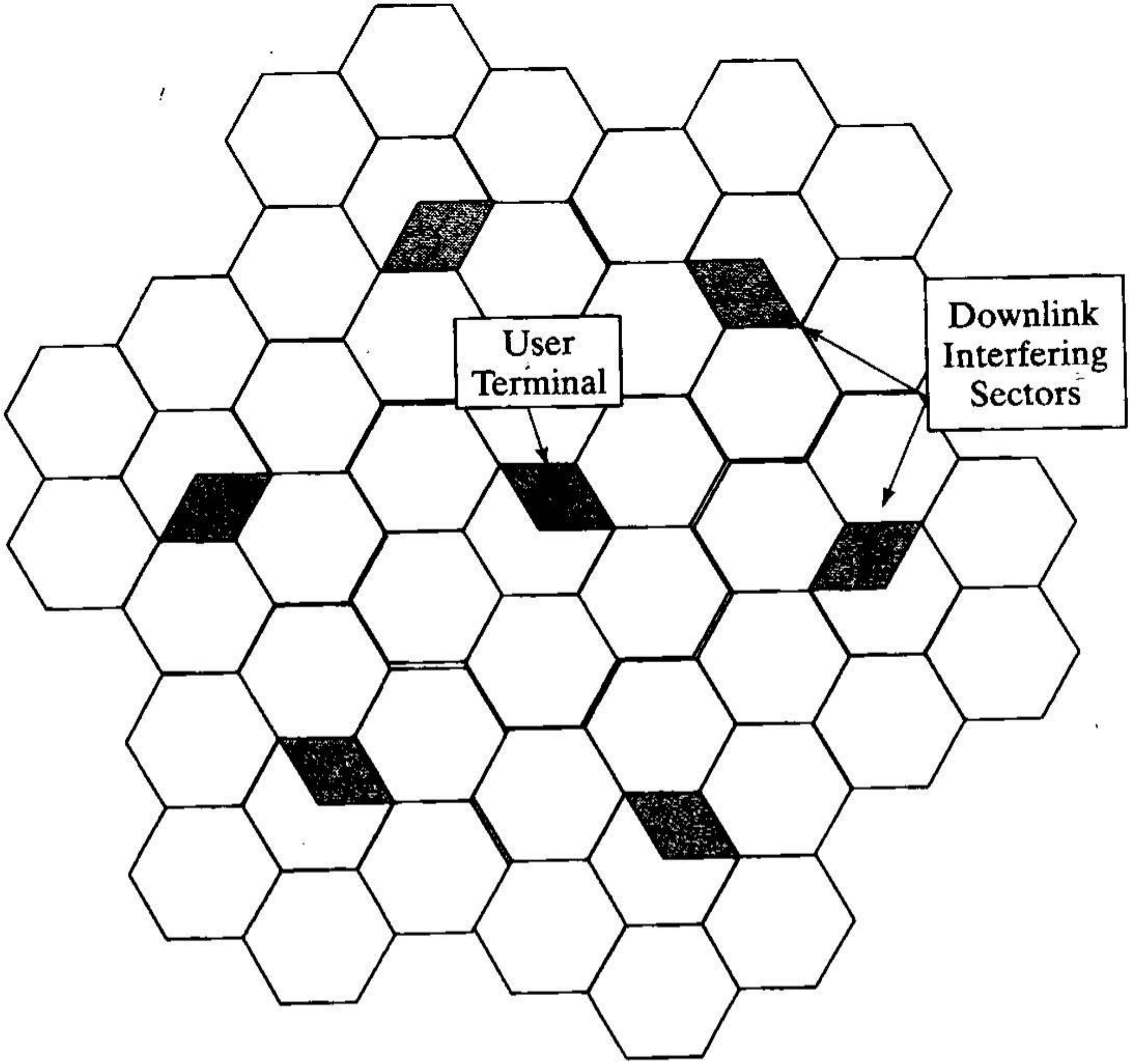


Fig.10.8 Cellular system with 120° sector antenna.



- Fig.10.8 shows a base station in a cellular system with sector antennas. Each antenna covers one sector---- in this case, 120° ---- of the cell.
- To close the communications link, $P_T G_T$ must be the same whether the antenna is directional or omnidirectional. Consequently, the total power radiated with a sector antenna is *1/3* of that produced by an omnidirectional antenna.

  Furthermore, a user terminal receiver suffers only *1/3* of the interference that would be produced by omnidirectional base-station antennas with the same number of users.
- In the uplink, all users terminals have omnidirectional antennas , but only *1/3* of them are in the field of view of the base-station antenna. So the interference is reduced by *1/3* in this direction as well.

- Thus , we can conclude that the number of user terminals can be tripled relative to the omnidirectional case and still maintain the same interference level.
- SDMA relies on smart antennas, in the sense that it takes advantage of the directional nature of radio communications.
- Some examples of smart antennas are :

--- sector antenna

--- switched beam antennas

--- adaptive antenna

■ SDMA improves system capacity by allowing greater spectrum reuse through

(1) minimizing of the effects of interference and

(2) increasing signal strength for both the user terminal and the base station.

Chapter 10-2

Multiantenna Systems

10.5 MIMO Antenna System

10.5.1 Coantenna Interference

10.5.2 Basic Baseband Channel Model

10.5.3 MIMO Classifications

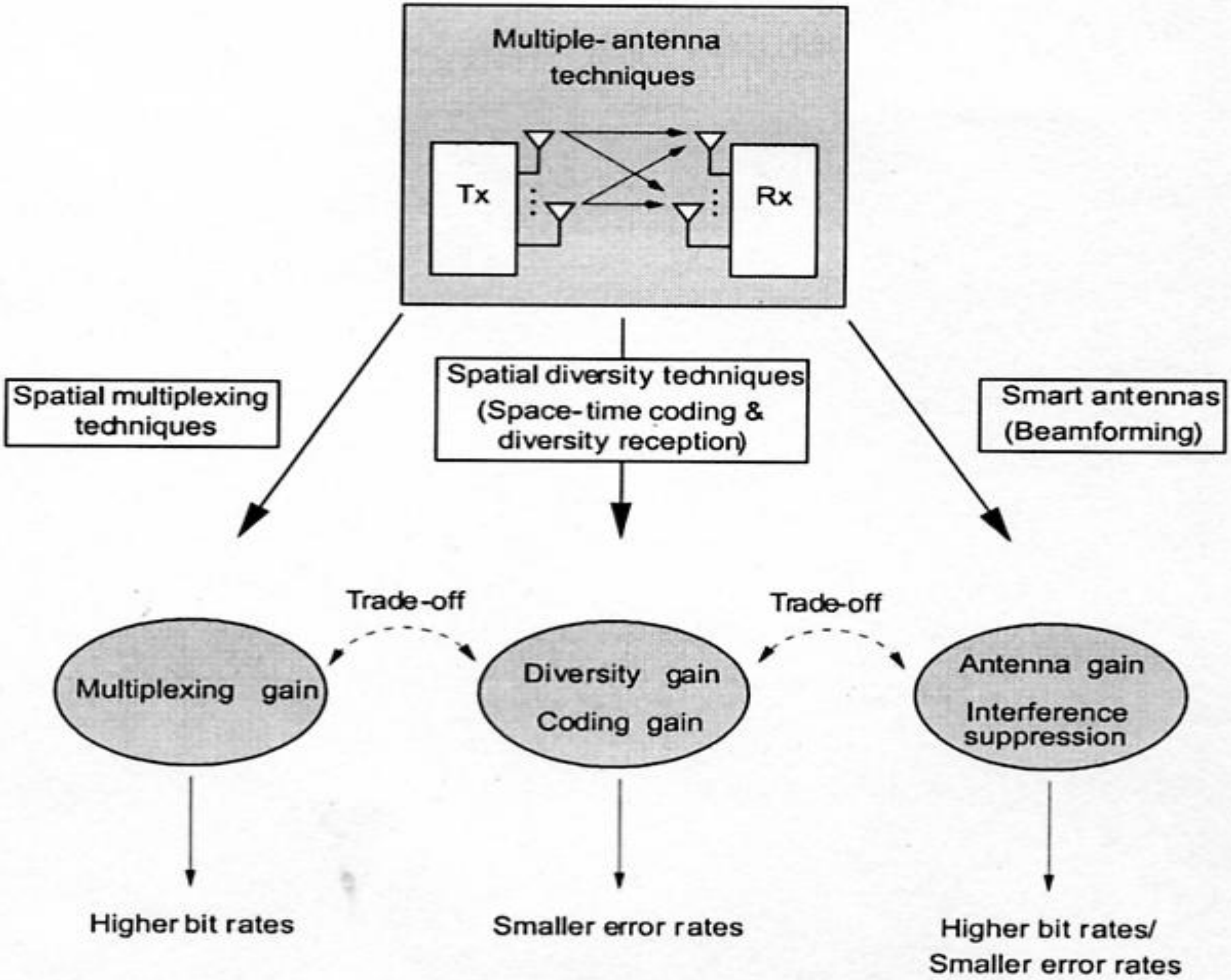
References

1. **S.Haykin , Modern Wireless Communications, Chapter 6.**
2. **J.G. Andrews et al , Fundamentals of WiMAX , Chapter 5.**

10.5 MIMO Antenna Systems

Introduction :

- In wireless communication systems with single transmit antenna , fading is treated as a source that degrades performance . Space- diversity employing multiple receive antennas can be used to mitigate the multipath fading problem.
- In MIMO system, the fading phenomenon is viewed as an environmental source of possible enrichment.
- Space diversity at both the transmit and receive ends of the wireless link provides the basis for increasing the channel capacity or spectral efficiency at the cost of increasing computational complexity.
- MIMO wireless communications include space-diversity on receive as a special case.


Multiple- antenna techniques
Tx
Rx
Spatial multiplexing techniques
Spatial diversity techniques (Space-time coding & diversity reception)
Smart antennas (Beamforming)
Trade-off
Trade-off
Multiplexing gain
Diversity gain
Coding gain
Antenna gain
Interference suppression
Higher bit rates
Smaller error rates
Higher bit rates/ Smaller error rates

Spatial Gain :

(a) Array gain ---

Array gain is defined as the average increase in SNR , typically linear with number of antennas irrespective of channel correlation. The signals are coherently combined to improved the signal strength. Note that even if the channel are correlated (line-of-sight) the array gain is still present and SNR increases linearly. Also , linear increase in SNR also increases the capacity according to Shannon's formula

$C = \log_2 (1 + SNR)$ bps / Hz .

(b) Diversity gain ---

Diversity gain is defined as the reduction in the error probability due to multiple independent (uncorrelated) paths created between the transmitter and receiver . In other words , if there are *M* transmit and *N* receive antennas , the diversity order is *M.N* , and the error probability improves proportionally with approximately $(S/N)^{-M.N}$.

(c) Multiplexing gain ---

Multiplexing gain is defined as the increase in the data rate , since independent paths between multiple transmitters and multiple receivers may be utilized to send independent data streams. If there are *M* transmit antennas and *N* receive antennas , the increase in the data rate is min (*M,N*)-fold .

10.5.1 Coantenna Interference

- Fig. 10.9 shows the block diagram of a MIMO wireless link . The signal transmitted by the N_t transmit antennas over the wireless channel are all chosen to lie inside a common frequency band.
- Due to multiple signal transmissions , the system experiences a spatial form of signal-dependent interference referred to as coantenna interference (CAI) .
- The challenge for the receiver is how to mitigate the CAI problem and thereby make it possible to provide a spectacular increase in spectral efficiency.

Fig.10.9

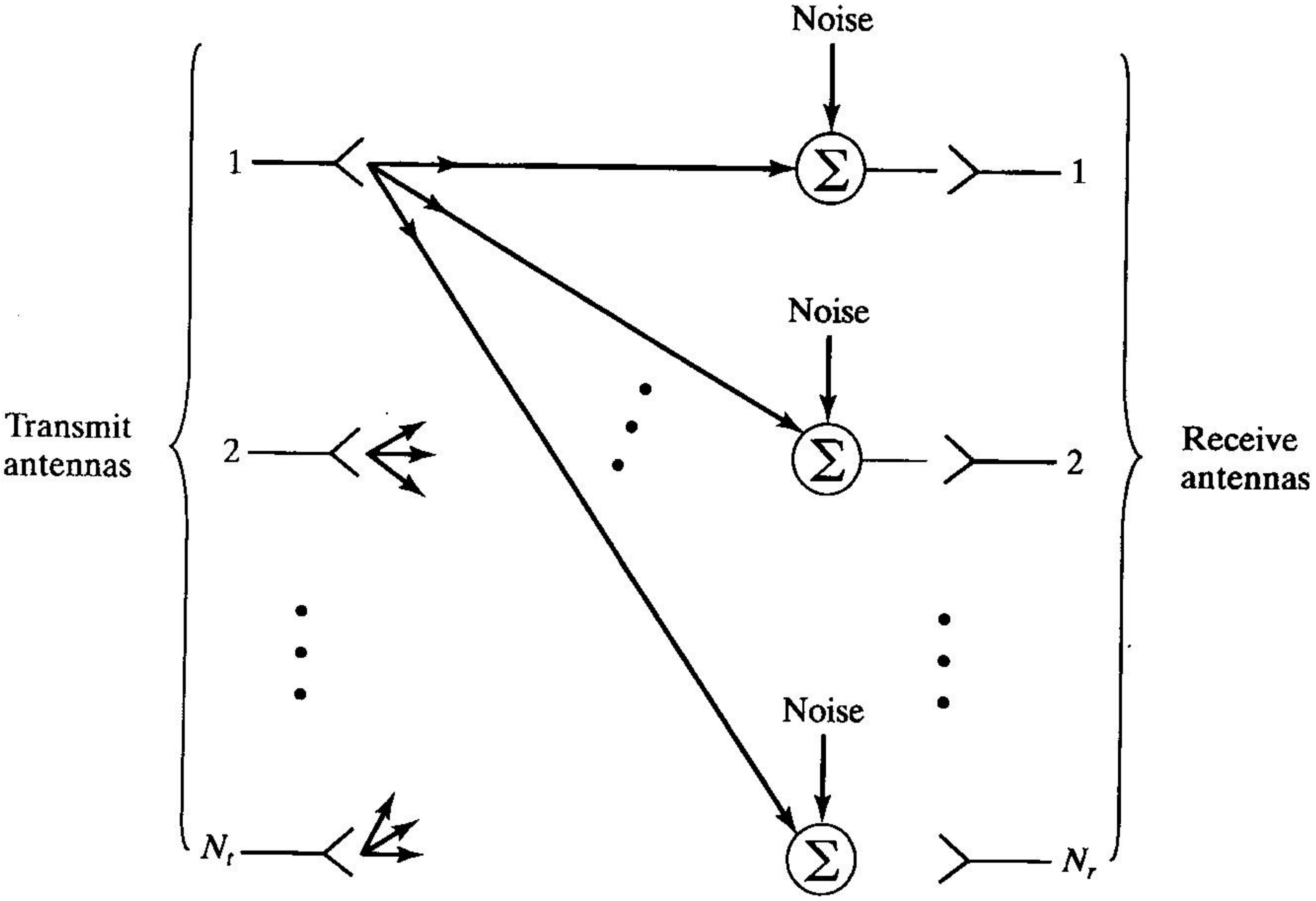


FIGURE 6.10 Block diagram of MIMO wireless link with N_t transmit antennas and N_r receive antennas.

10.5.2 Basic Baseband Channel Model

- **Consider a MIMO narrowband wireless communication system built around a flat-fading channel and with N_t transmit antennas and N_r receive antennas.**
- **The antenna configuration is hereafter referred to as the pair (N_t , N_r) . In the following ,we use baseband representation of the transmitted and received signals as well as of the channel.**
- **Notations :**

a. Spatial parameter N_{min} = mini {N_t , N_r} defines a new degree of freedom introduced into the (N_t , N_r) MIMO wireless communication system.

b. The N_t –by- 1 vector $s(n) = [\, s_1(n), s_2(n),\ldots,S_{Nt}\,(n)\,]^T$ denotes the complex signal vector transmitted by the N_t antennas at discrete time n.

The symbols constituting the vector $s(n)$ are assumed to have zero mean and common variance $\sigma_s^{\,2}$. The total transmit power is fixed at the value $P = N_t\,\sigma_s^{\,2}$.

c . For the flat fading, and therefore memoryless, channel, we may use $h_{ik}(n)$ to denote the sampled complex gain of the channel from transmit antenna k to receive antenna i at discrete time n, where $k = 1,2,\ldots, N_t$ and $i = 1,2,\ldots, N_r$.

Thus we may express the N_r–by- N_t complex channel matrix as

$$H(n)= \begin{array}{cccc} h_{11}(n) & h_{21}(n) & \ldots & h_{1\,Nt}(n) \\ h_{21}(n) & h_{22}(n) & \ldots & h_{2Nt}(n) \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ h_{Nr1}(n) & h_{Nr2}(n) & \ldots & h_{Nr\,Nt}(n) \end{array}$$

(10.13)

- **The system of equations**

$$x_i(n) = \Sigma \ h_{ik}(n)\, s_k(n) + w_i(n) \qquad (10.14)$$

defines the complex signal received at the *i-th* antenna due to the transmitted symbol $s_k(n)$ radiated by the *k-th* antenna . The term $w_i(n)$ denotes the additive complex channel noise perturbing $x_i(n)$.

- **Let $\mathbf{x}(n) = [\, x_1(n), x_2(n) \ldots, x_N(n)\,]^T$**

and $\mathbf{w}(n) = [w_1(n), w_2(n) \ldots\ w_N(n)\,]^T$

Then ,we have the compact matrix form of the basic complex channel model for MIMO wireless communications

$$\mathbf{x}(n) = H(n)\, s(n) + W(n) \qquad (10.15)$$

- **We assume a Gaussian model made of three elements relating the transmitter, channel, and receiver, respectively :**

1.The correlation matrix of the transmitted signal vector s is defined by

$$R_s = \mathrm{E}\,[\,s\,s^{+}\,] = \sigma_s^{2}\ \mathrm{I}_N$$

where I_N is the N_t - by- N_t identity matrix .

2. The elements of H are i.i.d. complex random variables with zero mean and unit variance .

$$h_{ik} = N\,(0,\ 1/\surd 2\,) + j\,N\,(0,\ 1/\surd 2\,)$$

where *N (…)* denotes a real Gaussian distribution *.*

The Amplitude component h_{ik} is Rayleigh distributed , and the squared amplitude component, $|\ h_{ik}\ |^{2}$ is a chi-square random variable with unity mean .

3. The elements of the channel noise vector w are i.i.d. Complex Gaussian random variables with zero mean and common variance σ_w^2 . The correlation matrix of the noise vector w is given by $R_w = E[\, w\, w{+}\,] = \sigma_w^2 \; I_N$.

- The average signal-to-noise ratio (SNR) at each receiver input is given by

$$\rho = P \,/\, \sigma_w^2$$

$$= N_t\, \sigma_s^2 \,/\, \sigma_w^2 \qquad (10.16)$$

- This idealized Gaussian model is applicable to indoor local area network and other wireless environments where the mobility of the user terminals are limited .

10.5.3 MIMO Classifications

- **MIMO configuration can be classified as ‘open loop “ or “closed loop “ .**

  The WiMAX standard includes two versions of Open Loop MIMO techniques referred to as Matrix and Matrix B.

  Closed Loop MIMO techniques ,as shown in Fig.10.10, also known as Transmitter Adaptive Antenna techniques.

- **With open loop MIMO , the communications channel does not utilize explicit information regarding the propagation channel.**

Fig.10.10

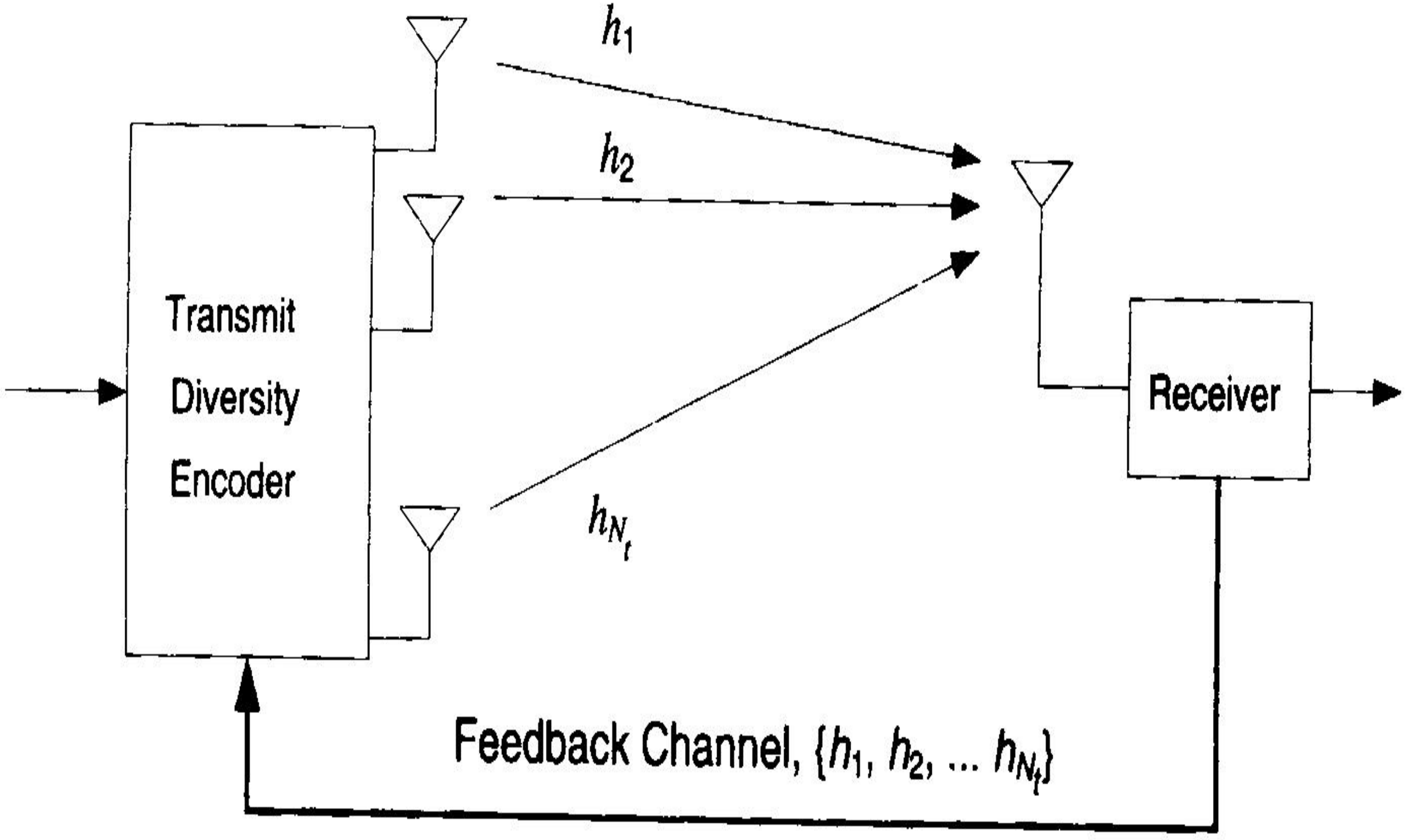


Figure 5.8 Closed-loop transmit diversity

Andrews et al

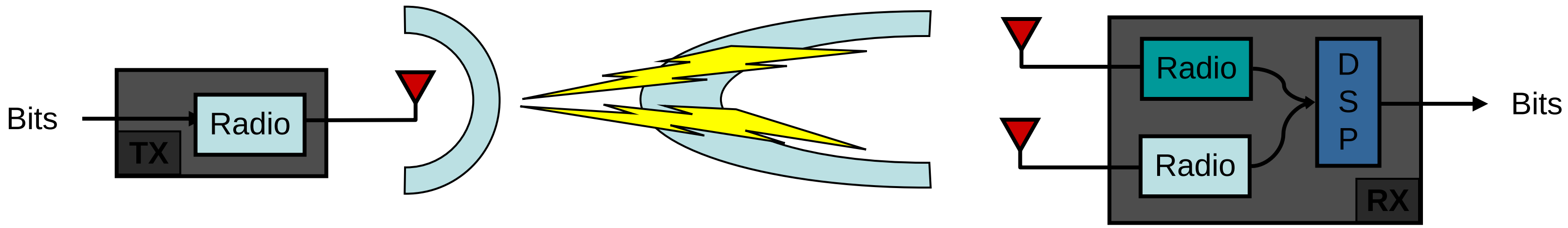
- **Common open loop MIMO techniques include space-time block coding (STBC) , spatial multiplexing (SM-MIMO) .**
- **In WiMAX systems , MIMO Matrix *A* refers to the STBC technique and MIMO Matrix *B* refers to the SM-MIMO.**
- **In IEEE 802.16-2004 OFDM-256 , the Alamouti code is applied to a specific subcarrier index k.**
- **Beamforming : A closed loop MIMO**

  With closed loop MIMO , the transmitter collects information regarding the channel to optimize communications to the intended receiver.

Beamforming MIMO Overview

Uses multiple transmit and/or receive radios to form coherent signals

- **Receive beamforming / combining** boosts reception of standard 802.11 signals



- Phased array **transmit beamforming to focus energy to each receiver**