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Internal Assessment Test 2 – April. 2019

Sub:	Wireless Cellular and LTE 4G Broadband					Sub Code:	15EC81	Branch:	ECE
Date:	15/04/2019	Duration:	90 min's	Max Marks:	50	Sem / Sec:	VIII A,B,C & D		OBE

<u>Answer any FIVE FULL Questions</u>

	MARKS	CO	RBT
1. Explain the key steps in OFDM communication system with the help of block diagram.	[10]	CO1	L1
2. What is meant by PAR? Derive the equation for analog and discrete representation of PAR. Explain any one method for the reduction of PAR.	[10]	CO1	L2
3. Illustrate the use of Cyclic Prefix in OFDM and derive the formula for rate loss	[10]	CO1	L3
4. Describe the principle of OFDMA in LTE Downlink with relevant block diagrams	[10]	CO1	L2
5. Show that the received SNR increase linearly with the number of receiver antennas in the concept of Spatial Diversity.	[10]	CO1	L3
6. Distinguish between Selection combining and maximal ratio combining in terms of average received SNR.	[10]	CO1	L2
7. Analyze Open-Loop Transmit diversity with the help of 2x2 SFBC, 4X2 Stacked STBCs and 4X2 in LTE.	[10]	CO1	L4

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Scheme Of Evaluation

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Note: Answer Any Five Questions

Question #	Description	Marks Distribution	Max Marks
1	**Explain the key steps in OFDM communication system with the help of block diagram.** • Block Diagram • Explanation • OFDM in LTE	4 M 4 M 2 M	10 M
2	**What is meant by PAR? Derive the equation for analog and discrete representation of PAR. Explain any one method for the reduction of PAR.** • Definition of PAR • Equations of PAR • Method for reduction of PAR	2 M 5 M 3 M	10 M
3	**Illustrate the use of Cyclic Prefix in OFDM and derive the formula for rate loss** • Cyclic Prefix added Input diagram • Explanation with equations • Formula for Rate Loss	2 M 6 M 2 M	10 M
4	**Describe the principle of OFDMA in LTE Downlink with relevant block diagrams** • Block Diagram • Explanation	4 M 6 M	10 M
5	**Show that the received SNR increase linearly with the number of receiver antennas in the concept of Spatial Diversity.** • Explanation of	2 M 6 M	10 M

		Array Gain • Equations for Array Gain • Performance Graph	2 M	
6		**Distinguish between Selection combining and maximal ratio combining in terms of average received SNR.** • Selection Combining • Maximal Ratio Combining	5 M 5 M	10 M
7		**Analyze Open-Loop Transmit diversity with the help of 2x2 SFBC, 4X2 Stacked STBCs and 4X2 in LTE.** • **Explanation of 2x2 SFBC with equations** • **Explanation of 4x2 stacked STBC with equations** • **Explanation of 4x2 in LTE**	3 M 4 M 3 M	10 M

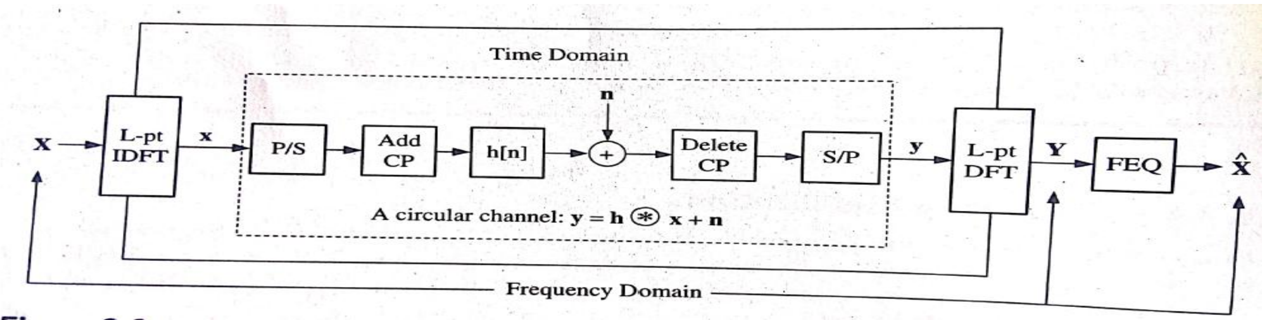
1. Explain the key steps in OFDM communication system with the help of block diagram. – 10 Marks

OFDM Block Diagram

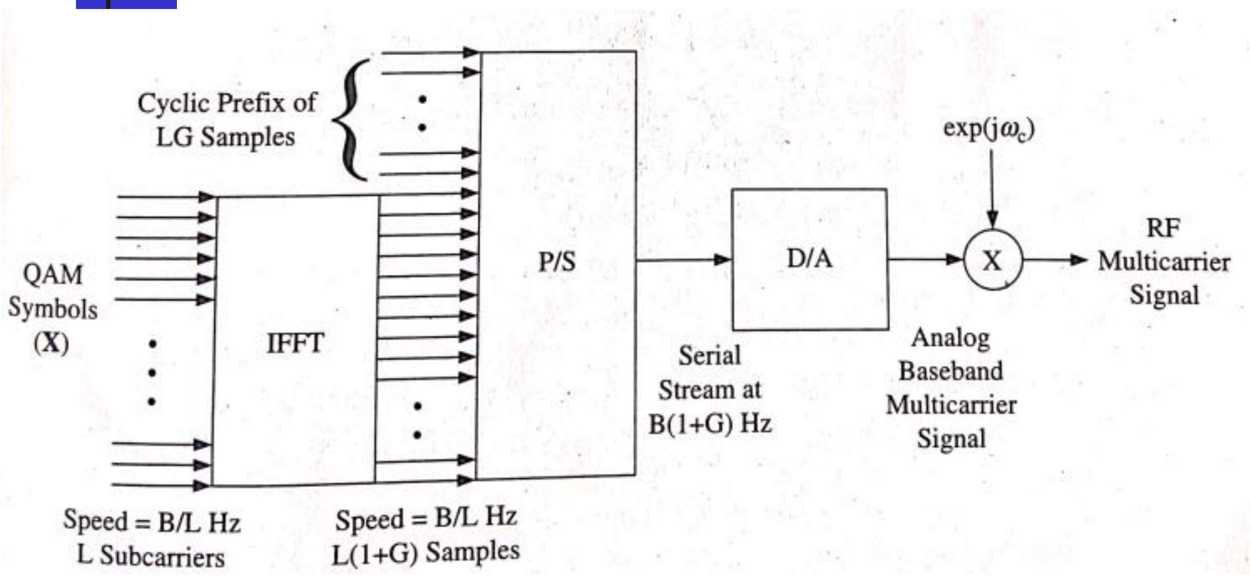
- 1^{st} step in OFDM is to break a wideband signal of BW ***B*** into ***L*** narrowband signals (subcarriers)each of BW ***B/L***.
- **Symbol rate is maintained** but each subcarrier experiences flat fading or ISI free communication – as long as ***cyclic prefix >> delay spread*** is used.
- The ***L*** subcarriers for a given OFDM symbol are represented by a vector ***X***, which contains the ***L*** current symbols.
- To use a single wideband radio instead of ***L*** independent narrow band radios, the subcarriers are created digitally using an IFFT operation.
- In order for the IFFT/FFT to decompose the ISI channel into orthogonal subcarriers, a cyclic prefix of length ***v*** must be appended after the IFFT operation.

OFDM Block Diagram

- ***L+v*** symbols are sent **serially** through the **wideband channel.**
- At the RX the cyclic prefix is discarded and the ***L*** received symbols are demodulated using FFT operation - giving ***L*** data symbols, each of the form $Y_\ell = H_\ell X_\ell + N_\ell$ for subcarrier ℓ
- Each subcarrier is equalized by FEQ – by dividing by H_ℓ
- Result is $\mathbf{X}_\ell = X_\ell + N_\ell / H_\ell$.



OFDM in LTE



3.3 - OFDM in LTE

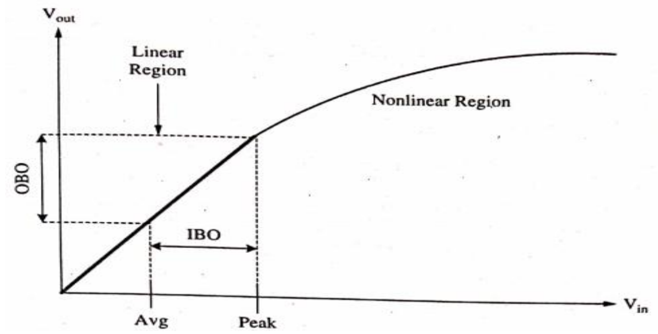
- Inputs are ***L*** independent QAM symbols (vector X), these ***L*** symbols are treated as separate subcarriers.
- These ***L*** data-bearing symbols can be created from a bit stream by a ***symbol mapper*** and ***serial-to-parallel converter***.
- ***L*** point IFFT then creates a time domain ***L***-vector ***X*** that is cyclic extended to have a length ***L(1+G)***, G- fractional overhead. G = 0.07 - normal cyclic prefix, G = 0.25 -extended cyclic prefix.
- This vector is then parallel-to-serial converted into a wideband digital signal, that can be amplitude modulated at a carrier frequency ***Wc/2π.***
- **Data rate** of LTE system with 16QAM

$$R = \frac{B}{L}\frac{L_d \log_2(M)}{1+G} = \frac{10^7\text{MHz}}{1024}\frac{600\log_2(16)}{1.07} = 21.9\text{ Mbps.}$$

2. What is meant by PAR? Derive the equation for analog and discrete representation of PAR. Explain any one method for the reduction of PAR. – 10 Marks

- OFDM signals have high PAR – peak-to-average power ratio (PAPR).
- Because – in the time domain a multicarrier signal is **the sum of many narrowband signals** – this value can be large and small – ***larger than average value***.
- High PAR is an important challenge as it reduces efficiency and increases cost of **RF power amplifier.**
- Same power amplifier can be used with reduced input power **– input backoff IBO –** causes lower average SNR at the Rx.
- When high-peak signal is transmitted through nonlinear device – HPA / DAC – generates **in-band distortion** – severely degrading the system performances.
- Typical Power amplifier response with input & output backoff regions

- **To avoid distortion** - High peak power signals are transmitted in the **Linear region** – by decreasing average power of input signal.
- Input backoff IBO resulting in proportional output backoff OBO.



Quantifying the PAR

- Since multicarrier systems transmit data over a no. of parallel frequency channels, resulting waveform is superposition of L narrowband signals.
- Each of the output samples from an L-point IFFT operation involves sum of L complex numbers.
- Due to Central Limit Theorem resulting output values{x1, x2,…xL} can be accurately modelled as complex Gaussian random variables with zero mean & varianc $\sigma^2 = \mathcal{E}_x/2$,
- Amplitude of the output signa $|x[n]| = \sqrt{(\Re\{x[n]\})^2 + (\Im\{x[n]\})^2}$,
- , $|x[n]|$ is complex Gaussian like narrowband fading the envelop $|x[n]|$ is Rayleigh distributed.
- Output power $|x[n]|^2 = (\Re\{x[n]\})^2 + (\Im\{x[n]\})^2$, which is exponentially distributed with m $2\sigma^2$.

Quantifying the PAR

- PAR of the transmitted signal is defined as : $PAR \triangleq \frac{\max_t |x(t)|^2}{E[|x(t)|^2]}$,
- Usually PAR is considered for a single OFDM symbol, consisting of ***L+Ng*** samples or a time duration of ***T.***
- Discrete PAR for IFFT output : $PAR \triangleq \frac{\max_{l \in (0, L+N_g)} |x_l|^2}{E[|x_l|^2]} = \frac{\mathcal{E}_{\max}}{\mathcal{E}_x}$.
- Complementary cumulative distribution function CCDF= 1-CDF of the PAR is the most commonly used measure.
- Van Nee and de Wild introduced a simple and accurate approximation of the CCDF for large L(≥64)
- $\mathrm{CCDF}(L, \mathcal{E}_{\max}) = 1 - F(L, \mathcal{E}_{\max})^{\beta L} = 1 - \left(1 - \exp\left(-\frac{\mathcal{E}_{\max}}{2\sigma^2}\right)\right)^{\beta L}$

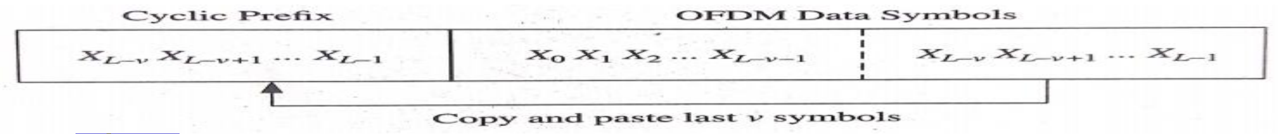
Clipping and Other PAR Reduction Techniques

- To avoid HPA operating in the nonlinear region, input power is reduced to an amount equal to PAR – this will reduce SNR by the same amount.
- PAR reduction –
- Some highest PAR values can be clipped off – reducing some amount of distortion – still some amount of distortion remains.
- **Clipping** – also called soft limiting – truncates the amplitude of the signal that exceed the clipping level as $\tilde{x}[n] = \begin{cases} Ae^{j\angle x[n]}, & \text{if } |x[n]| > A \\ x[n], & \text{if } |x[n]| \leq A, \end{cases}$
- Original signal is $x[n]$, output after clipping $\tilde{x}[n]$
- A = clipping level.
- Clipping ratio is defined as $\gamma \triangleq \frac{A}{\sqrt{E\{|x[n]|^2\}}} = \frac{A}{\sqrt{\mathcal{E}_x}}$
- Clipping reduces PAR at the expense of distorting the desired signal.

3. Illustrate the use of Cyclic Prefix in OFDM and derive the formula for rate loss – 10 Marks

Cyclic Prefix

- To realize OFDM in practice – FFT algorithm is utilized for computing DFT and IFFT algorithm for computing IDFT – *reduces no. of multiplication & addition.*
- IFFT operation at the transmitter allows all the subcarriers to be created in the digital domain and **requires a single radio link.**
- Channel must provide circular convolution for IFFT/FFT to create ISI free channel – $y[n] = x[n] \circledast h[n]$
- If maximum delay spread has a duration – ***v+1*** samples, then by adding a ***guard band of v samples*** between OFDM symbols, each OFDM symbol is made **independent** of those coming before and after it.
- Such OFDM symbol is represented in time domain as a length ***L*** vector ***X=[x1, x2, ...xL]***



- After applying a cyclic prefix of length ***v*** – transmitted signal

$$\mathbf{x}_{cp} = [\underbrace{x_{L-v}\ x_{L-v+1}\ \cdots\ x_{L-1}}_{\text{Cyclic prefix}}\ \underbrace{x_0\ x_1\ \cdots\ x_{L-1}}_{\text{Original data}}].$$

- Channel output is $\mathbf{y}_{cp} = \mathbf{h} * \mathbf{x}_{cp}$,
- Where h – is a length ***v+1*** vector describing the impulse response of the channel during the OFDM symbol.
- Output ***Ycp*** has ***(L+v) + (v+1) -1 = L+2v*** samples – input ***(L+v)*** impulse response ***(v+1)***
- 1st ***v*** samples of ***Ycp*** has interference from the preceding OFDM symbol - discarded. Last ***v*** samples disperse into the subsequent OFDM symbol – discarded.
- This leaves exactly ***L*** samples for the desired output ***Y***.

Cyclic Prefix

- Consider only the 1st element of ***y*** – ***yo***. Due to cyclic prefix ***yo*** depends on ***Xo*** and the circularly wrapped values $x_{L-v} \cdots x_{L-1}$.
- That is

$$\begin{aligned} y_0 &= h_0x_0 + h_1x_{L-1} + \cdots + h_vx_{L-v} \\ y_1 &= h_0x_1 + h_1x_0 + \cdots + h_vx_{L-v+1} \\ &\vdots \\ y_{L-1} &= h_0x_{L-1} + h_1x_{L-2} + \cdots + h_vx_{L-v-1} \end{aligned}$$

- Due to circular convolution – a cyclic prefix that is at least as long as the ***channel duration*** allows the channel output ***y*** to be decomposed into a simple multiplication of the channel frequency response ***H=DFT{h}*** and the channel frequency domain input ***X=DFT{x}.***
- ***Rate Loss = Power Loss = L/(L+v). If L>>v –*** inefficiency can be reduced.

4. Describe the principle of OFDMA in LTE Downlink with relevant block diagrams – 10 Marks

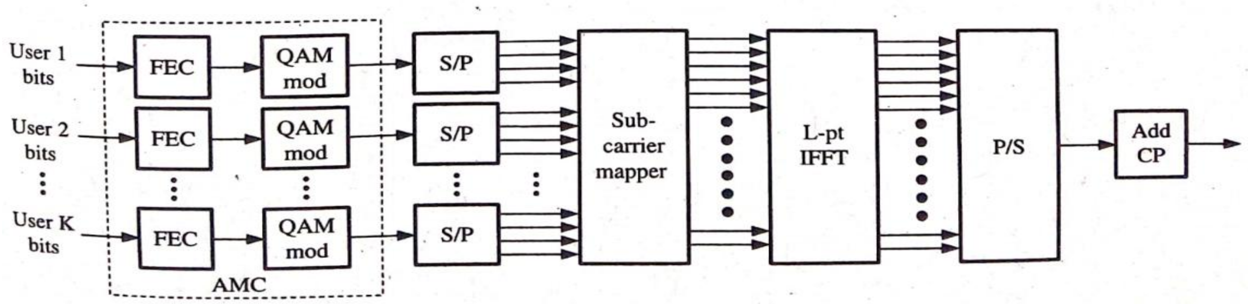
4.2- Orthogonal Frequency Division Multiple Access (OFDMA)

- OFDMA system allocates users time-frequency slices consisting of M sub-carriers over some no. of consecutive OFDM symbols.
- The M sub-carriers can be arranged as :
- **Bunched together** in M contiguous sub-carriers –
  - Band AMC – uses subcarriers with almost equal SINR and chooses the best coding and modulation scheme for it.
  - If accurate SINR information is available at the RX, band AMC gives better performance.
- **Spread out over the band** – distributed allocation -
  - Provides frequency diversity over the entire band and uses interleaving and coding to correct errors.
  - For a highly mobile system distributed allocation provides maximum diversity.

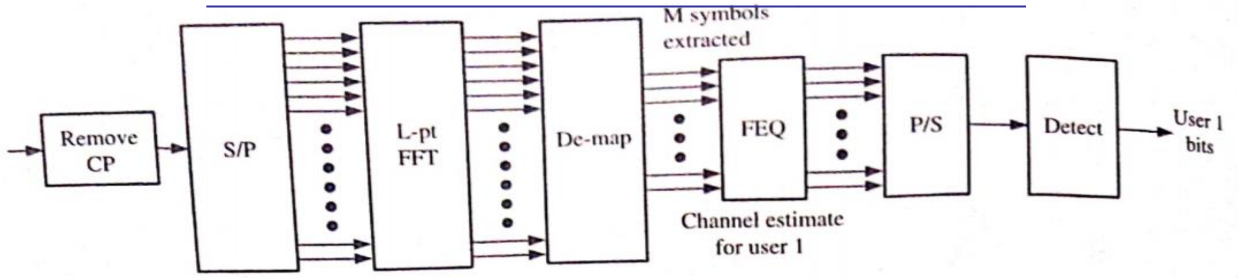
OFDMA : How it works

- Basic flow of OFDMA is similar to OFDM system – except for now K users share the L subcarriers, with each user being allocated *Mk* subcarriers.
- In practise each user have one subcarrier assigned to them.
- At each Rx, user is concerned only about its **own *Mk* subcarrier**, but it applies L point FFT on the entire received signal to extract the desired subset of subcarriers.
- OFDMA downlink Rx must demodulate the entire received signal – wastes power.
- Digital separation of users is simple to implement at the Rx .
- Interferences are low in OFDMA compared to CDMA, FDMA.

OFDMA Downlink Tx



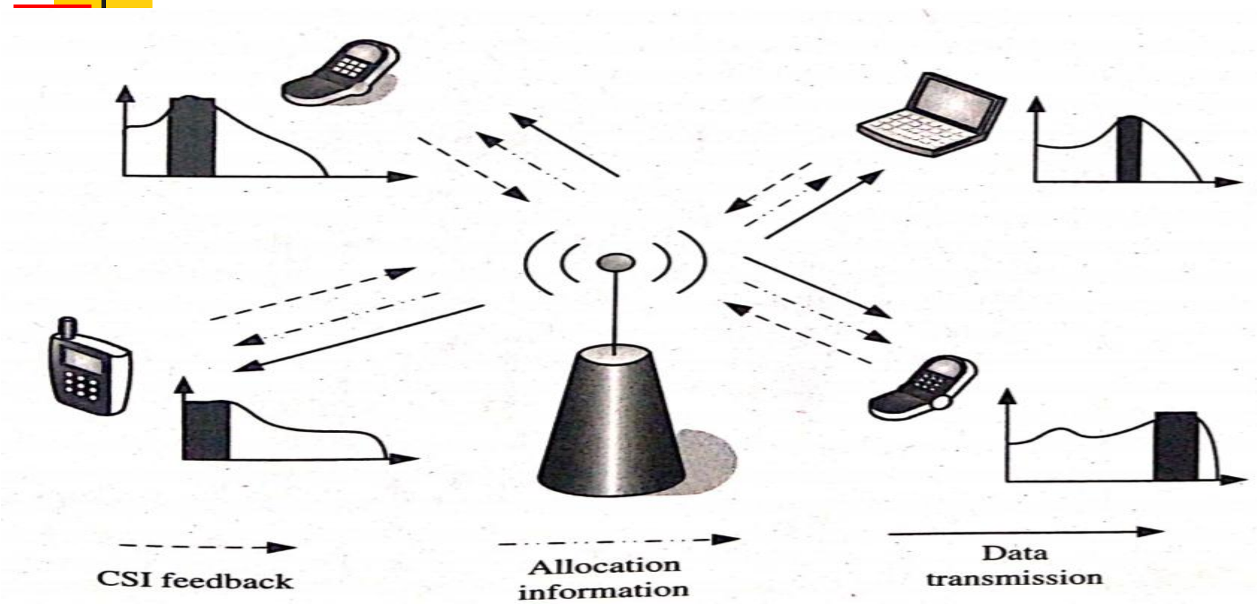
OFDMA Downlink Rx for user 1



OFDMA : How it works

- Base station is transmitting a **band AMC type OFDMA** signal to 4 different devices simultaneously.
- 3 arrows of each user – **signaling** that must happen for band AMC to work.
- 1st the MS measures and **feedback their channel quality** – **CSI channel state information (SINR)** to the BS.
- **BS then allocates subcarriers** to the 4 users and send this **subcarrier allocation information** to the 4 users in a **overhead message**.
- Finally actual data is transmitted over the subcarriers assigned to each users.

OFDMA : How it works



5. Show that the received SNR increase linearly with the number of receiver antennas in the concept of Spatial Diversity. – 10 Marks

5. Show that the received SNR increase linearly with the number of receiver antennas in the concept of Spatial Diversity.

- Spatial diversity is achieved by 2 or more antennas, separated by some distance. No additional BW or power is needed.
- **Array Gain** - combination of energy of each antenna. For ***Nt x Nr*** system, where Nt & Nr are Tx & Rx array gain.
- Each antenna *i* receives a signal characterized by: $y_i = h_i x + n_i = hx + n_i$, SNR on single antenna $\gamma_i = \frac{|h|^2}{\sigma^2}$
- hi=h for all the correlated antennas, σ^2 = noise power
- Resulting signal after adding all the received paths $y = \sum_{i=1}^{N_r} y_i = N_r h x + \sum_{i=1}^{N_r} n_i$
- Combined SNR $\gamma_\Sigma = \frac{|N_r h|^2}{N_r \sigma^2} = \frac{N_r |h|^2}{\sigma^2}$ for correlated channels - received SNR increases linearly with no. of Rx antenna – no diversity gain.

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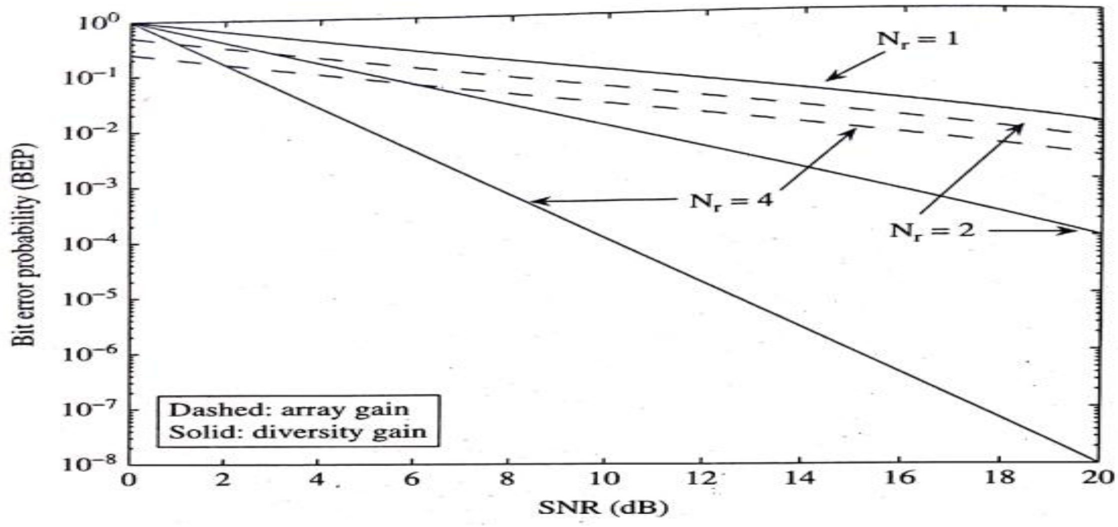
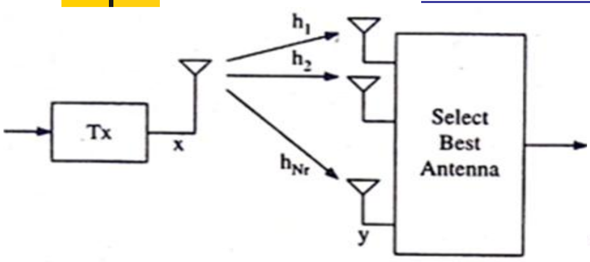
Relative BEP for Nt=1, Nr=1, 2, 4

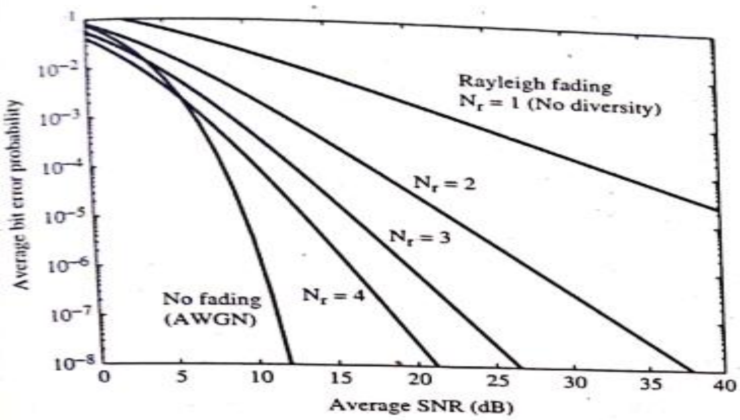
- For LOS channel average BEP decreases. $\bar{P}_b \approx c_5(N_d\gamma)^{-1}$,
- Sufficient spacing for the antenna is critical for increasing the system reliability.



6. Distinguish between Selection combining and maximal ratio combining in terms of average received SNR. – 10 Marks

Selection Combining





Selection Combining

- Simplest type- ***estimates the instantaneous strengths of each of Nr streams and selects the highest one***.
- Simple as its reduces hardware and power requirements. Used mostly in narrowband channels.
- SC ignores the useful energy of other streams so it's a suboptimal type.
- Wideband channels have different coherence bands with different SNR and requires all the antennas to be active – mostly used in MRC.
- Diversity gain can be confirmed by **outage probability** – defined as the probability that the **received SNR drops below some required threshol** $P_{out} = P[\gamma < \gamma_o] = p.$

Selection Combining

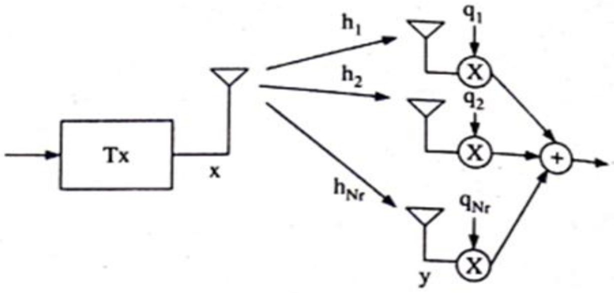
- For ***Nr*** uncorrelated received signals

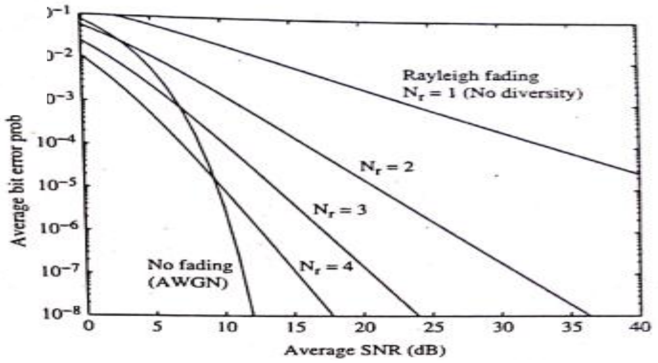
$$\begin{aligned} P_{out} &= P[\gamma_1 < \gamma_o, \gamma_2 < \gamma_o, \ldots, \gamma_M < \gamma_o], \\ &= P[\gamma_1 < \gamma_o] P[\gamma_2 < \gamma_o] \ldots P[\gamma_M < \gamma_o], \\ &= p^{N_r}. \end{aligned}$$

- For a Rayleigh fading channel $p = 1 - e^{-\gamma_o/\bar{\gamma}}$, where $\bar{\gamma}$ = average received SNR.
- SC decreases the outage probability to $P_{out} = (1 - e^{-\gamma_o/\bar{\gamma}})^{N_r}.$
- Average received SNR for Nr-branch SC can be derived in Rayleigh fading

$$\begin{aligned} \gamma_{sc} &= \bar{\gamma} \sum_{i=1}^{N_r} \frac{1}{i}, \\ &= \bar{\gamma}\left(1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{N_r}\right). \end{aligned}$$

Maximal Ratio combining - MRC





Maximal Ratio combining - MRC

- MRC combines the information from all the received branches to maximize SNR.
- **MRC works by weighing each branch by a complex factor** $q_i = |q_i|e^{j\phi_i}$ and then **adding up the branches**.
- Received signal on each branch can be written as ***x(t)hi*** assuming flat fading with a complex value of $h_i = |h_i|e^{j\theta_i}$ on the ith branch.
- Combined signal is $y(t) = x(t)\sum_{i=1}^{N_r} |q_i||h_i| \exp\{j(\phi_i + \theta_i)\}.$
- SNR of ***y(t)*** is $\mathcal{E}_x$ = transmit signal energy

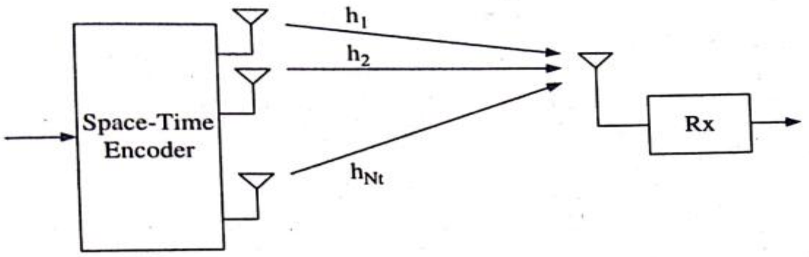
$$\gamma_{\mathrm{mrc}} = \frac{\mathcal{E}_x(\sum_{i=1}^{N_r} |q_i||h_i|)^2}{\sigma^2 \sum_{i=1}^{N_r} |q_i|^2},$$

- Branches with higher SNR are enhanced and branches with lower SNR are given less weight.

7. Analyze Open-Loop Transmit diversity with the help of 2x2 SFBC, 4X2 Stacked STBCs and 4X2 in LTE. – 10Marks

Transmit Diversity

- Transmit diversity is more useful in downlink as BS can accommodate more antennas than MS.
- Multiple antenna transmit schemes:
- **Open-loop –** systems that don't require the knowledge of the channel at the TX.
- **Closed-loop –** systems that require the channel knowledge at the Tx through a feedback channel from the Rx.
- Open-loop transmit diversity is shown – no feedback.



Open-loop Transmit Diversity: 2x1 Space-Frequency Block Coding

- Most popular open-loop transmit diversity scheme is space-time coding – a code known to the Rx is also applied to the Tx.
- 1990 – space-time block code (STBC) also called Alamouti code / orthogonal space-time block code.
- s1 transmitted by Tx1 and s2 transmitted by Tx2 over subcarriers f1 & f2.

		Antenna 1	2
Subcarrier	f_1	s_1	s_2
	f_2	$-s_2^*$	s_1^*

- 2x1 Alamouti code is a rate 1 code as there is no increase/ decrease in data rates.
- ***h1(f1)*** & ***h2(f2)*** are the complex channel gains of Tx antenna 1 & 2 to the Rx antenna
- Assuming constant channels ***h1(f1) = h2(f2) = h1.***

Open-loop Transmit Diversity: 2x1 Space-Frequency Block Coding

- Received signal r(f) is
$$r(f_1) = h_1 s_1 + h_2 s_2 + n(f_1),$$
$$r(f_2) = -h_1 s_2^* + h_2 s_1^* + n(f_2),$$
- Assuming channel is known to Rx
$$y_1 = h_1^* r(f_1) + h_2 r^*(f_2),$$
$$y_2 = h_2^* r(f_1) - h_1 r^*(f_2).$$
$$y_1 = h_1^*(h_1 s_1 + h_2 s_2 + n(f_1)) + h_2(-h_1^* s_2 + h_2^* s_1 + n^*(f_2)),$$
$$= (|h_1|^2 + |h_2|^2) s_1 + h_1^* n(f_1) + h_2 n^*(f_2),$$
$$y_2 = (|h_1|^2 + |h_2|^2) s_2 + h_2^* n(f_1) - h_1 n^*(f_2).$$
- Resulting SNR
- Each TX antenna halves its Tx Power as total TX power per data symbol is ***Єx.***
- ***2x1 Alamouti code gives same Diversity as 1x2with MRC***

$$\gamma_\Sigma = \frac{(|h_1|^2 + |h_2|^2)^2}{|h_1|^2\sigma^2 + |h_2|^2\sigma^2} \frac{\mathcal{E}_x}{2},$$
$$= \frac{(|h_1|^2 + |h_2|^2)}{\sigma^2} \frac{\mathcal{E}_x}{2},$$
$$= \frac{\sum_{i=1}^{2} |h_i|^2}{\sigma^2} \frac{\mathcal{E}_x}{2}.$$

Open-loop Transmit Diversity with more Antennas

- 2x2 SFBC – represented as 2x2 matrix $\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}.$
- Resulting signals at
- subcarriers f1 & f2
- on antenna 1 & 2

$$r_1(f_1) = h_{11} s_1 + h_{21} s_2 + n_1(f_1),$$
$$r_1(f_2) = -h_{11} s_2^* + h_{21} s_1^* + n_1(f_2),$$
$$r_2(f_1) = h_{12} s_1 + h_{22} s_2 + n_2(f_1),$$
$$r_2(f_2) = -h_{12} s_2^* + h_{22} s_1^* + n_2(f_2).$$

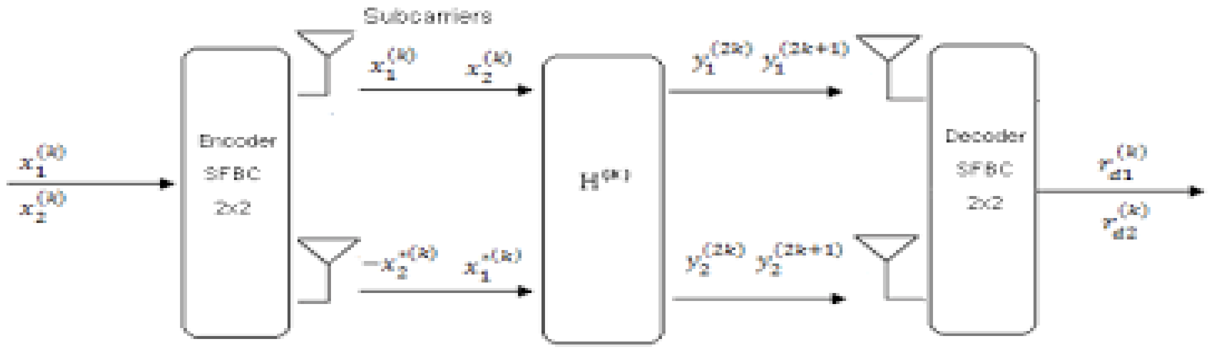
- Using the following combining scheme
$$y_1 = h_{11}^* r_1(f_1) + h_{21} r_1^*(f_2) + h_{12}^* r_2(f_1) + h_{22} r_2^*(f_2),$$
$$y_2 = h_{21}^* r_1(f_1) - h_{11} r_1^*(f_2) + h_{22}^* r_2(f_1) - h_{21} r_2^*(f_2)$$
- Giving the following decision :
$$y_1 = (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2) s_1 + 4 \text{ noise terms},$$
$$y_2 = (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2) s_2 + 4 \text{ noise terms},$$

Open-loop Transmit Diversity with more Antennas

- Resulting SNR

$$\gamma_\Sigma = \frac{\left(\sum_j \sum_i |h_{ij}|^2\right)^2}{\sigma^2 \sum_j \sum_i |h_{ij}|^2} \frac{\mathcal{E}_x}{2} = \frac{\sum_{j=1}^{2} \sum_{i=1}^{2} |h_{ij}|^2}{\sigma^2} \frac{\mathcal{E}_x}{2}.$$

- 2x2 Alamouti achieves full diversity gain.



Open-loop Transmit Diversity with more Antennas

- **4x2 Stacked STBC –** LTE will have 4 TX antenna. 2 data streams are sent using double space-time transmit diversity scheme (DSTTD)
- Similar to operating two 2x1 Alamouti code systems in parallel.
- Received signals at subcarrier f1 & f2 on antenna 1 & 2 are represented with equivalent channel models:

$$\begin{bmatrix} r_1(f_1) \\ r_1^*(f_2) \\ \hline r_2(f_1) \\ r_2^*(f_2) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{12}^* & -h_{11}^* & h_{14}^* & -h_{13}^* \\ \hline h_{21} & h_{22} & h_{23} & h_{24} \\ h_{22}^* & -h_{21}^* & h_{24}^* & -h_{23}^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \hline s_3 \\ s_4 \end{bmatrix} + \begin{bmatrix} n_1(f_1) \\ n_1^*(f_2) \\ \hline n_2(f_1) \\ n_2^*(f_2) \end{bmatrix}$$

- Equivalent matrix channel model of DSTTD

$$\begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{11} & \mathbf{H}_{12} \\ \mathbf{H}_{21} & \mathbf{H}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \end{bmatrix}.$$

Open-loop Transmit Diversity with more Antennas

- Using linear combining scheme for decision :

$$
\begin{aligned}
y_1 &= (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2)s_1 + I_3 + I_4 + 4 \text{ noise terms},\\
y_2 &= (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2)s_2 + I_3 + I_4 + 4 \text{ noise terms},\\
y_3 &= (|h_{13}|^2 + |h_{14}|^2 + |h_{23}|^2 + |h_{24}|^2)s_3 + I_1 + I_2 + 4 \text{ noise terms},\\
y_4 &= (|h_{13}|^2 + |h_{14}|^2 + |h_{23}|^2 + |h_{24}|^2)s_4 + I_1 + I_2 + 4 \text{ noise terms},
\end{aligned}
$$

- Ii is the interference from the ith Tx antenna due to transmitting 2 simultaneous data streams.

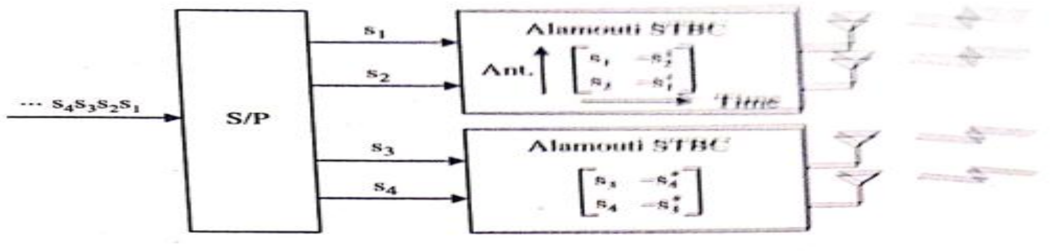


Figure 5.5 4 × 2 stacked STBC transmitter.

Open-loop Transmit Diversity with more Antennas

- **4x2 in LTE –** a combination of SFBC and frequency switched transmit diversity FSTD is used. Rate 1 encoder.
- This combination is a rate 1 diversity scheme – 2 modulation symbols are sent over 4 OFDM symbols, using the following space-time encoder.
- Rows are Tx antennas and columns are subcarrier index.
- 1st & 2nd symbols s1 & s2 are sent over antenna ports 0 & 2 on the first 2 OFDM subcarriers in the block.

$$
\frac{1}{\sqrt{2}}\begin{bmatrix} s_1 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & s_4 \\ -s_2^* & s_1^* & 0 & 0 \\ 0 & 0 & -s_4^* & s_3^* \end{bmatrix}
$$

- On the other 2 subcarriers 3rd & 4th symbols are sent using antenna port 1 & 3.