R N S Institute of Technology
Dept. of Electronics and Communication Engineering
15EC81: Wireless Cellular and LTE 4G Broadband

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1 Course Syllabus

Mod 1 : Evolution of Cellular systems, LTE features & Wireless fundamentals

Mod 2 : Multi carrier modulation, OFDMA, Multiple Antenna Transmission & Reception

Mod 3 : Channel structure of LTE & Downlink Transport Channel Processing

Mod 4 : Uplink Channel Transport Processing & Physical Layer Procedures

Mod 5 : Radio Resource Management & Mobility Management

2 Course Outcomes

At the end of the course, you will be able to:

CO1 : Understand the system architecture and functional standard specified in LTE 4G

CO2 : Understand the modulation techniques for LTE and communication using multiple antenna.

CO3 : Analyze the role of LTE radio interface protocols and its channel structure.

CO4 : Test the performance of resource management and packet data processing and transport algorithm.

CO5 : Demonstrate the UTRAN handling process from setup to release including the mobility management for a variety of all data cell scenarios.

Module 1

Part 1: Evolution of Cellular Technologies & LTE Features

1 Topics Covered

1. Evolution of Mobile Broadband
2. First Generation Cellular Systems
3. 2G Digital Cellular Systems
4. 3G Broadband Wireless Systems
5. Beyond 3G:HSPA+, WiMAX, LTE
6. Key Requirements of LTE Design
7. Key Enabling Technologies and Features of LTE
8. LTE Network Architecture

2 Evolution of Mobile Broadband

- Before 1892 - Theoretical basis for radio communication - Nikola Tesla, Jagadish Bose & Alexander Popov
- 1897 - Marconi demonstrated radio communication & awarded patent for it.
- 1934 - AM Radio Systems used in US.
- 1935 - Edwin Armstrong demonstrated FM.
- 1948 - Claude Shannon published theory on Channel Capacity: $C = Blog_2(1 + SNR)$
- 1960 to 70 - Bell labs developed Cellular concept.
- 1983 - AMPS (Advanced Mobile Phone Service) launched in Chicago.
- 1991 - First Commercial GSM in Europe.
- 1995 - First Commercial launch of CDMA (IS - 95).
- 2001 - NTT DoCoMo launched first commercial 3G service.
- 2005 - IEEE 802.16e standard, the air - interface for mobile WiMAX, completed & approved.

- 2007 - First Apple iPhone launched.
- 2009 - 3GPP Release 8 LTE/SAE specifications completed.

3 First Generation Cellular Systems

- The United States, Japan and parts of Europe led the development of cellular wireless systems.
- These systems were characterized by analog modulation schemes & were designed primarily for delivering voice services.
- Japan's Nippon Telephone & Telegraph Company (NTT) implemented the world's first commercial cellular system in 1979.
- Europe's Nordic Mobile Telephone (NMT - 400) system implemented automatic handover & international roaming.
- The more successful first generation systems were AMPS in the United States.
- Major First Generation Cellular Systems are
  - **AMPS** (Advanced Mobile Phone Service)
  - **ETACS** (Extended Total Access Communication Systems) in Europe
  - **NTACS** (Nippon Total Access Communication Systems) in Japan
  - **NMT - 450 / NMT - 900**

4 2G Digital Cellular Systems

- Improvements in processing abilities of hardware platforms enabled the development of 2G wireless systems.
- 2G systems were also focused on voice transmission, but used digital modulation techniques.
- Shifting from Analog to Digital enabled several improvements in system performance.
  1. System capacity was improved through the use of spectrally efficient digital speech codecs.
  2. Multiplexing techniques were used to accommodate several users on the same frequency channel.
  3. Frequency re-use enabled by better error performance of digital modulation.
- Major 2G Cellular Systems are

1. GSM : Introduced in 1990
2. blackIS - 54 / IS - 136: Introduced in 1991
3. IS - 95: Introduced in 1993

- Besides providing improved voice quality, capacity & security, 2G systems also enabled new application.

  That is **Short Message Service (SMS)**
- In addition to SMS, 2G systems also supported low data rate wireless data applications.
- These systems supported circuit switched data services.

5 3G Broadband Wireless Systems

- The circuit - switched paradigm based on which 2G systems were built, made these systems very inefficient for data, hence only low - data rates were supported.
- 3G systems employed packet data services. Hence provided much higher data rates.
- Voice quality significantly increased.
- 3G systems also supported **multimedia, Web browsing, e - mail & interactive games.**

  Major 3G Standards are

  - IMT - 2000
  - Wideband CDMA (W - CDMA)
  - CDMA 2000 (3G evolution of IS-95)
  - EV - DO (EVolution Data Only)
  - HSPA (High Speed Packet Access)

6 Beyond 3G

- From 2009, mobile operators around the world started planning their next step in the evolution of their networks.
- Major technologies are
  - **HSPA+**
  - **WiMAX**
  - **LTE**

7 Key Requirements of LTE Design

LTE was designed with the following objectives in mind to effectively meet the growing demand.

1. Performance on par with Wired Broadband.
   - High throughput and Low latency
   - Data rate targets: 100 Mbps for Downlink & 50 Mbps for Uplink
2. Flexible Spectrum Usage.
   - Operators can deploy LTE in 700 MHz, 900 MHz, 1800 MHz & 2.6 GHz Bands.
   - LTE supports a variety of channel bandwidths: 1.4, 3, 5, 10, 15 & 20 MHz.
3. Co-existence and Interworking with 3G Systems as well as Non-3GPP Systems.
4. Reducing Cost per Megabyte.

8 Key Enabling Technologies & Features of LTE

To meet its service and performance requirements, LTE design incorporates several important enabling radio & core network technologies. They are:

1. Orthogonal Frequency Division Multiplexing (OFDM)
2. Single Carrier Frequency Domain Equalization (SC-FDE) and SC-FDMA
3. Channel Dependent Multi-user Resource Scheduling
4. Multi antenna Techniques
5. IP - Based Flat Network Architecture

8.1 Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM has emerged as a technology of choice for achieving high data rates.
- It is the core technology used by a variety of systems including **Wi-Fi & WiMAX.**
- The following advantages of OFDM led to its selection for LTE:
  - Elegant solution to multipath interference.
  - Reduced computational complexity.
  - Graceful degradation of performance under excess delay.

- Exploitation of frequency diversity.
- Enables efficient multi-access scheme.
- Facilitates use of MIMO.
- Efficient support of broadcast services.

8.2 SC-FDE and SC-FDMA & Channel Dependent Multi-user Resource Scheduling

- Single Carrier Frequency Domain Equalization (SC-FDE) is conceptually similar to OFDM but instead of using IFFT, it uses QAM symbols with cyclic prefix.
- The uplink of LTE implements a multi-user version of SC-FDE, called SC-FDMA, which allows multiple users to use parts of the frequency spectrum.
- OFDMA allows for allocation in both time & frequency and it is possible to design algorithms to allocate resources in a flexible and dynamic manner.

8.3 Multi-antenna Techniques

- The LTE standard provides extensive support for implementing advanced multi-antenna solutions to improve link robustness, system capacity and spectral efficiency.
- Multiantenna techniques supported in LTE include:
  - Transmit diversity
  - Beam forming
  - Spatial multiplexing
  - Multi-user MIMO

8.4 IP - Based Flat Network Architecture

- The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs, as illustrated in Figure.
- For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be **flat.**
- The eNodeBs are normally inter-connected with each other by means of an interface known as X2, and to the EPC by means of the S1 interface.

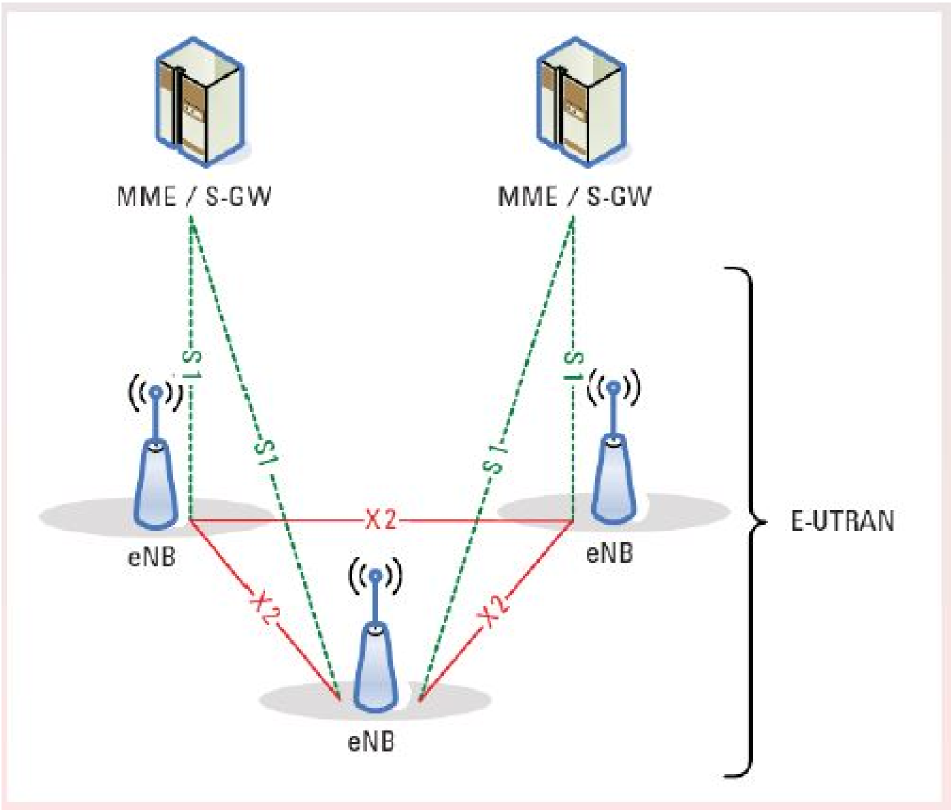

Figure 1: Overall E-UTRAN architecture.

- The protocols which run between the eNodeBs and the UE are known as the Access Stratum (AS) protocols.
- The E-UTRAN is responsible for all radio-related functions.

9 LTE Network Architecture

- LTE includes the evolution of:
  - the radio access through the E-UTRAN (Evolved - Terrestrial Radio Access Network)
  - the non-radio aspects under the term **System Architecture Evolution (SAE)**
- Entire system composed of both LTE and SAE is called the **Evolved Packet System (EPS)**
- At a high-level, the network is comprised of:
  - Core Network (CN), called **Evolved Packet Core (EPC)** in SAE
  - access network (E-UTRAN)
- A *bearer* (a messenger) is an IP packet flow with a defined QoS between the gateway and the User Terminal (UE).
- CN is responsible for overall control of UE and establishment of the bearers.

9.1 Evolved Packet Core Architecture

- Main logical nodes in EPC are:
  - Packet Data Network Gateway **(PGW)**
  - Serving Gateway **(SGW)**
  - Mobility Management Entity **(MME)**
- EPC also includes other nodes and functions, such as:
  - Home Subscriber Server **(HSS)**
  - Policy Control and Charging Rules Function **(PCRF)**
- EPS only provides a bearer path of a certain QoS, control of multimedia applications is provided by the IP Multimedia Subsystem **(IMS)**, which is considered outside of EPS.
- E-UTRAN solely contains the evolved base stations, called **eNodeB or eNB**

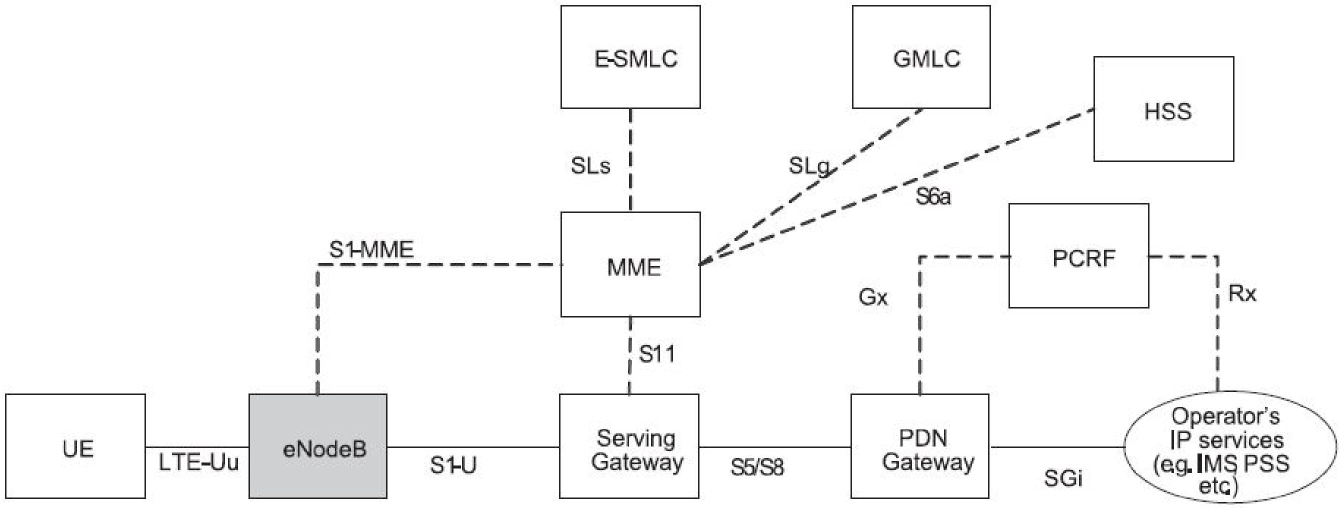

Figure 2: Evolved Packet Core Architecture

9.2 Four new elements of EPC

1. Serving Gateway (SGW)
    - It acts as a demarcation point between the RAN & core network.
    - It manages user plane mobility.
2. Packet Data Network Gateway (PGW)
    - It acts as the termination point of the EPC toward other networks such as Internet, private IP network or the multimedia service.
    - It provides functions such as user IP address allocation, policy enforcement, packet filtering & charging support.
3. Mobility Management Entity (MME)
    - It performs the signaling and control functions to manage the user terminal.
4. Policy & Charging Rules Function (PCRF)
    - It is a concatenation of Policy Decision Function (PDF) and Charging Rules Function (CRF).

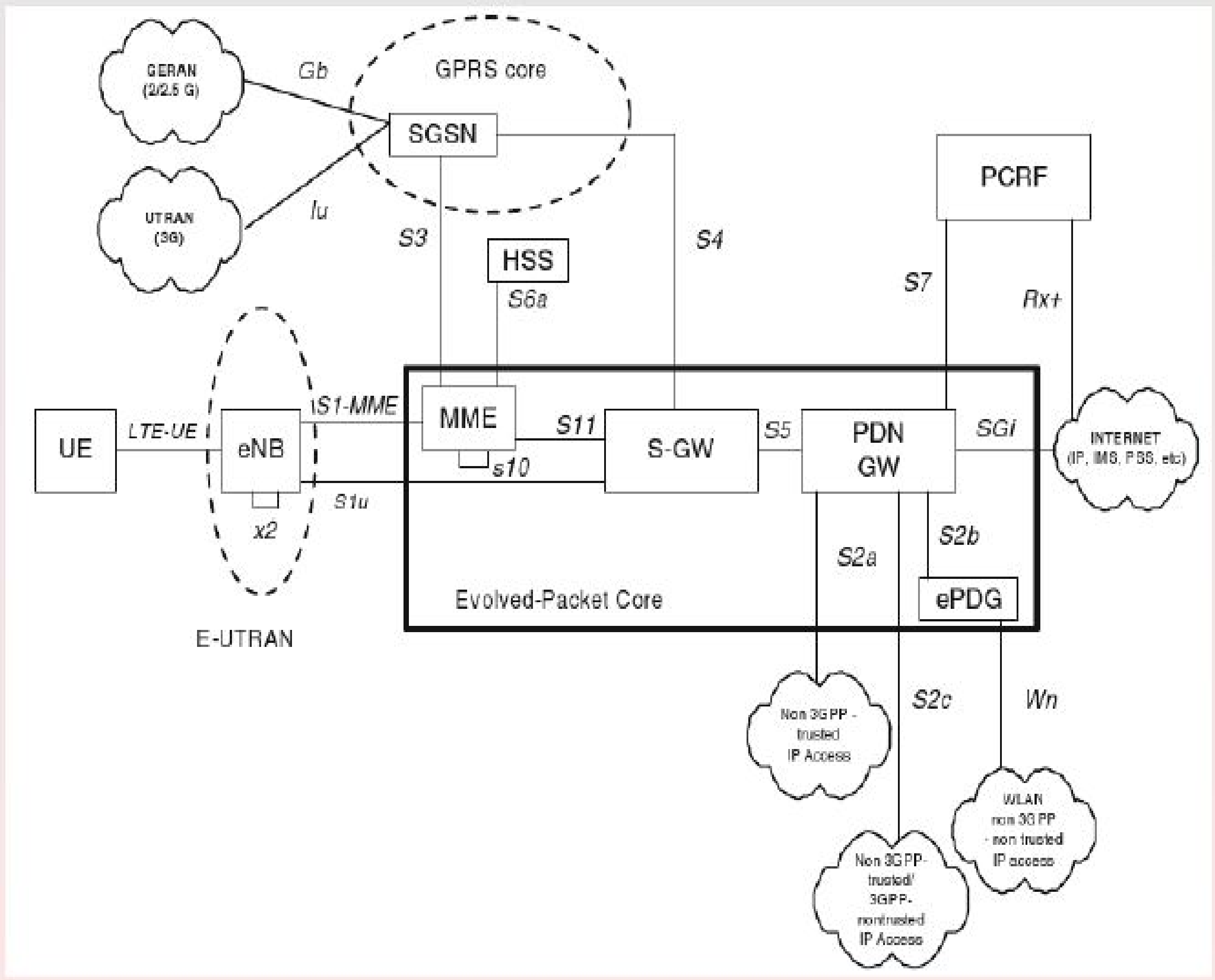

Figure 3: Evolved Packet Core Architecture

10 Home Work Exercise Questions

1. List out the features of major First Generation Systems.
2. List out the features of major 2G systems.
3. Draw GSM Network architecture and explain its sub-components.
4. Explain CDMA (IS-95) and its evolution.
5. Compare the features of major 3G Standards.
6. Write a note on HSPA.
7. What were the key requirements of LTE design? Briefly explain them.
8. Discuss the key enabling technologies of LTE.
9. What are the advantages of OFDM that has led to its selection for LTE?
10. Explain the IP - based Flat Network Architecture.
11. With a neat block diagram, explain the LTE Network Architecture and describe briefly the four new elements provided in it.

Module 1
Part 2: Wireless Fundamentals

Topics Covered

1. The Broadband Wireless Channel
2. Cellular Systems
3. Fading
4. Modeling of Broadband Fading Channels
5. Mitigation of Narrowband Fading
6. Mitigation of Broadband Fading

1 The Broadband Wireless Channel

In this topic we discuss the fundamental factors affecting the received signal in a wireless system, And how they can be modeled using the different parameters.

- Here we introduce the overall channel model, and discuss the large - scale trends that affect this model.
- In discrete-time, the overall channel model is described using a simple **tap-delay line (TDL).**

$$h[k,t] = h_0\delta[k,t] + h_1\delta[k-1,t] + \cdots + h_v\delta[k-v,t]$$

- Here, the discrete-time channel is time - varying and has **non - negligible** values over a span of $(v+1)$ channel taps.
- Here its assumed that the channel is sampled at a frequency $f_s = \frac{1}{T}$ where T is the symbol period.
- Hence, the duration of the channel is **vT**.
- Assuming that the channel is static over a period of (v+1)T seconds, the output of the channel can be described as

$$y[k,t] = \sum_{k=-\infty}^{\infty} h[j,t]x[k-j] = h[k,t] * x[k]$$

where x[k] is an input sequence of data symbols with rate $\frac{1}{T}$

- In a simple notation, the channel can be represented as a time-varying (v+1) x 1 column vector.

$$\text{i.e., } h(t) = \begin{bmatrix} h_0(t) \\ h_1(t) \\ \vdots \\ h_v(t) \end{bmatrix}$$

- Although this tapped-delay line model is general and accurate, it is difficult to design a communication system for the channel without knowing some of the key attributes about h(t).

1.1 Path Loss

- The first obvious difference between wired and wireless channels is the amount of transmitted power that actually reaches the receiver.
- Assuming an isotropic antenna is used, as shown in figure below
- The propagated signal energy expands over a spherical wavefront.
- Therefore, the energy received at an antenna a distance **d** away is inversely proportional to the sphere surface are, $4\pi d^2$
- The *free space path loss formula* or **Friis formula**, is given more precisely as

$$P_r = P_t \frac{\lambda^2 G_t G_r}{(4\pi d)^2}$$

where P_r and P_t are the received & transmitted powers and λ is the wavelength.

- As observed in Friis formula, $P_r \propto \lambda^2$, which means that $P_r \propto \frac{1}{f_c^2}$
- Clearly, higher frequencies suffer greater power loss than lower frequencies.
- As a result, lower carrier frequencies are generally more desirable, and hence very crowded.

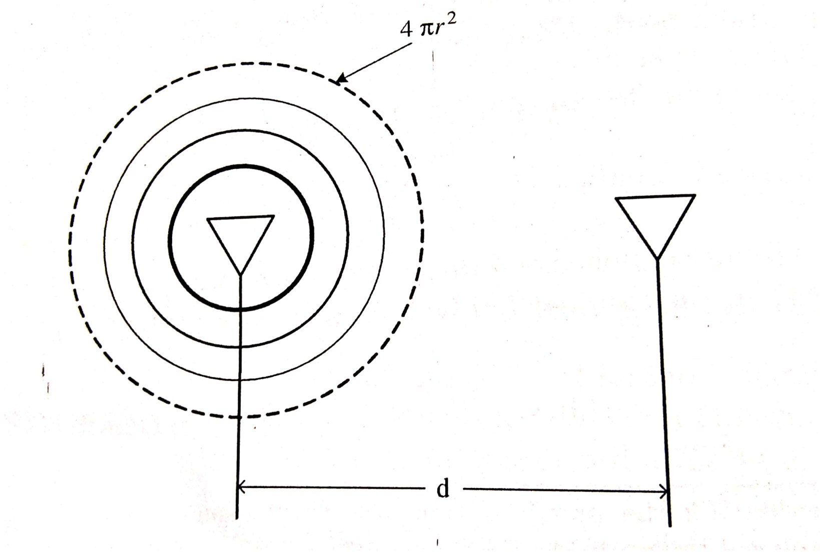

Figure 1: Free space propagation

- Therefore, bandwidth at higher carrier frequencies is more plentiful, more consistently available on a global basis, and almost always **less expensive.**
- Hence, a high-rate, low-cost system would generally prefer to operate at higher frequencies.
- But, the terrestrial propagation environment is not free space.
- The reflections from the Earth or other objects would actually increase the received power since more energy would reach the receiver.
- However, because a reflected wave often experiences a 180-degrees phase shift, at relatively large distances the reflection serves to create **destructive interference.**
- Therefore, the common 2 - ray approximation for path loss is:

$$P_r = P_t \frac{G_t G_r h_t^2 h_r^2}{d^4}$$

which is significantly different from free-space path loss in several aspects.

1.1.1 Empirical Path Loss Formula

- In order to more accurately describe different propagation environments, empirical models are often developed using experimental data.

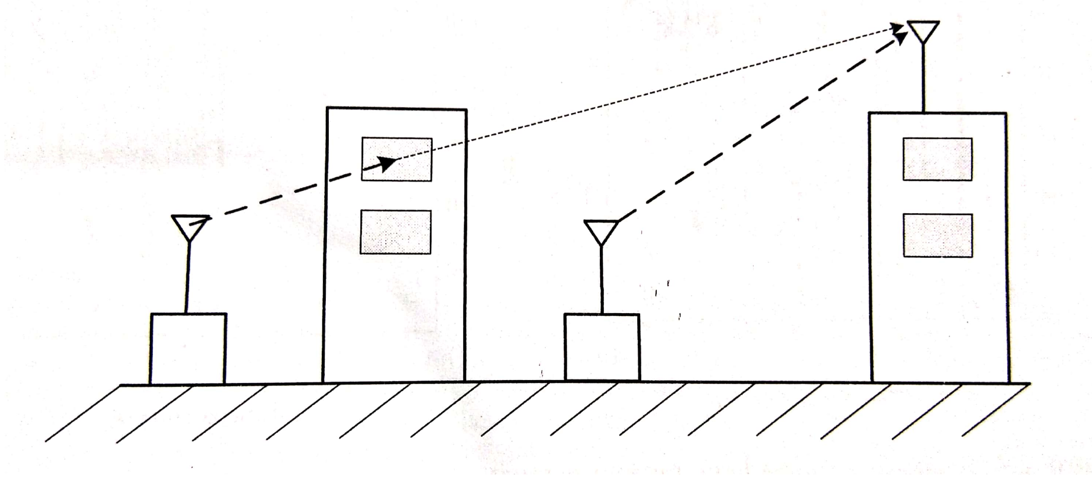

Figure 2: Shadowing can cause large deviations from path loss predictions.

- One of the simplest and most common is

$$P_r = P_t P_0 (\frac{d_0}{d})^\alpha$$

where α is the path loss exponent and the measured path loss P_0 at a reference distance of d_0

1.2 Shadowing

- Obstacles located between Transmitter & Receiver cause temporary degradation in received signal strength.
- Modeling the locations of all objects in every possible communication environment is generally impossible.
- Therefore, a random effect, called as **shadowing**, is introduced to measure these variations.
- With shadowing, the empirical path loss formula becomes

$$P_r = P_t P_0 \chi (\frac{d_0}{d})^\alpha$$

where χ is a sample of the shadowing random process.

- Hence, the received power is also now modeled as a random process.
- The shadowing value χ is typically modeled as a lognormal random variable, that is

$$\chi = 10^{x/10}, where x \sim N(0, \sigma_s^2)$$

where $N(0, \sigma_s^2)$ is a Gaussian (Normal) distribution with mean 0 and variance σ_s^2

- Thus, shadowing is an important effect in wireless networks because it causes the received SINR to vary dramatically over long time scales.
- In some given cell, reliable high-rate communication may be nearly impossible.

2 Cellular Systems

- In cellular systems, the service area is subdivided into smaller geographic areas called **cells**.
- Each cell is served by its own base station (BS).
- In order to minimize interference between cells, the transmit power level of each BS is regulated to be just enough to provide the required signal strength at the cell boundaries.
- The same frequency channels can be reassigned to different cells, as long as those cells are spatially isolated.
- The reuse of the same frequency channels should be intelligently planned in order to maximize the geographic distance between the co-channel base stations.

Some advantages of Cellular systems are:

- Cellular systems allow the overall system capacity to increase by simply making the cells smaller & turning down the power.
- Cellular systems support user mobility, seamless call transfer from one cell to another is provided.
- The handoff process provides a means of the seamless transfer of a connection from one BS to another.
- Small cells give a large capacity & reduce power consumption.
- Primary drawbacks are, **system needs more Base Stations, and their associated hardware costs, and the need for frequent handoffs.**

2.1 Cell Sectoring

- The performance of wireless cellular systems is significantly limited by co-channel interference (CCI).
- This comes from other users in the same cell or from other cells.

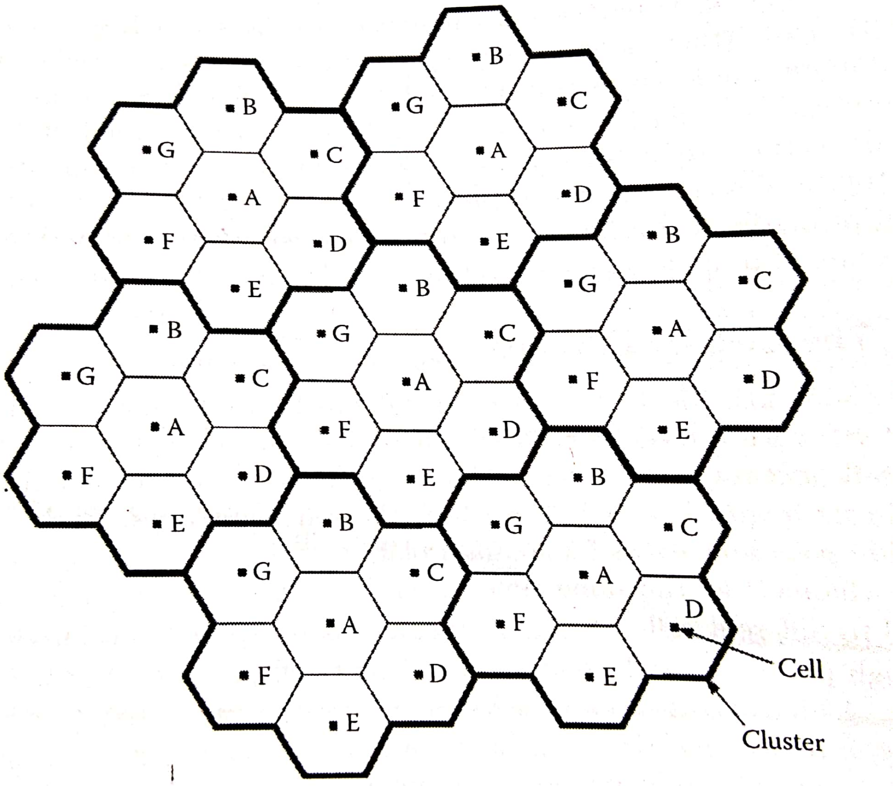

Figure 3: Standard figure of a hexagonal cellular system with f = 1/7

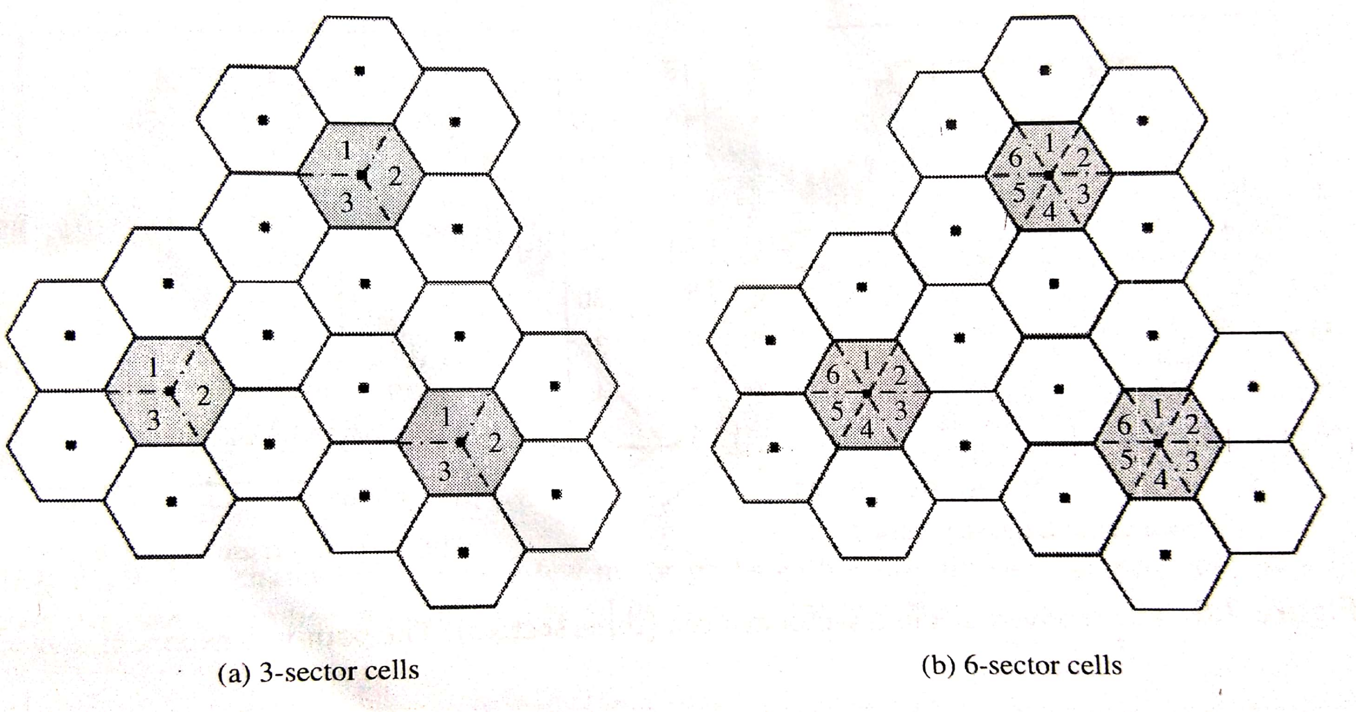

Figure 4: 3-Sector (120-degree) and 6-Sector (60-degree) cells.

- In Cellular Systems, Other Cell Interference (OCI) is a decreasing function of the radius of the cell (R) & the distance to the center of the neighbouring co-channel cell and an increasing function of transmit power.
- Since the SIR is so bad in most of the cell, it is desirable to find techniques to improve it without sacrificing so much bandwidth.
- A popular technique is to **sectorize** the cells, which is effective if frequencies are reused in each cell.

Directional antennas are used instead of omni-directional antenna at the base station.

3 The Broadband Wireless Channel: Fading

- One of the most disturbing aspects of wireless channels is the fading phenomenon.
- Unlike path loss or shadowing, which are large-scale attenuation effects due to distance or obstacles, fading is caused by the reception of multiple versions of the same signal.
- The multiple received versions are caused by reflections that are referred to as *multipath.*

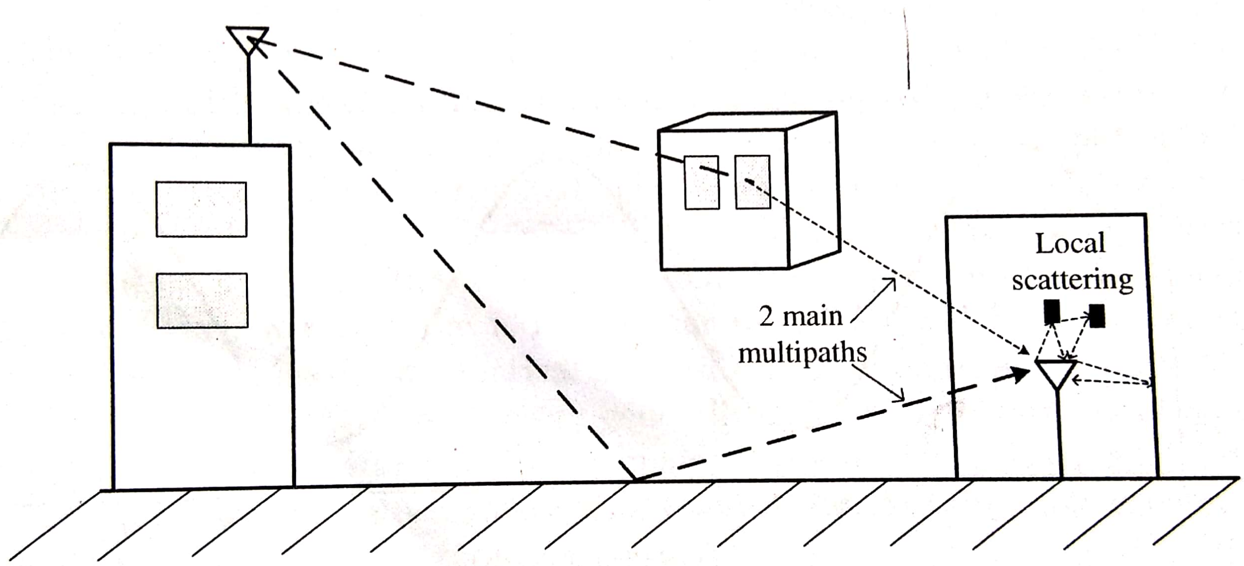

Figure 5: The channel may have a few major paths with quite diffrent lengths, and then the receiver may see a number of locally scattered versions of those paths.

- Depending on the phase difference between the arriving signals, the interference can be either constructive or destructive.
- This causes a very large observed difference in the amplitude of the received signal even over very short distances.

  Let us consider the time-varying tapped-delay line channel model.
- As either the Tx^r or Rx^r move relative to each other, the channel response $\mathbf{h(t)}$ will change.
- Movement in the propagation environment will also cause the channel response to change over time.
- This channel response can be thought of as having two dimensions:
  a delay dimension τ & **a time dimension t**
- Since the channel is highly variant in both the τ & **t** dimensions, in order to be able to discuss what the channel response is we must use statistical methods.
- The most important & fundamental function used to statistically describe broadband fading channels is the two-dimensional auto correlation function, $A(\Delta\tau, \Delta t)$.

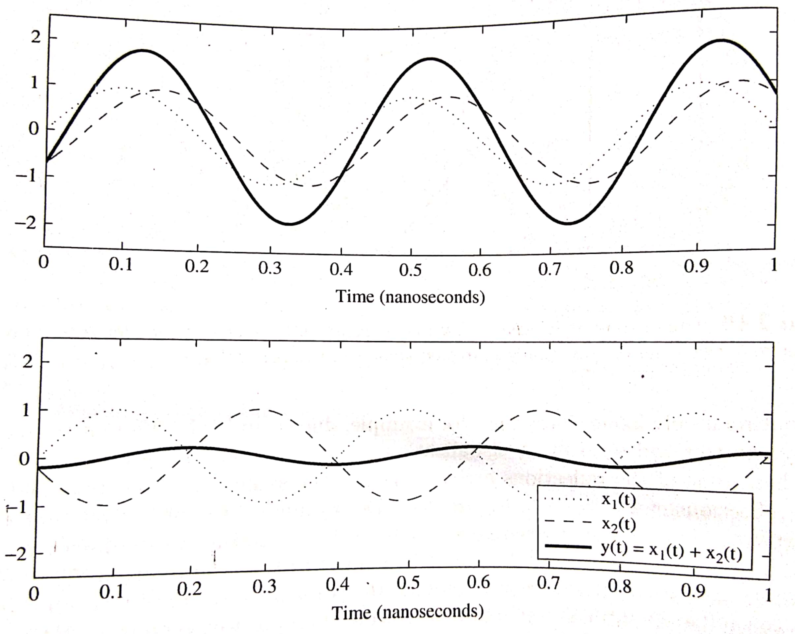

Figure 6:

And it is defined as

$$\begin{aligned} A(\Delta\tau, \Delta t) =& E[h(\tau_1, t_1)h^*(\tau_2, t_2)] \\ =& E[h(\tau_1, t)h^*(\tau_2, t + \Delta t)] \\ =& E[h(\tau, t)h^*(\tau + \Delta\tau, t + \Delta t)] \end{aligned}$$

- The channels described by this auto correlation function are referred to as **Wide Sense Stationary Uncorrelated Scattering (WSSUS).**
- This is the most popular model for wide band fading channels.

  From the auto correlation function, following wireless channel parameters can be estimated.

  1. Delay Spread, τ
  2. Coherence Bandwidth, B_c
  3. Doppler Spread, $f_D = \frac{f_c v}{c}$
  4. Coherence Time, T_c
  5. Angular Spread, θ_{rms}
  6. Coherence Distance, D_c

4 Modelling Broadband Fading Channels

- In order to design and benchmark wireless communication systems, it is important to develop channel models that incorporate their variations in time, frequency and space.
- The two main classes of models are **Statistical model** & **Empirical model.**
- Statistical models are simpler and are useful for analysis & simulations.
- The empirical models are more complicated, but usually represent a specific type of channel more accurately.

4.1 A Pedagogy for Developing Statistical Models

The methods for modelling wireless channels are broken into three steps:

Step 1 : First consider just a single channel sample corresponding to a single principle path between the Tx^r & Rx^r, that is

$$h(\tau, t) \rightarrow h_0 \delta(\tau, t)$$

Attempt to quantify: How is the value of $|h_0|$ statistically distributed?

Step 2 : Next consider how this channel sample h_0 evolves over time, that is:

$$h(\tau, t) \rightarrow h_0(t) \delta(\tau)$$

Attempt to quantify: How does the value $|h_0|$ change over time?

Step 3 : Finally, $h(\tau, t)$ is represented as a general time varying function.

4.2 Statistical Channel Models

- The received signal in a wireless system is the superposition of numerous reflections or multi path components.
- In this section, we will overview statistical methods that can be used to characterize the amplitude & power of received signal $r(t)$ when all the reflections arrive at about the same time.
- The following statistical models are considered in this section:
  1. Rayleigh Fading Model
  2. Line-of-Sight Channels - The Rician Distribution
  3. A more general model: Nakagami - m Fading

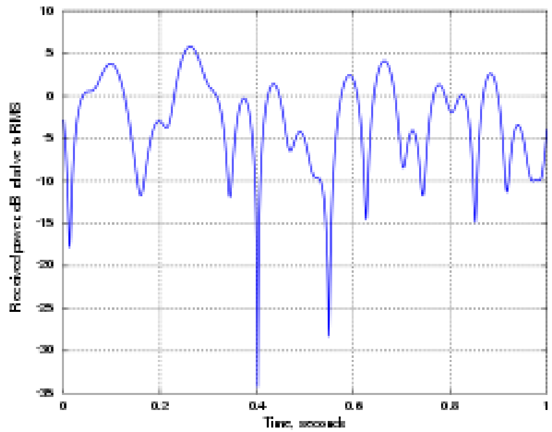

Figure 7: One second of Rayleigh fading with a maximum Doppler shift of 10 Hz.

4.3 Rayleigh Fading Model

- Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver.
- The in-phase (cosine) and quadrature (sine) components of received signal r(t) follow two independent time - correlated Gaussian random processes.
- The distribution of the envelope amplitude $|r| = \sqrt{r_I^2 + r_Q^2}$ is **Rayleigh distribution.**

$$f_{|r|}(x) = \frac{2x}{P_r} e^{-x^2/P_r}; x \geq 0$$

- The received power $|r|^2 = r_I^2 + r_Q^2$ is **exponentially distributed.**

$$f_{|r|^2}(x) = \frac{1}{P_r} e^{-x/P_r}; x \geq 0$$

- The GRVs r_I and r_Q each have zero mean and variance $\sigma^2 = P_r/2$.
- The phase of $r(t)$ is defined as $\theta_r = \tan^{-1}(\frac{r_Q}{r_I})$
- This phase is **uniformly distributed** from 0 to 2π, or equivalently from $[-\pi, \pi]$

4.4 LoS Channels - The Rician Distribution

- An important assumption in the Rayleigh fading model is that, the arriving reflections have a mean of zero.
- For LoS signal, the received envelope distribution is more accurately modelled by a Rician distribution.
- It is given by

$$f_{|r|}(x) = \frac{x}{\sigma^2} e^{-(x^2+\mu^2)/2\sigma^2} I_0(\frac{x\mu}{\sigma^2}); x \geq 0$$

where μ^2 is the power of the LoS component and
I_0 is the 0^{th} order, modified Bessel function of the first kind.

- The Rician phase distribution θ_r is not uniform in $[0, 2\pi]$ and is not distributed by a straight forward expression.
- It is more generalization of the Rayleigh distribution.

4.5 A more general model: Nakagami - m Fading

- The Nakagami distribution is relatively new, being first proposed in 1960.
- It has been used to model attenuation of wireless signals traversing multiple paths and to study the impact of fading channels on wireless communications.
- The Probability Density Function (PDF) of Nakagami - m fading is parameterized by m and is given as

$$f_{|r|}(x) = \frac{2m^m x^{2m-1}}{\Gamma(m) P_r^m} e^{-mx^2/P_r}; m \geq 0.5$$

- The power distribution for Nakagami fading is

$$f_{|r|^2}(x) = (\frac{m}{P_r})^m \frac{x^{m-1}}{\Gamma(m)} e^{-mx/P_r}; m \geq 0.5$$

4.6 Empirical Channel Model

- Actual environments are too complex to model accurately.
- In practice, most simulation studies use empirical models that have been developed based on measurements taken in various real environments.

- In 1968, **Okumura** conducted extensive measurements of base station to mobile signal attenuation throughout Tokyo and developed a set of curves giving median attenuation relative to free space path loss.
- To use this model one needs to use the empirical plots given in his paper. This is not very convenient to use.
- So in 1980, **Hata** developed closed-form expressions for Okumura's data.

4.7 LTE Channel Models for Path Loss : Hata Model

According to **Hata model** the path loss in an urban area at a distance d is:

$$L_U = 69.55 + 26.16log_{10}(f_c) - 13.82log_{10}(h_B) - a(h_r) + [44.9 - 6.55log_{10}(h_B)]log_{10}(d)$$

where
L_U = Path loss in Urban areas (dB)
h_B = Height of BS antenna (meters)
f_c = Carrier Frequency (MHz)
$a(h_r)$ = Antenna height correction factor
d = Distance between BS & MS (Kms)

4.8 COST Hata Model

- Hata model is intended for large cells with BS being placed higher than the surrounding rooftops.
- Both Okumura & Hata models are designed for **150-1500 MHz** and are applicable to the first generation cellular systems.
- The European Cooperative for Scientific and Technical (COST) research extended the Hata model to 2 GHz as follows:

$$P_{L,Urban} = 46.3 + 33.9log_{10}(f_c) - 13.82log_{10}(h_t) - a(h_r) + [44.9 - 6.55log_{10}(h_t)]log_{10}(d) + C_m$$

- This model is restricted to the following range of parameters:

Carrier Frequency	1.5 GHz to 2 GHz
Base Antenna Height	30 m to 300 m
Mobile Antenna Height	1 m to 10 m
Ditance d	100 m to 20 Km

- COST Hata model is designed for large and small macro-cells, i.e., base station antenna heights above rooftop levels adjacent to base station.

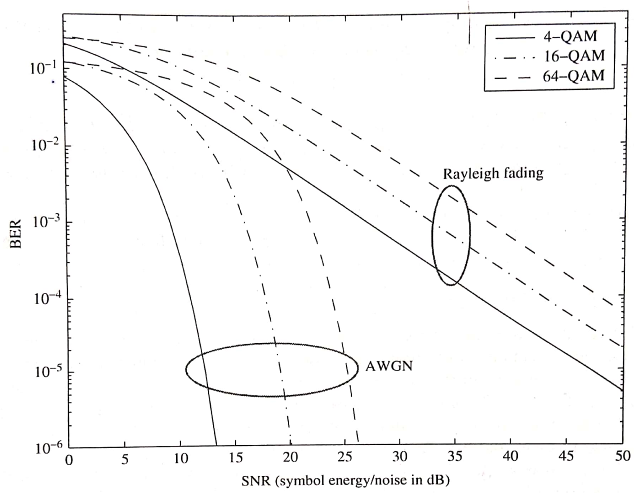

Figure 8: SNR vs. BER

5 Mitigation of Narrowband Fading

5.1 The Effects of Unmitigated Fading

- The probability of bit error (BER) is the principle metric of interest for the physical (PHY) layer of a communication system.
- For a QAM - based modulation system, the BER in an AWGN (no fading) can be approximated by the following bound:
  $P_b \leq 0.2e^{-1.5SNR/(M-1)}$
- The BER decreases rapidly (exponentially) with SNR.
- So decreasing SNR linearly causes the BER to increase exponentially.

5.2 Techniques to mitigate fading

The following techniques are used to mitigate the effects of fading.

1. Diversity - Spatial Diversity
2. Coding and Interleaving - Using ECCs or FECs
3. Automatic Repeat Request (ARQ)
4. Adaptive Modulation and Coding (AMC)

5.2.1 Spatial Diversity

- Diversity is the key to overcome performance loss from fading channels.
- Spatial diversity is a powerful form of diversity, and particularly desirable since it does not include redundancy in time or frequency.
- It is usually achieved by having two or more antennas at the receiver and / or the transmitter.
- The simplest form of space diversity consists of two receive antennas, where the stronger of the two signals is selected.
- This type of diversity is called as **Selection Diversity.**

6 Mitigation of Broadband Fading

- Since the data rate R is proportional to 1/T, high data rate systems almost invariably have multi path delay spread & hence experience very serious inter symbol interference (ISI).
- Choosing a technique to effectively reduce ISI is a central design decision for any high data rate system.
- OFDM is the most popular choice for reducing ISI in high rate systems, including WiFi, WiMAX and LTE.