Wireless Cellular & LTE 4G Broadband

VTU-18EC81

MODULE-1

Mr. Ajeya B
Asst. Professor, ECE Department
Canara Engineering College

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17EC81

Course In-charge: Mr. Ajeya B
Asst. Prof. Dept. of ECE

M1-L1: CONTENTS

- What is 4G?
- 1G to 4G mobile technology evolution highlights
- Course overview & references

M1-L1: SUMMARY

We have looked at:

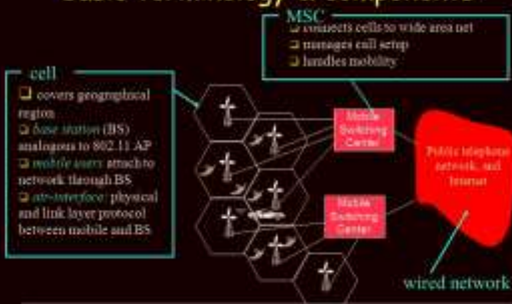
- What is 4G?
- 1G to 4G mobile technology evolution highlights
- Course overview & references

Next Lecture: Key Enablers for LTE features

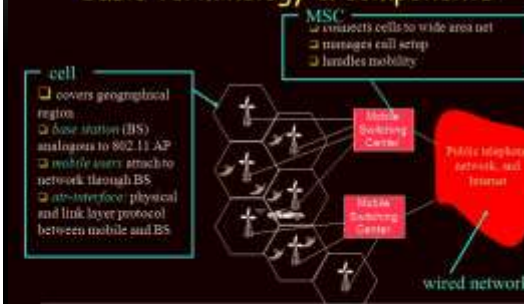
WHAT IS 4G?

- 4G is the fourth generation of mobile phone technology.
- 2G technology launched in the 1990s and made it possible to make digital phone calls and send texts (SMS).
- 3G came along in 2003 and made it possible to browse web pages, make video calls and download music and video on the move.
- 4G technology builds upon what 3G offers but does everything at a much faster speed.
- Of course, there's now 5G too, which follows the same pattern. It is the fifth generation and it is faster still.

Cellular Network Architecture: basic terminology & components



Cellular Network Architecture: basic terminology & components



Evolution of mobile phone communications

MODULATION SCHEMES

Communication system	Used modulation scheme
GSM (Global System for Mobile communications) 2G GPRS (General Packet Radio Service) 2.5G	GMSK
EDGE (Enhanced Data Rates for GSM Evolution) 2.75G	8PSK
CDMA 2000 (Code Division Multiple Access)	-QPSK in the forward channel (From BTS to MS). -OQPSK in the reverse channel
UMTS (Universal Mobile Telecommunications System) 3G	QPSK
HSDPA (High-Speed Downlink Packet Access) 3.5G	-Adaptive modulation: depending on signal quality and cell usage. - QPSK , data rate: 1.5 Mbit/s - 16QAM, data rate: 3.6 Mbit/s in good radio conditions.
Wi Fi (Wireless Fidelity)	BPSK , QPSK , 16 QAM , 64 QAM
WiMAX (the Worldwide Interoperability for Microwave Access) , Fixed and mobile	Adaptive Modulation: QPSK, 16 QAM, 64 QAM

SYLLABUS OVERVIEW

MODULE	Topics
I	• **Key Enablers for LTE features** • **Wireless Fundamentals**
II	• **Multicarrier Modulation** • **OFDMA and SCFDMA** • **Multiple Antenna Transmission and Reception**
III	• **Overview and Channel Structure of LTE** • **Downlink Transport Channel Processing**
IV	• **Uplink Channel Transport Processing** • **Physical Layer Procedures**
V	• **Radio Resource Management and Mobility Management**

TEXT BOOK AND REFERENCE

T1	Fundamentals of LTE -Arunabha Ghosh, Jan Zhang, Jefferey Andrews, Riaz Mohammed, Prentice Hall, 2010, Communications Engg. and Emerging Technologies
R1	LTE for UMTS Evolution to LTE-Advanced' Harri Holma and Antti Toskala, Second Edition - 2011, John Wiley & Sons, Ltd. Print ISBN: 9780470660003.
R2	EVOLVED PACKET SYSTEM (EPS) ; THE LTE AND SAE EVOLUTION OF 3G UMTS- Pierre Lescuyer and Thierry Lucidarme, 2008, John Wiley & Sons, Ltd. Print ISBN:978-0-470-05976-0.

COURSE OUTCOMES

This course enables students to:

1. Understand the basics of LTE standardization phases and specifications.
2. Explain the system architecture of LTE and E-UTRAN, the layer of LTE, based on the use of OFDMA and SC-FDMA principles.
3. Analyse the role of LTE radio interface protocols to set up, reconfigure and release the Radio Bearer, for transferring the EPS bearer.
4. Analyse the main factors affecting LTE performance including mobile speed and transmission bandwidth.

MODULE-1

Syllabus

- **Key Enablers for LTE features: 1.** OFDM, 2. Single carrier FDMA & Single carrier FDE, 3. Channel Dependent Multiuser Resource Scheduling, 4. Multi antenna Techniques, 5. IP based Flat network Architecture, LTE Network Architecture. (Sec 1.4- 1.5 of Text).
- **Wireless Fundamentals:** Cellular concept, Broadband wireless channel (BWC), Fading in BWC, Modeling BWC – Empirical and Statistical models, Mitigation of Narrow band and Broadband Fading (Sec 2.2 – 2.7of Text).

➤ RBT LEVEL L1, L2

KEY ENABLERS FOR LTE FEATURES:

1. OFDM
2. Single carrier FDMA & Single carrier FDE
3. Channel Dependent Multiuser Resource Scheduling
4. Multi antenna Techniques
5. IP based Flat network Architecture

KEY ENABLERS FOR LTE FEATURES

1. OFDM:

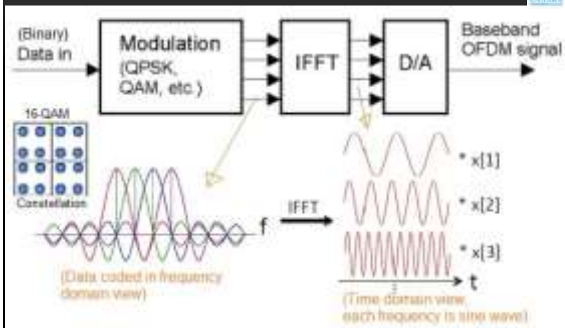
- One of the key differences between existing 3G systems and LTE is the use of Orthogonal Frequency Division Multiplexing (OFDM) as the underlying modulation technology.
- Widely deployed 3G systems such as UMTS and CDMA2000 are based on Code Division Multiple Access (CDMA) technology.

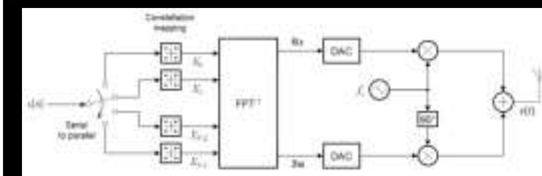
CDMA performs remarkably well for low data rate communications such as voice

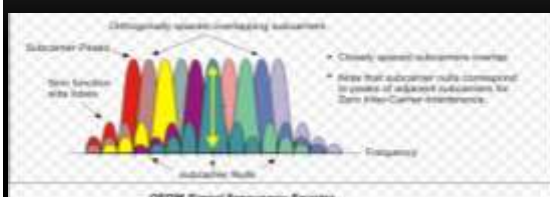
However, for high-speed applications, CDMA becomes untenable due to the large bandwidth needed to achieve useful amounts of spreading (Leading to ISI)

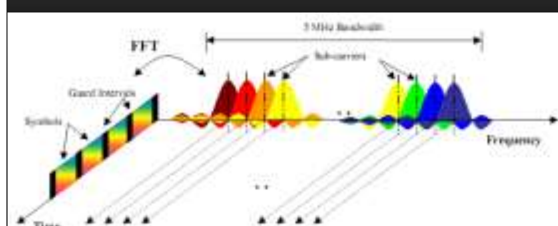
ADVANTAGES OF OFDM

- 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 and WiMAX.
- The following advantages of OFDM led to its selection for LTE:

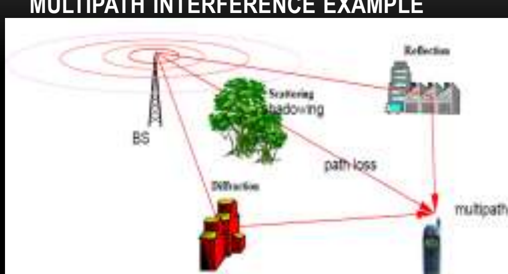








MULTIPATH INTERFERENCE EXAMPLE



ADVANTAGES OF OFDM…

ELEGANT SOLUTION TO MULTIPATH INTERFERENCE

- The critical challenge to high bit-rate transmissions in a wireless channel is intersymbol interference caused by multipath.
- In a multipath environment, when the time delay between the various signal paths is a significant fraction of the transmitted signal's symbol period, a transmitted symbol may arrive at the receiver during the next symbol and cause intersymbol interference (ISI).
- At high data rates, the symbol time is shorter; hence,it only takes a small delay to cause ISI, making it a bigger challenge for broadband wireless.
- OFDM is a multicarrier modulation technique that overcomes this challenge in an elegant manner.

ADVANTAGES OF OFDM…

- The basic idea behind multicarrier modulation is to divide a given high-bit-rate data stream into several parallel lower bit-rate streams and modulate each stream on separate carriers—often called subcarriers, or tones.
- Splitting the data stream into many parallel streams increases the symbol duration of each stream such that the multipath delay spread is only a small fraction of the symbol duration.
- OFDM is a spectrally efficient version of multicarrier modulation, where the subcarriers are selected such that they are all orthogonal to one another over the symbol duration, thereby avoiding the need to have non-overlapping subcarrier channels to eliminate inter-carrier interference.

ADVANTAGES OF OFDM…

- By making the guard interval larger than the expected multipath delay spread, ISI can be completely eliminated.
- Adding a guard interval, however, implies power wastage and a decrease in bandwidth efficiency

ADVANTAGES OF OFDM…

Reduced computational complexity:

- OFDM can be easily implemented using Fast Fourier Transforms (FFT/IFFT), and the computational requirements grow only slightly faster than linearly with data rate or bandwidth.

ADVANTAGES OF OFDM…

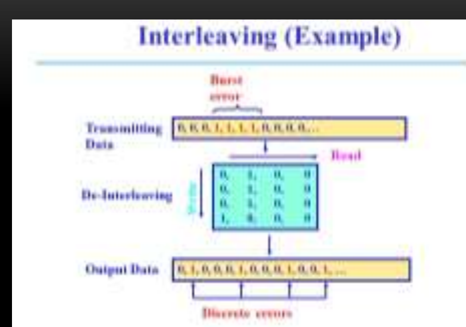
Graceful degradation of performance under excess delay:

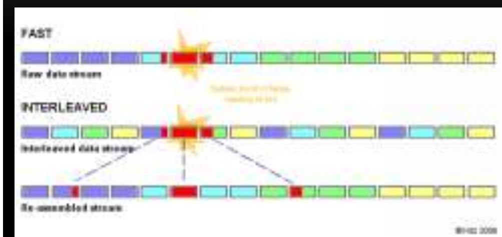
- The performance of an OFDM system degrades gracefully as the delay spread exceeds the value designed for Greater coding and low constellation sizes can be used to provide fallback rates that are significantly more robust against delay spread.
- In other words, OFDM is well suited for adaptive modulation and coding, which allows the system to make the best of the available channel conditions.

ADVANTAGES OF OFDM…

Exploitation of frequency diversity

- OFDM facilitates coding and interleaving across subcarriers in the frequency domain
  - *which can provide robustness against burst errors caused by portions of the transmitted spectrum undergoing deep fades.*
- OFDM also allows for the channel bandwidth to be scalable without impacting the hardware design of the base station and the mobile station.
- This allows LTE to be deployed in a variety of spectrum allocations and different channel bandwidths.





ADVANTAGES OF OFDM

Enables efficient multi-access scheme:

- OFDM can be used as a multi-access scheme by partitioning different subcarriers among multiple users.
- This scheme is referred to as OFDMA and is exploited in LTE.
- OFDMA offers the ability to provide fine granularity in channel allocation, which can be exploited to achieve significant capacity improvements, particularly in slow time-varying channels.

ADVANTAGES OF OFDM…

Robust against narrowband interference:

- OFDM is relatively robust against narrowband interference, since such interference affects only a fraction of the subcarriers.

Suitable for coherent demodulation:

- It is relatively easy to do pilot-based channel estimation in OFDM systems, which renders them suitable for coherent demodulation schemes that are more power efficient.

ADVANTAGES OF OFDM…

- **Facilitates use of MIMO:**
- MIMO- Refers to a collection of signal processing techniques that use multiple antennas at both the transmitter and receiver to improve system performance.
- For MIMO techniques to be effective, it is required that the channel conditions are such that the multipath delays do not cause intersymbol interference
  - *—in other words, the channel has to be a flat fading channel and not a frequency selective one.*
- At very high data rates, this is not the case and therefore *MIMO techniques do not work well in traditional broadband channels.*
- OFDM, however, converts a frequency selective broad band channel into several narrowband flat fading channels where the MIMO models and techniques work well.

ADVANTAGES OF OFDM…

Efficient support of broadcast services:

- By synchronizing base stations to timing errors well within the OFDM guard interval, it is possible to operate an OFDM network as a single frequency network (SFN).
- This allows broadcast signals from different cells to combine over the air to significantly enhance the received signal power
  - *thereby enabling higher data rate broadcast transmissions for a given transmit power.*
- LTE design leverages this OFDM capability to improve efficient broadcast services.

OFDM DISADVANTAGES

- OFDM also suffers from a few disadvantages.
- Main problem associated with OFDM signals having high peak-to-average ratio (PAR), which causes non-linearities and clipping distortion when passed through an RF amplifier.
- Mitigating this problem requires the use of expensive and inefficient power amplifiers with high requirements on linearity, which increases the cost of the transmitter and is wasteful of power.
- While the increased amplifier costs and power inefficiency of OFDM is tolerated in the downlink as part of the design, for the uplink LTE selected a variation of OFDM that has a lower peak-to-average ratio.
- The modulation of choice for the uplink is called Single Carrier Frequency Division Multiple Access (SC-FDMA).

KEY ENABLERS FOR LTE FEATURES…..

2. SC-FDE AND SC-FDMA

- To keep the cost down and the battery life up, LTE incorporated a power efficient transmission scheme for the uplink.
- Single Carrier Frequency Domain Equalization (SC-FDE) is conceptually similar to OFDM but instead of transmitting the Inverse Fast Fourier Transform (IFFT) of the actual data symbols, the data symbols are sent as a sequence of QAM symbols with a cyclic prefix added
- the IFFT is added at the end of the receiver.

SC-FDE AND SC-FDMA…

- SC-FDE retains all the advantages of OFDM such as multipath resistance and low complexity, while having a low peak-to-average ratio of 4-5dB.
- 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.
- SC-FDMA closely resembles OFDMA and can in fact be thought of as "DFT precoded OFDMA."
- SC-FDMA also preserves the PAR properties of SC-FDE but increases the complexity of the transmitter and the receiver.

KEY ENABLERS FOR LTE FEATURES…

3. CHANNEL DEPENDENT MULTIUSER RESOURCE SCHEDULING

- The OFDMA scheme used in LTE provides enormous flexibility in how channel resources are allocated.
- OFDMA allows for allocation in both time and frequency and it is possible to design algorithms to allocate resources in a flexible and dynamic manner to meet arbitrary throughput, delay, and other requirements.
- The standard supports dynamic, channel-dependent scheduling to enhance overall system capacity.

CHANNEL DEPENDENT MULTIUSER RESOURCE SCHEDULING. . .

- Given that each user will be experiencing uncorrelated fading channels, it is possible to allocate subcarriers among users in such a way that the overall capacity is increased.
- This technique, called frequency selective multiuser scheduling, calls for focusing transmission power in each user's best channel portion, thereby increasing the overall capacity.
- Frequency selective scheduling requires good channel tracking and is generally only viable in slow varying channels.
- For fast varying channels, the overhead involved in doing this negates the potential capacity gains.

KEY ENABLERS FOR LTE FEATURES…

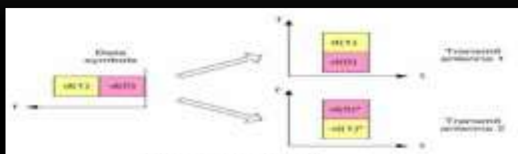
4. MULTI ANTENNA TECHNIQUES

- The LTE standard provides extensive support for implementing advanced multiantenna solutions to improve link robustness, system capacity, and spectral efficiency.
- Depending on the deployment scenario, one or more of the techniques can be used.
- Multiantenna techniques supported in LTE include
  - I. **Transmit diversity**
  - II. **Beamforming**
  - III. **Spatial multiplexing**
  - IV. **Multi-user MIMO**

MULTI ANTENNA TECHNIQUES…

I. TRANSMIT DIVERSITY

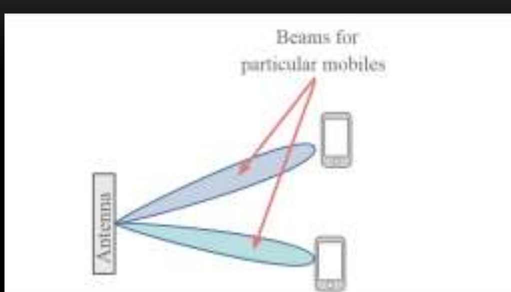
- This is a technique to combat multipath fading in the wireless channel.
- The idea here is to send copies of the same signal, coded differently, over multiple transmit antennas.
- LTE transmit diversity is based on space-frequency block coding (SFBC) techniques complemented with frequency shift time diversity (FSTD) when four transmit antenna are used.
- Transmit diversity is primarily intended for common downlink channels that cannot make use of channel-dependent scheduling.
- It can also be applied to user transmissions such as low data rate VoIP, where the additional overhead of channel-dependent scheduling may not be justified.
- Transmit diversity increases system capacity and cell range.

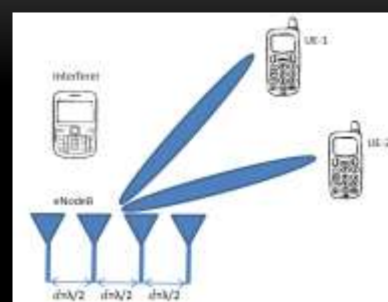

Transmit diversity (SFBC)

MULTI ANTENNA TECHNIQUES…

II. BEAMFORMING

- Multiple antennas in LTE may also be used to transmit the same signal appropriately weighted for each antenna element
  - such that the effect is to focus the transmitted beam in the direction of the receiver and away from interference, thereby improving the received signal-to-interference ratio.
- Beamforming can provide significant improvements in coverage range, capacity, reliability, and battery life.
- It can also be useful in providing angular information for user tracking.
- LTE supports beamforming in the downlink.



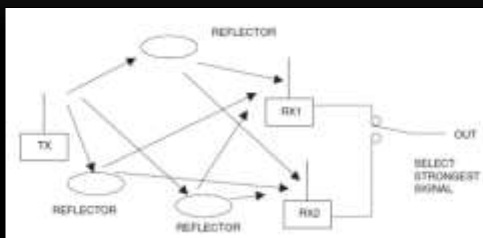


MULTI ANTENNA TECHNIQUES…

III. SPATIAL MULTIPLEXING

- The idea:
- Transmit independent channels separated in space
  - multiple independent streams can be transmitted in parallel over multiple antennas and
  - can be separated at the receiver using multiple receive chains through appropriate signal processing.
- This can be done as long as the multipath channels as seen by the different antennas are sufficiently decorrelated as would be the case in a scattering rich environment.
- In theory, spatial multiplexing provides data rate and capacity gains proportional to the number of antennas used.

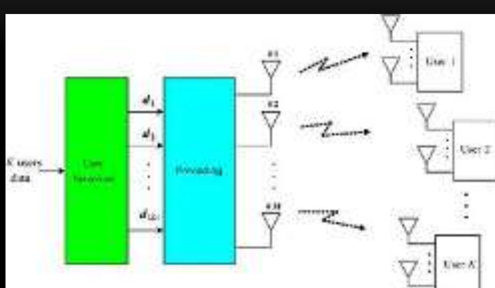
SPATIAL DIVERSITY…

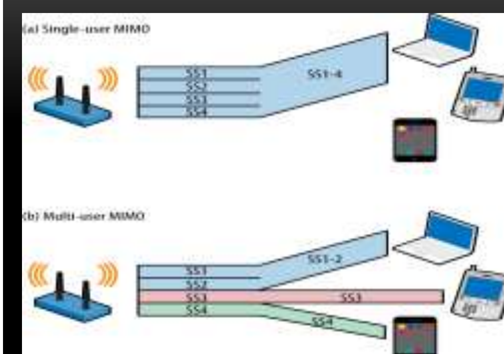


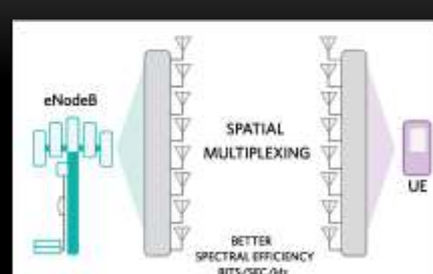
MULTI ANTENNA TECHNIQUES…

IV. MULTI-USER MIMO

- Since spatial multiplexing requires multiple transmit chains, it is currently not supported in the uplink due to complexity and cost considerations.
- However, multi-user MIMO (MU-MIMO), which allows multiple users in the uplink, each with a single antenna, to transmit using the same frequency and time resource, is supported.
- The signals from the different MU-MIMO users are separated at the base station receiver using accurate channel state information of each user obtained through uplink reference signals that are orthogonal between users





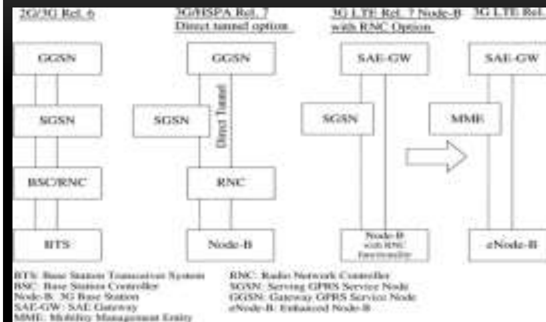


KEY ENABLERS FOR LTE FEATURES.....

5. IP BASED FLAT NETWORK ARCHITECTURE

- Besides the air-interface, the other radical aspect of LTE is the flat radio and core network architecture.
- "Flat" here implies fewer nodes and a less hierarchical structure for the network.
- The lower cost and lower latency requirements drove the design toward a flat architecture since fewer nodes obviously implies a lower infrastructure cost.
- It also means fewer interfaces and protocol-related processing, and reduced interoperability testing, which lowers the development and deployment cost.
- Fewer nodes also allow better optimization of radio interface, merging of some control plane protocols, and short session start-up time.

3GPP EVOLUTION TOWARD A FLAT LTE SAE ARCHITECTURE

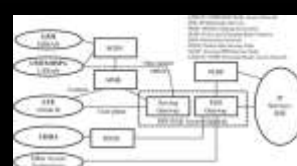


IP BASED FLAT NETWORK ARCHITECTURE…

- A key aspect of the LTE flat architecture is that all services, including voice, are supported on the IP packet network using IP protocols.
- Previous generation systems had a separate circuit-switched subnetwork for supporting voice with their own Mobile Switching Centers (MSC) and transport networks
- LTE envisions only a single evolved packet-switched core, the EPC, over which all services are supported, which could provide huge operational and infrastructure cost savings.
- Although LTE has been designed for IP services with a flat architecture, due to backwards compatibility reasons certain legacy, non-IP aspects of the 3GPP architecture such as the GPRS tunneling protocol and PDCP (packet data convergence protocol) still exists within the LTE network architecture.

LTE NETWORK ARCHITECTURE

Evolved Packet Core architecture.



SERVING GATEWAY (SGW):

- The SGW acts as a demarcation point between the RAN and core network, and manages user plane mobility.
- It serves as the mobility anchor when terminals move across areas served by different eNode-B elements in E-UTRAN, as well as across other 3GPP radio networks such as GERAN and UTRAN.
- SGW does downlink packet buffering and initiation of network-triggered service request procedures.
- Other functions include lawful interception, packet routing and forwarding, transport level packet marking in the uplink and the downlink, accounting support for per user, and inter-operator charging.

PACKET DATA NETWORK GATEWAY (PGW):

- The PGW acts as the termination point of the EPC toward other Packet Data Networks (PDN) such as the Internet, private IP network, or the IMS network providing end-user services.
- It serves as an anchor point for sessions toward external PDN and provides functions such as user IP address allocation, policy enforcement, packet filtering, and charging support.
- Policy enforcement includes operator-defined rules for resource allocation to control data rate, QoS, and usage.
- Packet filtering functions include deep packet inspection for application detection.

MOBILITY MANAGEMENT ENTITY (MME):

- The MME performs the signaling and control functions to manage the user terminal access to network connections, assignment of network resources, and mobility management function such as idle mode location tracking, paging, roaming, and handovers.
- MME controls all control plane functions related to subscriber and session management.
- The MME provides security functions such as providing temporary identities for user terminals, interacting with Home Subscriber Server (HSS) for authentication, and negotiation of ciphering and integrity protection algorithms.
- It is also responsible for selecting the appropriate serving and PDN gateways, and selecting legacy gateways for hand-overs to other GERAN or UTRAN networks.
- Further, MME is the point at which lawful interception of signaling is made. It should be noted that an MME manages thousands of eNode-B elements, which is one of the key differences from 2G or 3G platforms using RNC and SGSN platforms.

POLICY AND CHARGING RULES FUNCTION (PCRF):

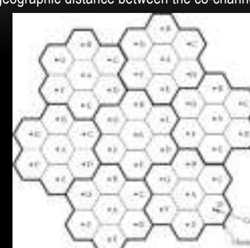
- The Policy and Charging Rules Function (PCRF) is a concatenation of Policy Decision Function (PDF) and Charging Rules Function (CRF).
- The PCRF interfaces with the PDN gateway and supports service data flow detection, policy enforcement, and flow-based charging.
- The PCRF was actually defined in Release 7 of 3GPP ahead of LTE. Although not much deployed with pre-LTE systems, it is mandatory for LTE.
- Release 8 further enhanced PCRF functionality to include support for non-3GPP access (e.g., Wi-Fi or fixed line access) to the network.

THE CELLULAR CONCEPT

- In cellular systems, the service area is subdivided into smaller geographic areas called *cells* that are each served by their own base station.
- In order to minimize interference between cells, the transmit power level of each base station is regulated to be just enough to provide the required signal strength at the cell boundaries.
- Then, as we have seen, propagation path loss allows for spatial isolation of different cells operating on the same frequency channels at the same time.
- Therefore, the same frequency channels can be reassigned to different cells, as long as those cells are spatially isolated.

THE CELLULAR CONCEPT

- The reuse of the same frequency channels should be intelligently planned in order to maximize the geographic distance between the co-channel base stations.



THE CELLULAR CONCEPT

- Cellular systems allow the overall system capacity to increase by simply making the cells smaller and turning down the power.
- In this manner, cellular systems have a very desirable scaling property

  —more capacity can be supplied by installing more base stations.
- As the cell size decreases, the transmit power of each base station also decreases correspondingly.
- For example, if the radius of a cell is reduced by half when the propagation path loss exponent is 4, the transmit power level of a base station is reduced by 12 dB (=10 log 16 dB).

THE CELLULAR CONCEPT...

- Since cellular systems support user mobility, seamless call transfer from one cell to another should be provided.
- The handoff process provides a means of the seamless transfer of a connection from one base station to another.
- Achieving smooth handoffs is a challenging aspect of cellular system design.
- Although small cells give a large capacity advantage and reduce power consumption, their primary drawbacks are the need for more base stations (and their associated hardware costs), and the need for frequent handoffs.
- The offered traffic in each cell also becomes more variable as the cell shrinks, resulting in inefficiency.
- As in most aspects of wireless systems, an appropriate tradeoff between these competing factors needs to be determined depending on the system requirements.

ANALYSIS OF CELLULAR SYSTEMS

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

ANALYSIS OF CELLULAR SYSTEMS

- Performance (capacity, reliability) is determined by the SIR,
  i.e., the amount of desired power to the amount of transmitted power.
- Therefore, if all users (or base stations) increased or decreased their power at once, the SIR and hence the performance is typically unchanged
  —which is known as an interference-limited system.
- The spatial isolation between co-channel cells can be measured by defining the parameter *Z*, called *co-channel reuse ratio*, as the ratio of the distance to the center of the nearest co-channel cell (*D*) to the radius of the cell.

- In a hexagonal cell structure, the co-channel reuse ratio is given by

$$Z = \frac{D}{R} = \sqrt{3/f}$$

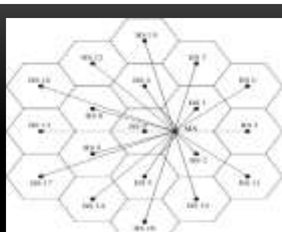
where $1/f$ is the size of a cluster and the inverse of the frequency reuse factor

- the overall spectral efficiency decreases with the size of a cluster.
  - so f should be chosen just small enough to keep the received signal-to-interference-plus-noise ratio (SINR) above acceptable levels.

- If the number of interfering cells is N_I, the SIR for a mobile station can be given by

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{N_I} I_i}$$

- where S is the received power of the desired signal and Ii is the interference power from the ith co-channel base station.
- The received SIR depends on the location of each mobile station, and it should be kept above an appropriate threshold for reliable communication
- SIR at the cell boundaries is of great interest since this corresponds to the worst interference scenario.



- the received SIR for the worst case given in following figure is expressed as

$$\frac{S}{I} = \frac{\chi_0}{\chi_0 + \sum_{i=1}^{2} \chi_i + 2^{-\alpha} \sum_{i=3}^{5} \chi_i + (2.633)^{-\alpha} \sum_{i=6}^{11} \chi_i}$$

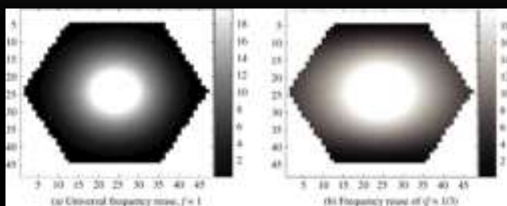
where χ_i denotes the shadowing from the *i*th base station.

If the mean and standard deviation of the lognormal distribution are μ and σ in dB, the outage probability is derived in the form of *Q* function

Outage Probability

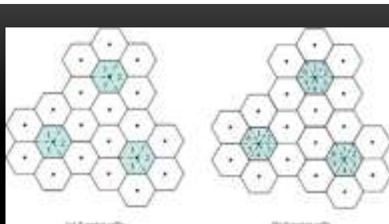
$$P_{out} = P[\text{SIR} < \gamma] = Q\left(\frac{\gamma - \mu}{\sigma}\right)$$

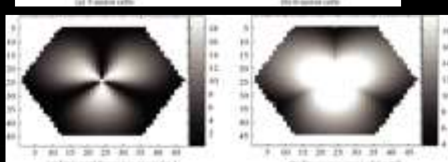
where γ is the threshold SIR level in dB.



SECTORING

- 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, as frequency reuse does.
- A popular technique is to sectorize the cells, which is effective if frequencies are reused in each cell.
- By using directional antennas instead of an omni-directional antenna at the base station, the co-channel interference can be significantly reduced.

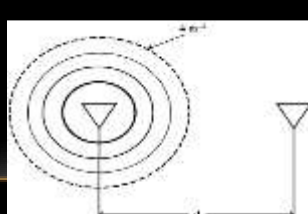




THE BROADBAND WIRELESS CHANNEL: PATH LOSS AND SHADOWING

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, the propagated signal energy expands over a spherical wavefront,
  - so the energy received at an antenna a distance d away is inversely proportional to the sphere surface area, $4\pi d^2$.



PATH LOSS

- 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 and transmitted powers and λ is the wavelength.
- The received power fall offs quadratically with the carrier frequency. In other words, for a given transmit power, the range is decreased when higher frequency waves are used.
- This has important implications for high-data rate systems, since most large bandwidths are available at higher frequencies.

PATH LOSS…

- The terrestrial propagation environment is not free space.
- Because a reflected wave often experiences a 180-degree phase shift, at relatively large distances (usually over a kilometer) the reflection serves to create destructive interference.
- The common *2-ray approximation* for path loss is:

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

PATH LOSS…

- In order to more accurately describe different propagation environments, empirical models are often developed using experimental data.
- One of the simplest and most common is the *empirical path loss formula*:

$$P_r = P_t P_o \left(\frac{d_o}{d}\right)^\alpha$$

- which groups all the various effects into two parameters, the path loss exponent α and the measured path loss P_o at a reference distance of d_o, which is often chosen as 1 meter.

EXAMPLE

- Consider a user in the downlink of a cellular system, where the desired base station is at a distance of 500 meters (.5 km), and there are numerous nearby interfering base stations transmitting at the same power level. If there are three interfering base stations at a distance of 1 km, three at a distance of 2 km, and ten at a distance of 4 km, use the empirical path loss formula to find the signal-to-interference ratio (SIR, i.e., the noise is neglected) when α = 3, and then when α = 5.
- Solution:
- For α = 3 and d_0 in units of kilometers, the desired received power is

$$P_{r,d} = P_t P_o d_o^3 (0.5)^{-3}$$

- and the interference power is

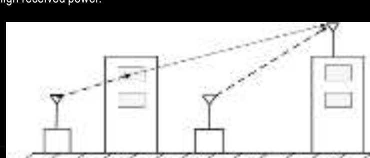
$$P_{r,I} = P_t P_o d_o^3 \left[3(1)^{-3} + 3(2)^{-3} + 10(4)^{-3}\right]$$

- The SIR expressions compute to

$$\mathrm{SIR}(\alpha = 3) = \frac{P_{r,d}}{P_{r,I}} = 2.27 \quad (3.55\ \mathrm{dB}),$$
$$\mathrm{SIR}(\alpha = 5) = 10.32 \quad (10.32\ \mathrm{dB}).$$

SHADOWING

- Path loss models attempt to account for the distance-dependent relationship between transmitted and received power.
- Many factors other than distance can have a large effect on the total received power.
- Obstacles such as trees and buildings may be located between the transmitter and receiver, and cause temporary degradation in received signal strength,
  - while on the other hand a temporary line-of-sight transmission path would result in abnormally high received power.



SHADOWING

- Since modelling the locations of all objects in every possible communication environment is generally impossible,
  - the standard method of accounting for these variations in signal strength is to introduce a random effect called *shadowing*.
- With shadowing, the empirical path loss formula becomes

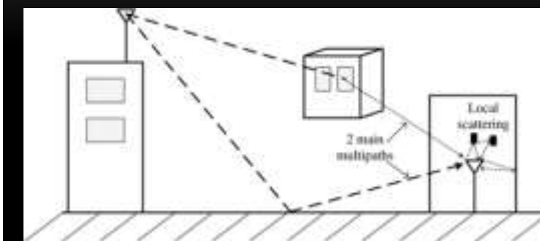
$$P_r = P_t P_o \chi \left(\frac{d_o}{d}\right)^\alpha$$

  - where χ is a sample of the *shadowing* random process.
- Hence, the received power is now also modelled as a random process.

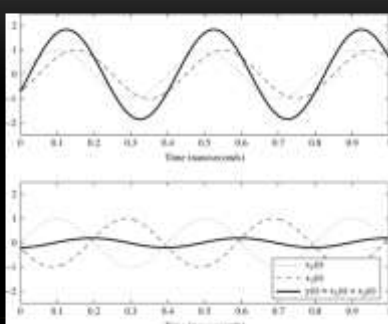
BROADBAND WIRELESS CHANNEL (BWC)

- One of the more intriguing 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.

FADING IN BWC

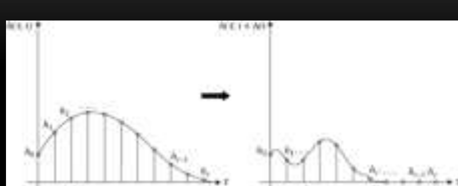


FADING IN BWC



FADING IN BWC

- As either the transmitter or receiver move relative to each other, the channel response **h**(t) will change.
- This channel response can be thought of as having two dimensions: a delay dimension τ and a time-dimension t.
- Since the channel changes over distance (and hence time), the values of $h_0, h_1, \ldots, h_v$ may be totally different at time t vs time $t + \Delta t$.



The delay τ corresponds to how *long* the channel impulse response lasts.
The channel is time varying, so the channel impulse response is also a function of time, i.e., $h(\tau, t)$, and can be quite different at time $t + \Delta t$ than it was at time t.

- The most important and fundamental function used to statistically describe broadband fading channels is the two-dimensional autocorrelation function, $A(\Delta\tau, \Delta t)$.

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

- Channels that can be described by the autocorrelation in above equation are thus referred to as Wide Sense Stationary Uncorrelated Scattering (WSSUS), which is the most popular model for wideband fading channels

DELAY SPREAD AND COHERENCE BANDWIDTH

- The delay spread is a very important property of a wireless channel, since it specifies the duration of the channel impulse response $h(\tau, t)$.
- the delay spread is the amount of time that elapses between the first arriving path and the last arriving (non-negligible) path
- The delay spread can be found by inspecting

$$A(\Delta\tau, 0) \triangleq A_\tau(\Delta\tau)$$

- $A_\tau(\Delta\tau)$ is often referred to as the *Multipath Intensity Profile*, or *power delay profile*.
- If $A_\tau(\Delta\tau)$ has non-negligible values from $(0, \tau_{max})$, the maximum delay spread is τ_{max}.
- Intuitively, this is an important definition because it specifies how many taps v will be needed in the discrete representation of the channel impulse response

$$v \approx \frac{\tau_{max}}{T_s},$$

COHERENCE BANDWIDTH

- **Coherence bandwidth** is a statistical measurement of the range of frequencies over which the channel can be considered "flat“
- The channel coherence bandwidth B_c is the frequency domain dual of the channel delay spread.
- The coherence bandwidth gives a rough measure for the maximum separation between a frequency f_1 and a frequency f_2 where the channel frequency response is correlated.
- That is:

  $|f_1 - f_2| \le B_c$ $H(f_1) \approx H(f_2)$
  $|f_1 - f_2| > B_c$ $H(f_1)$ and $H(f_2)$ are uncorrelated

- B_c is a ballpark value describing the range of frequencies over which the channel stays constant
- Given the channel delay spread, it can be shown that

$$B_c \approx \frac{1}{5\tau_{max}} \approx \frac{1}{\tau_{max}}$$

DOPPLER SPREAD AND COHERENCE TIME

- Delay spread and coherence bandwidth are parameters which describe the time dispersive nature of the channel in a local area.
  - However, they do not offer information about the time varying nature of the channel caused by either relative motion between the mobile and base station, or by movement of objects in the channel.
- Doppler spread and coherence time are parameters which describe the time varying nature of the channel in a small-scale region.

- Doppler power spectrum is caused by *motion* between the transmitter and receiver. The Doppler power spectrum is the Fourier transform of $A_t(\Delta t)$, that is:

$$\rho_t(\Delta f) = \int_{-\infty}^{\infty} A_t(\Delta t) e^{-j2\pi\Delta f\Delta t} d(\Delta t)$$

- The Doppler spread is $f_D = \frac{v f_c}{c}$
  - where v is the maximum speed between the transmitter and receiver, f_c is the carrier frequency, and c is the speed of light

COHERENCE TIME

- **Coherence time** is the **time** duration over which the channel impulse response is considered to be not varying.
- The coherence time and Doppler spread are also inversely related,

$$T_c \approx \frac{1}{f_D}$$

- This makes intuitive sense: if the transmitter and receiver are moving fast relative to each other and hence the Doppler is large, the channel will change much more quickly than if the transmitter and receiver are stationary.

Doppler Spreads and Approximate Coherence Times for LTE at Pedestrian, Vehicular, and Maximum Speeds

f_c	Speed (km/hr)	Speed (mph)	Max. Doppler, f_D (Hz)	Coherence Time, $T_c \approx \frac{1}{f_D}$ (msec)
700MHz	2	1.2	1.3	775
700MHz	45	27	29.1	34
700MHz	350	210	226.5	4.4
2.5GHz	2	1.2	4.6	200
2.5GHz	45	27	104.2	10
2.5GHz	350	210	810	1.2

- At high frequency and mobility, the channel may change up to 1000 times per second
- Which places a large burden on overhead channels, channel estimation algorithms
- And makes the assumption of accurate transmitter channel knowledge questionable
- Additionally, the large Doppler at high mobility and frequency can also degrade the OFDM subcarrier orthogonality

ANGULAR SPREAD AND COHERENCE DISTANCE

- The rms angular spread of a channel can be denoted as θ_{rms}, and refers to the statistical distribution of the angle of the arriving energy.
- A large θ_{rms} implies that channel energy is coming in from many directions, whereas a small θ_{rms} implies that the received channel energy is more focused.
- A large angular spread generally occurs when there is a lot of local scattering, and this results in more statistical diversity in the channel, whereas more focused energy results in less statistical diversity.

COHERENCE DISTANCE

- Spatial Distance over which the channel doesn't change appreciably
- The dual of angular spread is coherence distance, D_c.
- As the angular spread increases, the coherence distance decreases, and vice versa.
- A coherence distance of *d* means that any physical positions separated by *d* have an essentially uncorrelated received signal amplitude and phase.

$$D_c \approx \frac{.2\lambda}{\theta_{\text{rms}}},$$

- For the case of Rayleigh fading, which assumes a uniform angular spread, the well-known relation is

$$D_c \approx \frac{9\lambda}{16\pi}$$

- An important trend to note from the above relations is that the coherence distance increases with the carrier wavelength λ, so higher-frequency systems have shorter coherence distances.

VC

- Angular spread and coherence distance are particularly important in multiple antenna systems.
- The coherence distance gives a rule of thumb for how far antennas should be spaced apart, in order to be statistically independent.
- If the coherence distance is very small, antenna arrays can be effectively employed to provide rich diversity.

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 major classes of models are
  1. ***Statistical***
     - ✓ are simpler, and are useful for analysis and simulations.
  2. ***Empirical***
     - ✓ are more complicated but usually represent a specific type of channel more accurately.

STATISTICAL CHANNEL MODELS...

- Overview of Statistical methods that can be used to characterize the amplitude and power of $r(t)$ when all the reflections arrive at about the same time.

Popular models:

Rayleigh and Ricean Distributions

- In mobile radio channels, the Rayleigh distribution is commonly used to describe the statistical time varying nature of the received fading signal
- When there is a dominant (non-fading) signal component present such as LOS propagation path, the small scale fading envelope distribution is Ricean
- And **Nakagami-M fading**

RAYLEIGH FADING

- If the number of scatterers is large and the angles of arrival between them are uncorrelated, $r_I(t)$ and $r_Q(t)$ follow two independent time-correlated Gaussian random processes.
- Consider value of $r(t)$ at time $t = 0$, and note that $r(0) = r_I(0) + r_Q(0)$.
- Since $r_I(0)$ and $r_Q(0)$ are Gaussian random variables,

  distribution of the envelope amplitude $|r| = \sqrt{r_I^2 + r_Q^2}$ is Rayleigh
- and the received power $|r|^2 = r_I^2 + r_Q^2$ is exponentially distributed

- Formally the received envelope distribution,

$$f_{|r|}(x) = \frac{2x}{P_r} e^{-x^2/P_r}, \quad x \ge 0,$$

And

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

P_r is the average received power due to shadowing and path loss

The path loss and shadowing determine the mean received power, and the total received power fluctuates around this mean due to the fading.

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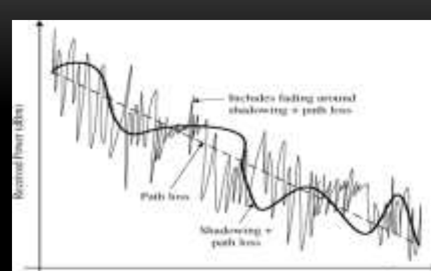


Figure: The three major channel attenuation factors are shown in terms of their relative spatial scales.

- the Gaussian random variables r_I and r_Q each have zero mean and variance $\sigma^2 = P_r/2$. The phase of $r(t)$ is defined as

$$\theta_r = \tan^{-1}\left(\frac{r_Q}{r_I}\right)$$

- which is uniformly distributed from 0 to 2π, or equivalently from $[-\pi, \pi]$ any other contiguous full period of the carrier signal

LINE-OF-SIGHT CHANNELS —THE RICEAN DISTRIBUTION

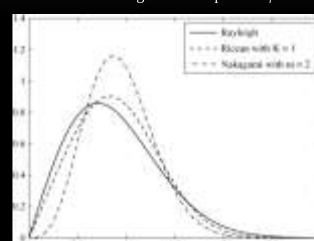
- For a LOS signal, the received envelope distribution is more accurately modelled by a Ricean distribution, which is given by

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

- where μ^2 is the power of the LOS component and I_0 is the 0th order, modified Bessel function of the first kind.
- it is a generalization of the Rayleigh distribution
- This can be confirmed by observing that $\mu = 0 \Rightarrow I_0\left(\frac{x\mu}{\sigma^2}\right) = 1$, so the Ricean distribution reduces to the Rayleigh distribution in the absence of a LOS component.

- The Ricean distribution is usually a more accurate depiction of wireless broadband systems
  - which typically have one or more dominant components.
- This is especially true of fixed wireless systems, which do not experience fast fading and often are deployed to maximize LOS propagation

- Probability distributions $f_{|r|}(x)$ for Rayleigh, Ricean w/K = 1, and Nakagami with m= 2. All have average received power P_r = 1.



A MORE GENERAL MODEL: NAKAGAMI-M FADING

- The probability density function (PDF) of Nakagami fading is parameterized by m and given as

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

- Nakagami distribution can in many cases be used in tractable analysis of fading channel performance
- Additionally, it is more general as $m = (K + 1)^2/(2K + 1)$ gives an approximate Ricean distribution, and m = 1 gives a Rayleigh.

- As $m \rightarrow \infty$, the receive power tends to be a constant, P_r. The power distribution for Nakagami fading is

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

LTE CHANNEL MODELS FOR PATH LOSS

- Also referred to as "3GPP" channel models as they derive from the earlier channel models from the same standards body.
- The path loss can then be specified by empirical models for these different scenarios.
- For the 3GPP macro-cell environment, the path loss is given by the so-called COST Hata model.

$$PL_u[\text{dB}] = (44.9 - 6.55\log_{10}(h_b))\log_{10}(d) + 46.3 + 33.9\log_{10}(f_c) - 13.82\log_{10}(h_b) - a(h_m) + C_m$$

Where h_b is the BS antenna height in meters,

f_c is the carrier frequency in MHz,

d is the distance between the BS and MS in kilometers

$a(h_m)$ is a relatively negligible correction function for the mobile height defined as $a(h_m) = (1.1\log_{10}(f_c) - 0.7)h_m - 1.56\log_{10}(f_c) - 0.8$ where h_m is the mobile antenna height in meters.

- The COST Hata model is generally considered to be accurate when d is between 100 meters and 20 km and f_c (1500, 2000) MHz.

- Several slightly different Hata models exist, depending on whether the environment is urban, suburban, or for open areas.
- The Hata Model for Urban Areas is:

$$PL_u[\text{dB}] = (44.9 - 6.55\log_{10}(h_b))\log_{10}(d) + 69.55 + 26.16\log_{10}(f_c) - 13.82\log_{10}(h_b) + C_1$$

- where C_1 is a corrective factor that further varies depending on the size of the city, but for a medium or small city is

$$C_1 = 0.8 + (1.1\log_{10}(f_c) - 0.7)h_m - 1.56\log_{10}(f_c)$$

- The Hata Model for both Suburban and Open Areas derives from the Urban model.
- The Suburban path loss is given as

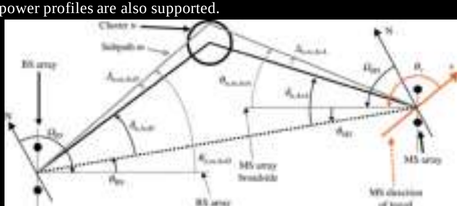
[illegible]

- while the Open Area Hata Model is
- $PL_o[\text{dB}] = PL_u - 4.78(\log_{10} f_c)^2 + 18.33\log_{10}(f_c) - 40.94$

"We do not suggest that readers spend too long searching for deep meaning in these equations—they can be viewed essentially as statistical curvefits based on experimentation."

LTE CHANNEL MODELS FOR MULTIPATH

- The number of paths N ranges from 1 to 20 and is dependent on the specific channel models.
- For example, the 3GPP channel model has $N = 6$ multipath components.
- The power distribution normally follows the exponential profile, but other power profiles are also supported.



- Each multipath component further corresponds to a cluster of M subpaths, where each subpath characterizes the incoming signal from a scatterer.
- The M subpaths define a cluster of adjacent scatterers, and therefore have the same multipath delay.
- The M subpaths have random phases and subpath gains, specified by the given procedure in different stands.
- For 3GPP, the phases are random variables uniformly distributed from 0 to 360 degrees

- The Angle of Departure (AoD) is usually within a narrow range in outdoor applications due to the lack of scatterers around the BS transmitter, and is often assumed to be uniformly distributed in indoor applications.
- The Angle of Arrival (AoA) is typically assumed to be uniformly distributed due to the abundance of local scattering around the mobile receiver.
- The final channel is created by summing up the *M* subpath components.
- In the 3GPP channel model, the *n*th multipath component from the *u*th transmit antenna to the *s*th receive antenna, is given as

$$h_{u,s,n}(t) = \sqrt{\frac{P_n \sigma_{SF}}{M}} \sum_{m=1}^{M} \begin{pmatrix} \sqrt{G_{BS}(\theta_{n,m,AoD})} \exp\left(j\left[k d_s \sin(\theta_{n,m,AoD}) + \Phi_{n,m}\right]\right) \\ \times \sqrt{G_{MS}(\theta_{n,m,AoA})} \exp\left(j k d_u \sin(\theta_{n,m,AoA})\right) \\ \times \exp\left(j k \|\mathbf{v}\| \cos(\theta_{n,m,AoA} - \theta_v) t\right) \end{pmatrix}$$

- Pn is the power of the nth path, following exponential distribution.
- σSF is the lognormal shadow fading, applied as a bulk parameter to the n paths. The shadow fading is determined by the delay spread (DS), angle spread (AS), and shadow fading (SF) parameters, which are correlated random variables generated with specific procedures.
- M is the number of subpaths per path.
- θn,m,AoD is the AoD for the mth subpath of the nth path.
- θn,m,AoA is the AoA for the mth subpath of the nth path.
- GBS (θn,m,AoD) is the BS antenna gain of each array element.
- GBS (θn,m,AoA) is the MS antenna gain of each array element.
- k is the wave number where λ is the carrier wavelength in meters.
- ds is the distance in meters from BS antenna element s from the reference (s = 1) antenna.
- du is the distance in meters from MS antenna element u from the reference (u = 1) antenna.
- Φn,m is the phase of the mth subpath of the nth path, uniformly distributed between 0 and 360 degrees.
- ||v|| is the magnitude of the MS velocity vector, which consists of the velocity of the MS array elements.
- θv is the angle of the MS velocity vector.

LTE SEMI-EMPIRICAL CHANNEL MODELS

- Constructing a fully empirical channel model is relatively time-consuming and computationally intensive due to the huge number of parameters involved.
- Therefore semi-empirical channel models provide the accurate inclusion of the practical parameters in a real wireless system, while maintaining the simplicity of statistical channel models.
- Well-known examples of the simpler multipath channel models include the 3GPP2 Pedestrian A, Pedestrian B, Vehicular A, and Vehicular B models, suited for low-mobility pedestrian mobile users and higher mobility vehicular mobile users.

Table 2.4 Extended Pedestrian A Model

Delay [nsec]	0	30	70	90	110	190	410
Relative Power [dB]	0	−1.0	−2.0	−3.0	−8.0	−17.2	−20.8

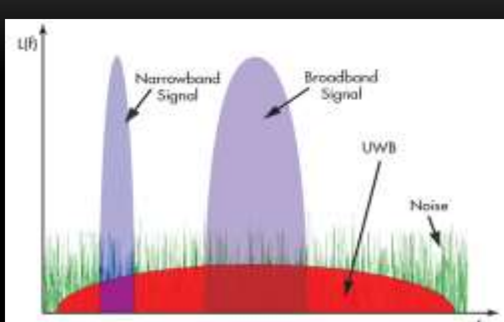
Table 2.5 Extended Vehicular A Model

Delay [nsec]	0	30	150	310	370	710	1090	1730	2510
Relative Power [dB]	0	−1.5	−1.4	−3.6	−0.6	−9.1	−7.0	−12.0	−16.9

Table 2.6 Extended Typical Urban Model

Delay [nsec]	0	50	120	200	230	500	1600	2300	5000
Relative Power [dB]	−1.0	−1.0	−1.0	0.0	0.0	0.0	−3.0	−5.0	−7.0

- The Pedestrian A is a flat fading model corresponding to a single Rayleigh fading component with a speed of 3 km/hr.
- Pedestrian B model corresponds to a power delay profile with four paths of delays at 3 km/hr
- Vehicular A model, the mobile speed is specified at 30 km/hr.
- vehicular B model, the mobile speed is 30 km/h, with six multipath components



MITIGATION OF NARROWBAND FADING

The Effects of Unmitigated Fading

- The probability of bit error (BER) is the principle metric of interest for the physical layer (PHY) of a communication system.
- For a QAM-based modulation system, the BER in an additive white Gaussian noise (AWGN, no fading) can accurately be approximated by the following bound

$$P_b \le 0.2e^{-1.5SNR/(M-1)}$$

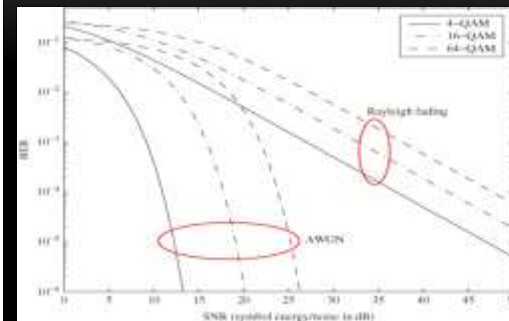
where *M* ≥ 4 is the M-QAM

- Decreasing the SNR linearly causes the BER to increase exponentially.
- Since the channel is constant, the BER is constant over time.

- However, in a fading channel, the BER become a random variable that depends on the instantaneous channel strength
- occasional instances, the channel is in a deep fade therefore dominate the average BER.
- When the required average BER is very low (say 10^{-6}), virtually all errors are made while in deep fades.
- The average BER varies depending on the precise constellation used, but roughly follows the relationship

$$P_b \propto \frac{1}{SNR}$$

- For fading channel, BER goes down very slowly with SNR



- A more common and relevant measure in LTE is the Packet Error Rate (PER), or equivalently Block Error Rate (BLER) or Frame Error Rate (FER).
- All these measures refer to the probability that at least one bit is in error in a block of *L* bits.
- This is the more relevant measure since the detection of a single bit error in a packet by the Cyclic Redundancy Check (CRC) requires the packet to either be discarded by the receiver or retransmitted.
- An expression for PER is

$$\text{PER} \leq 1-(1-P_b)^L$$

- where P_b is the BER and L is the packet length.

MITIGATION OF NARROWBAND FADING

The main techniques for mitigation of narrowband fading are

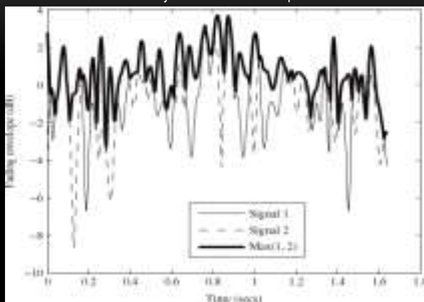
- Spatial Diversity
- Coding and Interleaving
- Automatic Repeat Request (A RQ)
- Adaptive Modulation and Coding (AMC)
- Combining Narrowband Diversity Techniques

SPATIAL DIVERSITY

- Spatial diversity is a powerful form of diversity, and particularly desirable since it does not necessitate redundancy in time or frequency.
- It usually is 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.

- As long as the antennas are spaced sufficiently, the two received signals will undergo approximately uncorrelated fading.
- This type of diversity is sensibly called *selection diversity*.
- Even though this simple technique completely discards "half" of the received signal, most of the deep fades can be avoided and the average SNR is also increased. .

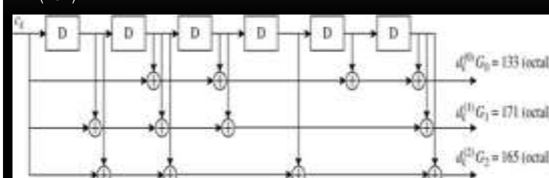
Simple two-branch selection diversity eliminates most deep fades.



CODING AND INTERLEAVING

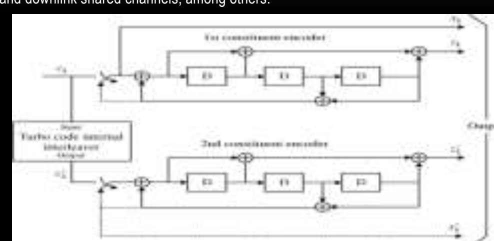
- A ubiquitous form of diversity in nearly all contemporary digital communication systems is the natural pair of coding and interleaving.
- Traditionally thought of as a form of time diversity, in a multicarrier system they also can capture frequency diversity.
- By coding, we mean the use of error correction codes (ECCs), which is also sometimes known as forward error correction.
- ECCs efficiently introduce redundancy at the transmitter to allow the receiver to recover the input signal even if the received signal is significantly degraded by attenuation, interference, and noise.

- The rate 1/3 convolutional encoder defined by LTE for use in the Broadcast Channel (BCH).



- Turbo codes build upon convolutional codes to provide increased resilience to errors through iterative decoding

The rate 1/3 parallel concatenated turbo encoder defined by LTE for use in the uplink and downlink shared channels, among others.



AUTOMATIC REPEAT REQUEST (ARQ)

- Another technique that is used LTE is ARQ (automatic repeat request) and Hybrid-ARQ.
- ARQ simply is a MAC layer retransmission protocol that allows erroneous packets to be quickly retransmitted.
- Such a protocol works in conjunction with PHY layer ECCs and parity checks to ensure reliable links even in hostile channels.
- Since a single bit error causes a packet error, with ARQ the entire packet must be retransmitted even when nearly all of the bits already received were correct, which is clearly inefficient.

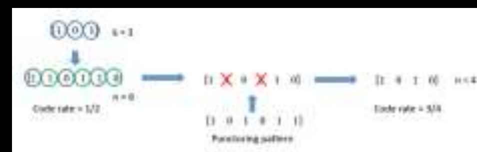
V

- Imagine the situation where the same packet is "dropped" twice in a row, despite the fact that 99% of its bits were received correctly.
- In such cases, it is likely that every bit was received correctly in one of the two packets.

HYBRID-ARQ

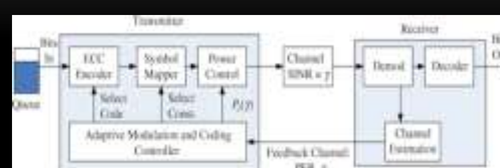
- Hybrid-ARQ combines the two concepts of ARQ and FEC to avoid such waste, by combining received packets.
- Hybrid-ARQ, therefore, is able to extract additional time diversity in a fading channel as well.
- In H-ARQ a channel encoder such as a convolution encoder or turbo encoder is used to generate additional redundancy to the information bits.
- However, instead of transmitting all the encoded bits (systematic bits + redundancy bits), only a fraction of the encoded bits are transmitted.
- This is achieved by puncturing some of the encoded bits to create an effective code rate greater than the native code rate of the encoder

- Short illustration of the puncturing procedure



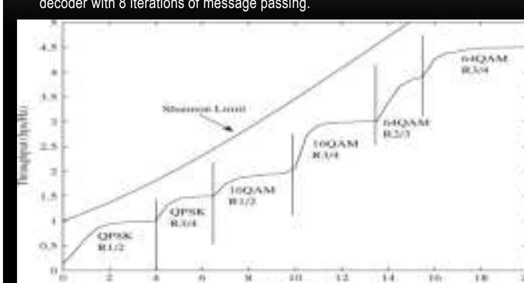
ADAPTIVE MODULATION AND CODING (AMC)

- LTE systems employ AMC in order to take advantage of fluctuations in the channel over time and frequency.
- The basic idea is quite simple:
  - ✓ transmit as high a data rate as possible when and where the channel is good, and
  - ✓ transmit at a lower rate when and where the channel is poor in order to avoid excessive dropped packets.
- Lower data rates are achieved by using a small constellation—such as QPSK—and low rate error correcting codes such as rate turbo codes.
- The higher data rates are achieved with large constellations—such as 64QAM—and less robust error correcting codes, for example, either higher rate (like) codes, or in LTE's case, *punctured* turbo codes



- The goal of the transmitter is to transmit data from its queue as rapidly as possible, subject to the data being demodulated and decoded reliably at the receiver.
- Feedback is critical for adaptive modulation and coding:
  - The transmitter needs to know the "channel SINR" γ—which is defined as the received SINR γ_r divided by the transmit power P_t (which itself is usually a function of γ).
- The received SINR is thus $\gamma_r = P_t\gamma$.

- **Throughput vs. SINR,** assuming the best available constellation and coding configuration is chosen for each SINR.
- Only 6 configurations are used in this figure, and the turbo decoder is a max log MAP decoder with 8 iterations of message passing.



MITIGATION OF BROADBAND FADING

- In LTE broadband channel Inter Symbol Interference (ISI) is very serious problem due to frequency-selective fading caused dispersion in time.
- Choosing a technique to effectively combat ISI is a central design decision for any high data rate system.
- OFDM is the most popular choice for combatting ISI in a range of high rate systems.

MITIGATION OF BROADBAND FADING

- Other main techniques for ISI mitigation are

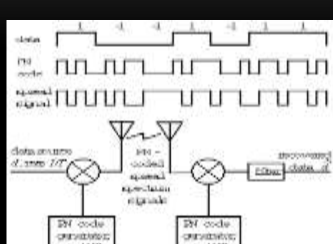
1. ***Spread Spectrum and RAKE Receivers***
2. ***Equalization***
3. ***Multicarrier Modulation: OFDM***
4. ***Single-Carrier Modulation with Frequency Domain Equalization***

SPREAD SPECTRUM AND RAKE RECEIVERS

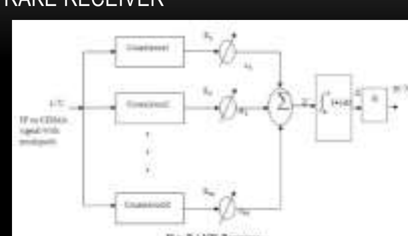
- Speeding up the *transmission* rate can help combat multipath fading, assuming the *data* rate is kept the same.
- Since speeding up the transmission rate for a narrowband data signal results in a wideband transmission, this technique is called *spread spectrum.*
- Two different categories:
  - direct sequence and frequency hopping.

SPREAD SPECTRUM AND RAKE RECEIVERS

- Two different categories:
  - direct sequence and frequency hopping.
- Direct sequence spread spectrum, also known as Code Division Multiple Access (CDMA), is used widely in cellular voice networks and is effective at multiplexing a large number of variable rate users in a cellular environment.
- Frequency hopping is used in some low-rate wireless LANs like Bluetooth, and also for its interference averaging properties in GSM cellular networks.



RAKE RECEIVER



EQUALIZATION

- Equalizers are the most logical alternative for ISI-suppression to OFDM, since they don't require additional antennas or bandwidth, and have moderate complexity.
- Equalizers are implemented at the receiver, and attempt to reverse the distortion introduced by the channel.
- Generally, equalizers are broken into two classes:
  1. *Linear*
  2. *Decision-directed (Nonlinear).*

LINEAR EQUALIZERS

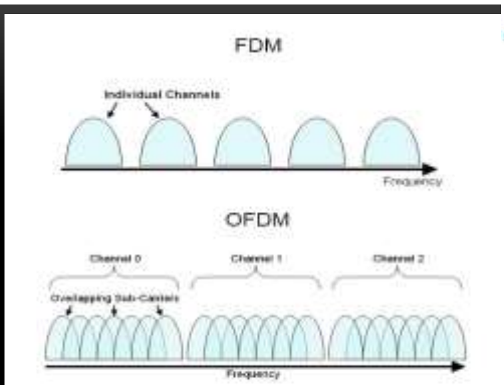
- A linear equalizer simply runs the received signal through a filter that roughly models the inverse of the channel.
- The problem with this approach is that it inverts not only the channel, but also the received noise.
- This noise enhancement can severely degrade the receiver performance, especially in a wireless channel with deep frequency fades.
- Linear receivers are relatively simple to implement, but achieve poor performance in a time-varying and severe-ISI channel.

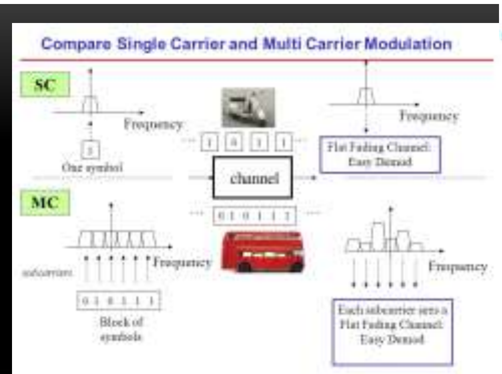
NONLINEAR EQUALIZERS:

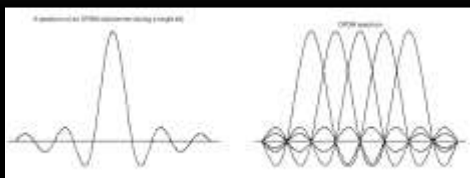
- Uses previous symbol decisions made by the receiver to cancel out their subsequent interference, and so is often called a *decision feedback equalizers (DFE).*
- One problem with this approach is that it is common to make mistakes about what the prior symbols were (especially at low SNR), which causes "***error propagation***."
- Nonlinear equalizers pay for their improved performance relative to linear receivers with sophisticated training and increased computational complexity.

MULTICARRIER MODULATION: OFDM

- The philosophy of multicarrier modulation is that rather than fighting the time-dispersive ISI channel, why not utilize its diversity?
- For this, a large number of subcarriers (L) are used in parallel, so that the symbol time for each goes from $T \rightarrow LT$.
- In other words, rather than sending a single signal with data rate R and bandwidth B, why not send L signals at the same time, each having bandwidth B/L and data rate R/L.
- In this way, each of the signals will undergo approximately flat fading and the time dispersion for each signal will be negligible.







SINGLE-CARRIER MODULATION WITH FREQUENCY DOMAIN EQUALIZATION

- Is there a way to effectively do OFDM without generating a high PAR?
- The answer is yes: one can transmit a single carrier signal with a cyclic prefix, which has a low PAR, and then do all the processing at the receiver.
- ***Single-Carrier Modulation with Frequency Domain Equalization***

END OF MODULE 1