

# ELEC5447M

## CELLULAR MOBILE COMMUNICATION SYSTEMS

### 25/26

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## READING LIST

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- Introduction to Wireless Systems, P.M. Shankar
- Fundamentals of Wireless Communications, D. Tse
- An Introduction to 5G: The New Radio, 5G Network and Beyond, C. Cox

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## USEFUL DOCUMENTS

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- Formula Sheet
- Unit 1: Introduction Notes
- Unit 1: Attenuation Notes
- Unit 1: Indoor Propagation Models Notes
- Unit 1: Fading Notes
- Unit 1: Fading 2 Notes

## LECTURE 1: BRIEF BACKGROUND

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### 1.1: CELLULAR NETWORKS

Cellular mobile systems took time to evolve. Below lists a brief timeline of key dates:

**1897** Marconi demonstrates radio communication.

**1934** 5000AM 'mobile phones' in use by American police.

**1946** First public mobile telephone service introduced in US cities.

**1950s** First mobile phone connectd to landline (PSTN).

**1970s** The 'cellular concept' was invented by Bell Labs engineers.

**1980s** The first-generation (1G) cellular mobile systems were deployed.

**1990** The second-generation (2G) cellular mobile systems were deployed.

**2000** 2.5G cellular mobile systems were deployed.

**2003** 3G was first deployed in Japan.

**2004** European & UK 3G deployment commenced.

**2009** First release of LTE & 4G LTE in Europe.

**2011** First release of 'true' 4G.

**2015** 5G development began.

**2019** Deployment of 5G began.

**2030** Finalisation of 6G specification by IMT.

Mobile phones took about 50 years to reach 10% market penetration. The penetration of mobile phones began very slowly, before rapidly increasing in the 90s and early 2000s. This is because of the rapid advances in semiconductor & battery production. These advances made mobile phones cheaper and thus more accessible.

### 1.1.1: 1G SYSTEMS

In the US, the standard used was the Advanced Mobile Phone System. It was based on FM and was therefore analogue. Uplink and downlink used 666 channels 20kHz wide for a total 30MHz of each uplink/downlink band.

In Europe, there were a variety of standards used, usually one per country. Most were also FM-based but with varying frequency allocations making roaming between countries impossible. Usually each channel was 25kHz wide.

### 1.1.2: 2G SYSTEMS

By the late 80s & early 90s, most of the 1G systems were running out of capacity and needed more bandwidth allocated to keep afloat. Ideally, future systems would need a way to fit more users into the same spectrum, have a lower power requirement, and keep security tight to stop people being able to eavesdrop into conversations.

It could be seen that a switch to digital-based cellular systems would be the correct move. Having a digital-based system would allow for coding to allow for higher capacity, along with encryption against eavesdropping. As the system was digital, both voice or data could be transmitted as there was no difference in representation.

In the US, two systems were both used simultaneously. IS-54 was an FDMA/TDMA-based system with FDD used for duplexing. For compatibility with previous systems, 30kHz channels were used, where 3 users could transmit per channel (via TDMA). IS-95 was the other system, based on CDMA, where a variable amount of users could transmit on each 1.25MHz channel. This is because CDMA allows for 'soft capacity limits', where the interference levels rise gradually before failing.

Whereas in the EU, one standardised system was used called the Global System for Mobile communication (GSM). Each channel has a 200kHz bandwidth where 8 users could share simultaneously using TDMA. Modulation and demodulation was based on digital FM, allowing for cheaper amplifiers to be used. Frequency hopping was used to rapidly change frequencies to reduce interference. Later on, upgrades to the network (2.5G) were made to allow for internet communication (GPRS) and an increase in data rate (EDGE). The core network was split in two, one for voice which used circuit-switching, and another for data which used packet-switching.

### 1.1.3: 3G SYSTEMS

In 1997, the International Telecommunications Union agency of the United Nations specified a set of requirements for what would be needed for 3G (aka IMT-2000). The aims were to allow for universal roaming and increased range in services and data formats (such as MMS).

The main system used was the Universal Mobile Telecommunications System (UMTS), which was developed by a partnership of worldwide telecommunication organizations called 3GPP. This was developed to design and develop the technical specs for a system that would meet the requirements of IMT-2000. UMTS was based on W-CDMA, with higher data rates and interoperability with the core network used by 2.5G systems like GPRS.

### 1.1.4: 4G SYSTEMS

In 2012, the ITU defined the new spec for 4G-capable (IMT-Advanced) systems. The main difference was that the core network would only be packet-switched, with even higher data rates, specially for users moving fast. The main system which tried to meet specification was LTE by the 3GPP (technically 3.9G). Downlink had rates of 100Mbps, with uplink having rates of 50Mbps with variable bandwidth support. Multiple access was controlled using OFDMA (see later).

## 1.2: WIRELESS SIGNALS

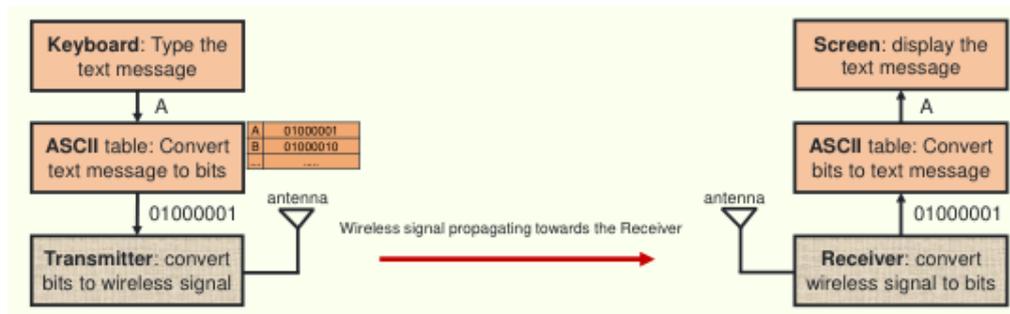


FIGURE 1: A simple example of wireless point-to-point communication.

Steps for wireless transmission:

1. A message in bits is passed to the transmitter (Tx).
2. The message is 'modulated' via the transmitter to convert the bits into a signal.
3. The signal is broadcast from the Tx antenna.

4. The signal propagates via the wireless channel.
5. The signal is received by the receiver (Rx) antenna.
6. The signal is 'demodulated' via the receiver from a signal into a message of bits.

A wireless signal is an electromagnetic wave that can be transmitted from an antenna. They are represented as a periodic sinusoidal wave:

$$s(t) = A\sin(2\pi Ft + \theta)$$

where  $A$  is amplitude (Volts),  $F$  is frequency (Hz),  $\theta$  is phase shift (radians). The power of the signal is equal to  $A^2/2$ .

The period ( $T$ ) is the time taken for the wave to complete one cycle, found with  $F = \frac{1}{T}$ .

The phase shift is the difference in where the signal starts, compared to a non-shifted signal, measured in radians. A delayed signal has a negative phase shift, while a leading signal has a positive phase shift. The 'phase difference' is the difference in phase between two signals.

### 1.2.1: EM WAVE PROPAGATION

An Electromagnetic (EM) wave propagates out of an antenna with an electric field. This electric field is a sinusoidal wave that has similar amplitude, frequency and phase shift to the EM wave. An antenna attached to a receiver will pickup the electric field and the electric signal will travel down the antenna to the receiver.

### 1.2.2: BANDWIDTH

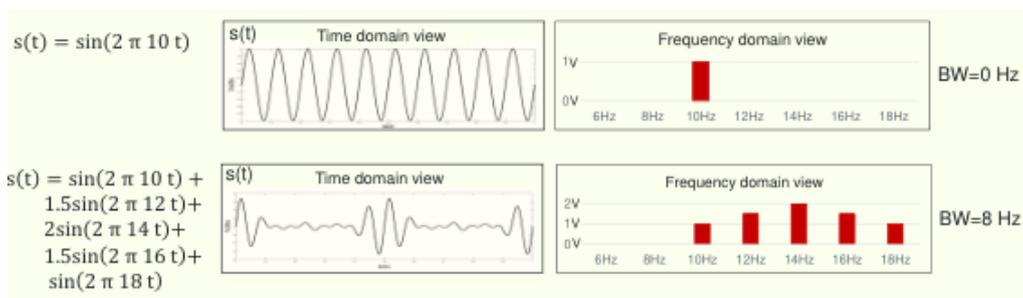


FIGURE 2: An example of the bandwidth of two signals.

The bandwidth (BW) of a signal is the range of frequencies that make up a given signal. For a simple sinusoidal signal, the BW will be 0 Hz, however for more complex signals the bandwidth may be larger. For a signal, the

bandwidth can be found by subtracting the minimum frequency component by the maximum frequency component.

The frequency-domain of a signal may be found by doing a Fourier transformation (usually Fast Fourier Transform or FFT) of the signal. The frequency-domain view of a signal is also referred to as the signal's spectrum.

### 1.3: MODULATION & DEMODULATION

There are a variety of ways to convert a message of bits into a signal. One such method is called Pulse Amplitude Modulation (PAM), where the signal has the same frequency throughout, but a higher amplitude for '1' and a lower amplitude for '0'.

Phase Shift Keying (PSK) is a method of modulation where each bit shifts the phase by (usually)  $\pi$  radians. Frequency Shift Keying (FSK) is a similar method where each bit has a distinct frequency.

Quadrature Amplitude Modulation (QAM) is a more complex method where both the phase and amplitude of the signal is modified for each bit (like PAM + PSK).

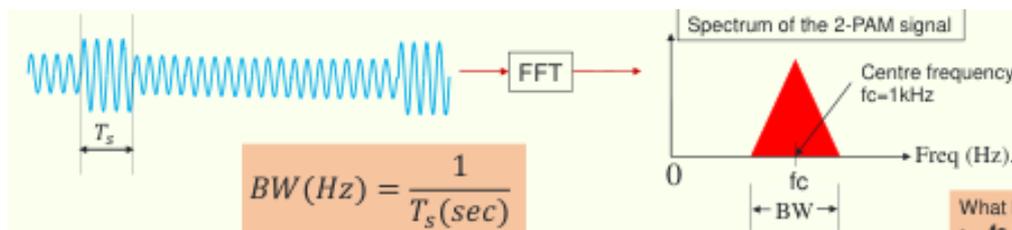


FIGURE 3: An example of the spectrum of a PAM-modulated signal.

Modulation of a signal introduces more frequencies than just the signal generator's frequency. For a PAM-modulated signal bandwidth of these frequencies is inversely proportional to the time of the high amplitude material in the signal. Then, the spectrum is centered around the signal generator's (carrier) frequency with a width equal to the BW.

#### 1.3.1: 2-PAM MODULATOR/DEMODULATOR DESIGN

A PAM modulator is easy to design. It requires two signal generator, one with a higher amplitude. When the bit '0' is received, the signal generator with a higher amplitude is sent across the antenna. When the bit '1' is received, the signal with the lower amplitude is sent across the antenna. Each bit sent has a fixed duration of time,  $T_s$ . A waveform that has a fixed period is known as a symbol.

A PAM demodulator works by reading how high the voltage is of the incoming voltage from the antenna. If the voltage is high, then output the

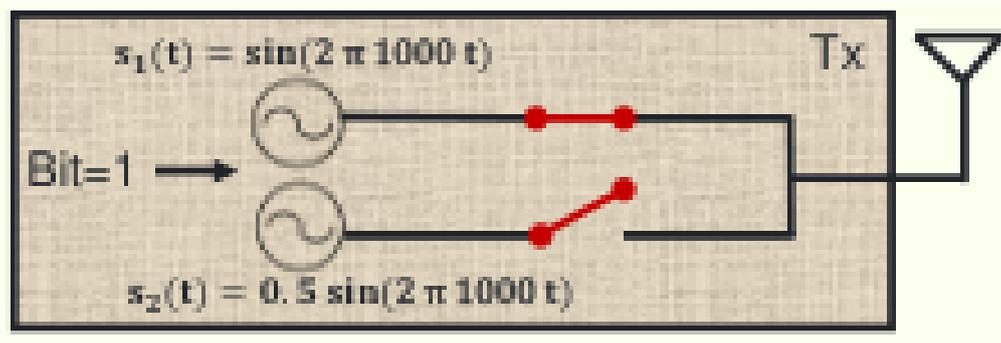


FIGURE 4: A design for a PAM-based modulator

representation for bit '1'. Else, output the representation for bit '0'. The symbol period can be estimated.

The bandwidth is related to the symbol time as  $BW = \frac{1}{T_s}$ .

### 1.3.2: FILTERS

Most modern receivers include filters which remove unwanted frequency components (or noise/interference) out of the spectrum of a received signal. One such filter is the bandpass filter, which includes a lower-bound and upper-bound to filter out. An ideal bandpass filter is a perfect rectangle from lower-bound to upper-bound. A non-ideal filter has roll-off, where noise close to the bounds have less effect but are still included. Others include a lowpass filter, which only filters out higher-frequency components, and a highpass filter, which filters only lower-frequency components.

### 1.4: THE CELLULAR CONCEPT

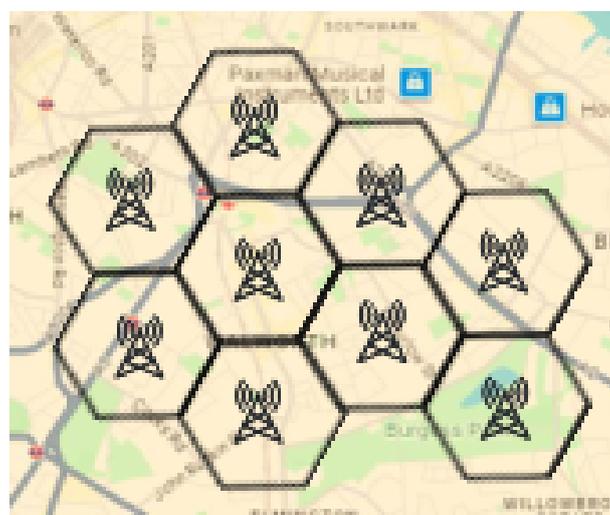


FIGURE 5: A visualisation of cells splitting up an area.

The Cellular Concept was developed by Bell Lab technicians in the late 1970s and were used as the foundation for 1G systems up until the present day. The idea behind it is that instead of having every user trying to communicate with one receiver, we instead split up the area into 'cells' of fixed area with only one transceiver responsible per cell. Each cell then has its own channel and own 'base station' that every user within the cell communicates with. When moving between cells, a 'handover' process is undertaken, where the user stops communicating with the previous BS and instead the new BS.

Different sizes of cells have different names. In order (from biggest to smallest) is: macrocell, microcell, picocell, femtocell.

#### 1.4.1: MULTIPLE ACCESS TECHNIQUES

Multiple Access is the technique of allowing multiple users to communicate simultaneously with the same base station. One such method is Frequency Division Multiple Access (FDMA), where each user has a different frequency within the cell, reducing interference to negligible. Time Division Multiple Access (TDMA) instead gives each user a different 'time slot' within the same frequency to communicate with the BS. Once again, interference is negligible but a time delay is added. Code Division Multiple Access (CDMA) is more complex, where each user is given a different 'spreading code' on the same frequency to communicate with every MU, where each MU decodes its own signal.

When the BS broadcasts a signal, a bandpass filter must be utilised to suppress unwanted signals from other MUs.

#### 1.4.2: DUPLEXING

Duplexing is the technique of separating uplink & downlink communication. Frequency Division Duplexing is the method where uplink & downlink communication are given separated bands (with a 'guard band' between) of allocated frequency. Time Division Duplexing is where uplink & downlink communication is separated by time on the same frequency.

#### 1.4.3: FREQUENCY REUSE

As described previously, cells next to each other use different groups of frequencies. This lessens the effect of co-channel interference between cells. After some number of cells, a new cell may reuse a previous set of frequencies. The number of cells in between is known as the 'cluster size'.

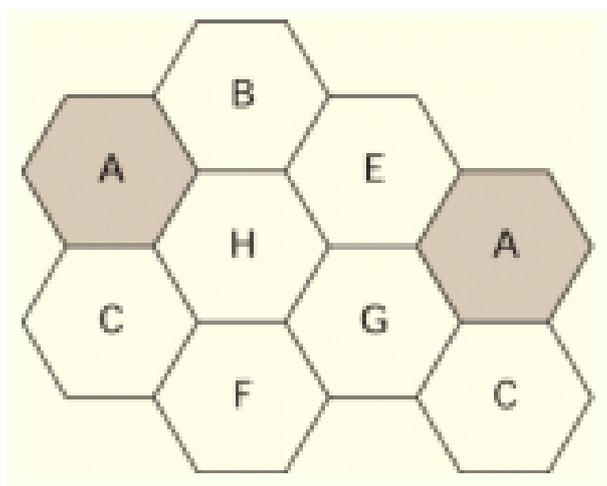


FIGURE 6: An example of frequency reuse with cluster size 7.

#### 1.4.4: CELLULAR PLAN

A cellular network contains two distinct parts: the Radio Access Network (RAN), and the Core Network (CN). The RAN contains the base stations, antennas and links to the core network (back-haul lines). The core network is responsible for the switching, control, and management functions that keep the messages being routed, the network healthy and the users being billed.

A cellular plan consists of the layout & organization of the cellular network and must take into consideration a variety of factors.

## LECTURE 2: ATTENUATION

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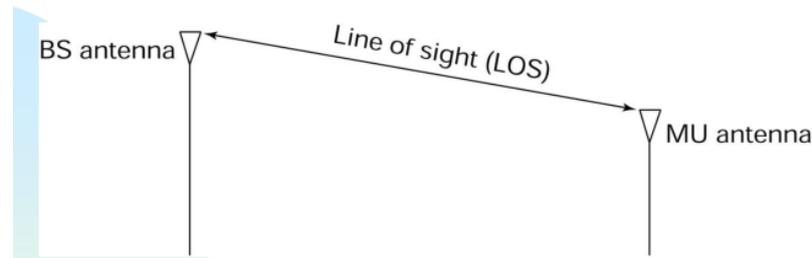


FIGURE 7: Diagram for Line of Sight propagation from BS to MU.

There are three phenomenons that govern losses from EM propagation:

- Attenuation (due to distance, mainly seen at several km distances.)
- Long term fading (fluctuation at same point, mainly seen at 1-2 kms.)
- Short term fading (rapid fluctuation, seen at 100m.)

For this lecture, we only consider attenuation.

Attenuation is the loss of power due to distance travelled. For Line-of-Sight (LOS) propagation, the received signal will be lower than the transmitted signal, but not by much. For Non Line-of-Sight (NLOS), there are more losses.

The signal from a BS can still reach the MU via reflection off walls/obstacles in the way, along with smaller components via diffraction & scattering.

**Reflection** The signal collides with an object that is much larger than the wavelength of the signal, and at an angle of incidence that is relatively acute (but not too small.)

**Diffraction** The signal is close to a sharp corner of a large object (i.e. a building), thus the signal bends and spreads.

**Scattering** The signal collides with an object that is similar or smaller than the signal's wavelength. The energy from the wave splits into multiple parts and scatters in varying directions.

The losses by NLOS propagation are much larger than LOS propagation due to the amount of the wave which is either absorbed by the obstacles or scattered away from the receiver. Another thing to note is that the transmitter radiates multiple waves from the antenna, so the receiver can receive a signal that has come from multiple different paths (including ones that are reflected/diffracted/scattered/from LOS).

Propagation is a combination of both LOS and NLOS, meaning that you can get the signal even in non-ideal conditions, even if the received signal is lower.

## 2.1: MODELS FOR LINE-OF-SIGHT PROPAGATION

Simple free space electromagnetic propagation models do not take into account NLOS losses. Simple models assume that the distance between antennas is sufficiently large (several kms). In the case of LOS between antennas, the received power can be seen to follow a simple inverse relationship with distance (the inverse-square law).

$$P_r \propto \frac{1}{d^2}$$

This is because the power of the antenna spreads out in a sphere from the antenna. As the distance increases, the power density decreases, so the received signal is less. The difference in the received signals is known as the Path Loss (PL).

$$PL = \frac{P_t}{P_r}$$

A more complete model for LOS propagation is Friis's Power Transmission Equation, or Friis' Equation for short. It expresses the received power as a combination of the transmitted powers, gains, distance, wavelength, and losses (L) of the system.

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

The product  $P_t G_t$  is also known as the equivalent isotropic radiated power. The gain of a Tx antenna can be related as a change in the shape of the antenna, to 'direct' the signal in a given direction. The Rx antenna gain is increased by creating a dish to direct more of the radiated signal to the antenna. The total coupling loss (L) is the loss due to the cable between the transmitter & antenna and the receiver & antenna.

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

We can rearrange the equation to put together the losses due to propagation between the transmitter & receiver. This is known as the Free Space Path

Loss, or  $l_{\text{free}}$ .

$$P_r = \frac{P_t G_t G_r}{l_{\text{free}} L_{\text{coupling}}}$$

In decibel form, Friis' equation looks like:

$$P_t = P_r + G_t + G_r - L_{\text{free}} - L$$

$$L_{\text{free}} = -20 \log_{10} \frac{\lambda}{4\pi d}$$

It can be seen that the total path loss is a simplification of Friis' equation.

The power received at any distance can be calculated via knowing the received power at a reference distance. The reference distance is usually around 100-1000m.

$$P_r(d) = P_r(d_{\text{ref}}) \frac{d_{\text{ref}}^2}{d}$$

## 2.2: NON LINE-OF-SIGHT ATTENUATION MODELS

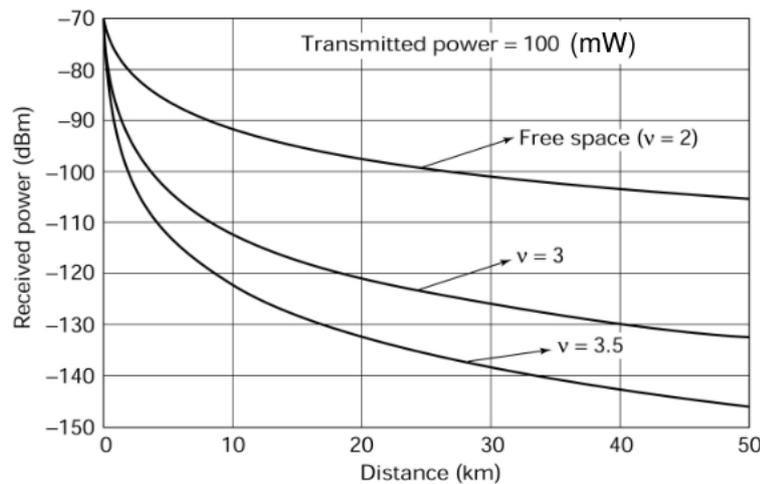


FIGURE 8: A graph of received power against distance for multiple values of  $\nu$ .

For NLOS propagation, it can be seen that the signal attenuates much faster than with LOS. It is roughly proportional to:

$$P_r \propto \frac{1}{d^\nu}$$

, where  $2 < \nu < 6$ .  $\nu$  is known as the path loss exponent. A higher value of  $\nu$  usually corresponds to an urban environment, whereas a lower value of  $\nu$  usually corresponds to a rural environment. For LOS conditions,  $\nu = 2$ . The received power under NLOS conditions is then calculated as:

$$P_r(\text{dBm}) = 10 \log_{10}(P_{r,\text{ref}}) + 10\nu \log_{10}\left(\frac{d_{\text{ref}}}{d}\right)$$

These use the same equations as before, but the path loss ( $L_p$  for NLOS, not  $L_{\text{free}}$ ) is calculated using a different model.

### 2.3: EMPIRICAL LOSS MODELS

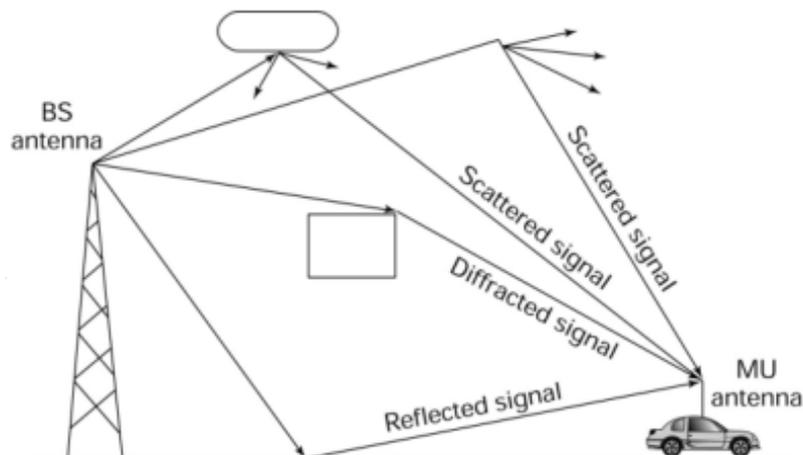


FIGURE 9: A diagram of the various routes possible to receive a signal.

Some models use measured data to produce higher accurate loss models tuned to specific environments.

Yoshihisa Okumura created a loss model based on the radio characteristics of Tokyo in the 1960s. The model contained many correction factors for antenna height, transmission frequencies, terrain openness, etc. This model was called the Okumura model. In order to calculate the loss, you must reference the specific graph for the current characteristics.

Masaharu Hata then simplified the model (now Okumura-Hata) into a set of equations that can then be used instead, depending on how large the city is.

## 2.3.1: OKUMURA-HATA MODEL

The median (all propagation losses in this model are given as mediums) propagation loss in an urban area is equal to:

$$L_p = 69.55 + 26.16 \log_{10}(f_0) + (44.9 - 6.55 \log_{10}(h_b)) \log_{10}(d) - 13.82 \log_{10}(h_b) - a(h_{mu})$$

- $f_0$  is the carrier frequency in MHz
- $d$  is the distance between BS and MU in km
- $h_b$  is the height of the BS in m
- $h_{mu}$  is the height of the MU in m
- $a(h_{mu})$  is the correction factor for MU antenna height

To note is that all heights are measured from the average ground level of the area.

The correction factor,  $a(h_{mu})$ , varies depending on the size of the city. For large cities, the correction factor is equal to:

$$a(h_{mu}) = 3.2[\log_{10}(11.75h_{mu})]^2 - 4.97 \quad (\text{where } f_0 \geq 400\text{MHz})$$

For small/medium cities, the correction factor equals to:

$$a(h_{mu}) = [1.1 \log_{f_0} - 0.7] h_{mu} - [1.56 \log_{10}(f_0) - 0.8]$$

For suburban & rural areas, the medial path loss is given by:

$$L_{\text{sub}} = L_p - 2[\log_{10}(f_0/28)]^2 - 5.4$$

$$L_{\text{rur}} = L_p - 4.78[\log_{10}(f_0)]^2 + 18.33 \log_{10}(f_0) - 40.49$$

For calculating rural & suburban propagation loss,  $a(h_{mu})$  should be the equation for small/medium cities. The difference between small/medium cities and large cities is only about 1dB, so quite slight.

### 2.3.2: PATH LOSS OF OKUMURA-HATO

Since the received power is inversely proportional to the distance, we can derive an expression for  $\nu$  in terms of the power loss at distances.

$$\nu = \frac{P_{\text{loss}} - P_{\text{loss,ref}}}{10[\log_{10}(d) - \log_{10}(d_{\text{ref}})]}$$

Please note that the units for distance should match on the denominator.

We can then rearrange the expression for  $P_{\text{loss}}$

$$P_{\text{loss,ref}} = 10 \log_{10} \left[ \frac{(4\pi d_{\text{ref}})^2}{\lambda^2} \right]$$

### 2.3.3: OKUMURA-HATA MODEL FOR PC BANDS

In the mid 90s, the model was updated to reflect the increase in wireless communication via the rapid rise of mobile phones. This model is known as the COST Hata model. It includes a modified correction factor for metropolitan areas.

$$L_p = 46.3 + 33.93 \log_{10}(f_0) - 13.82 \log_{10}(h_b) - a(h_{mu}) \\ + [44.9 - 6.55 \log_{10}(h_b)] \log_{10}(d) + \text{Corr}$$

$$\text{Corr} = \begin{cases} 0 \text{ dB} & \text{for medium cities and suburban areas} \\ 3 \text{ dB} & \text{for metropolitan areas} \end{cases}$$

### 2.4: LEE'S MODEL

Lee's model is based on measurements on US cities made during the 1980s. It predicts the loss in signal strength from an area-to-area basis. The median loss at a distance  $d$  is calculated as such:

$$L = L_0 + 10\nu \log_{10}(d) + a_c$$

, where  $L_0$  is the loss at a reference distance of 1km, and  $a_c$  is a correction factor. The correction factor is represented as a dB product of multiple parameters.

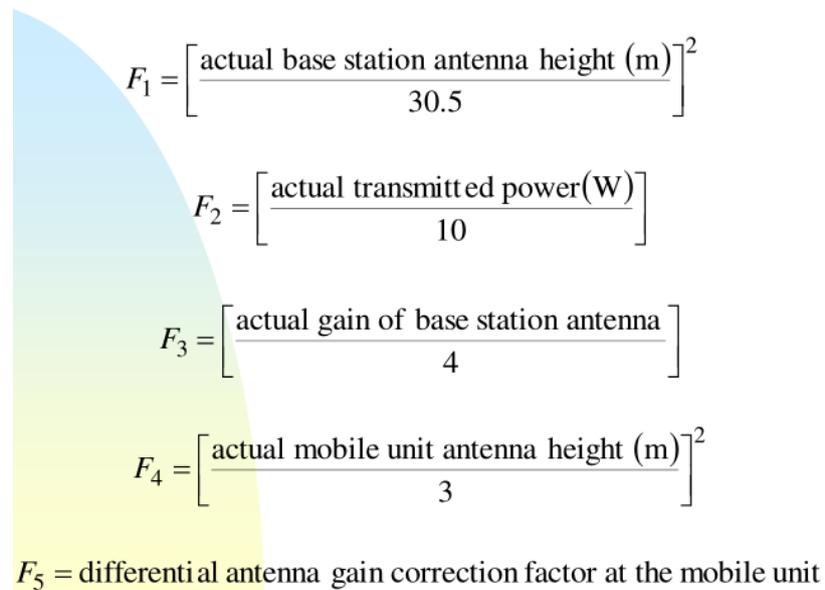


FIGURE 10: The factors responsible for the correction factor.

$$a_c = 10 \log_{10}(F_1 F_2 F_3 F_4 F_5)$$

The point-to-point loss in Lee's model can be expressed as:

$$L_p = L + 20 \log_{10} \left( \frac{h_{\text{eff}}}{10} \right)$$

, where  $h_{\text{eff}}$  is the effective height of the BS antenna.

## LECTURE 3: INDOOR PROPAGATION MODELS

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The NLOS models discussed previously are used to predict signal strength outdoors. For an indoor environment, different models are used since the amount of reflection, scattering & diffusion that makes up the received signal is much larger.

Akin to the Okumura-Hato Model, the equations used for indoor propagation vary based on different factors:

- Location of the BS
- How the BS handles traffic
- Whether the BS is inside or outside

We use these factors to classify indoor propagation into multiple 'zones'.

### 3.1: EXTRA LARGE ZONE

An extra large zone is a single BS outside of the building that handles all traffic. This is akin to having one BS managing all adjoining shops on a high street. Since the antenna is outside the building, there will be outdoor propagation loss, penetration loss, and indoor propagation loss. The equation for ELZ can be represented as:

$$L_{\text{ELZ}}(\text{dB}) = 10 \log_{10} \left[ L_d \left( \frac{d}{d_0} \right)^{\nu_d} L_B \left( \frac{d}{d_0} \right)^{\nu_B} A_B \right]$$

, where  $L_d$  is attenuation due to outdoor propagation when  $d = d_0$ ,  $L_B$  is attenuation due to indoor propagation when  $d = d_0$ ,  $\nu_d$  is the path loss exponent outside the building,  $\nu_B$  is the path loss exponent inside the building, and  $A_B$  is the loss factor due to building penetration.

The outdoor propagation & indoor propagation loss is determined by the density of obstacles in the path as well as frequency dependant losses (higher frequencies are harder to penetrate into a building).  $\nu_d$  is similar to regular path loss exponent and should be in the range  $2 < \nu_d < 6$ , whereas  $\nu_B$  should be within the range  $0.5 < \nu_B < 1.5$ .  $\nu_B$  is lower because of the amount of reflections occurring within the building (the waveguide effect).  $A_B$  depends on the difference between antenna heights & the penetration depth of the material the building is made of.

### 3.2: LARGE ZONE

A large zone is where the BS is within the building itself, where the building is very large but has a low population density. This is akin to a warehouse. The equation for LZ can be derived from the ELZ equation, as it is a special case of it with only indoor loss:

$$L_{LZ} = 10 \log_{10} \left[ L_d \left( \frac{d}{d_0} \right)^{\nu_0} \right]$$

It can be seen that the parameter for loss due to penetration into a building and the outside propagation loss has been removed, as for a LZ the BS is within the building and loss between floor penetration is much less. Therefore  $\nu_0$  is around 2-3 if the MU is on the same floor and greater than 3 if they are of different floors. There is no waveguide effect due to the large size of the building.

### 3.3: MIDDLE ZONE

A middle zone is similar to a LZ, but heavily populated. This can be a shopping centre. For a MZ, there are multiple BSs within the building to serve MUs. The equation for a MZ is:

$$L_{MZ} = 10 \log_{10} \left[ \left( \frac{4\pi f_0 d}{c} \right)^2 F^{k_1} W^{k_2} R \right]$$

, where  $F$  is floor loss,  $W$  is wall loss,  $R$  is reflection loss,  $k_1$  is no. of floor in the path, and  $k_2$  is number of walls in the path.

It can be seen that the equation is based off the FSPL with additional losses for penetration of walls, floors, and reflections.

## LECTURE 4: RAYLEIGH FADING

Fading is the random fluctuation in received power due to a change in time or space. There are multiple classifications for different causes of fading. The power received at a fixed distance will vary over time, so the actual power is random, whereas the average power (the one given by attenuation models) is constant for a given distance. This is due to multiple copies of the signal being received at slightly different times, interfering with each other.

Small-scale fading is when the received signal fluctuates with a minutew change in distance. For small-scale fading, the power received may be below a threshold power, where the BS is communicating with the MU, but due to conditions the MU does not receive any communication. When this occurs, the MU is in 'outage'. The outage probability is an important metric for mobile communication systems.

Small-scale fading has two different statistical random models: Rayleigh, and Rician. A Rayleigh model is one which has only NLOS components, whereas a Rician model has a LOS component in addition.

### 4.1: MULTIPATH FADING

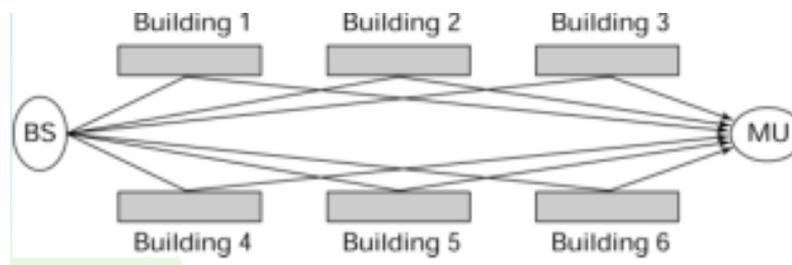


FIGURE 11: A diagram showing multiple different routes a signal may take from BS to MU.

Multipath fading is the fading due to multiple signals being received through different routes. Each copy of the signal that arrives at the MU can be assumed to be independent of each other, and may have a difference in phase and amplitude. The signals received may then constructively or destructively interfere.

The signal at the receiver can be written as the sum of these signals reflected from different structures. Assuming the receiver is stationary, the received signal is:

$$e_r(t) = \sum_{i=1}^N a_i p(t - t_i)$$

, where  $N$  is the number of paths,  $a_i$  is the amplitude of the scatter component,  $t_i$  is the associated delay, and  $p(t)$  is the shape of the pulse transmitted.

#### 4.1.1: OUTAGE PROBABILITY

The probability of a power being received is distributed with a Rayleigh distribution (roughly negative exponential distribution). It has the function:

$$f = \frac{1}{p_0} \exp\left(-\frac{p}{p_0}\right)$$

When plotted, the area below the probability threshold gives the output probability.

$$\begin{aligned} P_{\text{outage}} &= \int_0^{P_{th}} \frac{1}{p_0} \exp\left(-\frac{p}{p_0}\right) dp \\ &= 1 - \exp\left(-\frac{P_{th}}{p_0}\right) \end{aligned}$$

#### 4.1.2: MULTIPATH DELAY



FIGURE 12: A pulse broadened by 4 multipath signals received.

When copies of the signal receive at the router, they have gone differing lengths and are out of phase with each other. If the transmitted signal is a pulse (which it is for a symbol), the received pulse is a broadened version of the pulse. The duration may be longer, causing interference with the next symbol transmitted. This interference is known as Inter-Symbol Interference (ISI).

We can calculate the delay of the received symbol by averaging out each signal from each multipath. The average channel delay is a measure of the delay of the resultant signal via multipaths:

$$\langle \tau \rangle = \frac{\sum_{i=1}^N (p_i \tau_i)}{\sum_{i=1}^N (p_i)}$$

, where  $p_i$  is the received power of the signal, and  $\tau_i$  is the delay of the signal.

The RMS delay,  $\sigma_d$ , is a more accurate measurement of the delay of the resultant signal. It is also known as the spreading time.

$$\sigma_d = \sqrt{\langle \tau^2 \rangle - \langle \tau \rangle^2}$$

$$\langle \tau^2 \rangle = \frac{\sum_{i=1}^N (p_i \tau_i^2)}{\sum_{i=1}^N (p_i)}$$

If  $\sigma_d$  is small then the pulse spreading is minimal with no/little ISI, and if  $\sigma_d$  is large then the pulse spreading is high with a large ISI.

#### 4.1.3: FADING CHANNELS

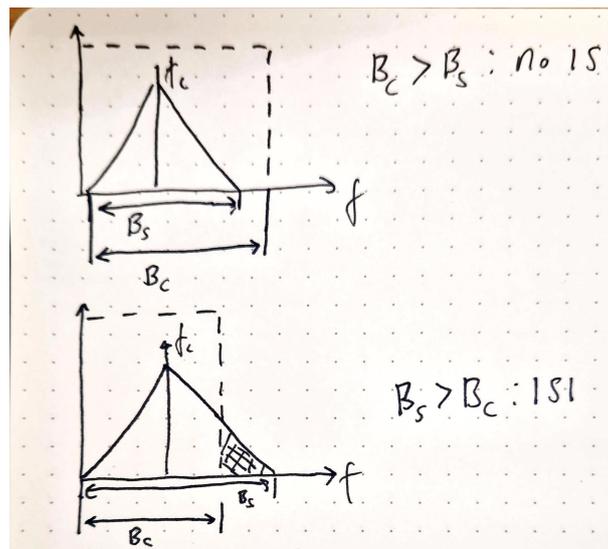


FIGURE 13: A diagram of the coherence bandwidth against the signal bandwidth, where the coherence bandwidth acts as a filter of the signal.

We can convert the spreading time into a 'bandwidth' to be able to tell at a glance if ISI will occur. We convert the spreading time into a filter, known as the coherence bandwidth,  $B_c$ :

$$B_c = \frac{1}{5\sigma_d}$$

From the figure, we can see much more clearly how  $B_c$  acts as a filter for the signal. If the coherence bandwidth is too low, the signal will interfere with the next symbol, causing ISI. This is known as a frequency-selective fading

channel. If the coherence bandwidth is sufficiently large, then the signal will not interfere with the next symbol, so no ISI occurs. This is known as a flat fading channel.

Since  $B_c$  is dependent on only the delay,  $B_c$  is dependant on the environmental conditions only and will not be able to be modified by an engineer. Since  $B_s = 1/T_s$ , the bandwidth of the symbol is defined by the engineer, and can be modified. By increasing the symbol time, we can decrease  $B_s$ , making a frequency selective fading channel into a flat fading channel. Likewise, a flat fading channel may become a frequency-selective fading channel if  $T_s$  is decreased.

## LECTURE 5: MORE FADING TYPES

### 5.1: RICIAN FADING

Rician fading adds LOS propagation to Rayleigh fading. We should expect that the outage probability will be lessened, as the majority of the received power will be from stable LOS propagation. A Rician distribution has a sum of deterministic (LOS) components and a number of Gaussian components (NLOS).

$$f_A(a) = \frac{a}{\sigma^2} \exp\left(-\frac{a^2 + A_0^2}{2\sigma^2}\right) I_0\left(\frac{aA_0}{\sigma^2}\right)$$

, where  $A_0$  is the LOS component, and  $I_0$  is the modified Bessel function:

$$I_0(x) = 1 + \frac{x^2}{2^2(1!)^2} + \frac{x^4}{2^4(2!)^2} + \dots$$

The PDF of a Rician distribution is given as a dB ratio of the LOS and multipath powers:

$$\begin{aligned} K &= 10 \log_{10} \left( \frac{A_0^2}{2\sigma^2} \right) \\ &= 10 \log_{10} \left( \frac{\text{LOS power}}{\text{NLOS power}} \right) \end{aligned}$$

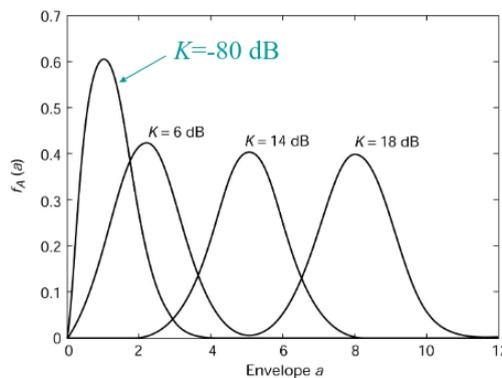


FIGURE 14: A graph showing multiple values of  $K$ .

At  $K = -\infty$ , then there is no LOS component, and the distribution is Rayleigh. It can be seen that as  $K$  increases, the closer the distribution comes

to being Gaussian in nature. This is because the LOS portion of the signal is greater, and the received signal will tend to be very close to the average received power. It can be seen that as  $K$  increases, the outage probability becomes less likely. The worst case for outage is Rayleigh, the average case is Rician, and the best (ideal) case is Gaussian.

## 5.2: LOGNORMAL FADING

Lognormal fading is a long-term fading model, where propagation is mainly composed of paths including multiple scatters & reflections. Large-scale fading is the fluctuation of the received power over large distances. The received power from a transmitter is now equal to:

$$P_r = 10 \log_{10} [P_{r,\text{ref}}] + 10\nu \log_{10} \left[ \frac{d_{\text{ref}}}{d} \right] + Y_g$$

, where  $Y_g$  is a zero-mean Gaussian random variable in dB with standard deviation  $\sigma_{dB}$ .  $Y_g$  represents the random fluctuation due to obstacles at the same distance but different directions. The probability of receiving a given average power then follows a lognormal distribution:

$$f(p_{LT}) = \frac{1}{\sqrt{2\pi\sigma^2 P_{LT}^2}} \exp \left[ -\frac{1}{2\sigma^2} \ln^2 \left( \frac{P_{LT}}{P_0} \right) \right]$$

, where  $P_0$  is the average power in milliwatts, and  $\sigma$  is given by:

$$\sigma = \frac{\sigma_{dB} \ln(10)}{10}$$

## 5.3: COHERENCE TIME

As a MU moves across the cell, there will be pockets of high, stable LOS power and pockets of low, fluctuating, unstable NLOS power. The received signal will then have periods of stability and instability. The time that the channel can be considered stable is known as the coherence time ( $T_c$ ). Depending on the speed of the MU, the coherence time will vary. If a symbol is received with  $T_s$  being within the coherence time, the symbol will not be received distorted (not in error). If  $T_s$  is large and is not contained within  $T_c$ , then the received symbol will be distorted (where the amplitude varies across the symbol). This will cause bit errors and BER will be high.

Slow fading occurs when  $T_s < T_c$ . Fast fading occurs when  $T_s > T_c$ . Ideally, we'd like our channel to be mainly slow fading, as that gives the lowest BERs.

#### 5.4: DOPPLER SHIFT

As an MU moves towards the BS, the received frequency will be shifted to be faster. As the MU moves away, the received frequency will be shifted to be slower. The shift amount of the frequency is called the Doppler shift ( $f_d$ ). The maximum frequency shift can be found with:

$$f_d = f_0 \frac{v}{c}$$

The coherence time of the channel is inversely related to the doppler shift:

$$\begin{aligned} T_c &= \frac{1}{f_d} \\ &= \frac{c}{f_0 v} \end{aligned}$$

If we want the coherence time to be great, we need the user to be moving slowly or the carrier frequency to be as low as possible.

The best possible channel characteristic to have is a flat, slow fading channel. Likewise, the worst is a frequency selective, fast fading channel.

## UNIT 2

### LECTURE 6: CELLULAR SYSTEMS

We need multiple base stations to cover as many users as possible across an entire city, as one BS per city would need too high a transmit power to be feasible. Multiple BSs need to be on different carrier frequencies, or co-channel interference (CCI) between the cells will occur.

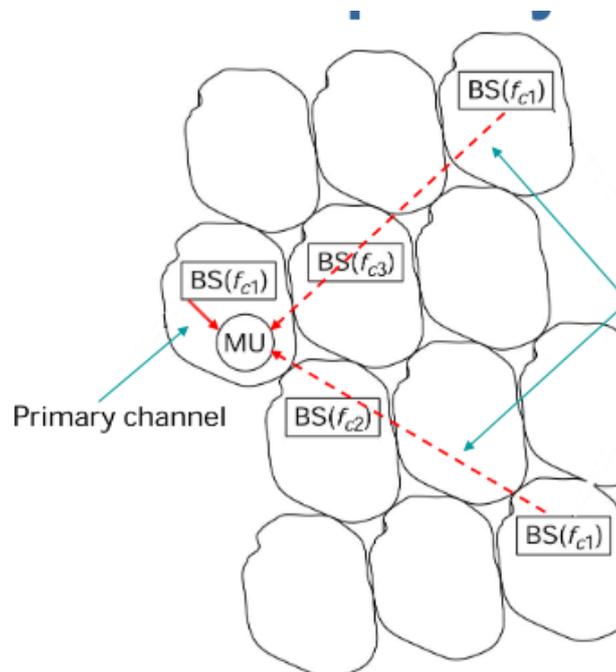


FIGURE 15: A diagram showing co-channel interference between cells with the same carrier frequency.

The power the MU receives from antenna is made up of the power from the primary channel and the co-channels. This cannot be filtered out as it is on the same frequency. Therefore, the co-channel interference can only be reduced by distance.

it would make sense to depict cells as spheres, as dipole or isotropic antennas radiate out as a sphere/circle, but this leaves gaps when tiled. A hexagon works as a depiction of the cell as it is able to be tiled effectively while being close to a circle.

## 6.1: THE CELLULAR CONCEPT

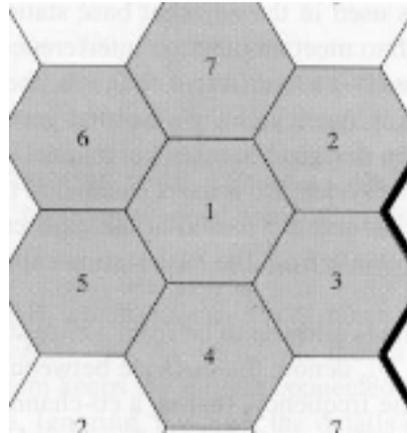


FIGURE 16: A cluster of size 7.

The cellular concept is the allocation of the available bandwidth into channels that can be given to adjacent cells. A 'cluster' of cells is the group of adjoining cells with different channels, with no repeated cells. These clusters can then be tiled across the necessary geographical area. Therefore, the number of channels stays constant as the area increases, with the downside of co-channel interference between clusters.

The system capacity is the number of channels in a cluster multiplied by the number of clusters in the area.

Since hexagons do not tile neatly in  $x,y$  grids, we instead use the  $u,v$  coordinate system, where  $v = y$ ,  $u = x$  angled by  $\pi/6$ . The origin is centered at the midpoint of a cell. The centre-to-centre distance between two neighbouring cells is:

$$d_{ctc} = 2R \cos(\pi/6) = R\sqrt{3}$$

, where  $R$  is the radius of a cell.

The general center-to-center distance between any two cells is:

$$D_{cc} = \sqrt{i^2 + j^2 + ij\sqrt{3}}R$$

, where  $i, j$  are the shift parameter. The cluster size is also related to  $i$  and  $j$ :

$$N_c = i^2 + j^2 + ij$$

## 6.2: CO-CHANNEL INTERFERENCE

Co-channel interference is the interference due to the re-use of cells. For a cluster size of 7, there are 6 interferers present.

The signal to CCI ratio is:

$$\frac{S}{I} = \frac{\text{signal power}}{\text{interfering signal power}}$$

This ratio is usually more important for cellular systems as there are more interferers than noise.

The received SIR (assuming that the receiver is at the centre of the cell) is equal to:

$$\frac{S}{I} = \frac{R^{-\nu}}{N_I D^{-\nu}}$$

## LECTURE 7: FADING MITIGATION

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## LECTURE 8: CHANNEL CAPACITY FOR CELLULAR SYSTEMS

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Information Theory is the study of the performance of channels. It provides the maximum rate of communication for which arbitrary small error probability can be achieved, known as CAPACITY. The study of information theory is invented by Claude Shannon in 1948, and provides the basis for modern wireless communication theory.

For an AWGN channel (one where noise is added independent over time), the channel capacity is shown to be:

$$C = W \log_2(1 + \text{SNR}) \quad \text{bits/s}$$

with a maximum spectral efficiency of:

$$C = \log_2(1 + \text{SNR}) \quad \text{bits/s/Hz}$$