Microwave Engineering
Professor Ratnajit Bhattacharjee
Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati
Lecture 36
Cellular Communication

So we have seen one major application area of microwave is radar. Let us now move on to another application area, which is cellular communication or cellular wireless communication.

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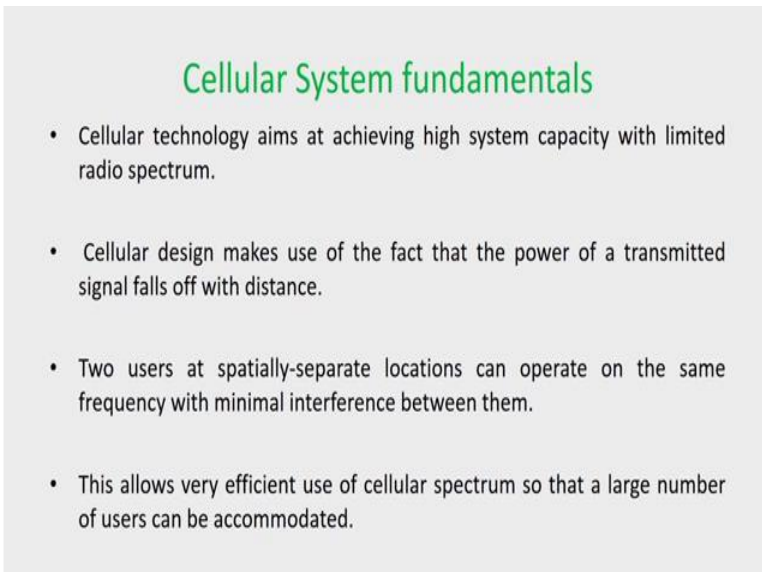

So we briefly review some of the cellular system fundamentals. Cellular Technology aims at achieving high system capacity with the limited radio spectrum. Now when it is a wired communication, if we lay cables or wires, we can transmit or reuse the same frequency in these cables without and increase the capacity of the system. When it comes to wireless communication, wireless is essentially a broadcast media.

So whenever we transmit in one particular frequency, if another transmission is there in the same frequency, there will be interference. And cellular technology aims at achieving high system capacity when you have a limited number of frequencies. The cellular design makes the use of the fact that the power of a transmitted signal falls off with distance. So this is the characteristic of wireless transmission. As we move away from the transmitter the signal strength reduces and sufficiently away from the transmitter the signal becomes very weak. And the same frequency now can be repeated. So cellular system architecture intelligently exploits this feature to improve the overall capacity of the system that means providing large number of channels while using only a limited set of frequencies.

So two users at spatially separated locations can operate on the same frequency with minimal interference between them. This is the objective. And this allows very efficient use of cellular spectrum so that a large number of users can be accommodated. So spectrum or the frequency is a very scarce commodity, and we want to utilize this very effectively so that a large number of users can be served. For example, if you consider the mobile communication scenario today, there are huge number of customers or users who are using these services. And this large number of users are essentially being supported only over a limited band of frequencies. And that is being possible because of the intelligent design of the cellular communication systems.

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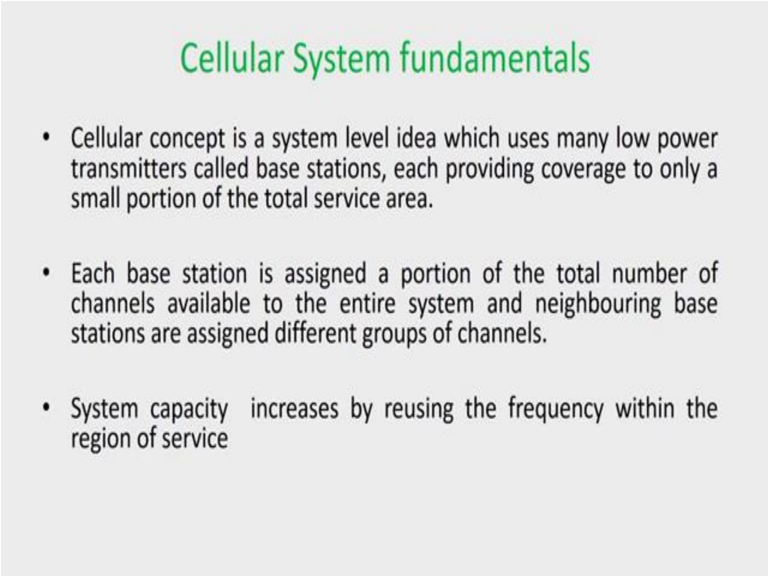

So cellular concepts by itself is a system-level idea which uses many low power transmitters are called base stations, each providing coverage to only a small portion of the total service area. So if we want to serve a vast, geographically vast area, maybe some cities, some suburban areas, so it is covering the entire country. So very small or low power transmitters called base stations to provide coverage to a limited service area, and there are a large number of such base stations deployed to provide the overall coverage. So in a city, there may be 100s of base stations, which provide coverage in its particular areas.

Each base station is assigned a portion of the total number of channels available to the entire system, and neighboring base stations are assigned different groups of channels, so in this way, the allocation of channels is made. System capacity increases by reusing the frequency within the region of service. So these are the concept based on which cellular communication technology was developed. Now of course, over the years many other advanced features or characteristics have been used to improve the coverage throughput and also the quality of service.

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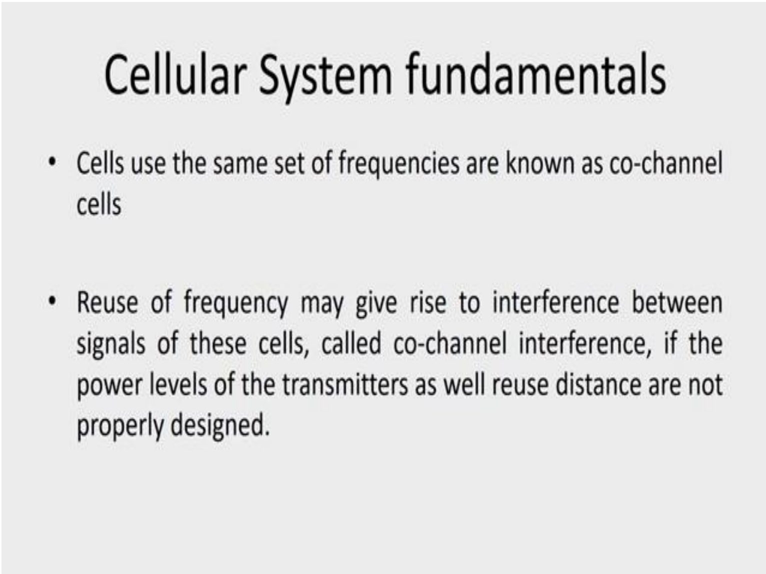

Now when we have a group of cells that use the same set of frequencies are known as co-channel cells. There reuse of frequency may give rise to interference between the signals of these cells, and this is called co-channel interference if the power level of the transmitters, as well as reuse distance, are not properly designed.

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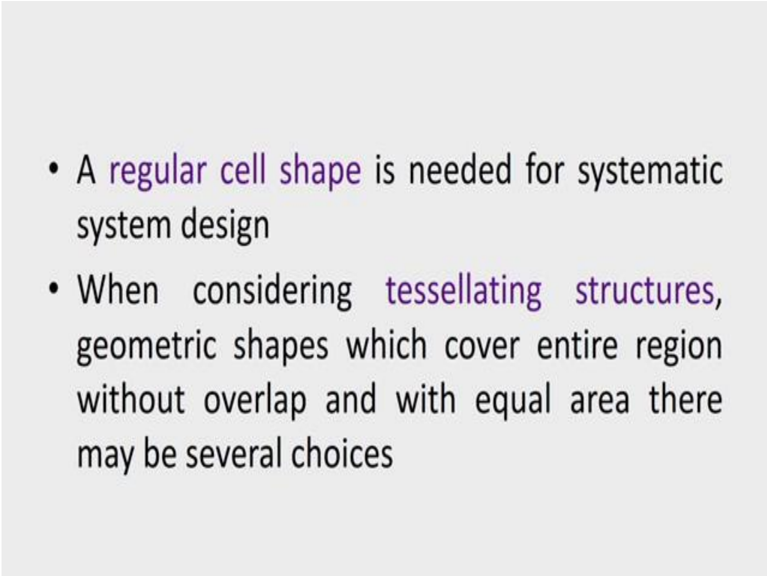

So we require the purpose of analyzing the performance of cellular communication system, a regular cell shape so that we can carry out systematic design. In principle the cell boundaries or the periphery of the cell will not be having a regular shape; it will be irregular because of many propagations affects the signal in different directions we get attenuated to different degrees and the coverage will be different even if the distance is same from the base station. So for the purpose of systematic design we consider a tessellating structure, a structure that can be repeated and the geometric shapes which cover the entire regions without overlap, and with equal area, there may be several choices. So the regular geometries like equilateral triangle, square, hexagon, these are the geometries which we can tessellate, and without any without void, we can cover the entire service area.

For example, circle, if you do not overlap then there will be void, so among all these geometries, hexagon is the most preferred one, and its shape is closer to a circle also. But at the same time we can repeat hexagons, and we can cover a geographical region without leaving any void. So that is why in the design of the cellular communication system, often cells are depicted as hexagons, although in reality the shape of the cell will be quite irregular, it will not be identical in all directions. There will be some places where the signal strength will be very low as compared to other places but when we do the system design representing cells with hexagonal geometries give lot of advantage, and that is why it is usually used.

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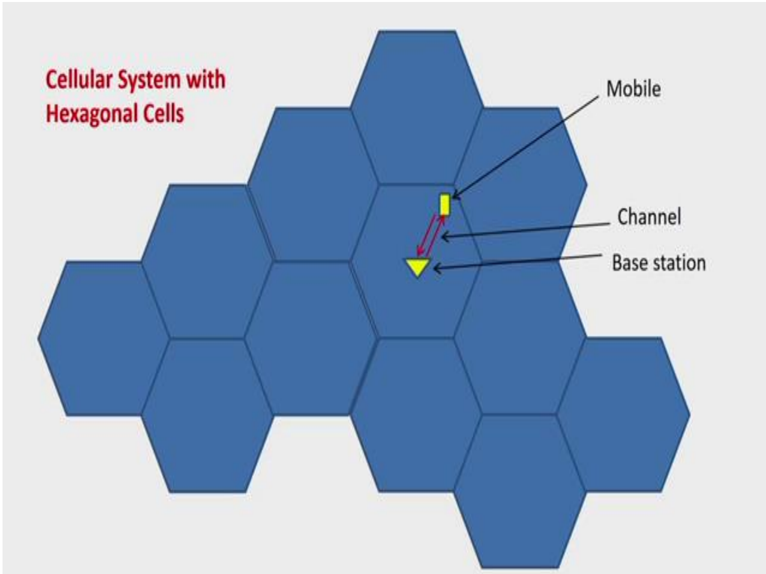

So we show the cellular system with hexagonal cells. So here we can see that we have covered one geographical region using hexagonal cells. And they do not leave any void in between. Now in one of those cells we are showing a base station. And then we have a mobile station and then between the base station and the mobile station the communication takes place using channels. So usually a channel will represent by uplink and downlink frequencies, which will be different, and this type of channel is also called frequency division duplex or FDD.

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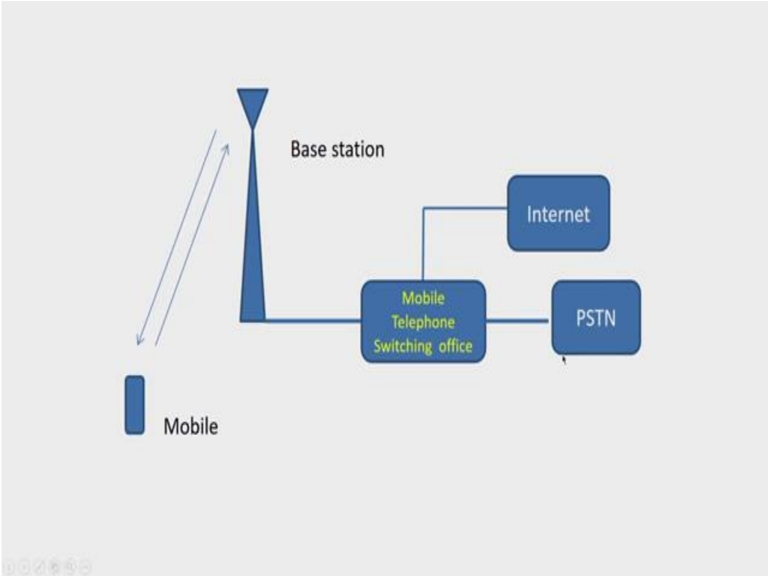

Now the basic architecture is like this; we have a base station serving many mobile stations, just one is shown here as a representative quantity. And then this link from base station to mobile station or from mobile to base station, these are wireless. Then these base stations are connected to another mobile telephone switching office, and usually they are connected by very high-speed lines such as optical fiber. Mobile switching stations have connection to PSTN or public switched telephone network and also so it is connected to the internet, so in that way although the mobile initially communicates with its base station through base station and mobile switching office, it can get connected to public switched telephone network and also to internet.

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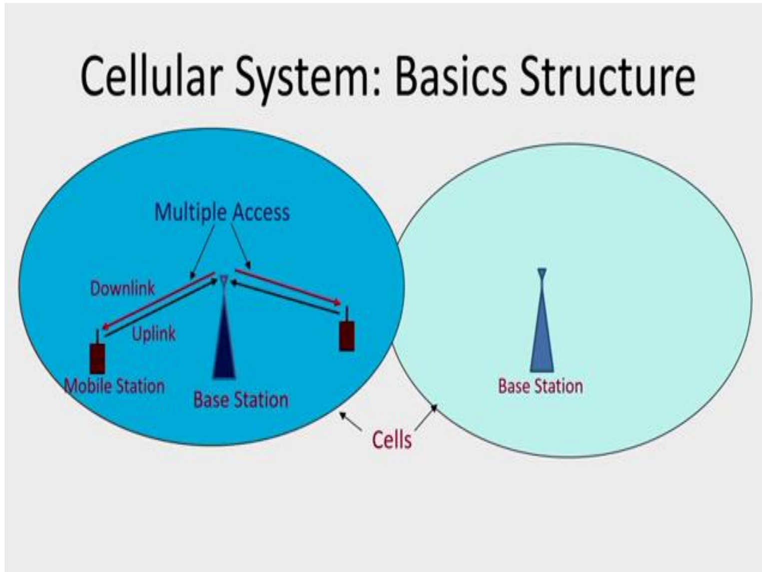

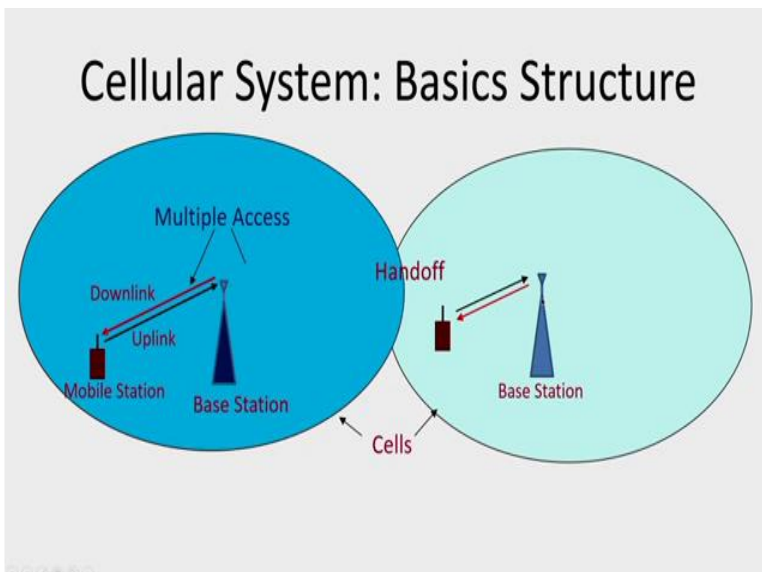

Here we explain the operation of the cellular system. So suppose we have 2 cells, and we have depicted this cell as overlapping regions here. Now we have 2 base stations serving these 2 regions, and we have mobile stations in the service area of each base station. Now we have downlink frequencies or channels through which the base station communicates with the mobile station, whereas we have uplink channels through which the mobile station communicates with the base stations. And suppose this mobile is to communicate with the other mobile, it does not communicate directly, all communications are routed through its base station. Now this type of simultaneous communication between more than 1 user, these are called multiple access.

So multiple access may take place using various methodologies. The oldest one was frequency division multiple access, the GSM or the second generation telephone systems mobile systems, they used TDMA, time division multiple access. Then the next generations used CDMA or code division multiple access. So in that way the resources may be shared by large group of users through the multiple access technology. Now all these mobiles are attached to this base station. But because of the mobility the mobiles may change the point of attachment as it moves.

Now at this location, it gets a better signal from the nearer base station, and therefore a connection is established with the second base station, whereas the earlier connection is snapped. And this is called handoff. So the mobile stations which are located near the periphery of a cell, they undergo handoff many times, and the user should not experience that it is now being served by a second base station. So it is essential to design the handover, which is very smooth without interrupting ongoing communication, which the mobile station might be carrying out with another mobile station.

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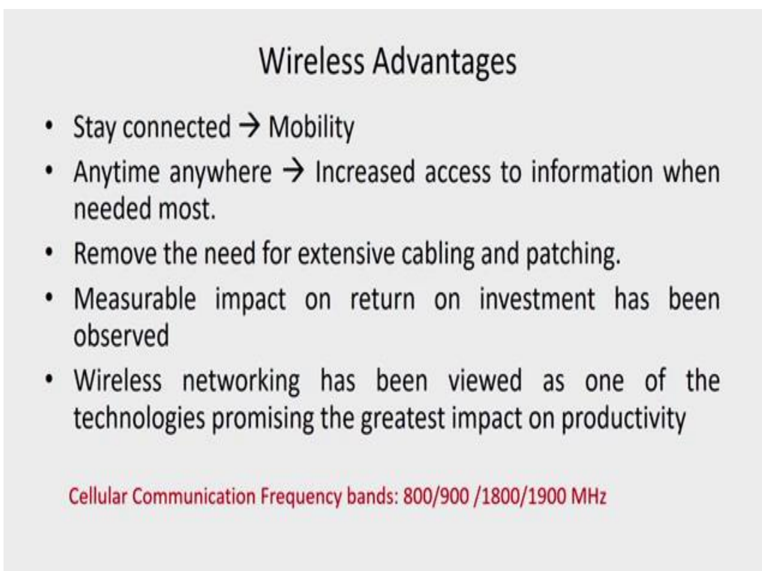

Now wireless communication or wireless technology has become the password because of several advantages. It allows us to be stayed connected and provides mobility; it is anytime anywhere increased access to information when needed most and remove the need for extensive cabling and patching. And it has produced a measurable impact on the return on investment, last several decades have shown tremendous growth because of wireless networking is viewed as one of the technologies promising the most significant impact on productivity in different front. Now the cellular communication system they operate in the microwave frequency band, and we have seen several frequency bands, the most common bands are 800 megahertz 900, 1800, 1900 megahertz so it depends. Some amount of variation is there from region to region and different countries.

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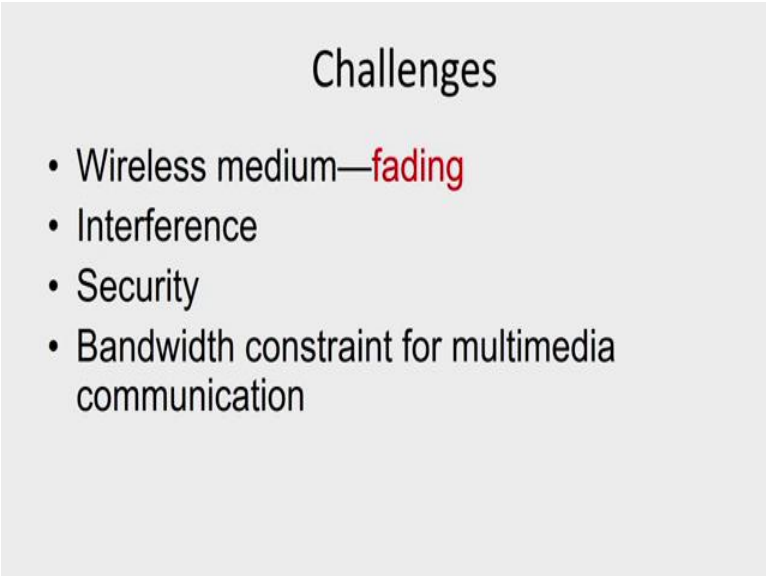

Although wireless communication is very exciting, it is also technologically very challenging. The major challenge comes from wireless media itself. And fading of the signal is a very challenging issue. Then there are interferences; security issues are there. Because when the information is being transmitted over the air, it can be easily intercepted and moreover the bandwidth constraint for multimedia communication. Over the years the traffic pattern has also changed considerably. Initially, cellular communication technologies were developed for delivering voice and text messages. But now the multimedia content in the form of images videos along with voice and text these are increasing, and once you go to these high-resolution images or videos the bandwidth requirement also increases. Now achieving or providing large bandwidth or broadband access using wireless is a quite challenging task.

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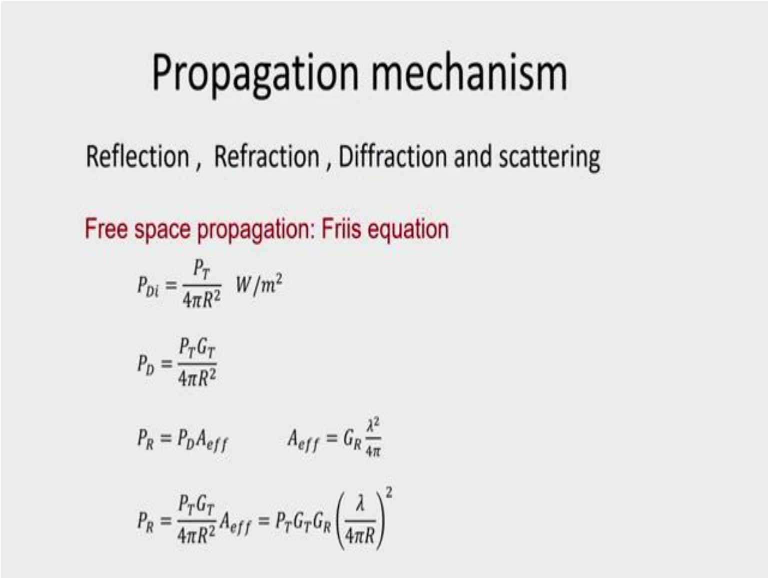
$$P_{Di} = \frac{P_T}{4\pi R^2} \quad W/m^2$$

$$P_D = \frac{P_T G_T}{4\pi R^2}$$

$$P_R = P_D A_{eff} \qquad A_{eff} = G_R \frac{\lambda^2}{4\pi}$$

$$P_R = \frac{P_T G_T}{4\pi R^2} A_{eff} = P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2$$



Now microwave frequencies used for cellular communication. They get affected by the propagation mechanism. Reflection takes place. There is refraction, diffraction, and scattering effect, and because of these a signal transmitted from the transmitter appears at a receiver through different paths, and we call these multipath effects. Now is, for example, this multipath, they appear with minimal delay between them. But because of the random phase change, they suffer these signals at the receiver, these multipath signals. They may interfere constructively or destructively, giving lot of fluctuations in the received signal. And this causes the fading of the signal, and depending upon the medium through which these signals are propagating, this type of spreading becomes very random.

Now one of the fundamental equations that are important for modelling of the system is the free space propagation Friis equation. So suppose we have one antenna which transmits power of PT in microwave frequency band and supposes that this antenna is unidirectional. In that case it will radiate equally in all directions, and therefore the power density will be let us denote it by PDi will be PT by 4 pi R square Watt per meter square, at a distance of R from the antenna. Now practical antennas will have some gain, that means they will radiate more in some particular directions as compared to the other. So maximum of this gain function is called the gain and let GT denotes this gain. Then the power density PD, when you consider the antenna gain will be PT GT by 4 pi R square.

And this is the power density in the direction of maximum radiation. Now suppose the receiver antenna is also aligned to pick up the signal from that direction then the received power in the receiving antenna can be written as incident power density PD multiplied by A effective, where A effective is the effective aperture of the receiving antenna. For an antenna the effective aperture the A effective and the gain of the receiving antenna, they are related as A effective is equal to GR gain of the receiving antenna into lambda square by 4 Pi. And once you substitute this expression for the effective aperture we get, received power is equal to PT into GT into GR lambda by 4 pi R square.

So we noticed two things here as the distance from the transmitter increases that means R increases; the received power decreases 1 by R square. So it decreases very fast. And this is, in fact, the reason why the signal strength at a particular frequency will become very weak even in free space after traveling some distance, and the frequency reuse can be made beyond that distance. We also find that the received power varies as lambda square. Now lambda is C by F. That means the received power will vary as 1 by F square.

So as we go to the higher and higher frequencies, our range reduces. Because the received power available range, it reduces because of the decay of power with frequency. So these are the considerations. While choosing the frequency for wireless cellular communication, it should provide sufficient range, and at the same time the frequency should be high enough so that circuits have reasonable dimensions because size of some of the circuitries in wireless systems, they are dependent on the operating wavelength.

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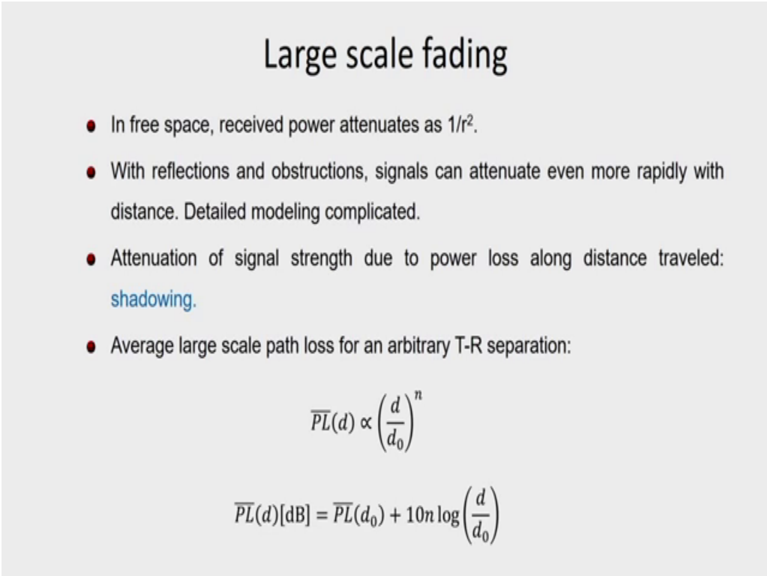
$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$$

$$\overline{PL}(d)[\text{dB}] = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$



So we discussed free space, how the signal attenuates. So in free space, the received power attenuates as 1 by R square. With reflections and obstructions, signal can attenuate even more rapidly with distance. And the detailed modelling is quite complicated. Attenuation of signal strength due to power loss along distance travelled, we consider this effect, which is known as shadowing. So shadowing occurs because of the obstacles present in the path and average large scale path loss for arbitrary transmitter-receiver separation; this is denoted as PL bar d, which means average path loss is proportional to d by d naught raised to the power n. Here n is the path loss exponent and d naught is reference distance usually close to the transmitting antenna, and it is in the far-field of the transmitting antenna with respect to which this path loss is specified. And therefore, in dB we can write average path loss at a distance d in dB is average path loss at d naught plus 10 n log d by d naught.

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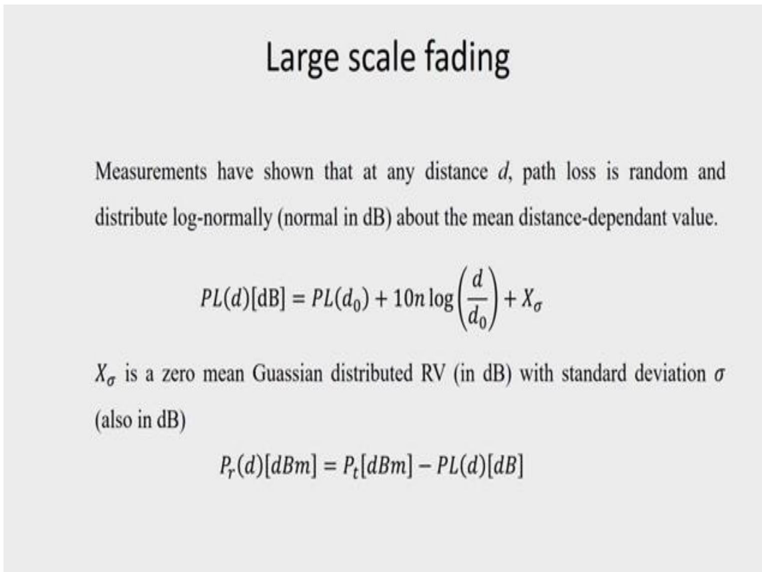
$$PL(d)[\text{dB}] = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

$$P_r(d)[dBm] = P_t[dBm] - PL(d)[dB]$$



So once we have this path loss and the path loss expression that we have shown, this is a deterministic expression. And when this path loss is subtracted from the transmitted power, it gives us the received power at a distance. But by measurement it has been found that at a distance d from the transmitter suppose we have a transmitter and we consider a radial distance d, so over this circle the path loss should be same in the ideal case. But in practical case through measurement it is found that the path loss is random, and it distributes log normally about the mean distance-dependent value.

So this is the path loss, mean path loss on top of that we add one quantity which is called X sigma, which is a 0 mean Gaussian random variable with standard deviation sigma and also in dB. So this part, it gives the random change in the path loss when measured under different conditions at the same distance. And once we have this expression for the path loss, we can find out the received power in dBm, which is equal to transmitted power in dBm, dBm is with reference to 1 Milli Watt. For example, 0 dBm represents 1 Milli Watt, 30 dBm 1 Watt, like that. So when we have PT in dBm minus path loss at a distance d expressed in dB. This is very important to know this Pr, because the design of the system particularly the RF system in a cellular communication system depends on what is the minimum received power with which the system would operate satisfactorily.

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Path loss exponent

Environment	Path loss exponent, n
Free space	2
Urban area cellular	2.7 to 3.5
Shadowed urban cellular	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Now we said that when the propagation environment is different from free space, the path loss exponent n or path loss parameter it usually changes wireless or mobile communication they take place in congested urban areas where there are lot of buildings or in semi-urban areas where there are lot of vegetations. So people have made extensive measurements and from that measurements the different values of path loss exponent, which are observed. So in free space it is 2, urban area cellular it maybe 2.7 to 3.5, with lot of shadowing present it may be as high as 3 to 5, in building l-o-s, here we can see that it is less than 2 because of some propagation effects, obstructed in building it may be as high as 4 to 6, obstructed in factories 2 to 3. So different environments people have done lot of measurement campaign, and we have a good idea about what is expected with the path loss in which range.

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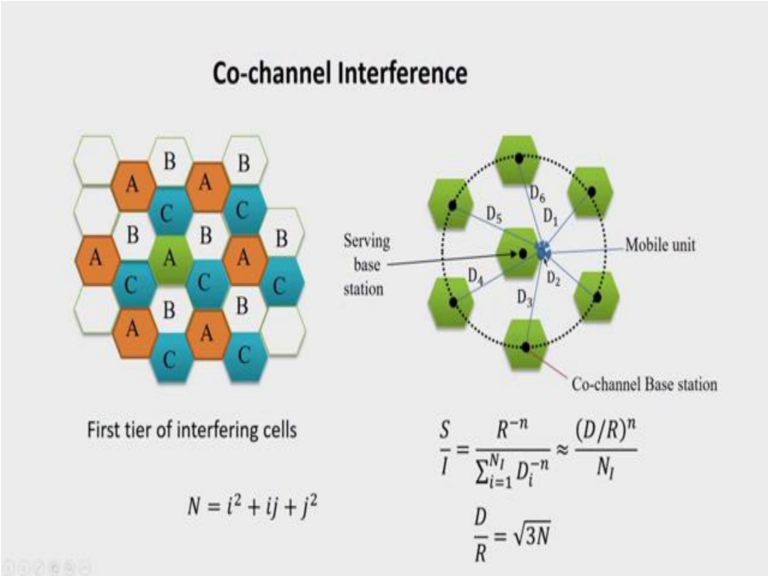
$$N = i^2 + ij + j^2$$

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{N_I} D_i^{-n}} \approx \frac{(D/R)^n}{N_I}$$

$$\frac{D}{R} = \sqrt{3N}$$



Now let us briefly touch upon the issue regarding co-channel interference, we have said that in cellular system frequency is reused at some distances, so here this cells marked as A, they will have the same frequency. Now a group of cells that actually divide the frequency among themselves is called a cluster. And the size of the cluster, the number of cells in a cluster is determined by N is equal to i square plus ij plus j square. For example if we had i equal to 1, j equal to 0. Then it this cluster contains only 1 cell. If i is equal to 1, j is equal to 1; then, it is a 3 cell cluster. If i equal to 2, and j equal to 0, then we have a 4 cell cluster.

Similarly, if we have i equal to 2, j equal to 1, in that case, we will have a 7 cell cluster, which is shown here. So these clusters can be having the number of cells satisfying this relation. Now let us consider this cell, it is surrounded by 6 other co-channel cells, and whenever there is transmission in these cells, their transmission may affect a transmission within the central cell. And this interference effect will be most pronounced when the mobile is at the edge of the parent cell that means when it's signal strength, it is likely to be very small or least from its own base station. So in that worst-case scenario, we can calculate roughly the signal to interference ratio. That will be experienced by mobile. So signal to interference ratio S by I can be written as R to the power minus n; this is because of the power decreasing inside this cell and assuming that the path loss exponent is same everywhere.

For this interference power, it is summation i equal to 1 to Ni Di raised to the power minus n, where D is the distances D1, D2, D3, etc from the base station of the location of the base station of the interfering cell to the location of the mobile. Now when these distances are large compared to radius R of the cell, all this Di's can be assumed to be equal to D., And therefore this can be written as D by R raised to the power n, divided by Ni. Ni is the number of interferers. For a hexagonal geometry we find that this type of centrally located cell will have 6 interferers. And also for this type of hexagonal geometry D by R can be shown to be equal to root 3N. So we can actually for this type of cellular geometry we can analytically estimate the expected signal to interference ratio that will be encountered at the edge of a cell. And this is the worst-case scenario when mobile is at the edge of this cell.

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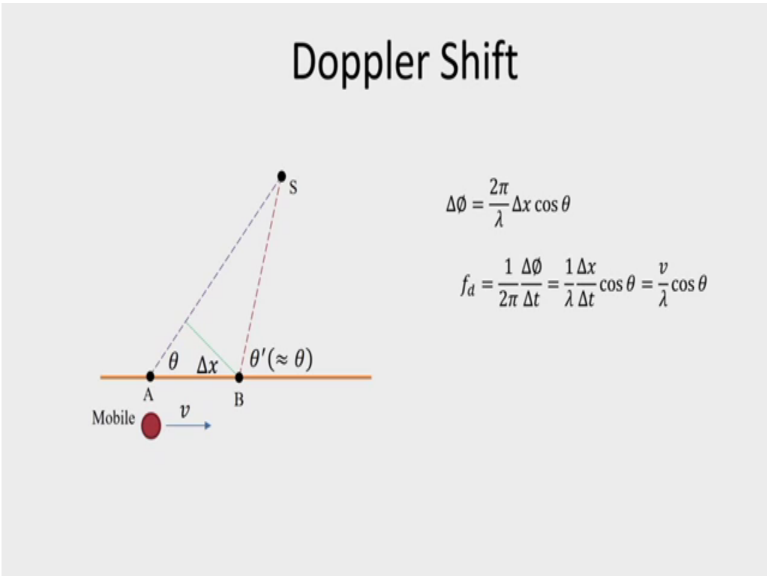
$$\Delta\emptyset = \frac{2\pi}{\lambda}\Delta x \cos\theta$$

$$f_d = \frac{1}{2\pi}\frac{\Delta\emptyset}{\Delta t} = \frac{1}{\lambda}\frac{\Delta x}{\Delta t}\cos\theta = \frac{v}{\lambda}\cos\theta$$



Another important parameter is the Doppler shift, and it plays a crucial role because when there is a relative motion between the transmitter and receiver, the frequency changes. Suppose we have a mobile user A and this is the source S at an angle theta, and mobile is moving with the velocity v as shown towards point B. And then theta dash is approximately equal to theta when this distance is less. And let it be delta x, and then the difference from source to the mobile in terms of distance is delta x cos theta. And we know that a distance of lambda produces a phase shift of 2 Pi, so delta phi, the phase difference is 2 pi by lambda delta x cos theta. Now Doppler shift fd can be written as 1 by 2 pi delta phi by delta t. If delta t is the time taken by the mobile to move from A to B, and this is same as 1 by lambda delta x by delta t cos theta.

And when this delta t tends to 0, then dx by dt it becomes v, so it becomes v by lambda cos theta. So depending upon the angle between the source and the mobile and the operating frequency and also based on the speed of the mobile V, it will experience a different amount of Doppler Shift. Manier time in cellular system design, the maximum Doppler Shift that is experienced is significant because it is related to one parameter of the channel called the coherence time. And for a time below that coherence time, the channel can be assumed to be steady. And it is assumed that after this time the channel experience will be different. So Doppler Shift plays an important role in designing the signal processing algorithms in the cellular system. And at microwave frequencies well lambda is very small Doppler Shift can be quite high.

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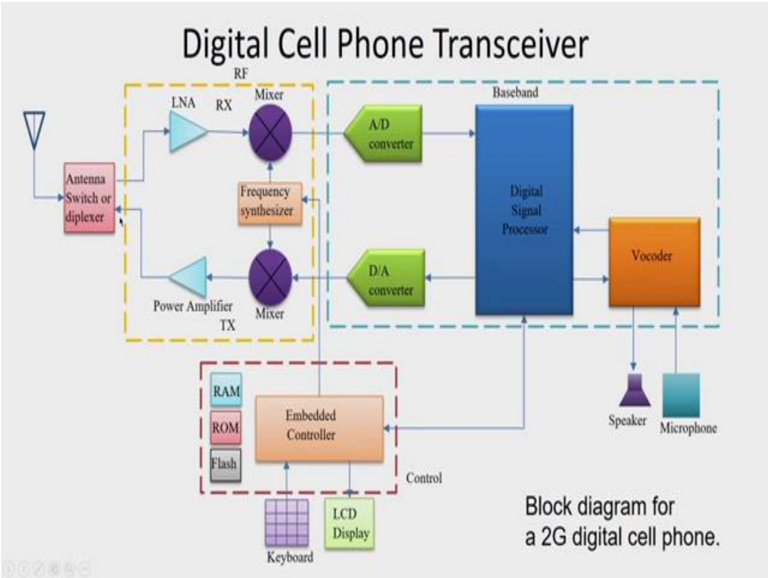

Without going much into the details of the cellular system, let us now quickly see some features of the mobile units, please note that mobile in a wireless or cellular system is a transceiver because there is two-way communication and therefore it receives as well as it transmits. So that is why we are talking of digital cell phone transceiver and the RF unit; it is broadly divided, this is, of course, an older generation of second-generation digital cell phone architecture, but it provides the insight of how the different tasks are divided. So we have the RF unit which operates in the microwave frequency. And then we have the baseband units which these RF units are analogue. Here we do a digital to analog conversion or analog to digital conversion, and this basement systems operate at much lower frequency and usually employ digital signal processing.

So we have an antenna that is shared between the transmitter and receiver changed to a switch or a diplexer. Now while transmitting the signal from the microphone it goes to the vocoder where it is encoded suitably; Digital Signal Processing takes place. Then it is converted in the analog form, and then we have frequency synthesizer which translates through this mixing process into an RF signal, and then it goes to a power amplifier, and it is transmitted. While receiving we have a low noise amplifier and then another level of mixer, which actually brings it to some lower frequency, usually called intermediate frequencies or baseband frequencies.

And then it is converted from analog to digital while receiving mode the signal goes through the LNA and then through a mixer which down-converts the signal. It is converted from analog to digital, and then the processing is done using a digital signal processor. And then, through vocoder it is given to the speaker. Now there is an embedded controller that controls the different interfaces, and it is also linked to frequency synthesizer, digital signal processor. So in mobile phone we have display, keyboard, memory, so it is a complex system out of which this part is the RF part, and we have already seen different principles of designing amplifiers, switches, etc.

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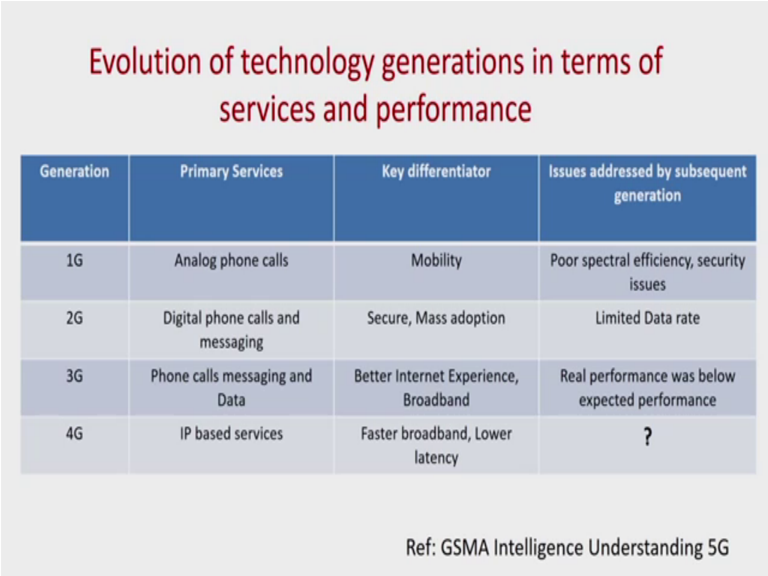

Generation	Primary Services	Key differentiator	Issues addressed by subsequent generation
1G	Analog phone calls	Mobility	Poor spectral efficiency, security issues
2G	Digital phone calls and messaging	Secure, Mass adoption	Limited Data rate
3G	Phone calls messaging and Data	Better Internet Experience, Broadband	Real performance was below expected performance
4G	IP based services	Faster broadband, Lower latency	?

Wireless cellular technology in terms of providing different services as well as technology-wise has changed very rapidly over the last few decades. And already 4th generation of wireless communication technologies have taken place, and we are looking towards 5th generation of such technologies. And this has happened within last about 50 years. So the first generation it was primary service was to provide analog phone calls and the key differentiator from the wire-based system was that it introduced mobility. There were many issues poor spectral efficiency, security issues and it was analog in nature.

Then the significant change came is second generation, where digital phone calls and messaging; this was the primary services. And key differentiator was security, and this is the time where the mass adoption of mobile phone technology has taken place. But it has the limitation of data rate, then 3G or 3rd Generation of phone calls, again messaging and data, but better internet experience and it offered broadband services. And there were lot of expectations from both industry and users. When 3G came into existence. But the real performance was below the expected performance. Then came the 4th generation of technologies, which is IP based services faster broadband, latency got reduced, and we are looking towards now the next generation 5G which is expected to arrive in few years of time.

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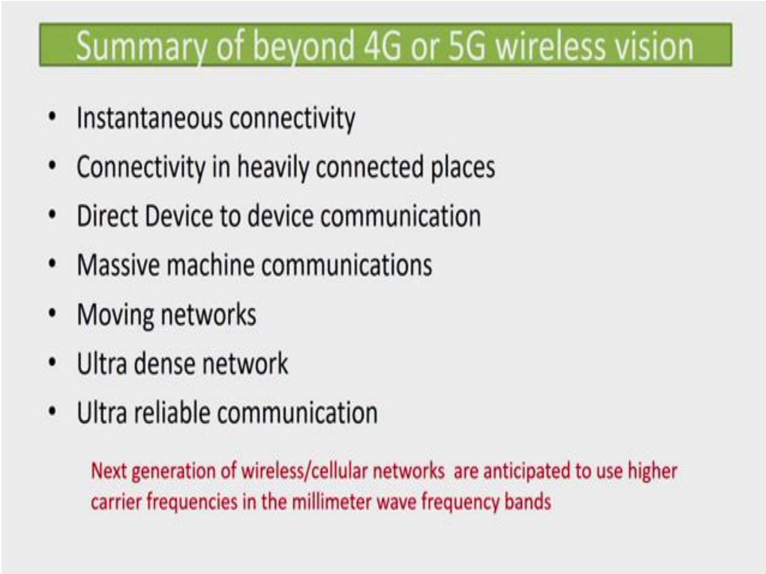

And beyond 4G, and we are looking towards 5G, which is expected to arrive very shortly, and when we move from 4G to 5G wireless system, it is expected to provide instantaneous connectivity. Connectivity in heavily connected places, is an issue where very large number of users are there, many a time getting a connection, and maintaining connection become very difficult. Then this type of technology also will support direct device to device communication and then massive machine communications where we will have large scale deployment. Well, at both ends of the communication link, we will have machines, and then moving networks, ultra-dense network. So these are some of the targets of the upcoming next-generation 5G technologies.

And ultra-reliable communication. Now the frequency band which we are using for wireless or cellular communication at this stage, all this is below 6 gigahertz, and already these bands are very, very congested. And therefore next generation of wireless and cellular networks are anticipated to use higher carrier frequencies in the millimeter-wave frequency bands. And technologies are being developed in the frequency bands around 28 gigahertz, in some cases around 60 gigahertz. So as we move higher up in the frequency, there are many technological challenges will come up. We have already discussed the range you will get reduced, the fading signal absorption, doppler; these issues need to be addressed properly, and this will cause lot of challenges to the designers who come up with this type of next-generation system.