Chapter 7

Cellular Networks

WiFi can provide connectivity at low cost, but its coverage is limited to within a home or office building. In contrast, cellular networks are designed to provide wide area coverage to both static and mobile users. Cellular network is the oldest communications network technology, which has now gone through several generations of evolution. In this chapter, we shall first learn the fundamentals concepts of cellular networks before examining the advancements brough forth by each generation.

7.1 Beginning of Cellular Networks

Back in 1968, AT&T Bell Labs submitted a plan [Rappaport2002] to FCC that they could provide radio communication services to the entire nation with limited spectrum by dividing the spectrum into several frequency bands and then allocating them in hexagonal cells as illustrated in Figure 7.1. Using this pattern, no two adjacent cells would be using the same frequency band, making it possible to cover the entire nation with the limited frequency bands and still avoid interference.

Figure 7.1 Reusing 7 frequencies to cover a large area with hexagonal cells. No two adjacent cells use the same frequency.

7.2 Initial Deployments of Cellular Systems in the US

In 1981, FCC set aside a total of 40MHz in 800MHz spectrum for cellular licensing [FCC800MHz]. For the initial deployment of cellular systems in US, the whole country was divided into 734 areas called Cellular Market Areas (CMAs). To avoid monopoly, it was decided that every CMA would be covered by two competing carriers, A and B. B stands for Bell, and A represents the *alternate*.

In the initial cellular deployments, uplink and downlink frequencies were different to avoid interference between transmit and receive antenna on the same device, i.e., Frequency Division Duplexing (FDD) was used. With FDD, a pair of frequencies therefore were needed to support a call. Each uplink/downlink channel was allocated 30kHz for a tota[illegible]plex voice call [Rappaport2002].

7.3 Cell Sites

Cellular systems [illegible]o towers (base stations) to transmit and receive calls. Where sh[illegible]wer. In the beginning they were building towers from scratch in [illegible] is very costly. Then the carriers wanted to use existing infrastructure, but due to wireless radiation as well as pollution of scenery, no one wanted cell towers near their house. There is this acronym NIMBY (not in my backyard). Finally, carrier started to install towers on roof tops of schools, churches, hotels, etc. as well on traffic lights, streetlamps and so on for a fee to the owners. For non-profit organizations, such as schools and churches, there was a great way of making money. Even some fake trees were planted to hide base stations as shown in Figure 7.2.

Figure 7.2 Base stations are erected on top of many different objects.

Fixed tower sites are good for most of the time, but they cannot handle sudden increase in demand in a given area. To serve a sudden surge of people in a given area, such as a big circus or fair, the operators bring CoWs or Cell on Wheels. The whole base station is fitted on top of a van, so the van can go anywhere where there is a demand as shown in Figure 7.3.

Figure 7.3 Cell on Wheels

7.4 Macro, Micro, Pico, Femto Cells

As the population started to grow, a single cell tower could not connect all users. So they started to deploy different sizes of cells to meet the demand. There are four different sizes of cell, Macro, Micro, Pico, and Femto, as shown in Figure 7.4.

Macro are the normal original cells with roughly 1Km radius. Micro covers a neighborhood of less than 1Km. Pico cells are deployed in busy public areas, such as malls, airports, etc., covering an area of about 200 m. Finally, femto cells are installed inside a home or office covering 10m to provide good coverage (strong signals). Some operators provide femto cells for free to attract and retain customers.

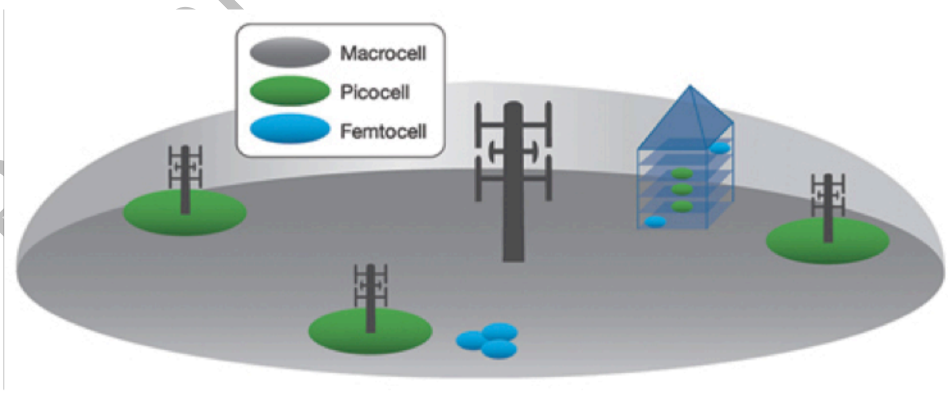


Figure 7.4 Macro, Micro, Pico, and Femto cells.

7.5 Cell geometry

Although there is no regular cell geometry in practice due to natural obstacles to radio propagations, a model is required for planning and evaluation purposes. A simple model would be for all cells to have identical geometry and tessellate perfectly to avoid any coverage gaps in the service area. Radio propagation models lead to circular cells, but unfortunately circles do not tessellate!

As shown in Figure 7.5, three options for tessellation are considered: equilateral triangle, square, [illegible]n. Hexagon has the largest area among the three; hence it is typica[illegible]ng cellular networks.

Figure 7.5 Tessellating cell shapes.

7.6 Frequency reuse and clustering

Earlier we discussed how AT&T proposed to cover the entire nation by simply reusing only 7 frequencies. Frequency reuse is possible because the signal from the cell tower gets weak at the cell border and hence loses its capacity to interfere with other communications happening far away from the current cell.

To keep the interference to a minimum, it's a common practice to avoid using the same frequency in adjacent cells. To achieve this, all cells in the service area are grouped into many clusters. The total spectrum is then divided into sub-bands that are distributed among the cells within a cluster in such a way that two adjacent cells do not share the same sub-band. Figure 7.6 shows examples of clusters sizes of 4, 7 and 19 where N represents the cluster size and the cluster borders are shown with solid black lines.

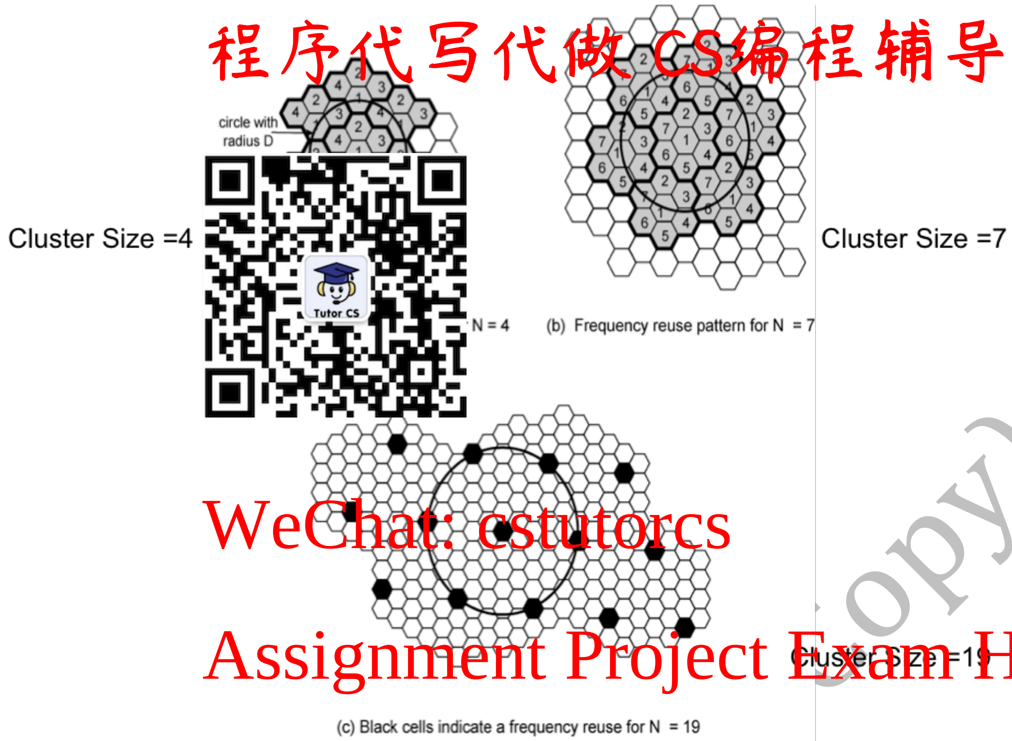


Figure 7.6 Frequency reuse with different cluster sizes.

7.7 Characterizing Frequency Reuse

The next question we want to answer is, how much reuse, or what is the extent of frequency reuse, can we achieve for a given cluster size? Let us do the mathematics and find out. Let us assume the following notations, which are also illustrated in Figure 7.7:

D = minimum distance between centers of cells that use the same band of frequencies (a.k.a. co-channel cells)
R = radius of a cell
d = distance between centers of adjacent cells. Note that d<2R due to the overlapping of cells, which enables seamless handover from cell to cell for a mobile user. The exact value is $d = R\sqrt{3}$.
N = number of cells in repetitious pattern (**Cluster**), also called the *reuse factor*[1]; note that each cell in the cluster uses unique band of frequencies

For hexagonal cell pattern, N cannot assume arbitrary numbers. It is rather given by the following formula [Rappaport2002]:

$N = I^2 + J^2 + (I \times J)$, where I, J = 0, 1, 2, 3, …

Therefore, the possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on. Note that some values are not possible. For example, we cannot have a cluster size of 5, because there are no combinations of integers, or I and J, that will provide 5.

[1] Sometimes, the reuse factor is represented by the fraction 1/N.

Finally, D/R is called the **reuse ratio**. From hexagonal geometry, it can be shown that that $D/R = \sqrt{3N}$, which means $D/d = \sqrt{N}$.

Example 7.1

What would be t e between the centers of two cells with the same band of frequenc km and the reuse factor is 1/12?

Solution:

R = 1 km, N = 1
$D/R = \sqrt{3N}$
D = $(3\text{x}12)^{1/2}$ 1 km
= 6 km

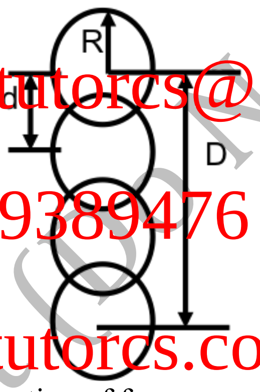
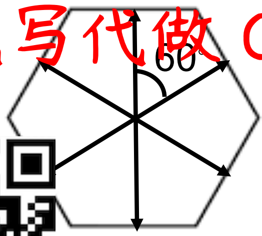


Figure 7.7 Illustration of frequency reuse notations.

7.8 Locating co-channel cells

Given a tessellated hexagonal cellular pattern of cluster size N, can we identify the co-channel cells? Yes, we can do this using the following simple rule.

First, obtain the I and J values that make up N. For example, for N=4, we could have I=0 and J=2, or I=2 and J=0. Now, to identify the cochannel cell of a particular cell A, move I cells in any direction from the centre of A, turn 60◦ counterclockwise and then move J cells. Note that there are 6 possible directions in a hexagonal cell, each separated by 60 degrees from their neighbours as illustrated in Figure 7.8. For N=19, Figure 7.9 illustrates the rule for finding the cochannel cells in a hexagonal cellular network.



x directions of a hexagon

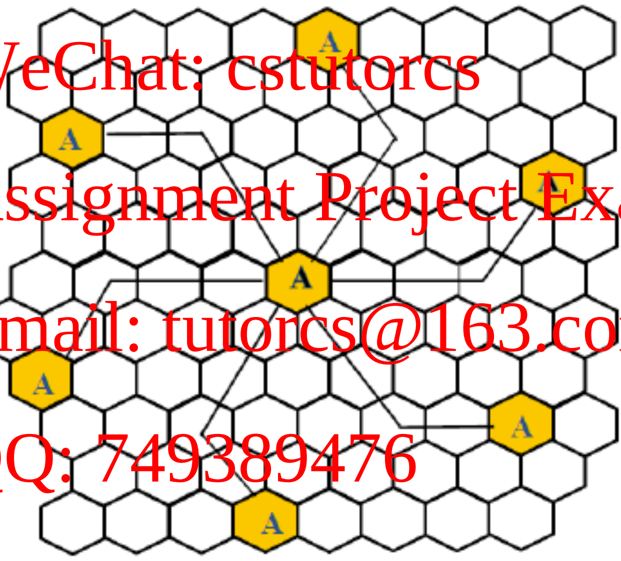


Figure 7.9 Locating co-channel cells in hexagonal cellular network: N=19 (I=3, J=2).

7.9 Spectrum distribution within cell cluster

We have learned that the spectrum available to a cellular operator can only be reused outside the cluster. Next, we are going to examine how the spectrum is distributed among the cells within the cluster.

For simplicity, it is assumed that the total spectrum is divided equally among all cells in the cluster. Let T denote the total number of available channels, N the cluster size, and K the number of channels per cell. Then we have K = T/N.

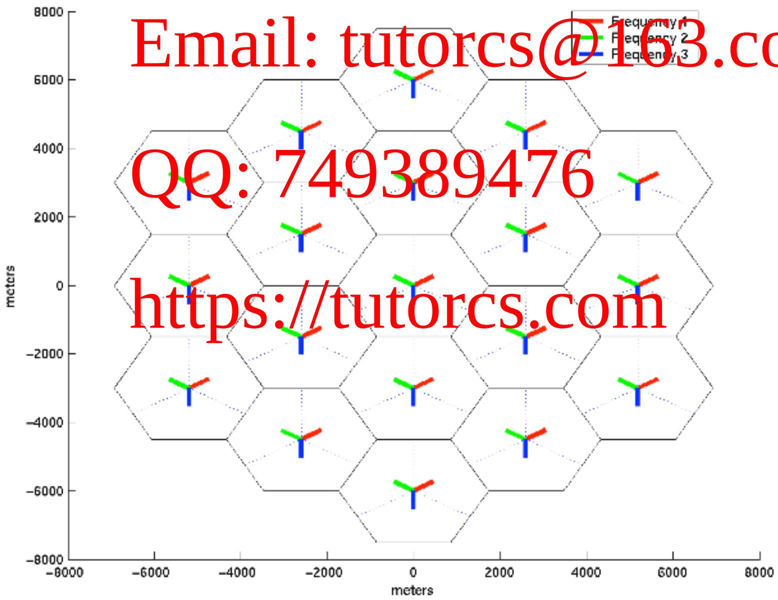
Cells are usually divided into sectors where a frequency received in one sector may not be received in another. Channels allocated to a cell is then further sub-allocated to different sectors according to the load or demand in each sector. Sectorized allocation of channels can also help minimize inter-cell interference, which is a major issue arising from spatial reuse of spectrum in cellular networks. For example, the cellular network in Figure 7.10 can reuse its spectrum with a cluster size of only 1 as two adjacent cell sectors do not use the same frequency.

7.10 Frequency Reuse Notation

To describe a gi pattern for sectorized cells, we can use a notation like NxSxK, wh of cells per cluster (cluster size), S is the number of sectors in a ce er of frequency allocations per cell.

Figure 7.9 is an 3 frequency reuse pattern where different colors represent differe that in this example, the same frequencies are used in every ce three sectors (S=3) in each cell, which is shown by dotted line dividing each cell into three equal geographical regions. Three frequencies have been allocated per cell (K=3).

In Figure 7.9, each sector uses one frequency, but in real life, multiple frequencies may be allocated to a given sector (heavily populated), while other sectors may have just one or even no frequency allocated. Here K=3 only means that three frequencies are allocated per cell, but how the frequencies are distributed between the sectors is not captured by the NxSxK notation.



1X3X3

Figure 7.10 An example of a frequency reuse with cluster size of 1 using sectorized antenna.

Figure 7.11 shows 6 more examples of frequency reuse notations. In this figure, frequencies are shown as numbers within the sector. Again, frequencies are evenly distributed among the sectors. For example, if a cell is allocated 3 frequencies, each sector is allocated a different frequency.

Figure 7.11 also shows the location of a subscriber station (SS) within the cell and which tower it is likely to get the signal from using a red arrow from tower to the SS. There is a red arrow from a tower if it is towards the sector with the same frequency. Let us examine how the SS receives signal from different towers by following the red arrows in the figure for different patterns.

For the first pattern (1x3x1) there is only one frequency. Given the current location of the SS shown in the figure, it can receive the same frequency signal from five other cells besides the current cell. Similarly, for 3x3x1, the SS is receiving frequency 2, so it will receive fr m 4 other cells. Fortunately, if the SS is located in the center of signal from the current cell tower will be the strongest, which ct to this tower without any confusion.

A problem arise cated close to the edge. If it receives the same frequency signal s, then the signal strengths may be close to each other creating co o a so-called *ping-pong effect*, where the SS may switch between towers as it moves.

Figure 7.11 Examples of 6 different frequency reuse patterns

7.11 Fractional Frequency Reuse

The cell-edge problem can be addressed by a concept called *fractional frequency reuse,* which controls the signals strengths of the frequencies in a way such that some frequencies can only be heard in the center (not heard in the edge) while only one of them can be heard in the edge. This is shown in Figure 7.12. We can see that with fractional frequency reuse concept, stations in the edge no more has the confusion because no border uses the same frequency.

Figure 7.12 Fractional frequency reuse

7.12 Handoff

User mobility poses challenges for cellular networks. As the user starts to leave the coverage of a cell, the RSS becomes too weak. The user then must connect to a new BS with a stronger RSS to keep the connection to the network. Disconnecting from one and connecting to a new BS during an on-going session is called handoff, which is illustrated in Figure 7.13.

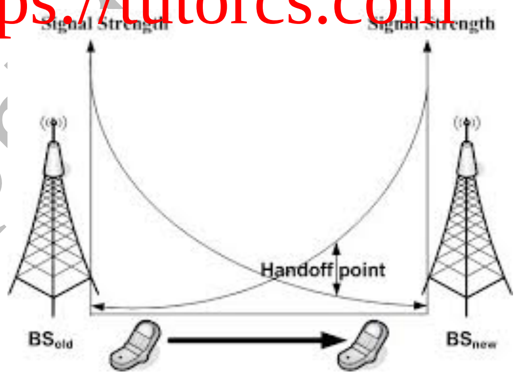


Figure 7.13 The handoff process in cellular networks.

To handoff successfully, the new BS must have available channels to support the on-going call; otherwise the call will be dropped. Dropping an ongoing call is worse than rejecting a new call. BSs therefore usually reserve some channels, called guard channels, exclusively for supporting handoff calls. Unfortunately, guard channels increase the blocking probability of new calls. The number of guard channels is left to the operators to optimize, i.e., it is not part of the standard.

Example 7.2

A particular cellular system has the following characteristics: cluster size=7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code [...] w many users per cell can be supported and what cell sizes are req[...]

Solution:

49 MHz/7 = 7 M[...]tric bandwidth requirement in uplink/downlink, we have 3.5 MH[...]
10 kbps/user = 10kHz/user (1bps/Hz); users/cell =3.5MHz/10kHz = 350
100 users/km^2; to connect 350 users, the cell area has to be 350/100= 3.5 km^2
$\pi r^2 = 3.5$; r = 1.056 km

Example 7.3

A particular cellular system has the following characteristics: cluster size=7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz. If the available spectrum for uplink/downlink is divided in to 35 channels and TDMA is employed within each channel:
1. What is the bandwidth and data rate per channel?
2. How many time slots are needed in a TDMA frame to support the required number of users?
3. If the TDMA frame is 10ms, how long is each user slot in the frame?
4. How many bits are transmitted in each time slot?

Solution:

1. 49 MHz/7 = 7 MHz/cell; For symmetric bandwidth requirement in uplink/downlink, we have 3.5 MHz/uplink or downlink
3.5 MHz/35 = 100 kHz/Channel = 100 kbps per channel
2. With 10 kbps/user, we have 10 users/channel
3. 10 ms/10 = 1ms
4. 1 ms x 100 kbps = 100 b/slot

7.13 Cellular Telephony Generations

As we have discussed, cellular telephony started back in 1980s. That was called the first generation of cellular networks. Since then, the technology continued to evolve to meet the demand in terms of number of people and devices that want to connect as well as the nature of traffic they want to send, such as voice vs. data.

In cellular word, the major changes are marked as a generation (G), which roughly lasts for 10 years. Any major changes in between the 10 years is then marked as fraction of 10, such as 2.5G. Figure 7.14 shows the evolution of these generations. The figure shows how the evolution in terms of standardization is happening in the

US (or North America) and in Europe in the core technology, such as Analog vs. Digital, and in traffic types, such as voice vs. data.

Following are some of the key points to note:

Technology and [illegible]eneration (1G) was analog and using FDMA to transmit only vo[illegible] transmission starting from 2G, but it was voice. Data could only [illegible] converting it to voice signals using modems. Actual data trans[illegible] 2.5G and by now it is mostly data. Voice is now transmitted over [illegible]

Standardization in North America and Europe: North America and Europe continued using different standards until the end of 3G, when they converged to LTE (Long Term Evolution).

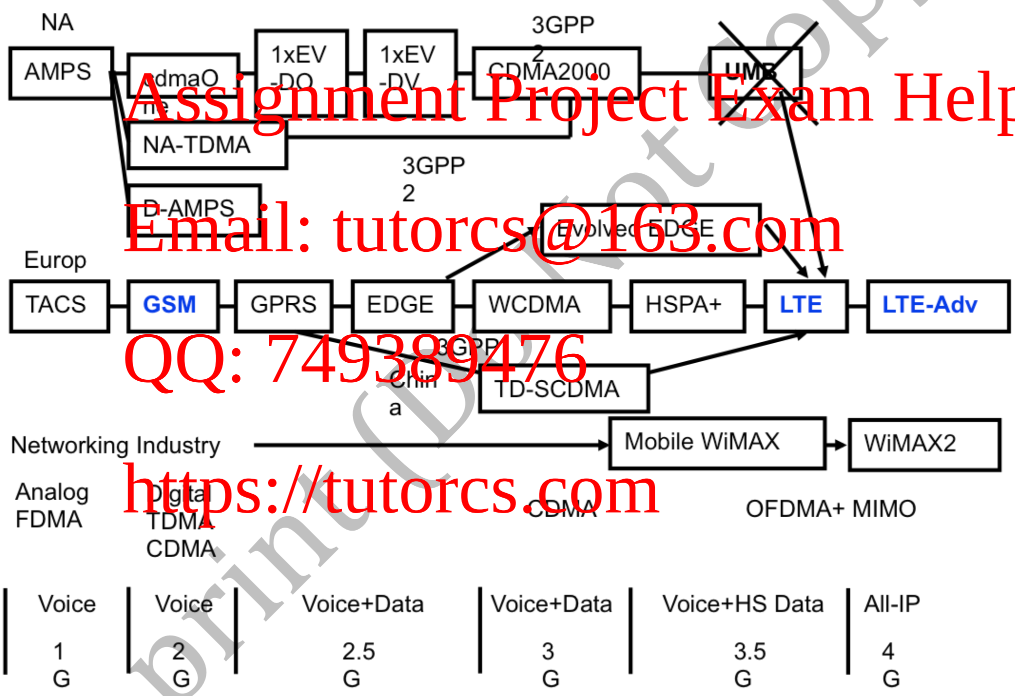


Figure 7.14 Evolution of cellular telephony

Table 13.1 shows more details of each generation. Most of the standards, such as GPRS, EDGE, WCDMA and so on are now almost extinct. One standard that survived and very much in use worldwide including in North America is GSM.

Table 7.1 Cellular generations

Generation	Traffic	Standards
1G – 1980s	Analog Voice. FDMA	• AMPS: Advanced Mobile Phone System • TACS: Total Access Communications System
2G - 1990	Digital Voice. TDMA	• cdmaOne: Qualcomm. International

		Standard IS-95 • NA-TDMA • Digital AMPS (D-AMPS) • **GSM**: Global System for Mobile Communications
2.5G - 1995	[illegible]	• 1xEV-DO: Evolution Data Optimized • 1xEV-DV: Evolution Data and Voice • General Packet Radio Service (GPRS) • Enhanced Data Rate for GSM Evolution (EDGE)
3G - 2000	Voice+High-speed data. All CDMA	• CDMA2000: Qualcomm. International Standard IS-2000. • W-CDMA: Wideband CDMA • TD-SCDMA: Time Division Synchronous Code Division Multiple Access (Chinese 3G) • 384 kbps to 2 Mbps
3.5G	Voice+Higher-speed Data	• EDGE Evolution • High-Speed Packet Access (HSPA) • Evolved HSPA (HSPA+) • Ultra Mobile Broadband (UMB)
3.9G	High-speed data+VOIP. OFDMA	• WiMAX 16e (Worldwide Interoperability for Microwave Access) • Long Term Evolution (LTE)
4G - 2013	Very High-speed Data	• WiMAX 16m or WiMAX2 • LTE-Advanced • 100 Mbps – 1 Gbps
5G - 2020	Ultra High-speed data + Ultra Low Latency + Massive connectivity	IP-based

7.14 GSM

GSM stands for Global System for Mobile Communications. It is now implemented in most cell phones world-wide and most countries are using GSM. A phone without GSM support therefore would not do much.

The interesting thing is that GSM was designed back in1990. Three decades on, it is still a very popular technology. GSM uses Time-Division Multiple Access (**TDMA**) instead of Frequency Division Multiple Access (FDMA) used in 1G. Figure 7.15

shows the difference between FDMA and TDMA. In FDMA, once a frequency is allocated to a user, no one else was allowed to use that frequency. This wasted a lot of system capacity. With TDMA, the same frequency could be used by multiple users shared in time. This is possible because there are many silence periods in voice communication, [illegible] other users.

GSM is define[illegible] frequency bands used throughout the world. Specifically, it s[illegible]ds, 850/900/1800/1900 MHz, hence called quad-band. Handsets [illegible] band may not operate in some countries.

The biggest inv[illegible] to separate the user from the handset. Prior to GSM, user subscript information was tied to the handset hardware. It made it difficult for people to change operators and share handsets. GSM introduced the concept of **Subscriber Identity Module (SIM)** card, which is a tiny plastic that contains user subscription information. Once inserted to a handset, that handset then is used for that user. With this concept, users can use the handset even when they switch subscriber.

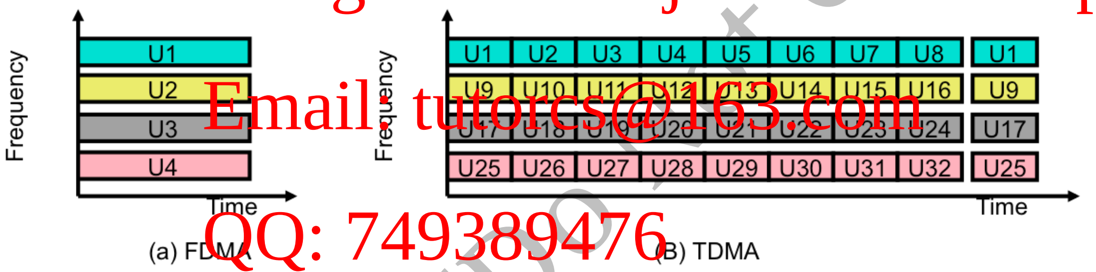


Figure 7.15 Difference between FDMA and TDMA

7.15 GSM Cellular Architecture

GSM system has many components. The architecture of GSM is shown in Figure 7.16. The phone handset is called a Mobile Equipment (ME), which has a SIM inside it. The SIM contains a micro-controller and storage. It contains authentication, encryption, and accounting info.

Using radio or wireless links, the ME connects to a radio tower, which is called a Base Transceiver Station (BTS). There is one BTS per cell.

A Base Station Controller (BSC) controls several BTSs via wired backbone. It allocates radio channels among BTSs, manages call handoff between BTSs, as well as controls handset power levels. MEs that are far from the tower, will be asked to increase its power level, while the MEs closer to the tower will be instructed to use lower powers.

Many BSCs in turn are then connected to a Mobile Switching Center (MSC). Inside the switching center, which is usually a building housing many equipment, the MSC is connected to a range of other entities and functions such as Home Location Register (HLR) and Visitor Location Register (VLR), Equipment Identify Register (EIR), Authentication Center (AuC), and so on.

The AuC stores the secret keys of all SIM cards. The EIR stores the unique hardware numbers for each handset. Each handset has an International Mobile Equipment Identity (IMEI) number. If a phone is stolen and reported as stolen, then that information, i.e., one, is stored there. So, if a call is made from that phone, the MSC s originated from a stolen phone (the hardware number is transn SIM) and take some action.

The MSC is also red telephony network, which is called the Public Switched Teleph) via a very high speed wired connection.

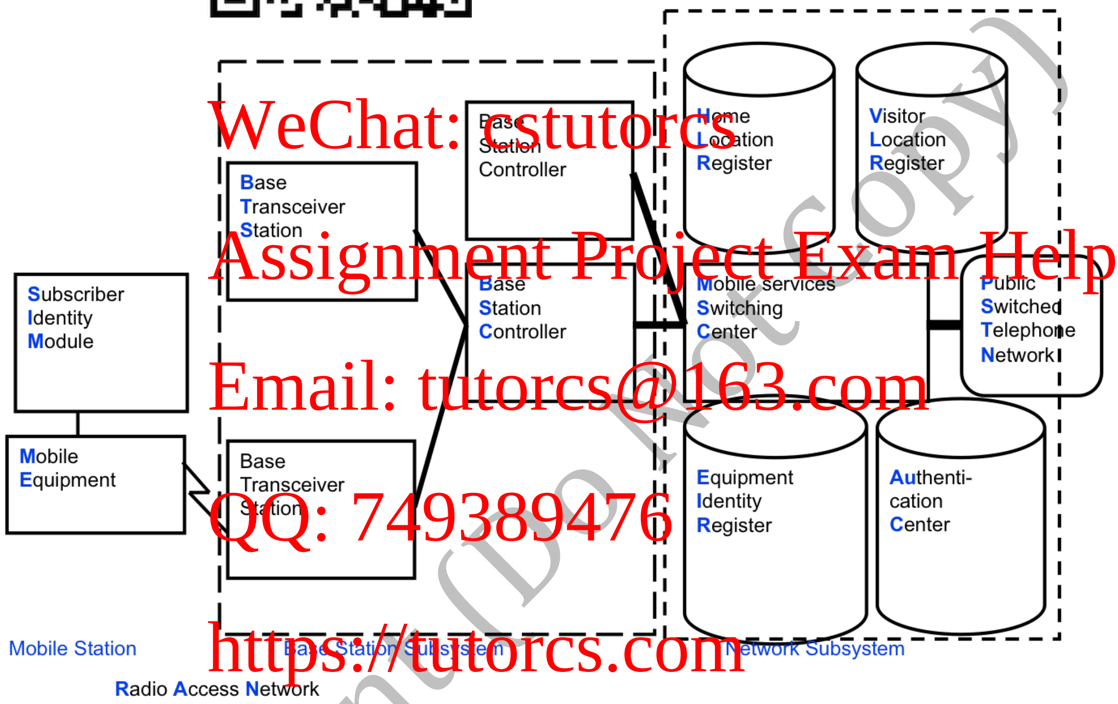


Figure 7.16 GSM cellular architecture

Figure 7.17 shows how the different functions are invoked when an end to end call is established between a caller and a callee. The functions invoked at both ends are symmetric.

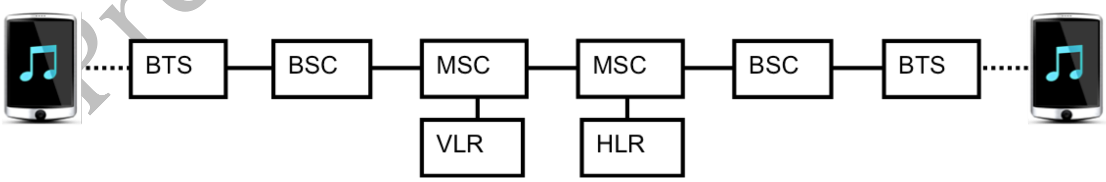


Figure 7.17 End-to-end call in GSM

7.16 GSM Radio Link

GSM supports 24 traffic channels over each frequency. The number 24 is for historical reason. In the beginning, 24 voice calls were carried over a T1 link. GSM therefore also started with combining 24 traffic channels into one multiframe.

This is achieved by dividing a frequency into a total of 26 equal-length time slots. The frame structure is shown in Figure 7.18. The frame is called a superframe because it supports many users. Basically, a superframe repeats every 120 ms. Therefore, each slot is 120/26 ms long. There are 24 slots used for carrying user traffic. Two out of 26 are not used for ... sed for control, and one is unused.

Each 120/26 m... ded into 8 Burst Period. Therefore, each Burst Period is one 8... 6 ms long. One user is allocated to each burst period.

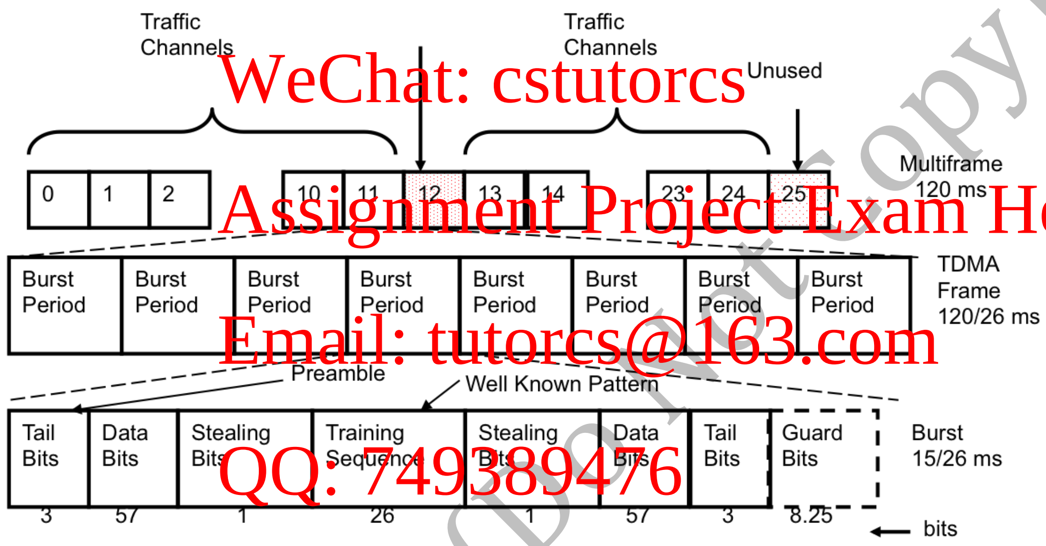


Figure 7.18 Frame structure of GSM radio link

GSM has separate frequencies for uplink and downlink. 25 MHz between 890-915 MHz is used fir uplink and 25 MHz between 935-960 MHz for downlink. The 25 MHz bandwidth is divided in frequency domain into 125 channels, each 200kHz wide. Each of these 200kHz channel is then divided in time domain into 24 traffic slots.

The control channel is usually called Slow Associated Control Channel (SACCH). It uses one traffic slot of 120/26 ms. If the control traffic requires more bandwidth than this, then it can steal some bandwidth from user slots as follows.

Note in Figure 7.18, that each user burst has two bits reserved as “stealing bits”. The control channel can set these bits to indicate to the receiving end that hand of the user burst has been stolen and now carrier control information instead of user data. Because voice is error-tolerant, occasional loss of bits can still be tolerated within limit.

Interestingly, the reverse use is also possible with control channels. If the control channel has no control information to carry, then some user traffic could be sent over it. But it has to be very short. This is how the short message service (SMS) concept was developed. Now SMS is so popular that carriers probably are dimensioning more control channels to make profit from it.

Each 200 kHz channel is ultimately used by 8 user slots. Each 200 kHz channel is modulated to 270.8 kbps data rate. That gives 270.8/8 = 33.85 kbps per user. After encryption and FEC, only 9.6kbps per slot. This means, if we send data over GSM, we can get 9.6kb[illegible]

Voice, on the ot[illegible]eed high FEC. Therefore, voice can use a higher bit rate. It turns [illegible] kbps, which is a compressed version of the 64-kbps original vo[illegible]l voice is 64 kbps because it is sampled at 8,000 samples per sec[illegible]le is coded with 8 bits. The telephone system (PSTN) has a cu[illegible]Hz because human voice does not carry very high frequency. Nyquist sampling theory says that we need sample at twice the frequency of the original analog signal to avoid loss of information. That's why voice signals are sampled at 8000 samples per second, which is twice the 4kHz bandwidth.

This means that if you play music from a CD player over the phone, the quality of the music will be very poor at the other end as music contains some very high frequency components which will be filtered out by the telephone system.

7.17 LTE

LTE stands for Long Term Evolution. The whole world, Europe as well as North America converges to the same cellular telephony technology starting with LTE. This is also the kick start for the 4th generation of telephony. 3GPP is now the single body that coordinates all standards for cellular telephony. Every year it releases new documents. LTE was released as 3GPP Release 8 in 2009.

LTE is the precursor for 4G. Technically, for a technology to be called 4G, it has to meet all the requirements specified in International Mobile Telecommunication (IMT) Advanced Requirements in ITU M.2134-2008. LTE did not meet every criterion in that document, so it is sometimes called pre-4G or 3.9G cellular technology. LTE was then later revised to LTE Advanced or LTE-A to meet all the 4G specifications.

LTE supports all different bands, 700/1500/1700/2100/2600 MHz, to satisfy spectrum allocations in different regions in the world as well flexible bandwidth, 1.4/3/5/10/15/20 MHz, depending on the country [ASTELY2009]. The bandwidth can be allocated very flexibly. It can be divided to many users during peak hours, or the whole network bandwidth can be allocated a single user at off-peak time if there are no other user competing. The maximum data rate possible in LTE there can be very high.

LTE supports both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). For FDD, *paired* spectrum allocation is required, which means that equal amount of spectrum or frequencies have to be allocated for uplinks and downlinks. This suits well when both uplink and downlink have equal usage, such voice. In voice calls, a person speaks 50% of the time and listen 50% of the time. However, for data, downlink is used more heavily than uplink, as we tend to download more data than upload, although upload traffic is increasing rapidly due to pervasive availability of cameras and videos in mobile phone and use of social networks. TDD does not required paired allocation. It can be *unpaired* and use the spectrum more flexibly for up and down use, which suits data very well.

LTE supports 4 multi-user collaborative MIMO. It supports beamforming o . When using 4x4 MIMO with 20 MHz, i.e., the full capacity, L Mbps for downlink and 86 Mbps for uplink. For modulation M with QPSK, 16 QAM, and 64 QAM. LTE supports OFDM

7.18 LTE Frame Structure

LTE superframes are 10 ms long. This means superframes just repeat every 10 ms. Each superframe contains 10 1-ms subframes as shown in Figure 7.19. Each subframe has two 0.5ms slots, one for downlink and one for uplink. This allows a very quick turnaround time, because a mobile handset can get an answer from the base station or vice versa within 0.5ms.

How many OFDM symbols can be sent per 0.5ms? This depends on the length of the cyclic prefix used for each symbol to address the multipath effect. Two types of cyclic prefixes are allowed. For small networks, cyclic prefix of 5.2μs for the 1st symbol and 4.7μs for others are used, which allows 7 symbols to be transmitted in a 0.5ms slot. On the other hand, for larger networks, which have longer multipath, extended cyclic prefix of 16.7μs is used, which allows only 6 symbols to be carried in a slot. These two types of cyclic prefixes are shown in Figure 7.20.

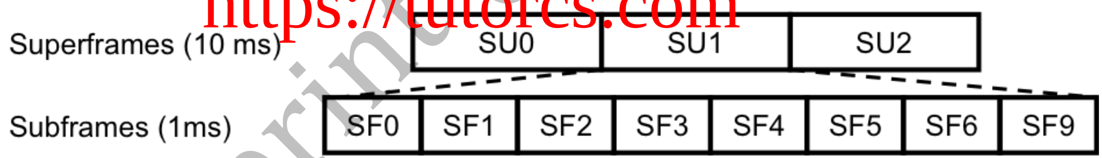


Figure 7.19 LTE Superframe structure. Each superframe contains 10 1-ms subframes

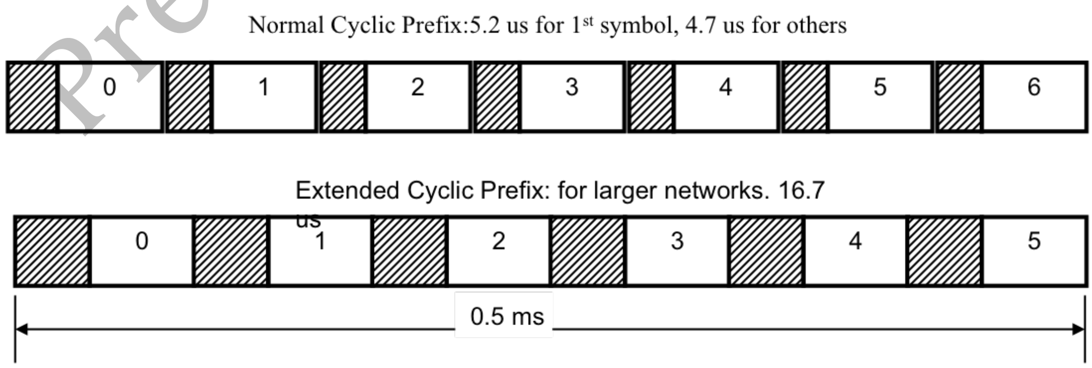


Figure 7.20 Two types of cyclic prefix.

7.19 LTE Resource Allocation

To transmit in the uplink or receive in the downlink, mobile handsets need to be allocated resources. Resources are defined by OFDM subcarriers (frequency) and slots (time). Each slot is 0.5ms (equivalent to 6 or 7 symbols) and Each subcarrier is 15 kHz.

With this defini[illegible]carriers, a Physical Resource Block (PRB) is defined as a rec[illegible]ubcarriers (180 kHz) over 1 time slot (0.5ms) in the resource [illegible]gure 7.21.

Given that each [illegible]k slot and an uplink slot in each subframe, the minimum alloc[illegible] is 2 PRBs. However, these two PRBs do not have to be contiguous in the resource map but could be from anywhere. An example of two PRB allocations to a subframe, or a single user equipment (UE) is shown in Figure 7.22.

The allocation of the blocks changes every superframe, i.e., every 10ms, unless for some persist scheduling, where the same resource blocks may be allocated over a long time (over several superframes).

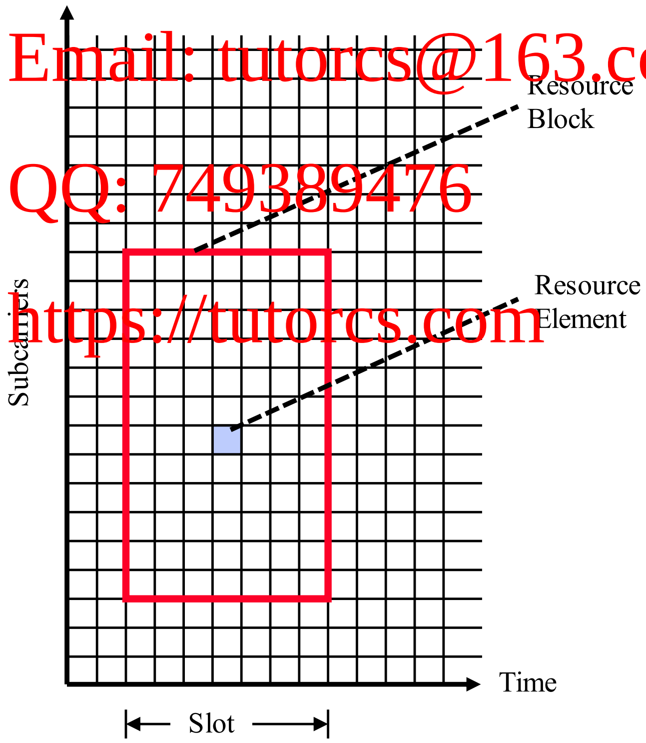


Figure 7.21 Physical Resource Block (PRB).

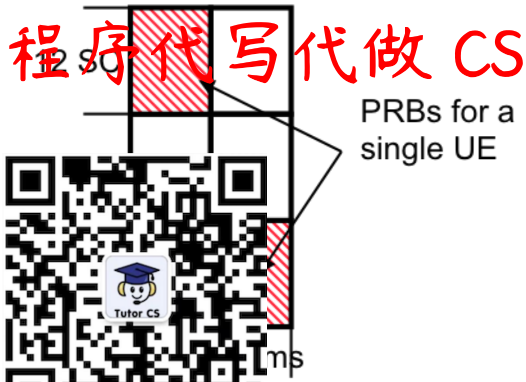


Figure 7.22 PRB allocations to a subframe (single UE).

Example 7.4

For *normal* cyclic prefix (CP), how many resource elements (REs) are there in 2 REs?

Solution:

With normal CP, we have 7 symbols per slot
Number of REs per RB = 12 x 7 = 84
Number of REs in 2 RB = 2 x 84 = 168

Example 7.5

What is the *peak data rate* of downlink LTE?

Solution:

For peak data rate, we assume best conditions, i.e., 64 QAM (6 bits per symbol), short CP (7 symbols per 0.5ms slot), and 20 MHz channel
Each symbol duration = 0.5ms / 7 = 71.4µs
Number of RB for 20 MHz = 100
Number of subcarriers per RB = 12
Number of subcarriers for 20 MHz channel = 100 x 12 = 1200
Number of bits transmitted per symbol time = 6 x 1200 bits
Data rate = (6 x 1200 bits) / (71.4µs) = 100.8 Mbps (without MIMO)

7.20 Chapter Summary

1. In a cellular cluster of size N, the minimum distance between co-channel cells is $D = R\sqrt{3N}$, where R represents the cell radius.

2. With sectorized antenna, it is possible to have a cluster size of just 1, i.e., two adjacent cells can reuse the same spectrum.
3. 1G was analog voice with FDMA
4. 2G was digital voice with TDMA. Most widely implemented 2G is GSM.
5. 3G was v[illegible]MA.
6. LTE is th[illegible]TE uses a **super-frame** of 10 subframes of 1ms each. Eac[illegible] 0.5ms **slot** for uplink and downlink each. Each subcarrie[illegible]2 subcarriers (180kHz) over 1ms slot is used as a unit of re[illegible]

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End of Chapter 7