

MODULE 3

Evolution of Cellular Technologies

Evolution of Cellular Technologies: First Generation Cellular Systems, 2G Digital cellular systems – GSM and its Evolution, 3G Broadband Wireless Systems, Key Enabling Technologies and features of LTE, LTE Network Architecture.

Frequency Domain Multiple Accesses: Multiple Access for OFDM Systems, Orthogonal Frequency Division Multiple Access, Single Carrier Frequency Division Multiple Access.

[Text2: 1.2.1, 1.2.1.1, 1.2.2, 1.2.2.1, 1.2.3 (Only the mentioned sections and subsections), 1.4, 1.5, 4.1, 4.2, 4.3]

Text 2: Arunabha Ghosh, Jun Zhang, Jeffrey G. Andrews, Rias Muhamed, “Fundamentals of LTE”, Pearson India Education Services Private Limited, 2018, ISBN: 978-93-530-6239-2.

3.1 First Generation Cellular Systems

- The United States, Japan, and parts of Europe led the development of the first generation of cellular wireless systems.
- The first generation systems were characterized by their **analog modulation schemes** and were designed primarily for **delivering voice services**.
- They were different from their predecessor mobile communications systems in that they used the cellular concept and provided automatic switching and handover of on-going calls.
- Japan's Nippon Telephone and Telegraph Company (NTT) implemented the world's first commercial cellular system in 1979. Nordic Mobile Telephone (NMT-400) system, deployed in Europe in 1981, was the first system that supported automatic handover and international roaming.
- NMT-400 was deployed in Denmark, Finland, Sweden, Norway, Austria, and Spain. Most NMT-400 subscribers used car phones that transmitted up to 15 watts of power.
- The more successful first generation systems were **AMPS** in the United States and its variant Total Access Communication Systems (ETACS and NTACS) in Europe and Japan.
- These systems were almost identical from a radio standpoint, with the major difference being the channel bandwidth.
- The AMPS system was built on a 30kHz channel size, whereas ETACS and NTACS used 25kHz and 12.5kHz, respectively.
- Table 1.1 provides a quick summary of first generation cellular systems.

	AMPS	ETACS	NTACS	NMT- 450/ NMT-900
Year of Introduction	1983	1985	1988	1981
Frequency Bands	D/L:869- 894MHz U/L:824- 849MHz	D/L:916-949MHz U/L:871- 904MHz	D/L:860- 870MHz U/L:915- 925MHz	NMT-450:450- 470MHz NMT-900:890- 960MHz

Channel Bandwidth	30kHz	25kHz	12.5kHz	NMT-450:25kHz NMT-900:12.5kHz
Multiple Access	FDMA	FDMA	FDMA	FDMA
Duplexing	FDD	FDD	FDD	FDD
Voice Modulation	FM	FM	FM	FM
Number of Channels	832	1240	400	NMT-450:200 NMT-900:1999

3.1.1 Advanced Mobile Phone Service (AMPS)

- AMPS was developed by AT&T Bell Labs in the late 1970s and was first deployed commercially in 1983 in Chicago and its nearby suburbs.
- The first system used **large cell areas and omni-directional base station antennas**.
- The system covered **2,100 square miles with only ten base stations, each with antenna tower height between 150 ft. and 550 ft.**
- Most of the early systems were designed for a carrier-to-interference ratio (CIR) of 18dB for satisfactory voice quality, and were deployed in a 7-cell frequency reuse pattern with 3 sectors per cell.
- AMPS was deployed in several countries in South America, Asia, and North America.
- In the United States, the FCC assigned spectrum to two operators per market—one an incumbent telecommunications carrier and the other a new non-incumbent operator.
- Each operator was assigned **20MHz of spectrum, supporting a total of 416 AMPS channels in each market. Of the 416 channels, 21 channels were designated for control information and the remaining 395 channels carried voice traffic.**
- AMPS systems used **Frequency Modulation (FM) for the transmission of analog voice and Frequency Shift Keying (FSK) for the control channel.**

3.2 2G Digital Cellular Systems

- 2G systems used digital modulation.
- Shifting from analog to digital enabled several improvements in systems performance.
- System capacity was improved through
 - (1) the use of spectrally efficient digital speech codecs,
 - (2) multiplexing several users on the same frequency channel via time division or code division multiplexing techniques, and
 - (3) tighter frequency re-use enabled by better error performance of digital modulation, coding, and equalization techniques, which reduced the required carrier-to-interference ratio from 18dB to just a few dB.
- Voice quality was also improved through the use of good speech codecs and robust link level signal processing.
- 2G systems also used simple encryption to provide a measure of security against eavesdropping and fraud, which were a source of major concern with first generation analog systems.
- Examples of 2G digital cellular systems include the Global System for Mobile Communications (GSM), IS-95 CDMA, and IS-136 TDMA systems.

- GSM is by far the most widely deployed of these systems; IS-95 is deployed in North America and parts of Asia; IS-54 (later enhanced to IS-136) was initially deployed in North America but was later discontinued and replaced mostly by GSM. IS-136 was a TDMA-based system that was designed as a digital evolution of AMPS using 30kHz channels.
- The Personal Handyphone System (PHS) deployed in China, Japan, Taiwan, and some other Asian countries is also often considered a 2G system.
- PHS is a cordless telephone system like the Digital Enhanced Cordless Telephone (DECT) system but with capability to handover from one cell to another, and operated in the 1880-1930MHz frequency band.
- Table 1.2 provides a summary comparison of the various 2G digital cellular systems.

	GSM	IS-95	IS-54/IS-136
Year of Introduction	1990	1993	1991
Frequency Bands	850/900MHz, 1.8/1.9GHz	850MHz/1.9GHz	850MHz/1.9GHz
Channel Bandwidth	200kHz	1.25MHz	30kHz
Multiple Access	TDMA/FDMA	CDMA	TDMA/FDMA
Duplexing	FDD	FDD	FDD
Voice Modulation	GMSK	DS-SS:BPSK, QPSK	$\pi/4$ QPSK
Data Evolution	GPRS, EDGE	IS-95-B	CDPD
Peak Data Rate	GPRS:107kbps; EDGE:384kbps	IS-95-B:115kbps	~12kbps
Typical User Rate	GPRS:20-40kbps; EDGE:80-120kbps	IS-95B: < 64kbps;	9.6kbps
User Plane Latency	600-700ms	> 600ms	> 600ms

- Besides providing improved voice quality, capacity, and security, 2G systems also enabled new applications.
- 2G systems applications –
 - i) Short Messaging Service (SMS). Today, over 2.5 billion SMS messages are sent each day in the United States alone, and the service has been used for delivering news updates, business process alerts, mobile payments, voting, and micro-blogging, among other things.
 - ii) Supports low data rate wireless data applications. Original 2G systems supported **circuit switched data services** (similar in concept to dial-up modems), and **packet data services** as well.
 - iii) Early wireless data services included information services such as the delivery of news, stock quotes, weather, and directions, etc.
- **Limitations** in data rate and available space for display in handheld devices meant that specialized technologies, such as the Wireless Access Protocol (WAP), had to be developed to tailor and deliver Internet content to handheld devices.

3.2.1 GSM and Its Evolution

Global System for Mobile Communications (GSM) services are a standard collection of applications and features available to mobile phone subscribers all over the world. The GSM standards are defined by the 3GPP collaboration and implemented in hardware and software by equipment manufacturers and mobile phone operators. The common standard makes it possible to use the same phones with different companies' services, or even roam into different countries. GSM is the world's most dominant mobile phone standard.

- GSM stands for Global System for Mobile Communication.
- It is a digital cellular technology used for transmitting mobile voice and data services using digital modulation .

GSM: History

- Developed by Group Special Mobile (founded 1982) which was an initiative of CEPT (Conference of European Post and Telecommunication).
 - Under European Telecommunicationn Standards Institute (ETSI), GSM is named as “ Global System for Mobile communication “ in 1989.
 - Full set of specifications phase-I became available in 1990.
 - Phase 2 of the GSM specifications occurs in 1995. Coverage is extended to rural areas.
 - Development of services evolved into phase 2+, which includes HSPA to GSM.
 - HSPA is used in GPRS (General Packet Radio Services) and EDGE (Enhanced data rates for global evolution .
- The GSM air-interface is based on a TDMA scheme where eight users are multiplexed on a single 200kHz wide frequency channel by assigning different time slots to each user.
 - GSM employed a variant of FSK called Gaussian Minimum Shift Keying (GMSK) as its modulation technique. GMSK was chosen due to its constant envelope property providing good power and spectral efficiency characteristics.
 - Besides voice and SMS, the original GSM standard also supported circuit-switched data at 9.6kbps.
 - By the mid-1990s, ETSI introduced the GSM Packet Radio Systems (GPRS) as an evolutionary step for GSM systems toward higher data rates.
 - GPRS and GSM systems share the same frequency bands, time slots, and signaling links. GPRS defined four different channel coding schemes supporting 8kbps to 20kbps per slot. Under favorable channel conditions, the higher 20kbps rate can be used, and if all eight slots in the GSM TDM frame were used for data transmission, in theory, GPRS could provide a maximum data rate of 160kbps. Typical implementations of GPRS provided a user data rate of 20-40kbps.
 - Figure 3.1 provides a high-level architecture of a GSM/GPRS network. The original GSM architecture had two sub-components:

Base Station Subsystem: This is comprised of the base-station transceiver (BTS) units that the mobile stations (MS) connect with over the air-interface and the base station controller (BSC), which manages and aggregates traffic from several BTSs for transport to the switching core, and manages mobility across BTSs connected directly to them. BSCs evolved to become Radio Network Controllers (RNC) in the 3G evolution of GSM.

Network Switching Sub-system: This is comprised of the Mobile Switching Center (MSC) and subscriber databases. The MSC provides the required switching to connect the calling party with the called party and is interconnected with the Public Switched

Telephone Network (PSTN). The MSC uses the Home Location Register (HLR) and Visitor Location Register (VLR) to determine the location of mobile subscribers for call control purposes.

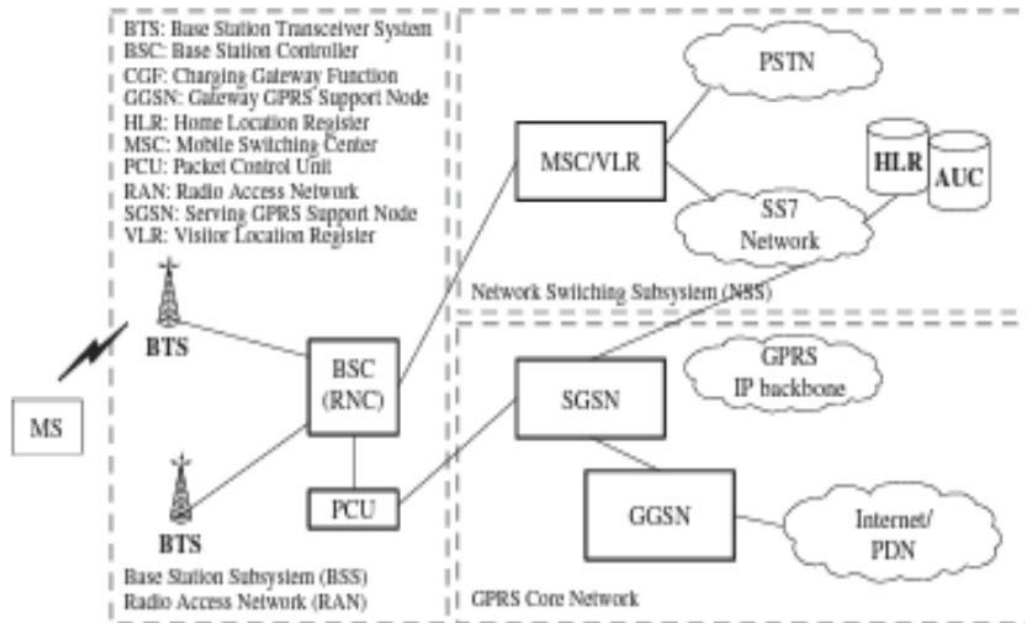


Figure 3.1 GSM network architecture.

- As shown in Figure 3.1, a GSM system may be upgraded to a GPRS system by introducing new elements, such as the Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN), and upgrading existing network elements such as the BTS with a packet control unit (PCU) for handling data.
- SGSN provides location and mobility management and may be thought of as the packet data equivalent of MSC.
- GGSN provides the IP access router functionality and connects the GPRS network to the Internet and other IP networks.
- The GSM standard got a further boost in its data handling capabilities with the introduction of Enhanced Data Rate for GSM Evolution, or EDGE, in the early part of 1997. EDGE added support for 8PSK modulation to boost the data rate. This allowed for a maximum per slot data rate of 59.2kbps a three-fold increase from GPRS speeds. Typical user rates for EDGE varied from 80 to 120kbps.

3.3 3G Broadband Wireless Systems

- 2G digital cellular systems provided significant increase in voice capacity, improved voice quality, and began support for data applications such as Internet access.
- The circuit-switched paradigm based on which these systems were built made 2G systems very inefficient for data, and hence provided only low-data rate support-tens of kilobits per second, typically-and limited capacity.
- Third generation (3G) systems provides much higher data rates with significant increase in voice capacity, and supports advanced services and applications, including multimedia.
- The ITU laid out the following data rate requirements as the criterion for IMT-2000:
 - 2Mbps in fixed or in building environments
 - 384kbps in pedestrian or urban environments

144kbps in wide area vehicular environments

- Besides high data rate, 3G systems also envisioned providing better Quality of Service (QoS) control tailored for a variety of applications-from voice telephony and interactive games, to Web browsing, e-mail, and streaming multimedia applications.
- Following are the terrestrial radio interfaces for IMT-2000:
 - ❖ **IMT-2000 CDMA Direct Spread (IMT-DS):** This standard is more commonly known as W-CDMA and was proposed as the air-interface for the Universal Mobile Telephone Service (UMTS) solution proposed by the Third Generation Partnership Project (3GPP) as the evolution of GSM systems.
 - ❖ **IMT-2000 CDMA Multi-carrier (IMT-MC):** This standard was proposed by the 3GPP2 organization and represents an evolution of the IS-95 systems. They are more commonly known as **IX-EV-DO**.
 - ❖ **IMT-2000 CDMA TDD (IMT-TC):** This standard is also proposed by 3GPP for operation in unpaired spectrum using Time Division Duplexing technology. It is also known as UMTS-TDD or TD-SCDMA (Time Division, Synchronous CDMA) and is mostly used in China.
 - ❖ **IMT-2000 TDMA Single Carrier (IMT-SC):** This standard was proposed by the Universal Wireless Consortium in the United States as a lower-cost evolution to 3G. Also called UWC-136, this is essentially the EDGE standard developed by 3GPP.
 - ❖ **IMT-2000 FDMA/TDMA (IMT-FT):** The Digital European Cordless Telephone (DECT) standard was also accepted as an IMT-2000 air-interface, primarily for indoor and pico-cell applications.
 - ❖ **IMT-2000 IP-OFDMA:** This standard, more commonly known as WiMAX or IEEE 802.16e, was accepted by the ITU as a sixth air-interface in 2007.

3.4 Key Enabling Technologies and Features of LTE

- ❖ To meet its service and performance requirements, LTE design incorporates important enabling radio and core network technologies.
- ❖ Here, we provide a brief introduction to some of the key enabling technologies used in the LTE design.

3.4.1 OFDM-Orthogonal Frequency Division Multiplexing (OFDM)

- ❖ One of the key differences between existing 3G systems and LTE is the use of Orthogonal Frequency Division Multiplexing (OFDM) as the underlying modulation technology.
- ❖ 3G systems such as UMTS (Universal Mobile Telecommunication Systems) and CDMA2000 (Code Division Multiple Access 2000) are based on Code Division Multiple Access (CDMA) technology.
- ❖ CDMA works by spreading a narrow band signal over a wider bandwidth to achieve interference resistance, and performs remarkably well for low data rate communications such as voice, where a large number of users can be multiplexed to achieve high system capacity.
- ❖ OFDM has emerged as a technology of choice for achieving high data rates.

- ❖ It is the core technology used by a variety of systems including Wi-Fi and Wi-MAX.
The following advantages of OFDM led to its selection for LTE:

- a) **Elegant solution to multipath interference**
- b) **Exploitation of frequency diversity**
- c) **Enables efficient multi-access scheme**
- d) **Efficient support of broadcast services**
- e) **Reduced computational complexity**
- f) **Robust Against narrowband interference**
- g) **Graceful degradation of performance under excess delay**
- h) **Suitable for coherent demodulation**
- i) **Facilitates use of MIMO**

1. **Elegant solution to multipath interference:**

- ❖ The critical challenge to high bit-rate transmissions in a wireless channel is **inter symbol interference** caused by multipath.
- ❖ In a multipath environment, when the time delay between the various signal paths is a significant fraction of the transmitted signal's symbol period, a transmitted symbol may arrive at the receiver during the next symbol and cause **inter symbol interference (ISI)**.
- ❖ At high data rates, the symbol time is shorter; hence, it only takes a small delay to cause ISI, making it a bigger challenge for broad band wireless.
- ❖ OFDM is a **multicarrier modulation** technique that overcomes this challenge in an elegant manner.
- ❖ The basic idea behind multicarrier modulation is to **divide a given high-bit-rate data stream into several parallel lower bit-rate streams and modulate each stream on separate carriers called subcarriers, or tones**.
- ❖ Splitting the data stream into mainly parallel streams increases the symbol duration of each stream such that the multipath delay spread is only a small fractional of the symbol duration.
- ❖ OFDM is a spectrally efficient version of multicarrier modulation, where the subcarriers are selected such that they are all orthogonal to one another over the symbol duration, thereby avoiding the need to have non overlapping sub carrier channels to **eliminate inter-carrier interference**.
- ❖ In OFDM, any residual inter symbol interference also be eliminated by using **guard intervals between OFDM symbols** that are larger than the **expected multipath delay**:
- ❖ By making the guard interval larger than the expected multipath delay spread, ISI can be completely eliminated.
- ❖ **Adding a guard interval, however, implies power wastage and a decrease in bandwidth efficiency.**

2. Exploitation of frequency diversity:

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

3. Enables efficient multi-access scheme:

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

4. Efficient support of broadcast services:

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

5. Robust Against narrowband interference:

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

6. Reduced computational complexity:

- ❖ OFDM can be easily implemented using Fast Fourier Transforms (FFT/IFFT), and the computational requirements grow only slightly faster than linearly with data rate or bandwidth.
- ❖ The computational complexity of OFDM can be shown to be **$O(\log BT_m)$** where B is the bandwidth and T_m is the delay spread.

7. Graceful degradation of performance under excess delay:

- ❖ The performance of an OFDM system degrades gracefully as the delay spread exceeds the value designed for.

- ❖ Greater coding and low constellation sizes can be used to provide **fallback rates** that are significantly more robust against delay spread.
- ❖ In other words, OFDM is well suited for **adaptive modulation and coding**, which allows the system to make the best of the available channel conditions.
- ❖ This contrasts with the abrupt degradation owing to error propagation that single-carrier system experience as the delay spread exceeds the value for which the equalizer is designed.

8. Suitable for coherent demodulation:

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

9. Facilitates use of MIMO:

- ❖ MIMO stands for multiple input multiple output and refers to a collection of signal processing techniques that use multiple antennas at both the transmitter and receiver to improve system performance.
- ❖ For MIMO techniques to be effective, it is required that the channel conditions are such that the multipath delays do not cause inter symbol interference in other words, the channel has to be a flat fading channel and not a frequency selective one.
- ❖ At very high data rates, this is not the case and therefore MIMO techniques **do not work** well in **traditional broadband channels**. OFDM, however, converts frequency selective broadband channel into several narrowband flat fading channels where the MIMO models and techniques work well.
- ❖ MIMO and OFDM are effectively used in Wi-Fi and WiMAX (Worldwide Interoperability for Microwave Access) systems.

Disadvantages of OFDM:

Peak-to-Average Ratio (PAR): OFDM has high PAR, which causes non-linearity and clipping distortion when passed through an RF amplifier. It increases the cost of the transmitter and is wasteful of power. OFDM is tolerated in the downlink as part of the design, for the uplink LTE selected a variation of OFDM that has a lower peak-to-average ratio. The modulation of choice for the uplink is called Single Carrier Frequency Division Multiple Access (SC-FDMA).

3.4.2 SC-FDE and SC-FDMA

3.4.2.1 Single-Carrier Frequency Domain Equalization (SC-FDE):

- ❖ It is a single-carrier (SC) modulation combined with frequency-domain equalization (FDE).

- ❖ It is an alternative approach to inter symbol interference (ISI) mitigation.
- ❖ It uses QAM rather than IFFT used OFDM to send data with a cyclic prefix added.
- ❖ SC-FDE retains all the advantages of OFDM such as multipath resistance and low complexity, while having a low peak-to-average ratio of 4-5dB.
- ❖ It keeps the MS cost down and the battery life up.
- ❖ LTE incorporated a SC-FDE as a power efficient transmission scheme for the uplink.

3.4.2.2 Single-Carrier Frequency Division Multiple Access(SC-FDMA)

- ❖ A multi-user version of SC-FDE, called SC-FDMA.
- ❖ The uplink of LTE implements uses to SC-FDMA, which allows multiple users to use parts of the frequency spectrum.
- ❖ SC-FDMA closely resembles OFDMA and also preserves the PAR properties.
- ❖ The drawback of SC-FDE is increases the complexity of the transmitter and the receiver.

3.4.3 Channel Dependent Multi-user Resource Scheduling

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

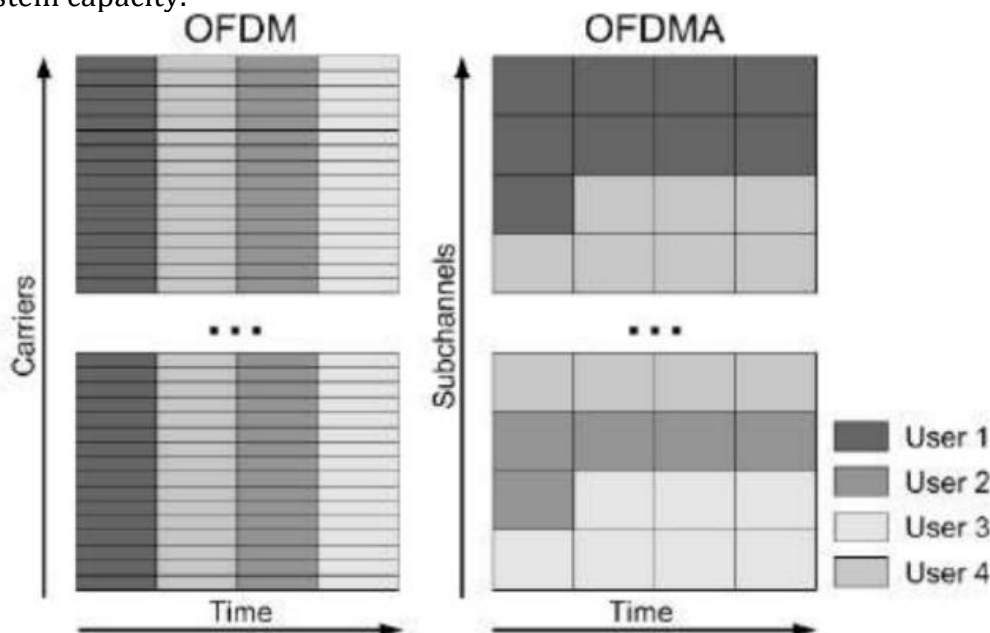


Figure 3.2 Resource mapping in OFDMA

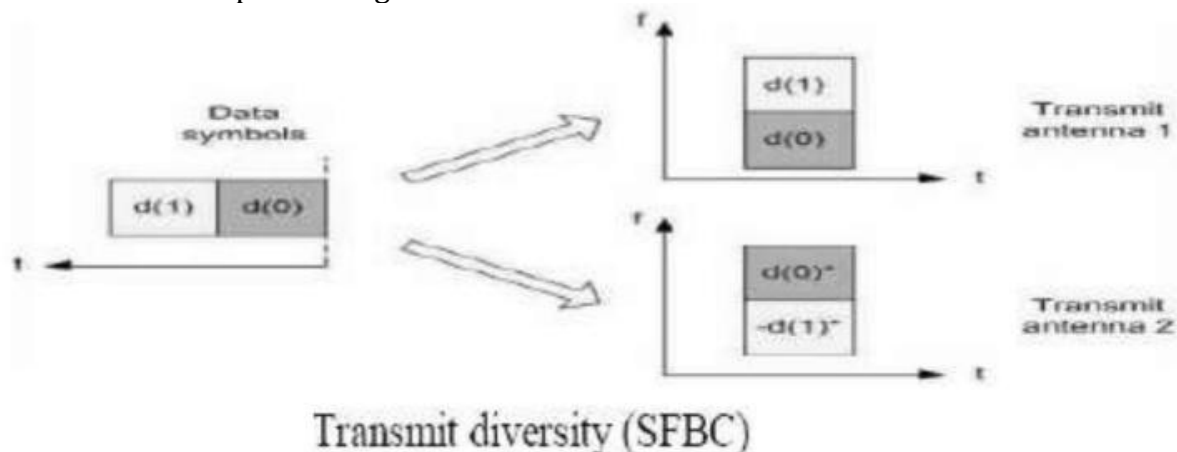
- ❖ In OFDM, it is possible to allocate subcarriers among users in such a way that the overall capacity is increased. This technique, called frequency selective multiuser scheduling, calls for focusing transmission power in each user's best channel portion.

- ❖ In OFDMA, frequency selective scheduling can be combined with multi-user time domain scheduling.
- ❖ Capacity gains are also obtained by adapting the modulation and coding to the instantaneous signal-to-noise ratio conditions for each user subcarrier.
- ❖ For high-mobility users, OFDMA can be used to achieve frequency diversity. By coding and interleaving across subcarriers. Frequency diverse scheduling is best suited for control signaling and delay sensitive services.

3.4.4. Multi-Antenna Techniques

- ❖ The LTE standard provides extensive support for implementing advanced multi-antenna solutions to improve link robustness, system capacity, and spectral efficiency.
- ❖ **Multi-antenna techniques supported in LTE include:**

1. **Transmit diversity:** Diversity means send copies of the same signal by using two or more communication channels with different characteristics. This is a technique to combat multipath fading in the wireless channel.



LTE transmit diversity is based on space-frequency block coding (SFBC) techniques. Transmit diversity is primarily intended for common downlink channels that cannot make use of channel-dependent scheduling. It increases system capacity and cell range.

2. **Beamforming:** It is a type of RF (radio frequency) management and signal processing technique in which an access point uses multiple antennas to send out the same signal.
 - Multiple antennas in LTE may also be used beamforming technique to transmit the beam in the direction of the receiver and away from interference, thereby improving the received signal-to-interference ratio.
 - It can provide significant improvements in coverage range, capacity, reliability, and battery life. It can also be useful in providing angular information for user tracking. LTE supports beamforming in the downlink.
 - Fig.3.3. shows the beamforming array Beamforming

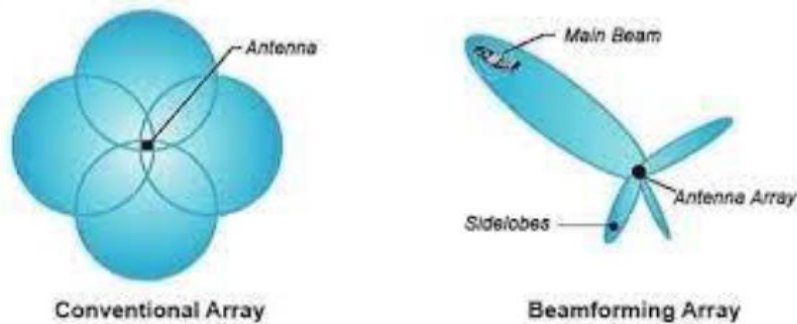


Fig.3.3 Beamforming

3. Spatial multiplexing:

In spatial multiplexing, multiple independent streams can be transmitted in parallel over multiple antennas and can be separated at the receiver using multiple receive chains through appropriate signal processing.

Spatial multiplexing provides **data rate** and **capacity gains proportional** to the number of antennas used.

LTE supports spatial multiplexing with four transmitting and four receiving antennas. Figure 3.4 shows the spatial multiplexing concept.

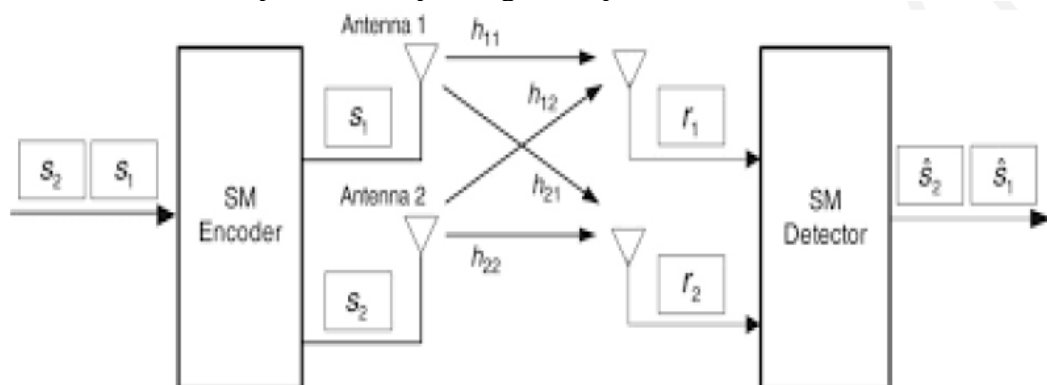


Fig.3.4 Spatial Multiplexing

4. Multi-user MIMO:

Since **spatial multiplexing** requires **multiple transmit chains**, it is currently not supported in the uplink due to **complexity and cost considerations**.

Multi-user Multiple input and Multiple Output (MU-MIMO) allows **multiple users in the uplink**, each with a **single antenna**, to transmit using same frequency and time resource.

The signals from MU-MIMO users are separated at the **base station receiver** using accurate channel state information of each user obtained through uplink reference signals that are orthogonal between users. Multi-user with multiple input and multiple output is shown in figure 3.5.

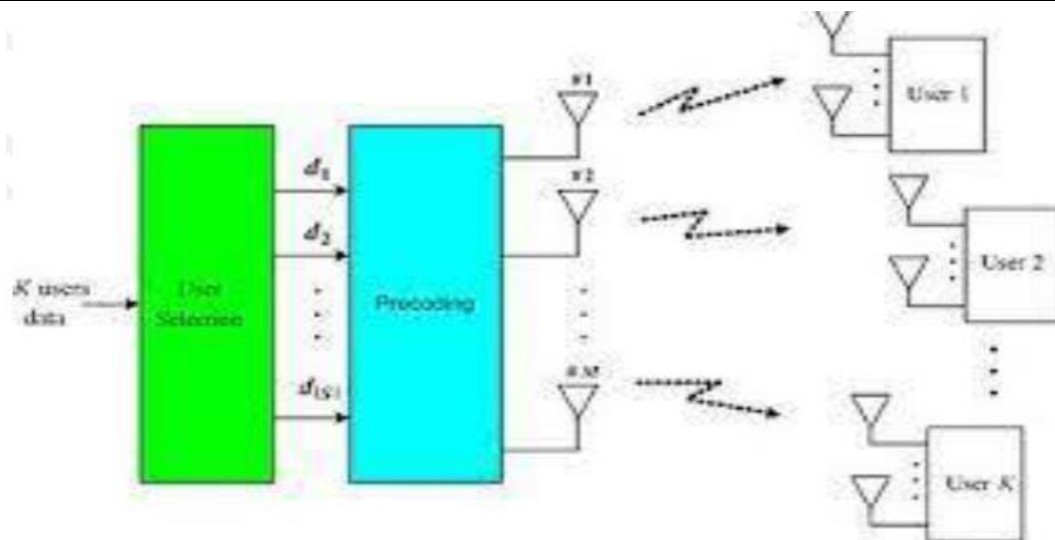


Fig.3.5. Multi-user MIMO

3.4.5 Flat IP Architecture or IP-Based Flat Network Architecture

- ❖ The lower infrastructure cost, lower latency and fewer nodes are requirements drove the design toward a flat architecture.
- ❖ It also means fewer interfaces and protocol-related processing, and reduced interoperability testing, which lowers the development and deployment cost. Fewer nodes also allow better optimization of **radio interface, merging of some control plane protocols, and short session start-up time.**

Figure 3.6. shows how the 3GPP network architecture evolved over a few releases.

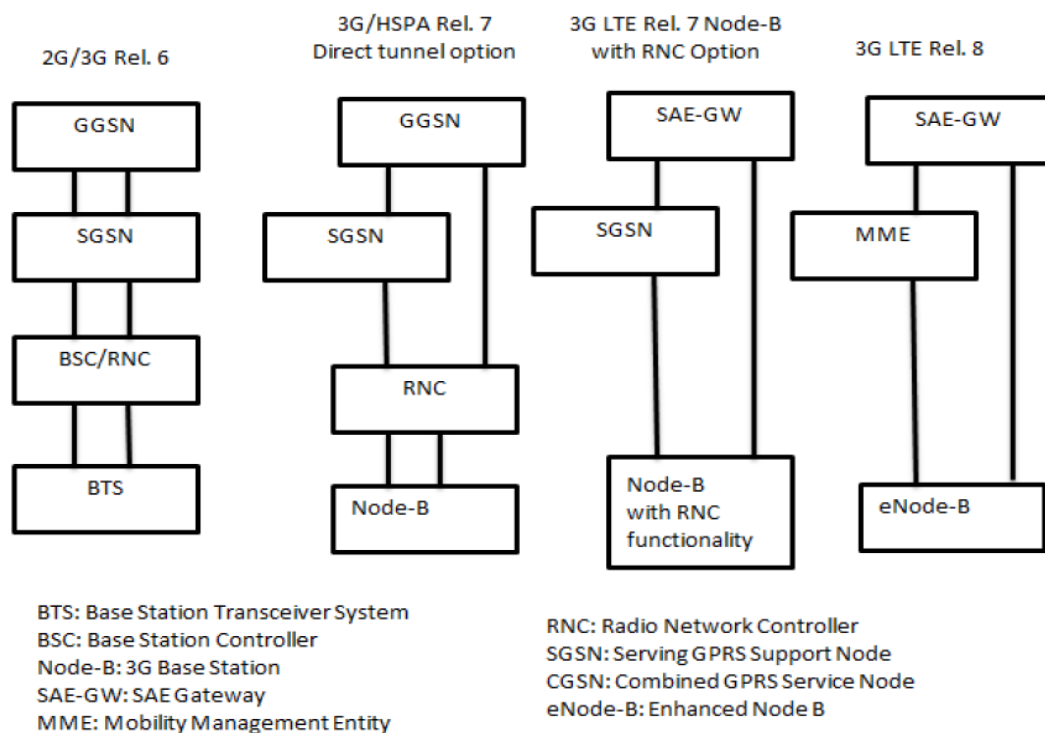


Fig.3.6. 3GPP evolution toward a flat LTE SAE architecture

❖ Flat LTE architecture description:

- 3GPP Release 6 architecture, has four network elements in the data path: Base station (BS), Radio Network Controller (RNC), Serving GPRS Service Node (SGSN), and Gateway GPRS Service Node (GGSN).
- Release 7 introduced a direct tunnel option from the RNC to GGSN, which eliminated SGSN from the data path.
- LTE on the other hand, will have only two network elements in the data path: the enhanced Node-B or eNode-B & a System Architecture Evolution Gateway (SAE-GW).
- LTE merges the BS and RNC functionality into a single unit. The control path includes a functional entity called the Mobility Management Entity (MME), which provides control plane functions related to subscriber, mobility, and session management.
- The MME and SAE-GW could be collocated in a single entity called the access gateway (a-GW).
- A key aspect of the LTE flat architecture is that all services, including voice, are supported on the IP packet network using IP protocols. Unlike previous 2g and 3g systems, which had a separate circuit-switched sub-network for supporting voice with their own Mobile Switching Centers (MSC) and transport networks, LTE envisions only a single evolved packet-switched core, the EPC, over which all services are supported, which could provide huge operational and infrastructure cost savings. However, that although LTE has been designed for IP services with a flat architecture, due to backwards compatibility reasons certain legacy, non-IP aspects of the 3GPP architecture such as the GPRS tunneling protocol and PDCP (packet data convergence protocol) still exists within the LTE network architecture.

3.5 LTE Network Architecture

The core network design presented in 3GPP Release 8 to support LTE is called the Evolved Packet Core (EPC).

EPC is designed to provide a high capacity, all IP, reduced latency, flat architecture that dramatically reduces cost and supports advanced real-time and media-rich services with quality of experience.

It is designed not only to support new radio access networks such as LTE, but also provide interworking with legacy 2G GERAN (**GSM (Global system for Mobile communication) EDGE (Enhanced data for Global Evolution) Radio Access Network**) and 3G UTRAN (**Universal Mobile Telephone service (UMTS) Terrestrial Radio Access Network**) networks connected via SGSN.

Functions provided by the EPC include access control, packet routing and transfer, mobility management, security, resource in management, and network management.

Fig. 3.7 shows the Evolved Packet Core (EPC) architecture and the **EPC includes four new elements**

- (1) **Serving Gateway (SGW)**, which terminates the interface toward the 3GPP (**3rd generation Partnership Project**) radio access networks

- (2) **Packet Data Network Gateway (PGW)**, which controls IP data services, does routing, allocates IP addresses, enforces policy, and provides access for non-3GPP access networks:
- (3) **Mobility Management Entity (MME)**, which supports user equipment context and identity as well as authenticates and authorizes users; and
- (4) **Policy and Charging Rules Function (PCRF)**. This manages QoS aspects. It is a concatenation of Policy Decision Function (PDF) and Charging Rules Function (CRF).

Serving Gateway (SGW):

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

Packet Data Network Gateway (PGW):

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

Mobility Management Entity (MME):

- ❖ The MME performs the signaling and control functions to manage the user terminal access to the network connections, assignment of network resources, and mobility management function such is idle mode location tracking. paging, roaming, and handovers.
- ❖ MME controls all control plane functions related to subscriber and session management.
- ❖ MME manages thousands of eNode-B elements; it's the key difference from 2G or 3G platforms using RNC and SGSN platform.

- ❖ MME provides security functions such as providing temporary identities for user terminal, interacting with Home Subscriber Server for authentication, and negotiation of ciphering and integrity protection algorithms.

Policy and Charging Rules Function (PCRF):

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

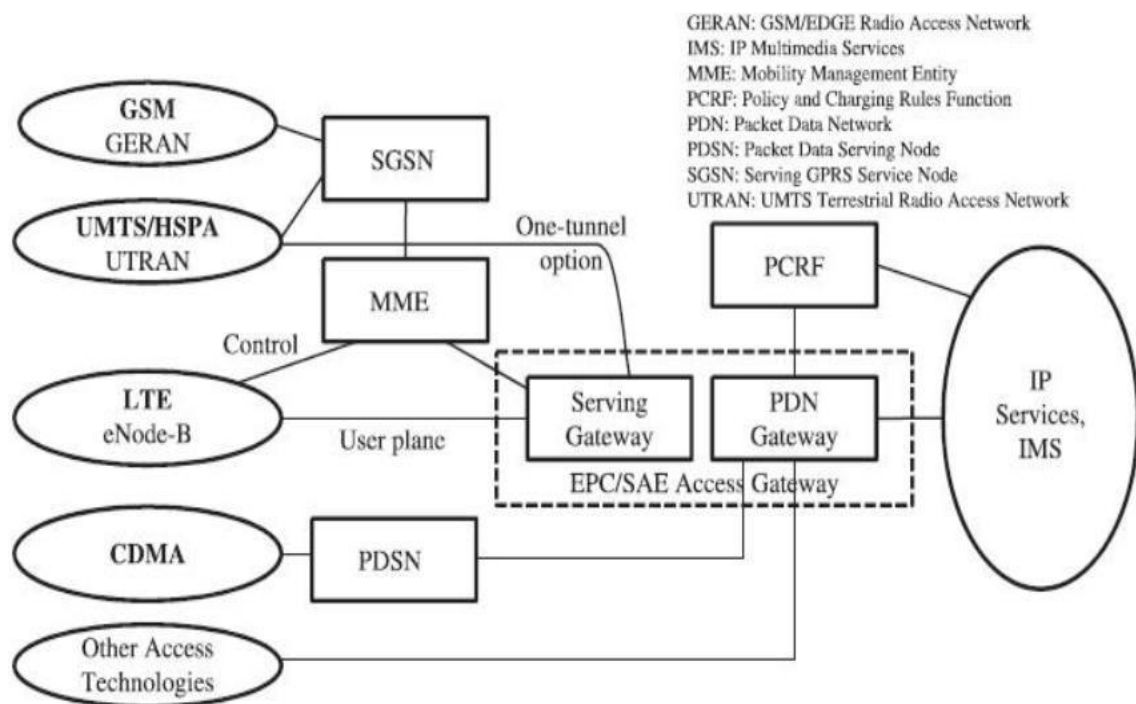


Fig. 3.7 Evolved Packet Core (EPC) architecture

3.8 Introduction:

Following multiple access strategy used in cellular communication.

- First Generation (1G), example AMPS (Advanced Mobile Phone Service): **FDMA**
- Second Generation (2G) example 2G GSM or IS-54: **TDMA, CDMA**.
- Third Generation (3G), example UMTS: **3G WCDMA**.
- Fourth Generation (4G), example LTE: **OFDMA for down link, SC-FDMA for uplink**.

3.8.1 Multiple Accesses for OFDM Systems

- OFDM has wide acceptance in wireless communications as an appropriate broadband modulation scheme.
- OFDM divides a wideband frequency-selective channel into narrowband flat fading subchannels.
- In multi-user systems, these sub-channels can be allocated among different users to provide multiple access schemes
- The use of adaptive techniques in these sub-channels can further increase the spectral efficiency of the wireless system.
- Therefore, a main advantages of OFDM is the flexibility in combining adaptive modulation and multiple access techniques.
- OFDM is a technique to overcome frequency selectivity (inter symbol Interference)
- OFDM create many parallel streams of data that can principle be used by different users.
- OFDM system such as DSL, 802.11a/g/WiMAX uses single user.

3.8.2 Multiple Access Overview

- Multiple-access strategies typically attempt to provide non-interfering, communication channels for each active base station-subscriber link.
- The most common ways to divide the available channel among the multiple users is through
 1. **Frequency Division Multiple Access (FDMA):** Each user receives a unique carrier frequency and bandwidth.
 2. **Time Division Multiple Access (TDMA):** Each user is given a unique time slot, either on demand or in a fixed rotation.
 3. **Code Division Multiple Access (CDMA):** Systems allow each user to share both the bandwidth and time slots with many other users. TDMA, FDMA, and orthogonal CDMA all have the almost same theoretical capacity in an additive noise channel.

Limitation of above multiple access:

- FDMA, TDMA, CDMA are bandwidth or interference limited system.
- Orthogonality is not possible in dense wireless systems.
- The above techniques only guarantee orthogonality between users in the same cell.
- Different multiple access techniques have different delay characteristics and so may be appropriate for different types of data.

Conclusion: The above limitation of conventional multiple access can be mitigated by principle merits of OFDMA.

3.8.3 Random Access Vs. Multiple Access

- Fixed multiple access methods (TDMA, FDMA, CDMA) become inefficient when the traffic is bursty.
- Random Access. Random access schemes dynamically assign radio resources to a large set of users, each with relatively bursty traffic.
- Well-known random access techniques include ALOHA and slotted ALOHA and CSMA.

1. In ALOHA, users simply transmit packets at will without regard to other users. This scheme becomes increasingly inefficient and delay prone as the intensity of the traffic increases, as many transmissions result in collisions and hence retransmissions.
 2. Slotted ALOHA improves on this by about a factor of two since users transmit on specified time boundaries, and hence collisions are about half as likely.
 3. CSMA improves upon ALOHA and slotted ALOHA through carrier sensing, in which users "listen" to the channel before transmitting in order to avoid collisions whenever possible.
- It should be noted that although FDMA and TDMA are certainly more efficient than CSMA when all users have packets to send, wasted (unused) frequency and time slots in FDMA and TDMA can also bring down the efficiency considerably.
 - In fact, around half the bandwidth is typically wasted in TDMA and FDMA voice systems.
 - CDMA system has proven so successful for voice.
 - The efficiency of a connection-oriented MAC can approach 90%, compared to at best 50% or less in most CSMA wireless systems such as 802.11.

Conclusion: The need for extremely high spectral efficiency and low delay in LTE make impossible to use of CSMA, and the burden of resource assignment is placed on the base stations.

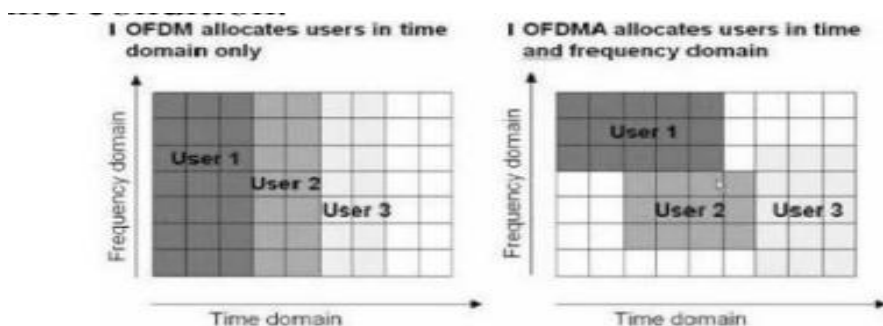
There are three fundamental multi-carrier based multiple access techniques for OFDM systems:

1. OFDM-FDMA
2. OFDM-TDMA
3. OFDM-CDMA

Among three schemes, OFDM-FDMA is the most straightforward (OFDMA).

3.8.4. Frequency Division Multiple Access (OFDM-FDMA)

- Frequency Division Multiple Access (FDMA) can be readily implemented in OFDM systems by assigning different users their own sets of subcarriers.
- Available sub-carriers are distributed among all the users for transmission at any time instant.
- Each user is allocated a pre-determined band of subcarriers. Allows adaptive techniques per sub-carrier, based on sub-channel condition.



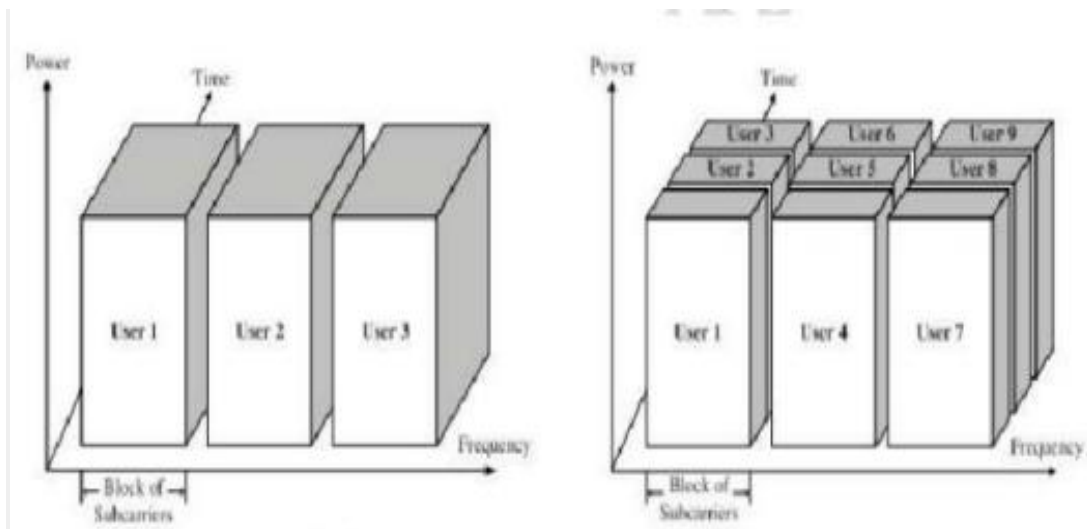
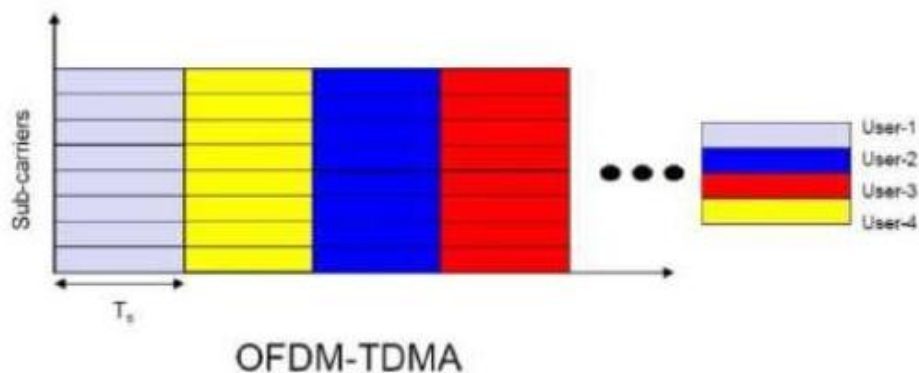


Figure 3.8 FDMA (left) and a combination of FDMA with TDMA (right).

- The simplest method is a static allocation of subcarriers to each user, as shown on the left of Figure 3.8. For example, in a 64- subcarrier OFDM system, user 1 could take subcarriers 1-16, with users 2, 3, and 4 using subcarriers 17-32, 33-48, and 49-64, respectively.
- The allocations are enforced with a multiplexer for the various users before the IFFT operation.
- OFDMA in LTE, however, has explicit time-sharing and procedures to allow for the dynamic allocation of subcarriers.
- In LTE use dynamic subcarrier allocation based upon channel state conditions. For example, due to frequency selective fading, user 1 may have relatively good channels on subcarriers 33- 48, while user 3 might have good channels on subcarriers 1-16. Obviously, it would be mutually beneficial for these users to swap the static allocations.

3.8.5 Time Division Multiple Access (OFDM-TDMA)

- A particular user is given all the sub-carrier of the system for any particular symbol duration.



- Each user is assigned a time slot during which all the subcarriers can be used for the particular user.

- Adaptive loading can be performed on all the subcarriers, depending on channel conditions.
- The number of symbols per frame can be varied based on each user's requirement .
- Power consumption reduction (less activity). Degrading performance should be taken into account in delay constrained systems.
- A packet-based system like LTE can employ more sophisticated scheduling algorithms based on queue-lengths, channel conditions, and delay constraints to achieve much better performance than static TDMA.

3.8.6 Code Division Multiple Access (OFDM-CDMA or MC-CDMA)

- User data is spread over several sub-carriers and/or OFDM symbols using spreading codes, and combined with signals from other users.
- Hybrid access scheme that combines benefits:
 1. OFDM: Provides a simple method to overcome the ISI effect of the multi-path frequency selective channel
 2. CDMA: Provides frequency diversity and multi-user access scheme
- Several users transmit over the same sub-carriers.
- In wireless broadband networks the data rates already are very large, so spreading the spectrum further is not viable.
- OFDM and CDMA are not fundamentally incompatible; they can be combined to create a Multicarrier CDMA (MC-CDMA) waveform. MC-CDMA is not part of the LTE standard.
- Comparison between OFDM_TDMA, OFDM_FDMA, OFDM_CDMA

→ Granularity

OFDM_TDMA	OFDM_FDMA	OFDM_CDMA
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→ complexity

Multiple Types	Advantages	Disadvantages
OFDM_TDMA	<ul style="list-style-type: none"> • Simple Implementation • Flexibility 	<ul style="list-style-type: none"> • Frequency-reuse factor ≥ 3
OFDM_FDMA	<ul style="list-style-type: none"> • Power savings simple resource allocation • Easiest to implement 	Relatively high latency Frequency-reuse factor ≥ 3 Lowest flexibility
OFDM_CDMA	<ul style="list-style-type: none"> • Spectral efficiency • Frequency diversity • MAI and ICI interference resistance • Frequency reuse factor =1 • Highest flexibility 	<ul style="list-style-type: none"> • Requirement of power control • Implementation complexity

3.9. Orthogonal Frequency Division Multiple Access (OFDMA)

- OFDMA systems allocate subscribers time-frequency slices (in LTE, "resource grids").
- A resource block (RB) is the smallest unit of resources that can be allocated to a user.
- It consisting of M subcarriers over some number of consecutive OFDM symbols in time.
- The M subcarriers can either be
 1. ***Spread out over the band*** : It often called a "distributed," "comb," or "diversity" allocation. The distributed allocation achieves frequency diversity over the entire band, and would typically rely on interleaving and coding to correct errors caused by poor subcarriers. In a highly mobile system, then a distributed allocation would typically be preferred in order to maximize diversity.
 2. ***Bunched together in M contiguous subcarriers*** : Which is often called a "band AMC," "localized," or "grouped" cluster. The band AMC mode, instead attempts to use subcarriers where the SINR is roughly equal and to choose the best coding and modulation scheme for that SINR. If accurate SINR information can be obtained at the receiver about each band's SINR, then band AMC outperforms distributed subcarrier allocation.

Table 3.3 OFDMA Notation

K	<i>Number of active users</i>
L	<i>Total number of subcarriers</i>
M_k, M	<i>Number of subcarriers per active user k</i>
$h_{k,l}$	<i>Envelope of channel gain for user k in subcarrier l</i>
$P_{k,l}$	<i>Transmit power allocated for user k in subcarrier l</i>
σ^2	<i>AWGN power spectrum density</i>
P_{tot}	<i>Total transmit power available at the base station</i>
B	<i>Total transmission bandwidth</i>

3.9.1 OFDMA: How It Works

The block diagram for a downlink OFDMA system is shown in Figures 3.9 and 3.10.

- The basic flow is very similar to an OFDM system except for now K users share the L subcarriers, with each user being allocated M_k subcarriers.
- In theory it is possible to have users share subcarriers, this never occurs in practice, so $\sum_k M_k = L$ and each subcarrier only has one user assigned to it.

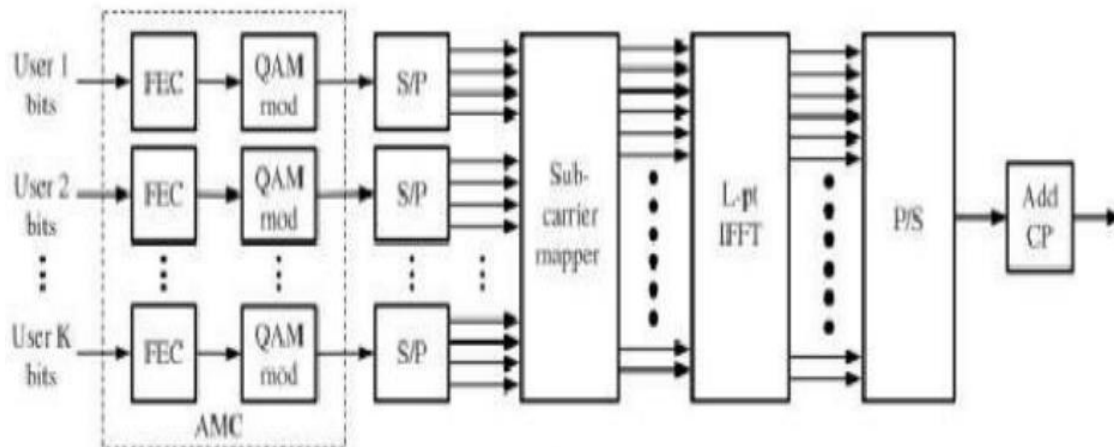


Figure 3.9 OFDMA downlink transmitter

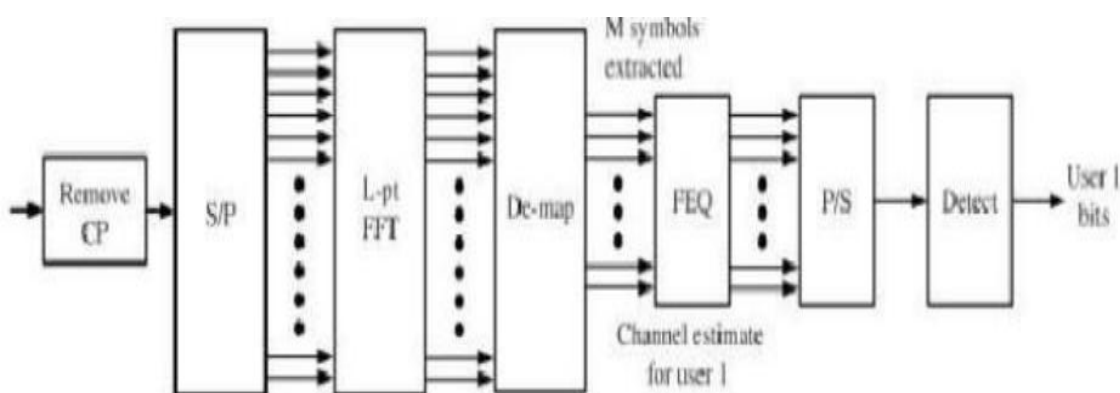


Figure 3.10 OFDMA downlink receiver for user 1. Each of the K active users—who by design have orthogonal subcarrier assignments—have a different receiver that only detects the M_k subcarriers intended for it

- At each receiver, the user cares only about its own M_k subcarriers, but still has to apply an L point FFT to the received digital waveform in order to extract the desired subset of subcarriers.
- Receiver has to know which time-frequency resources it has been allocated in order to extract the correct subcarriers: the control signaling that achieves.
- OFDMA downlink receiver must mostly demodulate the entire waveform, which wastes power, but digital separation of users is simple to enforce at the receiver and the amount of residual inter user interference is very low compared to either CDMA or FDMA.
- OFDMA uplink block diagrams in Figures 3.11 and 3.12 to clearly show the differences and numerous similarities between OFDMA and SC-FDMA.

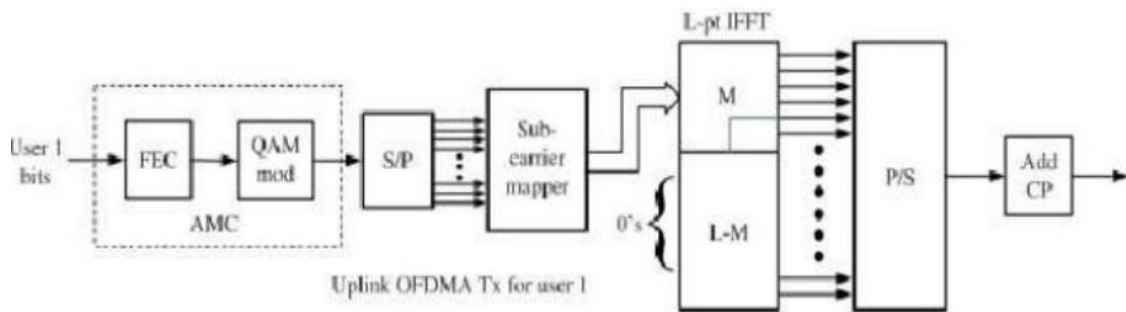


Figure 3.11 OFDMA uplink transmitter for user 1, where user 1 is allocated subcarriers 1, 2.....M of L total subcarriers.

- The transmitter modulates user k 's bits over just the M_k subcarriers of interest: in this case, we have chosen $M_k = M$ for all users, and shown user 1 occupying subcarriers 1, 2, ..., M of the L total subcarriers. All the users' signals collide at the receiver's antenna, and are collectively demodulated using the receiver's FFT.
- Assuming each subcarrier has only a single user on it, the demodulated subcarriers can be de-mapped to the detectors for each of the K served users.

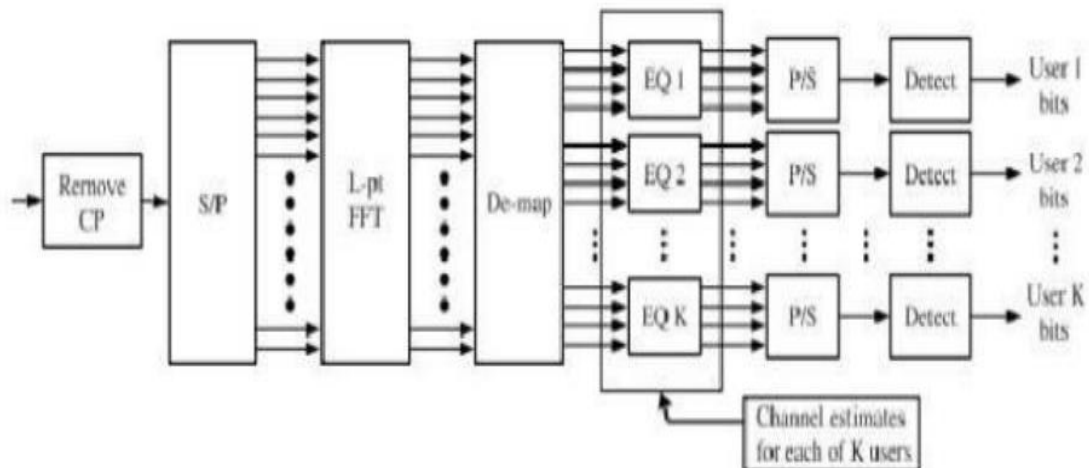


Figure 3.12 OFDMA uplink receiver. All K active users—who by design have orthogonal subcarrier assignments—are aggregated at the receiver and demultiplexed after the FFT.

- It should be noted that uplink OFDMA is considerably more challenging than downlink OFDMA since the uplink is naturally asynchronous, that is the users' signals arrive at the receiver offset slightly in time (and frequency) from each other.
- This is not the case in the downlink since the transmitter is common for all users. These time and frequency offsets can result in considerable self-interference if they become large.
- Particularly in the distributed subcarrier mode, sufficiently large frequency offsets can severely degrade the orthogonality across all subcarriers.
- The timing offsets also must typically be small, within a fraction of a cyclic prefix.
- In LTE the uplink multi access scheme uses only the localized subcarrier mode due to the SC-FDMA nature of the uplink.
- In this case, the lack of perfect frequency and time synchronization between the multiple users leads to some ICI but this is limited only to the subcarriers at the edge of the transmission band of each user.

- Frequency and timing synchronization for the uplink is achieved relative to the downlink synchronization, which is done using the synchronization channels.
- A higher level view of OFDMA can be seen in Figure 3.13. Here, a base station is transmitting a band AMC-type OFDMA waveform to four different devices simultaneously.

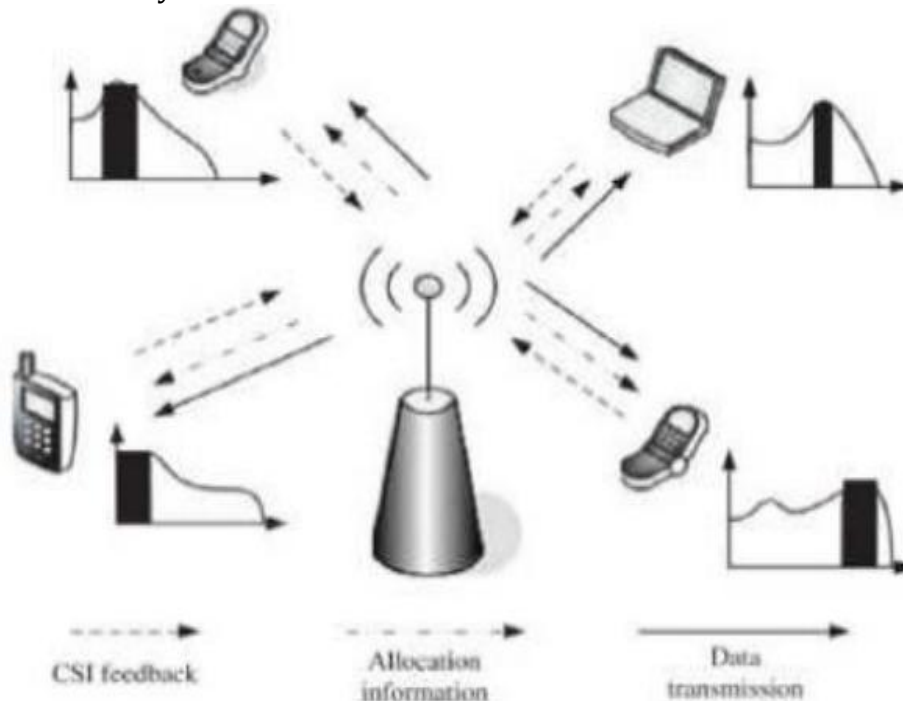


Figure 3.13 In OFDMA, the base station allocates each user a fraction of the subcarriers, preferably, in a range where they have a strong channel.

- The three arrows for each user indicate the signaling that must happen in order for band AMC-type OFDMA to work.
 - First, the mobiles measure and feedback the quality of their channel, or channel state information (CSI) to the base station.
 - Usually, the CSI feedback would be a measurement corresponding to SINR. The base station would then allocate subcarriers to the four users and send that subcarrier allocation information to the four users in an overhead message.
 - Finally, the actual data is transmitted over the subcarriers assigned to each user.
- Here, it can be seen that the base station was successful in assigning each user a portion of the spectrum where it had a relatively strong signal.

3.9.2 OFDMA Advantages and Disadvantages

Advantages of OFDMA:

1. OFDMA is a flexible multiple access technique that can accommodate many users with widely varying applications, data rates, and QoS requirements.
2. OFDMA provide robust multipath suppression, relatively low complexity, and the creation of frequency diversity.
3. Multiple access is performed in the digital domain, dynamic, flexible, and efficient bandwidth allocation is possible.

4. Lower data rates (such as voice) and bursty data are handled much more efficiently in OFDMA than in single-user OFDM (i.e., OFDM-TDMA) or with CSMA.
5. It makes receiver simple as it eliminates intra-cell interference which avoids multi-user detection of CDMA type. Here only FFT processing is needed.
6. Fading environment leads to better BER performance.

Disadvantages of OFDMA

1. Since the switching between users would have to be very rapid, more frequency overhead signaling would be required, reducing the overall system throughput.
2. The permutation and depermutation rules of subcarriers for allocation and deallocation to sub channels are complex. This makes transmitter and receiver algorithms complex for data processing/extraction unlike OFDM.
3. OFDMA has higher PAPR (Peak to Average Power Ratio). Hence large amplitude variations lead to increase of in-band noise.
4. OFDMA requires very tight time/frequency/channel equalizations between users. This is achieved with the help of preamble, pilot signals and other signal processing techniques.
5. Co-channel interference is more complex compared to CDMA technique.

3.10. Single Carrier Frequency Division Multiple Access (SCFDMA)

- SC-FDMA is employed in the LTE uplink.
- Conceptually, this system evolves naturally from SC-FDE modulation approach.
- SC-FDE is a single-carrier modulation technique, it is not possible for an uplink user to use only part of the spectrum. SC-FDMA can reasonably be called "FFT(or DFT) pre-coded OFDMA."
- SC-FDMA more closely resembles OFDMA because it still requires an IFFT operation at the transmitter in order to separate the users.
- The goal of SC-FDMA is
 1. Take the low peak-to-average ratio (PAR) properties of SC-FDE.
 2. Achieve an OFDMA-type system that allows partial usage of the frequency band.

3.10.1 SCFDMA-Working

SC-FDMA uplink transmitter:

• SC-FDMA uplink transmitter is shown in figure 3.14.

- SC-FDMA uplink transmitter is very similar to the OFDMA uplink transmitter (see fig 3.14).
- The only difference is that the user's M_k complex symbols are preprocessed with an FFT of size M_k and referred to as time-domain complex symbols as $x[n]$.
- In LTE, M_k is related to the number of resource blocks allocated to the user k for its uplink transmission. The FFT operation creates a frequency domain version of the signal $X[m] = \text{FFT}(x[n])$,
- The time-domain outputs of the IFFT correspond to an over-sampled and phase-shifted version of the original time-domain signal $x[n]$. $x[n]$ is oversampled by a factor

of L/M and experiences a phase shift that depends on which inputs to the IFFT are used.

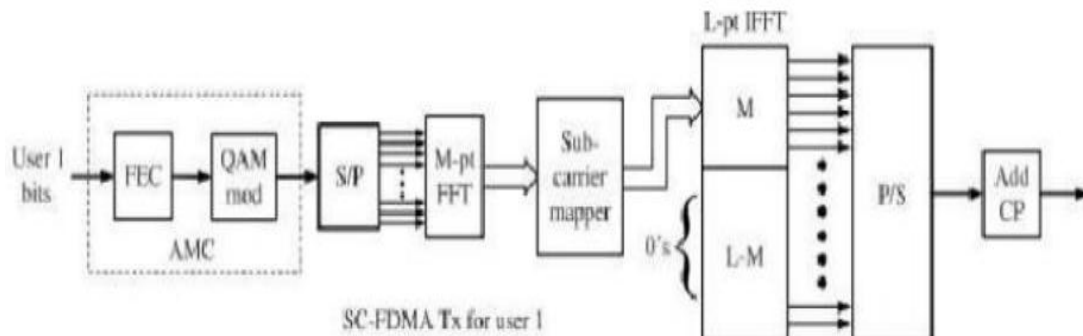


Figure 3.14 SC-FDMA uplink transmitter for user 1, where user 1 is allocated subcarriers 1, 2.....M of L total subcarriers.

The SC-FDMA uplink receiver: It is shown in Figure 3.15. Clearly, this is also very similar to the OFDMA uplink receiver of Figure 3.12.

- Here we explicitly assume that each user occupies a fraction M/L of the spectrum like OFDM.
The difference now being that for each user's M_k "subcarriers," an additional small IFFT must be applied prior to detection to bring the received data back into the time domain.
- Frequency domain equalization is applied to each user's signal independently after the FFT, and users' signals are de-mapped based on the current subcarrier allocation

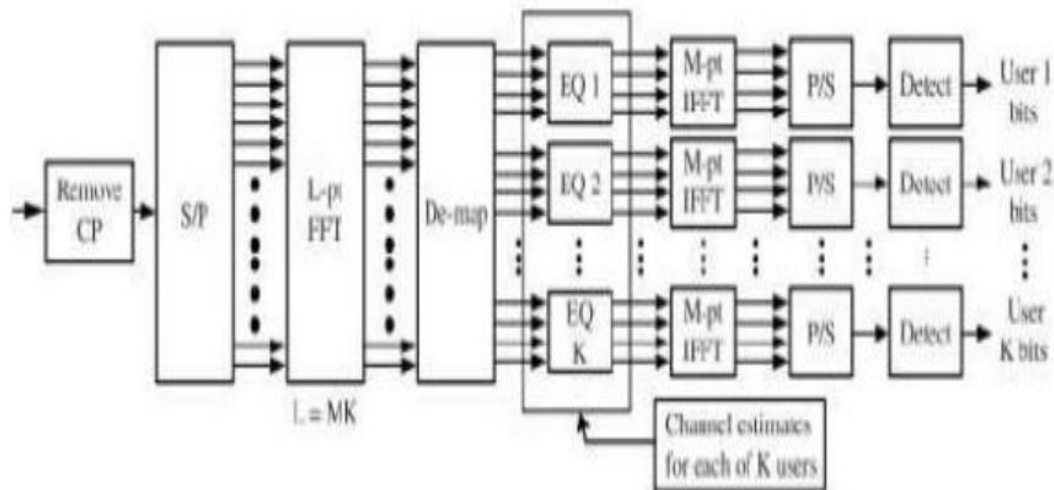


Figure 3.15 SC-FDMA uplink receiver

3.10.2. SC-FDMA Advantages and Disadvantages

SC-FDMA Advantages .

1. PAR of SC-FDMA is significantly lower than OFDMA.
2. Low cost and power constraints experienced by mobile handsets.
3. Only part of the frequency spectrum is used by any one user at a time, like in OFDM.

4. Reducing PAR reduces the cost of RF power amplifier. Hence the SC-FDMA is suitable for uplink.
5. Suitable For uplink due to simple transmitter.

SC-FDMA disadvantages .

1. SC-FDMA can experience more spectral leakage than OFDMA.
2. Achieve frequency diversity differently, leading to slight differences in performance.
3. SC-FDMA has more complexity both the transmitter and receiver compare to OFDM.
4. Need additional FFT of size M_k has to be performed for each user at the transmitter and receiver.

Question Bank

1. Compare 1G and 2G cellular systems.
2. Explain the concept of multiple access techniques used in LTE. **OR**
Briefly explain the different multiple access system which can be implemented with OFDM. **OR**
Discuss the different types of access techniques used in OFDM system with neat block diagram.
3. Write the block diagram of OFDMA downlink transmitter and downlink receiver and explain the principle of operation **OR**
Explain the principle of operation of OFDMA downlink transmitter with neat sketch.
4. Discuss the OFDMA advantages and disadvantages.
5. Explain SC-FDMA uplink transmitter and uplink receiver with a neat block diagram. **OR**
Explain SC-FDMA uplink transmitter with a neat figure .
6. Discuss the SC-FDMA advantages and disadvantages.
7. Discuss the advantages of OFDM leading to its selection for LTE. (8M) **OR**
Discuss the key enabling technologies used in LTE design. **OR**
Explain the advantages of OFDM leading to its selection for LTE.
8. With a neat diagram, explain SC-FDMA. List out the advantages and disadvantages of SC-FDM
9. Explain the concept of Channel Dependent Multiuser Resource Scheduling (5M)
10. Explain Multi-Antenna Techniques which support LTE (8M) **OR**
Explain the multi antenna techniques. **OR**
Explain spatial diversity of multiple antenna techniques **OR**
Explain pen-loop MIMO in spatial multiplexing
11. Discuss with the block diagram of IP based Flat Network architecture. (8M)

OR

Explain Flat LTE SAE Architecture.

OR

Explain with a neat diagram, how 3GPP network evolved towards flat LTE-SAE architecture.

12. Write the block diagram, Explain LTE Network Architecture and describe briefly the new elements provided in it. (8M)

OR

Give a brief description of evolved packet core architecture

OR

Discuss with block diagram of LTE Network architecture.

OR

Write the block diagram of end to end architecture of EPC supporting current and Legacy Radio access networks and discuss the elements of EPC.

OR

Explain briefly EPC architecture .

13. With a neat diagram explain the LTE end-to-end Network architecture. (8M)
14. Explain an elegant approach to intersymbol interference. (8M)

OR

Explain the basic multicarriers transmitter and receiver with neat block diagram.

15. With a neat block diagram, explain the orthogonal frequency division multiplexing (OFDM) used in LTE. (8M)