Wireless and Mobile
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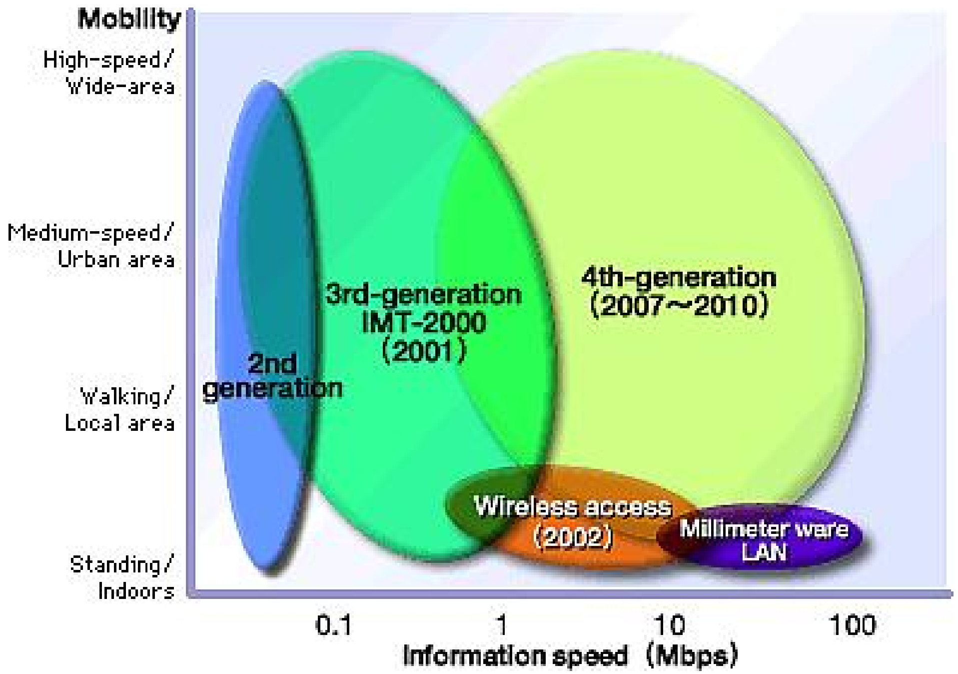
LTE: 4G



Generation of Cellular Communication

1G: Analog voice/ AMPS, ~ 1990

2G: Digital voice/ GSM, CDMA, 1990~2000

3G: Digital voice + data/ WCDMA, 2000~2010

4G: High speed data/ LTE, 2010~

Transition of Technologies

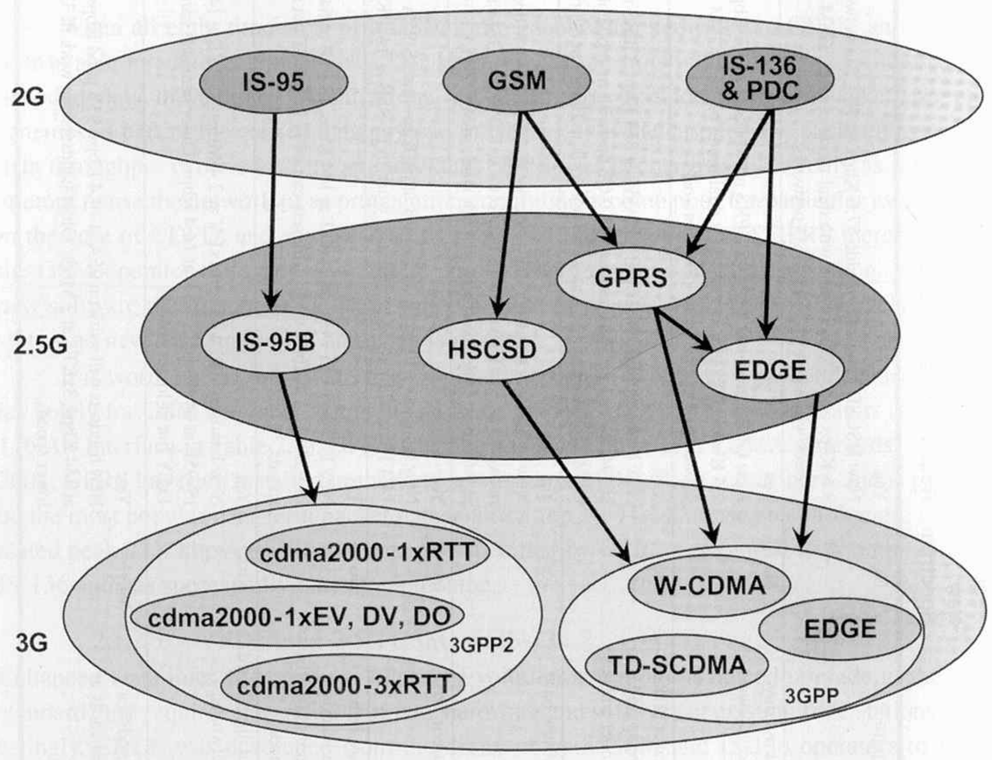


Figure 2.3 Various upgrade paths for 2G technologies.

New Requirements of the 3G System

Table 1.1. Main differences between WCDMA and GSM air interfaces

	WCDMA	GSM
Carrier spacing	5 MHz	200 kHz
Frequency reuse factor	1	1–18
Power control frequency	1500 Hz	2 Hz or lower
Quality control	Radio resource management algorithms	Network planning (frequency planning)
Frequency diversity	5 MHz bandwidth gives multipath diversity with Rake receiver	Frequency hopping
Packet data	Load-based packet scheduling	Time slot based scheduling with GPRS
Downlink transmit diversity	Supported for improving downlink capacity	Not supported by the standard, but can be applied

Comparison of 3G and 4G

Major Requirement Driving Architecture	Predominantly voice-driven; data was always add-on	Converged data and voice over IP
Network Architecture	Wide area cell-based	Hybrid - Integration of Wireless LAN (WiFi, Bluetooth) and wide area
Speeds	384 Kbps to 2 Mbps	20 to 100 Mbps in mobile mode
Frequency Band	Dependent on country or continent (1800-2400 MHz)	Higher frequency bands (2-8 GHz)
IP	A number of air link protocols, including IPv4	All-IP (IPv6)

Mobile Voice Subscriber Growth

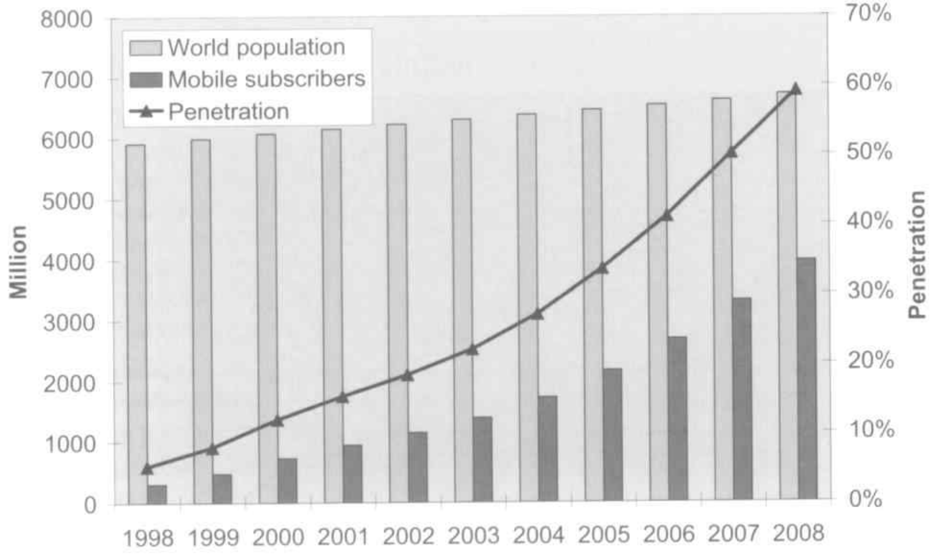
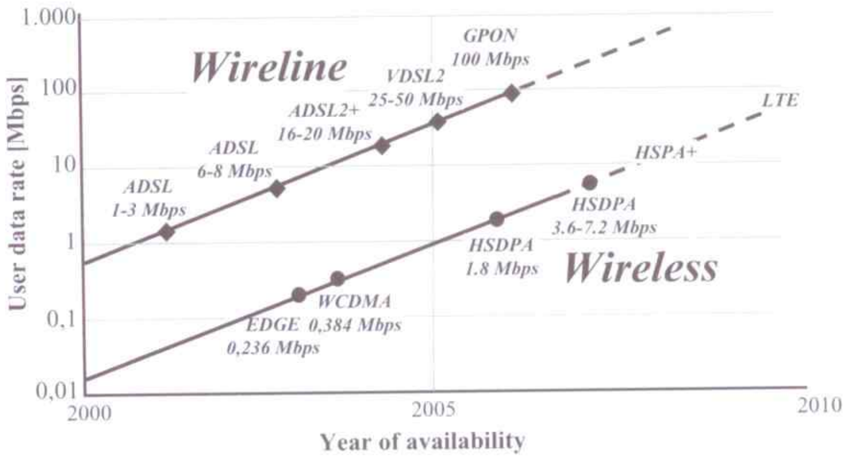


Figure 1.1 Growth of mobile subscribers

Mobile Data Usage Growth

Figure 1.2 Growth of HSDPA data traffic

Technologies Evolution



Motivation and Targets for LTE

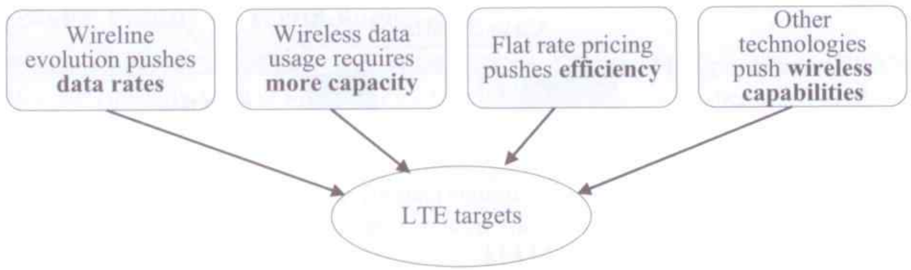


Figure 1.5 Driving forces for LTE development

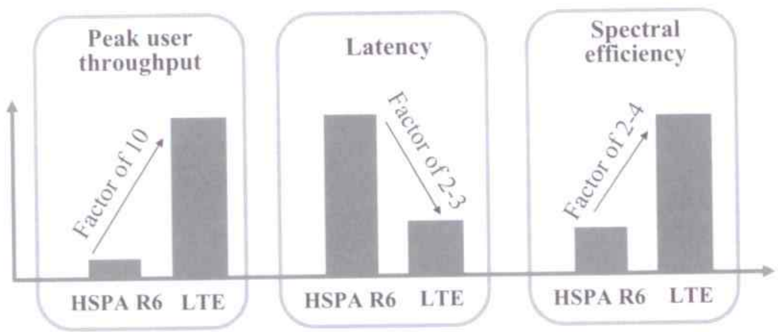


Figure 1.6 Main LTE performance targets

Motivation and Targets for LTE

Main performance targets

- Spectral efficiency 2-4 times more than with HSPA Release 6
- Peak rates exceed 100Mbps in downlink and 50Mbps in uplink
- Round trip time < 10ms
- Packet switched optimized
- High level of mobility and security
- Optimized terminal power efficiency
- Frequency flexibility (tx bandwidth) with 1.5-20 MHz

Overview of LTE

Multiple access scheme in downlink: OFDMA

Multiple access scheme in uplink: SC-FDMA

- Information is modulated only to one carrier, adjusting the phase or amplitude of the carrier or both
- Designed to allow efficient terminal power amplifier, which is relevant for the terminal battery life

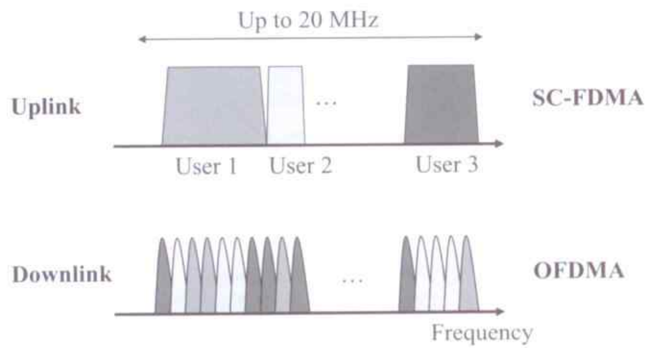


Figure 1.7 LTE multiple access schemes

Overview of LTE

3GPP Release 8 (2008)

improves the network scalability for traffic increase and minimizes the end-to-end latency by reducing the number of network elements

Overview of LTE

eNodeB includes all those algorithms that are located in RNC in 3GPP Release 6 (2004)

all radio protocols, mobility mgt, header compression and all packet retx are located in eNodeB

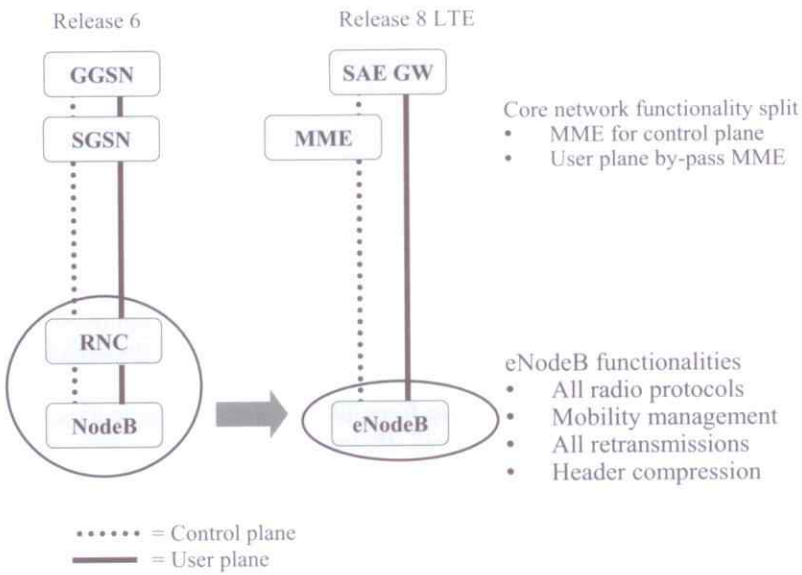


Figure 1.8 LTE network architecture

Packet Data Rate Evolution of 3GPP Tech

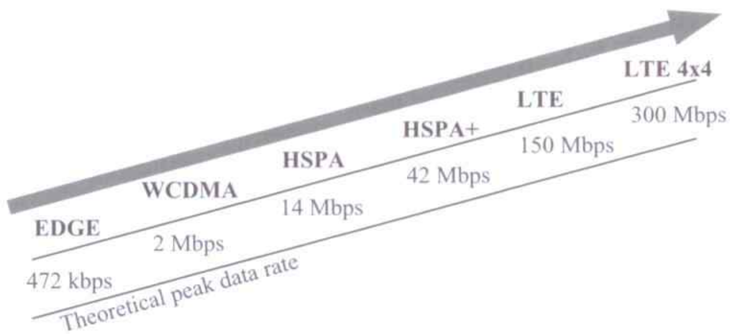


Figure 1.11 Peak data rate evolution of 3GPP technologies

Enabling Technology

MIMO (Multi-Input Multi-Output)

OFDM (Orthogonal Frequency Division Multiplexing)

H-ARQ (Hybrid-ARQ)

OFDM Basics

OFDM is a *multicarrier modulation*

Divide a given high-bit-rate data stream into several lower bit-rate streams

Modulate each stream on separate subcarriers

Multicarrier modulation schemes eliminate or minimize ISI: symbol time >> delay spread (typically < 10%)

To completely eliminate ISI, guard intervals are used between OFDM symbols

OFDM Basics: Single Carrier vs. Multi-carrier

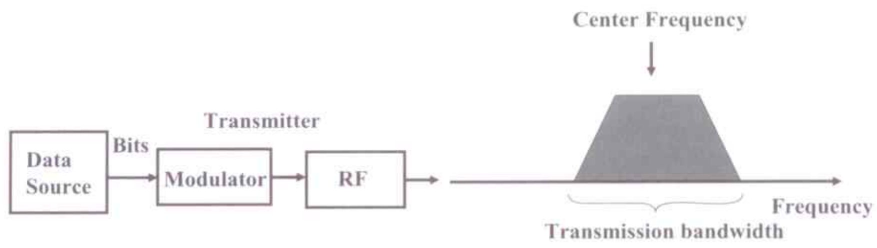


Figure 4.1 Single carrier transmitter

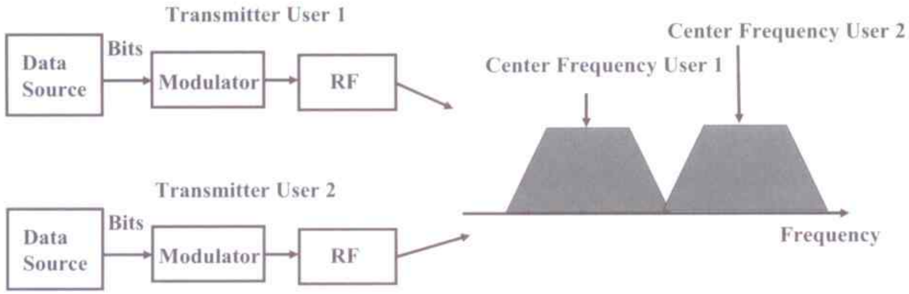


Figure 4.2 FDMA principle

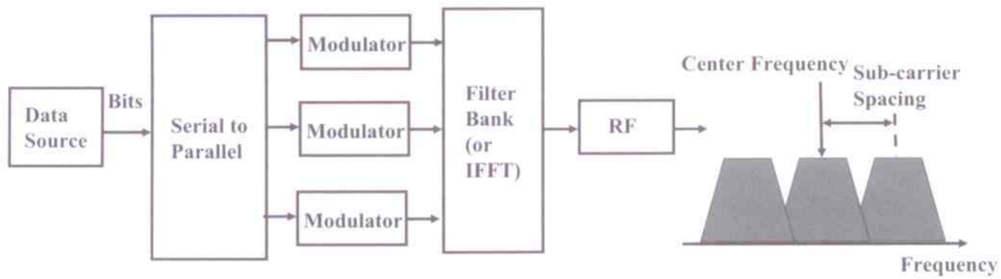


Figure 4.3 Multi-carrier principle

OFDM Basics

Subcarriers may be divided into several groups of subcarriers called subchannels

Different subchannels (each with different number of subcarriers) may be allocated to different users: OFDMA

OFDM Basics

Subchannels formed using distributed (not contiguous) subcarriers provide more frequency diversity, which is useful for mobile applications

Subchannels based on contiguous subcarriers is called band *adaptive modulation and coding* (AMC)

Band AMC, although frequency diversity is lost, allows system designers to exploit multiuser diversity, allocating subchannels to users based on their frequency response

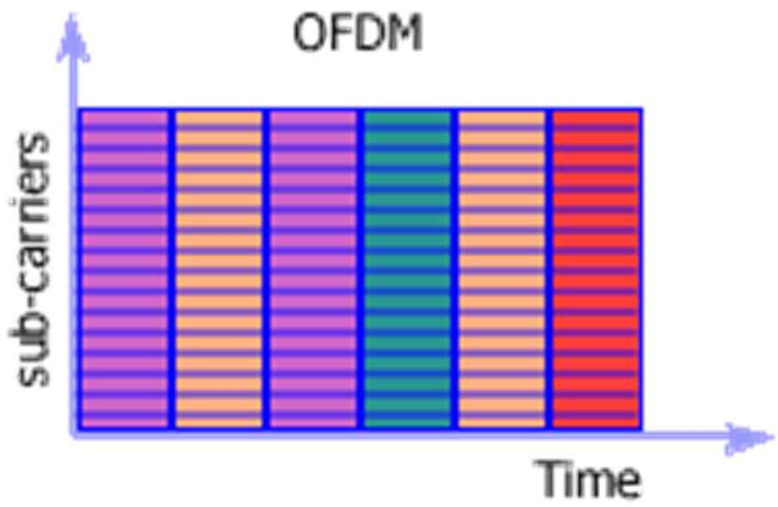
Subchannelization: OFDMA

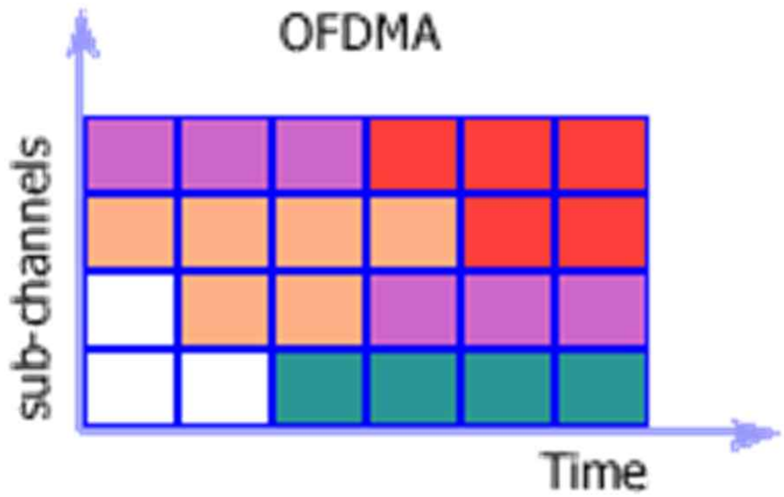
Multiuser diversity provides significant gains in overall system capacity, if the system provides each user with a subchannel that maximizes its received SINR

OFDMA

OFDMA: FDMA + TDMA

Users are dynamically assigned subcarriers (FDMA) in different time slots (TDMA)





OFDMA

DSL, 802.11 a/g use single user OFDM: all the subcarriers are used by a single user at a time

OFDMA is a flexible multiple access technique that can be accommodate many users with widely varying applications, data rates and QoS requirements

Time- and frequency- domain scheduling algorithm has to be integrated to best serve the user population

OFDMA: Multiuser Diversity

Two key sources of capacity gain in OFDMA

1. Multiuser diversity
2. Adaptive modulation and coding (AMC)

Multiuser diversity

- Gains available by selecting subset of users having good channel condition
- As the number of users increases, the probability of getting a large channel gain improves
- But the majority of channel gain is achieved from only the first few users

OFDMA: Multiuser Diversity

Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver.

Opportunistic user scheduling is as follows: the transmitter selects the best user among candidate receivers according to the qualities of each channel between the transmitter and each receiver.

In FDD systems, a receiver must feed back the channel quality information to the transmitter with the limited level of resolution.

OFDMA Adaptive Modulation and Coding

Adaptive modulation and coding (AMC)

- It is used in order to take advantage of fluctuations in the channel
- Transmit as high a data rate (such as 64QAM) as possible when the channel is good, and transmit at a lower rate (such as QPSK) when the channel is poor

OFDMA: Resource Allocation

Ways to take advantage of multiuser diversity and AMC

Algorithms for determining which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier

Algorithms to balance the high *throughput* and *fairness* among the users in the system

OFDMA: Resource Allocation

The resource allocation is usually formulated as a constrained optimization problem

(1) minimize the total transmit power with a constraint on the user darta rate

(2) maximize the total darta rate with a constraint on total transmit power

OFDMA Basics for LTE Downlink

15KHz subcarrier spacing

Different subcarriers are orthogonal to each other:

- at the sampling instant of a single subcarrier the other subcarriers have a zero value

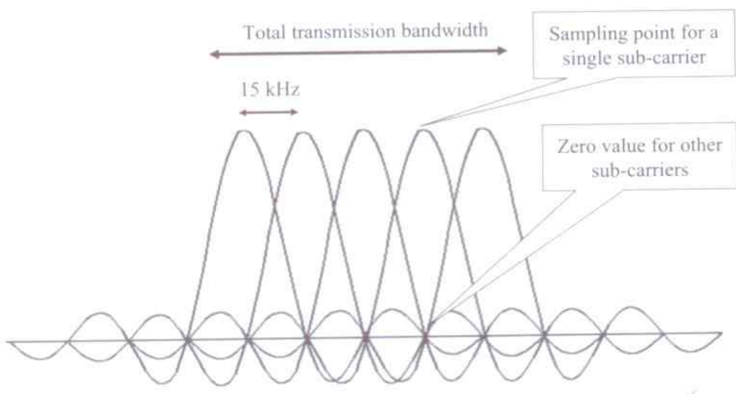


Figure 4.4 Maintaining the sub-carriers' orthogonality

OFDMA Basics for LTE Downlink

The Tx of an OFDMA system uses IFFT block to create the signal

Each input for the IFFT block corresponds to the input representing a particular subcarrier and can be modulated independently of the other subcarriers

The IFFT block is followed by adding the cyclic extension (cyclic prefix)

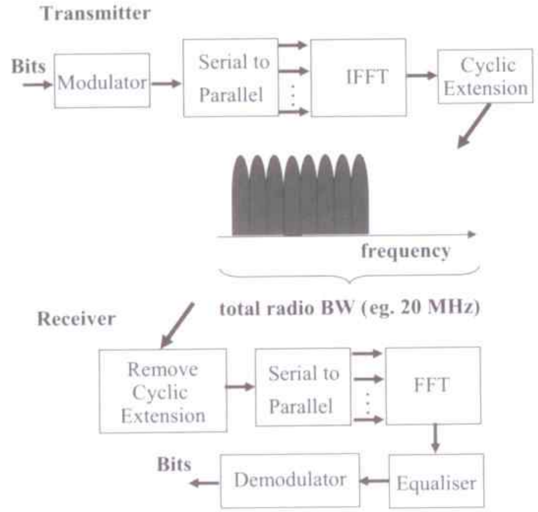


Figure 4.6 OFDMA transmitter and receiver

OFDMA Basics for LTE Downlink

Cyclic extension is to avoid inter-symbol interference and designed to exceeds the delay spread

Reference (or pilot) symbols are tx and rx to deal with the channel impact for the individual subcarriers that have experienced frequency dependent phase and amplitude changes:

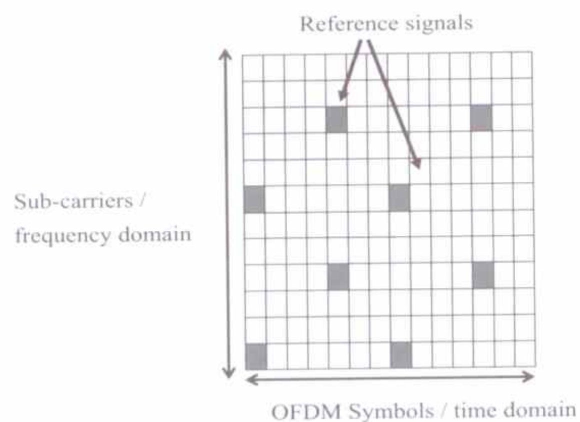


Figure 4.8 Reference symbols spread over OFDMA sub-carriers and symbols

OFDMA Resource Allocation in LTE

Users in downlink can be allocated basically to any of the subcarriers in the frequency domain

Practical limitation is that the allocation is not done on an individual subcarrier basis but is based on resource blocks, each consisting of 12 sub-carriers

The downlink tx resource allocation is to fill the resource pool with 180KHz blocks at 1 ms resolution

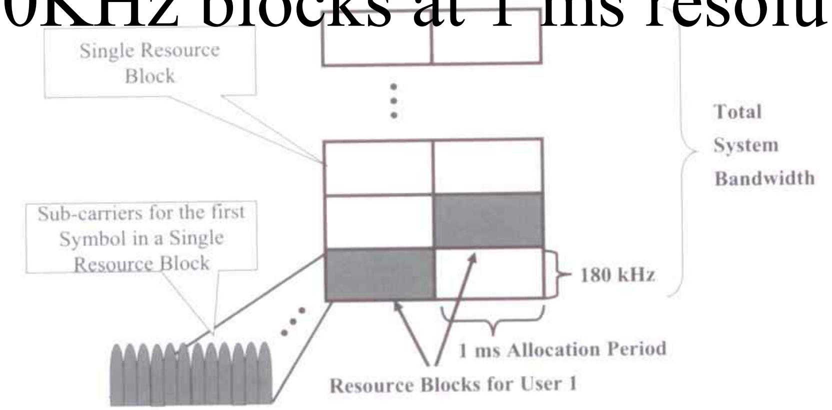


Figure 4.10 OFDMA resource allocation in LTE

OFDMA Resource Allocation in LTE

The OFDMA tx in the frequency domain consists of several parallel subcarriers, which in the time domain correspond to multiple sinusoidal waves with different frequencies

This causes the signal envelope to vary strongly

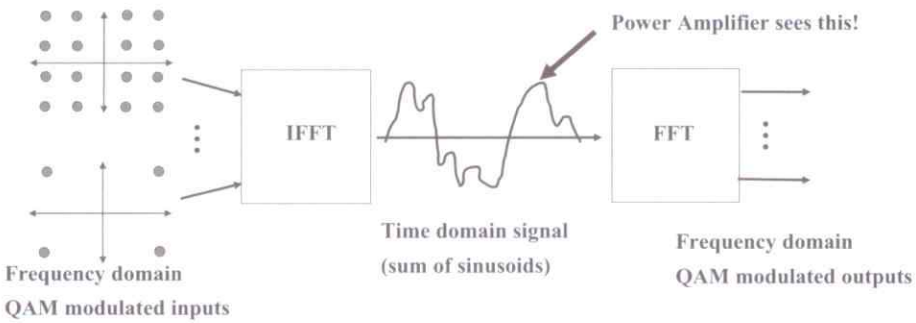


Figure 4.11 OFDMA signal envelope characteristics

OFDMA Resource Allocation in LTE

A signal with a higher envelope variation requires the amplifier to use additional backoff compared to a regular single carrier signal

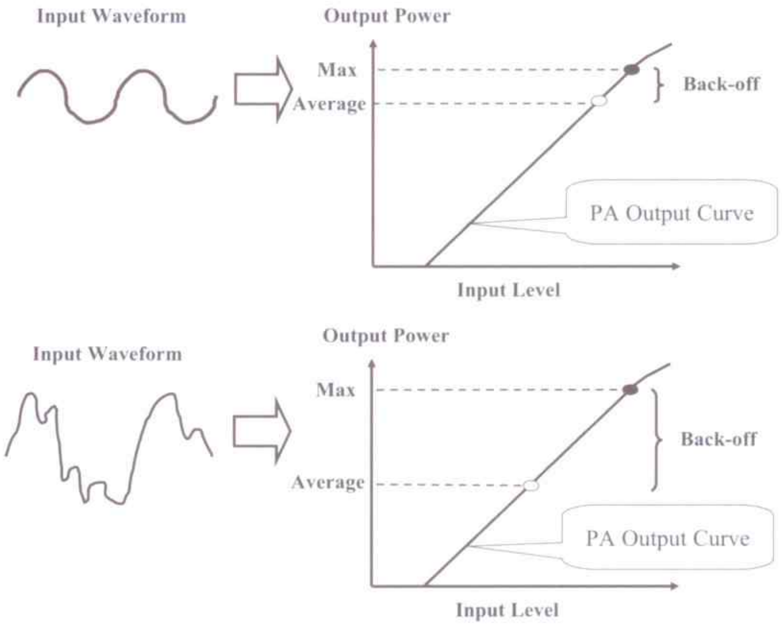


Figure 4.12 Power amplifier back-off requirements for different input waveforms

OFDMA Resource Allocation in LTE

This was the key reason why 3GPP decided to use OFDMA in the downlink direction but to use the power efficient SC-FDMA in the uplink

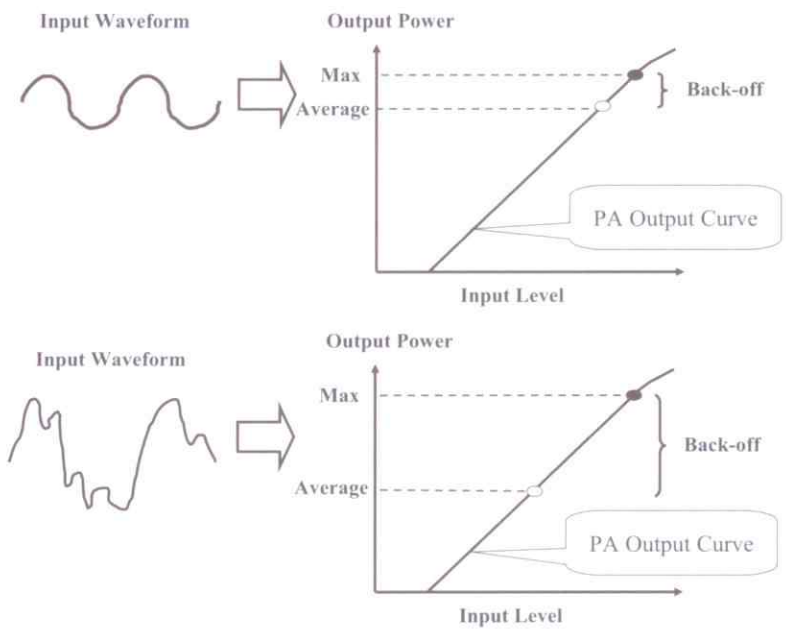


Figure 4.12 Power amplifier back-off requirements for different input waveforms

SC-FDMA Basics for LTE Uplink

Some of the desirable attributes for the LTE uplink

- Orthogonal uplink tx by different UEs to minimize intracell interference and maximize capacity
- Flexibility to support a wide range of data rates, and to enable data rate to be adapted to the SINR
- Sufficiently low PAPR of the transmitted waveform to avoid excessive power consumption of the UE power amplifier
- Ability to exploit the frequency diversity afforded by the wideband channel (up to 20MHz), even when tx at low data rate

SC-FDMA Basics for LTE Uplink

Time domain signal generation

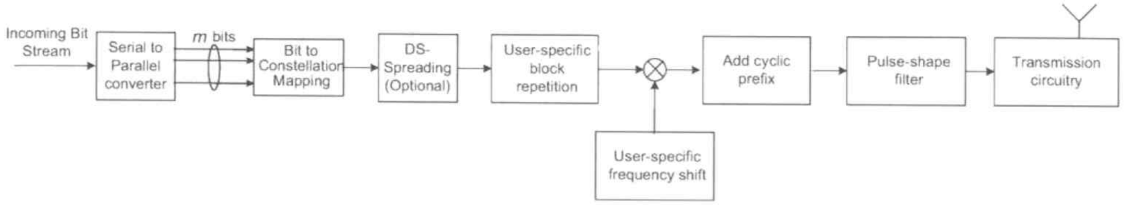


Figure 15.1 SC-FDMA time-domain transmit processing.

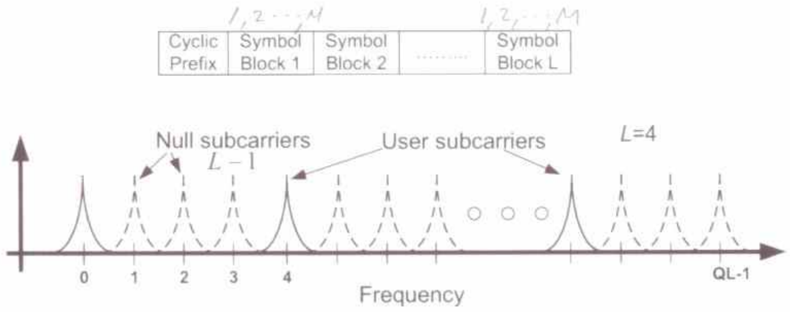


Figure 15.2 Distributed transmission with equal-spacing between occupied subcarriers.

SC-FDMA Basics for LTE Uplink

Frequency domain signal generation

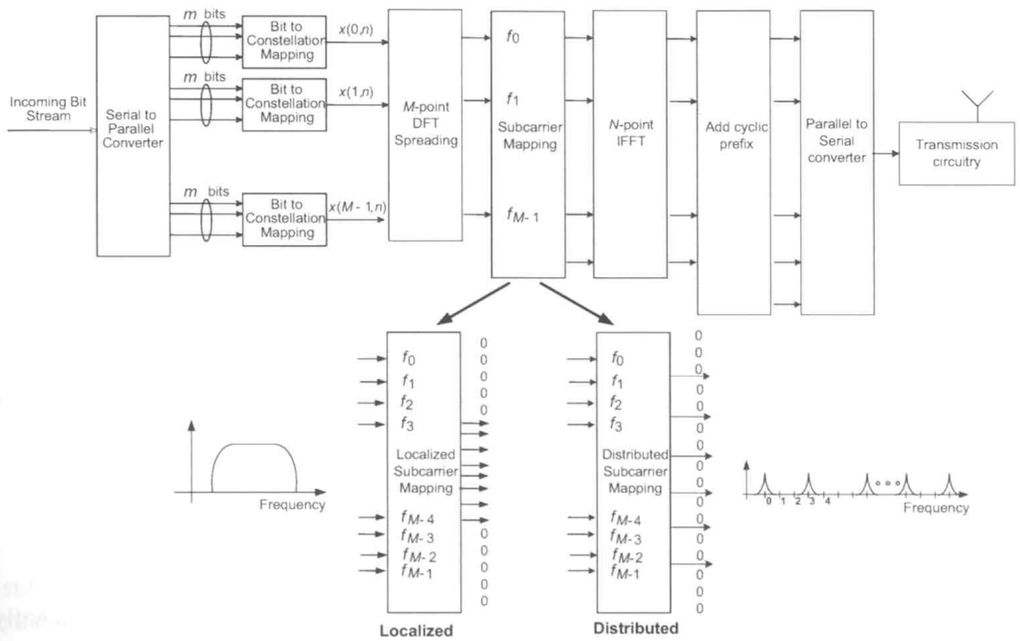


Figure 15.3 SC-FDMA frequency-domain transmit processing (DFT-S-OFDM) showing localized and distributed subcarrier mappings.

Downlink User Data Transmission

Carried on the PDSCH

1 ms 180KHz (12 subcarriers) resource block

The eNodeB carries out the resource allocation based on the Channel Quality Indicator (CQI) from the terminal

PDCCH informs the device which 1 ms resource blocks are allocated to it

6 (extended CF) or 7 (short CF) symbols are fitted into a 0.5 ms slot

Downlink User Data Transmission

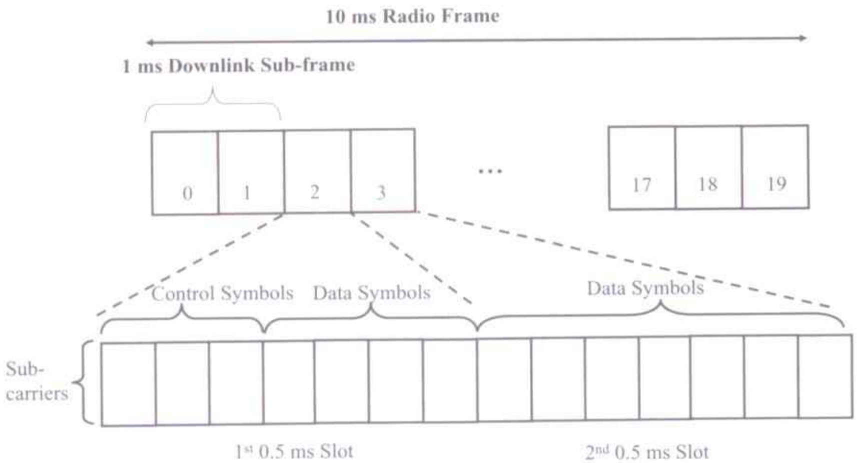


Figure 5.11 Downlink slot structure for bandwidths above 1.4 MHz

Uplink User Data Transmission

Carried on PUSCH which has 10 ms frame structure

1 ms 180KHz (12 subcarriers) resource block

2 x 0.5 ms slot (1 subframe) structure

Within the 0.5 ms slot reference symbols, user data symbols and signaling are inserted

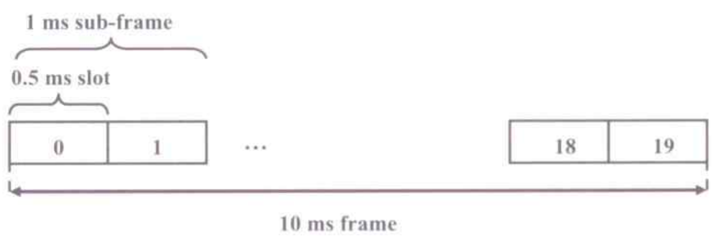


Figure 5.5 LTE FDD frame structure

Uplink User Data Transmission

The 0.5 ms slot accommodates either 6 or 7 symbols

Table 15.1 LTE uplink SC-FDMA physical layer parameters.

Parameter	Value	Description
Subframe duration	1 ms	
Slot duration	0.5 ms	
Subcarrier spacing	15 kHz	
SC-FDMA symbol duration	66.67 μs	
CP duration	Normal CP:	5.2 μs first symbol in each slot, 4.69 μs all other symbols
	Extended CP:	16.67 μs all symbols
Number of symbols per slot	7 (Normal CP) 6 (Extended CP)	
Number of subcarriers per RB	12	