Sistemi di Telecomunicazione

Prof. Gianluigi Ferrari

Dipartimento di Ingegneria e Architettura – Pal. 2
Internet of Things (IoT) Lab
Università di Parma
gianluigi.ferrari@unipr.it
http://www.tlc.unipr.it/ferrari
http://iotlab. unipr.it/

Tel: 0521 90**6513**

Il Calendario

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February-March						
Mon	Tue	Wed	Thu	Fri	Sat	Sun
25	26	27	28	1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

April						
Mon	Tue	Wed	Thu	Fri	Sat	Sun
1 – 8:30	2	3	4	5	6	7
8	9	10	11	12	13	14
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22	23	24	25	26	27	28
29	30					

May						
Mon	Tue	Wed	Thu	Fri	Sat	Sun
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

June						
Mon	Tue	Wed	Thu	Fri	Sat	Sun
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3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

Al più 21 lezioni

Lezioni

"Compitini"

Download: http://www.tlc.unipr.it/ferrari/SdT_19.pdf

Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- Physical layer: modulation
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - WiFi (CSMA/CA)
- Personal Area Networks
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

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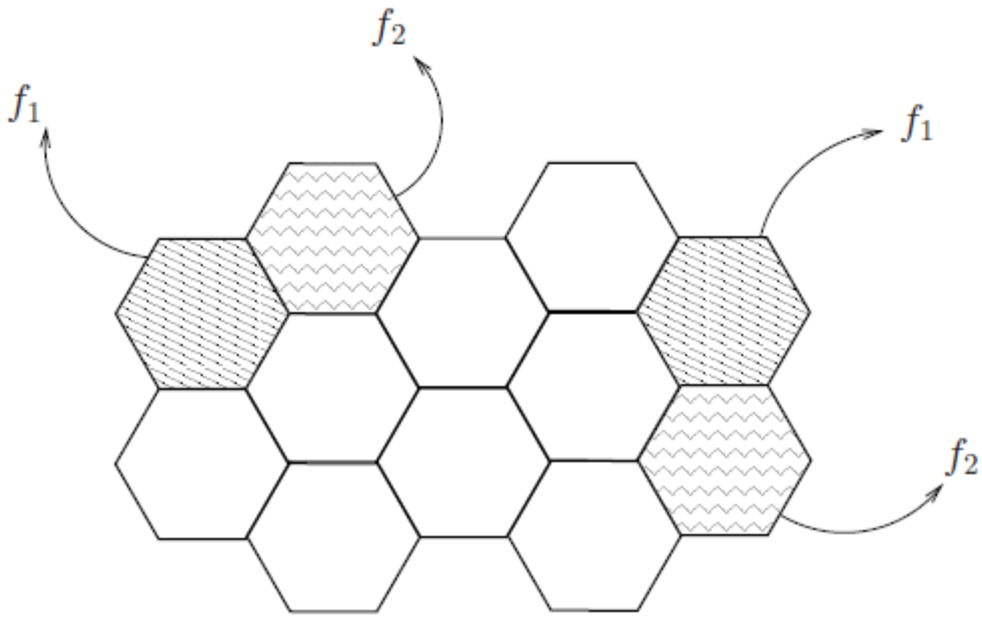
History of Wireless Networks

- First examples by policemen and firemen: only half-duplex.
- IMTS (Improved Mobile Telephone System): first full-duplex system, but not really cellular.
- First cellular network by AT&T USA: space reuse concept.



Cellular Networks in USA

1983 AMPS (Advanced Mobile Phone System): analogical and with only a few channels.

1991 IS 54: first digital network with TDMA (Time Division Multiple Access), $\pi/4$-QPSK (Quaternary Phase Shift Keying) modulation, and carrier modulation at 1.9 GHz.

1995 IS 95: 2G mobile system with use of CDMA (Code Division Multiple Access).

2000 IS 2000: 3G mobile system with an improved CDMA. It is backward-compatible with IS 95.

2008 Qualcomm announced for 4G systems that UMB (Ultra Mobile Broadband) was ending development of the technology, favoring LTE (Long Term Evolution) instead.

Cellular Networks in Europe

1985 TACS (Total Access Communication System): European variant of AMPS with a similar analogical technology. In UK, the last TACS service was discontinued on 31 May 2001 (Vodafone). ETACS is however still in use in a handful of countries elsewhere in the world.

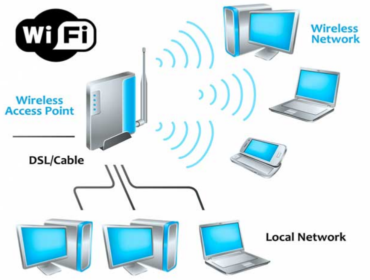
1991 GSM (Global System for Mobile Communications, originally from Groupe Special Mobile): first digital 2G technology with GMSK (Gaussian Minimum Shift Keying) modulation and TDMA medium access.

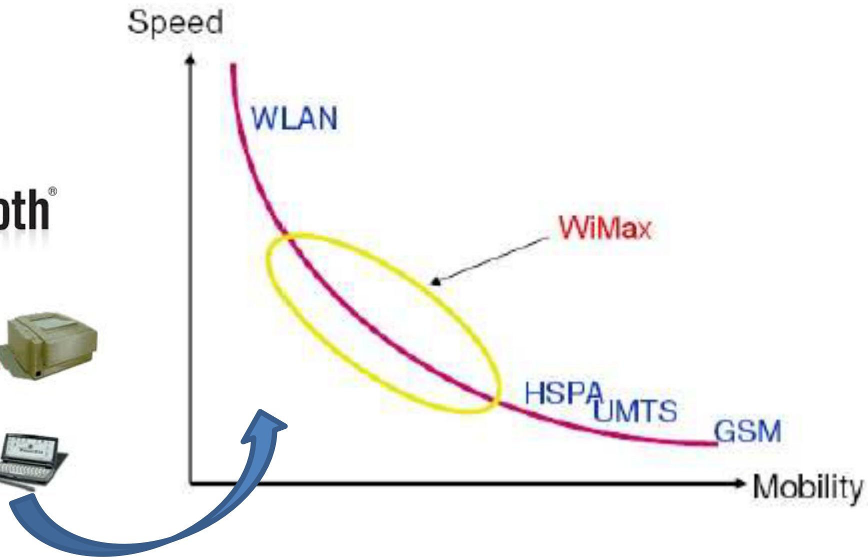
2000 UMTS (Universal Mobile Telecommunications System): 3G mobile system with use of CDMA and maximum theoretical data transfer rate of 21 Mbit/s (with HSDPA, High Speed Downlink Packet Access).

2006 The 3GPP LTE project plans to move UMTS to 4G (higher) speeds, using a next generation technology based upon Orthogonal Frequency-Division Multiplexing (OFDM).

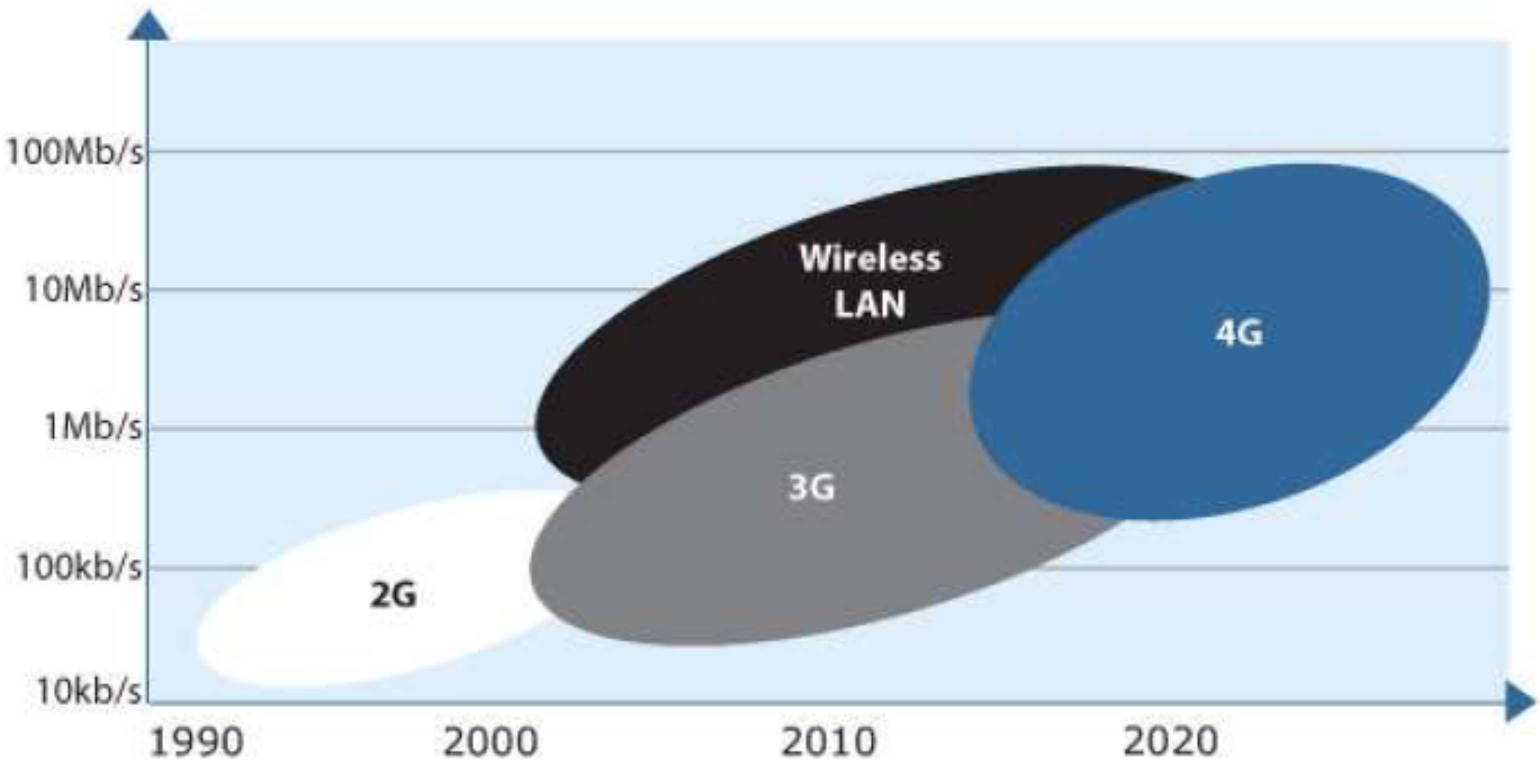
Other Examples

- WiMAX (Worldwide Interoperability for Microwave Access): IEEE 802.16 standard for providing large bandwidth and high mobility (last mile connectivity).
- WiFi: wireless local area networks (WLANs) based on the IEEE 802.11 standards (802.11a/g/n).
- Ethernet: standardized as IEEE 802.3 for wired-based communications.





Transmission Capacity



Key Aspects of Infrastructure-Based Networks

- Many users want to exchange information by using a shared medium (e.g., the air)

$$\Downarrow$$

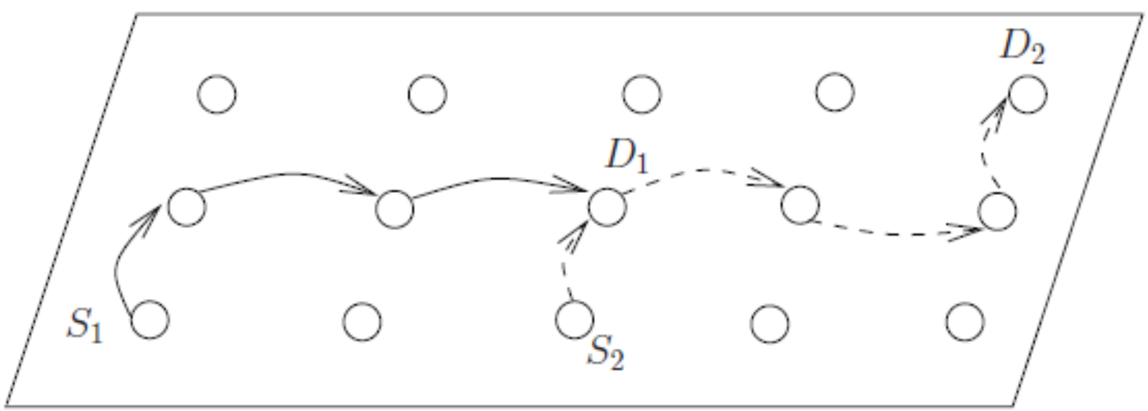
Need of a MAC (Medium Access Control) protocol.

- Received power experiences (possibly high) statistical fluctuations due to fading and shadowing.

- The presence of neighbors leads to interference and, therefore, central authorities are needed.

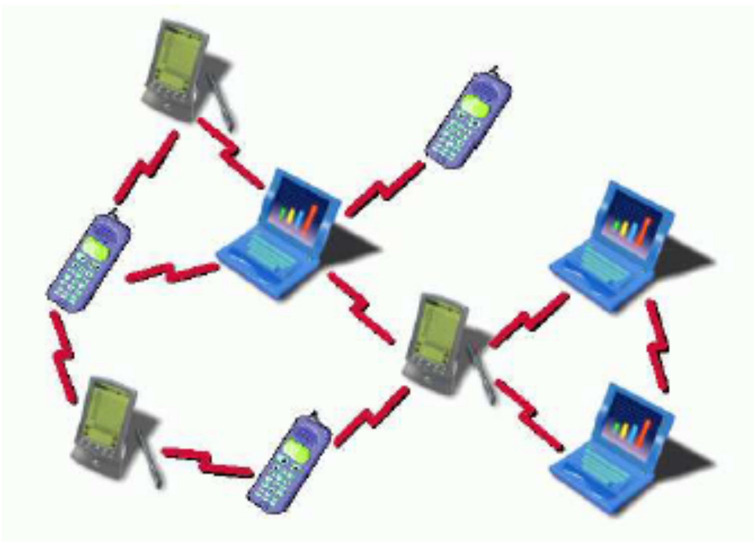
From Cellular Networks to Pervasive Computing

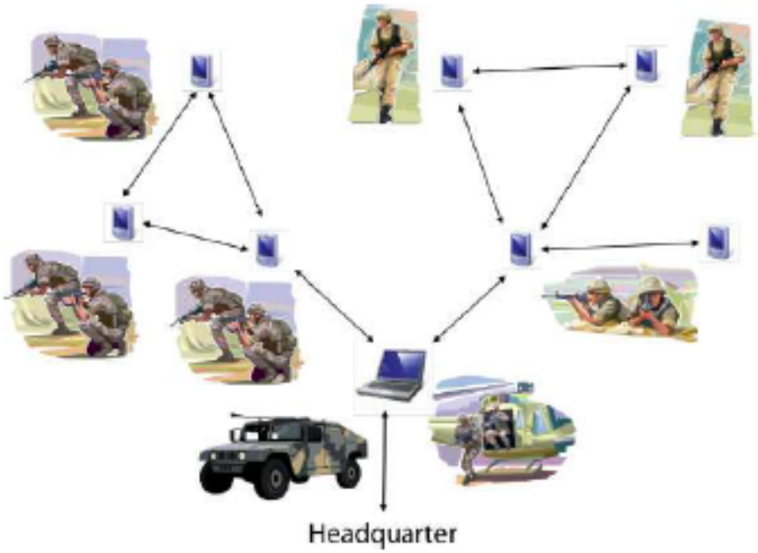
- The central authority should be cancelled: decentralized control of the network.
- Concept of networking on demand: paths between pairs of nodes are established iif they want to communicate.
- A lot of small and low-complexity devices are placed in a given area $\Longrightarrow$ need for distributed computing.
- Topology can change dynamically.



Mobile Ad hoc NETworks (MANETs)

Wireless Ad Hoc Networks: like WiFi, but without any central entity and with need of proper physical/MAC layer protocols.





Characteristics of MANETs

- Autonomous system of nodes.
- Lack of fixed infrastructure relays.
- Absence of centralized authority.
- Peer-to-peer connectivity and multi-hop forwarding to ensure network connectivity.
- Topology may change dynamically.
- Random multi-hop graph.
- Energy-constrained (battery) and bandwidth-constrained (variable capacity links).

Applications of MANETs

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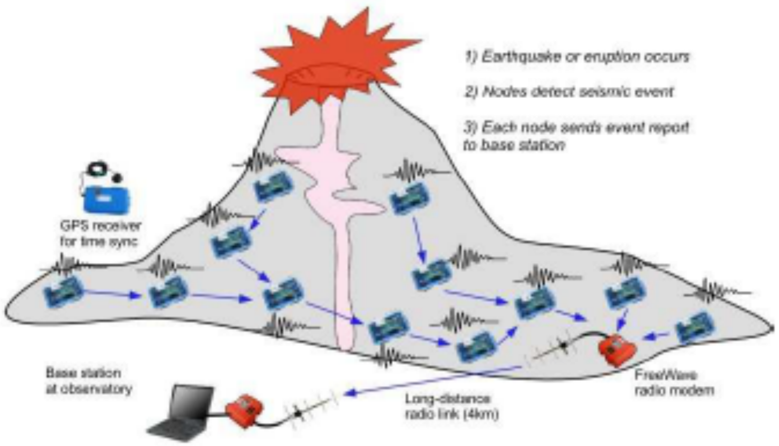
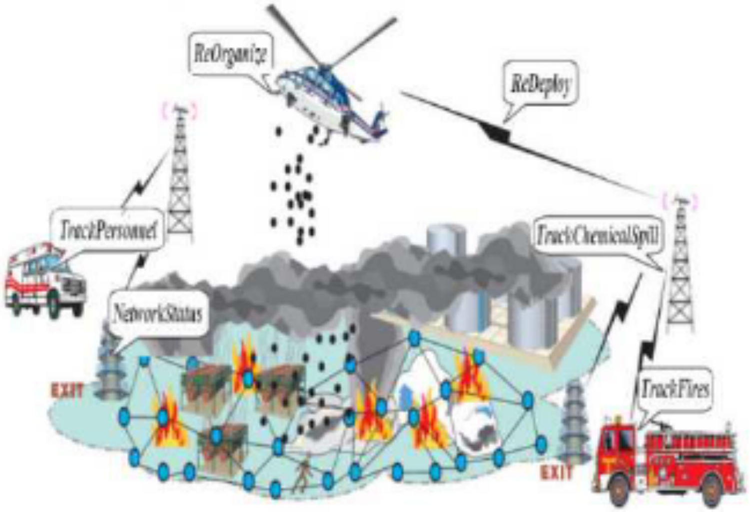
- Defense: on-the-fly communications for soldiers on the ground, fighter planes in the air, etc.
- Crisis management: natural disasters where the entire infrastructure may fail.
- Tele-medicine: paramedic assisting a victim at a remote location can access medical records, can get video conference assistance, etc.
- Tele-geoprocessing and virtual navigation: combines geographical information system (e.g., GPS and high capacity MSs), queries dependent of location information of users, and environmental monitoring using sensors.
- Education via Internet: educational opportunities on Internet to students and other interested individuals.

Wireless Sensor Networks (WSNs)

Spatially distributed autonomous sensors cooperatively monitor physical or environmental conditions, such as temperature, pressure, humidity, etc. $\Longrightarrow$ ZigBee standard.





Sensors

- Sensors are portable and self-sustained (power, communication, intelligence).
- Sensor nodes are capable of embedded (complex) data processing.
- Technology trends predict small memory footprint may not be a limitation in future.
- Sensor devices are equipped with multiple sensing, programmable computing, and communication capability.
- Sensors are capable of surviving harsh environments.

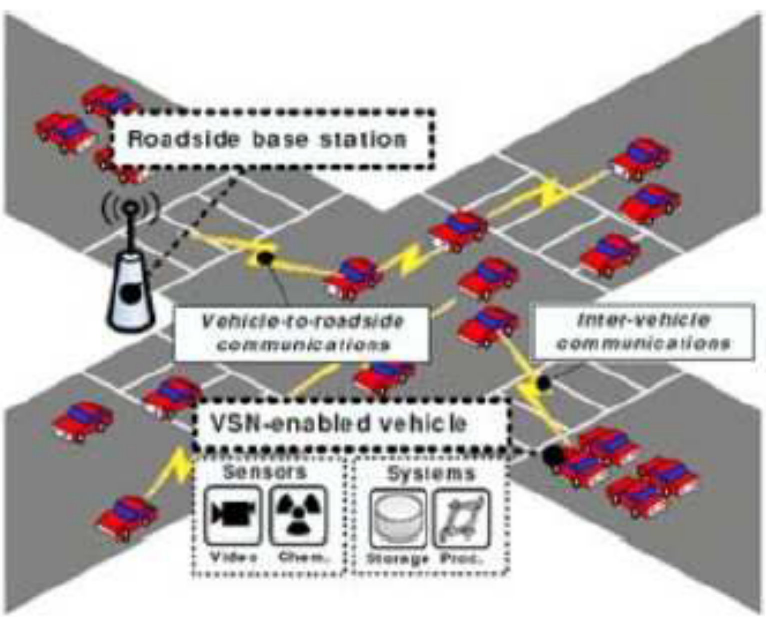
Sensor Networks

- Collection of tiny disposable and low power devices.
- The sensed attributes are converted into a form understandable by human users.
- The number of sensors can be large to cover as much area as desirable.
- Sensor networks are usually unattended and some degree of fault-tolerance needed.

Vehicular Ad hoc NETworks (VANETs)

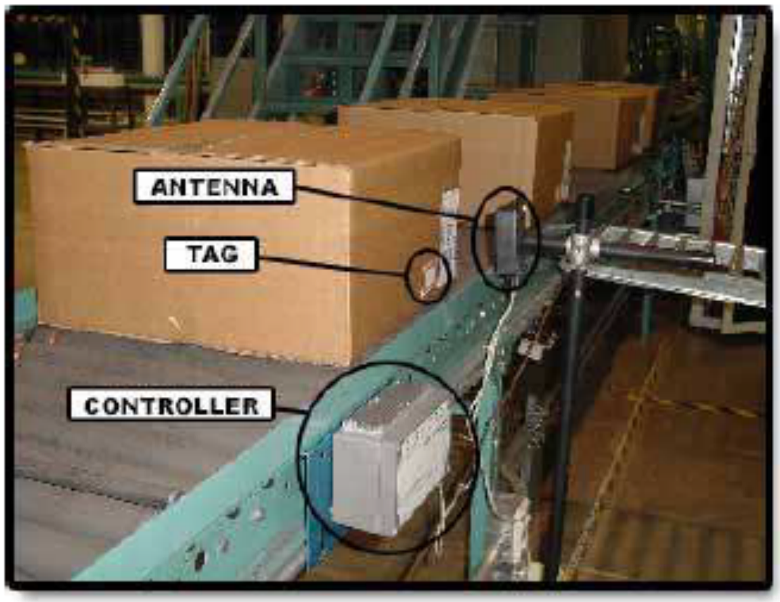
Vehicles communicate with each other (V2V) as well as with roadside base stations (V2I) in order to contribute to safer and more efficient roads.

IEEE 802.11™



Radio Frequency IDentification (RFID)

As with barcodes, tags are applied to or incorporate into a product, animal, or person for identification and tracking using radio waves.



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Propagation characteriscs

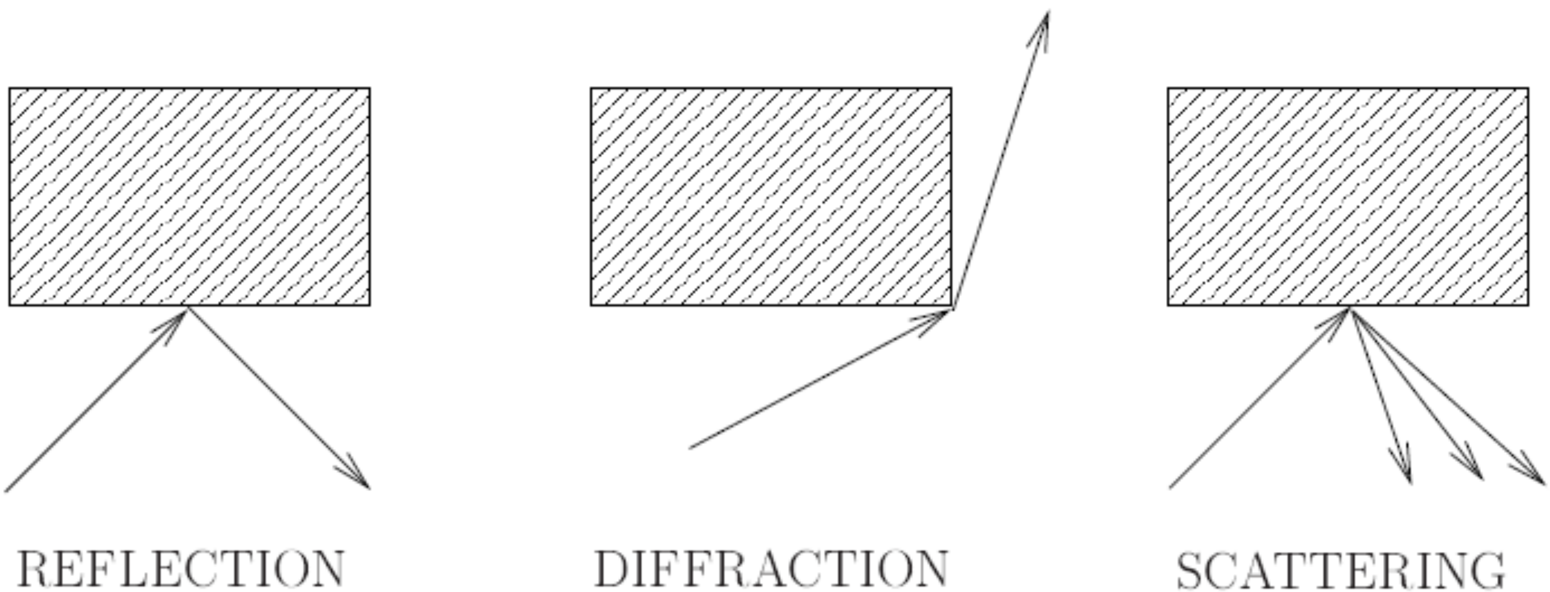
- Alla lavagna:
  - Power gain
  - Transmission loss and repeaters
  - Radio transmission

A. B. Carlson e P. B. Crilly, *Communication Systems: an Introduction to Signals and Noise in Electrical Communication*, Mcgraw Hill Higher Education, 5th edition, 2009. ISBN-13: 978-0071263320.

Propagation modes

- Line-Of-Sight (LOS): there is a direct path between source and destination (typical of countryside).

- Non-Line-Of-Sight (N-LOS): there is no direct path between source and destination (typical of urban).



Effects in N-LOS Environments

- Attenuation: becomes remarkable at long distances (e.g., 10 km).

Friis Formula

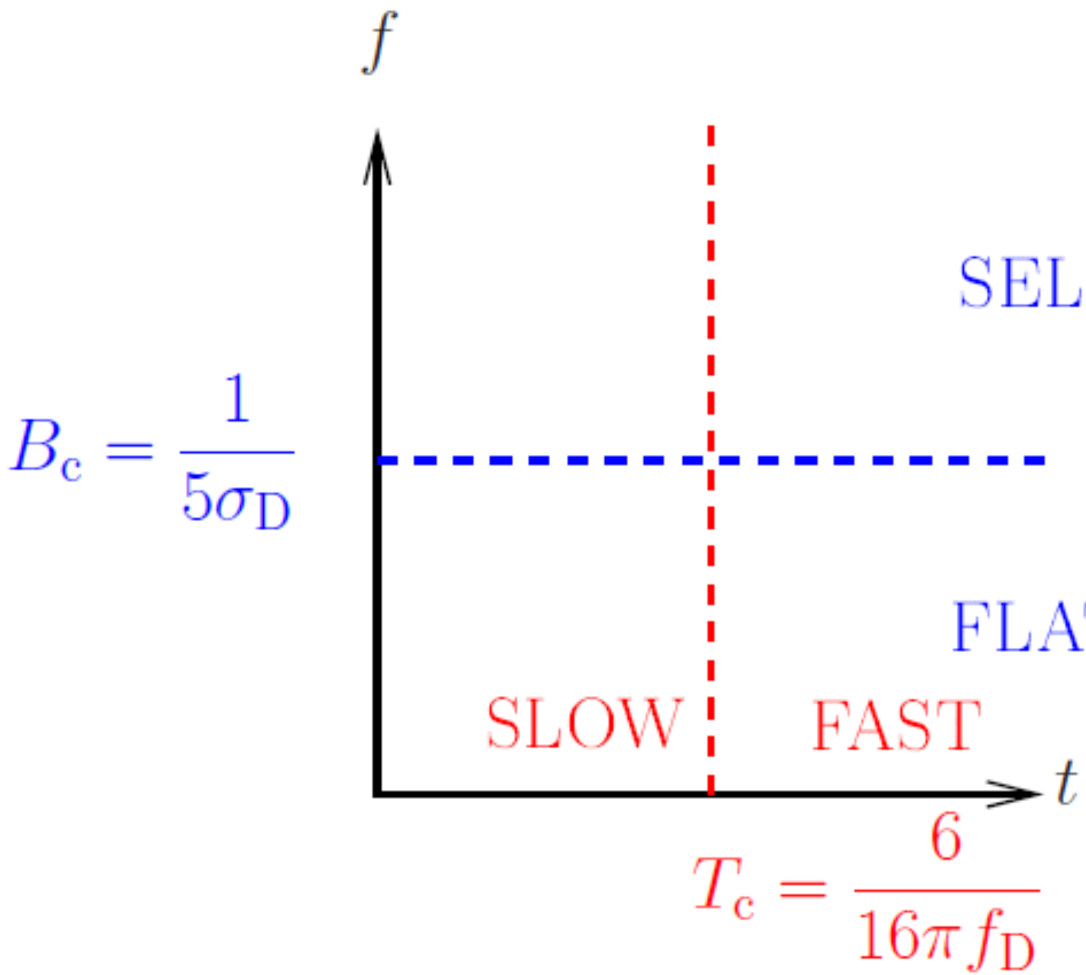
$$P_r(d) = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^{\nu} = P_t G_t G_r \left(\frac{c}{4\pi d f_c} \right)^{\nu}$$

with $\nu = 2 \div 4$.

- Shadowing: becomes remarkable at medium distances (e.g., 1 km). It is a fluctuation of the received power around a mean value and it can be described by a lognormal distribution.

- Short-term fading: becomes remarkable at short distances (e.g., 100 m). It is a rapid fluctuation of the received power around the mean value (with also negative spikes) and it can be described by a Rayleigh distribution.

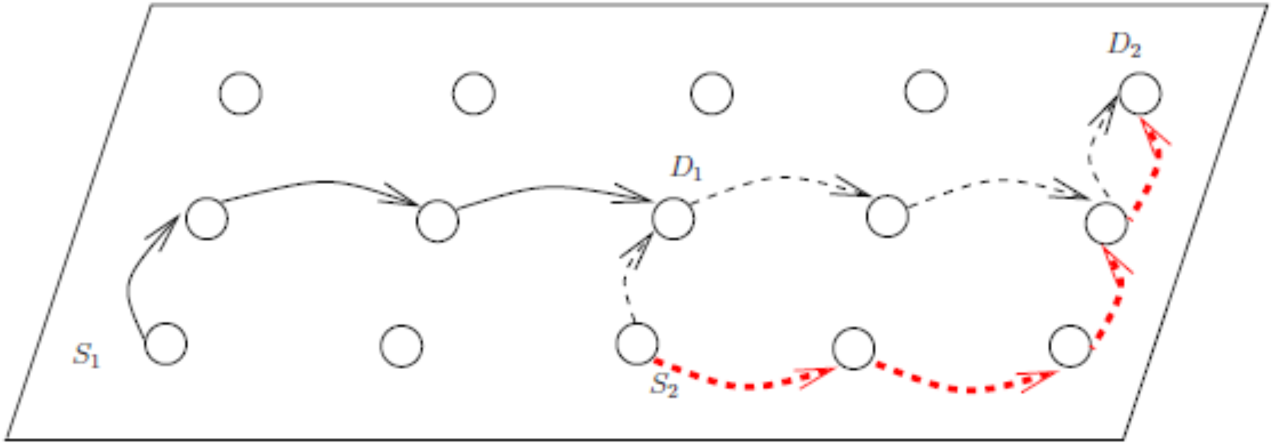
Fading Characterization



Fading Counter-acts

- Diversity: in time (rake receiver), frequency (frequency hopping), space (multiple antennas, space-time codes, polarization diversity, etc.).

- Smart Antennas: antennas' lobes are properly modulated according to the direction they transmit $\Longrightarrow$ a lot of problems in the presence of mobility!!!



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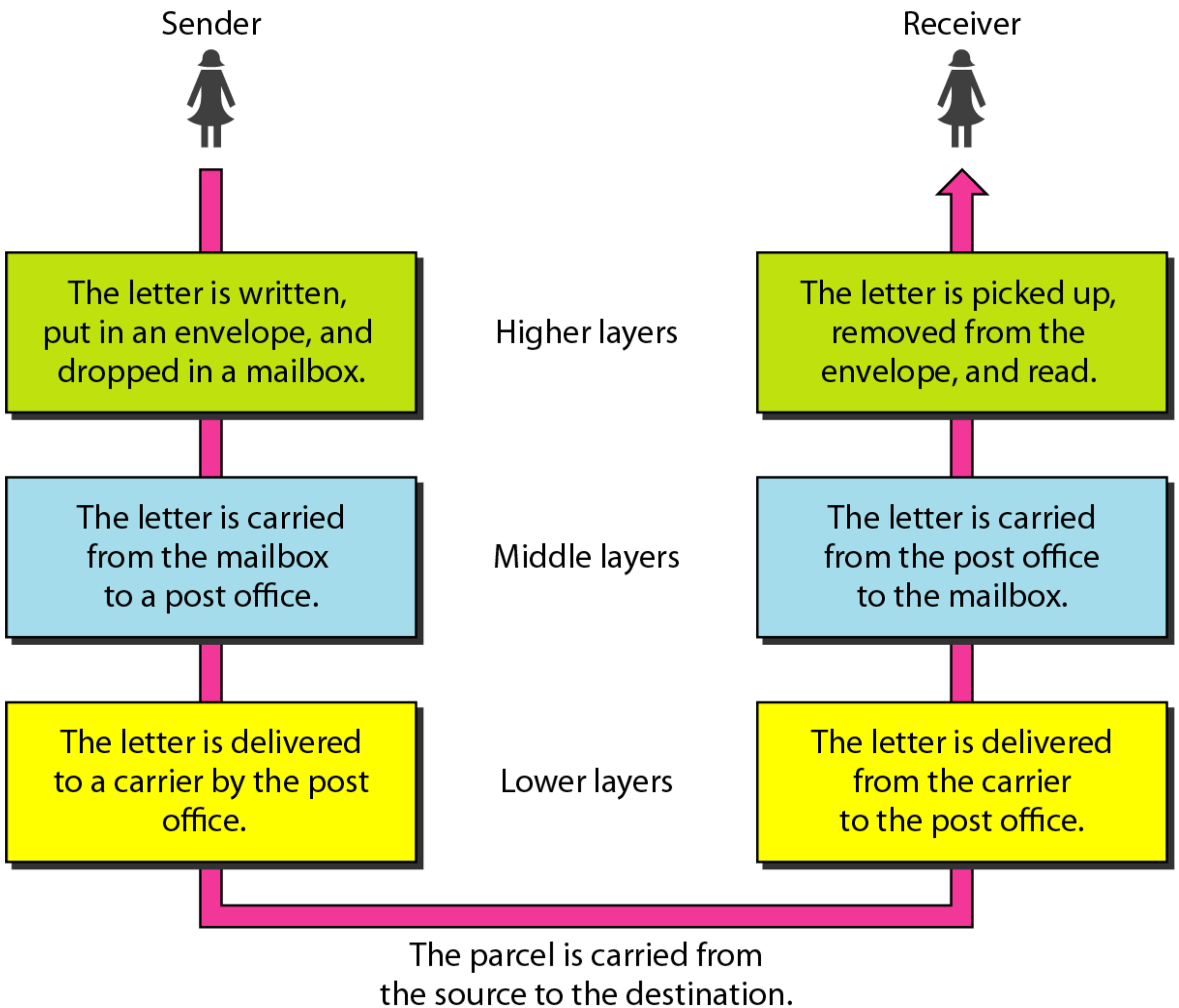
Layered Tasks

We use the concept of layers in our daily life. As an example, let us consider two friends who communicate through postal mail. The process of sending a letter to a friend would be complex if there were no services available from the post office.

Main concepts:

- Sender, receiver, and carrier
- Hierarchy

Tasks involved in sending a letter



The OSI Model

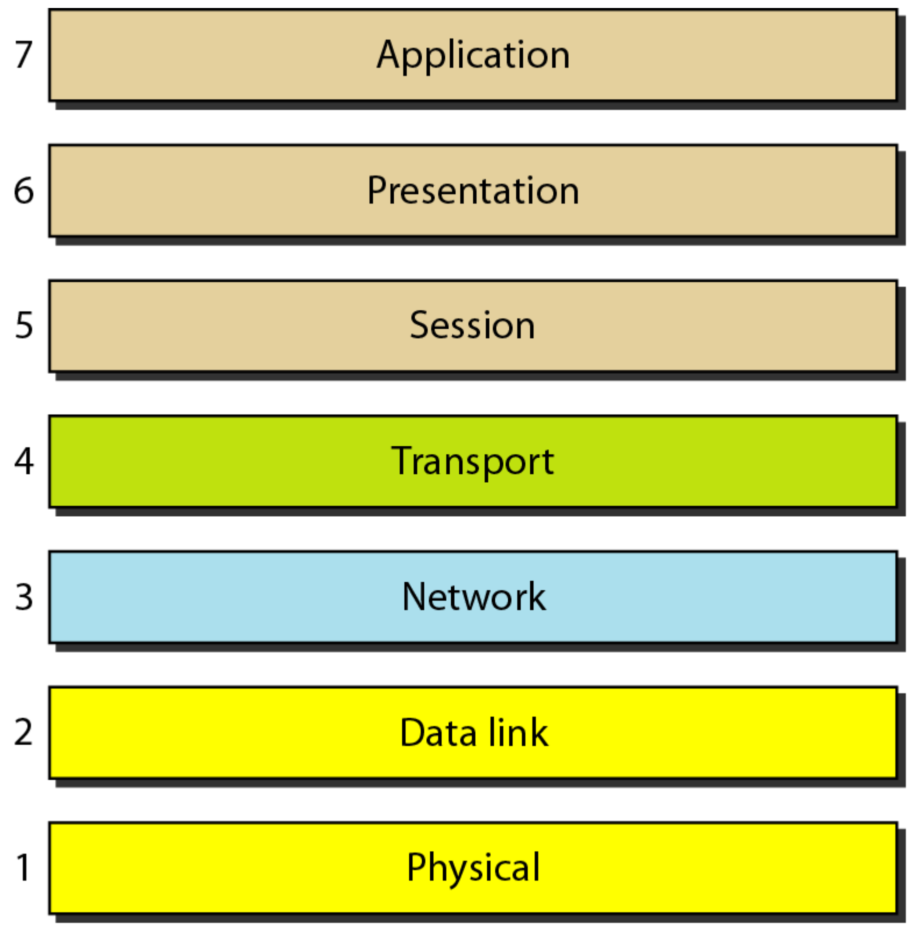
Established in 1947, the International Standards Organization (ISO) is a multinational body dedicated to worldwide agreement on international standards. An ISO standard that covers all aspects of network communications is the Open Systems Interconnection (OSI) model. It was first introduced in the late 1970s.

ISO is the organization.
OSI is the model.

Main concepts:

- Layered architecture
- Peer-to-peer processes
- Encapsulation

The Seven Layers of the OSI Model



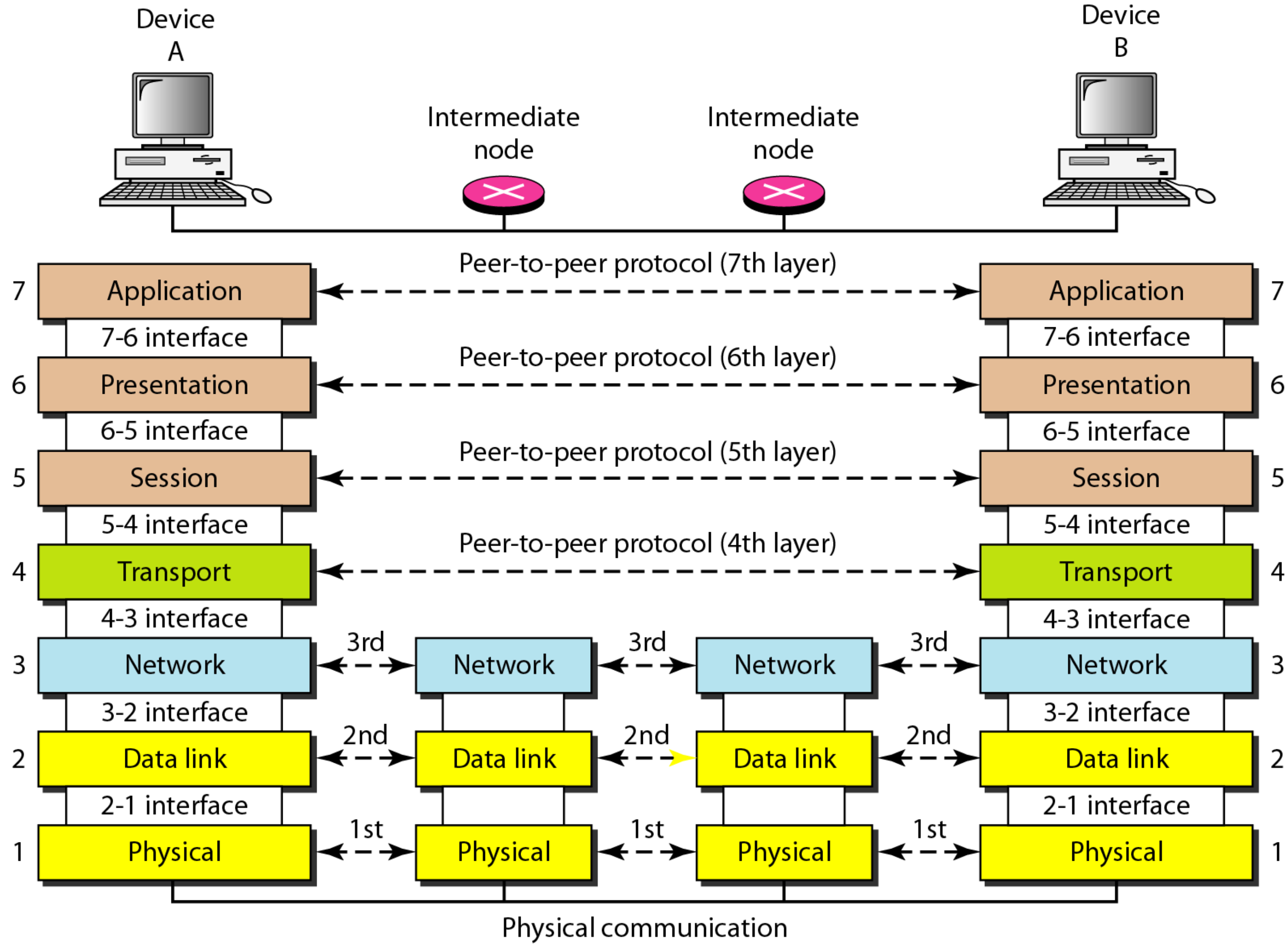
The Seven Layers of the OSI Model (ctd)

Layer	Responsible For:
7.) Application	Provides Services to User Apps
6.) Presentation	Data Representation
5.) Session	Communication Between Hosts
4.) Transport	Flow Ctrl, Error Detection/Correction
3.) Network	End to End Delivery, Logical Addr
2.) Data Link	Media Access Ctrl, Physical Addr
1.) Physical	Medium, Interfaces, Puts Bits on Med.

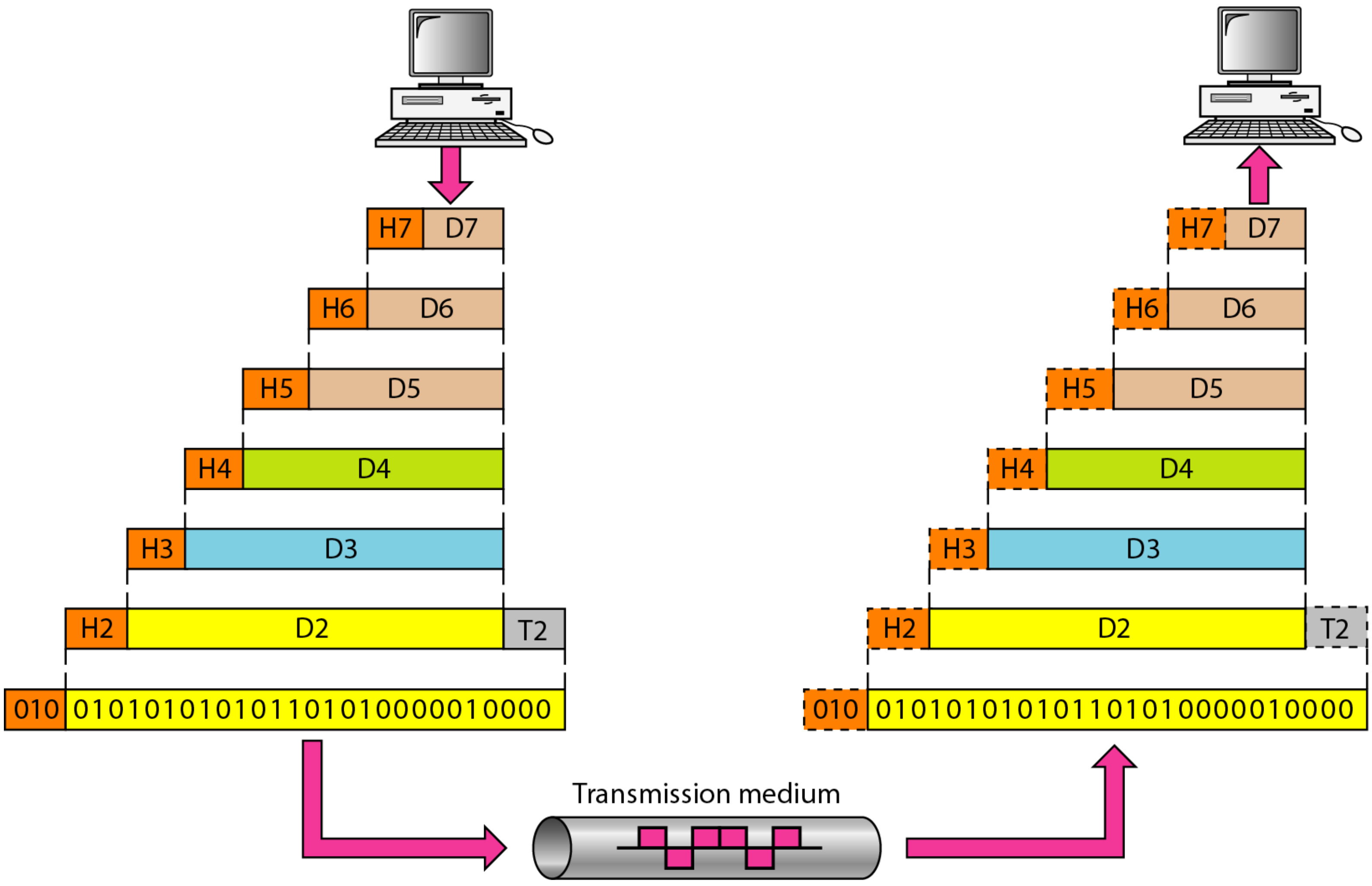
Examples

Layer	Example
7.) Application	HTTP, FTP, SMTP
6.) Presentation	ASCII, JPEG, PGP
5.) Session	BOOTP, NetBIOS, DHCP, DNS
4.) Transport	TCP, UDP, SPX
3.) Network	IP, IPX, ICMP
2.) Data Link	Ethernet, Token Ring, Frame Relay
1.) Physical	Bits, Interfaces, Hubs

The interaction between layers in the OSI Model



An exchange using the OSI model

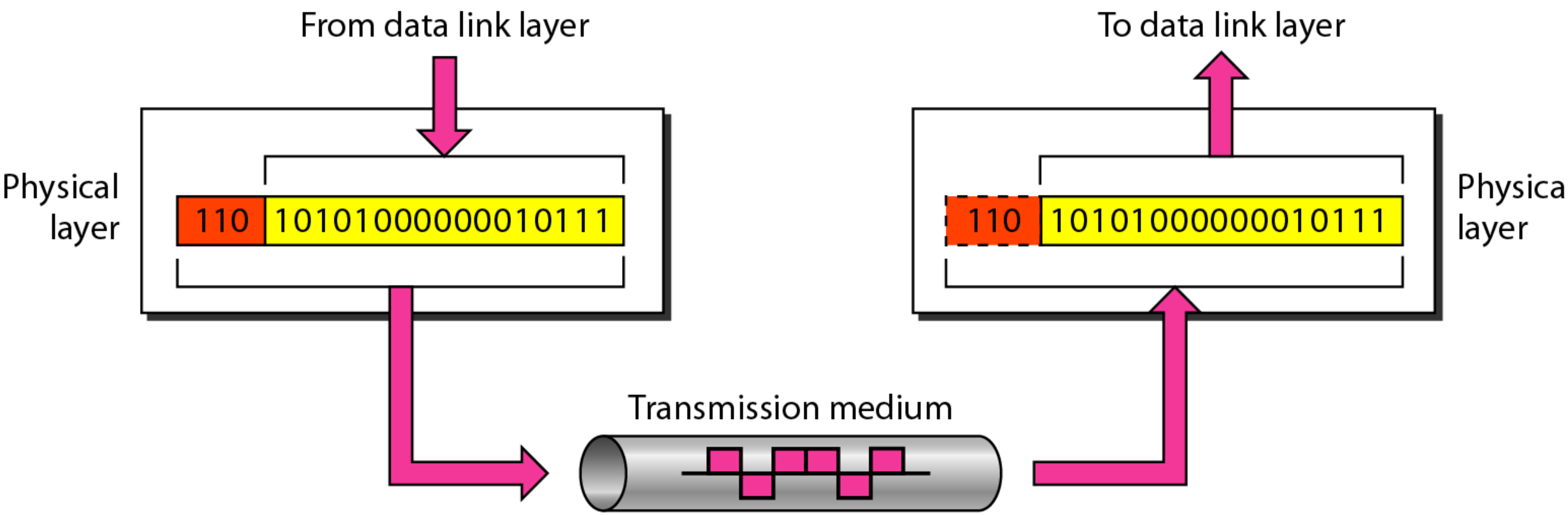


Layers in the OSI model

In this section we briefly describe the functions of each layer in the OSI model

- Physical Layer
  Data Link Layer
- Network Layer
- Transport Layer
- Session Layer
- Presentation Layer
- Application Layer

Physical Layer



Physical Layer (ctd)

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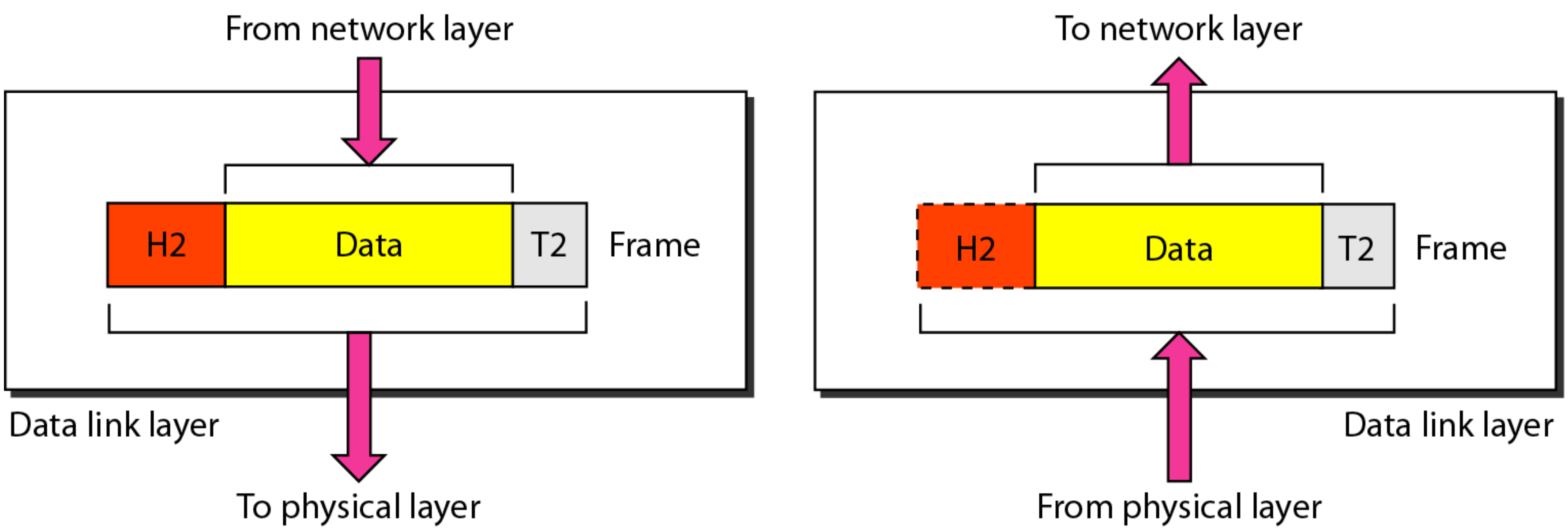
- The physical layer is responsible for movements of individual bits from one hop (node) to the next.
- Defines physical medium and interfaces
- Determines how bits are represented
- Controls transmission rate & bit synchronization
- Controls transmission mode: simplex, half-duplex, & full duplex
- PDU: Bits
- Devices: hubs, cables, connectors, etc…

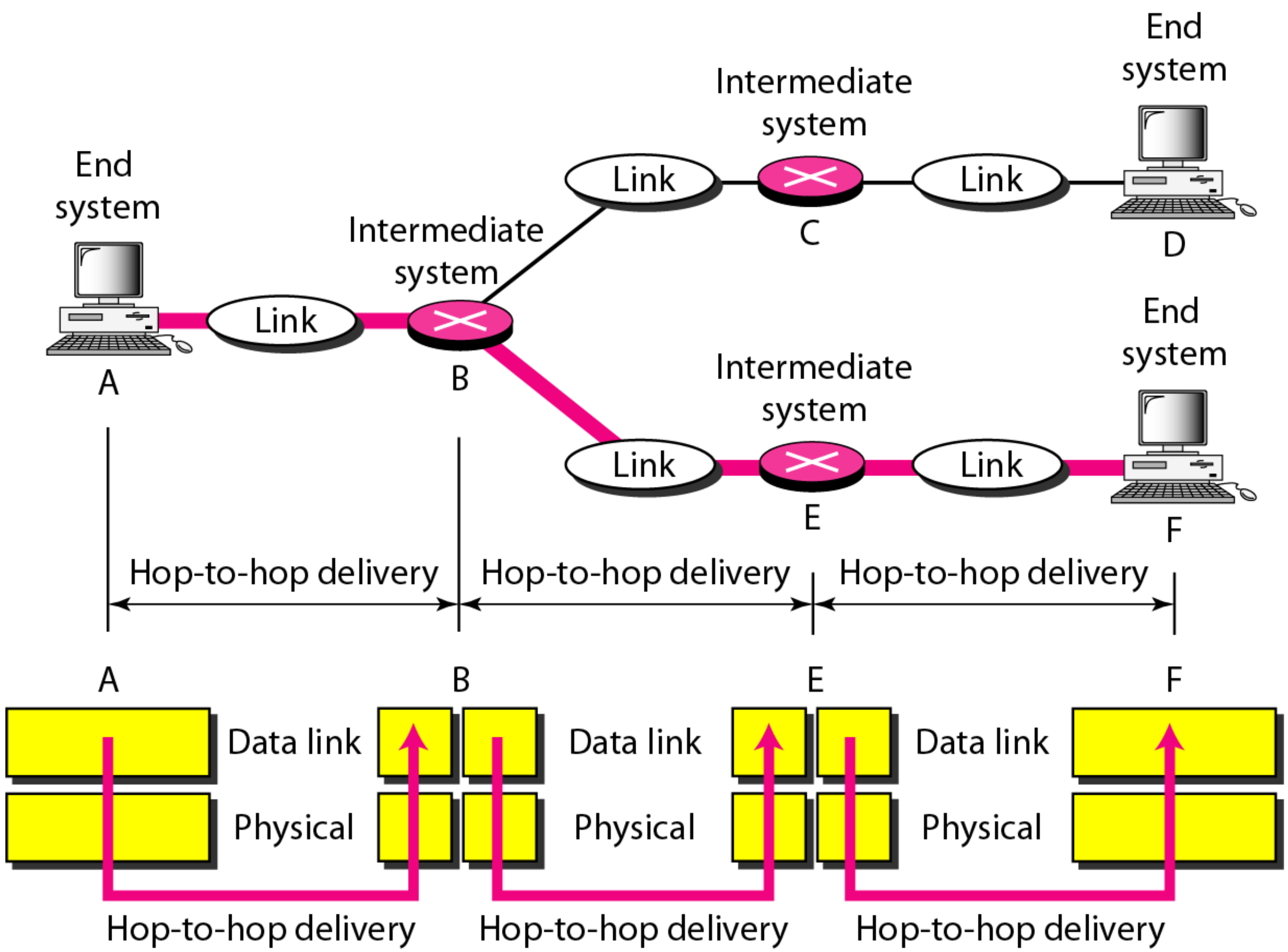
Data Link Layer



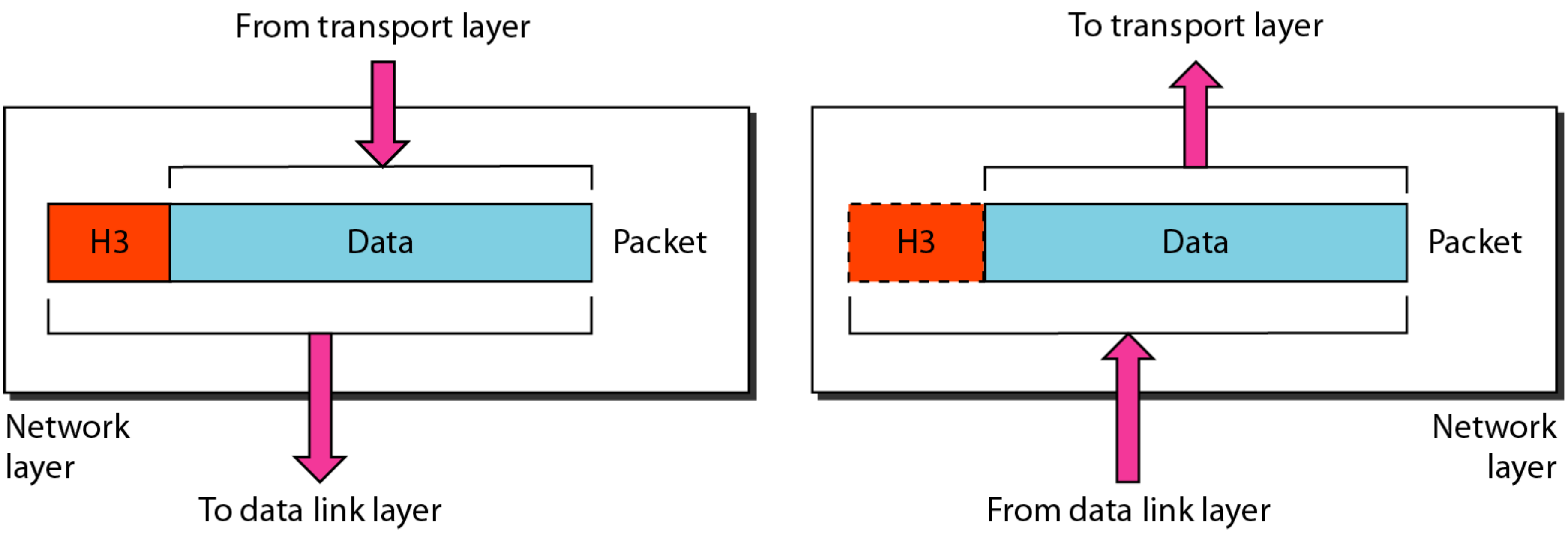
Data Link Layer (ctd)

- The data link layer is responsible for moving frames from one hop (node) to the next.
- PDU: Frames
- Keeps Link alive & provides connection for upper layer protocols
- Based on physical (flat) address space
- Physical addresses are fixed and don't change when the node is moved
- Medium/media access control
- Flow control and error detection/correction at the frame level. Think collisions…
- Topology
- Ex: Ethernet, Token Ring, ISDN
- Sublayers: MAC (framing, addressing, & MAC) & LLC (logical link control – gives error control & flow control)
- Devices: switches, bridges, NIC's

Hop-to-hop delivery



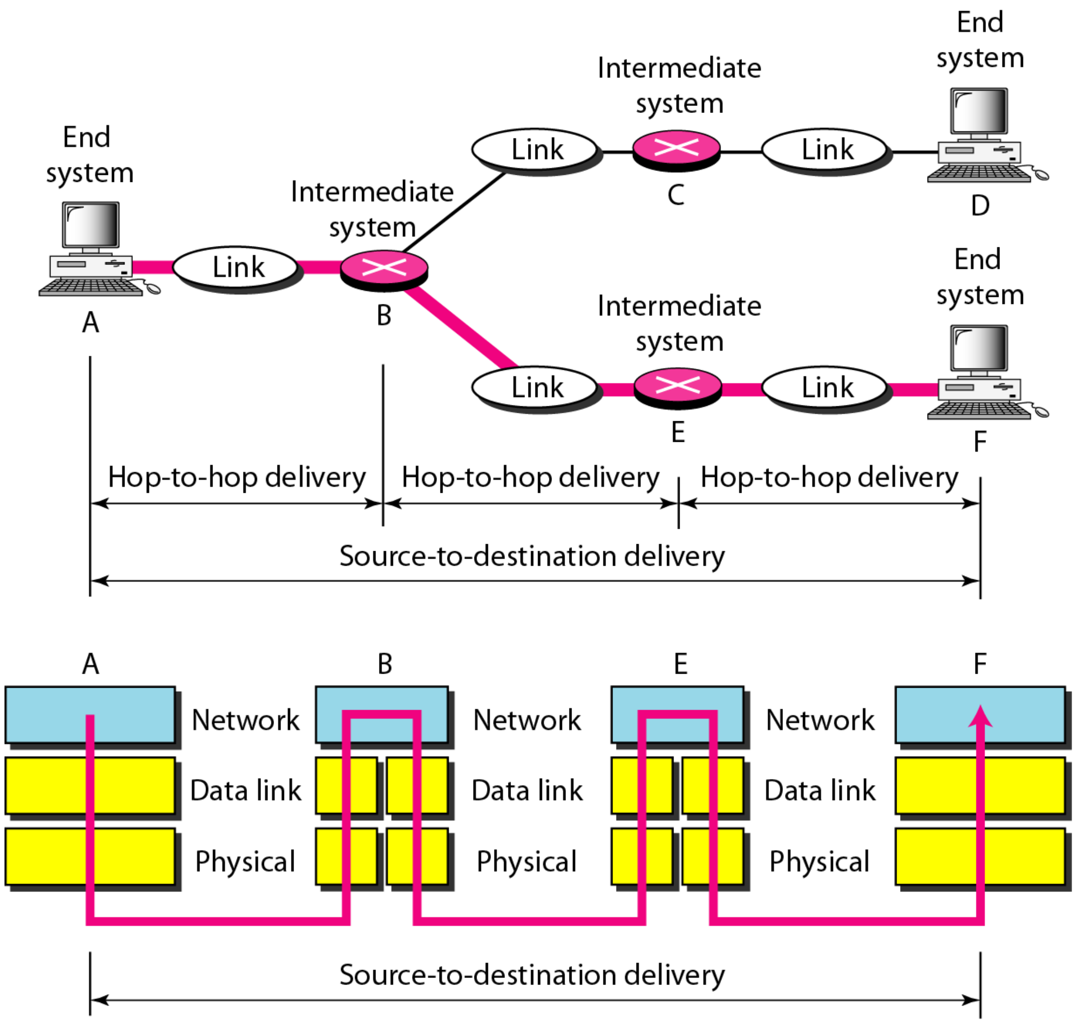
Network Layer



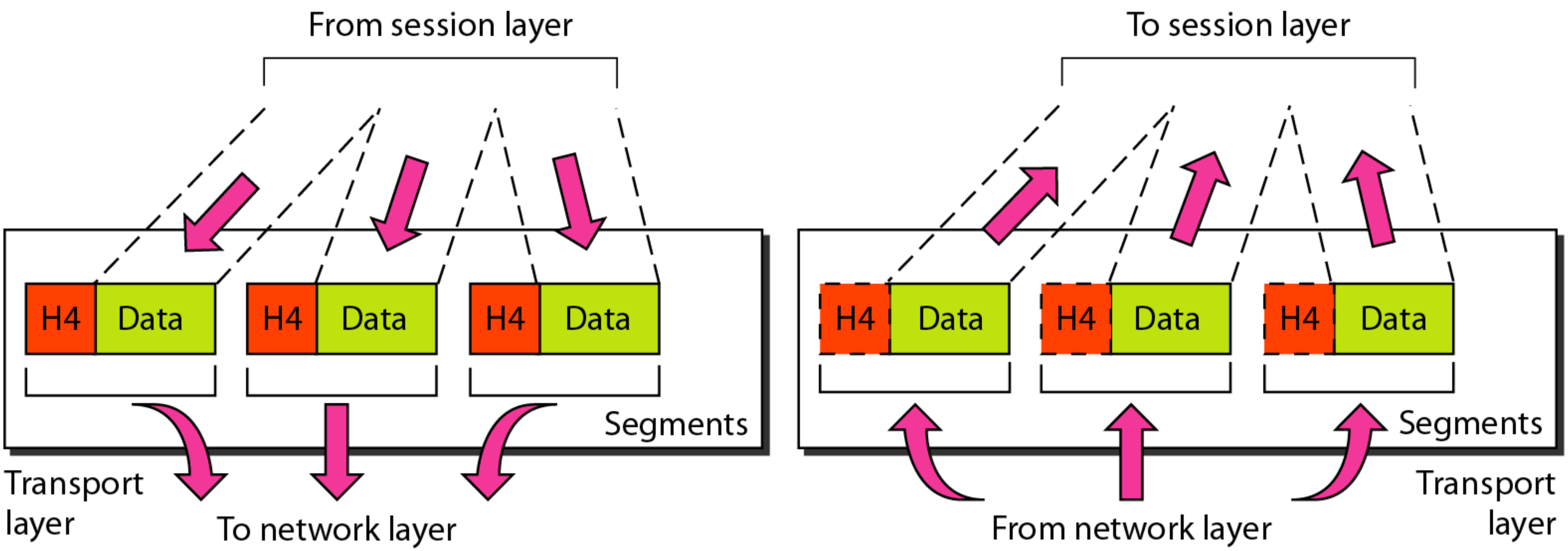
Network Layer (ctd)

- The network layer is responsible for the delivery of individual packets from the source host to the destination host
- PDU: Packet
- End to end delivery of packets
- Creates logical paths
- Path determination (routing)
- Hides the lower layers making things hardware independent
- Uses logical hierarchical addresses
- Logical hierarchical addresses do change when a node is moved to a new subnet
- Devices: routers, firewalls

Source-to-destination delivery



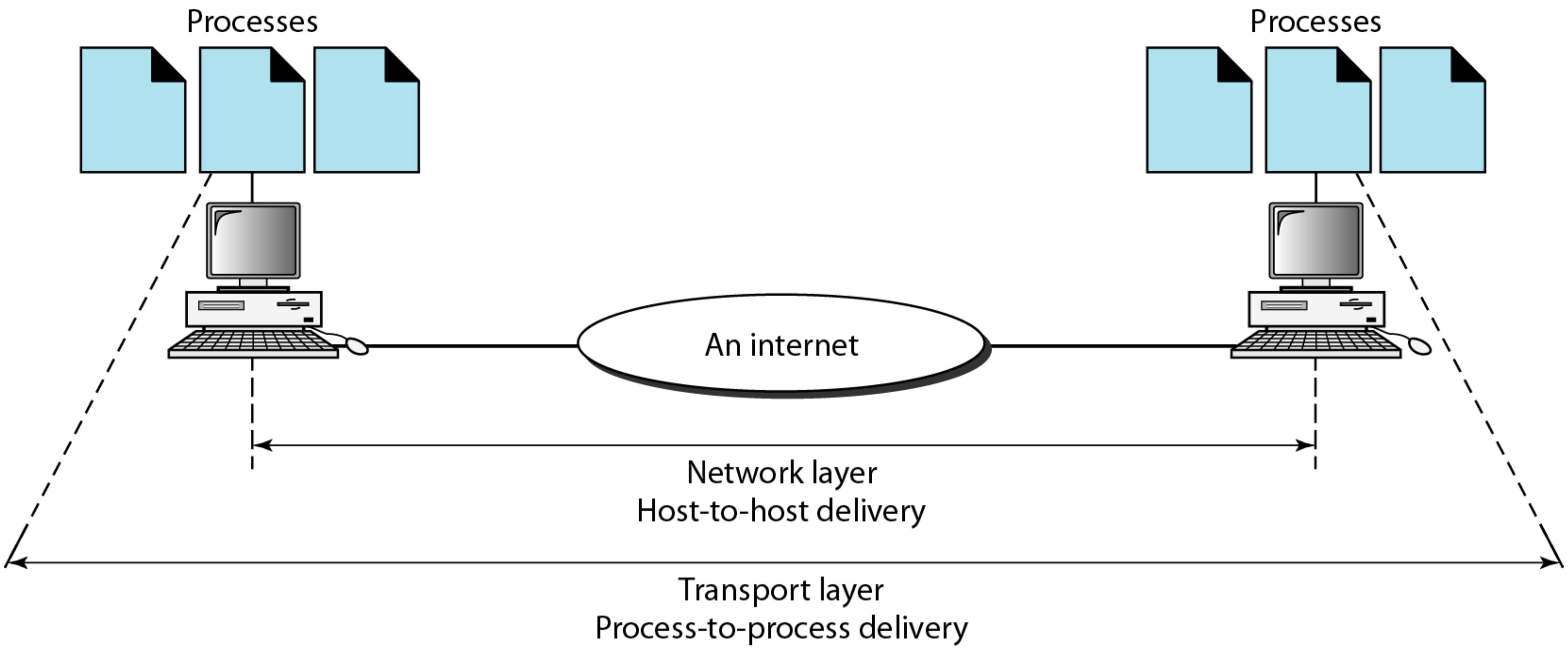
Transport Layer



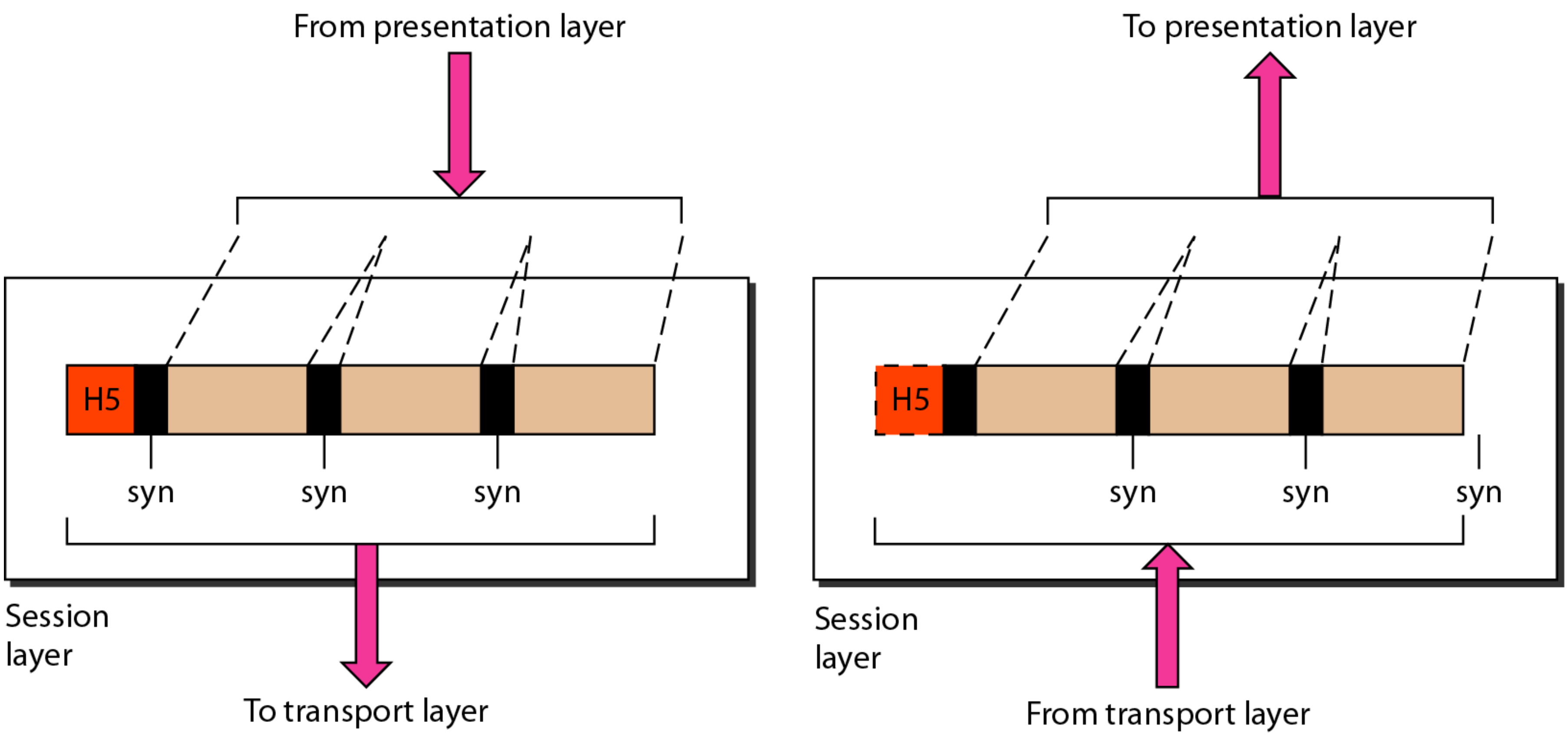
Transport Layer (ctd)

- The transport layer is responsible for the delivery of a message from one process to another
- PDU: Segment
- Service Point Address (more often called a port) used to track multiple sessions between the same systems. SPA's are used to allow a node to offer more than one service (i.e. it could offer both mail and web services)
- This layer is why you have to specify TCP or UDP when dealing with TCP/IP
- Must reassemble segments into data using sequence numbers
- Can use either connectionless or connection oriented sessions
- Connectionless sessions rely on upper layer protocols for error control and are often used for faster less reliable links
- Ex: UDP (used by things like NFS & DNS)
- Connection oriented sessions require the sender to first request a connection, the receiver to acknowledge the connection, and that they negotiate how much data can be sent/received before its reception is acknowledged
- Uses acknowledgements & retransmission for error correction
- Example: TCP (used by things like telnet, http)

Reliable process-to-process delivery of a message



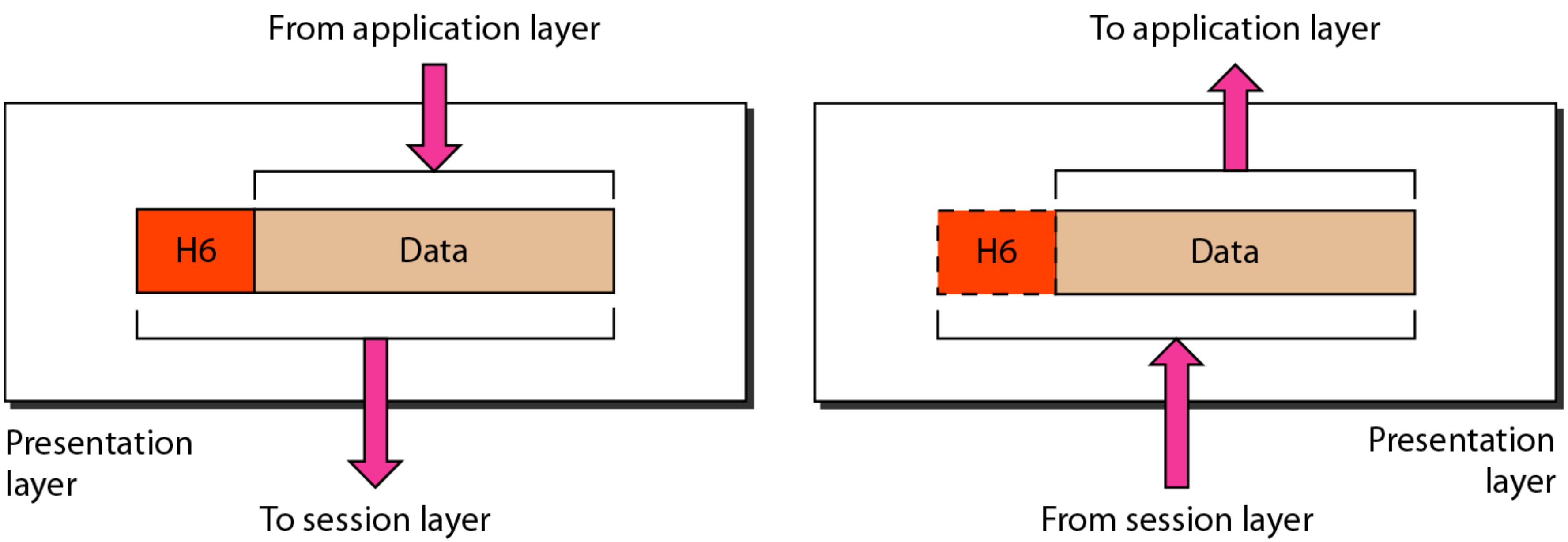
Session layer



Session layer (ctd)

- The session layer is responsible for dialog control and synchronization
- PDU: Data (from here on up)
- Sometimes called the dialog controller, this layer establishes, maintains, and terminates sessions between applications
- Sets duplex between applications
- Defines checkpoints for acknowledgements during sessions between applications
- Provides atomization – Multiple connections can be treated as one virtual session. If one fails or is terminated, all should be terminated.
- Identifies raw data as either application data or session control information
- Uses fields provided by layers 3 & 4 to track dialogs between applications / services
- Provides translations for naming services
- Ex: RPC, X-Windows, LDAP, NFS

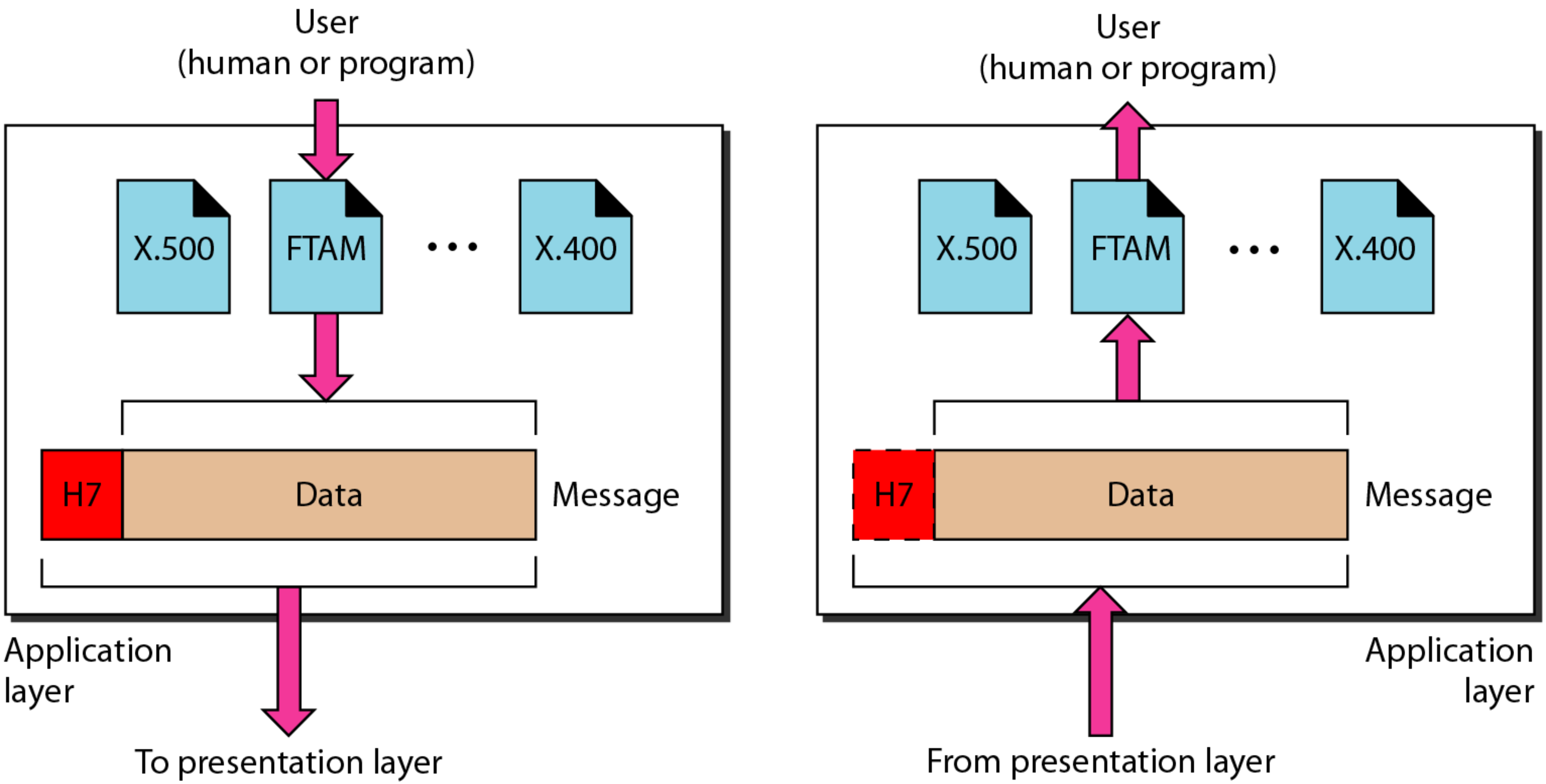
Presentation layer



Presentation layer (ctd)

- The presentation layer is responsible for translation, compression, and encryption
- Data formatting, translation, encryption, and compression
- Ex: ASCII, EBCDIC, HTML, JPEG

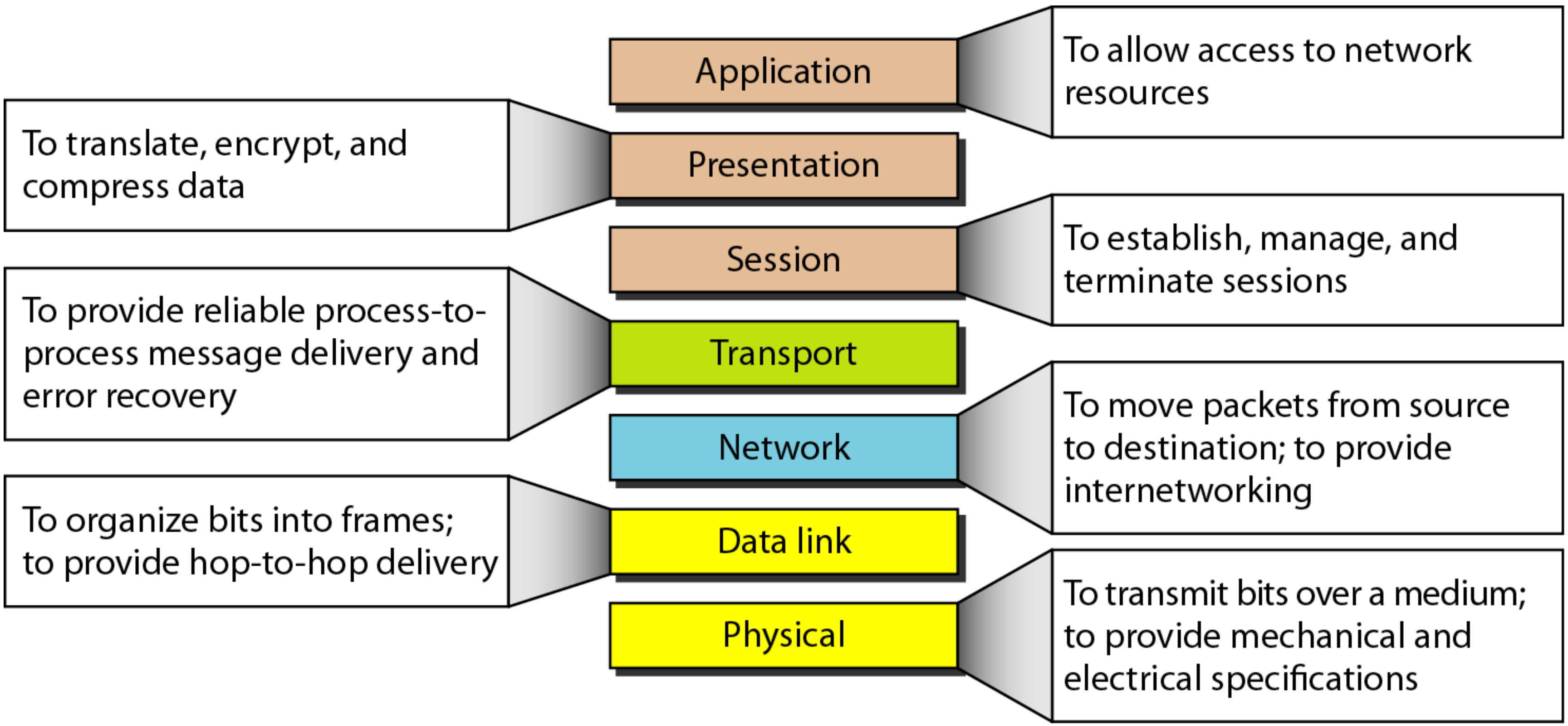
Application layer



Application layer (ctd)

- The application layer is responsible for providing services to the user
- Provides communication services to applications
- Ex: HTTP, FTP, SMTP

Summary of layers

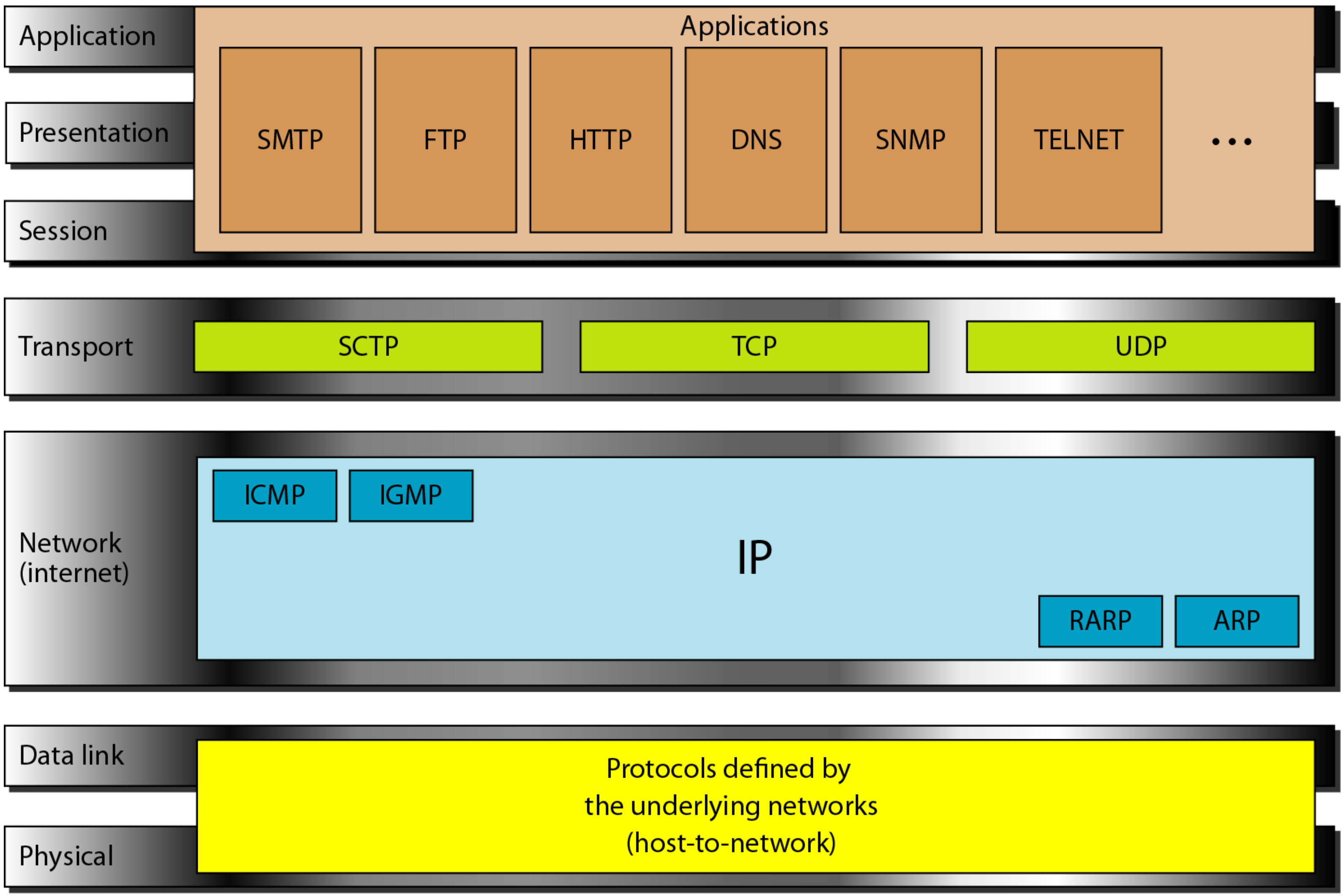


TCP/IP Protocol Suite

The layers in the TCP/IP protocol suite do not exactly match those in the OSI model. The original TCP/IP protocol suite was defined as having four layers: host-to-network, internet, transport, and application. However, when TCP/IP is compared to OSI, we can say that the TCP/IP protocol suite is made of five layers:

- Application
- Transport
- Network
- Data link
- Physical

TCP/IP and OSI model



TCP/IP and OSI model

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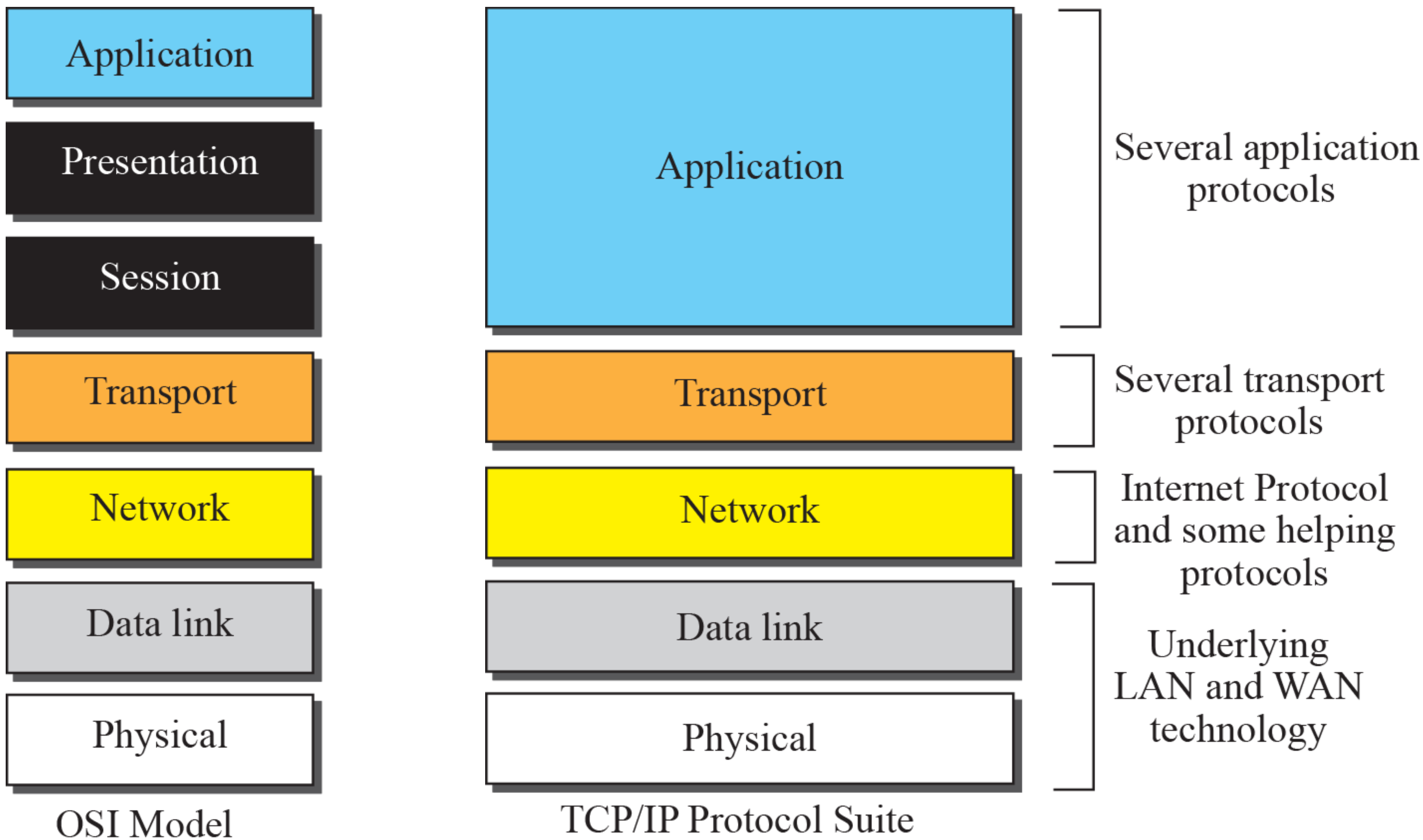
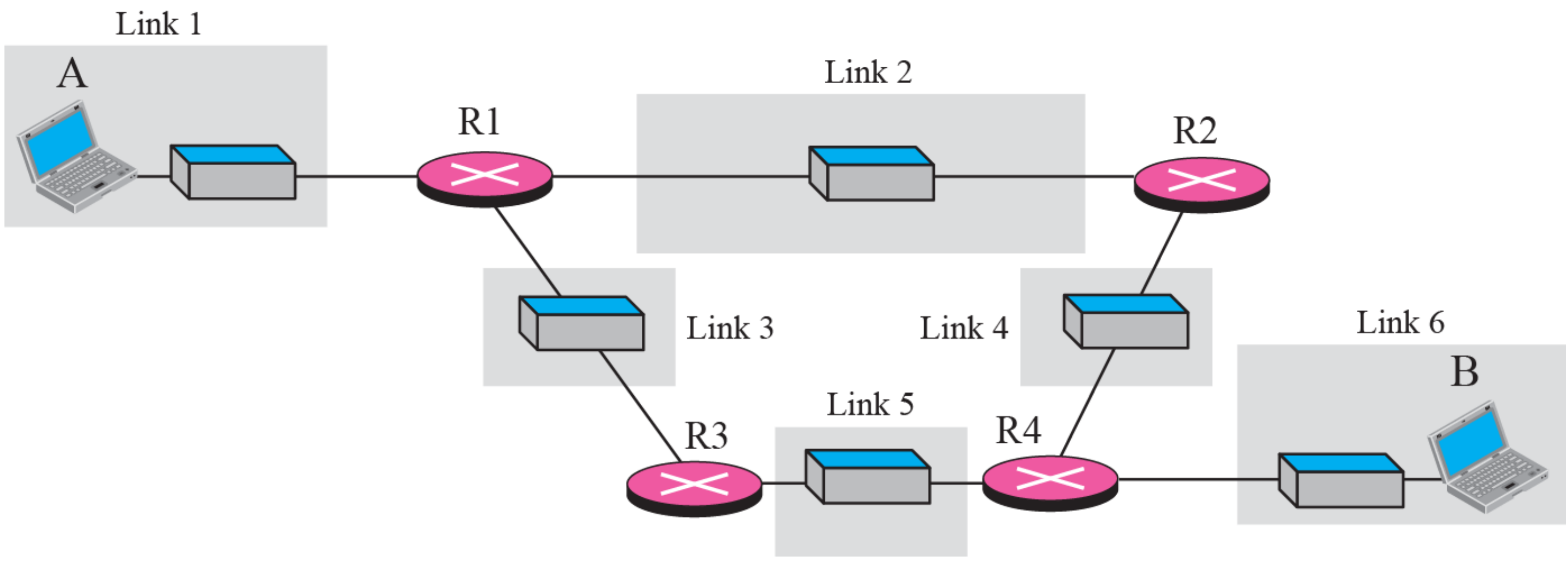
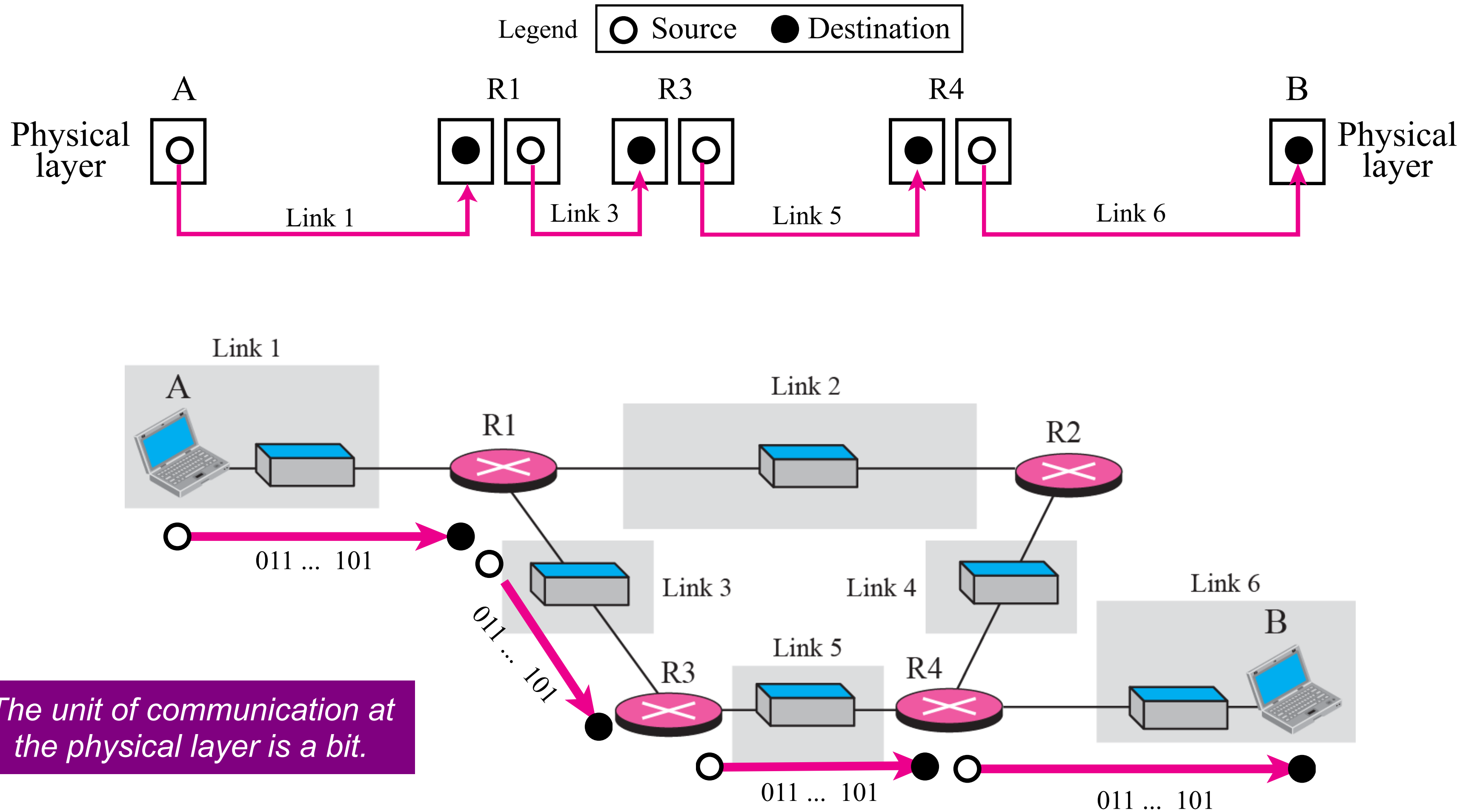


A private internet

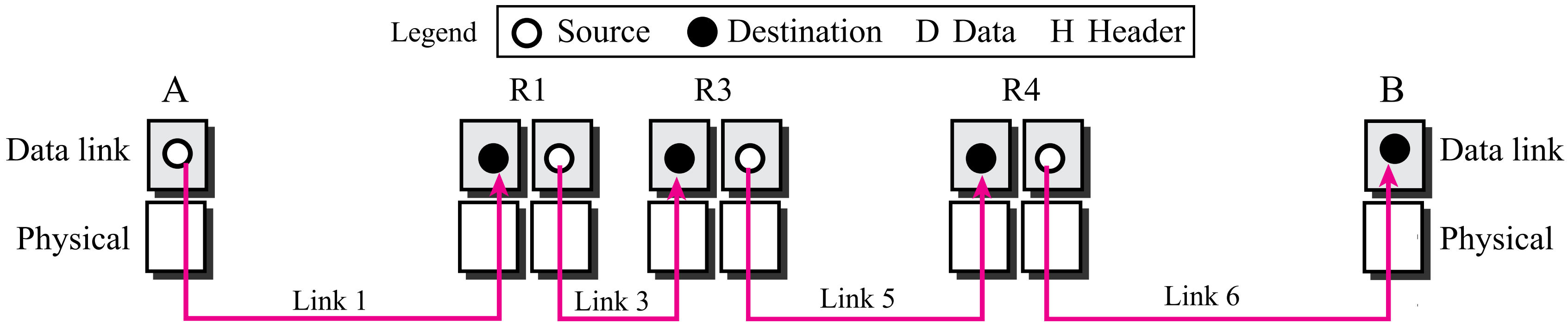


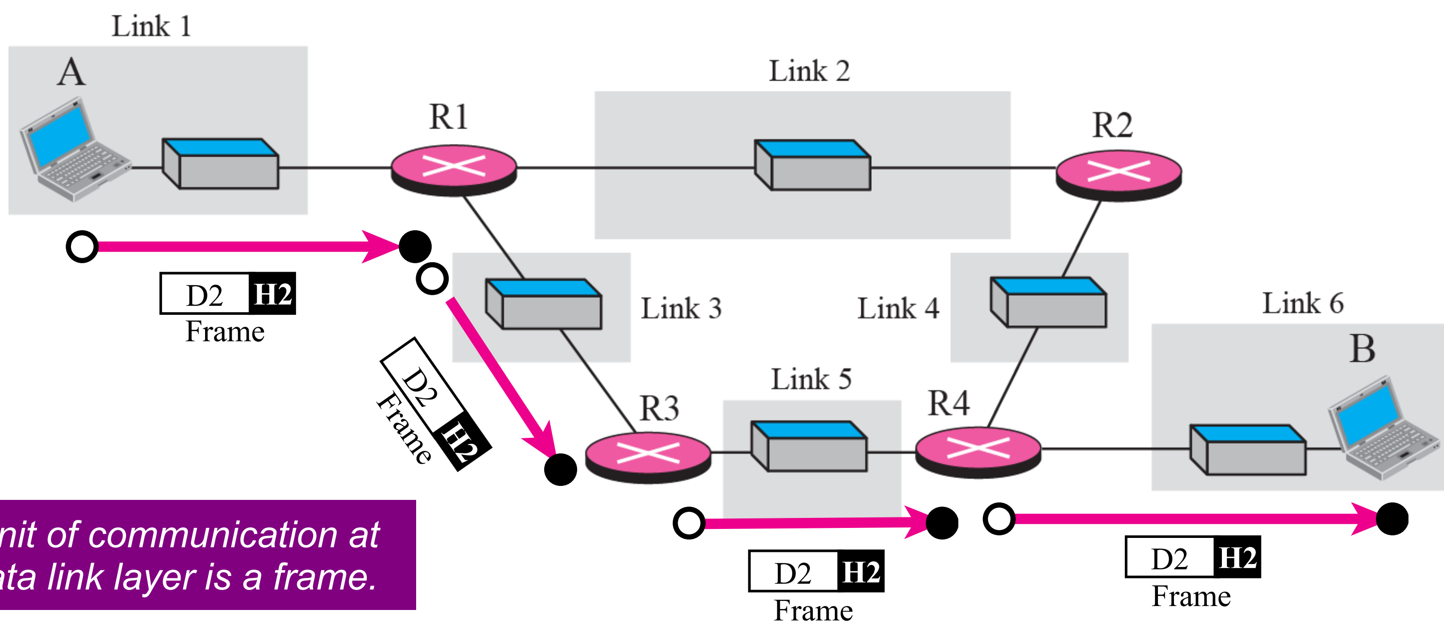
Communication at the physical layer



The unit of communication at the physical layer is a bit.

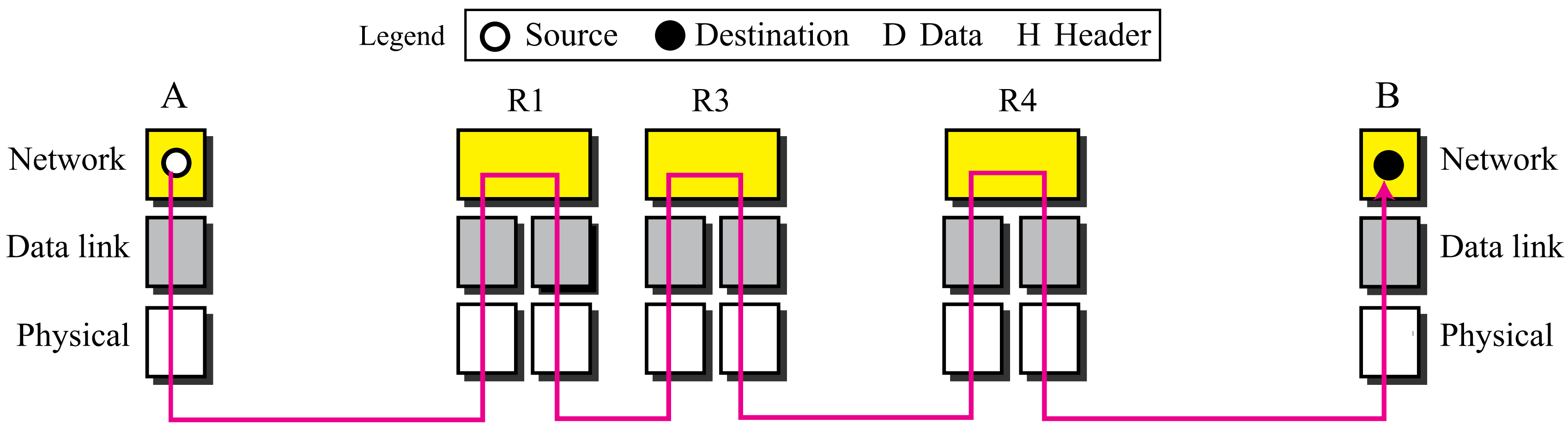
Communication at the data link layer

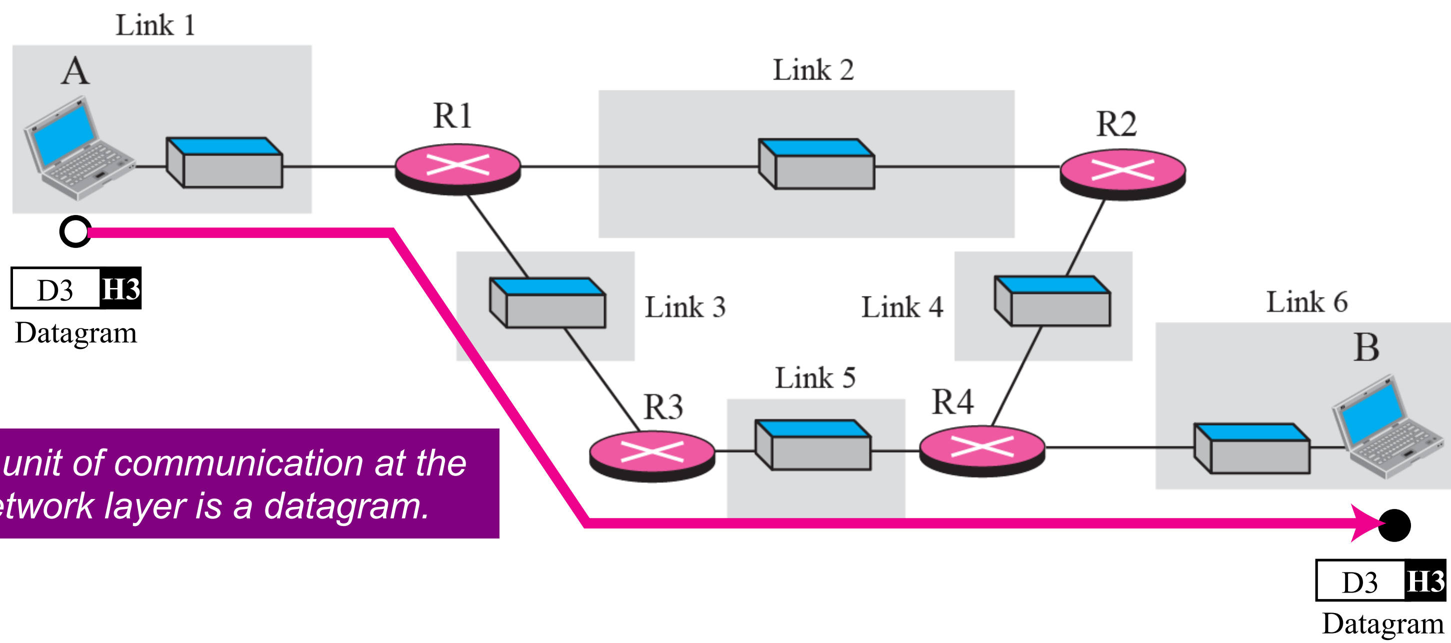




The unit of communication at the data link layer is a frame.

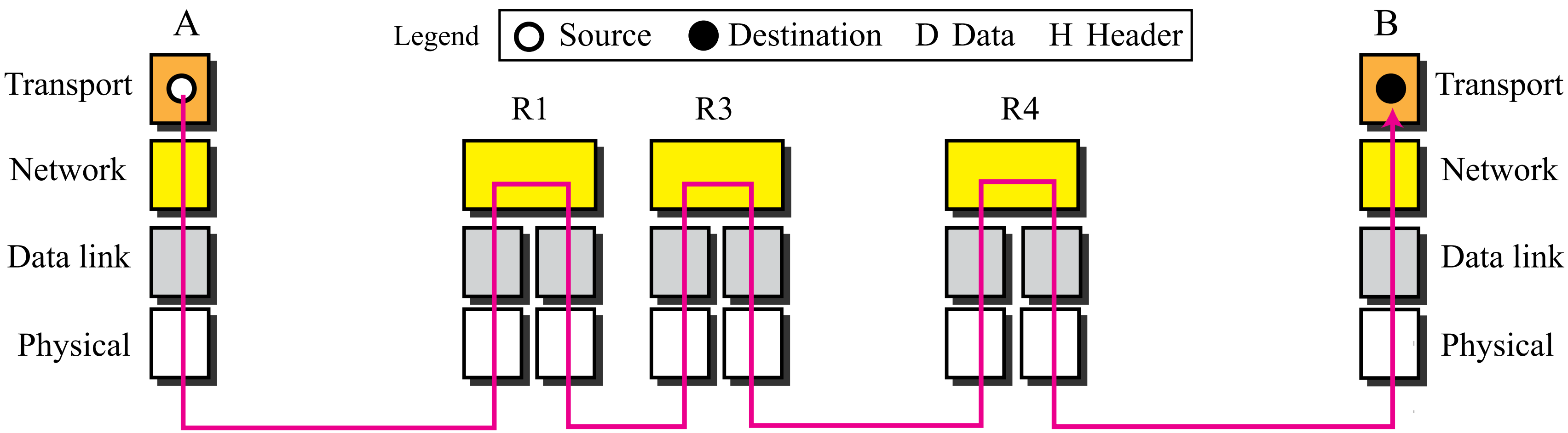
Communication at the network layer

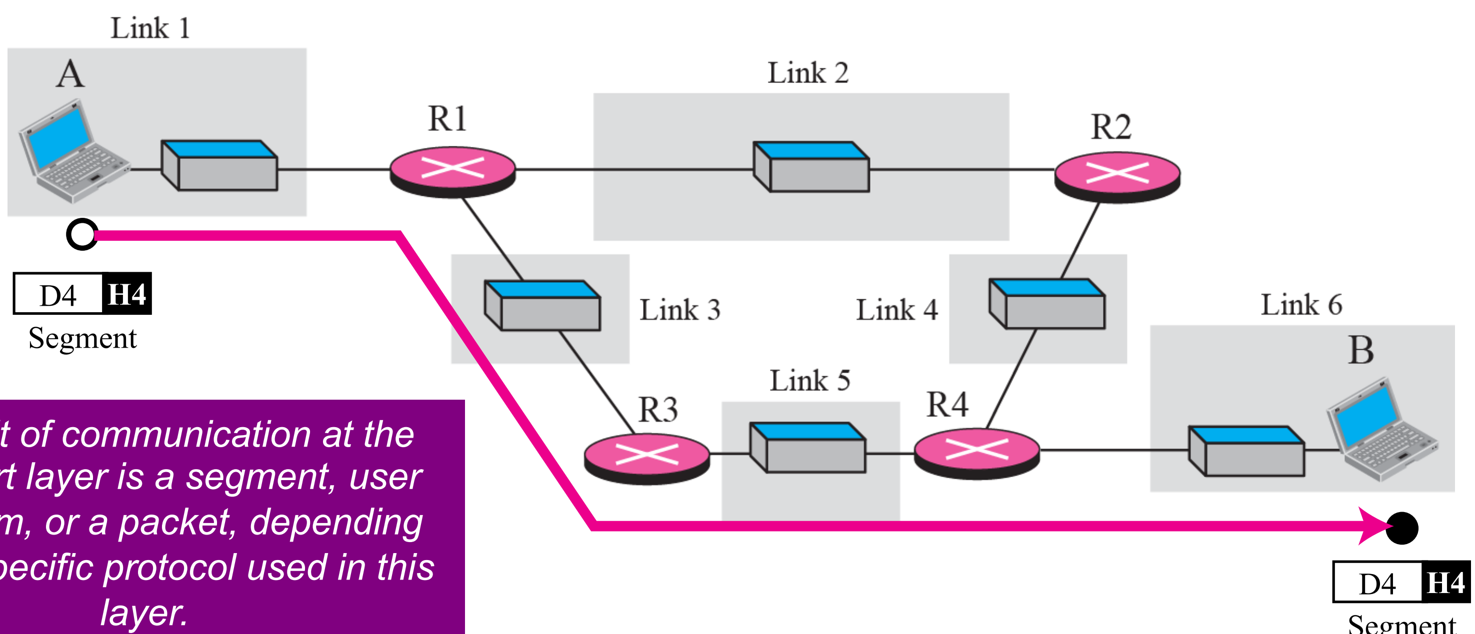




The unit of communication at the network layer is a datagram.

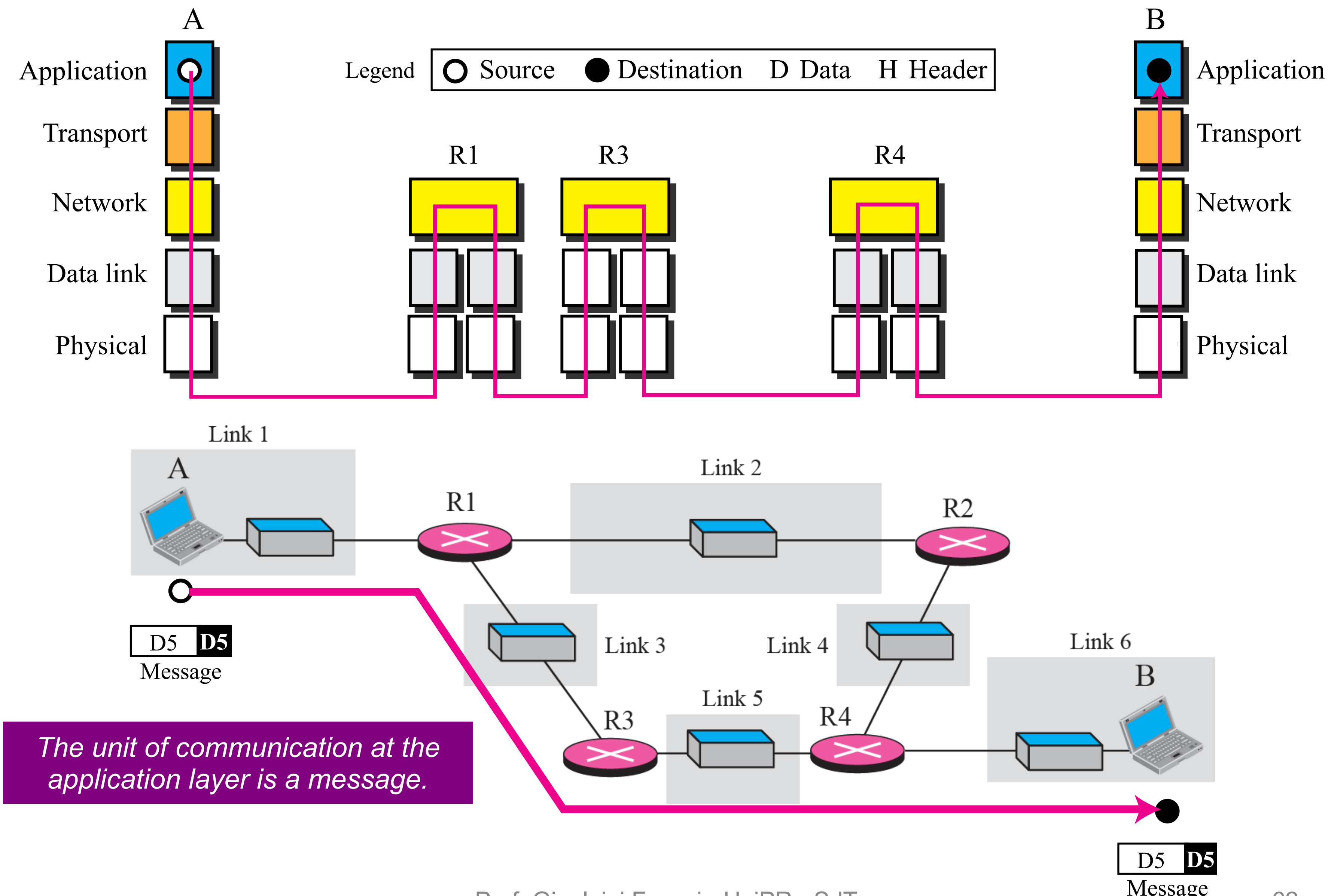
Communication at transport layer





The unit of communication at the transport layer is a segment, user datagram, or a packet, depending on the specific protocol used in this layer.

Communication at application layer



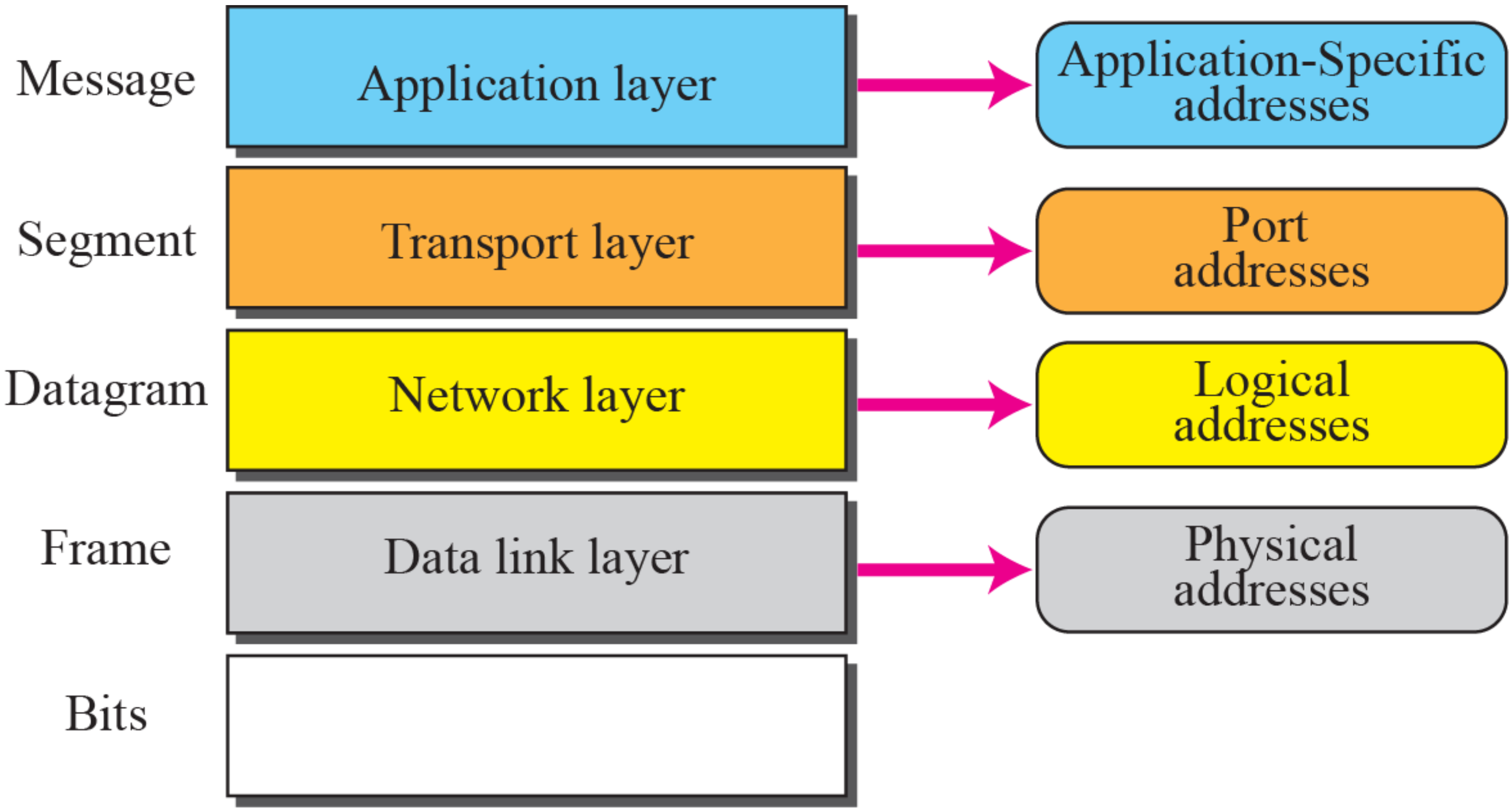
The unit of communication at the application layer is a message.

Addressing

Four levels of addresses are used in an internet employing the TCP/IP protocols: physical address, logical address, port address, and application-specific address. Each address is related to a one layer in the TCP/IP architecture, as shown in Figure 2.15.

- ✓ Physical Addresses
- ✓ Logical Addresses
- ✓ Port Addresses
- ✓ Application-Specific Addresses

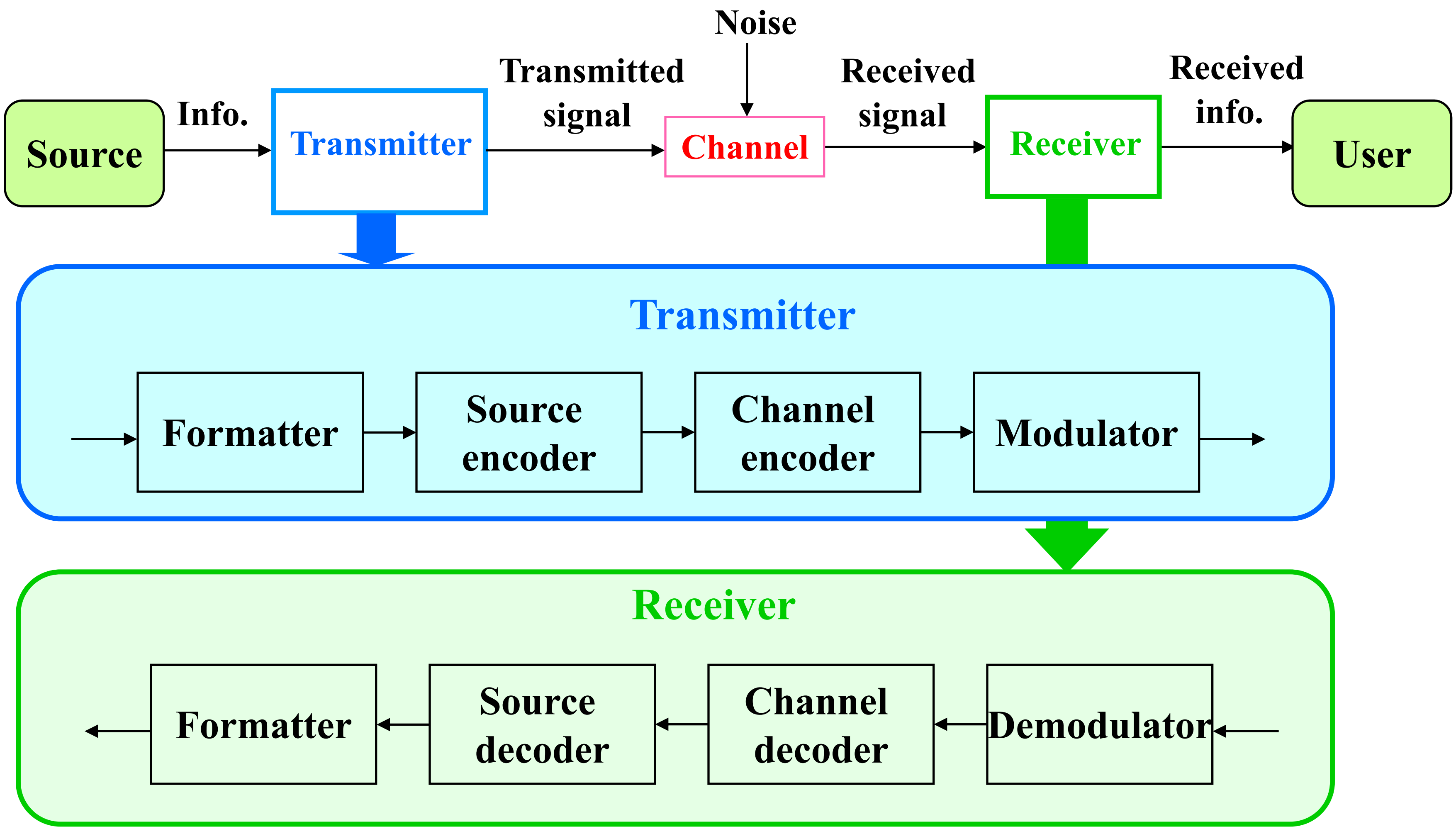
Addresses in the TCP/IP protocol suite



Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- **Physical layer: modulation**
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - WiFi (CSMA/CA)
- Personal Area Networks
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

General Structure of a Communication System



Channel Capacity

- Channel Capacity (C)
  - the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions
- Data rate (bps)
  - rate at which data can be communicated , impairments, such as noise, limit data rate that can be achieved
- Bandwidth (B)
  - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise (N)
  - impairments on the communications path
- Error rate - rate at which errors occur (BER)
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

Reasons for choosing encoding techniques

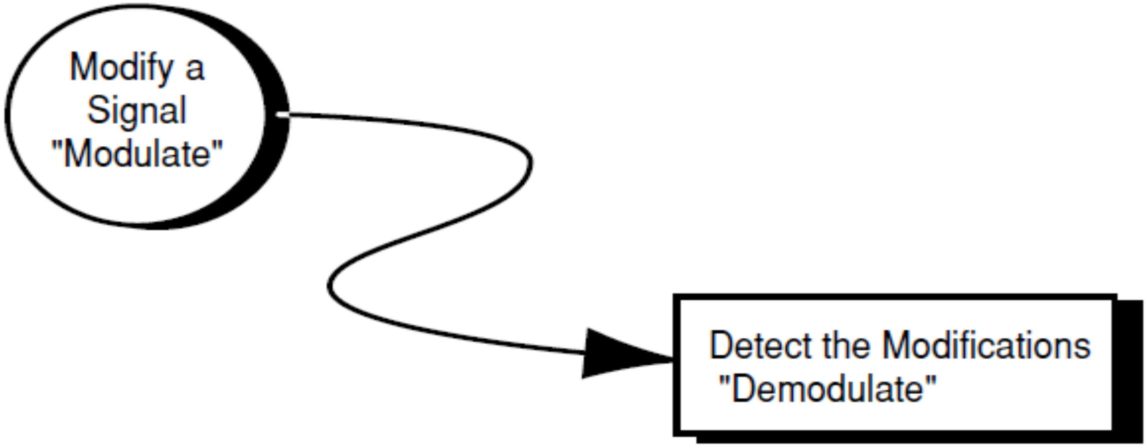
- Digital data, digital signal
  - Equipment less complex and expensive than digital-to-analog modulation equipment
- Analog data, digital signal
  - Permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - E.g., unguided media (air)
- Analog data, analog signal
  - Analog data in electrical form can be transmitted easily and cheaply
  - E.g., AM Radio

What is modulation ?

- Modulation = Adding information to a carrier signal

$$x(t) = A\cos(2\pi f t + \Phi)$$

  - A – amplitude
  - f – frequency
  - Φ – phase (initial angle of the sinusoidal function at its origin
- The sine wave on which the characteristics of the information signal are modulated is called a carrier signal



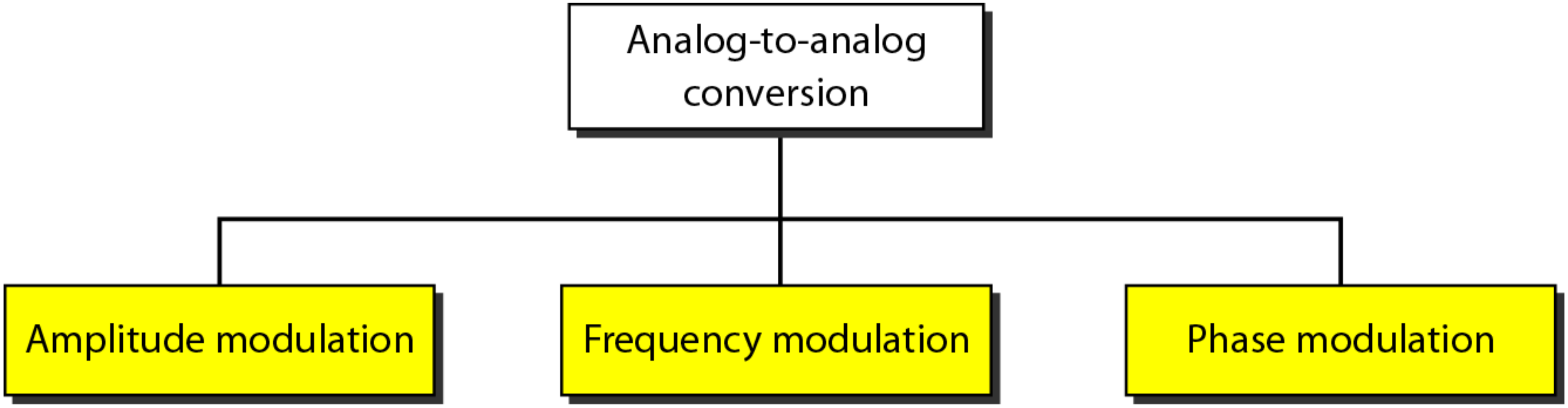
Any reliably detectable change in signal characteristics can carry information

Analog(-to-analog) modulation

Analog-to-analog conversion is the representation of analog information by an analog signal. One may ask why we need to modulate an analog signal; it is already analog. Modulation is needed if the medium is bandpass in nature or if only a bandpass channel is available to us.

- Amplitude Modulation
- Frequency Modulation
- Phase Modulation

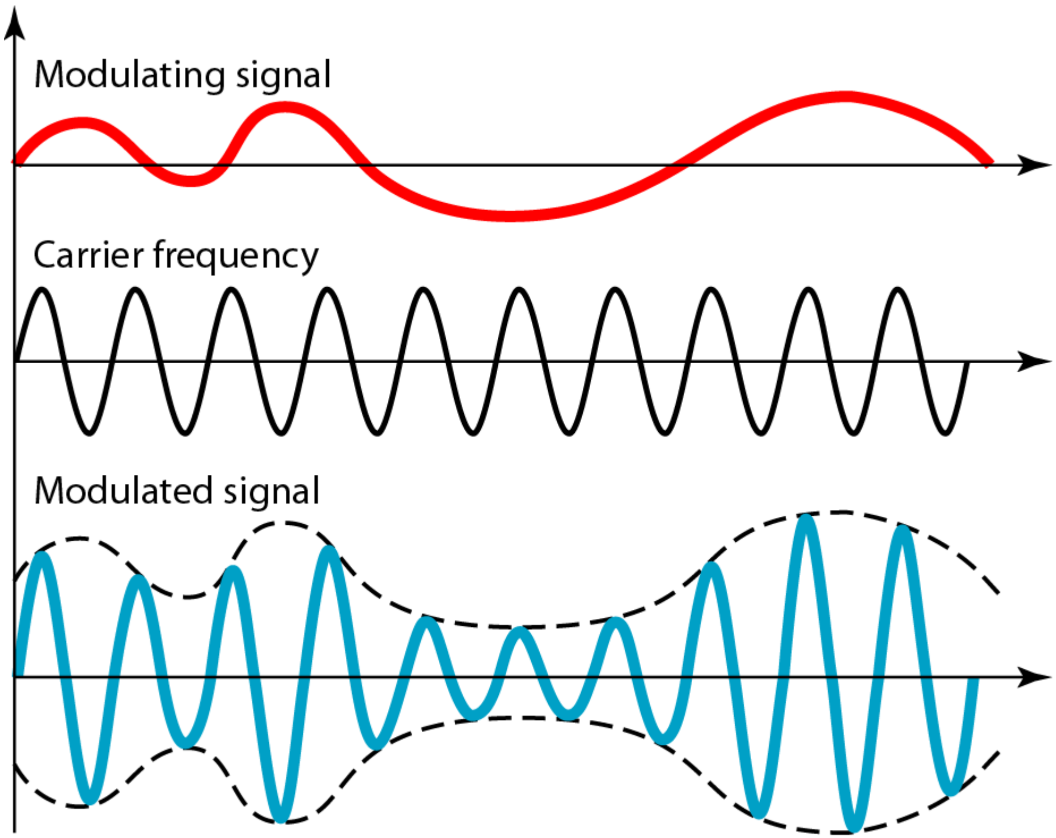
Types of analog-to-analog modulation

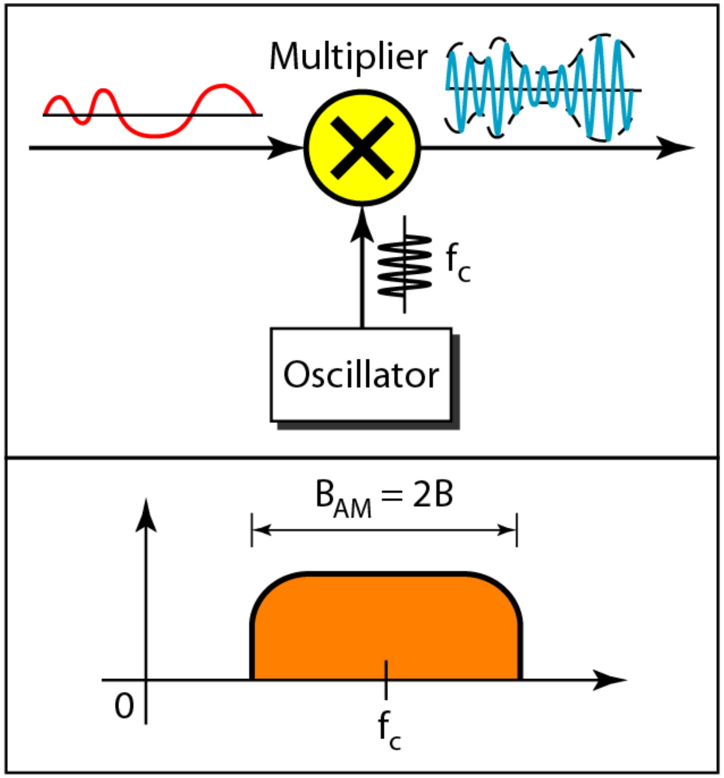


Amplitude Modulation (AM)

- A carrier signal is modulated only in amplitude value
- The modulating signal is the envelope of the carrier
- The required bandwidth is 2B, where B is the bandwidth of the modulating signal
- Since on both sides of the carrier freq. f_c, the spectrum is identical, we can discard one half, thus requiring a smaller bandwidth for transmission.

Amplitude Modulation (AM) - ctd





Amplitude Modulation (AM) - ctd

- The total bandwidth required for AM can be determined from the bandwidth of the audio signal: $B_{AM} = 2B$.

$$m(t) \quad \rightarrow \quad \text{information signal}$$

$$A_c \cos[2\pi f_c t] \quad \rightarrow \quad \text{carrier}$$

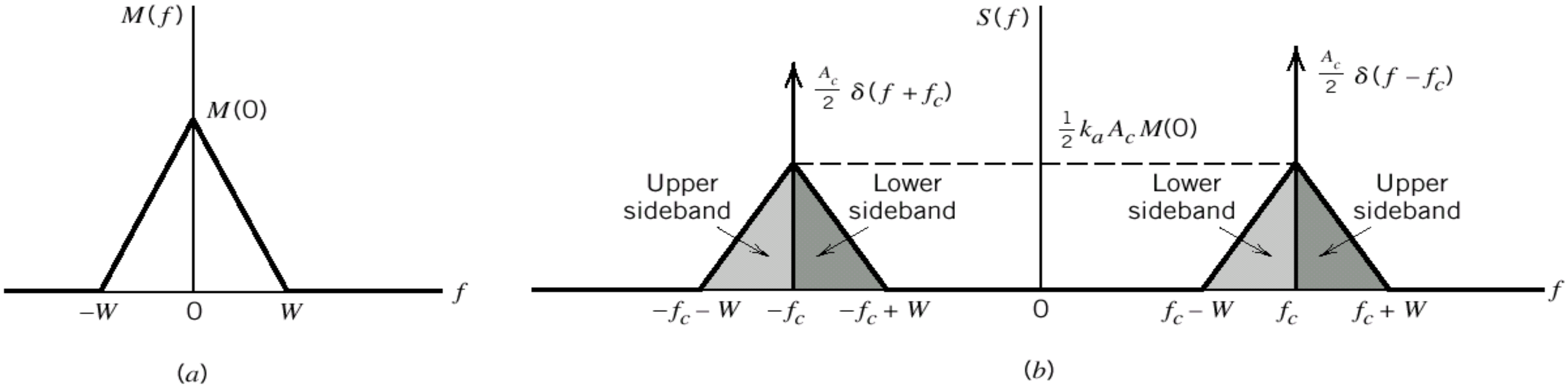
$$f_c \quad \rightarrow \quad \text{carrier frequency}$$

$$S_{AM}(t) = A_c [1 + m(t)] \cos[2\pi f_c t] \quad \rightarrow \quad \text{transmitted signal}$$

k_a

Spectrum of AM signal

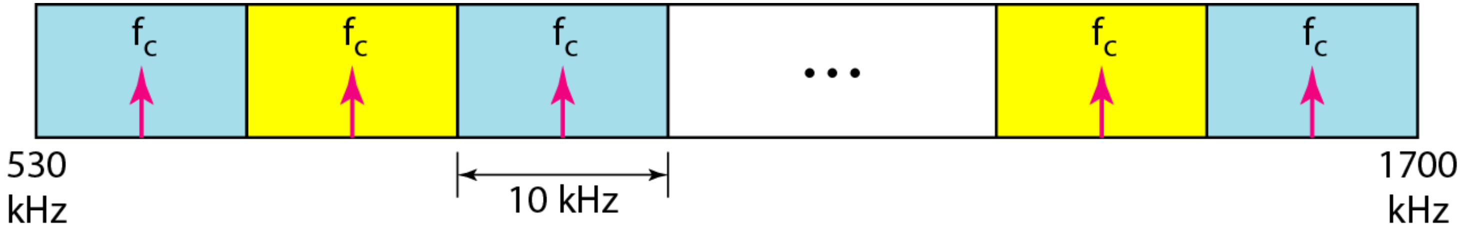
$$S(f)=\frac{A_c}{2}[\delta(f-f_c)+\delta(f+f_c)]+\frac{k_a A_c}{2}[M(f-f_c)+M(f+f_c)]$$



Spectrum of baseband signal.

Spectrum of AM signal.

Band allocation



Frequency Modulation

- Unlike AM, the amplitude of the FM carrier is kept constant (constant envelope) & the *carrier* frequency is varied proportional to the modulating signal $m(t)$:

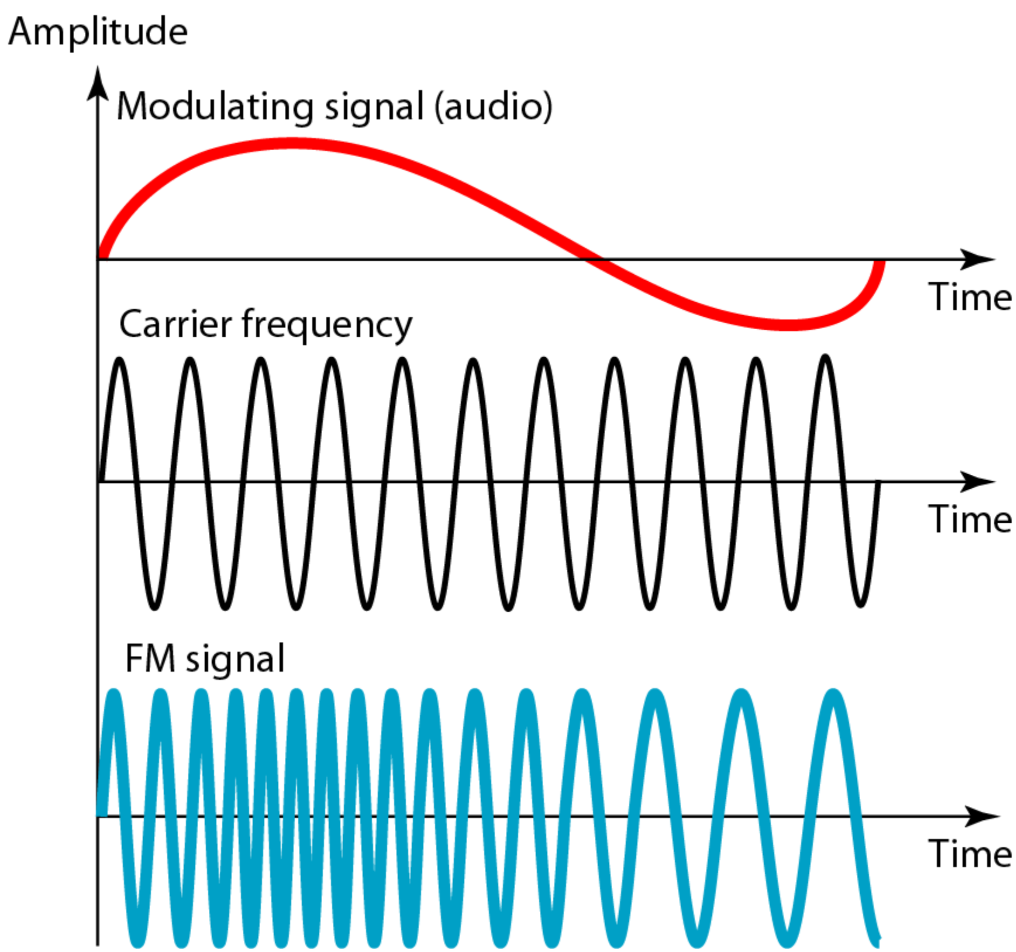
$$S_{FM}(t) = A_c \cos[\theta(t)]$$

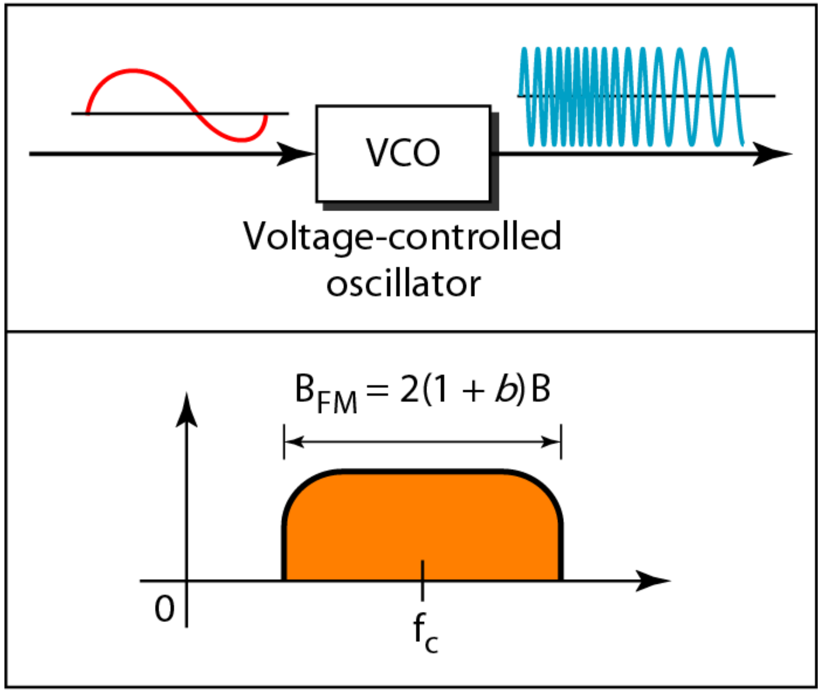
$$\omega(t) = \text{instatantaneous angular frequency}$$

$$= \frac{d\theta}{dt} = 2\pi f_c + 2\pi k_f m(t) \quad \leftarrow \quad \text{desired}$$

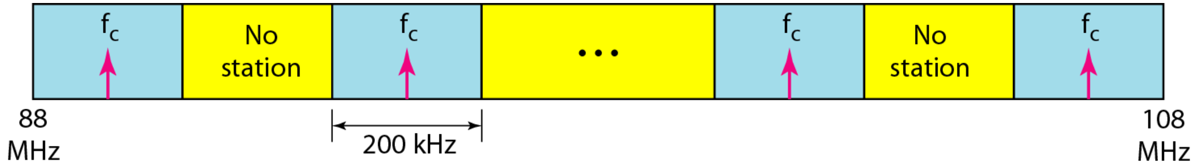
  - f_c plus a deviation of $k_f m(t)$
  - k_f : frequency deviation constant (in Hz/V) - defines amount magnitude of allowable frequency change
- The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{FM} = 2(1 + \beta)B$, where β is usually 4 ($B_{FM} = 10\ B$).

Frequency Modulation (ctd)





Band allocation



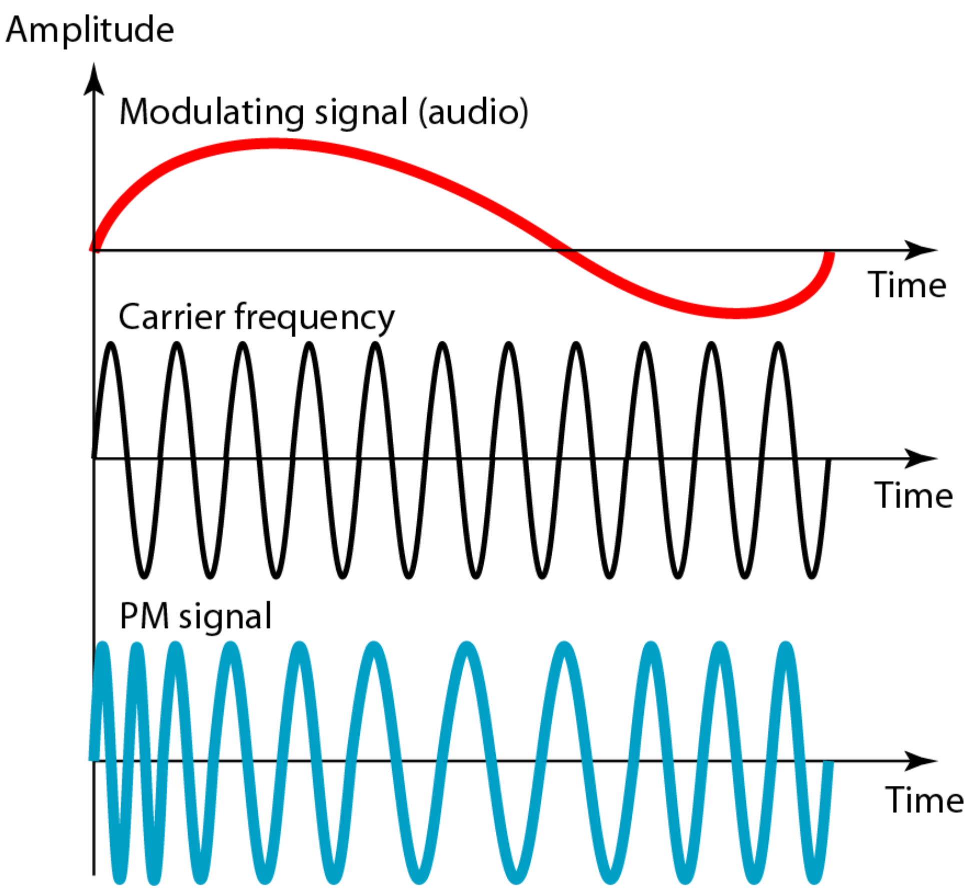
Phase Modulation (PM)

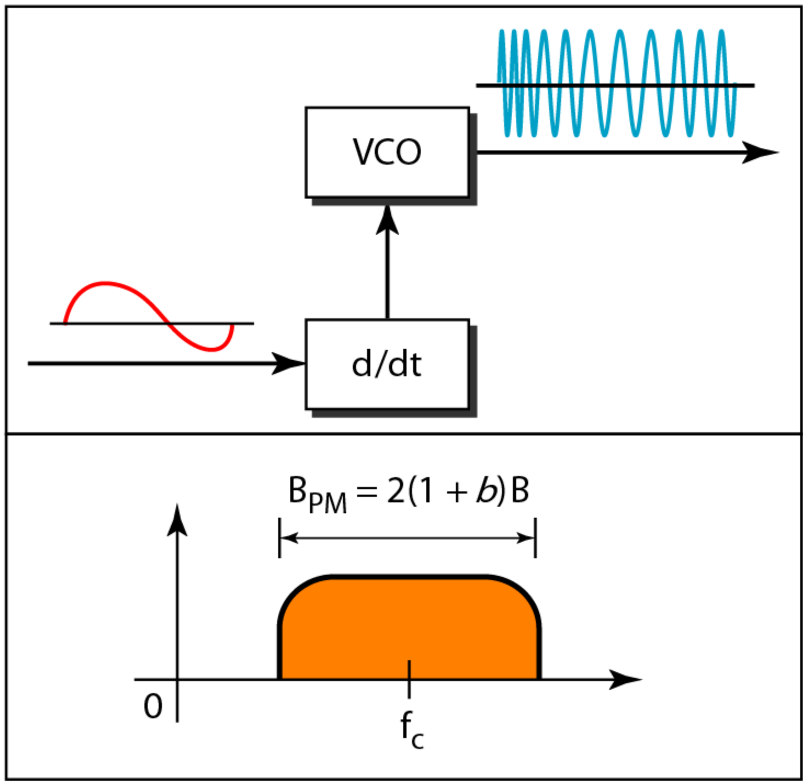
- The modulating signal only changes the phase of the carrier signal.

$$S_{PM}(t) = A_c \cos[2\pi f_c t + k_P m(t)]$$

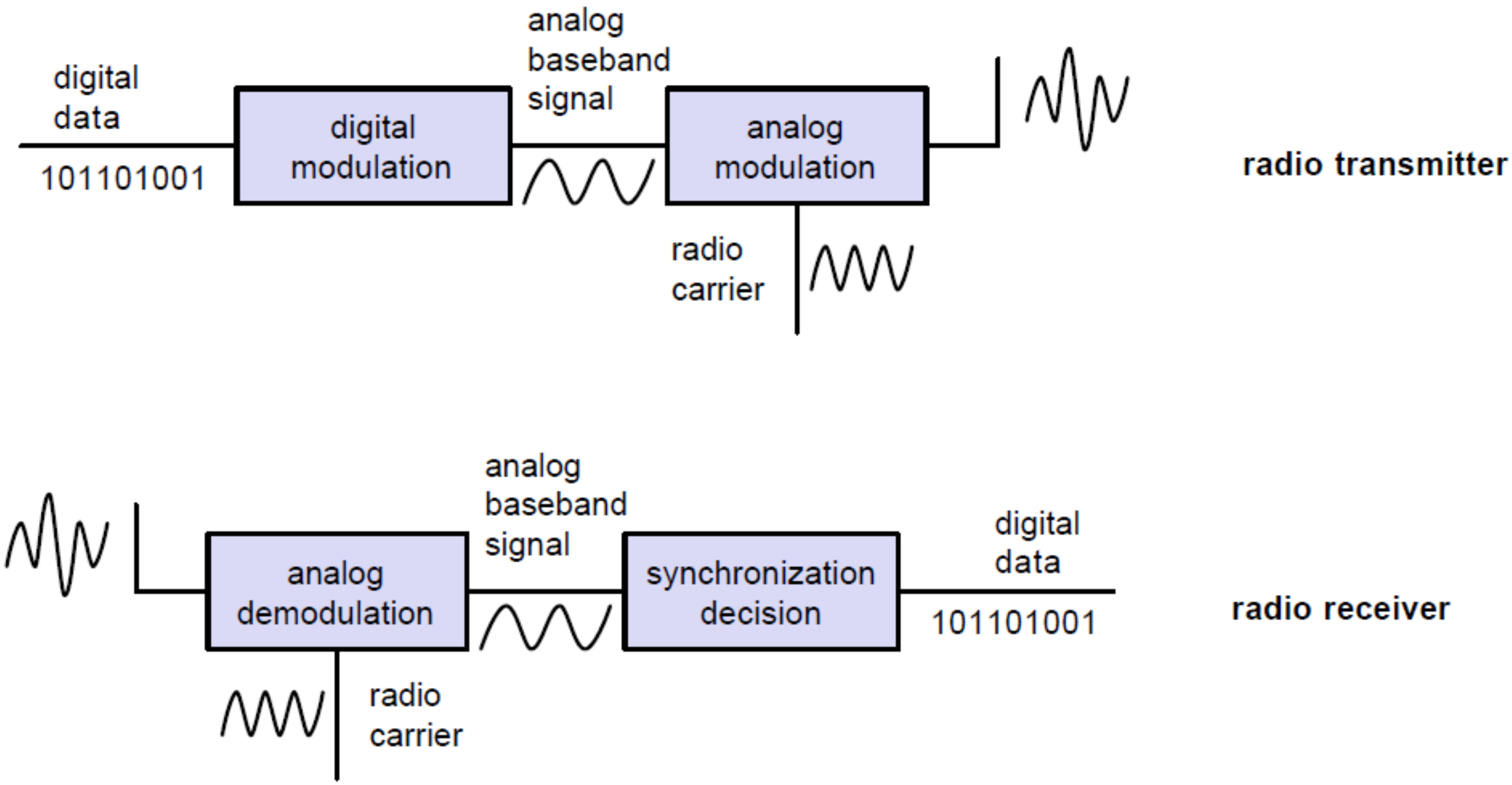
- The phase change manifests itself as a frequency change but the instantaneous frequency change is proportional to the derivative of the amplitude.
- The bandwidth is higher than for AM.
- The total bandwidth required for PM can be determined from the bandwidth and maximum amplitude of the modulating signal: $B_{PM} = 2(1 + \beta)B$, where β is usually 2 ($B_{PM} = 6\ B$).

Phase Modulation (ctd)





Digital modulation and demodulation



If the information is digital, changing parameters is called "keying"

Digital modulation: classification

Digital modulation can be broadly classified as:

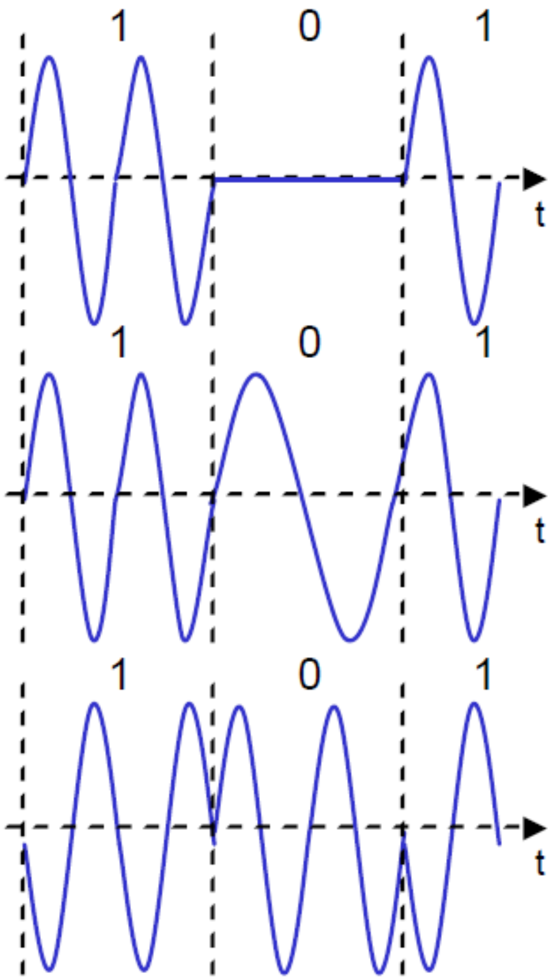
1. Linear (change Amplitude or phase)
2. Non linear modulation techniques (change frequency).

Linear Modulation Techniques:

- The amplitude/phase of the transmitted signal *s(t)* varies linearly with the modulating digital signal *m(t)*.
- They are bandwidth efficient (because the frequency does not change) and, hence, are very attractive for use in wireless communication systems where there is an increasing demand to accommodate more and more users within a limited spectrum.

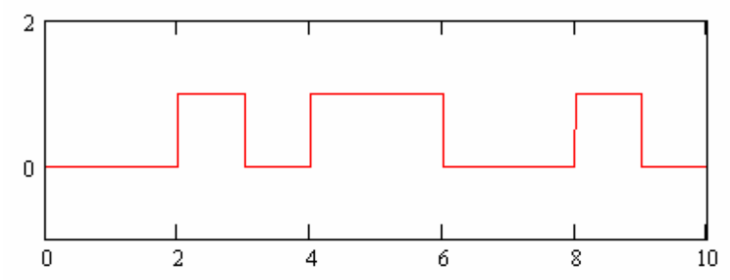
Digital modulation techniques

- Amplitude Shift Keying (ASK):
  - change amplitude with each symbol – frequency constant
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - change frequency with each symbol
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - Change phase with each symbol
  - More complex
  - robust against interference

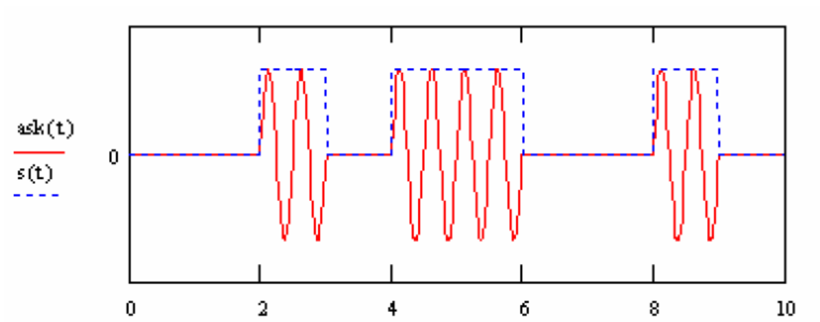


Amplitude Shift Keying (ASK)

- ASK On-off keying (OOK) – frequency is kept constant, amplitude has 2 levels (for bit 1 and for bit 0)



$$ASK(t) = s(t)\sin(2\pi f t)$$

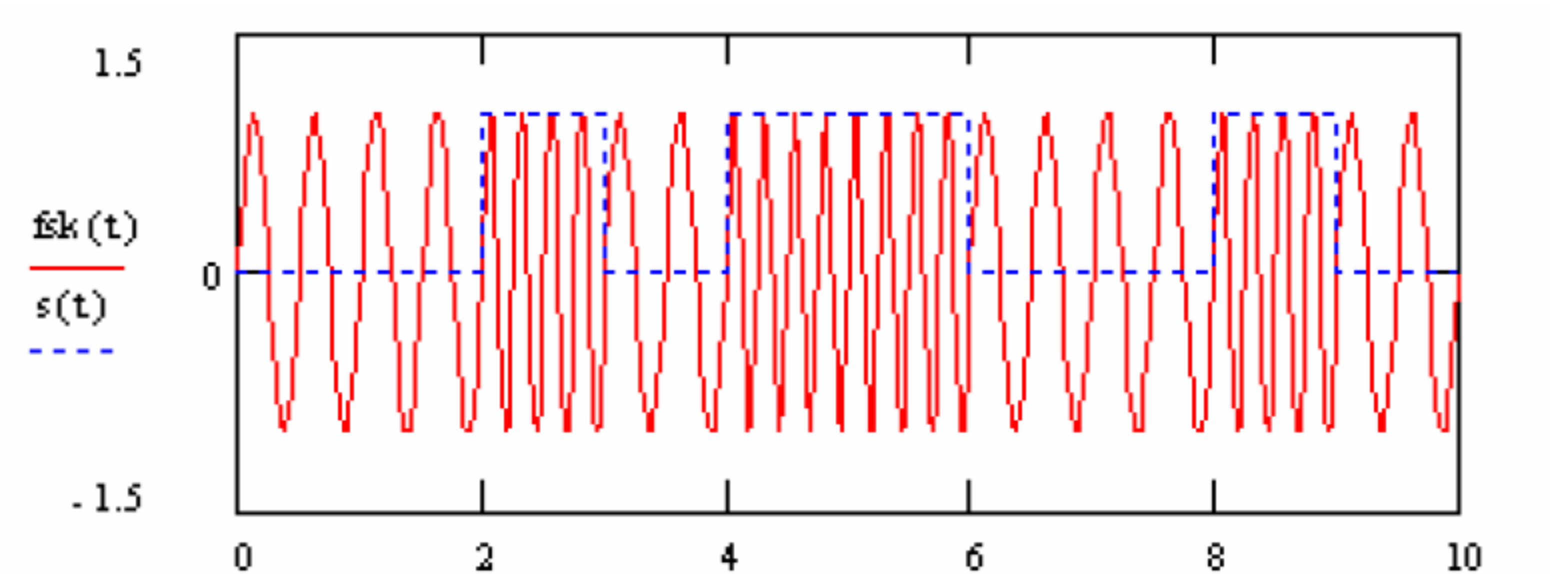


The binary sequence 0010110010

Frequency shift keying (FSK)

$$FSK(t) = \begin{cases} \sin(2\pi f_1 t) & for\ bit\ 1 \\ \sin(2\pi f_2 t) & for\ bit\ 0 \end{cases}$$

The carrier frequency can assume two values (f_1 and f_2)

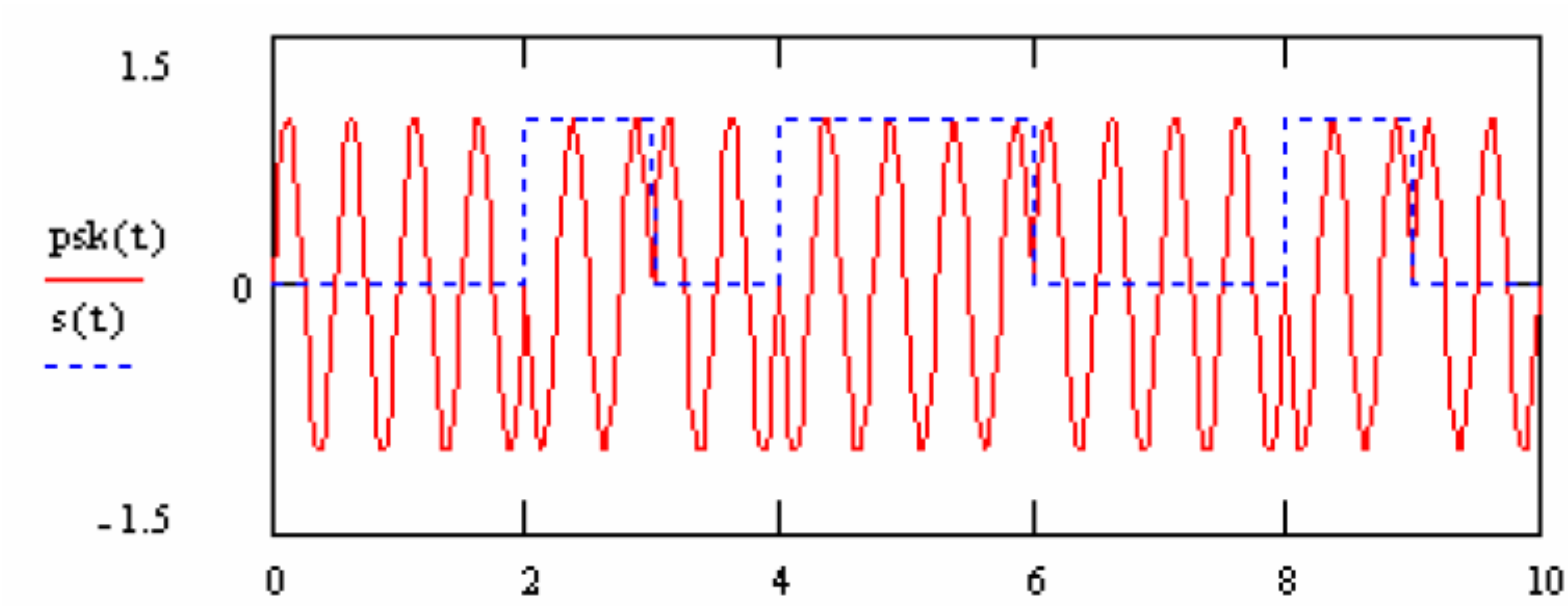


The binary sequence 0010110010 (as before)

Phase shift keying (PSK)

$$PSK(t) = \begin{cases} \sin(2\pi f t) & for\, bit\, 1 \\ \sin(2\pi f t + \pi) & for\, bit\, 0 \end{cases}$$

The phase offset can assume two values (*0* and π) - **BINARY**



The binary sequence 0010110010 (as before)

Binary phase shift keying (BPSK)

If the sinusoidal carrier has energy per bit E_b and bit duration T_b, then the transmitted BPSK signal is either:

$$S_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c) \qquad 0 \le t \le T_b \quad \text{(binary 1)}$$

$$S_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \pi + \theta_c)$$

$$= -\sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c) \qquad 0 \le t \le T_b \quad \text{(binary 0)}$$

Quadrature phase shift keying (QPSK)

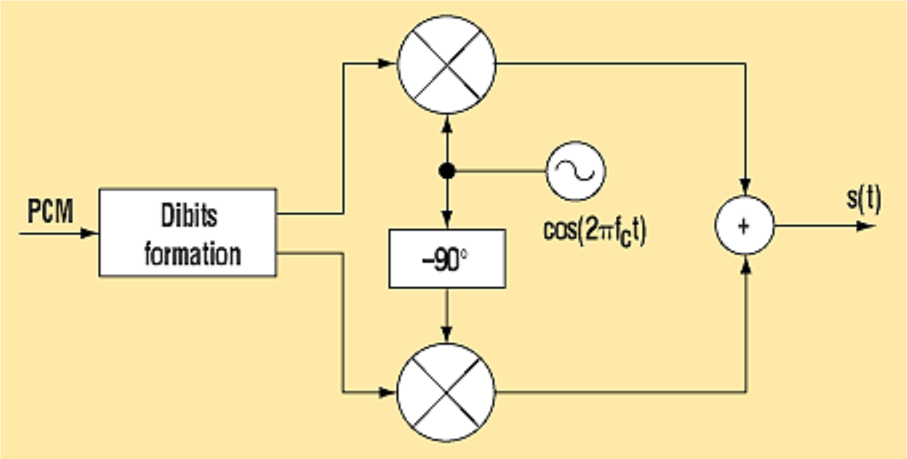
- A linear modulation scheme
- The phase of the carrier takes on 1 of 4 equally spaced values, such as $0, \pi/2, \pi,$ and $3\pi/2$, where each value of phase corresponds to a unique pair of message bits.
- The QPSK signal for this set of symbol states may be defined as:

$$\boxed{S_{QPSK}(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left[2\pi f_c t + (i-1)\frac{\pi}{2}\right] \quad 0 \le t \le T_s \quad i = 1, 2, 3, 4.}$$

- QPSK has twice the bandwidth efficiency of BPSK, since 2 bits are transmitted in a single modulation symbol.

QPSK as two BPSKs

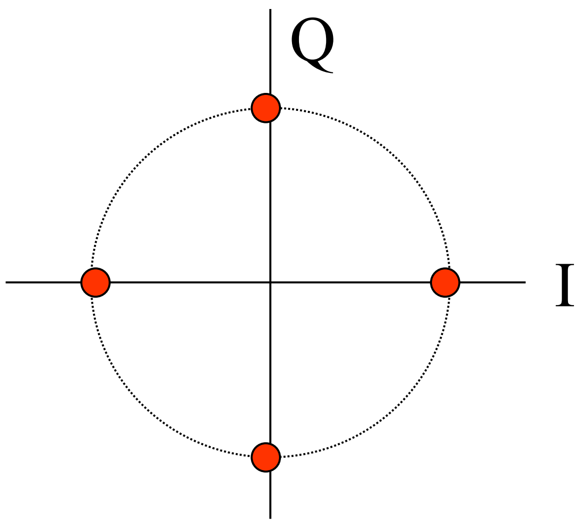
$$S_{QPSK} = \{\sqrt{E_s}\cos\left[(i-1)\frac{\pi}{2}\right]\phi_1(t) - \sqrt{E_s}\sin\left[(i-1)\frac{\pi}{2}\right]\phi_2(t)\} \quad i = 1,2,3,4$$



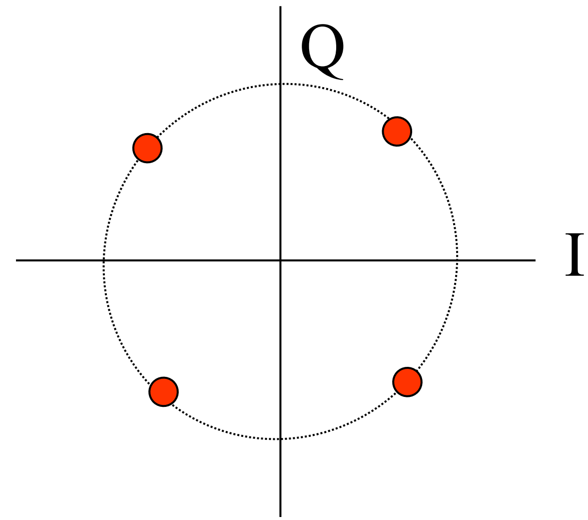
1. The classical method of implementing s(t) for a QPSK modulator is shown by this block diagram.

- QPSK can be interpreted as two independent BPSK systems (one on the I-channel and one on Q-channel) → same performance (bit error rate) but twice the bandwidth (spectrum) efficiency.

QPSK Constellation Diagram



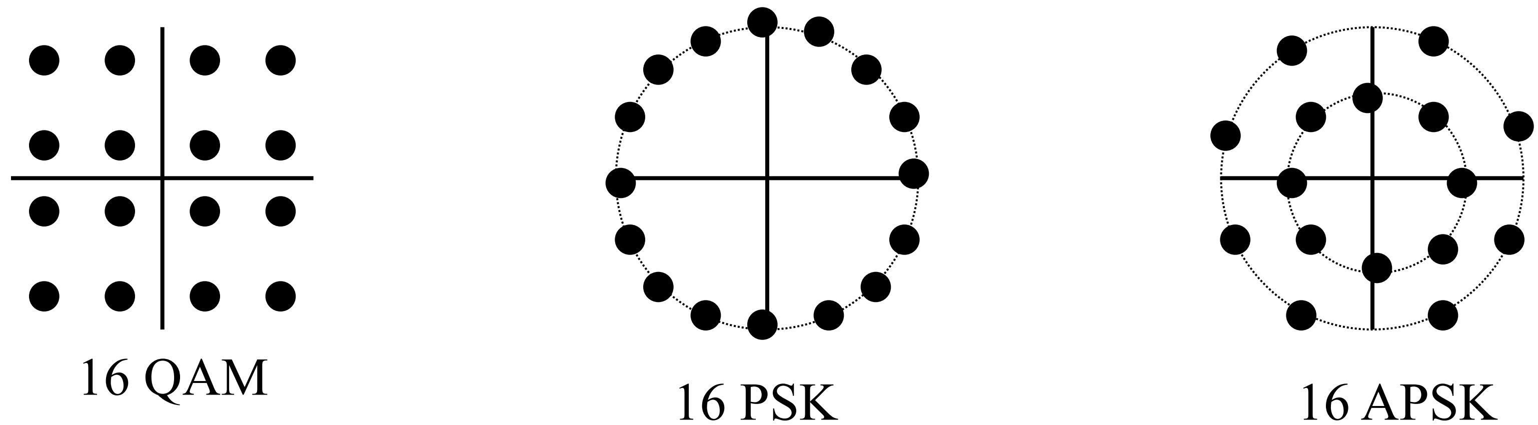
Carrier phases
$\{0, \pi/2, \pi, 3\pi/2\}$



Carrier phases
$\{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$

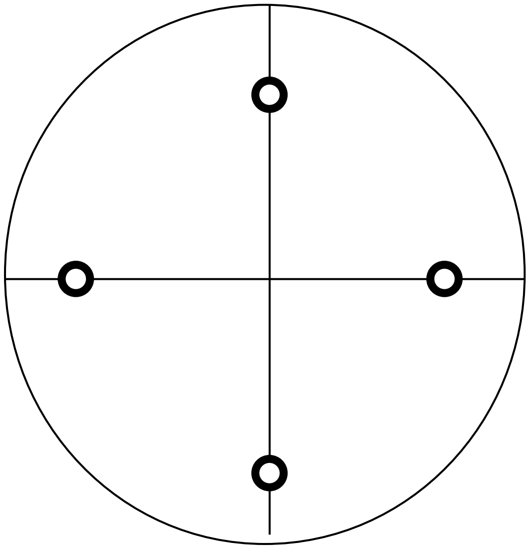
- Quadrature Phase Shift Keying has twice the bandwidth efficiency of BPSK since 2 bits are transmitted in a single modulation symbol

Multi-level (M-ary) Phase and Amplitude Modulation

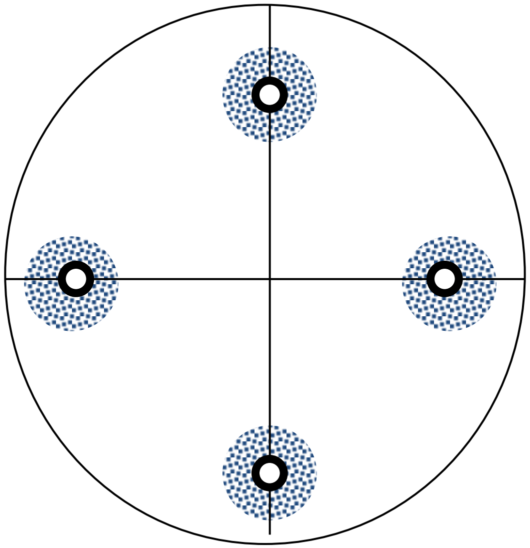


- Amplitude and phase shift keying can be combined to transmit several bits per symbol.
  - Often referred to as *linear* as they require linear amplification.
  - More bandwidth-efficient, but more susceptible to noise.
- For *M=4*, 16QAM has the largest distance between points, but requires very linear amplification. 16PSK has less stringent linearity requirements, but has less spacing between constellation points, and is therefore more affected by noise.

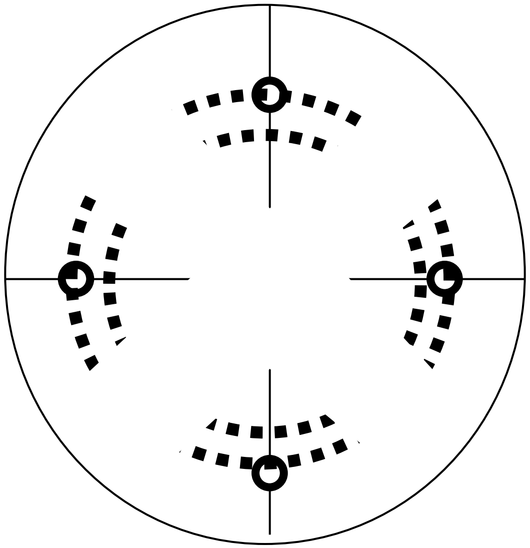
Distortions



Perfect channel



White noise



Phase jitter

Bandwidth Efficiency

$$\boxed{\frac{f_b}{W} = \log_2\left(1 + \frac{E_b f_b}{\eta W}\right)}$$

$f_b =$ capacity (bits per second)

$W =$ bandwidth of the modulating baseband signal (Hz)

$E_b =$ energy per bit

$\eta =$ noise power density (watts/Hz)

Thus

$E_b f_b =$ total signal power

$\eta W =$ total noise power

$\frac{f_b}{W} =$ bandwidth use efficiency

$=$ bits per second per Hz

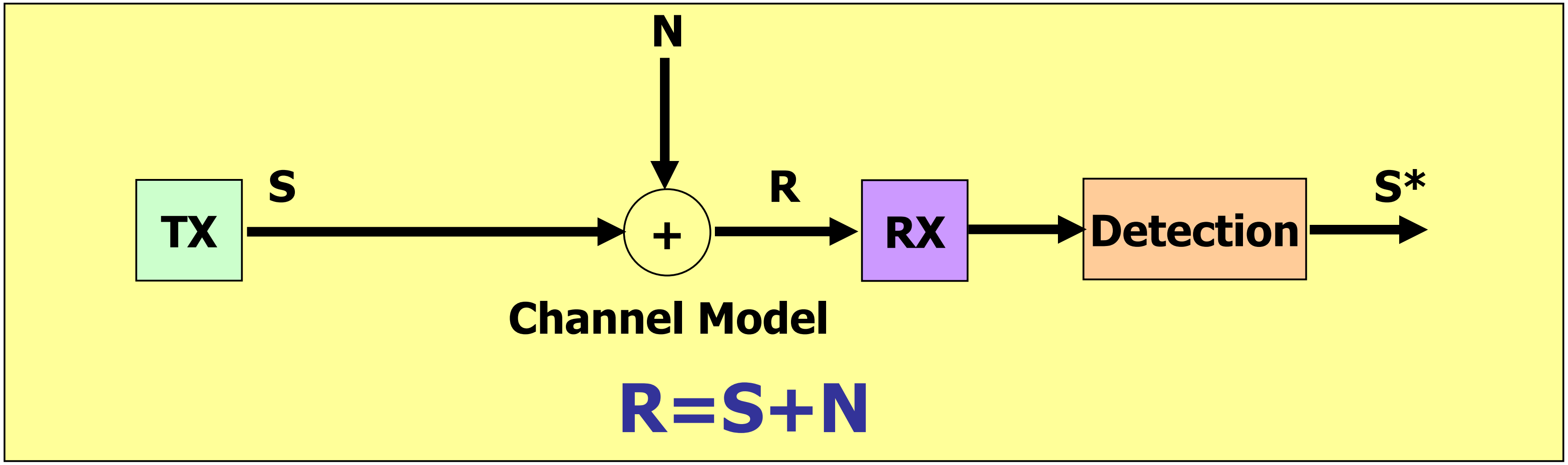
Comparison of Modulation Types

Modulation Format	Bandwidth efficiency C/B	Log2(C/B)	Error-free Eb/N0
16 PSK	4	2	18dB
16 QAM	4	2	15dB
8 PSK	3	1.6	14.5dB
4 PSK	2	1	10dB
4 QAM	2	1	10dB
BFSK	1	0	13dB
BPSK	1	0	10.5dB

Spectral Efficiencies - Examples

- GSM Europe Digital Cellular
  - Data Rate = 270kb/s; Bandwidth = 200kHz
  - Bandwidth efficiency = 270/200 = 1.35bits/sec/Hz
- IS-95 North American Digital Cellular
  - Data Rate = 48kb/s; Bandwidth = 30kHz
  - Bandwidth efficiency = 48/30 = 1.6bits/sec/Hz

Basic Communication Model in AWGN



Detection Performance:

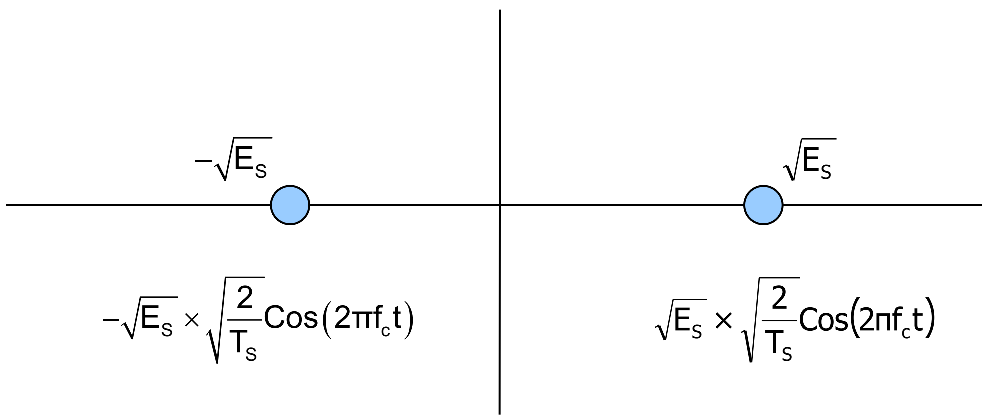
– Correct Detection
  - S = S*

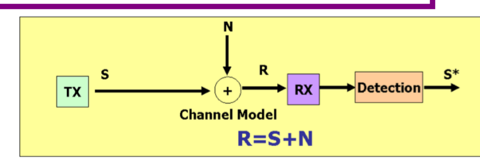
– Erroneous Detection
  - S ≠ S*

BPSK Modulation over AWGN Channels

$S \in \left\{ -\sqrt{E_S}, \sqrt{E_S} \right\}$

$E_S \rightarrow$ Energy per Symbol



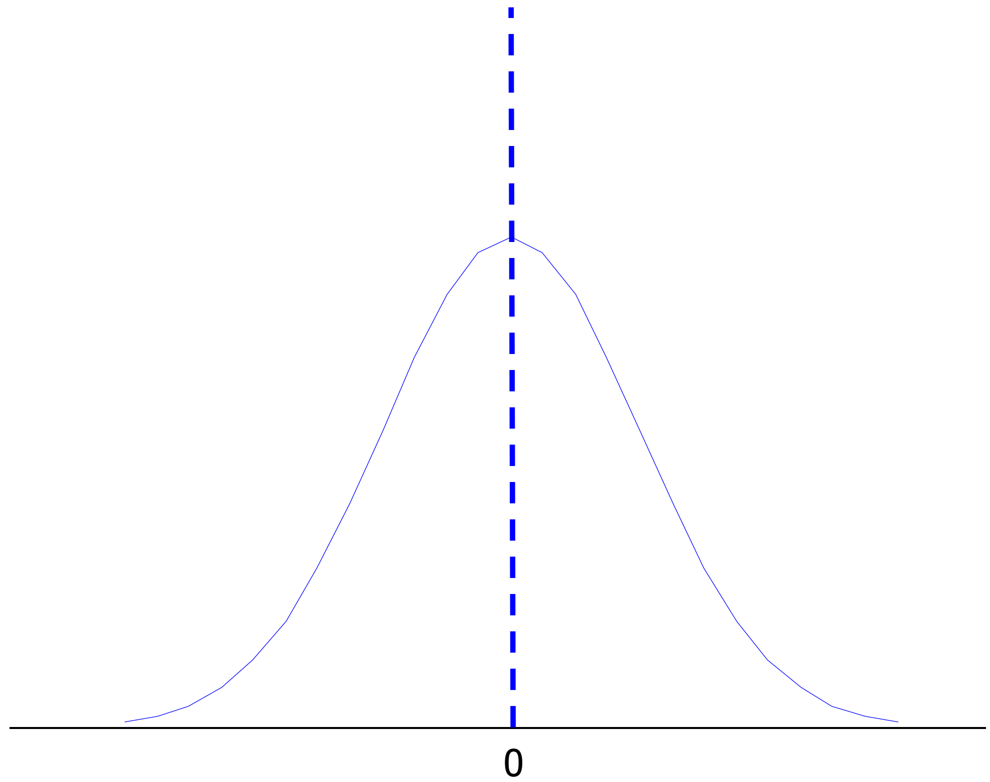


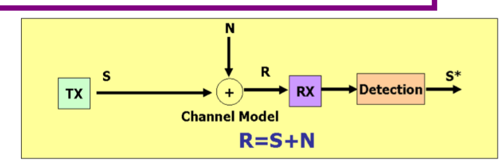
BPSK Modulation over AWGN Channels

$N \in \left]-\infty, \infty\right[$

Gaussian Noise

$$f_N(n) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}}$$



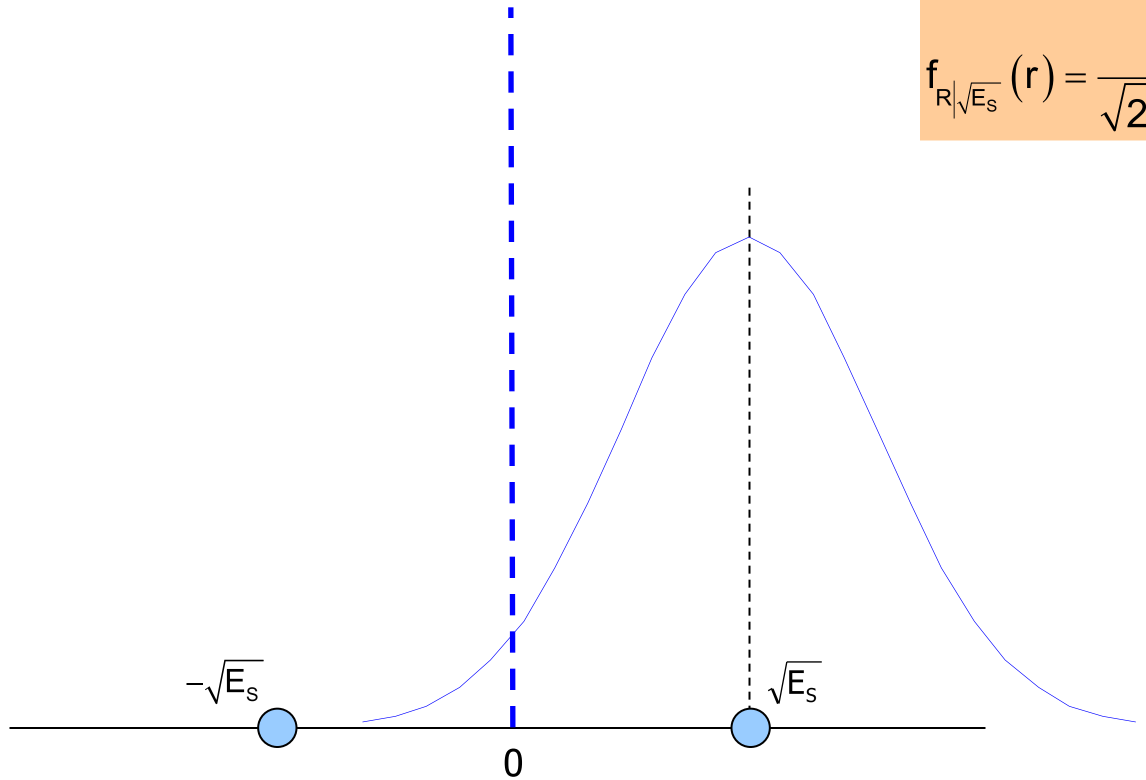


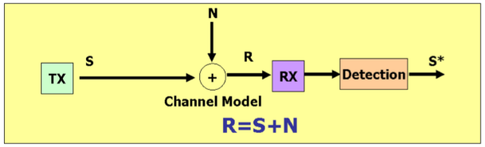
BPSK Modulation over AWGN Channels

$R \in \left]-\infty, \infty\right[$

Received signal distribution given $\sqrt{E_S}$ transmitted

$$f_{R|\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r-\sqrt{E_S}\right)^2}{2\sigma^2}}$$





BPSK Modulation over AWGN Channels

$R \in]-\infty, \infty[$

Error Calculation given $\sqrt{E_S}$ transmitted

$$P_{e|\sqrt{E_S}} = \Pr[r<0] = \Pr\left[n < -\sqrt{E_S}\right]$$

$$f_{R|\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r-\sqrt{E_S}\right)^2}{2\sigma^2}}$$

$$P_{e|\sqrt{E_S}} = \int_{-\infty}^{-\sqrt{E_S}} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

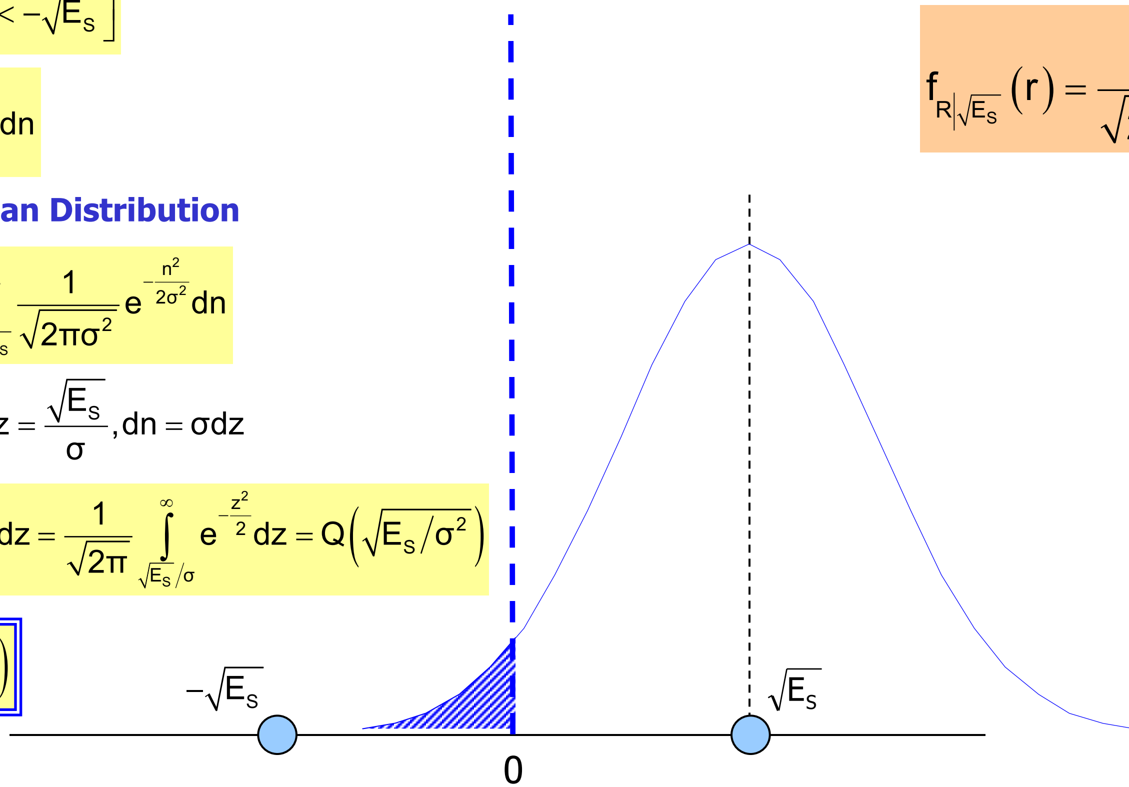
Symmetry of Gaussian Distribution

$$\int_{-\infty}^{-\sqrt{E_S}} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn = \int_{\sqrt{E_S}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

Let $z = \frac{n}{\sigma}, n = \sqrt{E_S} \Rightarrow z = \frac{\sqrt{E_S}}{\sigma}, dn = \sigma dz$

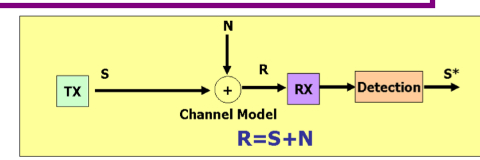
$$P_{e|\sqrt{E_S}} = \int_{\sqrt{E_S}/\sigma}^{\infty} \frac{\sigma}{\sqrt{2\pi\sigma^2}} e^{-\frac{z^2}{2}} dz = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{E_S}/\sigma}^{\infty} e^{-\frac{z^2}{2}} dz = Q\left(\sqrt{E_S/\sigma^2}\right)$$

$$\boxed{P_{e|\sqrt{E_S}} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{E_S/2\sigma^2}\right)}$$



$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{z^2}{2}} dz$$

$$Q(x) = \frac{1}{2}\mathrm{erfc}\left(x/\sqrt{2}\right)$$

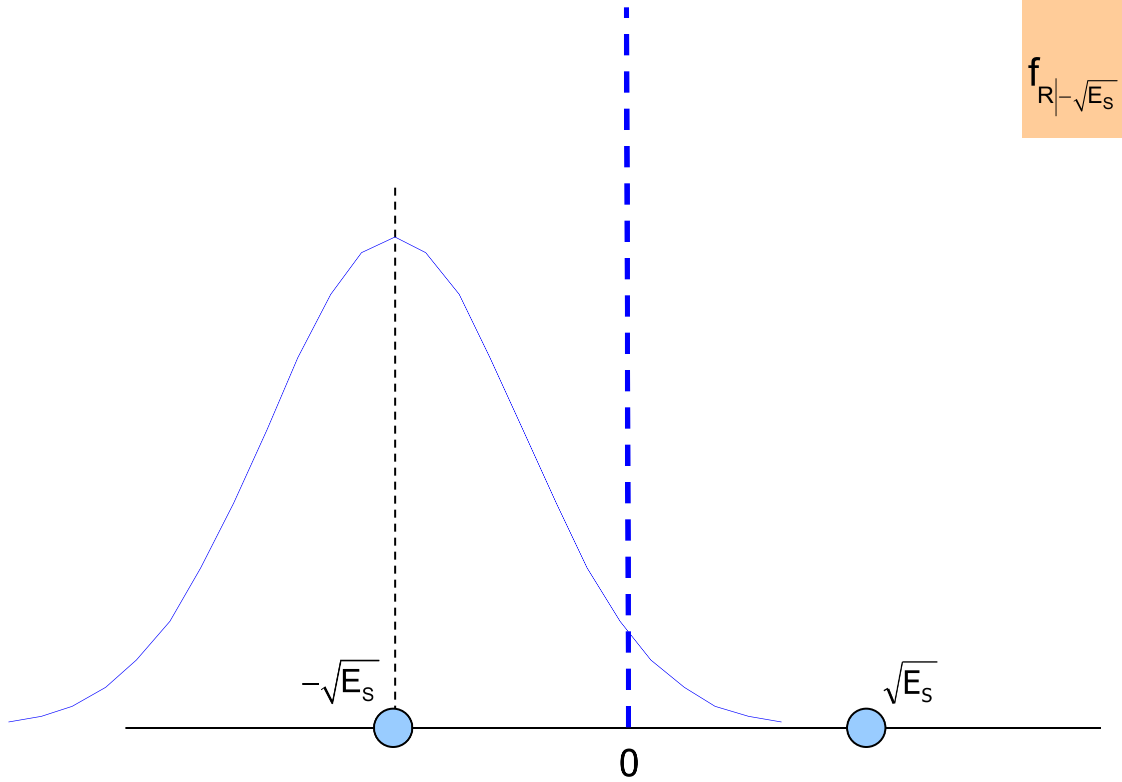


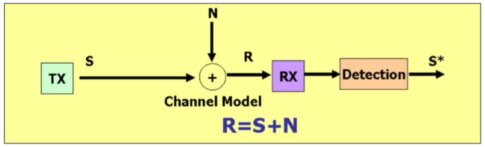
BPSK Modulation over AWGN Channels

$R \in]-\infty, \infty[$

Received signal distribution given $-\sqrt{E_S}$ transmitted

$$f_{R|-\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r+\sqrt{E_S}\right)^2}{2\sigma^2}}$$





BPSK Modulation over AWGN Channels

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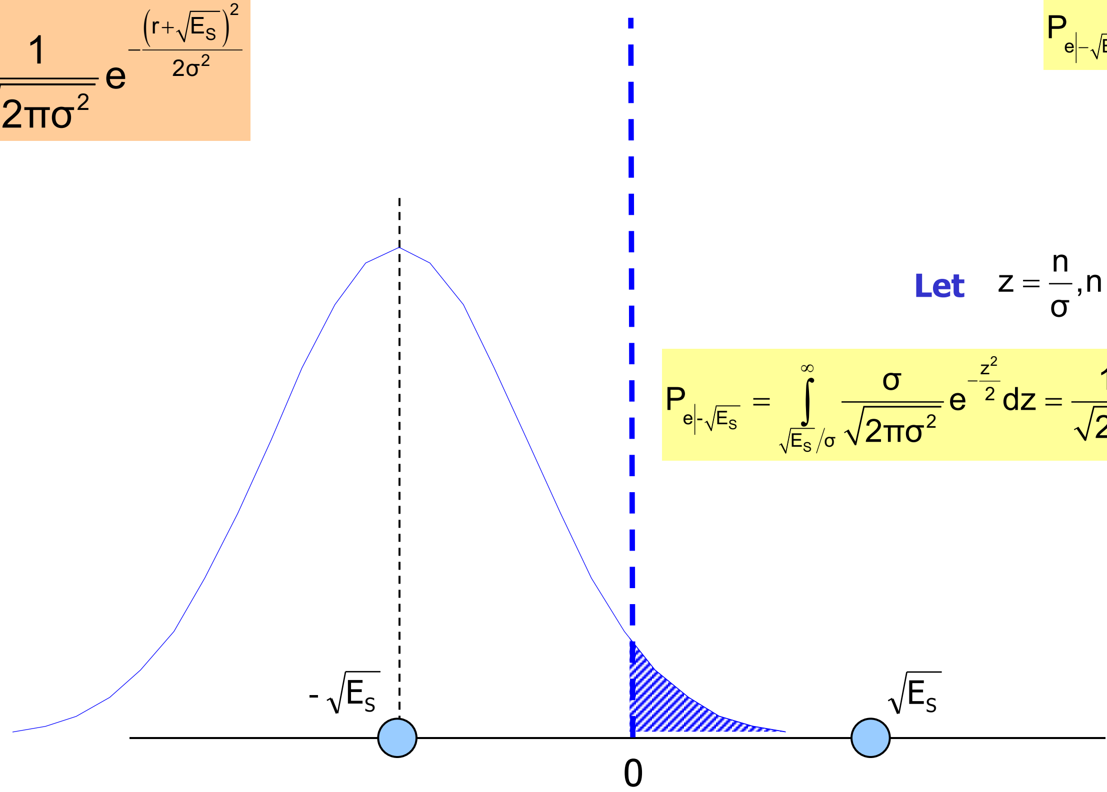


Error Calculation given $-\sqrt{E_S}$ transmitted

$$P_{e|-\sqrt{E_S}} = \Pr[r > 0] = \Pr\left[n > \sqrt{E_S}\right]$$

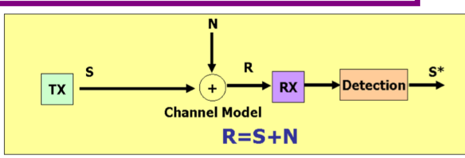
$$P_{e|-\sqrt{E_S}} = \int_{\sqrt{E_S}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

Let $z = \frac{n}{\sigma}, n = \sqrt{E_S} \Rightarrow z = \frac{\sqrt{E_S}}{\sigma}, dn = \sigma dz$

$$P_{e|-\sqrt{E_S}} = \int_{\sqrt{E_S}/\sigma}^{\infty} \frac{\sigma}{\sqrt{2\pi\sigma^2}} e^{-\frac{z^2}{2}} dz = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{E_S}/\sigma}^{\infty} e^{-\frac{z^2}{2}} dz = Q\left(\sqrt{E_S/\sigma^2}\right)$$

$$\boxed{P_{e|-\sqrt{E_S}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right)}$$

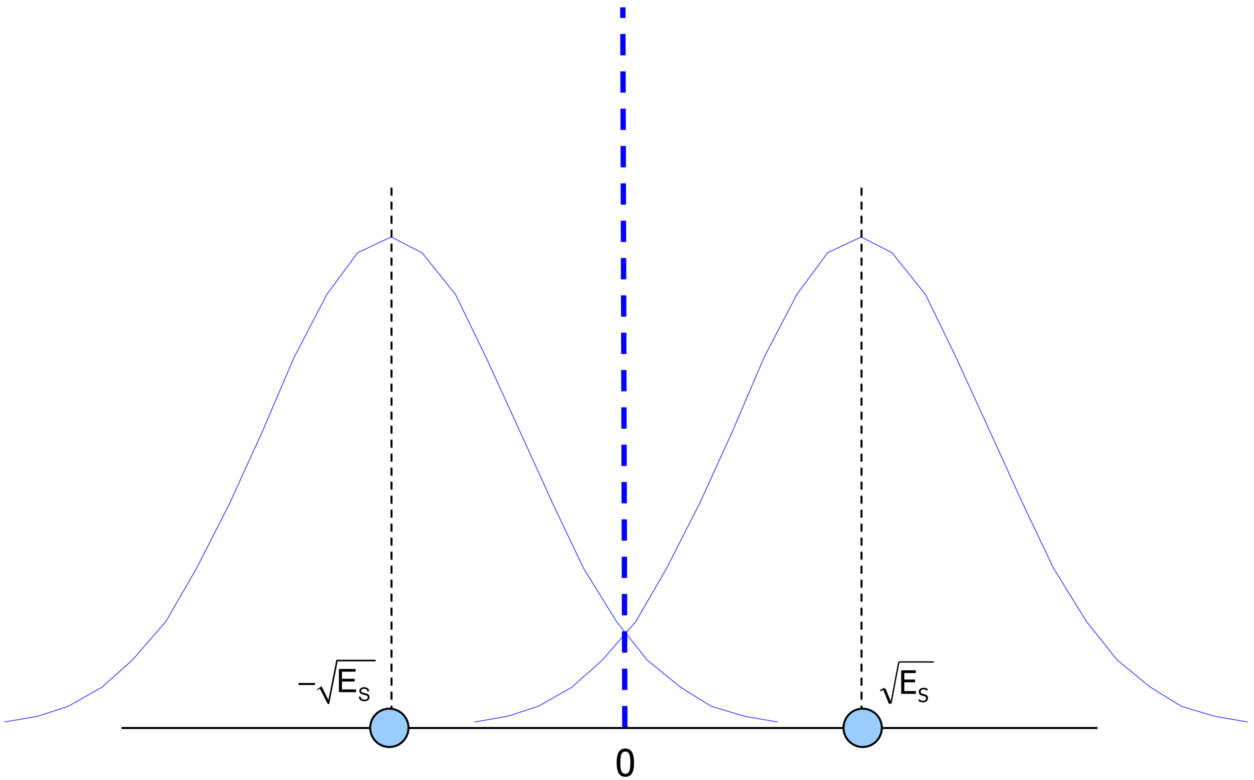
$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{z^2}{2}} dz \qquad Q(x) = \frac{1}{2}\operatorname{erfc}\left(x/\sqrt{2}\right)$$

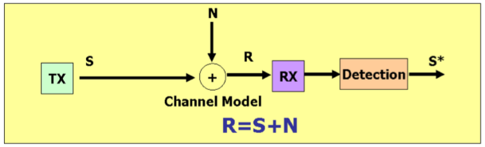


BPSK Modulation over AWGN Channels

$E_S \uparrow \Rightarrow P_e \downarrow$

Signal Power & Symbol Error Performance

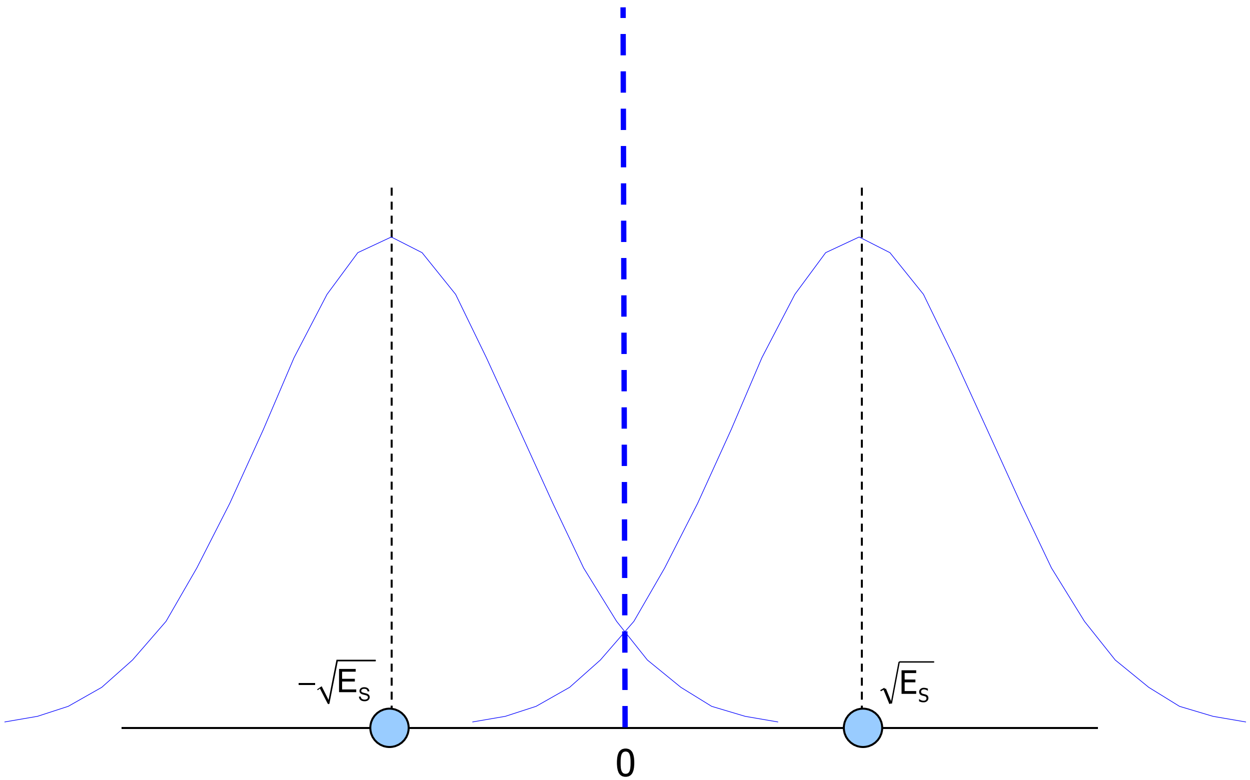


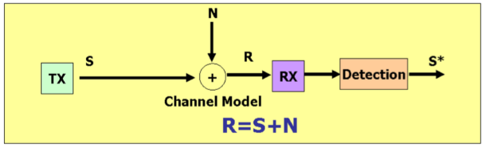


BPSK Modulation over AWGN Channels

$\sigma^2 \downarrow \Rightarrow P_e \downarrow$

Signal Power & Symbol Error Performance





BER of BPSK over AWGN Channels

$$P_e = \Pr\left[-\sqrt{E_S}\right] \times P_{e|-\sqrt{E_S}} + \Pr\left[\sqrt{E_S}\right] \times P_{e|\sqrt{E_S}}$$

$$P_e = \frac{1}{2} \times \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right) + \frac{1}{2} \times \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right) = \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right)$$

Notes:

- Define N_0 Total Noise Power
  - $N_0/2$ ➔ Noise Power over Cosine axis, i.e., $\sigma^2 = N_0/2$
- Each symbol corresponds to a single bit
  - $E_b = E_S$
  - $P_b = P_e$

$$P_b = \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_b/N_0}\right)$$

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Wired vs. Wireless LANs

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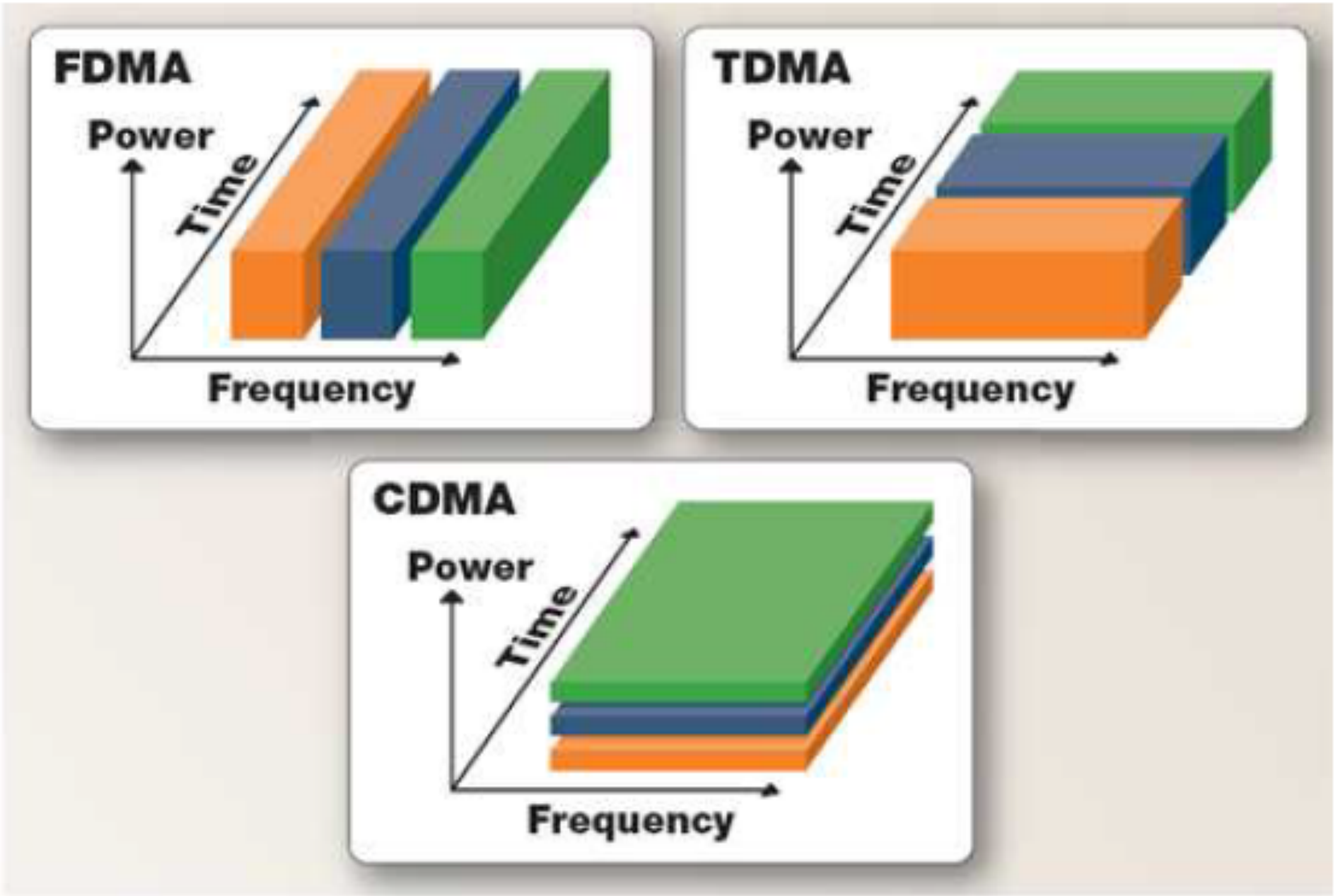
- The first approach was to apply the same MAC protocols for wired networks (e.g., IEEE 802.3 with CSMA/CD) to wireless networks.
- There are, however, two main differences:
  - available bandwidth;
  - transmission reliability.
- It is not possible to duplicate the shared medium, i.e., the air.
- If something goes wrong, it may be due to fading and not collisions.

Reservation-Based Approaches

- Suitable for voice-oriented applications.
- Reservation can be done by signaling channels.
- It is necessary for (possible) long conversations.
- Three possible quantities can be reserved:
  - time slots (TDMA), as in GSM;
  - frequency bands (FDMA), as in GSM;
  - expansion codes (CDMA), as in UMTS.
- Other (random access) techniques may be used for various reasons (see, e.g., slotted Aloha in GSM).

TDMA, FDMA, CDMA



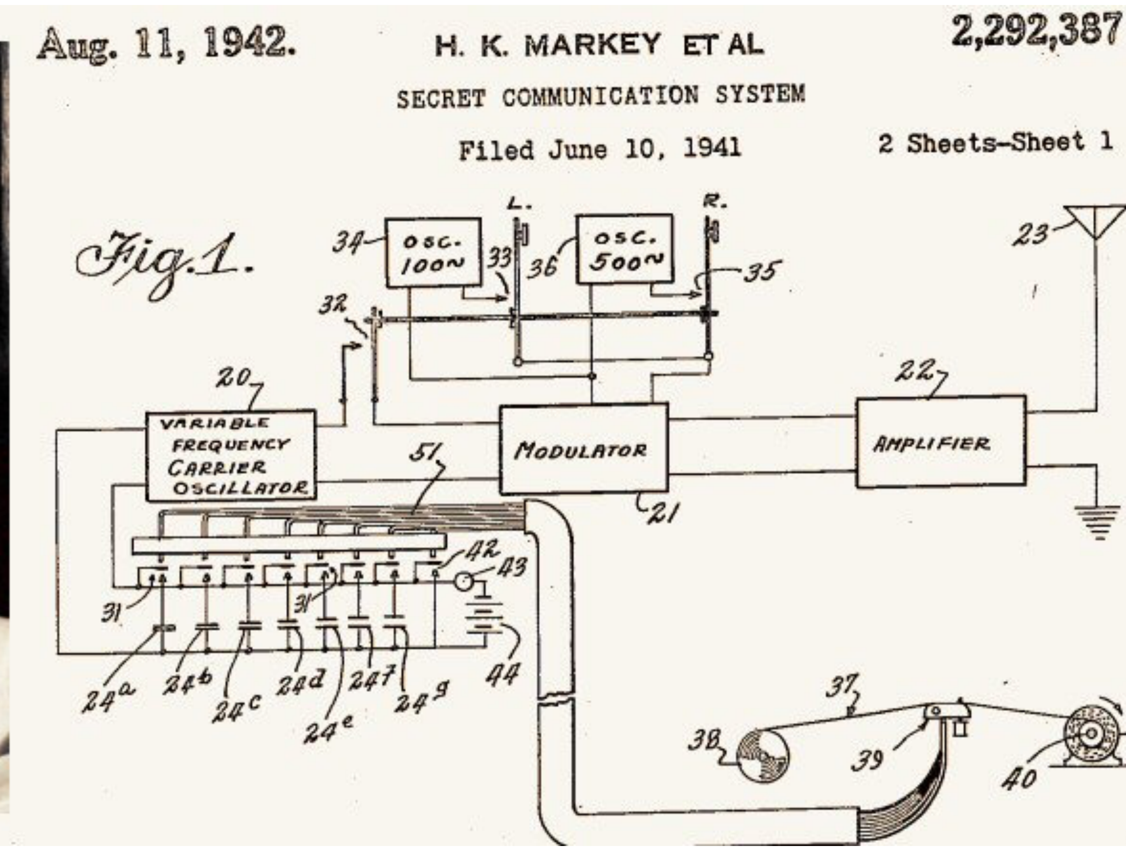
DSSS e CDMA

- Alla lavagna:
  - Modulazione a spettro espanso
  - Direct sequence spread spectrum
  - Sistemi CDMA con interferenza da accesso multiplo

P. M. Shankar, *Introduction to Wireless Systems*, Wiley, 2001, ISBN-13: 978-0471321675.

Hedy Lamarr

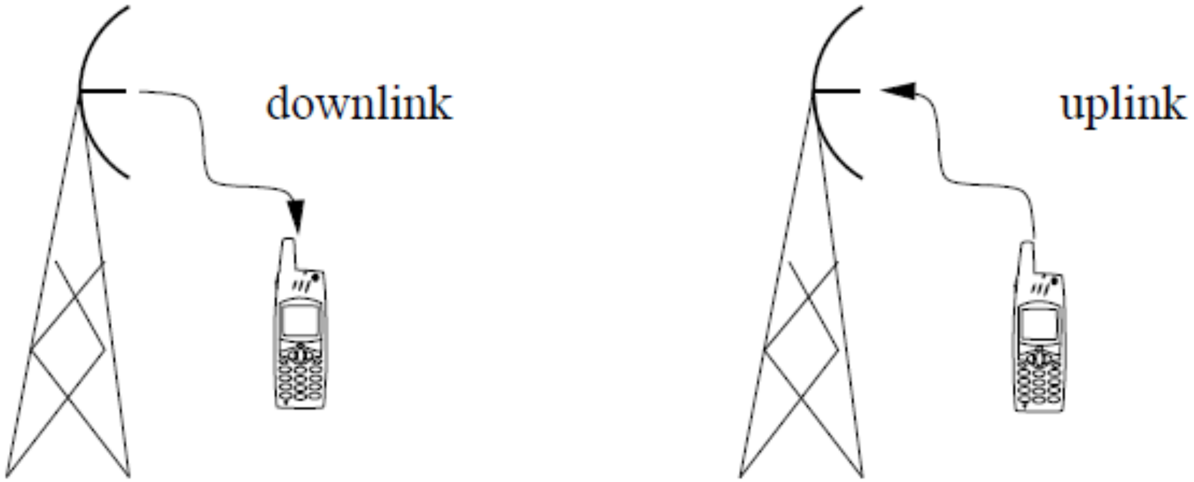
At the beginning of World War II, she and composer George Antheil developed a radio guidance system for Allied torpedoes that used spread spectrum and frequency hopping technology to defeat the threat of jamming by the Axis powers. Although the US Navy did not adopt the technology until the 1960s,[7] the principles of their work are incorporated into Bluetooth technology and are similar to methods used in legacy versions of CDMA and Wi-Fi.[8][9][10] This work led to their induction into the National Inventors Hall of Fame in 2014. [Wikipedia]



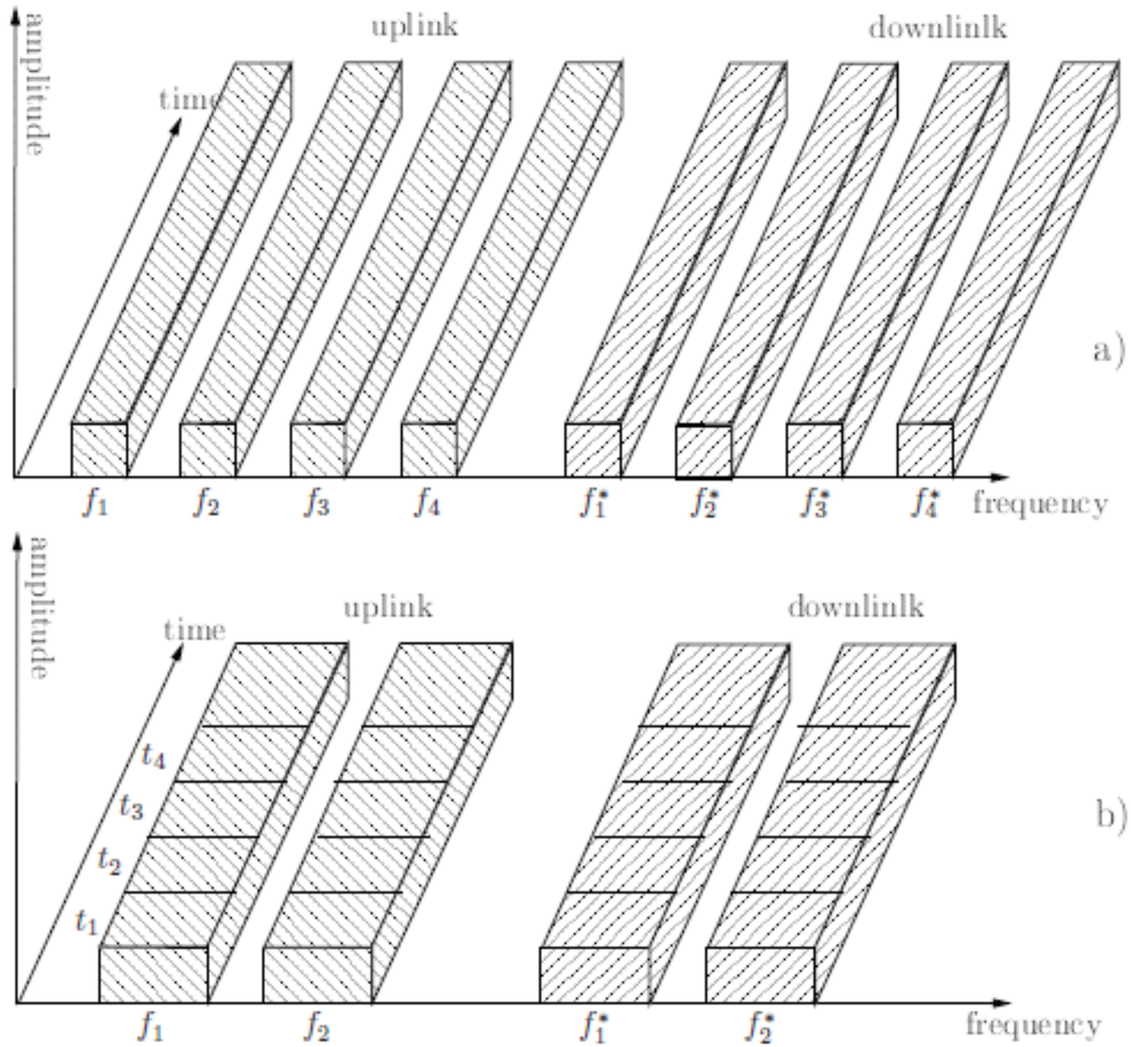
Uplink vs. Downlink

- Time Division Duplex (TDD): the two channels use the same carrier frequency and, therefore, it is necessary to alternate time slots.

- Frequency Division Duplex (FDD): the two channels use separate carrier frequencies and, therefore, they can operate during the same time slots.

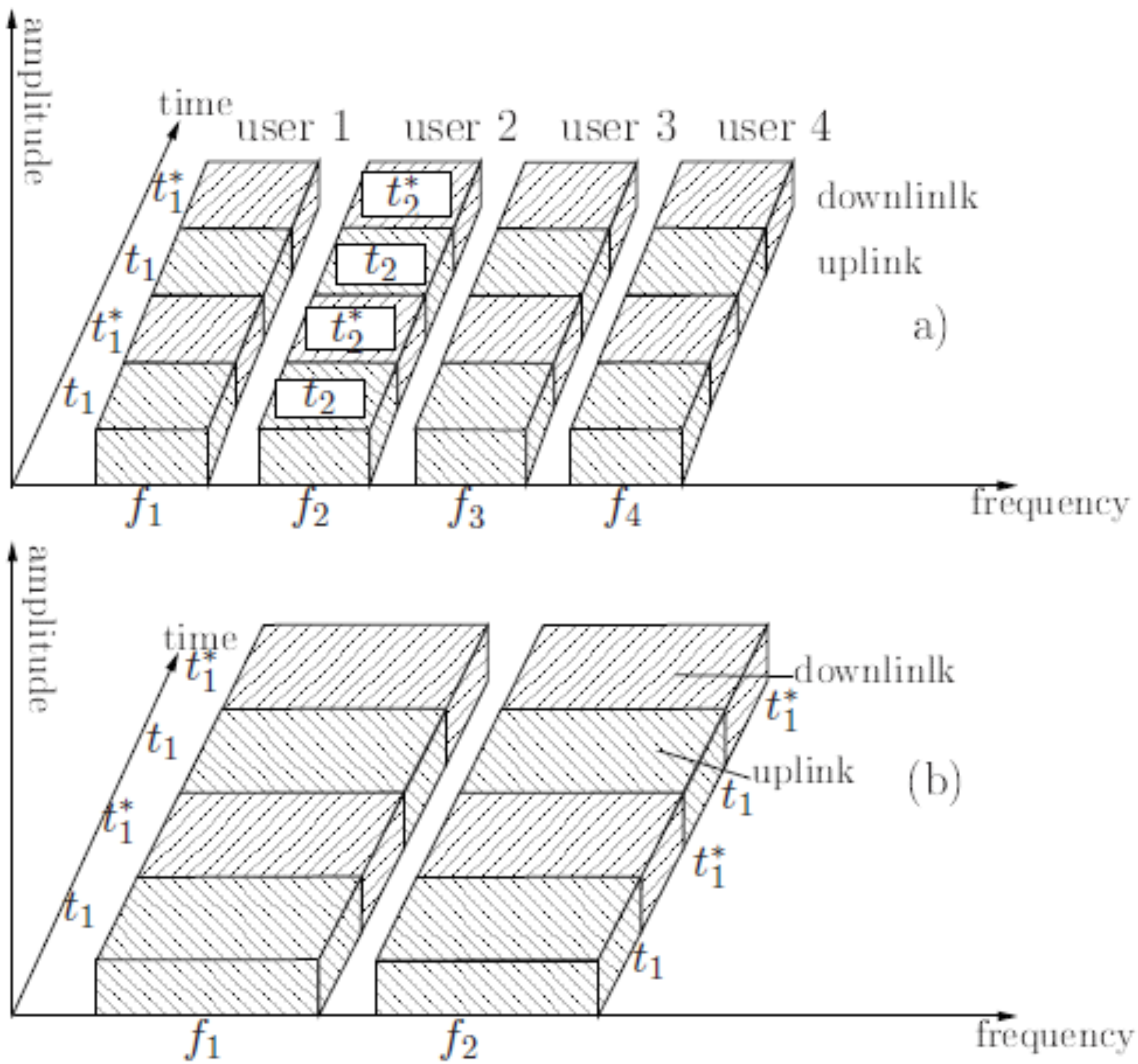


FDD



amplitude
uplink
downlinlk
time
a)
f_1
f_2
f_3
f_4
f_1^*
f_2^*
f_3^*
f_4^*
frequency
amplitude
uplink
downlinlk
time
t_4
t_3
t_2
t_1
b)
f_1
f_2
f_1^*
f_2^*
frequency

TDD



amplitude
time
user 1
user 2
user 3
user 4
t_1^*
t_1
t_1^*
t_1
t_2^*
t_2
t_2^*
t_2
downlinlk
uplink
a)
f_1
f_2
f_3
f_4
frequency
amplitude
time
t_1^*
t_1
t_1^*
t_1
downlinlk
t_1^*
uplink
t_1
t_1^*
t_1
(b)
f_1
f_2
frequency

CDMA

- Attractive since it is possible to mix different users without any specific coordination.

- Power control becomes essential, since all users share the same bandwidth. In other schemes, interference comes from adjacent (time or frequency) channels.

- Use of spread spectrum modulation:

$$\underbrace{B}_{\text{bandwidth}} = \underbrace{g}_{\text{spreading factor}} \cdot \underbrace{R_{\text{b}}}_{\text{bit rate}}$$

$$\underbrace{P_{\text{s}}}_{\text{signal power}} = \underbrace{g}_{\text{spreading factor}} \cdot \underbrace{P_{\text{r}}}_{\text{received power}}$$

$$\underbrace{P_{\text{int}}}_{\text{interference power}} = \underbrace{N-1}_{\text{interferers}} \cdot \underbrace{P_{\text{r}}}_{\text{received power}}$$

Number of Active Users (I)

- The Signal-to-Noise Ratio (SNR) is

$$\mathrm{SNR} = \frac{P_\mathrm{s}}{P_\mathrm{th} + P_\mathrm{int}}$$

with thermal noise $P_\mathrm{th} = F k T_0 R_\mathrm{b}$, where: F is the noise figure; $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant; and $T_0 = 290$ K.

- Supposing that the thermal noise is negligible with respect to interference, one obtains:

$$\mathrm{SNR} \simeq \frac{P_\mathrm{s}}{P_\mathrm{int}} = \frac{g P_\mathrm{r}}{(N-1) P_\mathrm{r}}$$

i.e., with ideal power control, the SNR does not depend on the receive power.

- If $N \gg 1$, then

$$\mathrm{SNR} \simeq \frac{g}{N} = \frac{B}{R_\mathrm{b} N}.$$

Number of Active Users (II)

- Suppose to require a given Quality of Service (QoS):

$$\mathrm{SNR} \geq \mathrm{SNR}_{\min}$$

where $\mathrm{SNR}_{\min}$ depends on the specific application.

- At this point, it easy to obtain

$$N \leq \frac{B}{R_{\mathrm{b}}\mathrm{SNR}_{\min}} = N_{\max}.$$

- In the presence of TDMA or FDMA, the capacity is simply given by the number of allocated time slots or frequency bands.

Maximum Number of Sustainable Users

$$N_{\max} \simeq \frac{B}{R_{\mathrm{b}}\mathrm{SNR}_{\min}} \times K$$

where K is a performance improvement factor[1] given by

$$K = \frac{G_{\mathrm{A}} G_{\nu}}{H_{\mathrm{O}}}.$$

- G_{A}: sectorization gain factor; for three sector antennas, $G_{\mathrm{A}} = 2.5 < 3$ due to reflections.
- G_{ν}: voice activity factor; for instance, if voice flows have pauses for almost 60% of time, then $G_{\nu} = 2.5$.
- H_{O}: interference factor due to adjacent cells; a possible value is $H_{\mathrm{O}} = 1.6$ dB.

---

[1] Note that k is the Boltzmann constant and K is the performance improvement factor.

Rumore termico

- Alla lavagna:
  - Rumore termico
  - Temperatura equivalente di rumore
  - Cifra di rumore
  - Sensitività di un ricevitore

S. Haykin e M. Moher, *Modern Wireless Communications*, Prentice Hall, 2004, ISBN-13: 978-0130224729.

C/T/F-DMA Comparison: Format Flexibility

- TDMA is more flexible than FDMA, since dynamic slot allocation is possible; however, TDMA suffers of synchronization problems.

- In CDMA, it is possible to easily set different QoS to each user and there is no need to synchronize nodes (quasi-orthogonal spreading sequences are good codes).

C/T/F-DMA Comparison: Multipath Fading

- FDMA is a narrow-band system and can suffer from holes in the power spectral density.

- CDMA takes advantage of spreading by using the portion of the transmission bandwidth which is not corrupted by fading.

- GSM/IS-36: $B_c = 200$ kHz/30 kHz vs $B = 1250$ kHz.

- IS-95: $B_c = 1250$ kHz vs $B = 1250$ kHz.

- Note that the carrier bandwidth may not be equal to data rate, due to the employed modulation.

C/T/F-DMA Comparison: System Capacity (1)

- For IS-136:

$$N_{\max} = \frac{B}{B_c} \underbrace{\frac{N_u}{K}} = \frac{1.25 \cdot 10^6}{30 \cdot 10^3} \frac{3}{4} \simeq 31 \,\mathrm{users/cell}$$

where N_u is the number of users per cell and K is the reuse factor.

- For IS-95:

$$N_{\max} \simeq \frac{B}{R_b \mathrm{SNR}_{\min}} \frac{G_A G_\nu}{H_O} = \frac{1.2510^6}{9.610^3 4} \frac{22.75}{1.6} \simeq 108 \,\mathrm{users/cell.}$$

C/T/F-DMA Comparison: System Capacity (2)

- For AMPS (FDMA):

$$N_{\max} = \frac{B}{B_c}\frac{1}{K} = \frac{1.25 \cdot 10^6}{30 \cdot 10^3}\frac{1}{7} \simeq 6 \,\text{users/cell}.$$

- For GSM:

$$N_{\max} = \frac{B}{B_c}\frac{N_u}{K} = \frac{1.25 \cdot 10^6}{200 \cdot 10^3}\frac{8}{7} \simeq 16 \,\text{users/cell}.$$

C/T/F-DMA Comparison: Hand-off (Horizontal Handover)

- For 1G (FDMA): base station controller (BSC) makes a "hard" switch.
- From 2G-TDMA: mobile-assisted handoff $\longrightarrow$ the mobile tells the BSC how the received signal strength varies.
- From 2G-CDMA: since adjacent cells use the same frequencies, there is a "seamless" (soft) handoff (provided that the same spreading code is available in the two cells).

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Multiple Access protocols

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
  - Collision if node receives two or more signals at the same time

Multiple Access Protocol

- Distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- Communication about channel sharing must use channel itself!
  - No out-of-band channel for coordination

Channel Partitioning

- Frequency Division Multiplexing
  – Each node has a frequency band
- Time Division Multiplexing
  – Each node has a series of fixed time slots
- What networks are these good for?

Computer Network Characteristics

- Transmission needs vary
  - Between different nodes
  - Over time
- Network is not fully utilized

Ideal Multiple Access Protocol

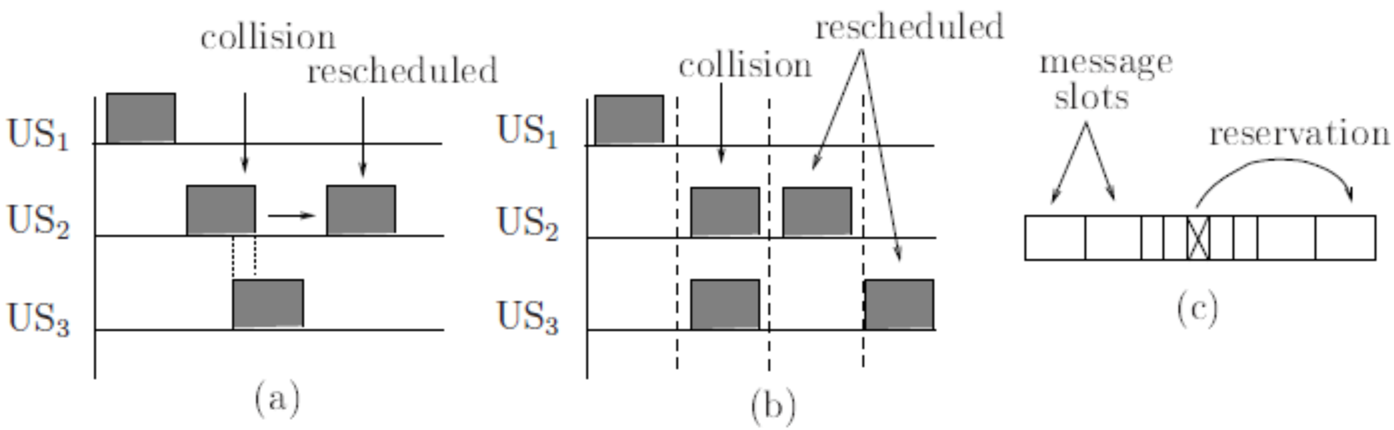
Broadcast channel of rate R bps

1. When one node wants to transmit, it can send at rate R.
2. When M nodes want to transmit, each can send at average rate R/M
3. Fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. Simple

Random Access Protocols

- When node has packet to send
  - transmit at full channel data rate R.
  - no *a priori* coordination among nodes
- two or more transmitting nodes ➜ "collision",
- random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)
- Examples of random access MAC protocols:
  - slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Aloha: the idea



(a) Pure Aloha;

(b) slotted Aloha;

(c) reservation Aloha.

- Created at the University of Hawaii in 1970 under the leadership of Norman Abramson.
- The idea was to use shared radio to create a computer network linking the far-flung campuses of the University.
- Two distinct frequencies in a star configuration were used, one for downlink channel and one for the uplink channel.

Slotted Aloha

Assumptions

- all frames same size
- time is divided into equal size slots, time to transmit 1 frame
- nodes start to transmit frames only at beginning of slots
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

Operation

- when node obtains fresh frame, it transmits in next slot
- no collision, node can send new frame in next slot
- if collision, node retransmits frame in each subsequent slot with prob. p until success

Slotted Aloha

Pros

- single active node can continuously transmit at full rate of channel
- highly decentralized: only slots in nodes need to be in sync
- simple

Cons

- collisions, wasting slots
- idle slots
- nodes may be able to detect collision in less than time to transmit packet
- clock synchronization

Slotted Aloha efficiency

- **Efficiency** is the long-run fraction of successful slots when there are many nodes, each with many frames to send
- Suppose N nodes with many frames to send, each transmits in slot with probability *p*
- prob that node 1 has success in a slot = $p(1-p)^{N-1}$
- prob that any node has a success = $Np(1-p)^{N-1}$

Optimal choice of p

- For max efficiency with N nodes, find p* that maximizes
  $Np(1-p)^{N-1}$
- For many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives 1/e = .37
- Efficiency is 37%, even with optimal p

Throughput of the Slotted Aloha Protocol

- It can be easily proved (Reti B) that the throughput is twice that of the pure Aloha:

$$S = Ge^{-G}.$$

- A maximum can be identified as

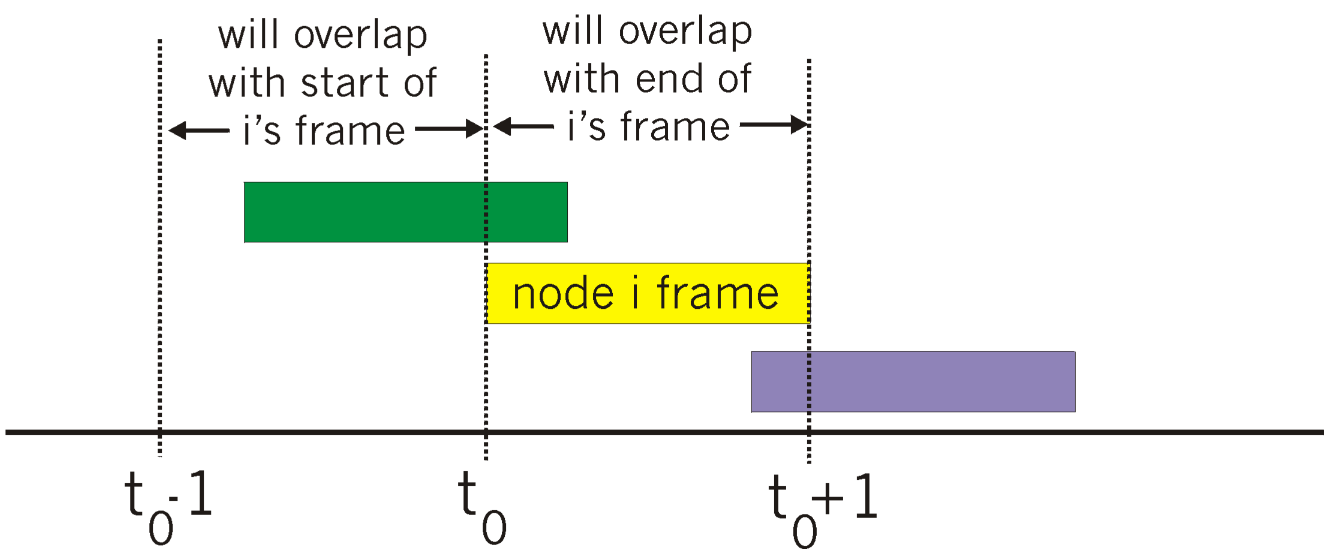
$$S' = e^{-G} - Ge^{-G} = e^{-G}(1 - G)$$

obtaining

$$S' = 0 \Longrightarrow S_{\max} = e^{-1} = 0.36.$$

Pure (unslotted) Aloha

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
  - transmit immediately
- collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0-1,t_0+1]$



Pure Aloha efficiency

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P(success by given node) = P(node transmits) ·

P(no other node transmits in $[t_0-1,t_0]$ ·

P(no other node transmits in $[t_0,t_0+1]$

$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$

$= p \cdot (1-p)^{2(N-1)}$

… choosing optimum p and then letting n -> ∞ ...

Even worse !

Efficiency = 1/(2e) = .18

Throughput of the Pure Aloha Protocol

- It can be easily proved (Reti B) that

$$S = Ge^{-2G}$$

where G is the offered load.

- A maximum can be identified by deriving:

$$S' = e^{-2G} - 2Ge^{-2G} = e^{-2G}(1 - 2G)$$

and setting the derivative to zero:

$$S' = 0 \Longrightarrow S_{\max} = \frac{1}{2}e^{-1} = 0.18.$$

- If $\lambda = 1$ Mb/s, then $\lambda S_{\max} = 180$ Kb/s.
- In TDMA-based systems, instead, $\lambda S_{\max} = 1$ Mb/s, since the maximum throughput of 1 can be achieved without any synchronization error.

Carrier Sense Multiple Access

CSMA: listen before transmit:

If channel sensed idle: transmit entire frame

- If channel sensed busy, defer transmission

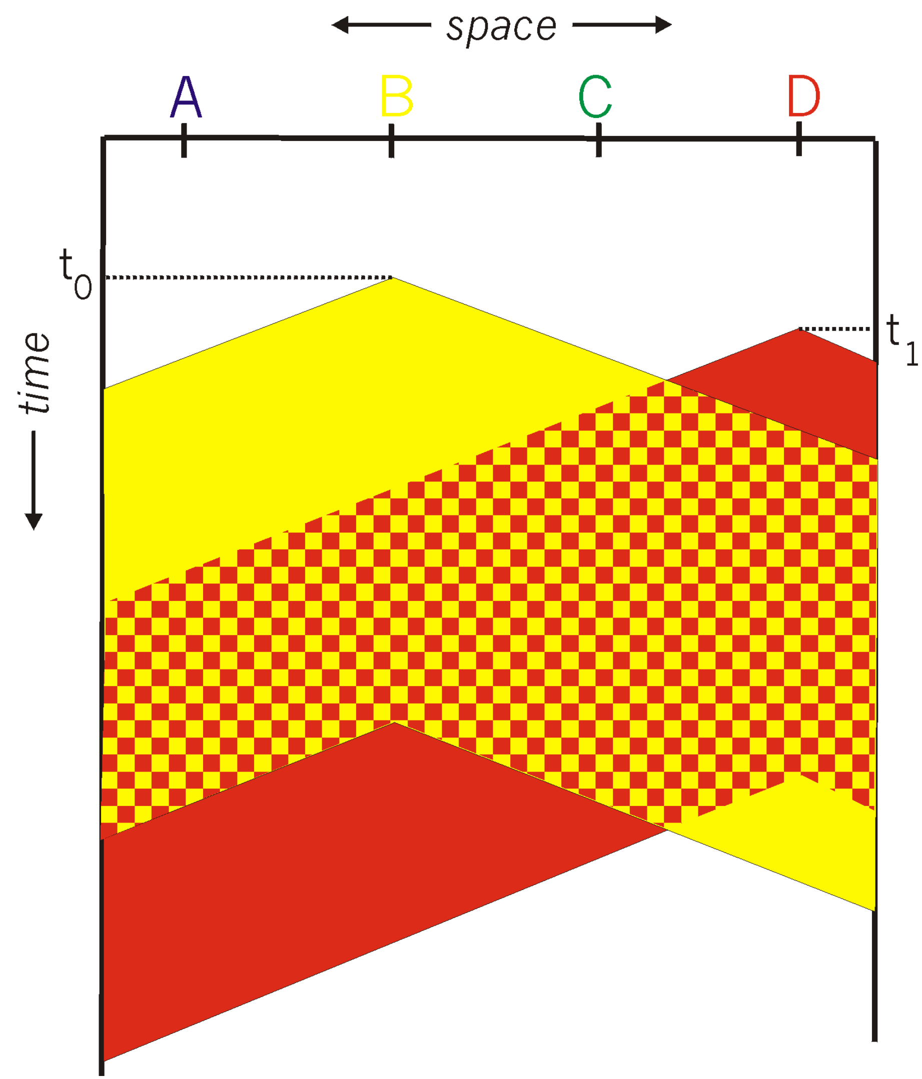
- Human analogy: don't interrupt others!

CSMA collisions

collisions *can* still occur: propagation delay means two nodes may not hear each other's transmission

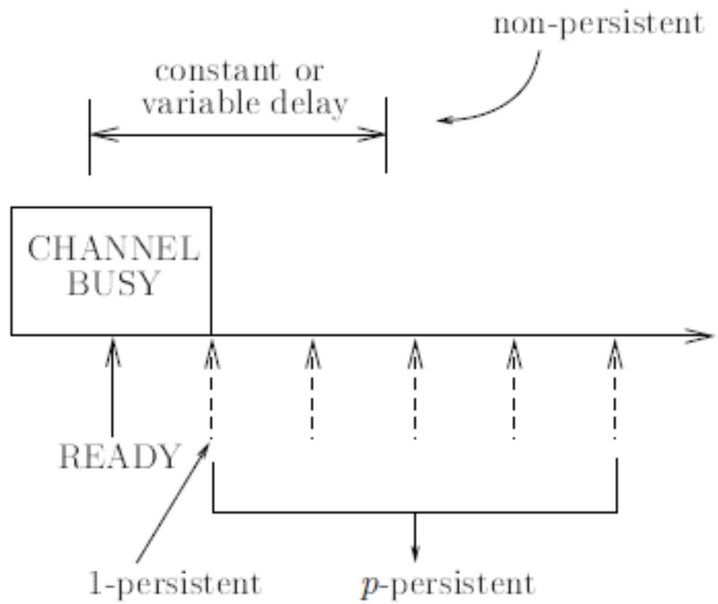
collision: entire packet transmission time wasted

note: role of distance & propagation delay in determining collision probability

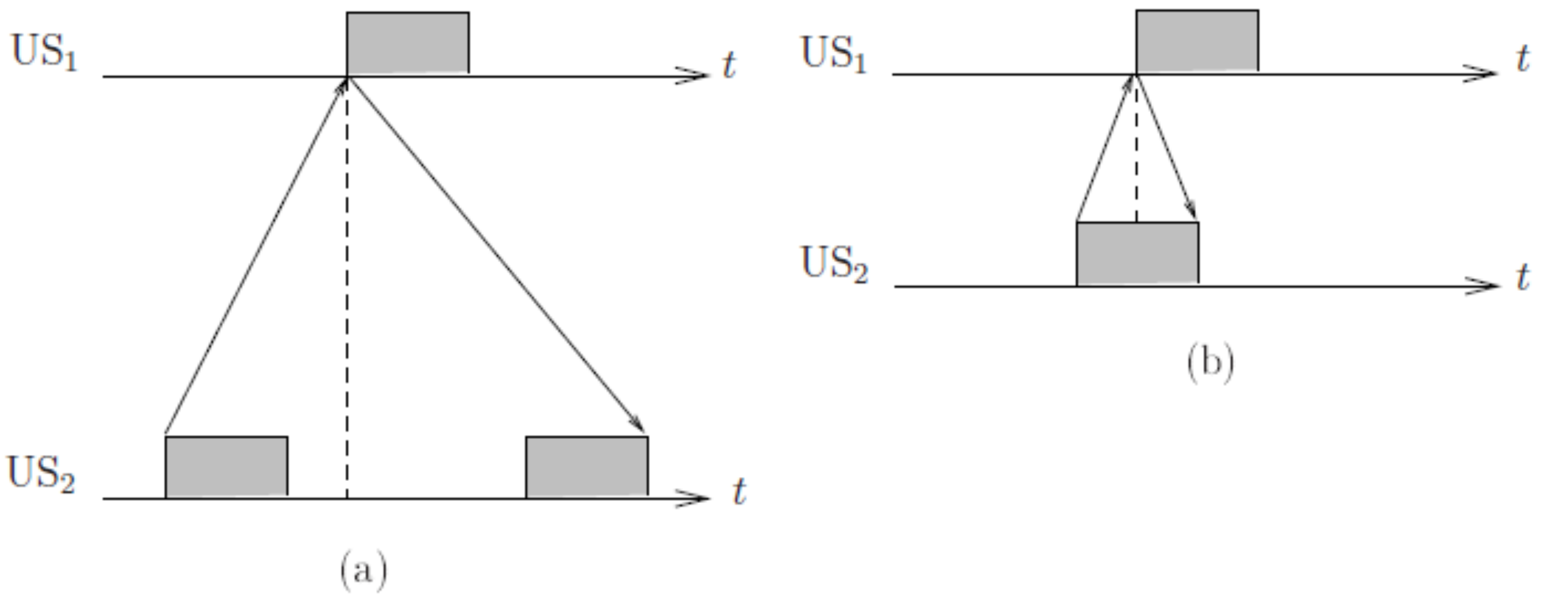


Retransmission strategies

- Non-persistent: if an user senses the channel busy, the transmission is deferred by a constant or pseudo-random delay.
- 1-persistent: if the medium becomes idle, the sender transmits with probability *p*, and so on.
- *p*-persistent: the sender waits a random period of time, checks the channel, and if it is idle, transmits with a probability *p*, and so on.



Vulnerable interval



$$\text{vulnerable interval} = \min\{t_p, 2\tau\}$$

where t_p is the packet time and τ is the propagation delay (i.e., 2τ is round trip delay).

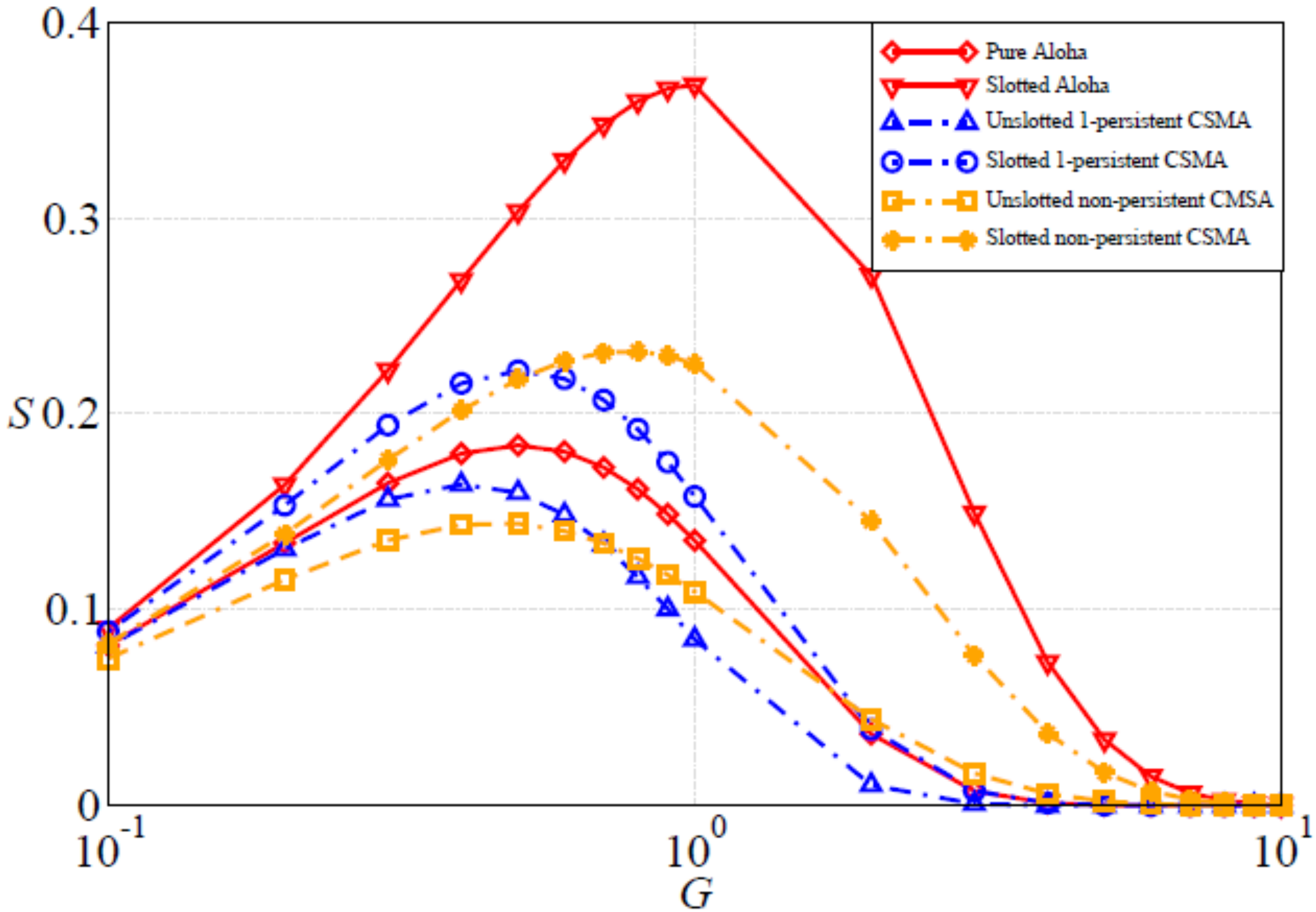
A Few Formulas

Protocol	Throughput (S)
Aloha	Ge^{-2G}
Slotted Aloha	Ge^{-G}
Unslotted 1-persistent CSMA	$\frac{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}{G(1+2a)-(1-e^{-aG})+(1+aG)e^{-G(1+a)}}$
Slotted 1-persistent CSMA	$\frac{G(1+a-e^{-aG})e^{-G(1+a)}}{(1+a)(1-e^{-aG})+ae^{-G(1+a)}}$
Unslotted nonpersistent CSMA	$\frac{Ge^{-aG}}{G(1+2a)+e^{-aG}}$
Slotted nonpersistent CSMA	$\frac{aGe^{-aG}}{1-e^{-aG}+a}$

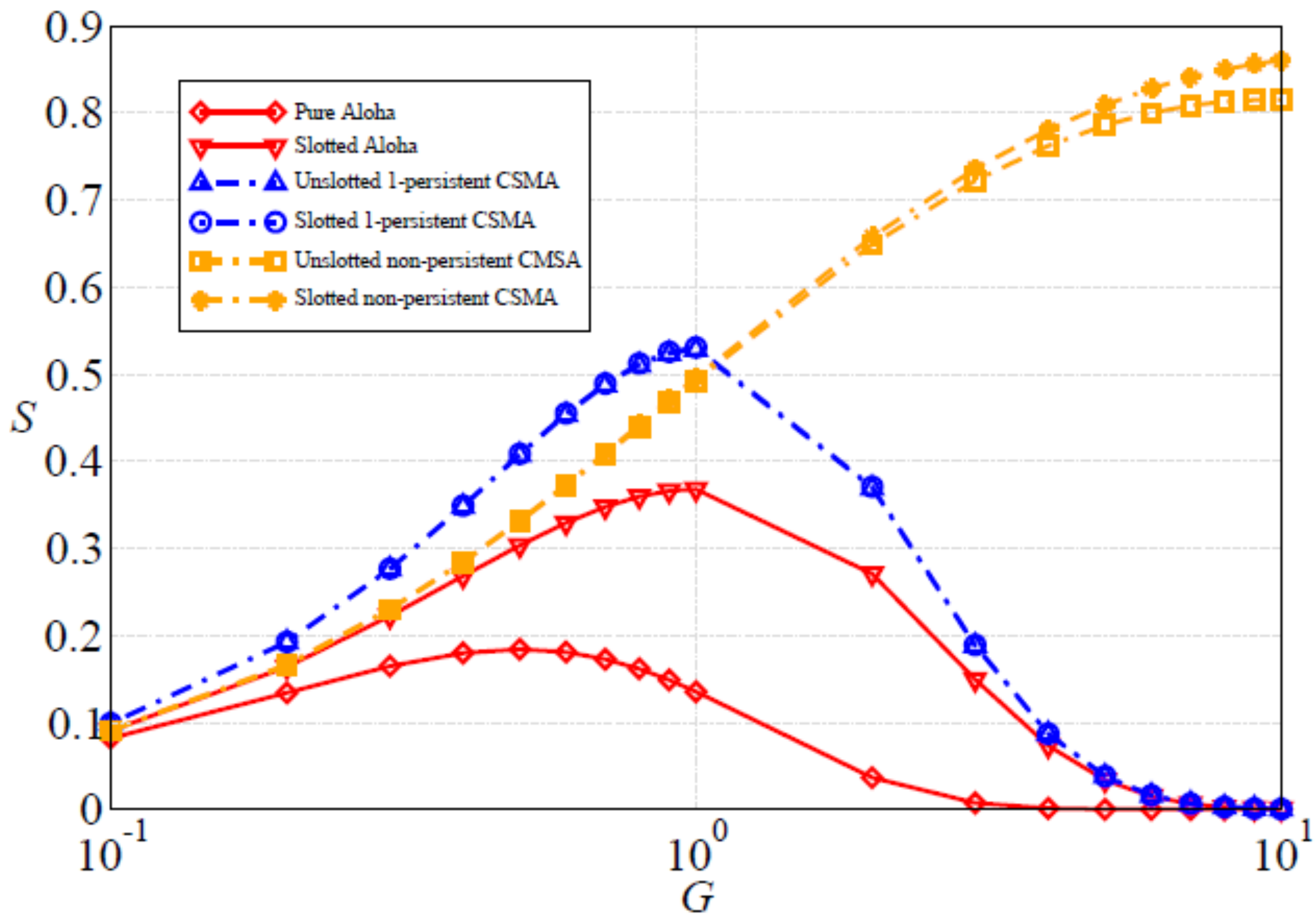
where

- $a \triangleq \frac{\tau}{T_{\mathrm{pck}}}$ (normalized propagation delay);
- S is the average number of successful transmissions in T_{pck};
- G is the average number of packets generated (network-wide) in T_{pck}

Throughput Comparison (CSMA with $a = 1$)



Throughput Comparison (CSMA with $a = 0.01$)



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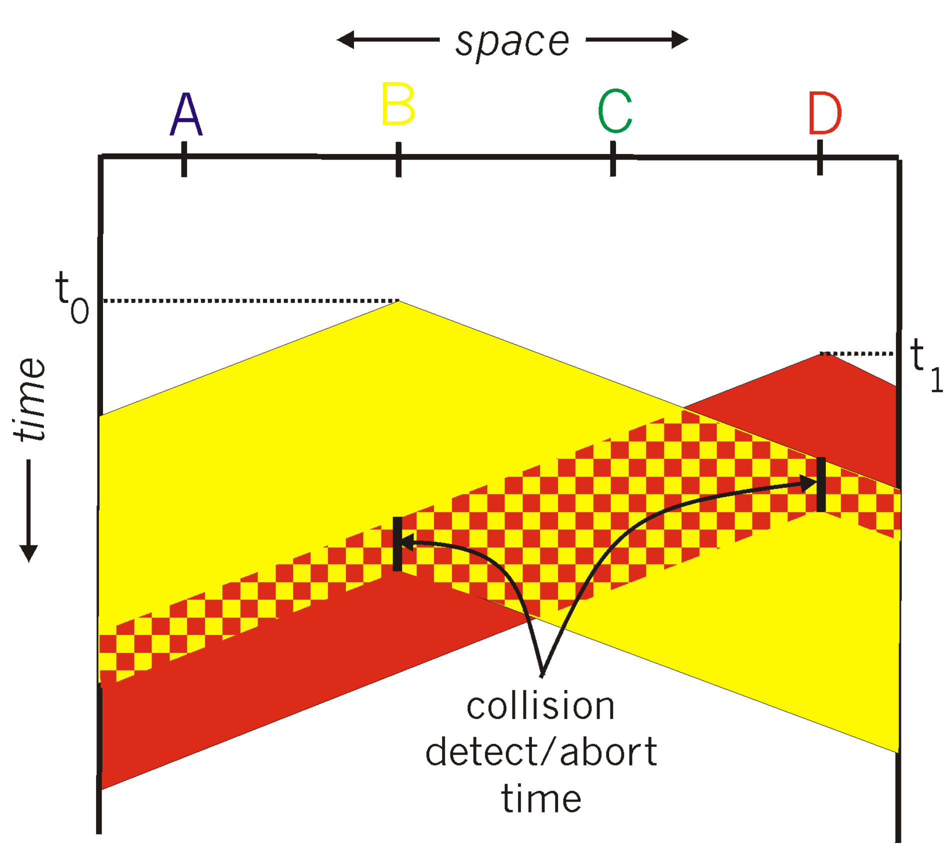
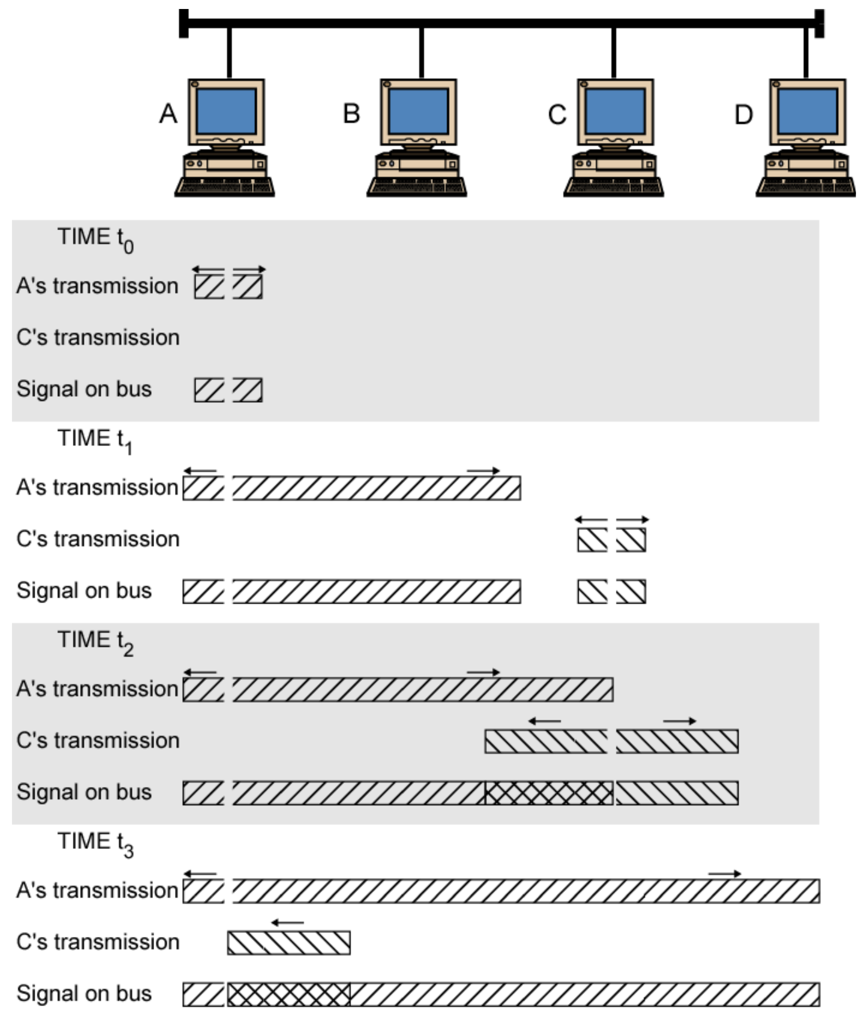
CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA
  - collisions *detected* within short time
  - colliding transmissions aborted, reducing channel wastage
- collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: receiver shut off while transmitting
- human analogy: the polite conversationalist

CSMA/CD collision detection

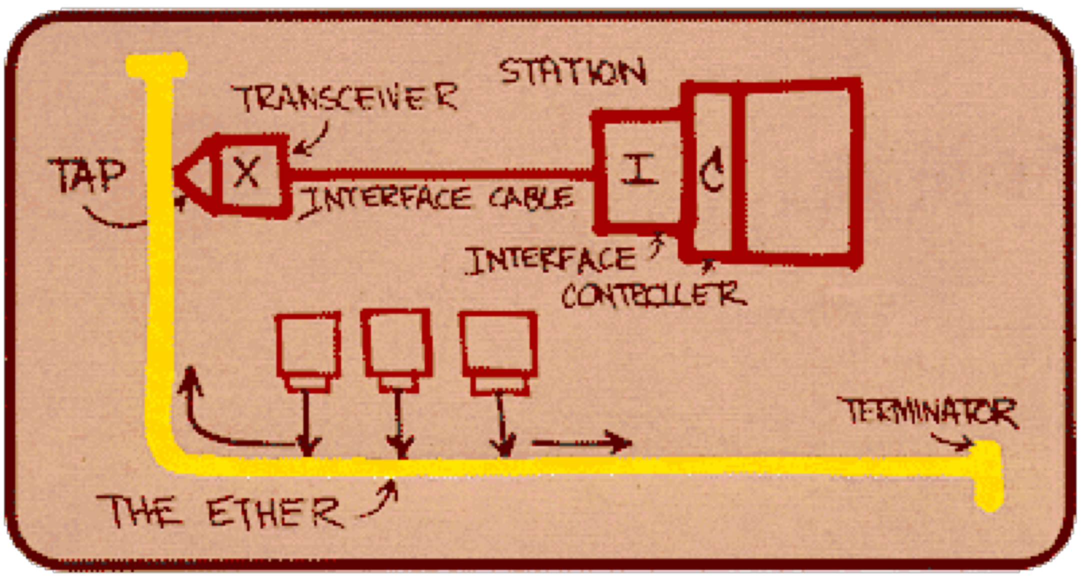




Ethernet

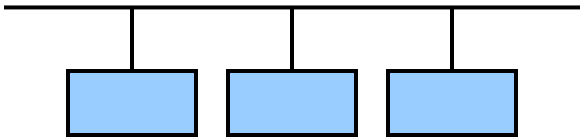
dominant wired LAN technology:

- cheap $20 for 100Mbs!
- first widely used LAN technology
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10 Mbps – 10 Gbps



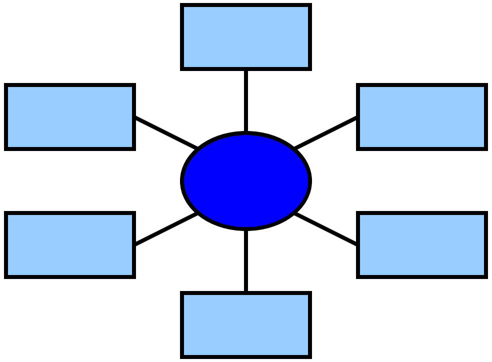
Metcalfe's Ethernet sketch

Ethernet Topologies



Bus Topology: Shared

All nodes connected to a wire



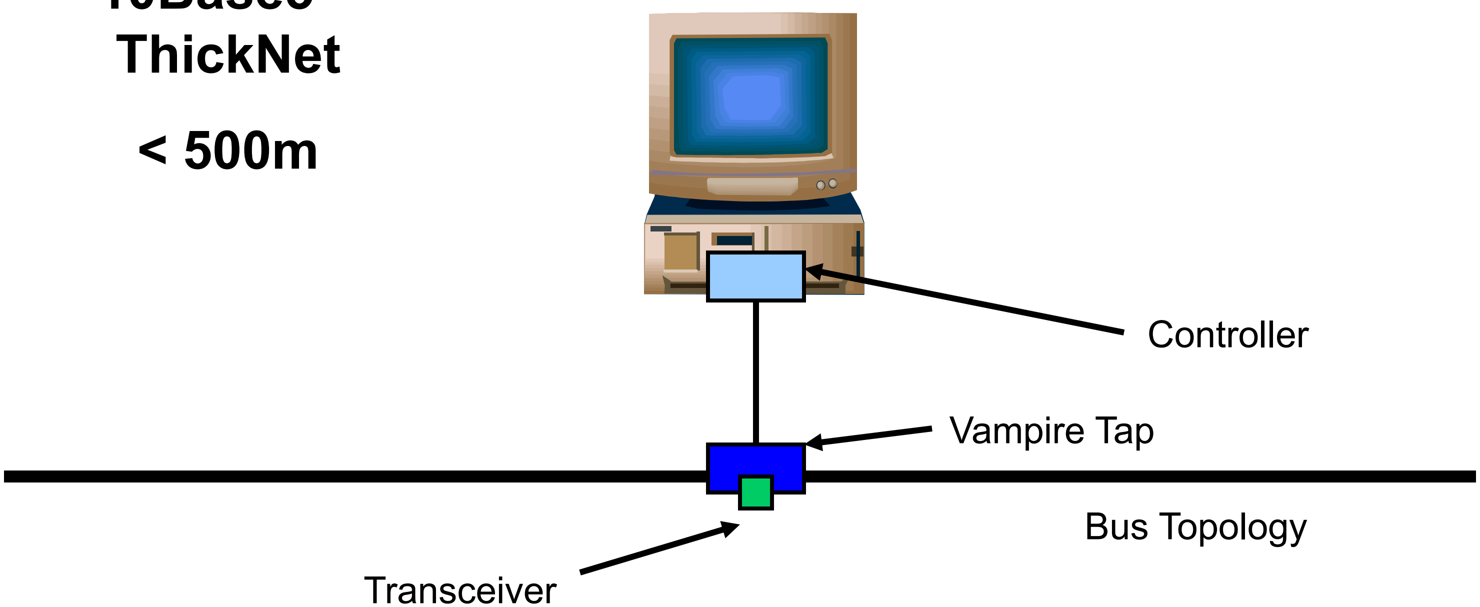
Star Topology:

All nodes connected to a central repeater

Ethernet Connectivity

10Base5 – ThickNet

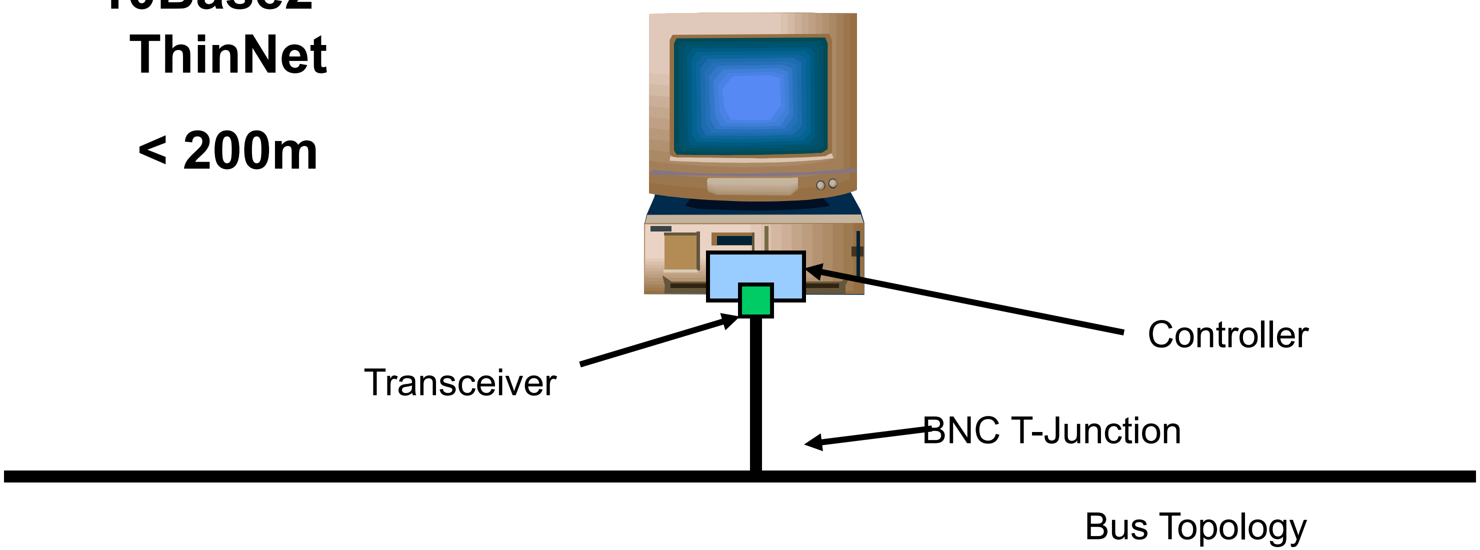
< 500m



Ethernet Connectivity

10Base2 – ThinNet

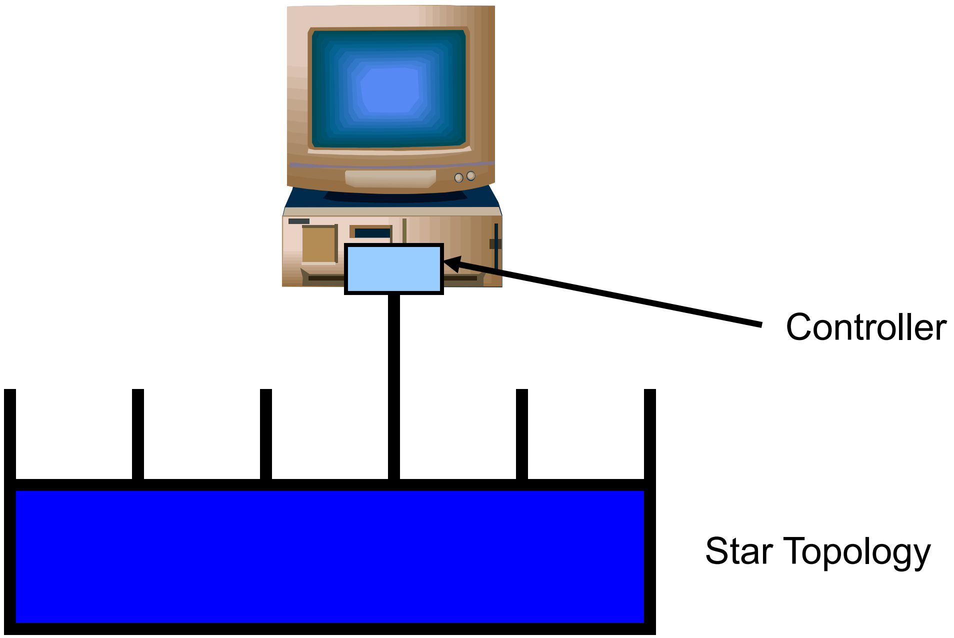
< 200m



Ethernet Connectivity

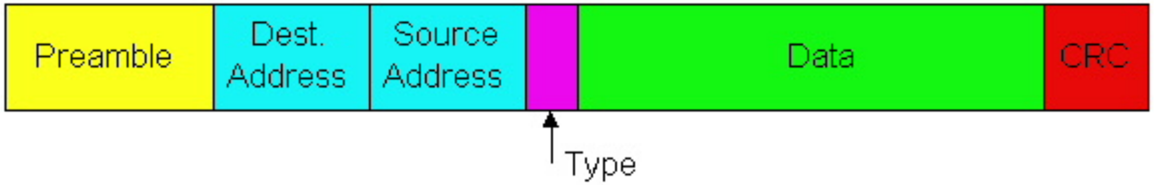
10BaseT

< 100m



Ethernet Frame Structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in Ethernet frame

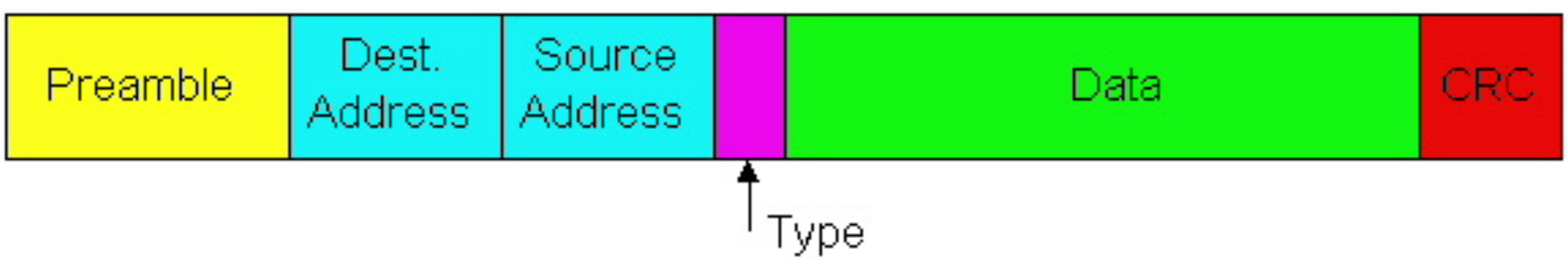


Preamble:

- 7 bytes with pattern 10101010 followed by one byte with pattern 10101011
- Used to synchronize receiver, sender clock rates (Manchester encoding)

Ethernet Frame Structure (ctd)

- Addresses: 6 bytes
  - if adapter receives frame with matching destination address, or with broadcast address (eg ARP packet), it passes data in frame to net-layer protocol
  - otherwise, adapter discards frame
- Type: indicates the higher layer protocol (mostly IP but others may be supported such as Novell IPX and AppleTalk)
- CRC: checked at receiver, if error is detected, the frame is simply dropped



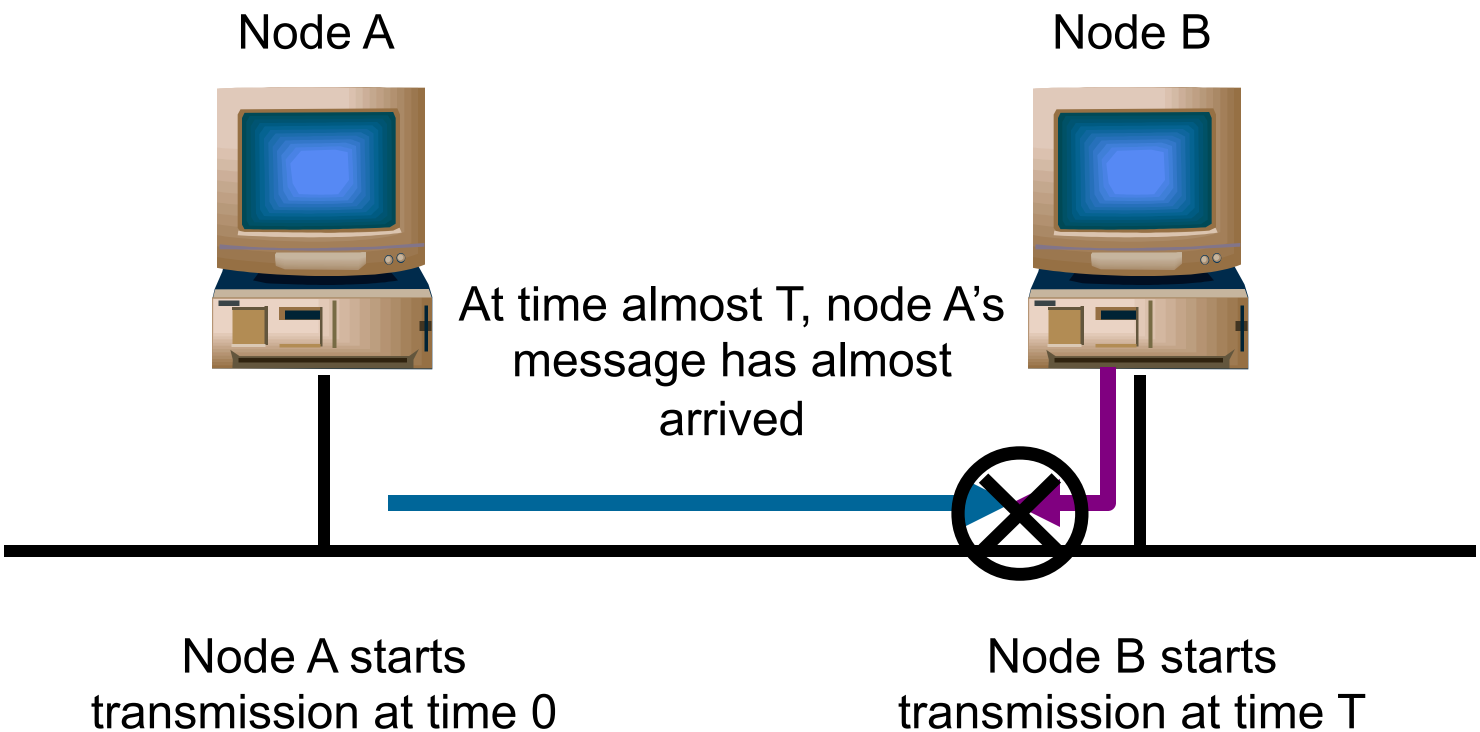
Ethernet Specifications

- Coaxial Cable
  – Up to 500m
- Taps
  – > 2.5m apart
- Transceiver
  – Idle detection
  – Sends/Receives signal
- Repeater
  – Joins multiple Ethernet segments
  – < 5 repeaters between any two hosts
- < 1024 hosts

Ethernet MAC Algorithm

- Sender/Transmitter
  - If line is idle (carrier sensed)
    - Send immediately
    - Send maximum of 1500B data (1527B total)
    - Wait 9.6 μs before sending again
  - If line is busy (no carrier sense)
    - Wait until line becomes idle
    - Send immediately
  - If collision detected
    - Stop sending and jam signal
    - Try again later

Ethernet MAC Algorithm

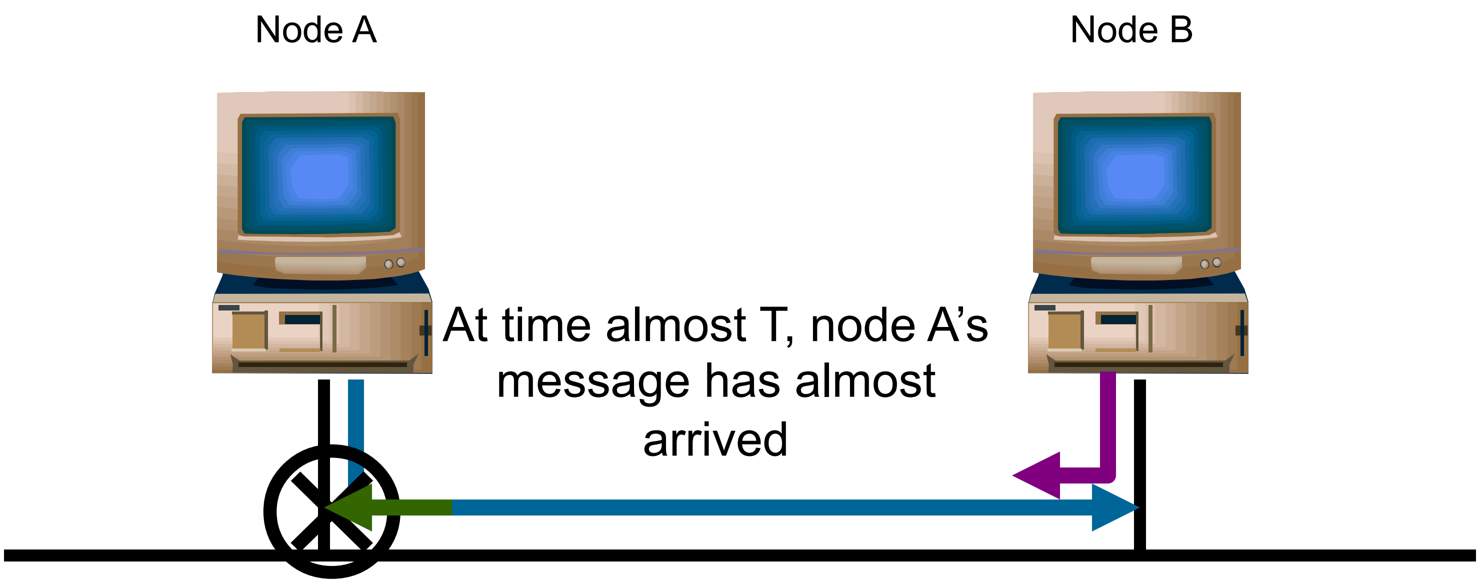


How can we ensure that A knows about the collision?

Collision Detection

- Example
  - Node A’s message reaches node B at time T
  - Node B’s message reaches node A at time 2T
  - For node A to detect a collision, node A must still be transmitting at time 2T
- 802.3
  - 2T is bounded to 51.2μs
  - At 10Mbps 51.2μs = 512b or 64B
  - Packet length $\geq$ 64B
- Jam after collision
  - Ensures that all hosts notice the collision

Ethernet MAC Algorithm



Node A starts transmission at time 0

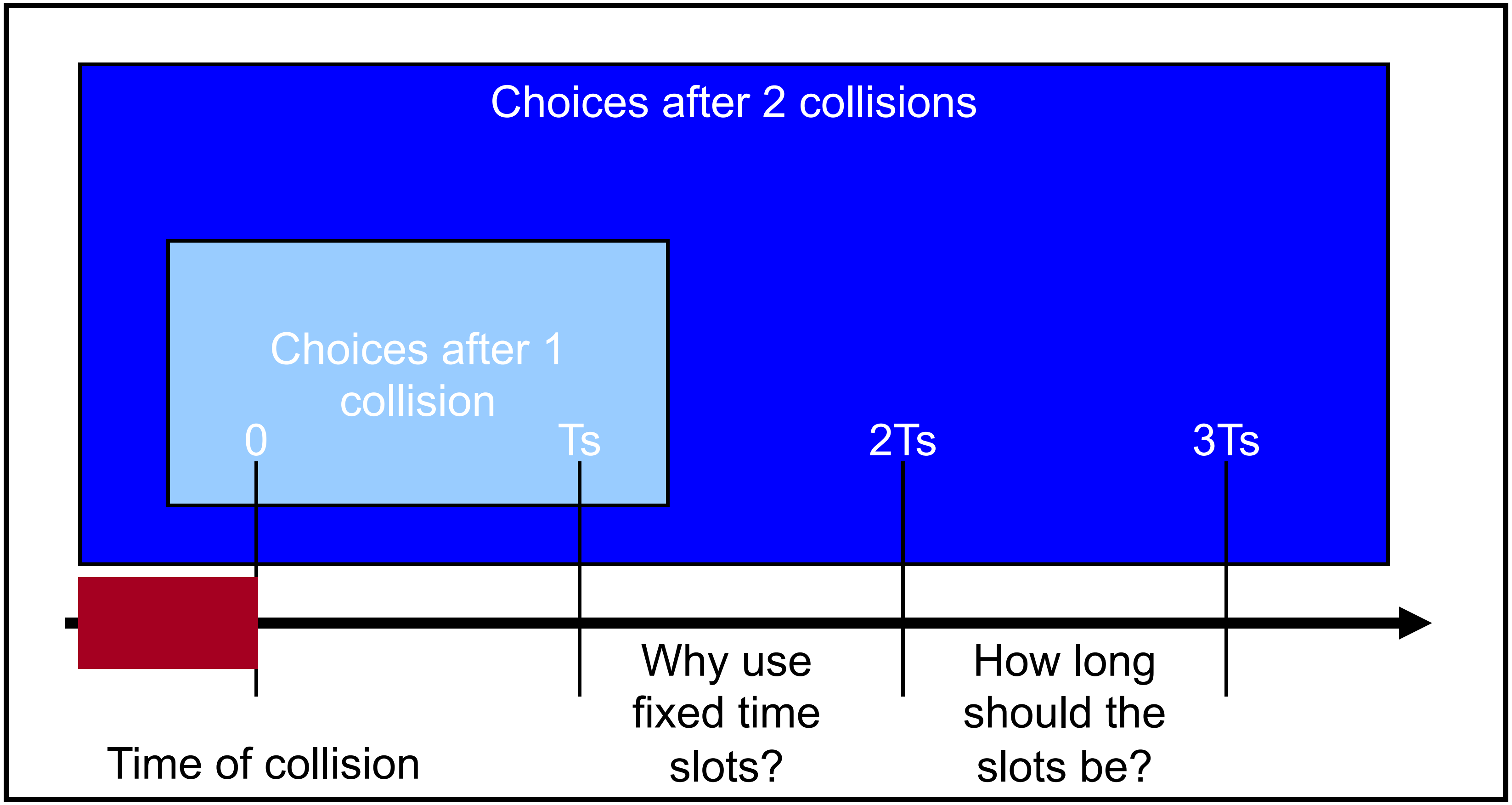
Node B starts transmission at time T

At time 2T, A is still transmitting and notices a collision

Retransmission

- How long should a host wait to retry after a collision?
  - Binary exponential backoff
    - Maximum backoff doubles with each failure
    - After N failures, pick an N-bit number
    - 2^N discrete possibilities from 0 to maximum

Binary Exponential Backoff



Binary Exponential Backoff

- For 802.3, $T = 51.2\ \mu s$
- Consider the following
  - k hosts collide
  - Each picks a random number from 0 to $2^{(N-1)}$
  - If the minimum value is unique
    - All other hosts see a busy line
    - Note: Ethernet RTT < $51.2\ \mu s$
  - if the minimum value is not unique
    - Hosts with minimum value slot collide again!
    - Next slot is idle
    - Consider the next smallest backoff value

CSMA/CD efficiency

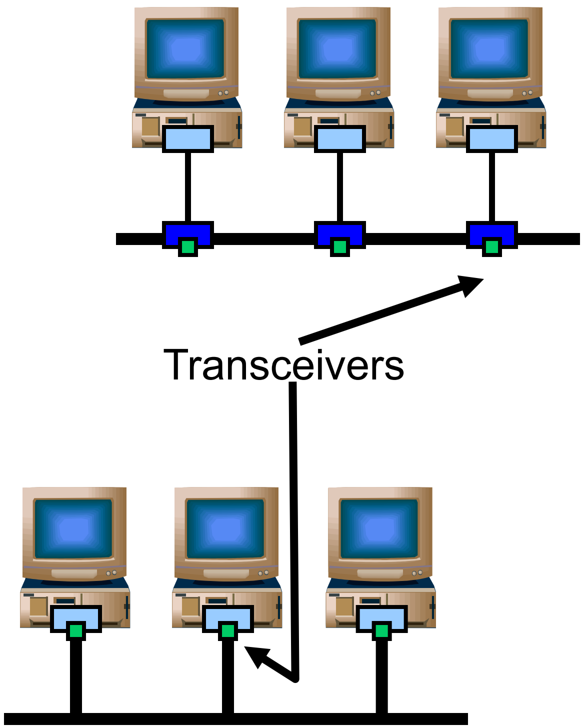
- t_{prop} = max prop between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame
  - Efficiency = $1/(1+5 * t_{prop} / t_{trans})$
  - For 10 Mbit Ethernet, t_{prop} = 51.2 us, t_{trans} = 1.2 ms
  - Efficiency is 82.6%!
- Much better than ALOHA, but still decentralized, simple, and cheap
- Efficiency goes to 1 as t_{prop} goes to 0
- Goes to 1 as t_{trans} goes to infinity

Frame Reception

- Sender handles all access control
- Receiver simply pulls the frame from the network
- Ethernet controller/card
  - Sees all frames
  - Selectively passes frames to host processor
- Acceptable frames
  - Addressed to host
  - Addressed to broadcast
  - Addressed to multicast address to which host belongs
  - Anything (if in promiscuous mode)
    - Need this for packet sniffers/TCPDump

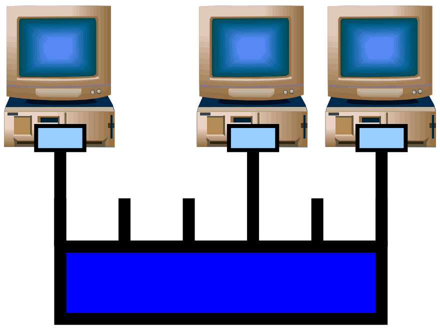
Collision Detection Techniques: Bus Topology

- Transceiver handles
  - Carrier detection
  - Collision detection
  - Jamming after collision
- Transceiver sees sum of voltages
  - Outgoing signal
  - Incoming signal
- Transceiver looks for
  - Voltages impossible for only outgoing



Collision Detection Techniques: Hub Topology

- Controller/Card handles
  - Carrier detection
- Hub handles
  - Collision detection
  - Jamming after collision
- Need to detect activity on all lines
  - If more than one line is active
    - Assert collision to all lines
    - Continue until no lines are active



10Mbps Ethernet Media

Name	Cable	Advantages	Max. Segment Length	Max Nodes on Segment
10Base5	Thick Coaxial (10mm)	Good for backbones	500m	100
10Base2	Thin Coaxial (5mm)	Cheapest system	200m	30
10BaseT	Twisted Pair (0.5mm)	Easy Maintenance	100m	1 (to hub)
10BaseFP	Fiber (0.1mm)	Best between buildings	500m	33
Extended segments may have up to 4 repeaters (total of 2.5km)				

100Mbps Ethernet Media

Name	Cable	Max. Segment Length	Advantages
100BaseT4	4 Twisted Pair	100m	Cat 3, 4 or 5 UTP
100BaseTX	Twisted Pair	100m	Full duplex on Cat 5 UTP
100BaseFX	Fiber Pair	100m	Full duplex, long runs
All hub based. Other types not allowed. Hubs can be shared or switched			

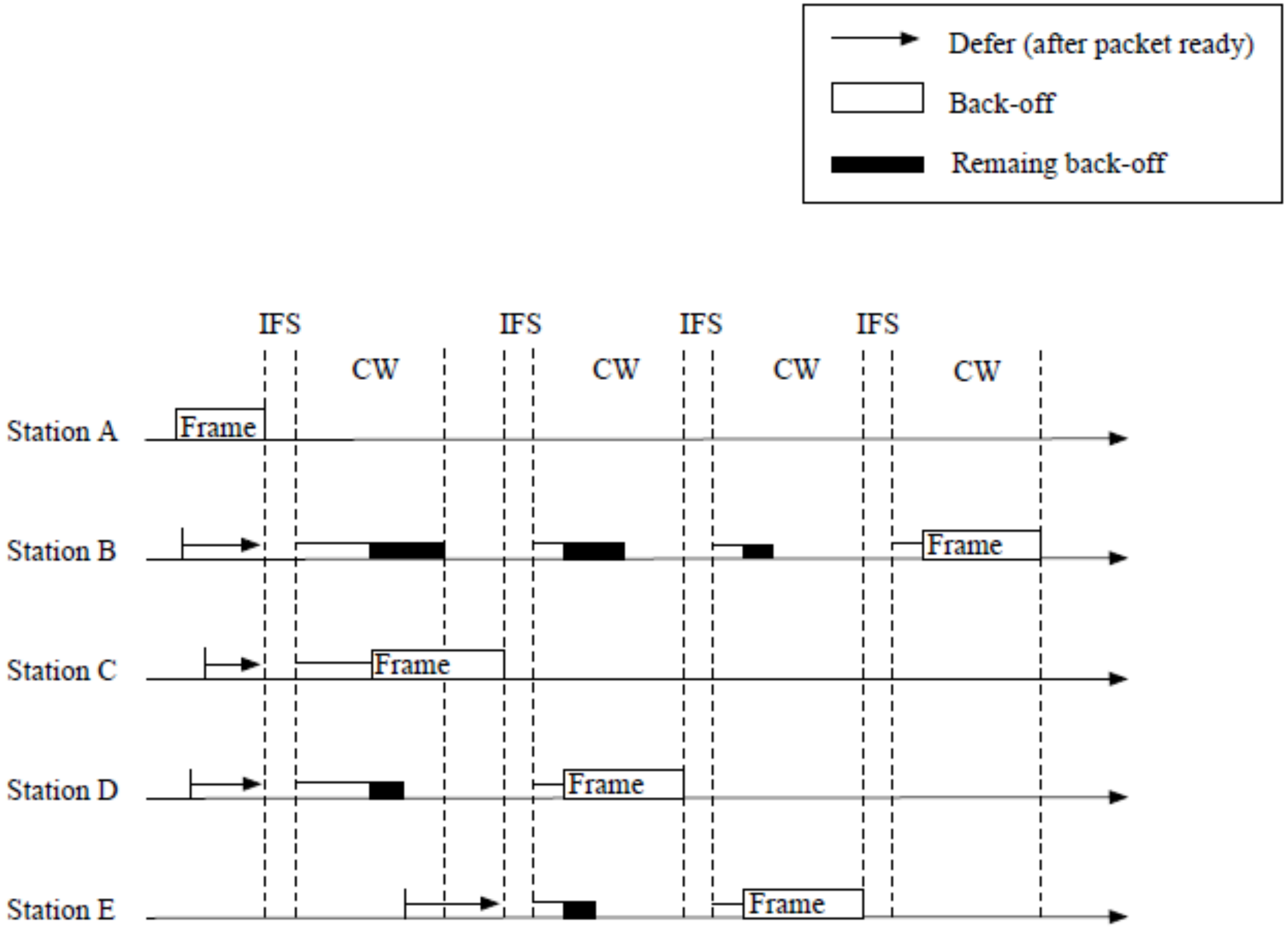
Ethernet in Practice

- Number of hosts
  - Limited to 200 in practice, standard allows 1024
- Range
  - Typically much shorter than 2.5km limit in standard
- Round Trip Time
  - Typically 5 or 10 μs, not 50
- Flow Control
  - Higher level flow control limits load (e.g. TCP)
- Topology
  - Star easier to administer than bus

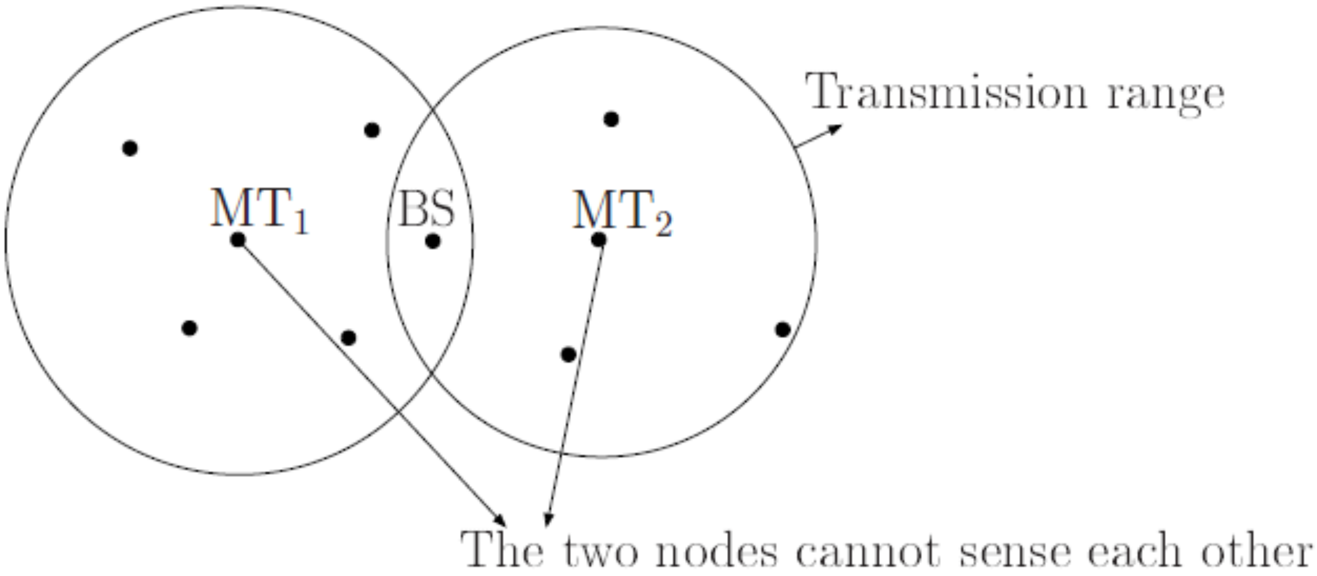
Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- Physical layer: modulation
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - **WiFi (CSMA/CA)**
- Personal Area Networks
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

CSMA/CA in IEEE 802.11 Networks



Hidden and Exposed Terminal Problems



- Busy Tone Multiple Access (BTMA): bandwidth is divided into a message channel (for data) and a busy-tone channel (for requests).
- Request-To-Send/Clear-To-Send (RTS/CTS): this couple of messages is handshaked between neighbor stations to detect on-going transmissions.

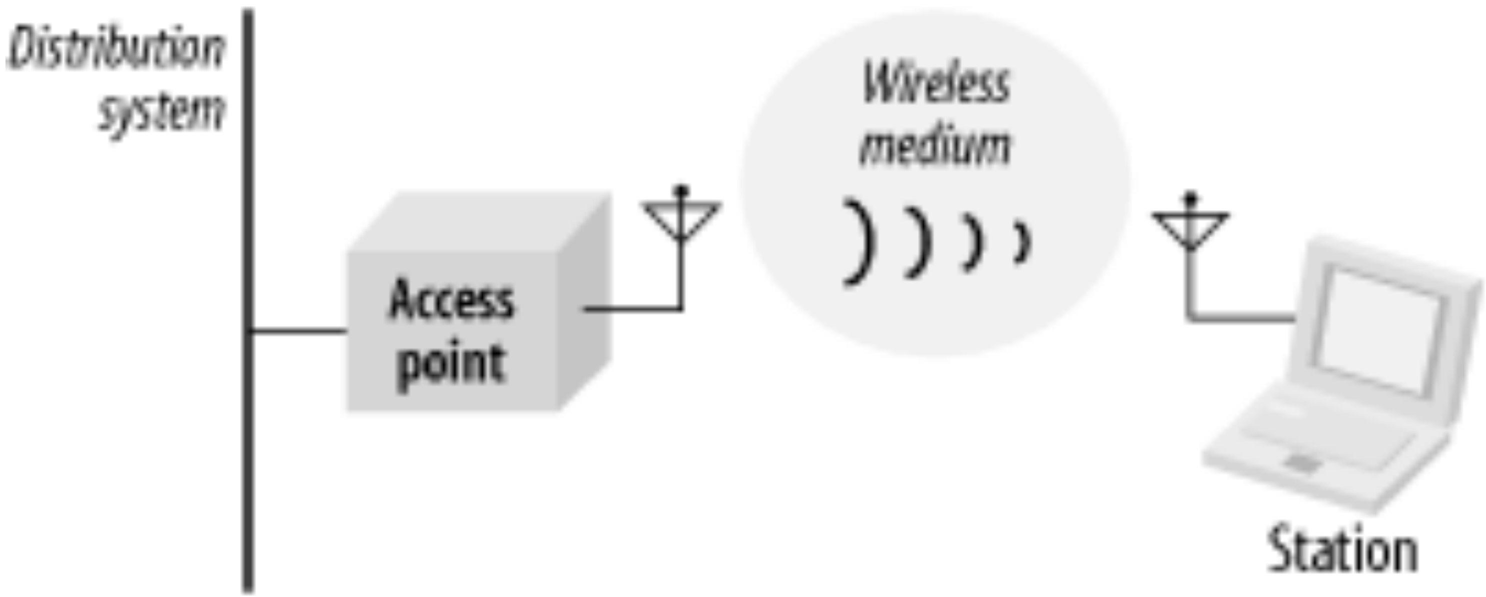
What is Wi-Fi?

- Short for ***wireless fidelity.***
- IEEE (Institute of Electrical and Electronics Engineers) established the 802.11 Group in 1990. Specifications for standard ratified in 1997.
- Initial speeds were 1 and 2 Mbps.
- IEEE modified the standard in 1999 to include:
  - 802.11b
  - 802.11a
  - 802.11g was added in 2003.
- IEEE Created standard, but Wi-Fi Alliance certifies products

Wi-Fi Alliance

- Non-profit standards organization.
- Global organization that created the Wi-Fi brand name.
- Formerly the Wireless Ethernet Compatibility Alliance.
- The Wi-Fi CERTIFIED logo from the Wi-Fi Alliance.
  - Rigorous interoperability testing requirements.
  - Certifies the interoperability of 802.11 products from the many different vendors.

Wireless LAN Networks

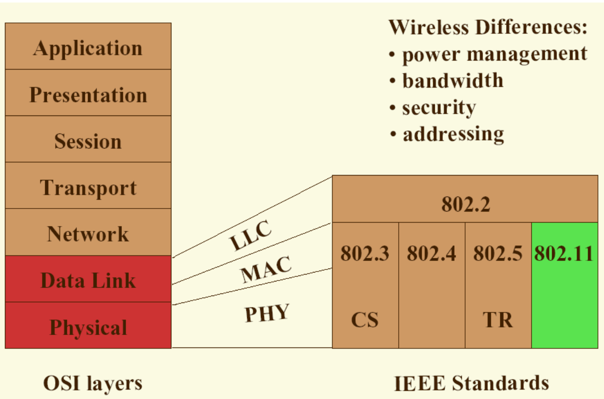


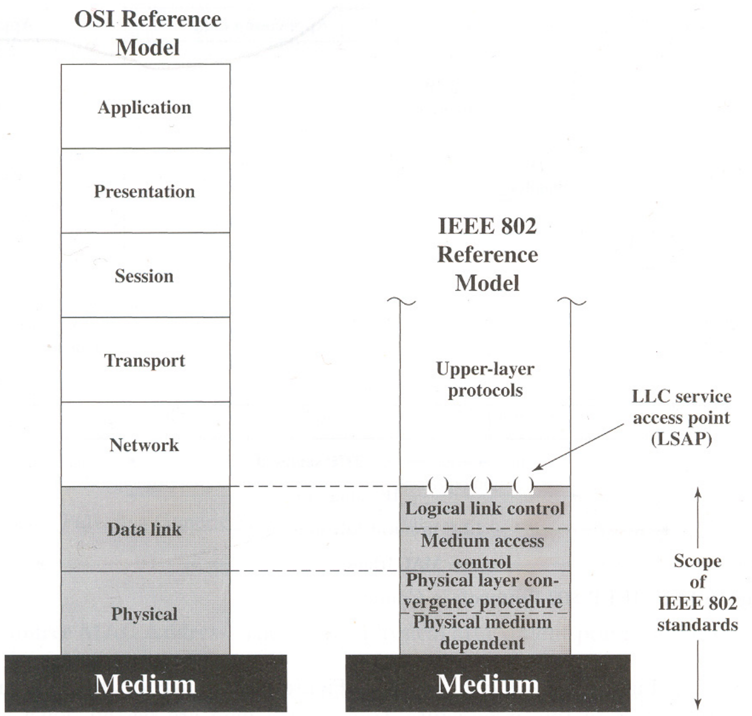
Advantages/Disadvantages

- Advantages
  - Freedom – You can work from any location that you can get a signal.
  - Setup Cost – No cabling required.
  - Flexibility – Quick and easy to setup in temp or permanent space.
  - Scaleable – Can be expanded with growth.
  - Mobile Access – Can access the network on the move.
- Disadvantages
  - Speed – Slower than cable.
  - Range – Affected by various medium.
  - Travels best through open space.
  - Reduced by walls, glass, water, etc
  - Security – Greater exposure to risks.
  - Unauthorized access.
  - Compromising data.
  - Denial of service.

802.11 Standard

- 802.11 is primarily concerned with the lower layers of the OSI model.
- Data Link Layer
  - Logical Link Control (LLC).
  - Medium Access Control (MAC).
- Physical Layer
  - Physical Layer Convergence Procedure (PLCP).
  - Physical Medium Dependent (PMD).





IEEE 802 Protocol Layers Compared to OSI Model

802.11 sub-standards (amendments)

- 802.11 MAC (Media Access Control) ratified 1999
- 802.11b PHY 2.4 GHz (max 11 Mbps) ratified 1999
- 802.11a PHY 5.0 GHz (max 54 Mbps) ratified 1999
- 802.11g PHY 2.0 GHz (max 54 Mbps) ratified 2003
- 802.11i Security draft number XXX
- 802.11e QoS, Multimedia draft number XXX
- 802.11h European regulations for 5GHz draft number XXX
- 802.11h Japan regulations for 5GHz draft number XXX

802.11b Standard

- Well-supported, stable, and cost effective, but runs in the **2.4 GHz range** that makes it prone to interference from other devices (microwave ovens, cordless phones, etc) and also has security disadvantages.

- Limits the number of **access points in range of each other** to **three**.

- Has 11 channels, with 3 non-overlapping, and supports rates from 1 to 11 Mbps, but realistically about **4-5 Mbps max**.

- Uses **direct-sequence spread-spectrum** technology.

802.11g Standard

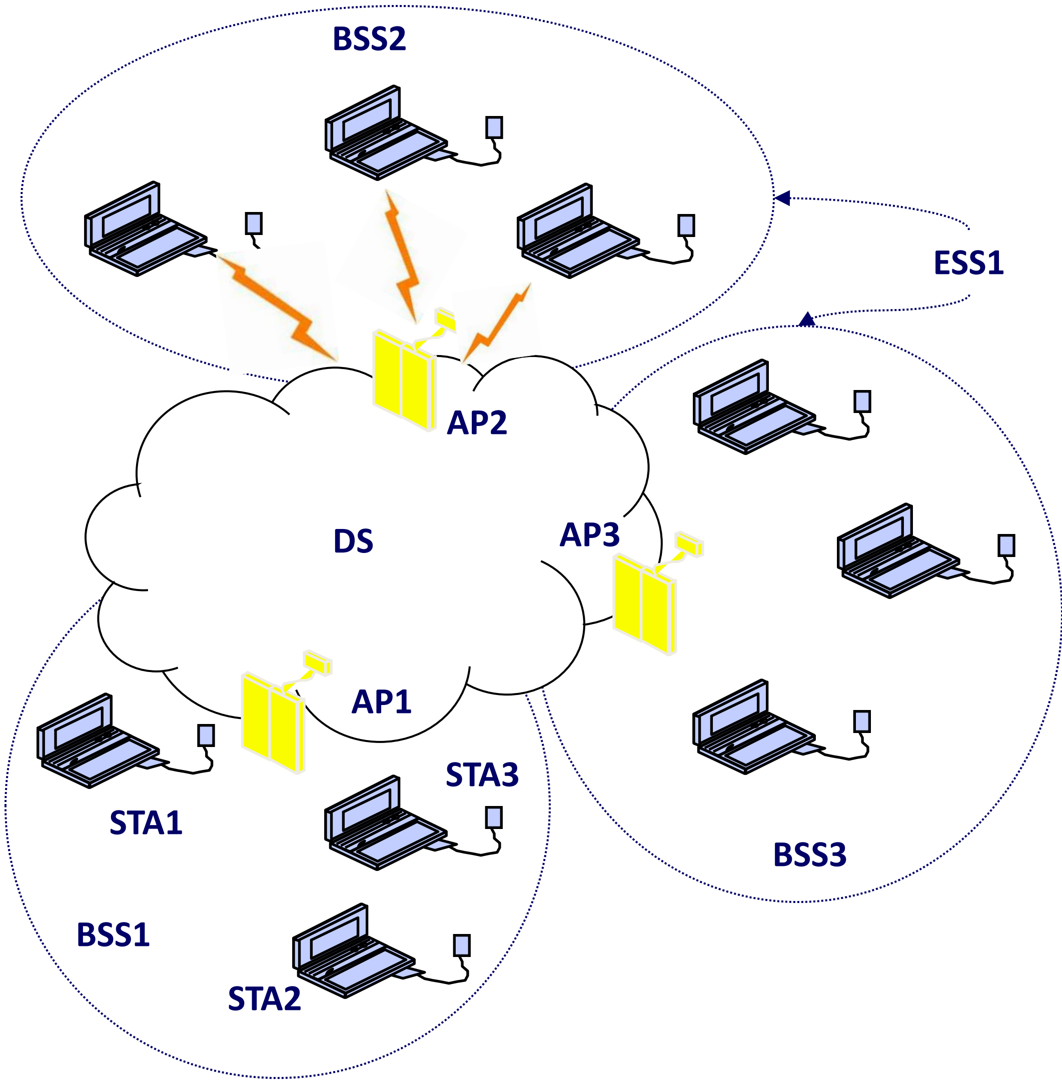
- Extension of 802.11b (still in **2.4 GHz band**), with the same disadvantages (security and interference).
- Has a **shorter range than 802.11b**.
- Is backwards compatible with 802.11b so it allows or a smooth transition from 11b to 11g.
- Flexible because multiple channels can be combined for faster throughput, but **limited to one access point**.
- Runs at 54 Mbps, but realistically about **20-25 Mbps** and about 14 Mbps when b associated
- Uses **frequency division multiplexing**

802.11a Standard

- Completely different from 11b and 11g.
- Flexible because **multiple channels can be combined** for higher throughput and **more access points can be co-located**.
- **Shorter range** than 11b and 11g.
- Runs in the **5 GHz range**, so **less interference** from other devices.
- Has **12 channels**, 8 non-overlapping, and supports rates from 6 to 54 Mbps, but realistically about **27 Mbps max**
- Uses **frequency division multiplexing**

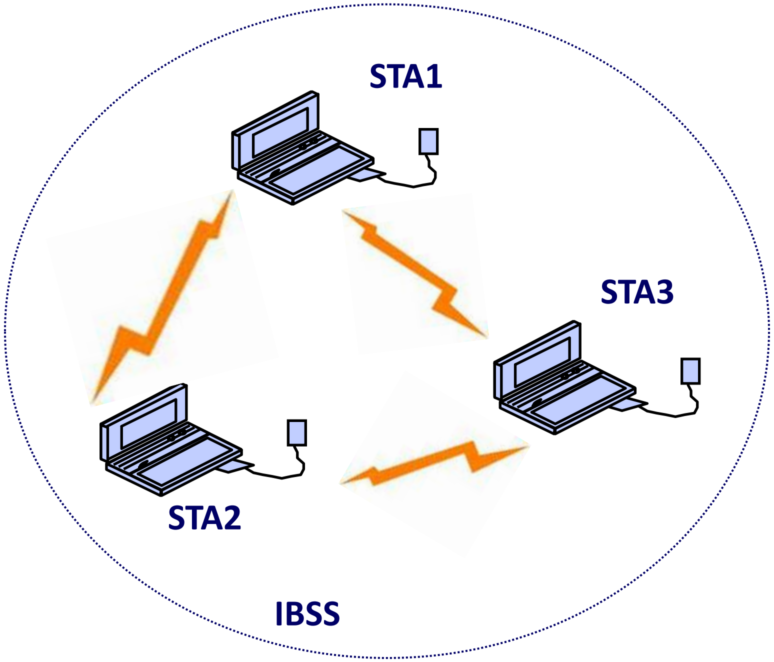
Infrastructure Mode (most common)

- Stations (STA)
  - any wireless device
- Access Point (AP)
  - connects BSS to DS
  - controls access by STA's
- Basic Service Set (BSS)
  - a region controlled by an AP
  - mobility is supported within a single BSS
- Extended Service Set (ESS)
  - a set of BSS's forming a virtual BSS
  - mobility is supported between BSS's in an ESS
- Distribution Service (DS)
  - connection between BSS's



Ad-hoc Mode

- Stations (STA)
  - any wireless device
  - act as distributed AP
- Independent Basic Service Set (IBSS)
  - BSS forming a self contained network
  - no AP and no connection to the DS



Security

- **WEP** (wired equivalent privacy) 64/128 bits

  Using RC4 algorithm, almost permanent key, very week

  security, able to crack by collecting statistic

  Current security level for 99.9% products on the market.
- **TKIP** (temporal key integrity protocol)

  Used RC4 algorithm with with a 128-bit "temporal key"

  but changes temporal keys every 10,000 packets and key dependes on address and sequence number.

  Will be required to obtain WiFi certification from 09/01/03
- **AES** (Advanced Encryption Standard)

  New, much more stronger encryption, protect against hacker frames in insertion. Need hardware accelerator. Optional feature.

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    - WiFi (CSMA/CA)
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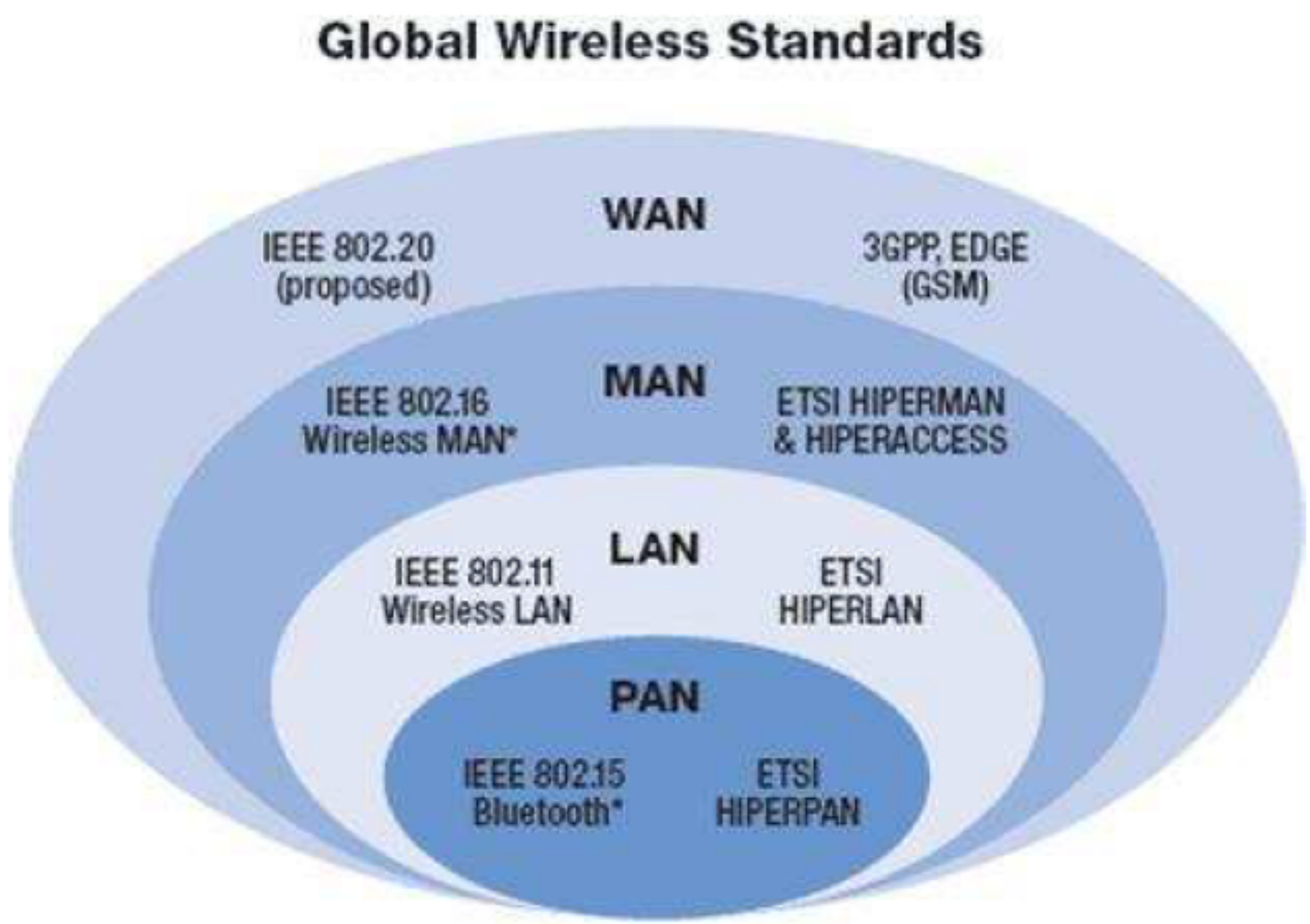
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

Where are PANs?



What is a PAN?

A PAN is a computer network used to communicate among devices, e.g., mobile phones, personal digital assistants (PDAs). The devices are placed close to the body of a specific person and their range is about few meters.

- Wired: connected to PCs or other devices via USB or FireWire.
- Wireless: connected to PCs or other devices via IrDA, Bluetooth, UWB, Z-Wave, and ZigBee.

Wireless PANs

- Short range (within, typically, 10 meters).
- Low computational complexity and energy consumption (battery-powered).
- Pugging-in: ideally, when any two wireless PAN-equipped devices come into close proximity, they can communicate.
- The main carrier frequency is 2.4 GHz.
- IEEE 802.15.x standard (Bluetooth, 802.15.1, and ZigBee, 802.15.4).

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  - Zigbee
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History Of Bluetooth

- Bluetooth was invented in 1994 by Ericsson.

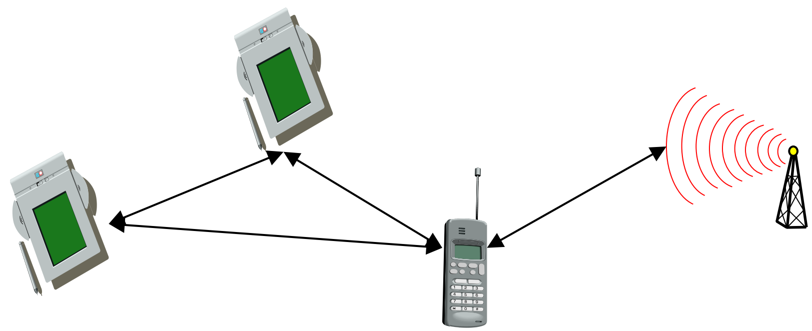
- The company later started working with a larger group of companies called the Bluetooth Special Interests Group, or "SIG," to develop the technology into what it is today.

- Bluetooth is not owned by any one company and is developed and maintained by SIG.

- The name Bluetooth came from a code name originally used by SIG for the project and is a reference to a 10th century Danish king named Harold Bluetooth (940-981 AC), who was responsible for uniting Norway, Sweden, and Denmark.

Bluetooth: Basics

- Consortium: Ericsson, Intel, IBM, Nokia, Toshiba…
- Scenarios:
  - connection of peripheral devices
    - loudspeaker, joystick, headset
  - support of ad-hoc networking
    - small devices, low-cost
  - bridging of networks
    - e.g., GSM via mobile phone - Bluetooth - laptop



- Simple, cheap, replacement of IrDA, low range, lower data rates, low-power
  - Worldwide operation: 2.4 GHz
  - Resistance to jamming and selective frequency fading:
    - FHSS over 79 channels (of 1MHz each), 1600hops/s
  - Coexistence of multiple piconets: like CDMA
  - Links: synchronous connections and asynchronous connectionless
  - Interoperability: protocol stack supporting TCP/IP, OBEX, SDP
  - Range: 10 meters, can be extended to 100 meters

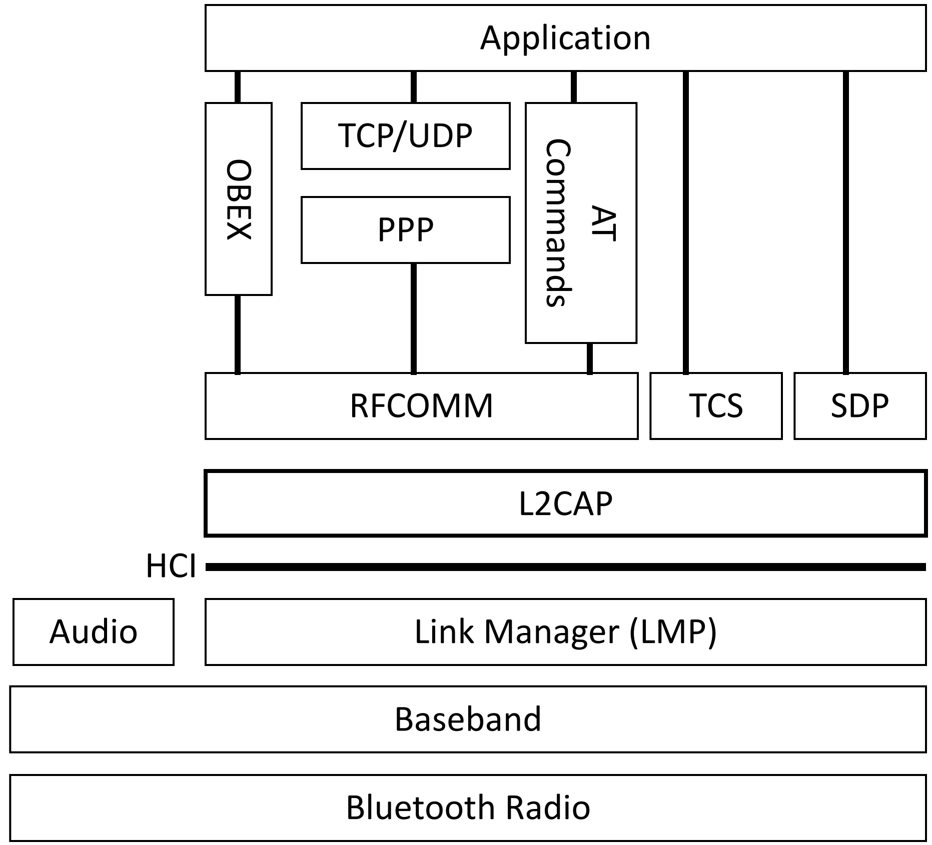
- Documentation: over 1000 pages specification: www.bluetooth.com

Bluetooth Application Areas

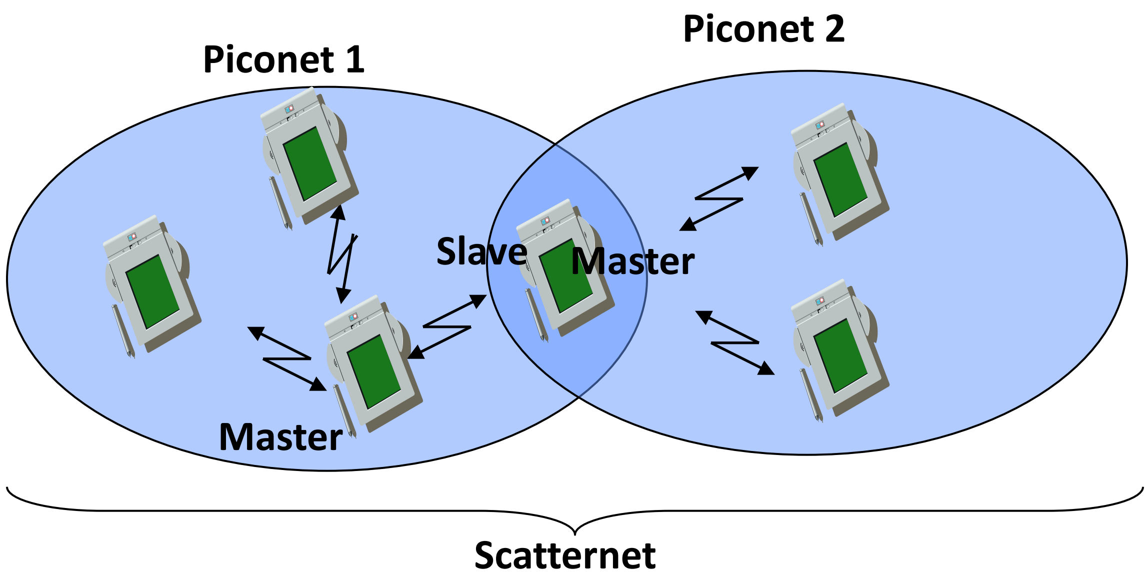
- Data and voice access points
  - Real-time voice and data transmissions
- Cable replacement
  - Eliminates need for numerous cable attachments for connection
- Low cost < $5
- Ad hoc networking
  - Device with Bluetooth radio can establish connection with another when in range
- Use modes:
  - File transfer
  - Internet bridge
  - LAN access
  - Synchronization
  - Three-in-one phone
  - Headset

Protocol Architecture

- BT **Radio** (2.4 GHZ Freq. Band):
- Modulation: Gaussian Frequency Shift Keying
- **Baseband**: FH-SS (79 carriers), CDMA (hopping sequence from the node MAC address)
- **Audio**: interfaces directly with the baseband. Each voice connection is over a 64Kbps SCO link. The voice coding scheme is the Continuous Variable Slope Delta (CVSD)
- Link Manager Protocol (**LMP**): link setup and control, authentication and encryption
- Host Controller Interface: provides a uniform method of access to the baseband, control registers, etc through USB, PCI, or UART
- Logical Link Control and Adaptation Layer (**L2CAP**): higher protocols multiplexing, packet segmentation/reassembly, QoS
- Service Discover Protocol (**SDP**): protocol of locating services provided by a Bluetooth device
- Telephony Control Specification (**TCS**): defines the call control signaling for the establishment of speech and data calls between Bluetooth devices
- **RFCOMM**: provides emulation of serial links (RS232). Upto 60 connections
- **OBEX**: OBject EXchange (e.g., vCard)



Network Topology



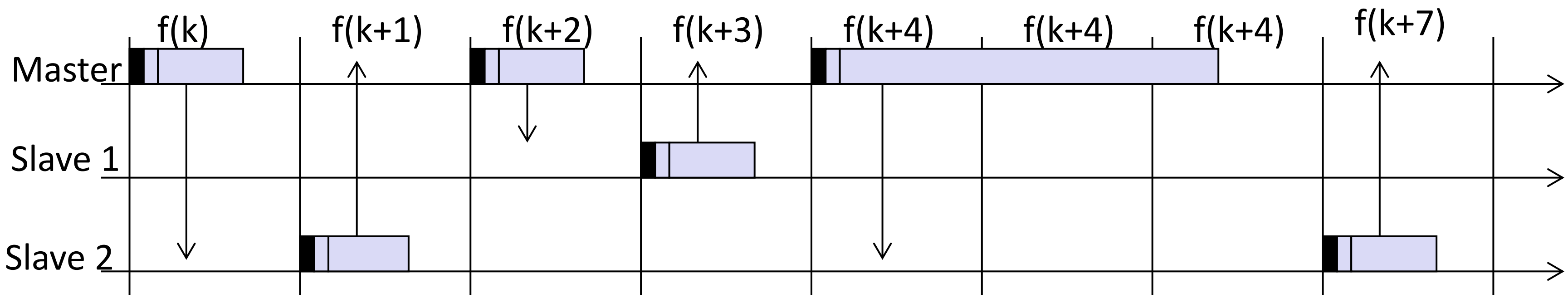
- Piconet = set of Bluetooth nodes synchronized to a unique master node
  - The piconet hopping sequence is derived from the master MAC address (BD_ADDR IEEE802 48 bits compatible address)
- Scatternet = set of piconets
- Master-Slaves can switch roles

Radio Specification

- Classes of transmitters
  - Class 1: Outputs 100 mW for maximum range
    - Power control mandatory
    - Provides greatest distance
  - Class 2: Outputs 2.4 mW at maximum
    - Power control optional
  - Class 3: Nominal output is 1 mW
    - Lowest power
- Frequency Hopping in Bluetooth
  - Provides resistance to interference and multipath effects
  - Provides a form of multiple access among co-located devices in different piconets

Bluetooth Piconet MAC

- Each node has a Bluetooth Device Address (BD_ADDR). The master BD_ADDR determines the sequence of frequency hops

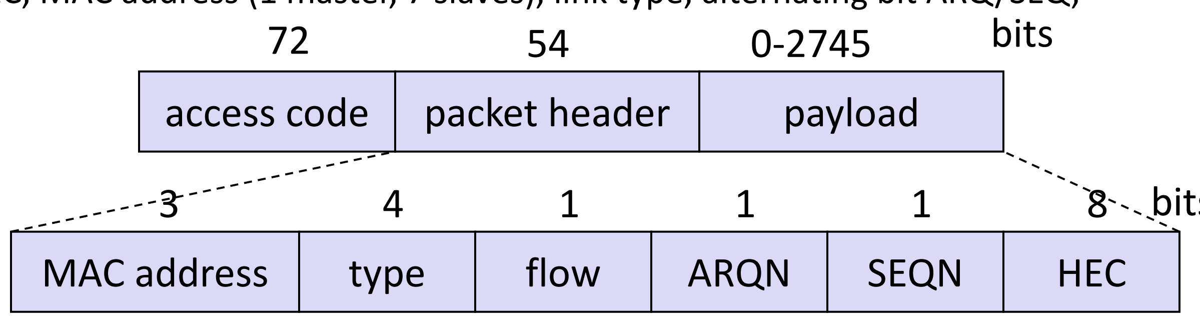


- Types of connections:

  Synchronous Connection-Oriented link (**SCO**) (symmetrical, circuit switched, point-to-point)

  Asynchronous Connectionless Link (**ACL**): (packet switched, point-to-multipoint, master-polls)

- Packet Format:
  - Access code: synchronization, when piconet active derived from master
  - Packet header (for ACL): 1/3-FEC, MAC address (1 master, 7 slaves), link type, alternating bit ARQ/SEQ, checksum



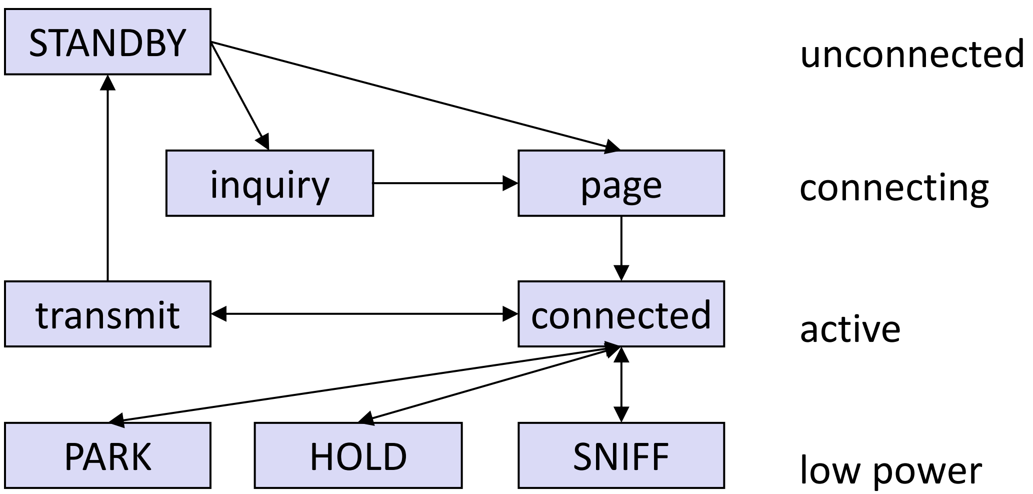
States of a Bluetooth Device

ACTIVE (connected/transmit): the device is uniquely identified by a 3bits AM_ADDR and is fully participating

SNIFF state: participates in the piconet only within the SNIFF interval

HOLD state: keeps only the SCO links

PARK state (low-power): releases AM_ADDR but stays synchronized with master



BT device addressing:

- BD_ADDR (48 bits)
- AM_ADDR (3bits): ACTIVE, HOLD, or SNIFF
- PM_ADDR (8 bits): PARK Mode address (exchanged with the AM_ADDR when entering PARK mode)
- AR_ADDR (8 bits): not unique used to come back from PARK to ACTIVE state

Bluetooth Link Security

- Elements:
  - Authentication – verify claimed identity
  - Encryption – privacy
  - Key management and usage
- Security algorithm parameters:
  - Unit address
  - Secret authentication key (128 bits key)
  - Secret privacy key (4-128 bits secret key)
  - Random number

Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- Physical layer: modulation
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - WiFi (CSMA/CA)
- Personal Area Networks
  - Bluetooth
  - **Zigbee**
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

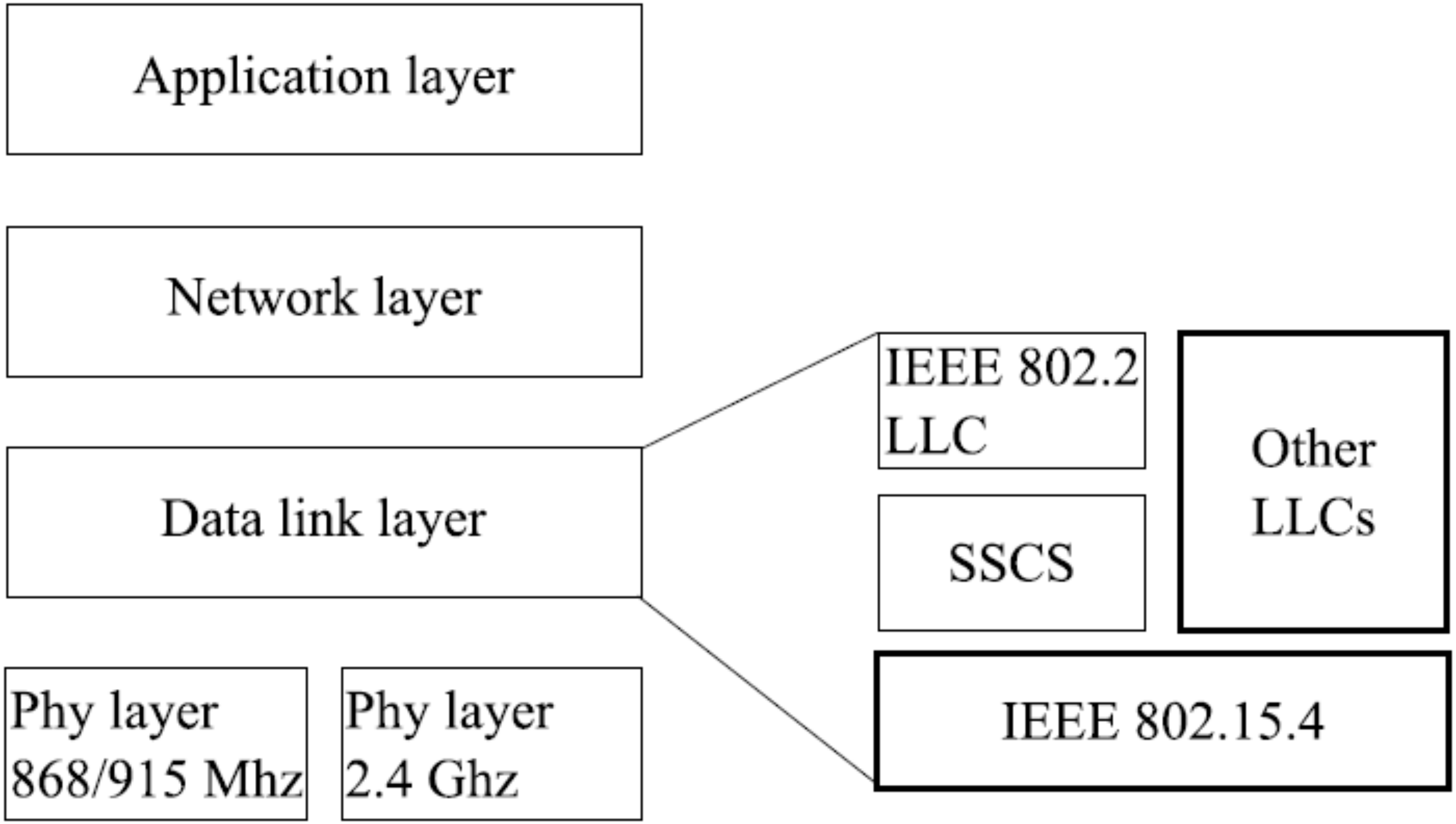
Zigbee

- Born in 2004—other versions in the next years.
- It can guarantee wireless data communication and, at the same time, high energy efficiency.
- It is explicitly designed for low-rate low-power PANs.
- First two layers of the ISO/OSI stack are derived from the IEEE 802.15.4 standard.
- Upon these, the other layers are defined by the ZigBee alliance.

IEEE 802.15.4: Main Functionalities

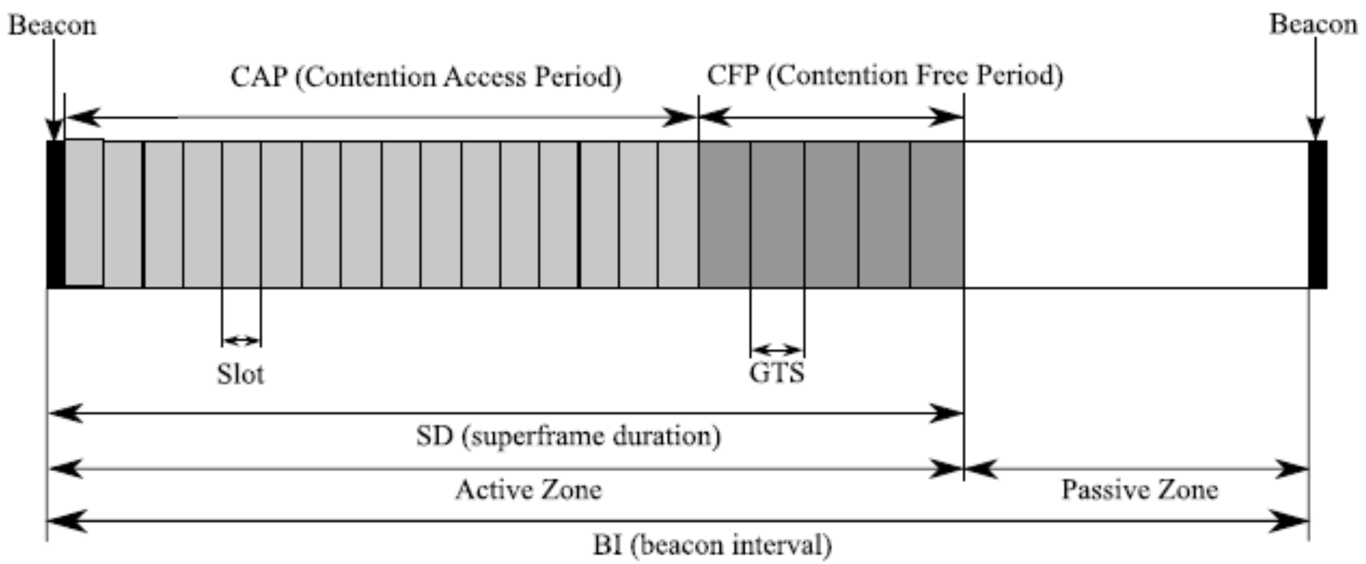
- Channel access management through a CSMA/CA mechanism.
- Reliable communication between two distinct MAC entities.
- Security management through a 128-bit symmetrical Advanced Encryption Standard (AES) key.
- Synchronization management through beacon packets.
- Support of (dis)association from the PAN.
- Management of Guaranteed Time Slots (GTS).

The ISO/OSI Stack of IEEE 802.15.4



Becon-Enabled Mode

- The use of beacon packets allows to synchronize the nodes.
- The time is divided into superframes.
- The nodes have, therefore, higher complexity, but duty cycle and channel access are better managed (GTSs).



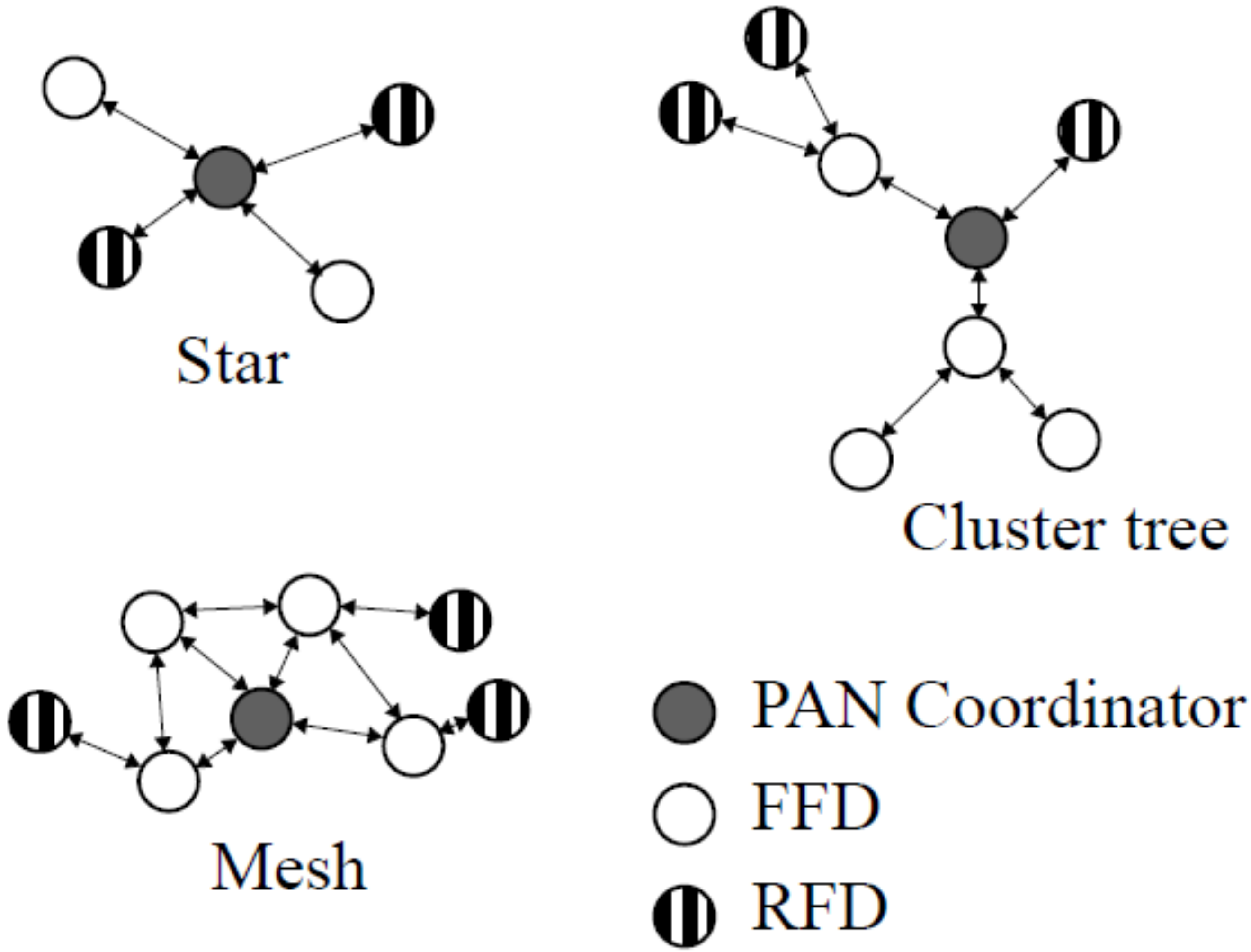
Beaconless Mode

- No synchronization between nodes.
- Nodes' structures are simpler, but, obviously the performance of beacon-enabled networks is better.
- The MAC protocol differs in terms of time management, synchronization, and packet retransmissions.

Network Topology

- Devices are grouped into PANs characterized by an identification number (PAN ID).
- At least one node is present and it has the role of coordinator.
- Coordinator tasks includes network initialization (e.g., PAN ID and parameter configuration), nodes' associations, and beacon transmission.
- Additional nodes are end devices with different functionalities.
- Nodes are logically divided into Full Function Devices (FFDs) and Reduced Function Devices (RFD).
- FFDs implement all functionalities of the ZigBee standard and can communicate with all other nodes in their transmission range.

Allowed Topologies



Specifications

- Three operating frequencies: 868 MHz (Europe), 916 MHz (USA), and 2.4 GHz (worldwide available) $\Longrightarrow$ UNLICESED BANDS!!!

- Co-channel interference with Bluetooth, WiFi, etc.

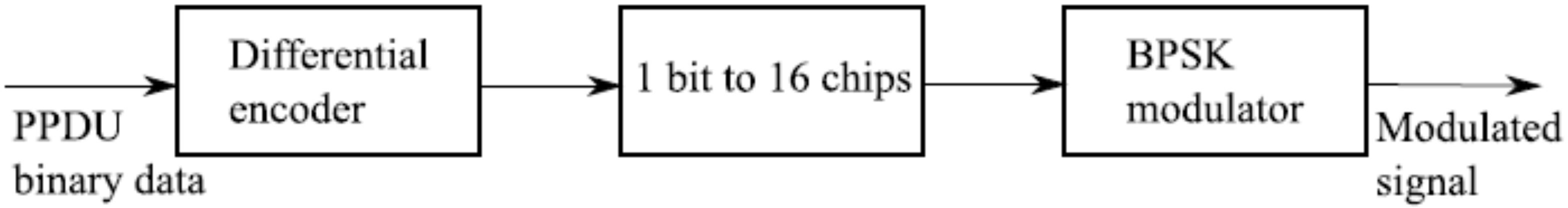
- Channel allocation:

Channel number	Frequency (MHz)
$k = 0$	868.3
$k = 1, \ldots, 10$	$906 + 2(k - 1)$
$k = 11, \ldots, 26$	$2405 + 5(k - 11)$

- Transmission rates: 20 and 40 kbps (at 868 and 916 MHz, respectively), and 250 kbps (at 2.4 GHz) $\Longrightarrow$ LOW RATES!!!

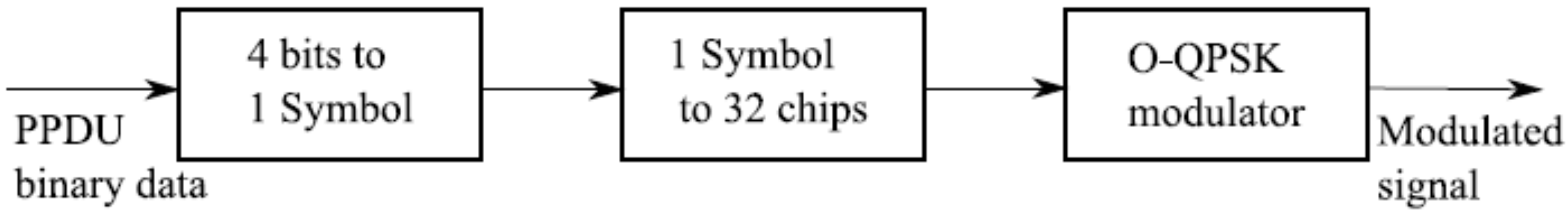
Modulation: 868 MHz and 916 MHz

- Differential encoding of the information bits.
- Direct Sequence Spread Spectrum (DSSS) expansion (factor 16).
- Binary Phase Shift Keying (BPSK) modulation before transmission.
- European and US bands differ for the chip rate.



Modulation: 2.4 GHz

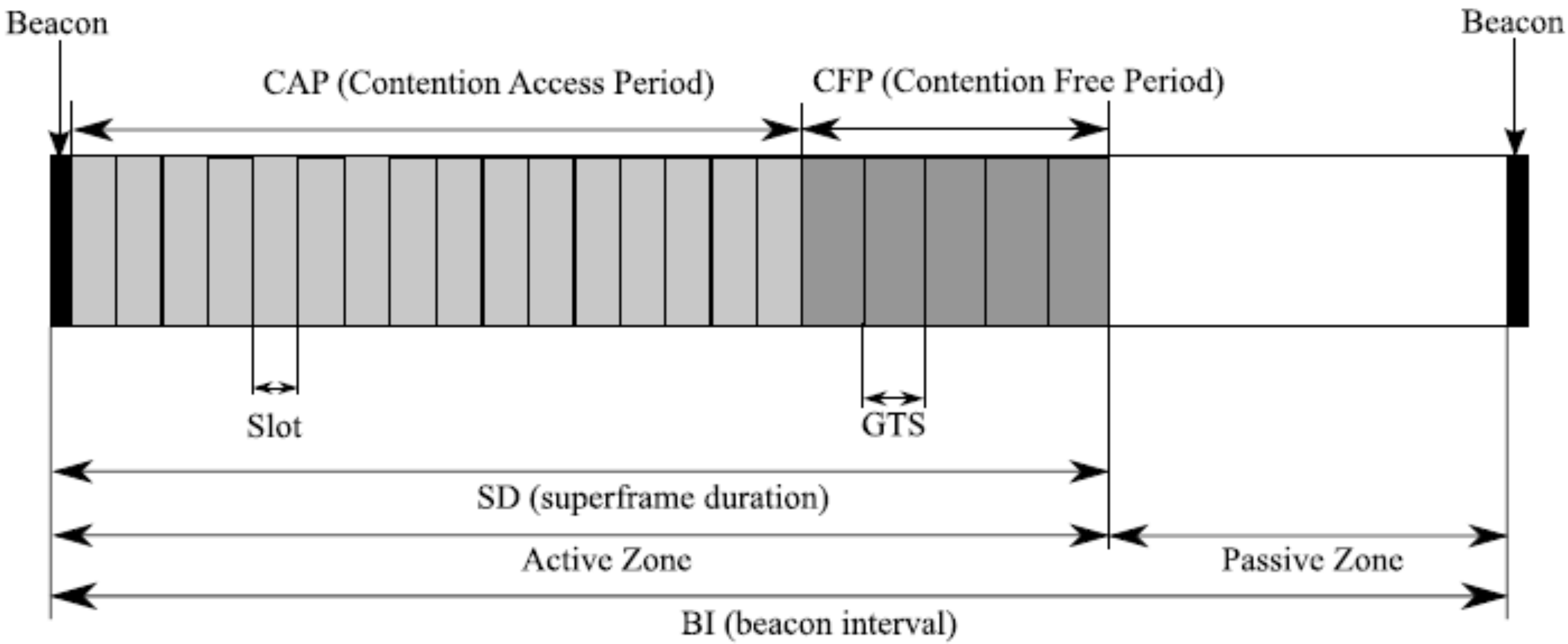
- 4 information bits are encoded with one of the 16 available symbols.
- DSSS spectral expansion (factor 32).
- Offset-Quadrature Phase Shift Keying (O-QPSK) modulation: odd indexes in the in-phase component and even indexes in the quadrature component.
- Lower error probability than WiFi.



Protocol

- The standard defines a Physical Protocol Data Unit (PPDU) with the following field.
  - Synchronization Header (SHR): 5 bytes used for the synchronization.
  - Physical Header (PHR): 1 byte used to carry the frame length.
  - Physical Service Data Unit (PSDU): contains the payload with maximum allowed length of 127 bytes.

Superframe Structure



Superframe Parameters

- The length is multiple of a physical modulated symbol $T_{\mathrm{symb}} = 1.6\ \mu$s (@ 2.4 GHz).
- $BI = d_{\mathrm{SF}} \cdot 2^{BO}$, where BO (Beacon Order) is in the range [0,15]—15 corresponds to beaconless mode.
- $SD = d_{\mathrm{SF}} \cdot 2^{SO}$, where SO (Superframe Order) is in the range $[0, BO]$. In the standard configuration, 16 slots are in the active zone with duration (in terms of physical symbols) equal to

$$d_{\mathrm{sl}} = \underbrace{\mathrm{aBaseSlotDuration}}_{\text{length when } SO = 0 = d_{\mathrm{SF}}} \cdot 2^{SO}.$$

- Contention Access Period (CAP): the access is performed through CSMA/CA.
- Contention Free Period (CFP): the access is deterministic through a given number of GTSs.

Packet Format

- Beacons: used by the PAN coordinator to send beacons.
- Data: used by the higher levels for data transfer.
- Acknowledgement (ACK): used to confirm the correct receipt of a packet.
- MAC command: used to manage all control information.

Dimension (byte)	2	1	0-20	Variable	2
MAC Layer	Frame control	Sequence Number	Addressing fields	Payload	Frame Check Sequence
	MAC Header (MHR)			MSDU	MFR
	MAC Payload Data Unit (MDPU)				

CSMA/CA MAC Protocol: Unslotted Version

- The source node waits for a number of slots randomly generated in the interval $\left[0, 2^{BE_i} - 1\right]$.
- Once elapsed this time, the node verifies the channel status through a Clear Channel Assessment (CCA), i.e., the energy on the RF interface is measured over $8T_{\mathrm{sym}}$.
- If the energy is above a threshold, the channel is busy; otherwise, it is assumed idle.
- If channel is idle, the node can transmit a packet in its queue. Otherwise, *NB* (number of backoff cycles for this packet) and *m* (maximum number of backoff cycles, denoted as backoff stage) are compared.
- If $NB = m$, the CSMA/CA is declared as failed. Otherwise, *BE* is incremented by 1. If $BE < BE_{\mathrm{max}}$, the procedure is repeated.

CSMA/CA MAC Protocol: Slotted Version

- The main difference is that all operations must be performed in the correspondence of a backoff boundary.
- CCAs of different nodes can collide. Therefore, two CCAs should be performed to prevent from collisions. However, this leads to waste in channel utilization.
- Obviously, in all cases collisions are still possible!!!

Performed Tasks

- Creation and management of the network.
- Choice of the network topology.
- Unicast and multicast routing of packets.
- Security management.
- Management of logical associations between the applications of different nodes (binding).

(ZigBee) Network Layer

- Provides functionalities for multihop communications, but it is not responsible for inter-PAN communications.

- Three classes of nodes are allowed:
  - router: optional node, which acts as a PAN coordinator at MAC level and it is able to relay packets according to the routing protocol;
  - coordinator: it has the same functionalities of a router, but it can set up the network and manage its parameters;
  - end device: it is the same of an end device at MAC level.

- All nodes hold also a neighborhood table, which contains information about all the surrounding nodes in their transmission range.

Routing Algorithms

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- Hierarchical Algorithm. It is based on the fact that ZigBee nodes have a direct parent-child degree of kinship with at least another node in the network. However, it exploits sub-optimal paths, which cannot be modified, since no routing tables are held.

- Ad hoc based on Ad hoc On demand Distance Vector (AODV). It is a reactive protocol based on RREQ/RREP packets.

- Neighborhood routing. If the destination address is in the neighborhood table, a direct transmission is performed.

Network Topologies

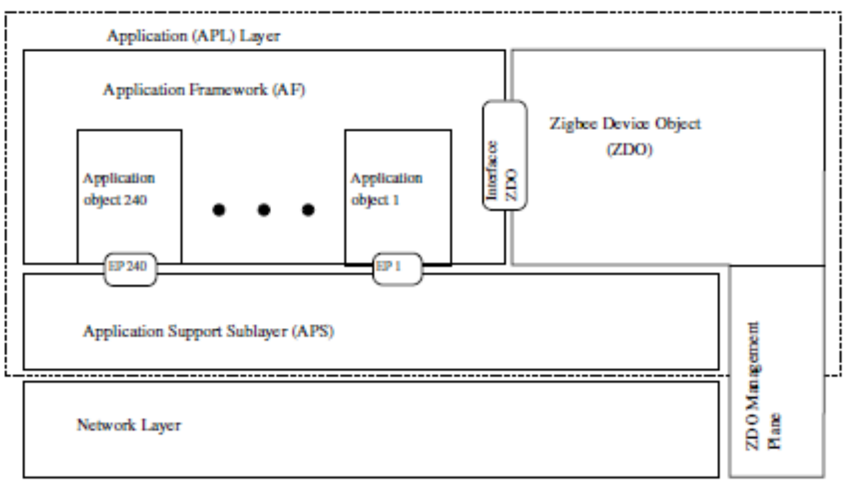
- Star. No routers are present in the network, only a parent-child communication, and a maximum number of hops equal to two. Simpler but problems if links are not reliable.

- Tree. The PAN coordinator is the root, the routers create the branches, and the end devices are the leaves (no other nodes connected to them). Thanks to the beacon packets and the tree routing algorithm, this topology is energy efficient.

- Mesh. All nodes can communicate with all other nodes in the network, under the constraints given by the transmission range and routing capabilities. The main problem is that beacon mode cannot be employed.

Definitions

- Up to 240 application objects can be configured on each device.
- Each object is associated to an unambiguous number (end-point).
- The interoperability between applications is guaranteed by profiles.
- Data are defined by the couple ID-attributes.
- The operation of mutual associations between couples is denoted as binding.



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  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

Dimensionamento di reti cellulari

- <u>Alla lavagna</u>:
  - Introduzione
  - Cluster di celle
  - Densità geografica di utenti
  - Distanza di riuso
  - Rapporto segnale-interferenti downlink e uplink

M. Luise, *Breve Introduzione alle Reti Cellulari GSM e UMTS* , Università di Pisa. Disponibile : http://www.iet.unipi.it/m.luise/

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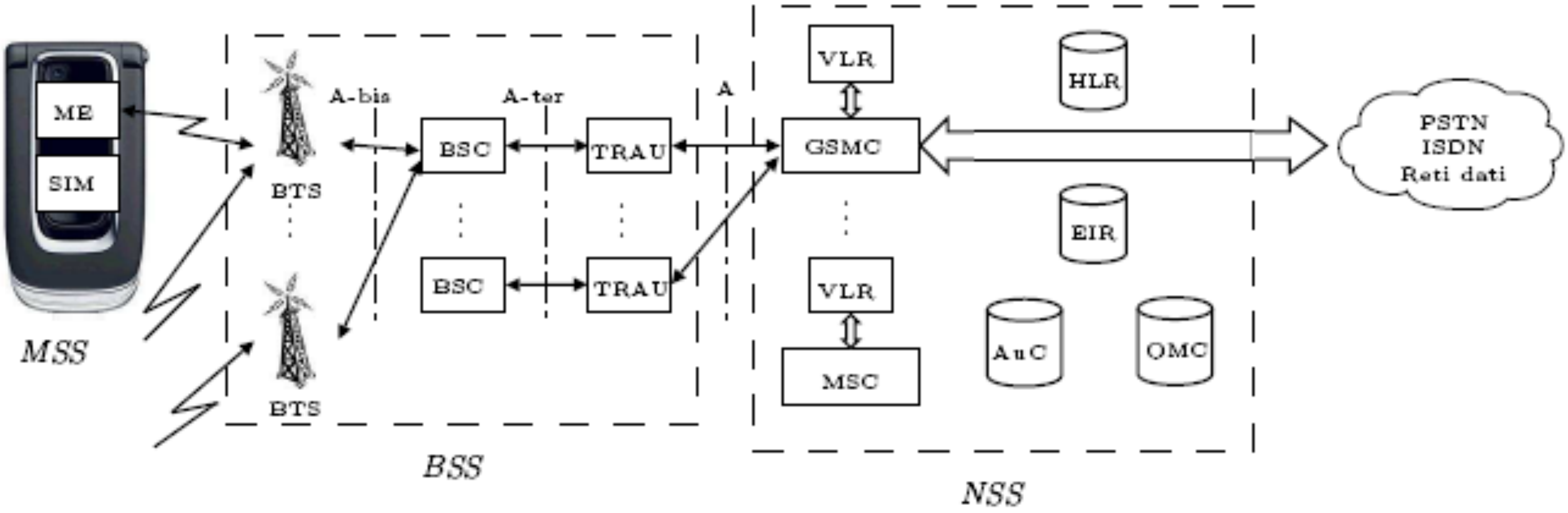
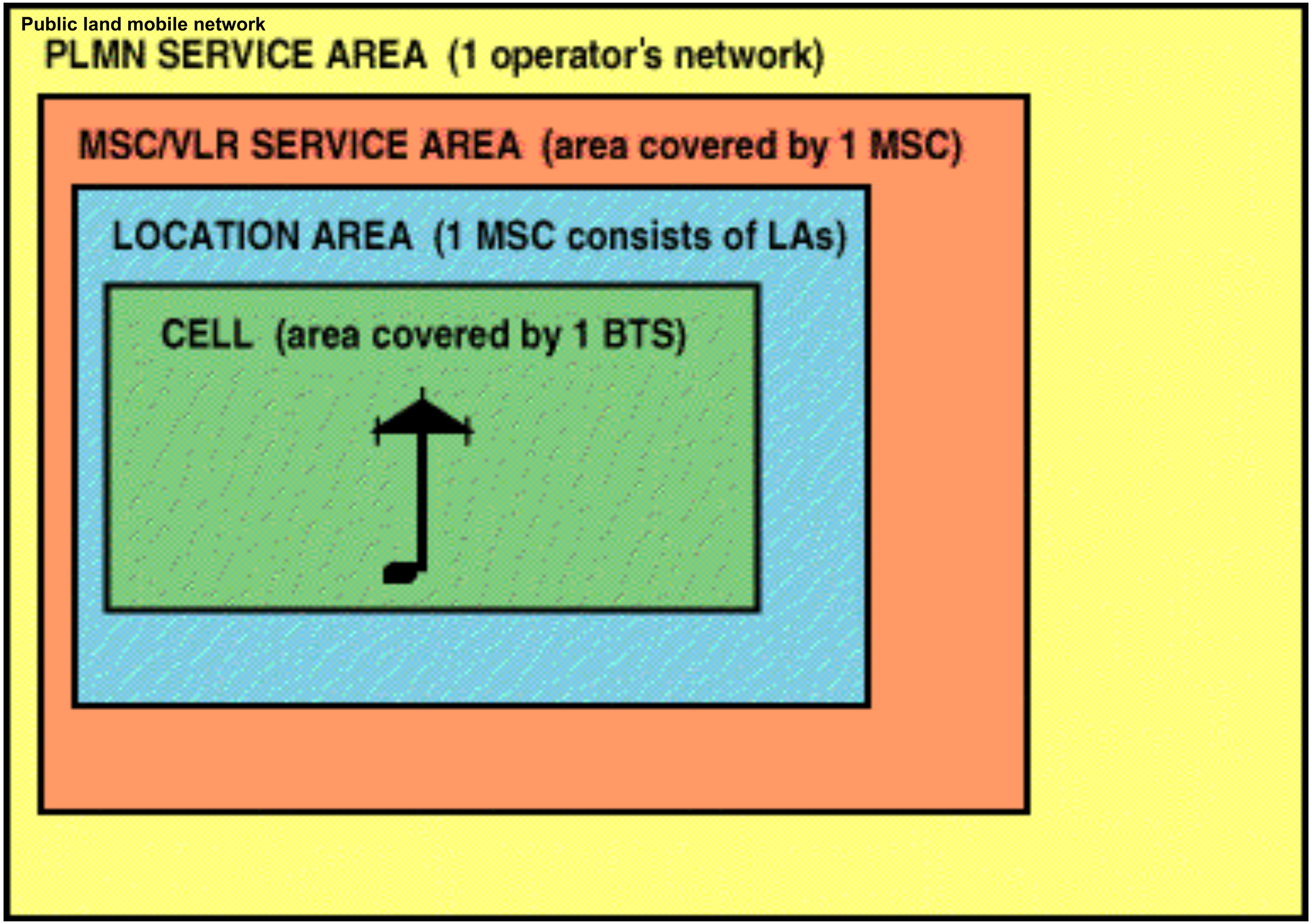
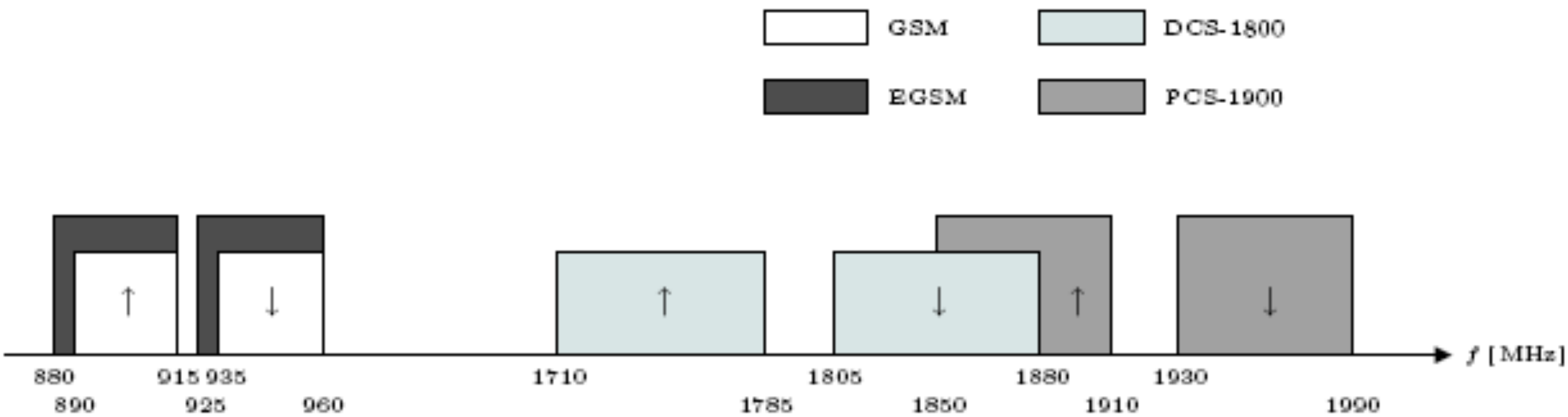
Architettura della rete GSM



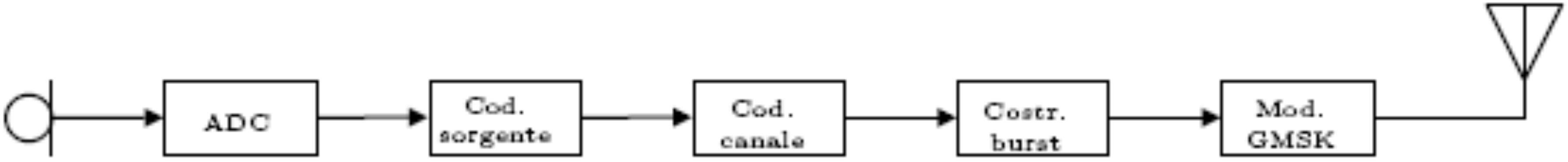
GSM - Aree della rete



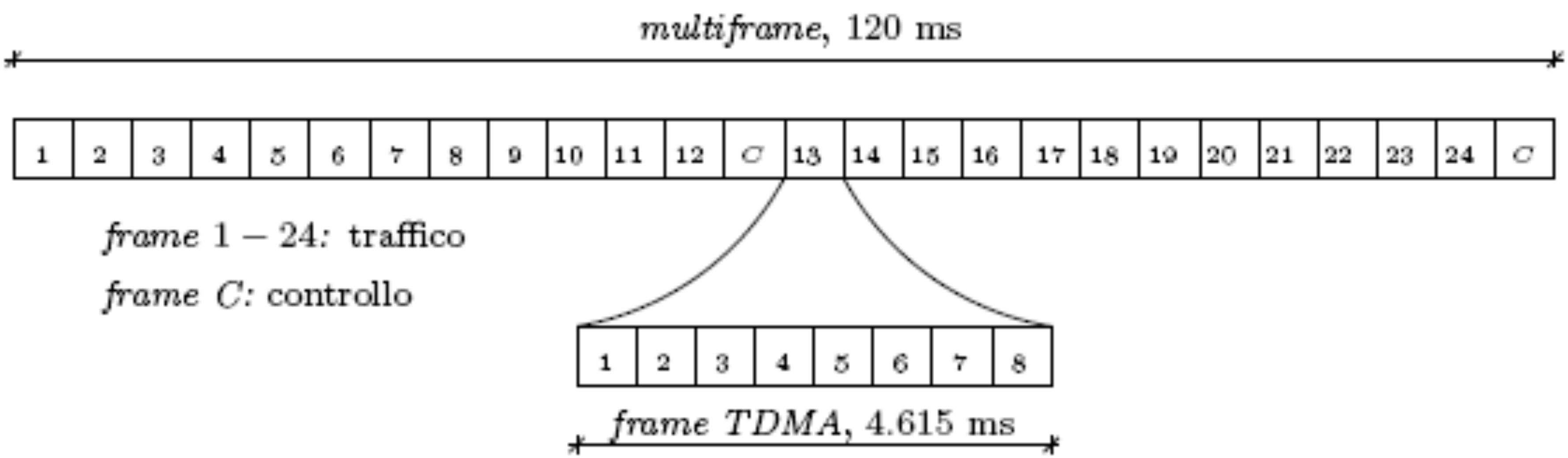
Occupazione di banda



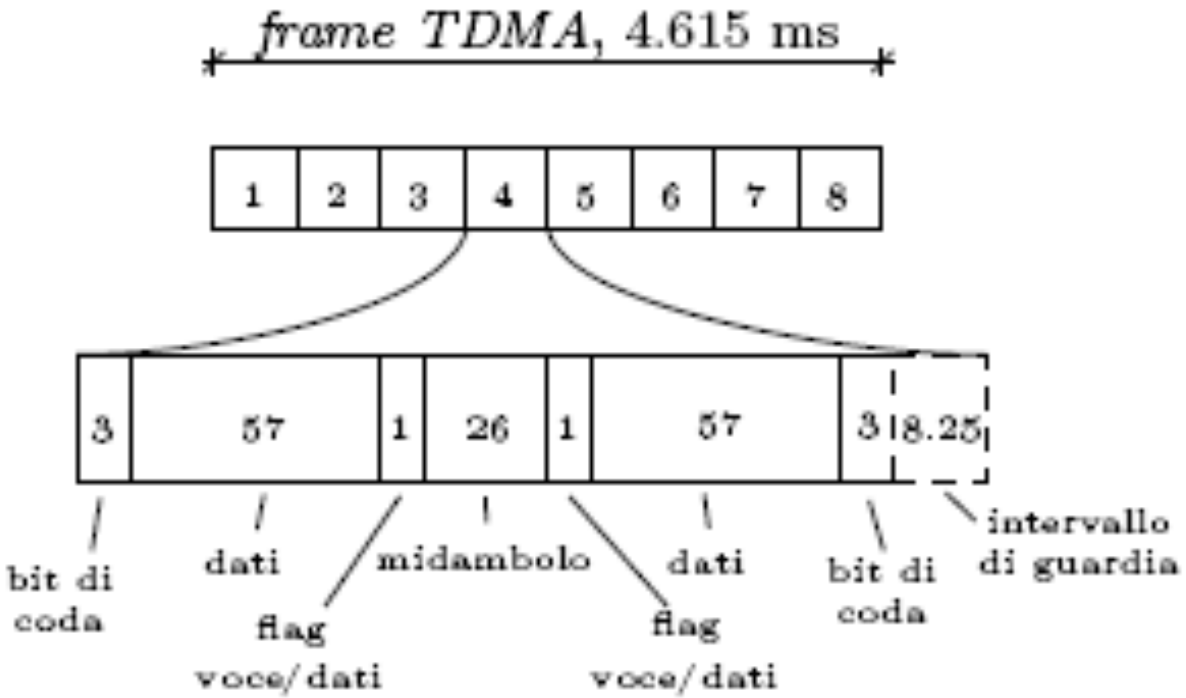
Schema a blocchi di un Trasmettitore GSM



Struttura multi-frame GSM



Struttura slot GSM



Modelli di canale GSM

MODELLO	*indice* i	*ritardo* τ_i [μs]	*ritardo norm.* τ_i/T_s	*potenza rel.* [dB]
TYPICAL URBAN (TU)	1	0.0	0.000	−3.0
	2	0.2	0.054	+0.0
	3	0.5	0.135	−2.0
	4	1.6	0.432	−6.0
	5	2.3	0.621	−8.0
	6	5.0	1.351	−10.0
HILLY TERRAIN (HT)	1	0.0	0.000	+0.0
	2	0.1	0.027	−1.5
	3	0.3	0.081	−4.5
	4	0.5	0.135	−7.5
	5	15.0	4.054	−8.0
	6	17.7	4.649	−17.7
RURAL AREA (RA)	1	0.0	0.000	+0.0
	2	0.1	0.027	−4.0
	3	0.2	0.054	−8.0
	4	0.3	0.081	−12.0
	5	0.4	0.108	−16.0
	6	0.5	0.135	−20.0

Una Visione d'Insieme

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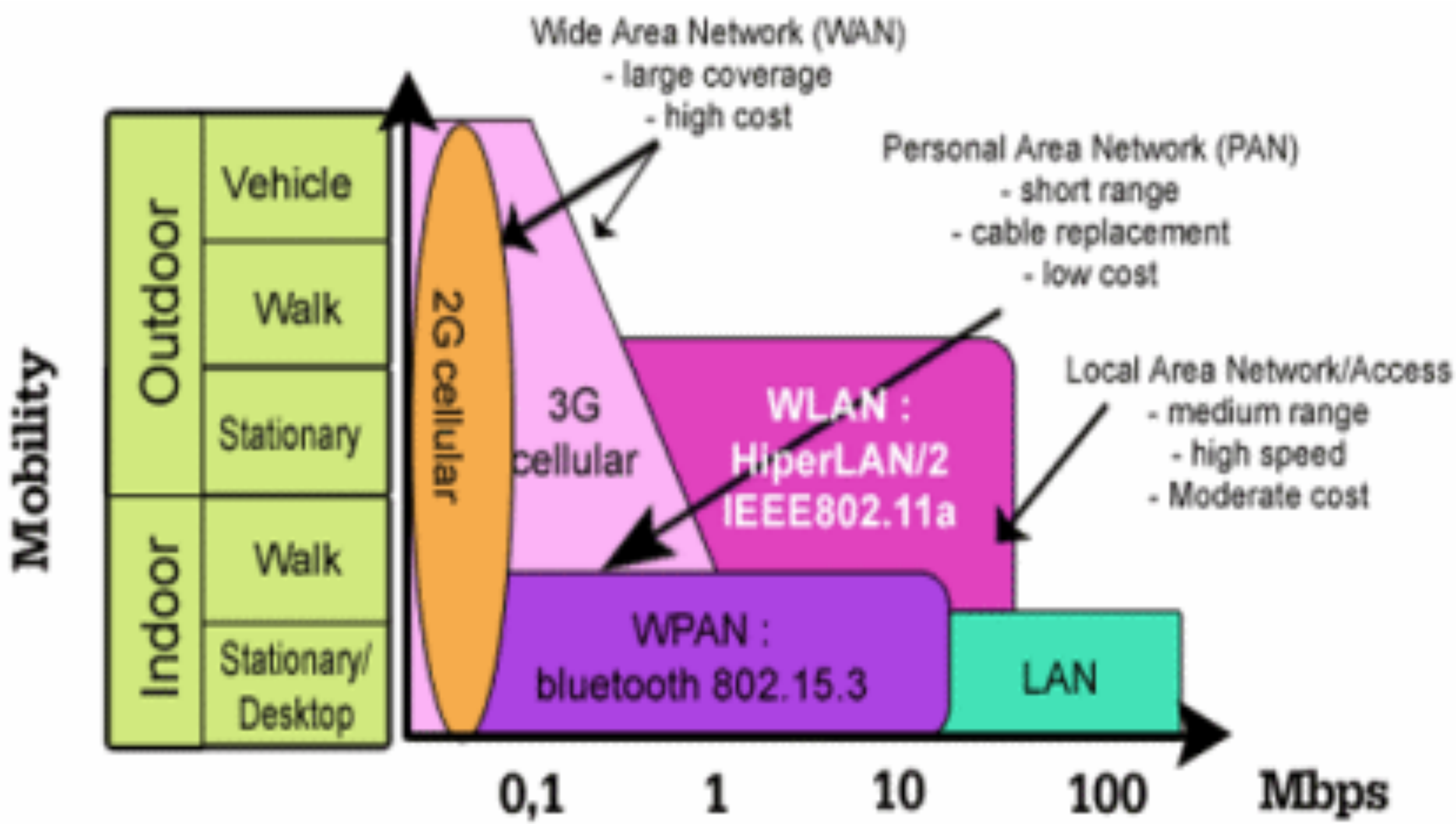
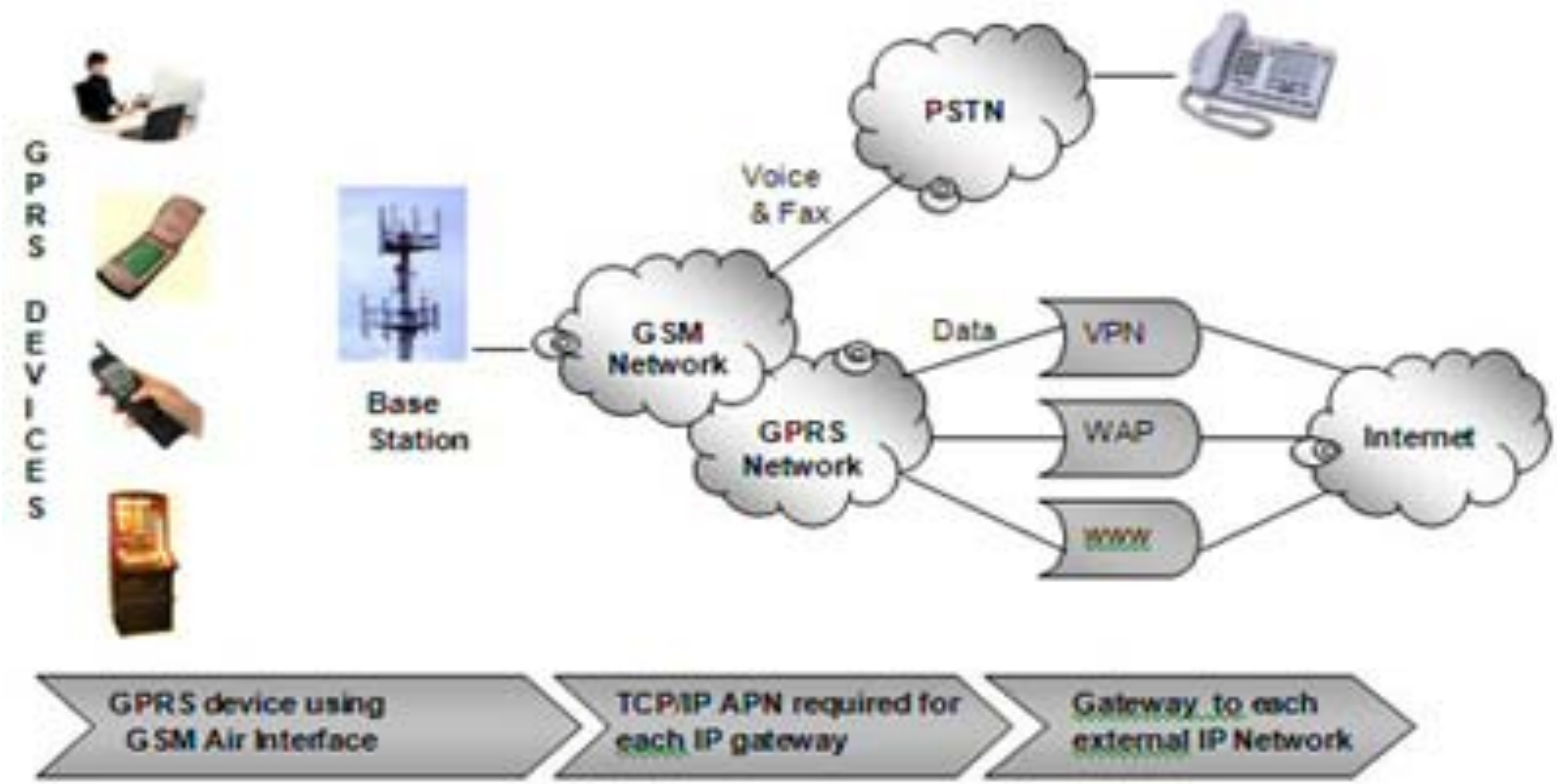


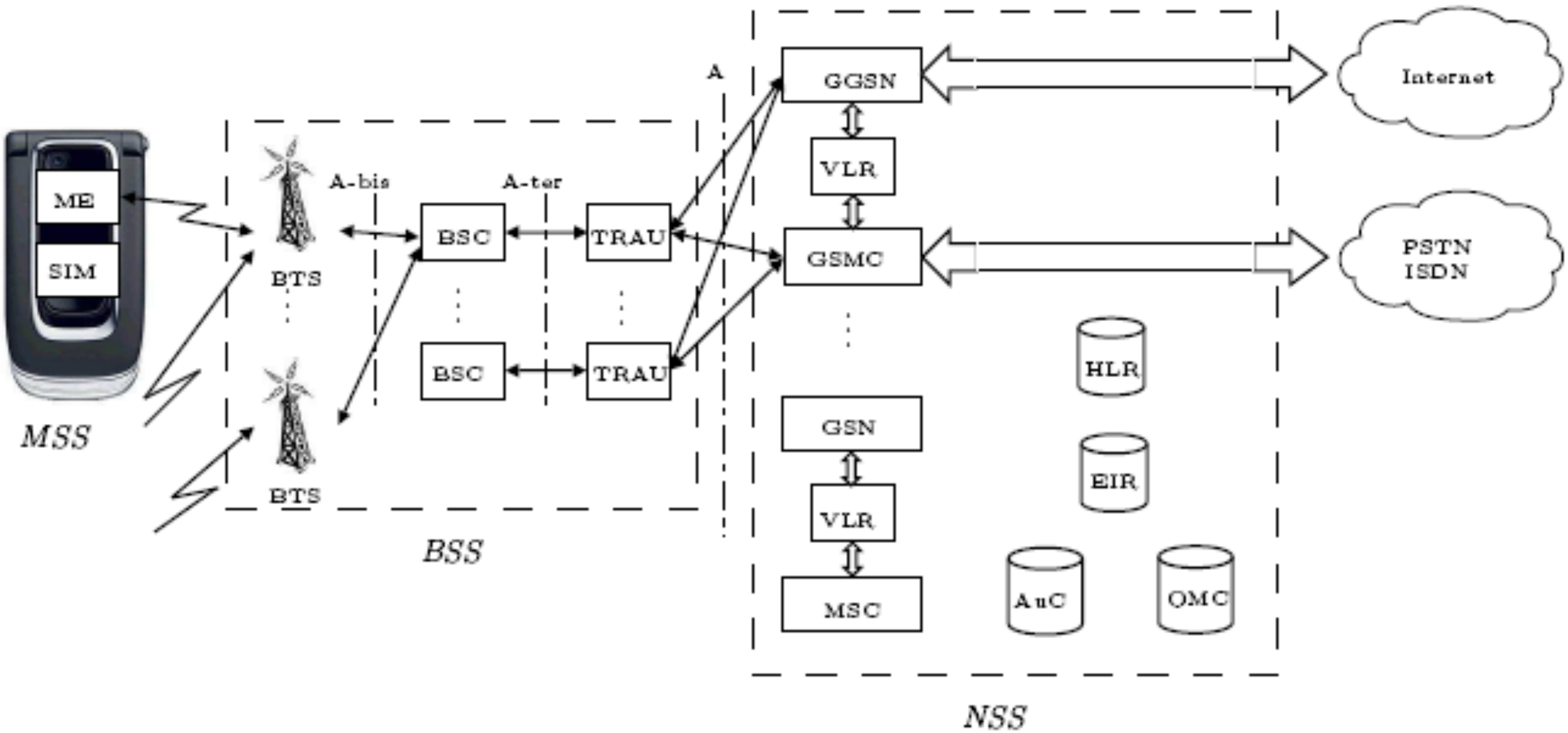
General Packet Radio Service GPRS (2.5G)



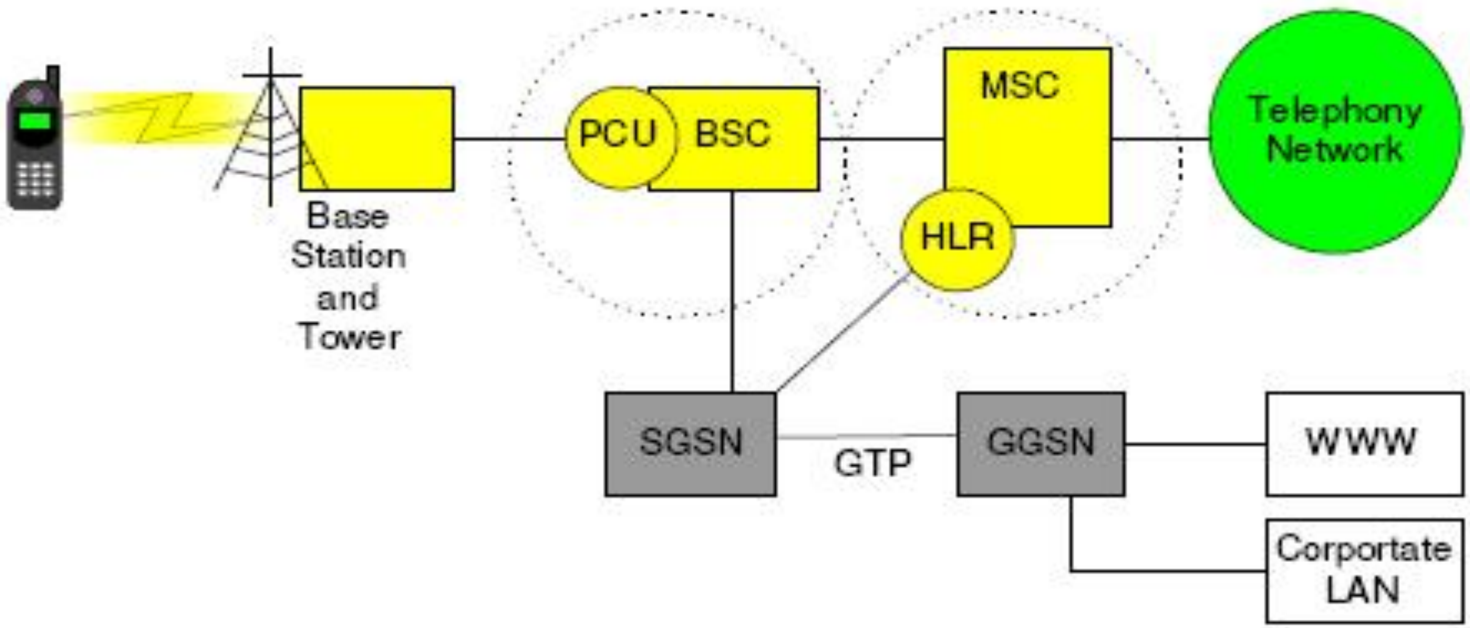
Motivazioni per GPRS

- **GSM**:
  - Ok per trasmissioni vocali (commutazione di circuito)
  - Non ok per trasmissioni dati (commutazione di pacchetto è l'ideale)
- **GPRS**: si appoggia alla rete GSM per trasmettere dati con TCP/IP
- Indirizzi IP: assegnati dinamicamente alle unità mobili
- Terminali: identificati sempre come on-line

Architettura GPRS



Architettura GRPS (bis)



- Nuovi elementi strutturali:
  - *Serving GPRS Support Node* (SGSN)
  - *Gateway GPRS Support Node* (GGSN)

Convivenza fra GSM e GPRS

- Diverse filosofie di rete
  - GSM: commutazione di circuito
  - GPRS: commutazione di pacchetto
- Come convivono? Il *base station controller* (BSC) della rete GSM ha bisogno di un "upgrade" (SW e HW)
- Upgrade HW: aggiungere *packet control unit* (PCU) che differenzia fra dati diretti a rete GSM e quelli diretti a rete GPRS

GPRS - Specifiche tecniche

- Commutazione di pacchetto
- Bande frequenziali:
  - Uplink: da 890 MHz a 915 MHz
  - Downlink: da 935 MHz a 960 MHz
- *Duplex distance* (fra canale uplink e downlink): 45 MHz
- Separazione fra canali adiacenti: 200 kHz
- Formato di modulazione: Gaussian minimum shift keying (GMSK)
- Tasso di trasmissione: max→171.2 kbps; realistico→ 50-60 kbps
- Protocollo di accesso al mezzo: combinazione di TDMA e FDMA
- Numero di canali duplex: 128
- Numero di slot TDMA per canale: 8
- Allocazione dinamica da 1 a 8 slots per TDMA (1 slot=0.57 ms, 1 frame=4.615 ms)
- *Frequency hopping*: 217 hops/s (1 s/217=4.615 ms)
- Livello fisico "potenziato": codifica di canale e decodifica con algoritmo di Viterbi

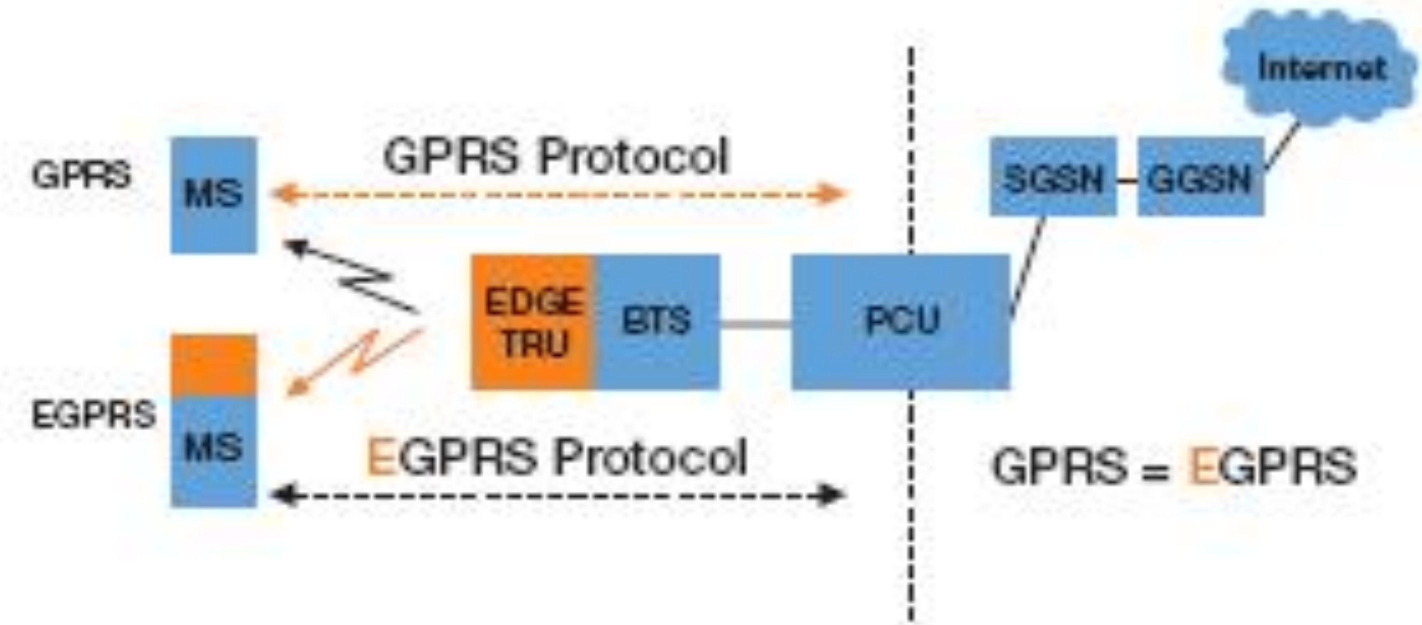
Enhanced Data for Global Evolution - EDGE (2.7G)

- EDGE può essere introdotto in due modi
  - Miglioramento (*enhancement*) di trasferimento dati a commutazione di pacchetto→*enhanced* GPRS (EGPRS)
  - Miglioramento di trasferimento dati a commutazione di circuito→*enhanced circuit-switched data* (ECSD)
- Si appoggia alla rete GSM (GPRS)
- Intermediario fra GSM e wideband code division multiple access (W-CDMA), cioè UMTS

EDGE in poche parole

- EDGE si adegua alle attuali specifiche del GSM
- Cosa combina allora?
- Livello fisico potenziato
  - Formato di modulazione spettralmente più efficiente: *8-phase shift keying* (8-PSK)
  - Codice di canale più potente
  - Meccanismi adattativi sul link
- Aumento di efficienza spettrale→wireless internet,e-mail,ftp
- Tasso di trasmissione:
    - GPRS: 171.2 kbps (max), 115 kbps (real)
    - EGPRS: 473.6 kbps (max), 384 kbps (real)

EDGE: Architettura di rete



LEGEND

BTS	Base Station	PCU	Packet control unit
EGPRS	Enhanced GPRS	SGSN	Serving GPRS support node
GGSN	Gateway GPRS support node	TRU	Transceiver unit
MS	Mobile station		

EDGE: Architettura protocollare

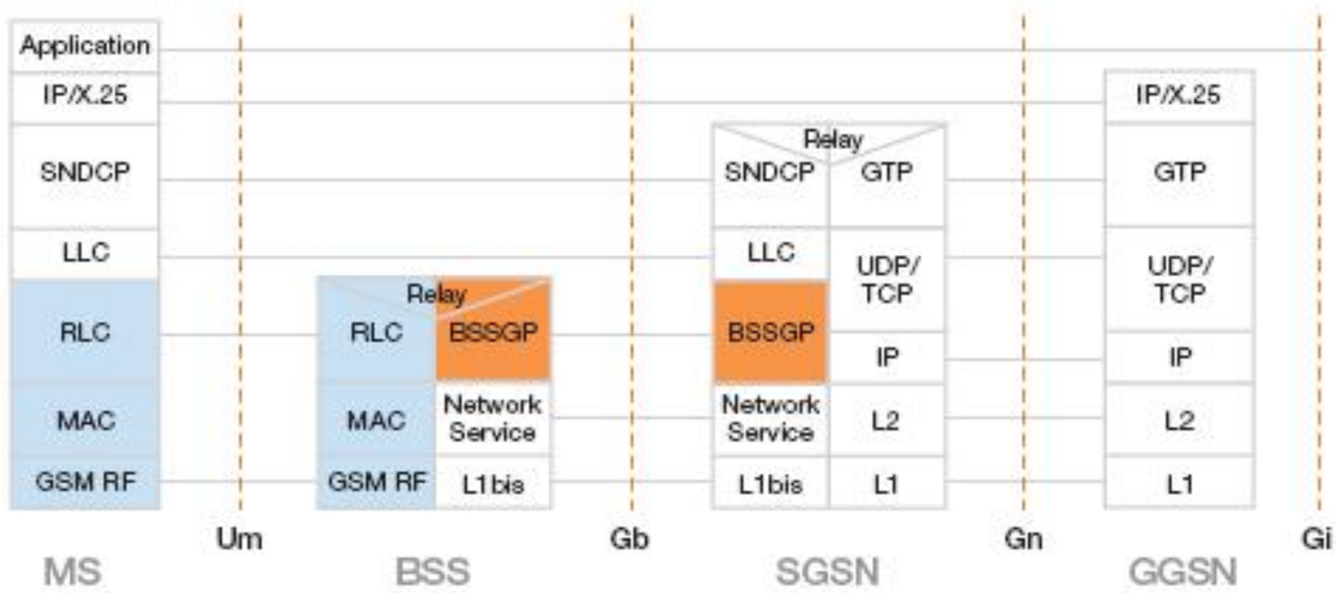


Figure 11. Transmission plane protocol architecture. (Legend: BSS, Base station system; BSSGP, BSS GPRS protocol; GGSN, Gateway GPRS support node; GTP, General telemetry processor; IP/X.25, Internet Protocol X.25; LLC, Low-layer capability; L1 and L2, memory caches; MAC, Mobile allocation control; MS, Mobile station; RF, Radio frequency; RLC, Radio link control; SGSN, Serving GPRS support node; SNDCP, Subnetwork-dependent convergence protocol; TCP, Transmission control protocol; UDP, User diagram protocol)

EDGE: Scelta dinamica del codice di canale

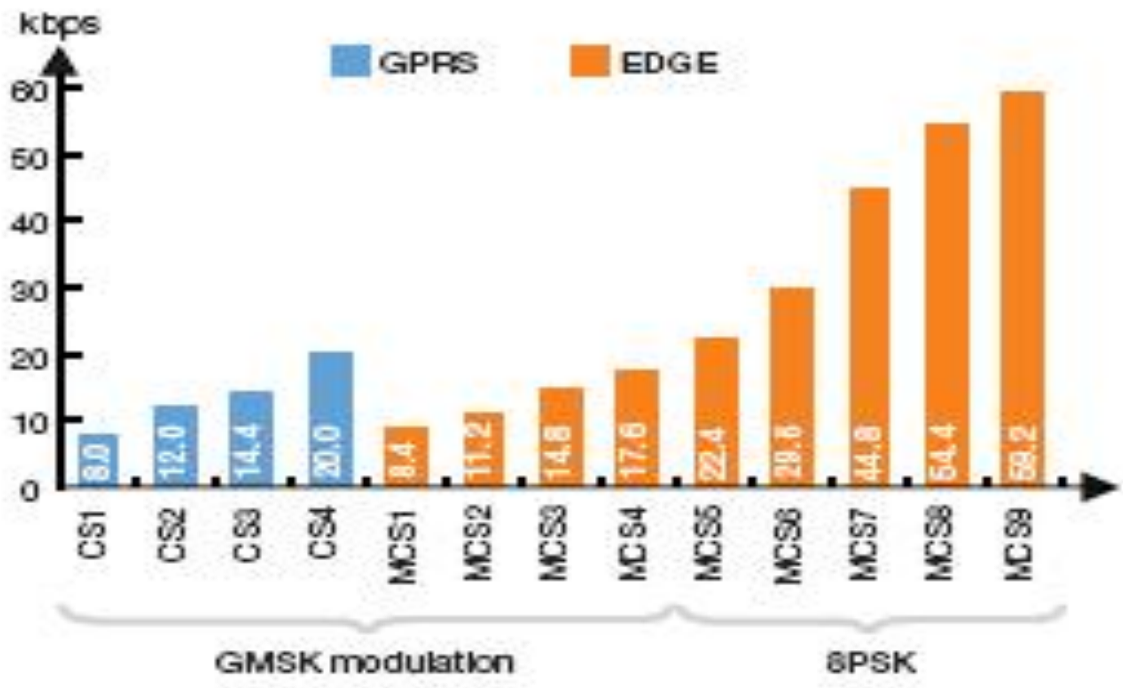
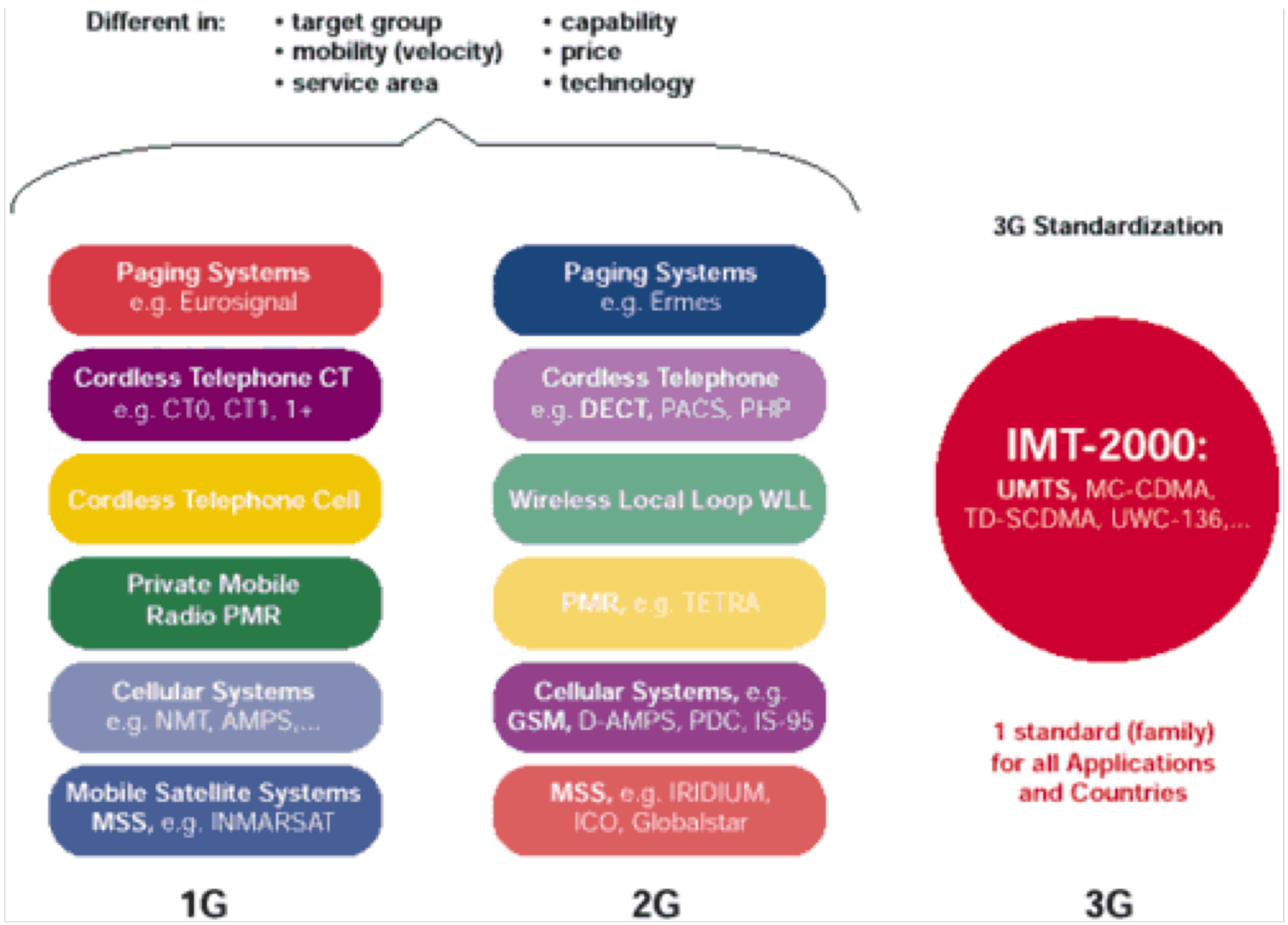


Figure 4. Coding schemes for GPRS and EGPRS (user data rate). (Key: 8PSK, 8-phase shift keying; CS, Coding scheme; EGPRS, Enhanced GPRS; GMSK, Gaussian minimum shift keying; MCS, Modulation coding scheme)

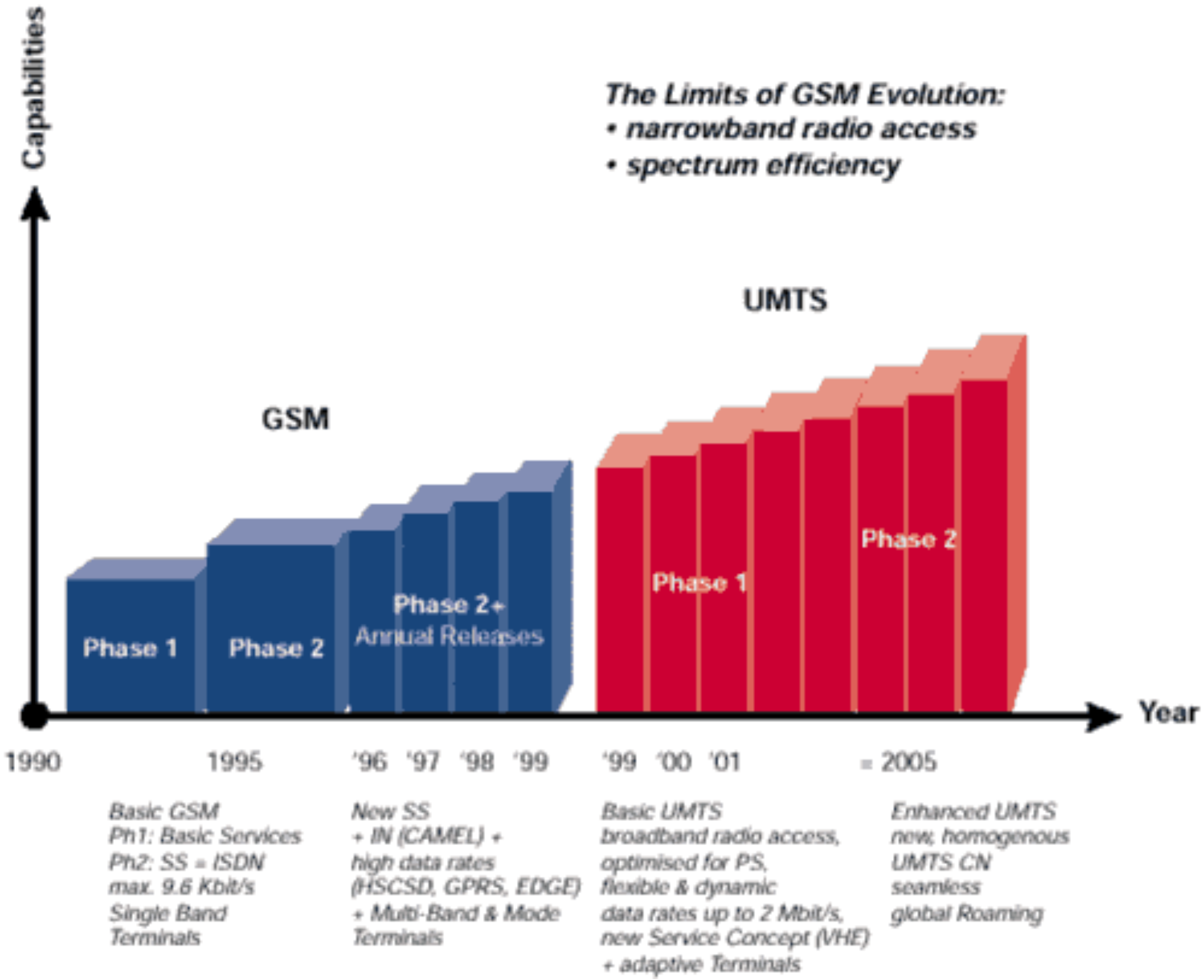
Universal Mobile Telecommunications System - UMTS (3G)

- Successore designato del sistema GSM
- Ponte fra le molte versioni del GSM e il singolo standard mondiale per comunicazioni mobili: International Mobile Telecommunications 2000 (IMT-2000)
- Caratteristiche 3G:
  - Applicazioni multimediali
  - Trasmissione dati a commutazione di circuito e pacchetto
  - Tasso di trasmissione fino a 2 Mbps

Uno sguardo olistico agli standard



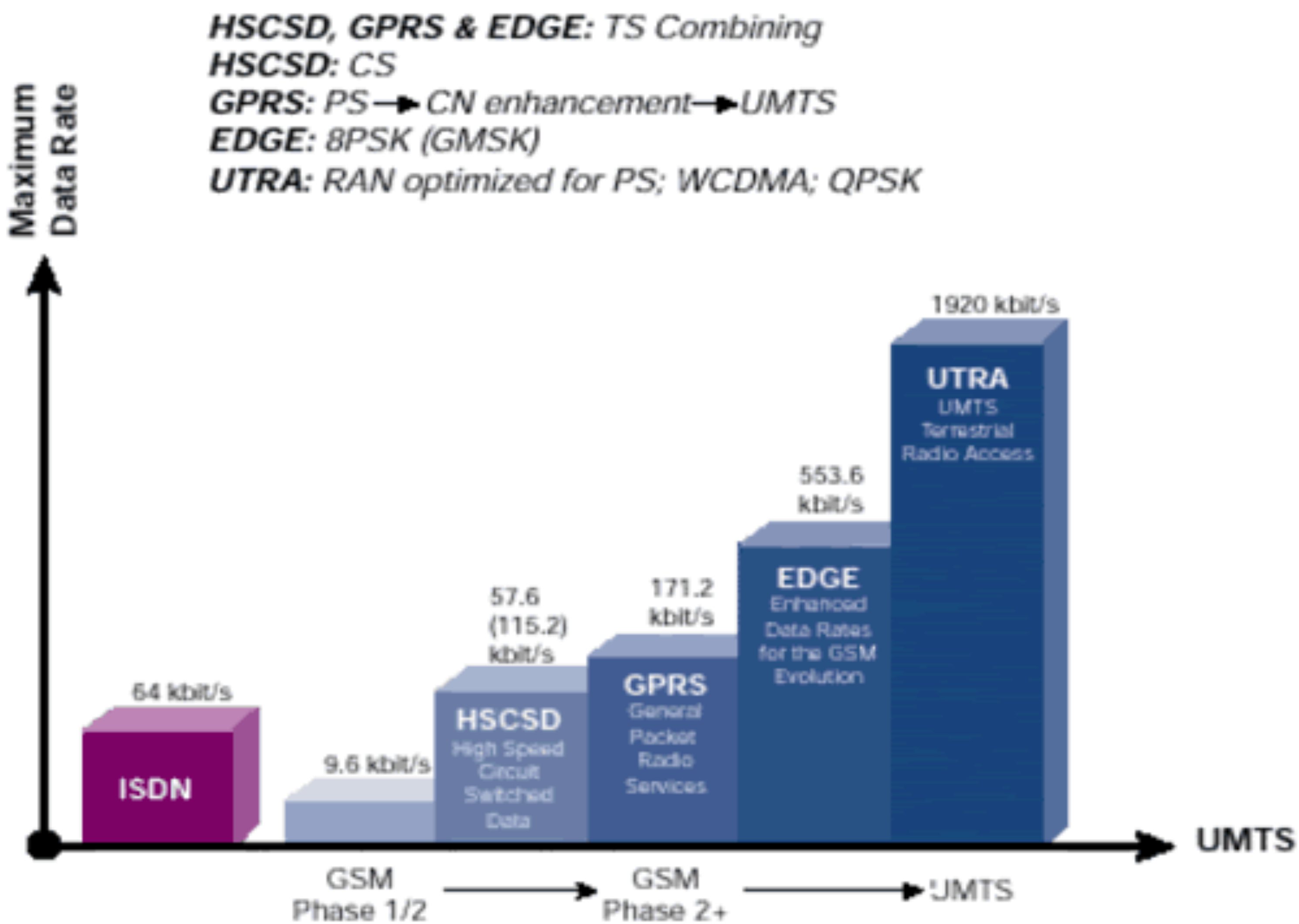
Evoluzione: GSM → UMTS



Progetto dello standard UMTS

- Sviluppato da third-generation patnership project (3GPP): ETSI (Europa), ARIB/TTC (Giappone), ANSI (USA), TTA (Corea del Sud), CWTS (Cina)
- Nel 1999 è introdotto UMTS terrestrial radio access (UTRA)→interfaccia radio WCDMA funzionante in modalità TDD (micro e pico celle) e FDD (grandi celle)

Tasso di trasmissione



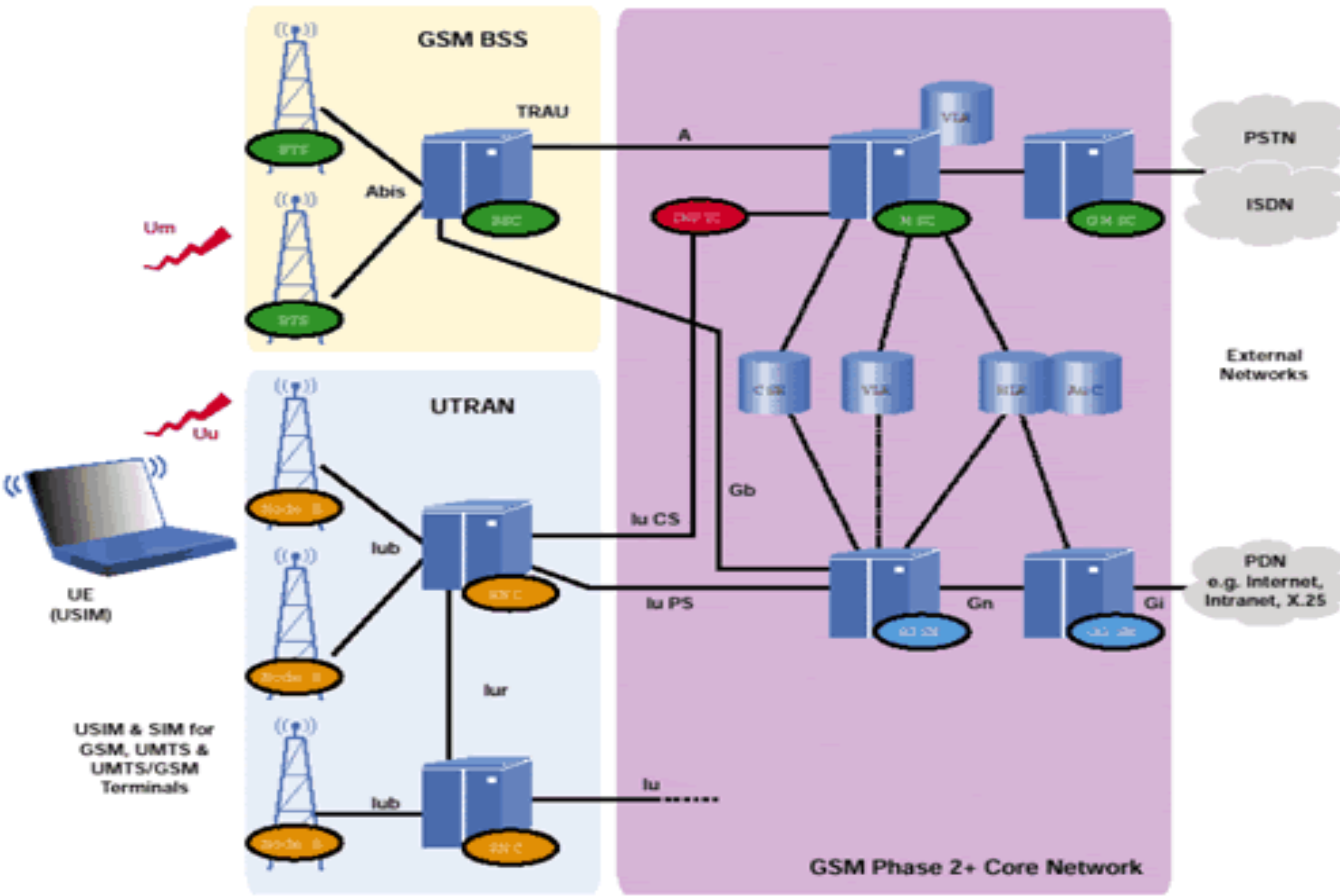
Principali differenze fra interfacce radio GSM e W-CDMA

	W-CDMA	GSM
spaziatura tra le portanti	5 MHz	200 kHz
fattore di riuso K	1	$1 \div 18$
frequenza di controllo di potenza	1500 Hz	≤ 2 Hz
controllo della qualità	algoritmi di gestione delle risorse radio	pianificazione della rete (pianificazione frequenziale)
diversità di frequenza	l'ampiezza di banda di 5 MHz consente di sfruttare la diversità da cammini multipli con ricevitori di tipo Rake	frequency hopping
dati a pacchetto	algoritmi di scheduling della trasmissione dei pacchetti su base traffico	nel GPRS scheduling dei pacchetti su base time slot
diversità di trasmissione in downlink	supportata per migliorare la capacità di downlink	non supportata dallo standard ma applicabile

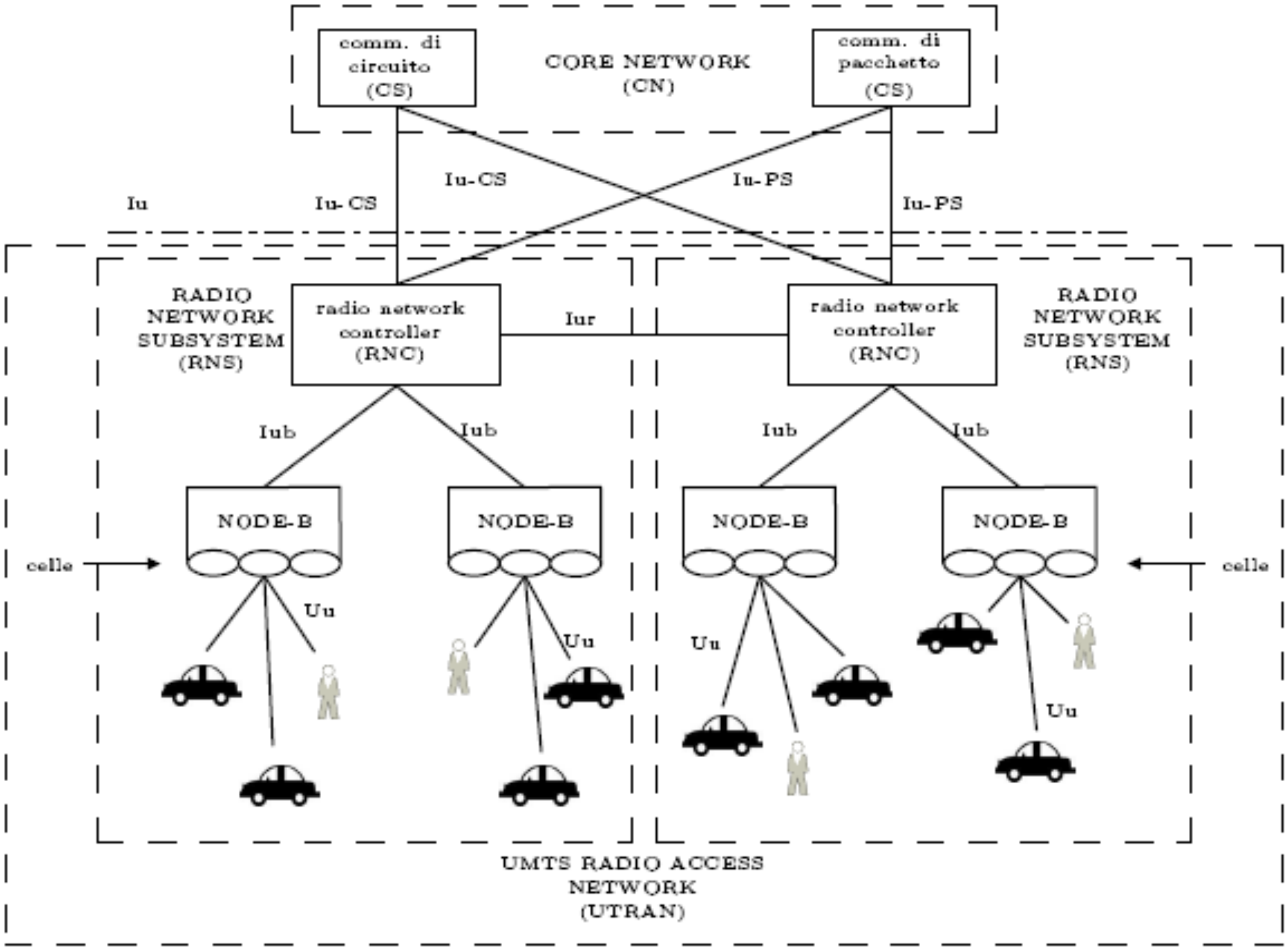
Classi di QoS di UMTS

classi di traffico	caratterstica di maggiore importanza	applicazioni
conversazionale	preservare la relazione temporale (variazione) tra le entità informative del flusso conversazionale campionato (bassi ritardi trasmissivi e bassa varianza dei ritardi)	voce, videogiochi videotelefonia
streaming	preservare la relazione temporale (variazione) tra le entità informative del flusso	streaming multimedia
interattiva	ottenere risposta dall'entità remota; preservare l'integrità dei dati	web-browsing giochi in rete
background	la destinazione finale non attende i dati in una finestra temporale predeterminata e vincolante; preservare l'integrità dei dati	download di email in background

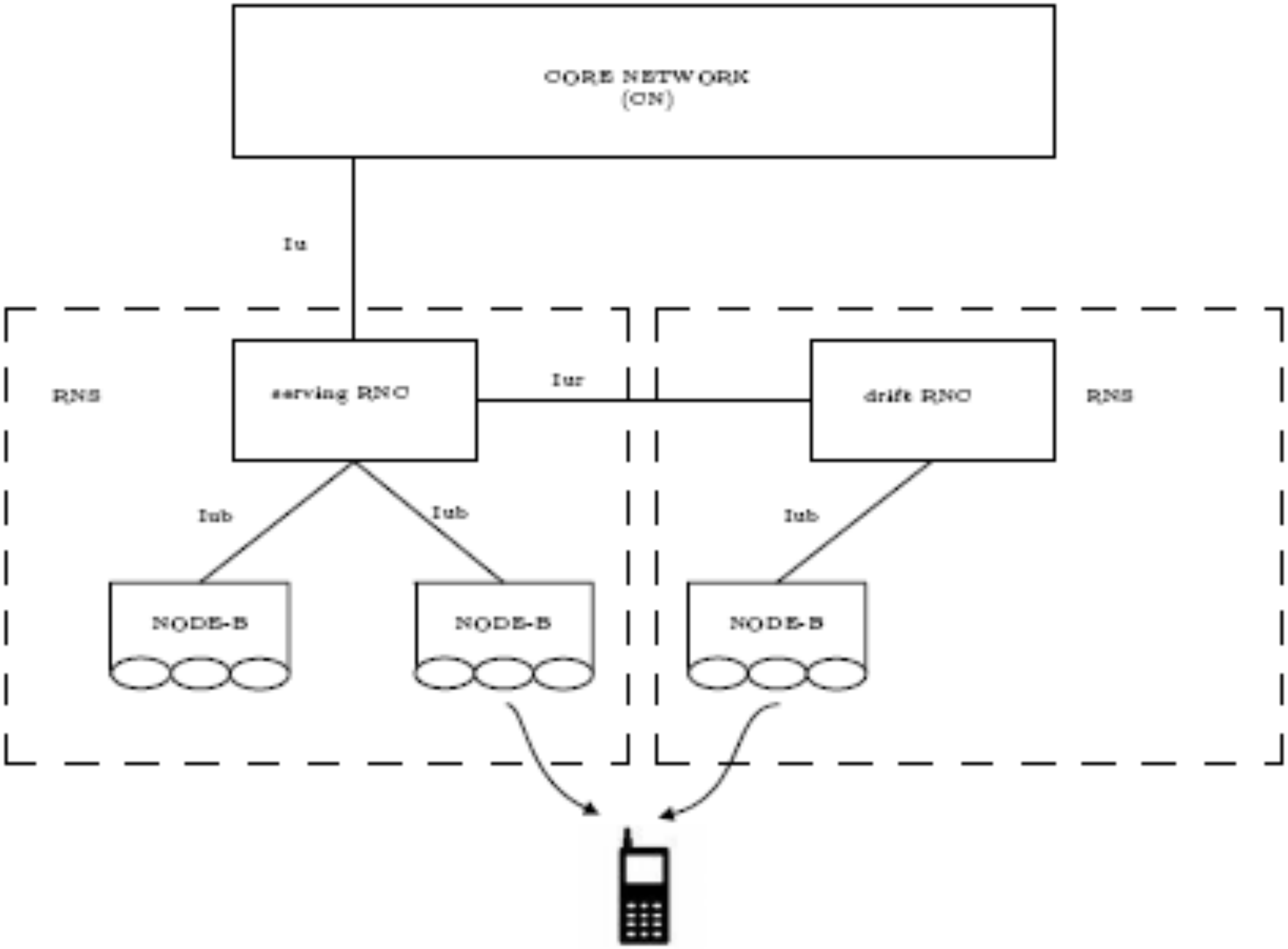
Architettura di rete GSM/UMTS (UTRAN=UMTS Terrestrial Radio Access Network)



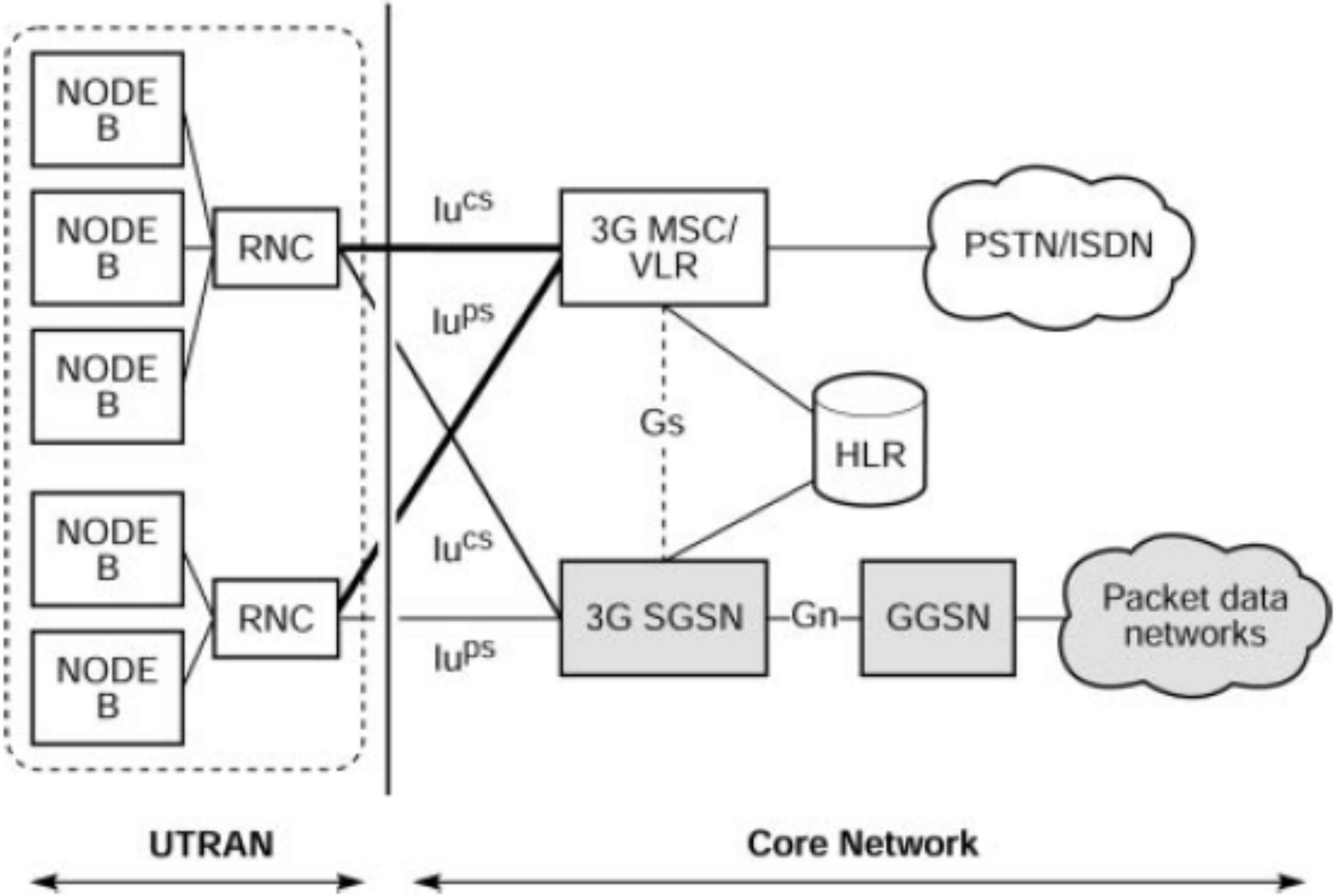
Architettura UTRAN



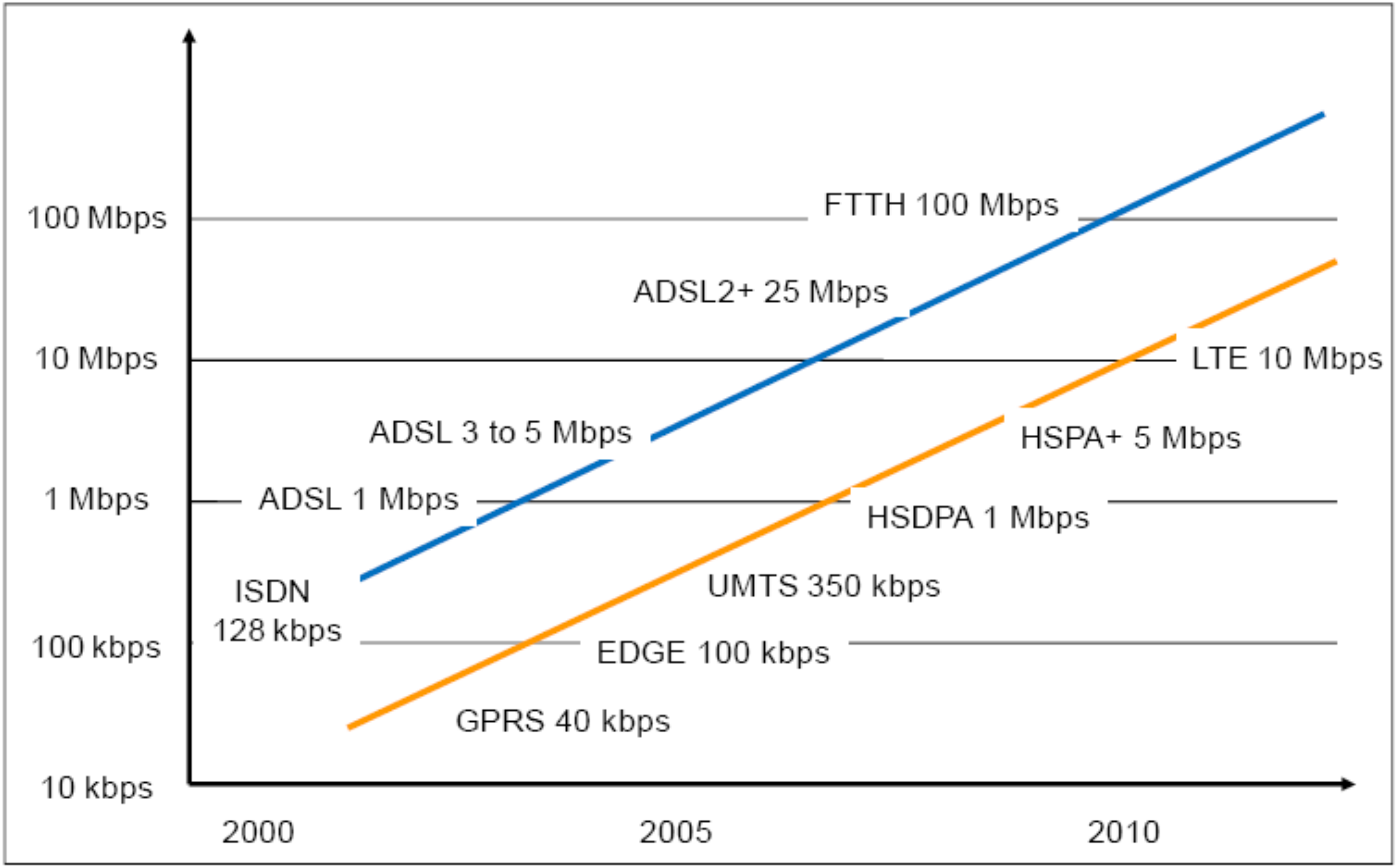
Serving e drift RNC



Architettura UMTS (CN)



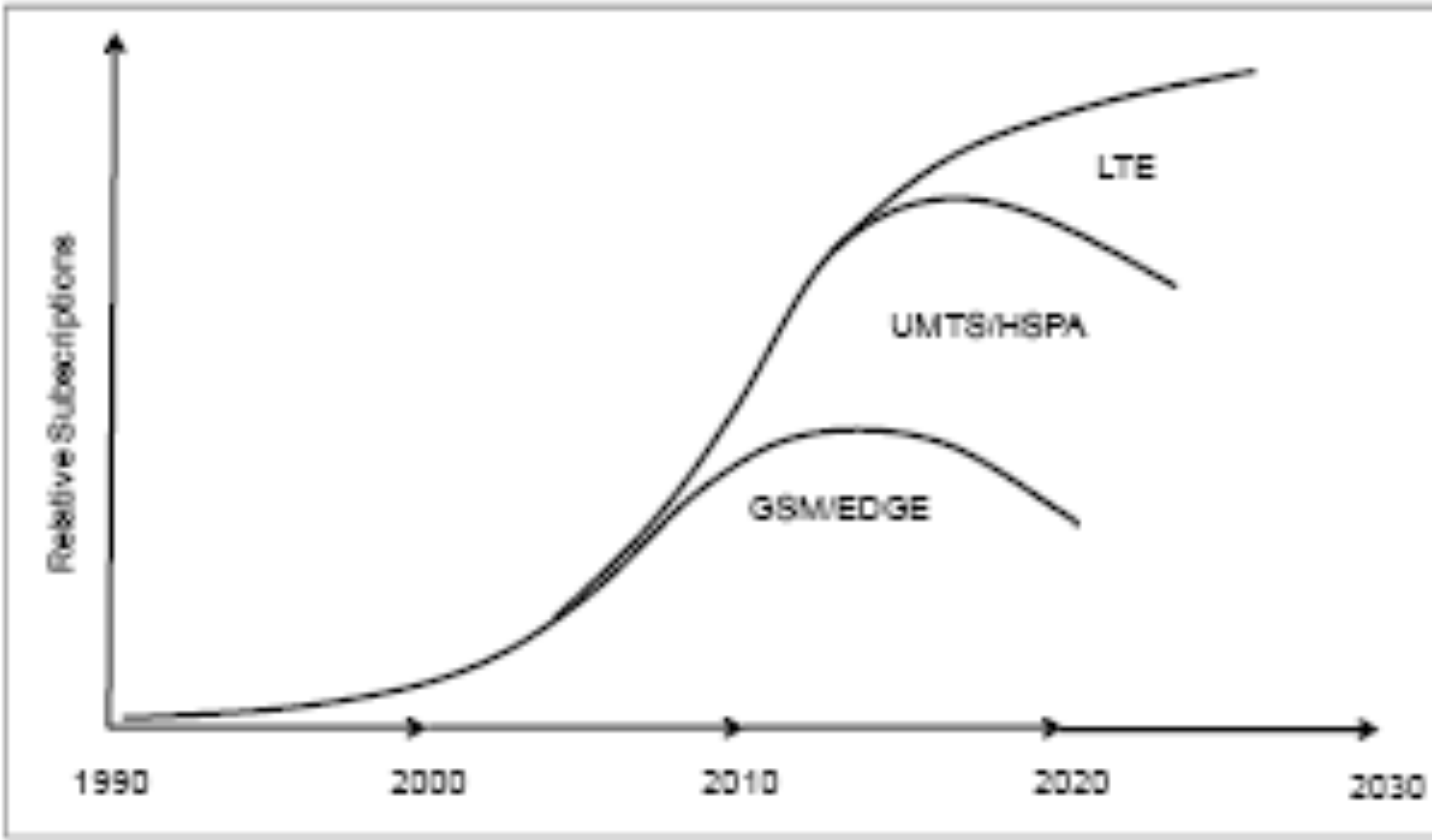
Cosa ci aspetta: evoluzioni Wireline e Wireless



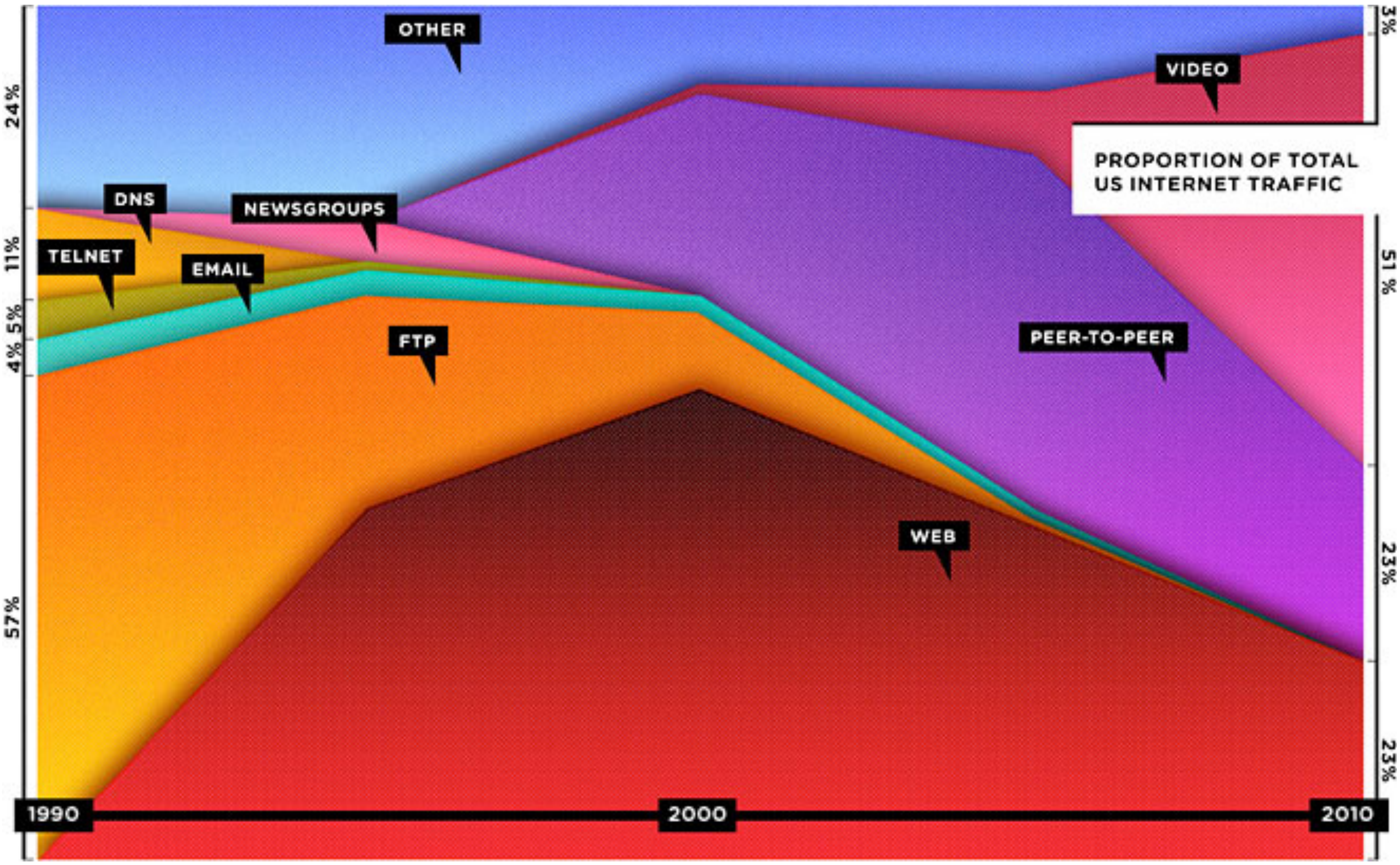
Cosa ci aspetta: Tecnologie 3GPP

Technology Name	Type	Characteristics	Typical Downlink Speed	Typical Uplink Speed
GSM	TDMA	Most widely deployed cellular technology in the world. Provides voice and data service via GPRS/EDGE.		
EDGE	TDMA	Data service for GSM networks. An enhancement to original GSM data service called GPRS.	70 kbps to 135 kbps	70 kbps to 135 kbps
Evolved EDGE	TDMA	Advanced version of EDGE that can double and eventually quadruple throughput rates, halve latency and increase spectral efficiency.	175 kbps to 350 kbps expected (Single Carrier) 350 kbps to 700 kbps expected (Dual Carrier)	150 kbps to 300 kbps expected
UMTS	CDMA	3G technology providing voice and data capabilities. Current deployments implement HSPA for data service.	200 to 300 kbps	200 to 300 kbps
HSPA	CDMA	Data service for UMTS networks. An enhancement to original UMTS data service.	1 Mbps to 4 Mbps	500 kbps to 2 Mbps
HSPA+	CDMA	Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.	1.5 Mbps to 7 Mbps	1 Mbps to 4 Mbps
LTE	OFDMA	New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.	4 Mbps to 24 Mbps (in 2 x 20 MHz)	
LTE-Advanced	OFDMA	Advanced version of LTE designed to meet IMT-Advanced requirements.		

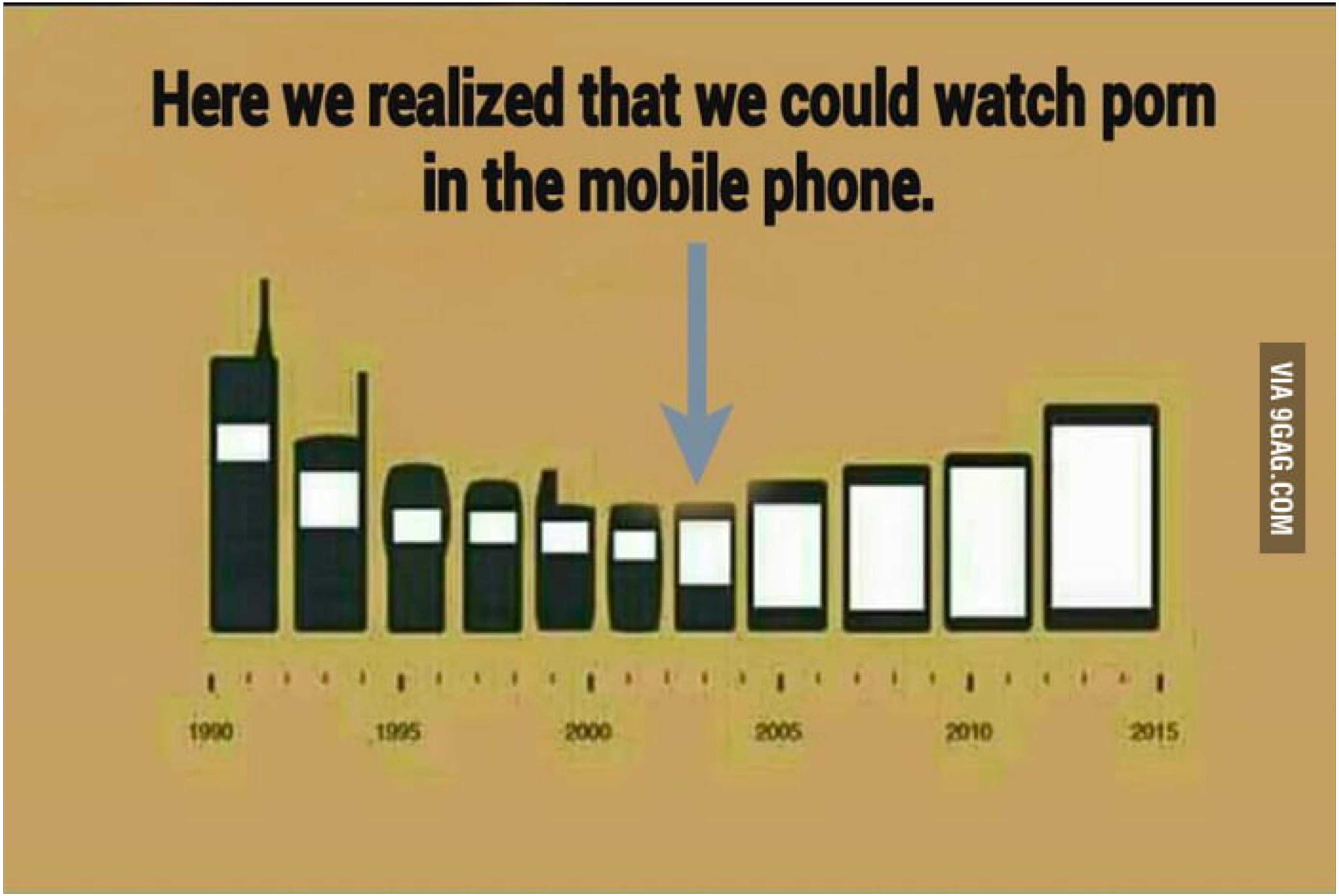
Cosa ci aspetta: adozione relativa delle tecnologie



Cosa ci aspetta: traffico Internet



Evoluzione del 'telefonino'



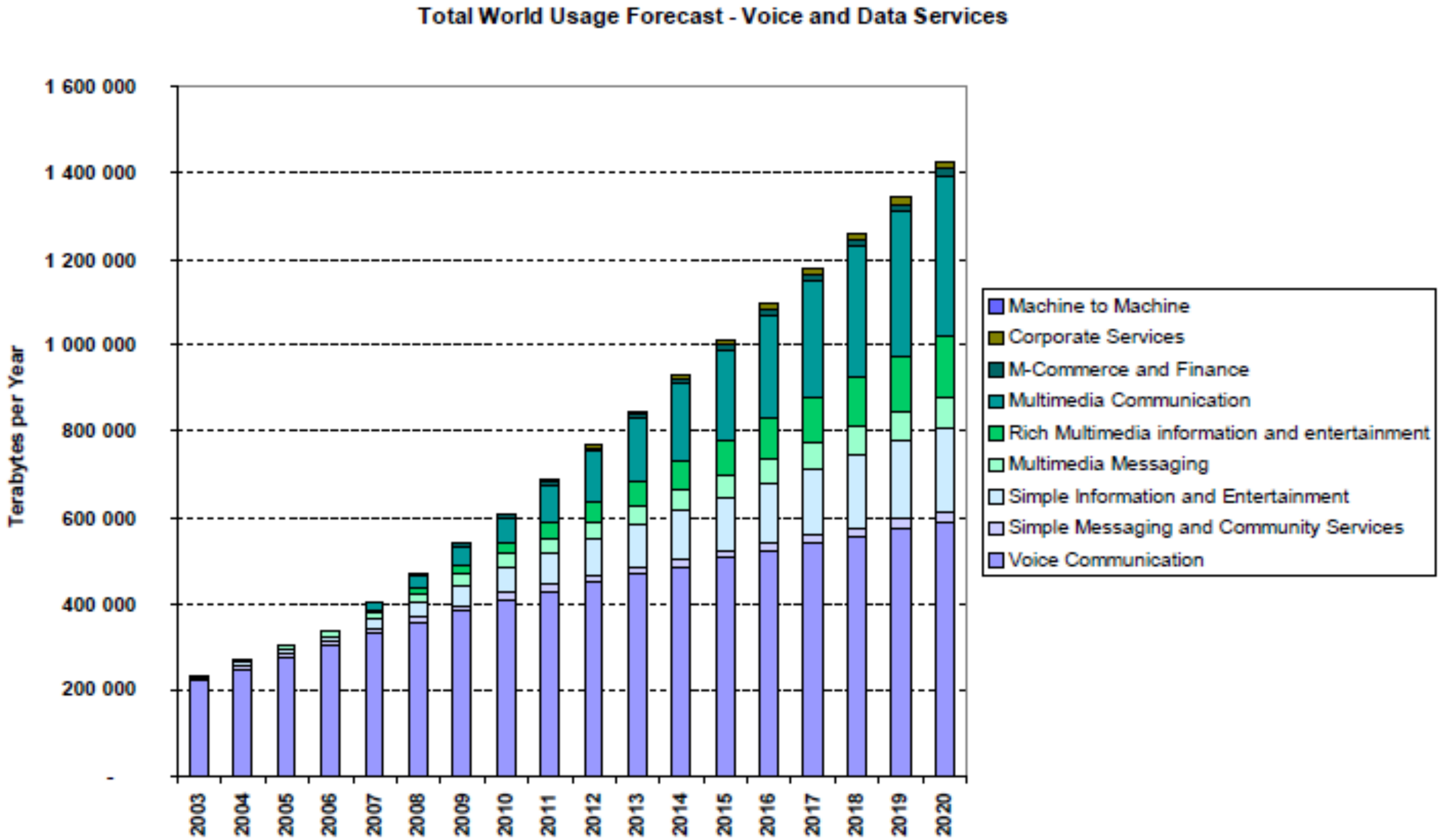
Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- Physical layer: modulation
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - WiFi (CSMA/CA)
- Personal Area Networks
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- **Cellular networks**
  - From GSM (2G) to UMTS (3G)
  - **LTE (4G)**

Agenda

- Standardization
- Motivation for LTE
- LTE performance requirements
- LTE challenges
- LTE/SAE Key Features
- LTE technology basics
- Air Interface Protocols

World Forecast per Service Category

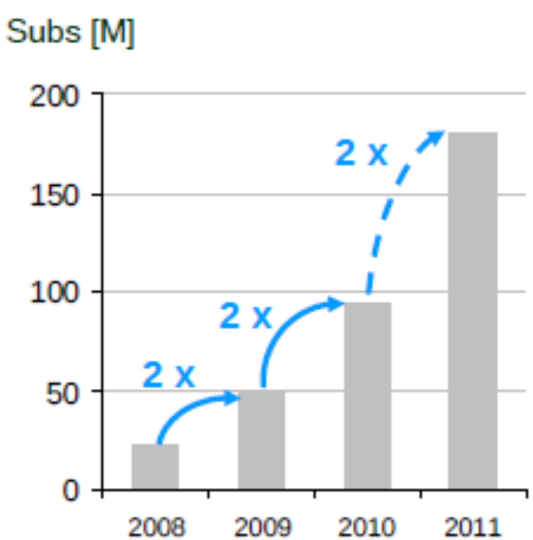


Source: Report ITU-R M.2072 "World mobile telecommunication market forecast"

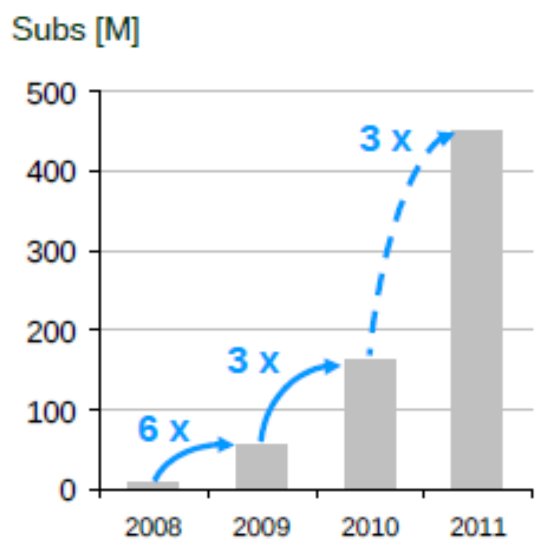
GLOBAL MBB HSPA SUBSCRIBER GROWTH

UNIVERSITÀ DI PARMA

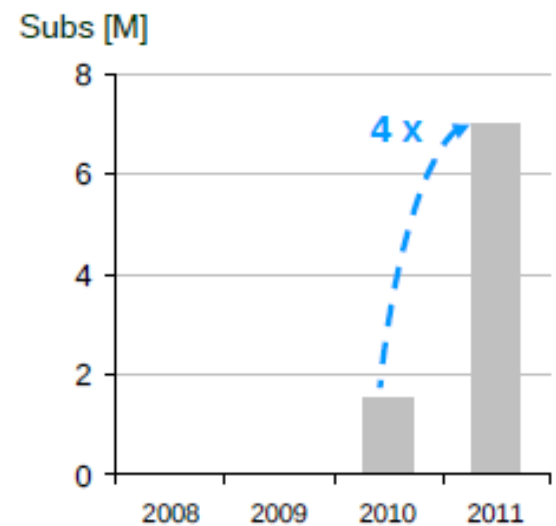
PC Connected Subs



Smartphone Subs

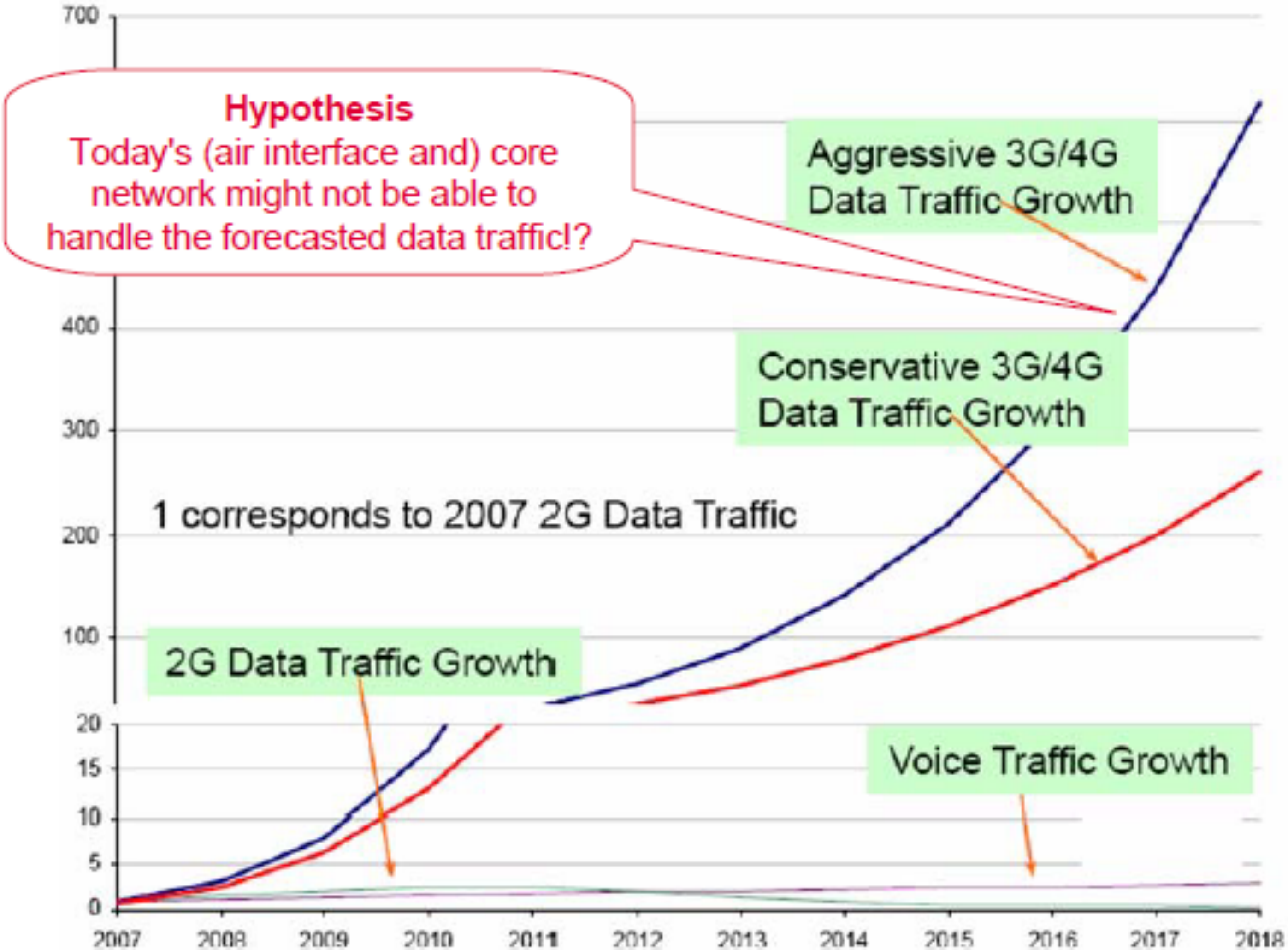


Tablet Subs



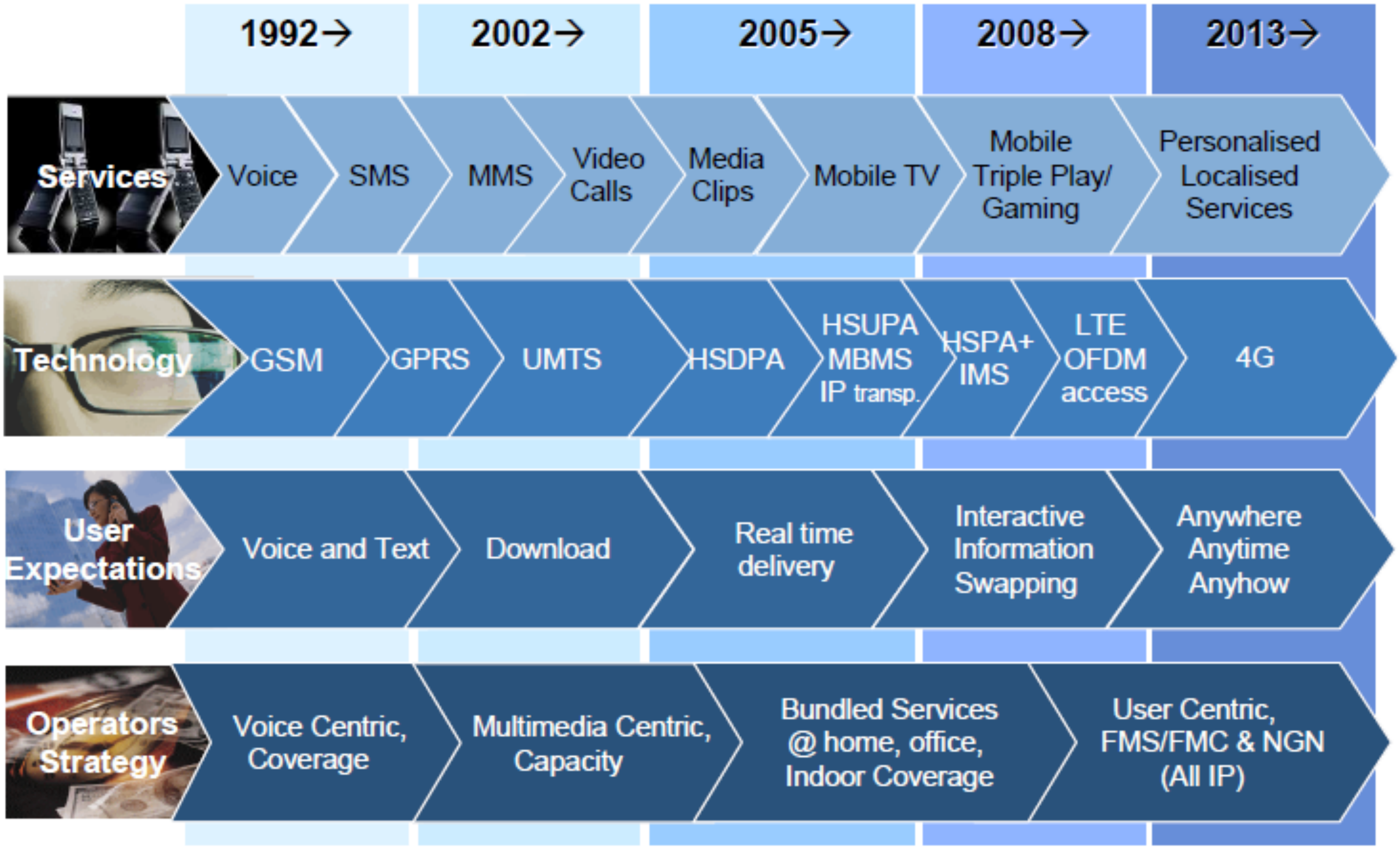
SMARTPHONE SURPASSING PC IN 2010
STRONG CONTINUED GROWTH EXPECTED

Data traffic growth forecast



Source: Peter Rysavy, 3G Americas

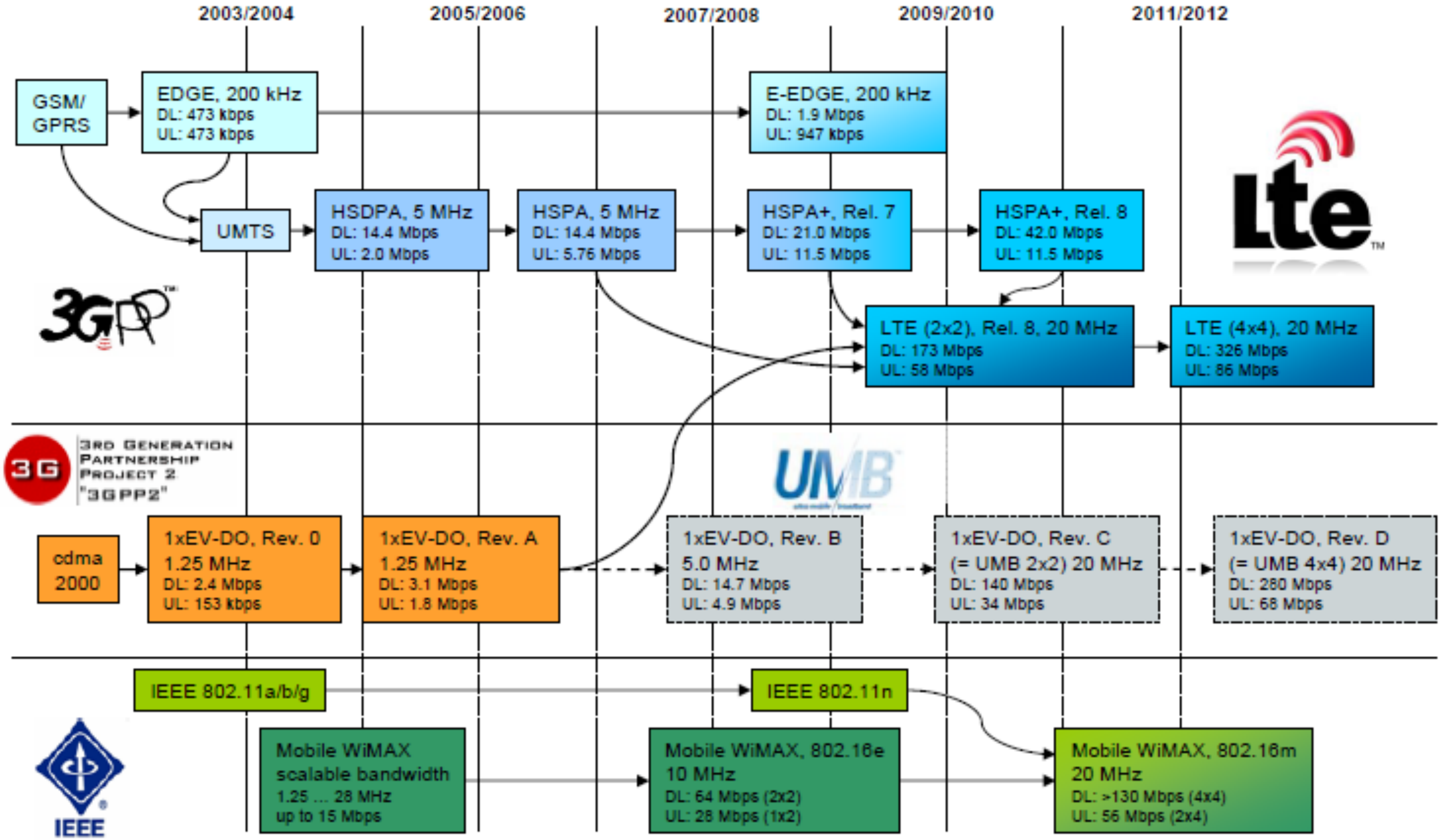
Mobile Evolution



Standardization

- LTE is the latest standard in the mobile network technology tree that previously realized the GSM/EDGE and UMTS/HSxPA network technologies that now account for over 85% of all mobile subscribers. LTE will ensure 3GPP's competitive edge over other cellular technologies.
- 3GPP work on the Evolution of the 3G Mobile System started in November 2004.
- Specifications scheduled finalized by the end of December 2009.
- Currently, standardization in progress in the form of Rel-9 and Rel-10.

Today's technology evolution path



Motivation for LTE

- Need for higher data rates and greater spectral efficiency
  - Can be achieved with HSDPA/HSUPA
  - and/or new air interface defined by 3GPP LTE
- Need for Packet Switched optimized system
  - Evolve UMTS towards packet only system
- Need for high quality of services
  - Use of licensed frequencies to guarantee quality of services
  - Always-on experience (reduce control plane latency significantly)
  - Reduce round trip delay
- Need for cheaper infrastructure
  - Simplify architecture, reduce number of network elements

LTE performance requirements

- Data Rate:
  - Instantaneous downlink peak data rate of 100Mbit/s in a 20MHz downlink spectrum (i.e. 5 bit/s/Hz)
  - Instantaneous uplink peak data rate of 50Mbit/s in a 20MHz uplink spectrum (i.e. 2.5 bit/s/Hz)
- Cell range
  - 5 km - optimal size
  - 30km sizes with reasonable performance
  - up to 100 km cell sizes supported with acceptable performance
- Cell capacity
  - up to 200 active users per cell(5 MHz) (i.e., 200 active data clients)

LTE performance requirements – Cont.

- Mobility
  - Optimized for low mobility(0-15km/h) but supports high speed
- Latency
  - user plane < 5ms
  - control plane < 50 ms
- Improved spectrum efficiency
- Improved broadcasting
- IP-optimized
- Scalable bandwidth of 20, 15, 10, 5, 3 and 1.4MHz
- Co-existence with legacy standards

The way to LTE: 3 main 3G limitations

1. The maximum bit rates still are factor of 20 and more behind the current state of the systems like 802.11n and 802.16e/m.
2. The latency of user plane traffic (UMTS: >30 ms) and of resource assignment procedures (UMTS: >100 ms) is too big to handle traffic with high bit rate variance efficiently.
3. The terminal complexity for WCDMA or MC-CDMA systems is quite high, making equipment expensive, resulting in poor performing implementations of receivers and inhibiting the implementation of other performance enhancements.

Suggested Technical Reading (see end)

LTE PART II: 3GPP RELEASE 8

LTE: The Evolution of Mobile Broadband

David Astély, Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindström, and Stefan Parkvall, Ericsson Research

IEEE Communications Magazine • April 2009

ABSTRACT

This article provides an overview of the LTE radio interface, recently approved by the 3GPP, together with a more in-depth description of its features such as spectrum flexibility, multi-antenna transmission, and inter-cell interference control. The performance of LTE and some of its key features is illustrated with simulation results. The article is concluded with an outlook into the future evolution of LTE.

LTE Overview – Design Targets and Multiple Access Technologies

LTE CHALLENGES

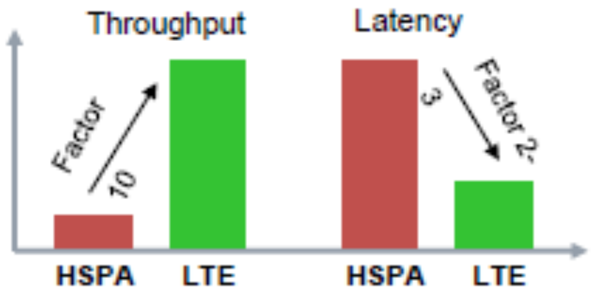
What are the LTE challenges?

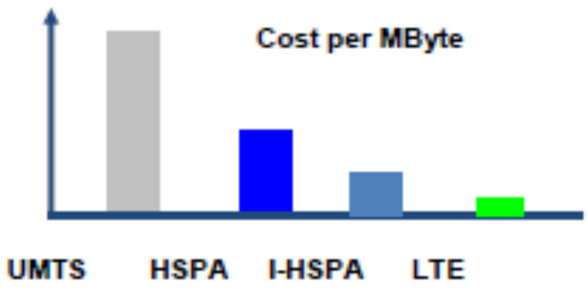
The Users' expectation…
Best price, transparent flat rate
Full Internet
Multimedia

..leads to the operator's challenges
reduce cost per bit
provide high data rate
provide low latency

User experience will have an impact on ARPU

Price per Mbyte has to be reduced to remain profitable

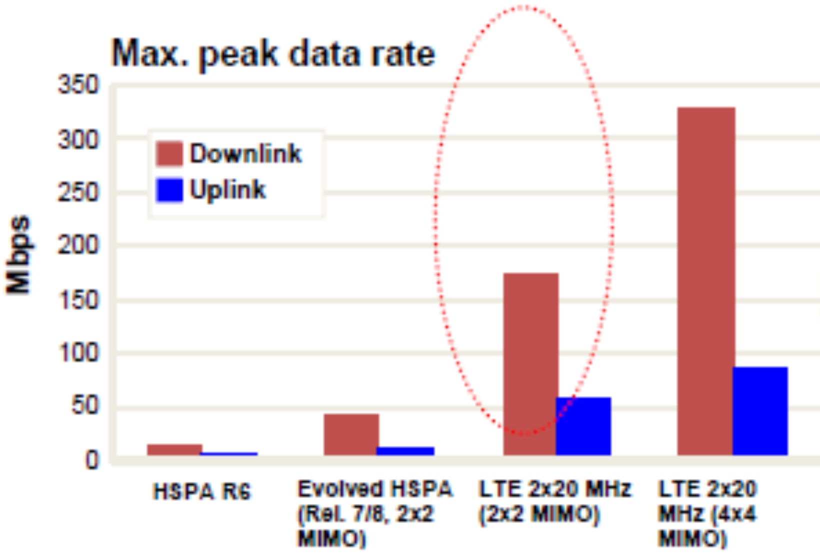


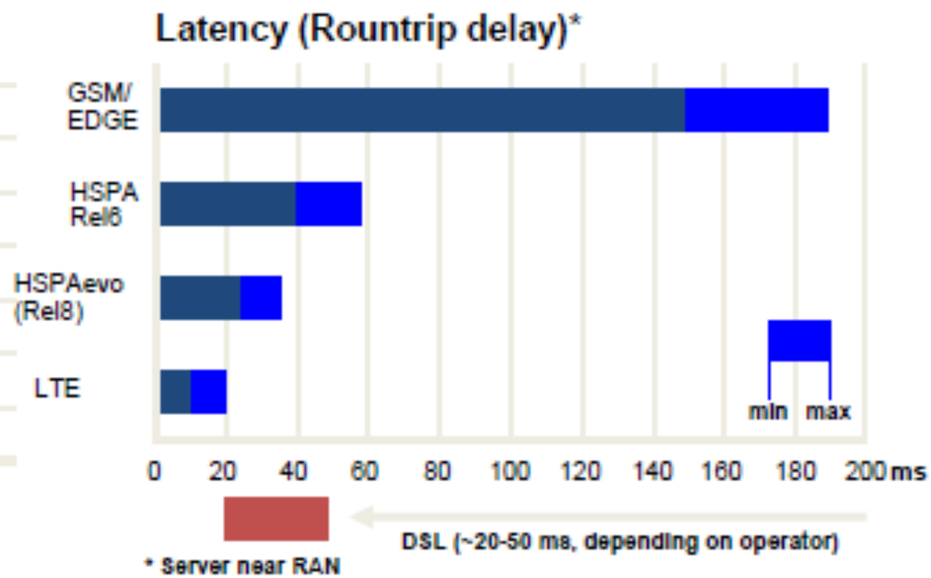


Comparison of Throughput and Latency

Peak data rates around 300Mbps/80 Mbps
Low latency 10-20 ms

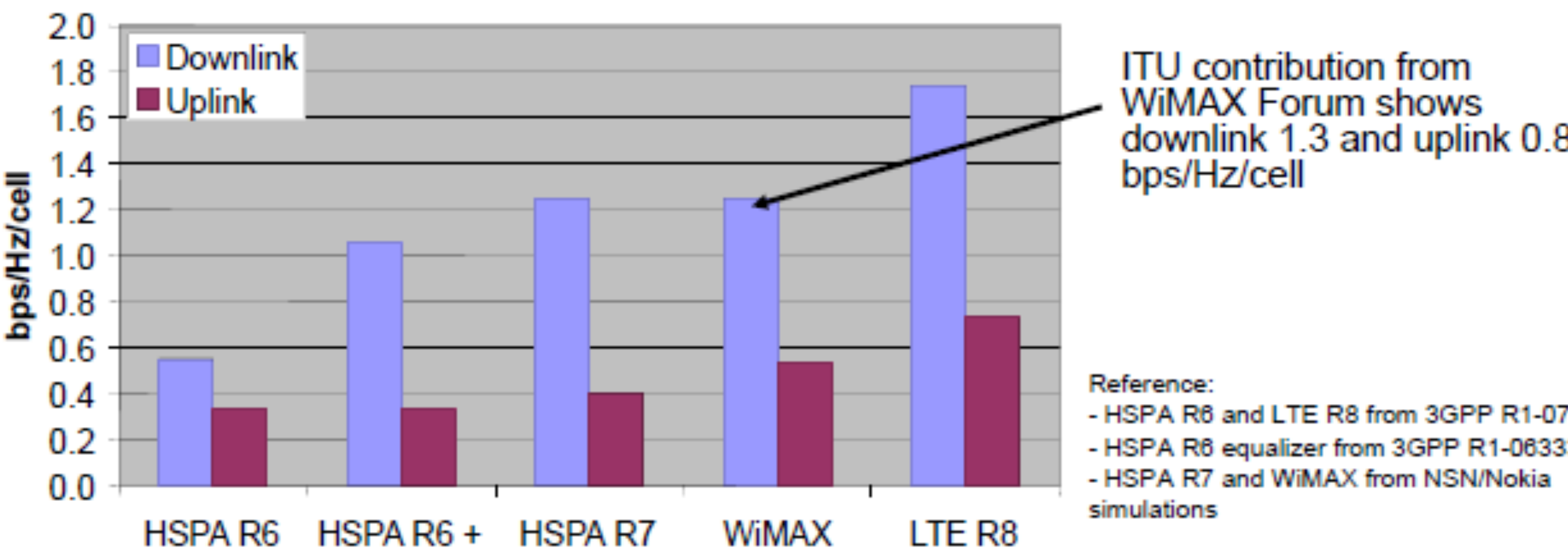
Enhanced consumer experience:
drives subscriber uptake
allow for new applications
provide additional revenue streams





Increased Spectral Efficiency

- All cases assume 2-antenna terminal reception
- HSPA R7, WiMAX and LTE assume 2-antenna BTS transmission (2x2 MIMO)

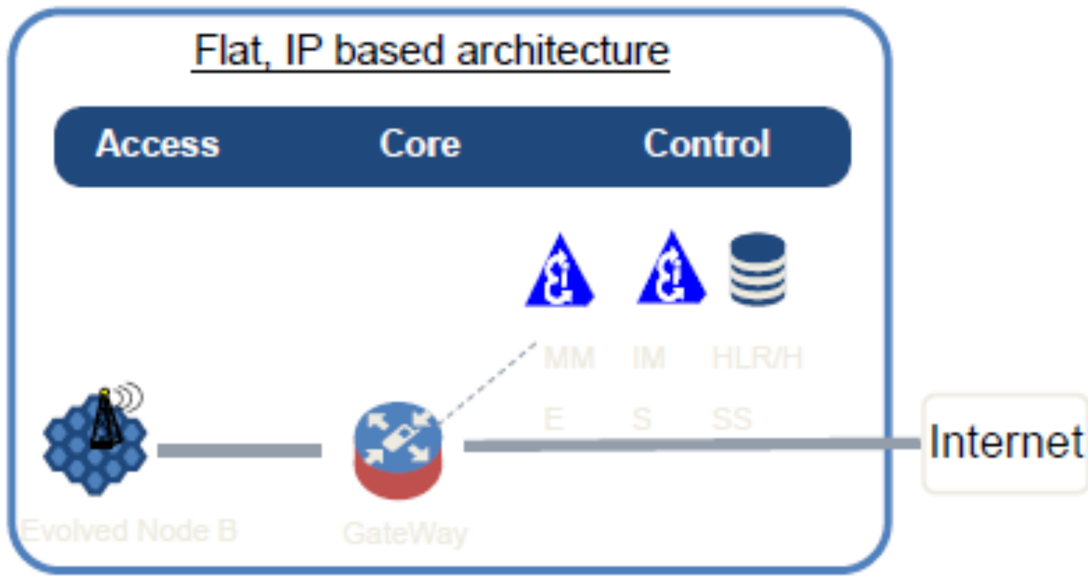


Reference:
- HSPA R6 and LTE R8 from 3GPP R1-071960
- HSPA R6 equalizer from 3GPP R1-063335
- HSPA R7 and WiMAX from NSN/Nokia simulations

Reduced Network Complexity

Flat, scalable IP based architecture ➡ Flat Architecture: 2 nodes architecture
IP based Interfaces

Flat networks are characterized by fewer network elements, lower latency, greater flexibility and lower operation cost



LTE Overview – Design Targets and Multiple Access Technologies

LTE/SAE KEY FEATURES

LTE Architecture

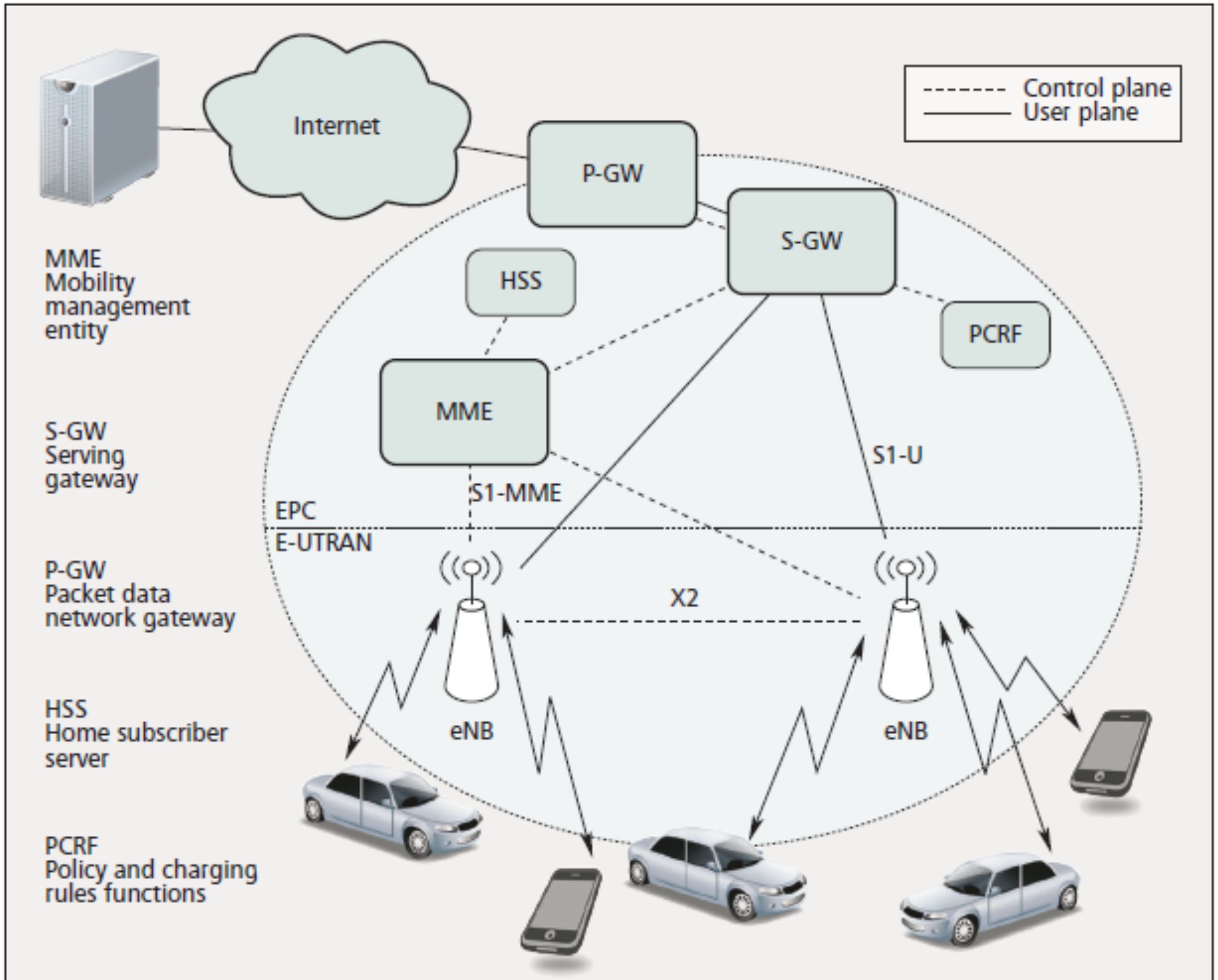
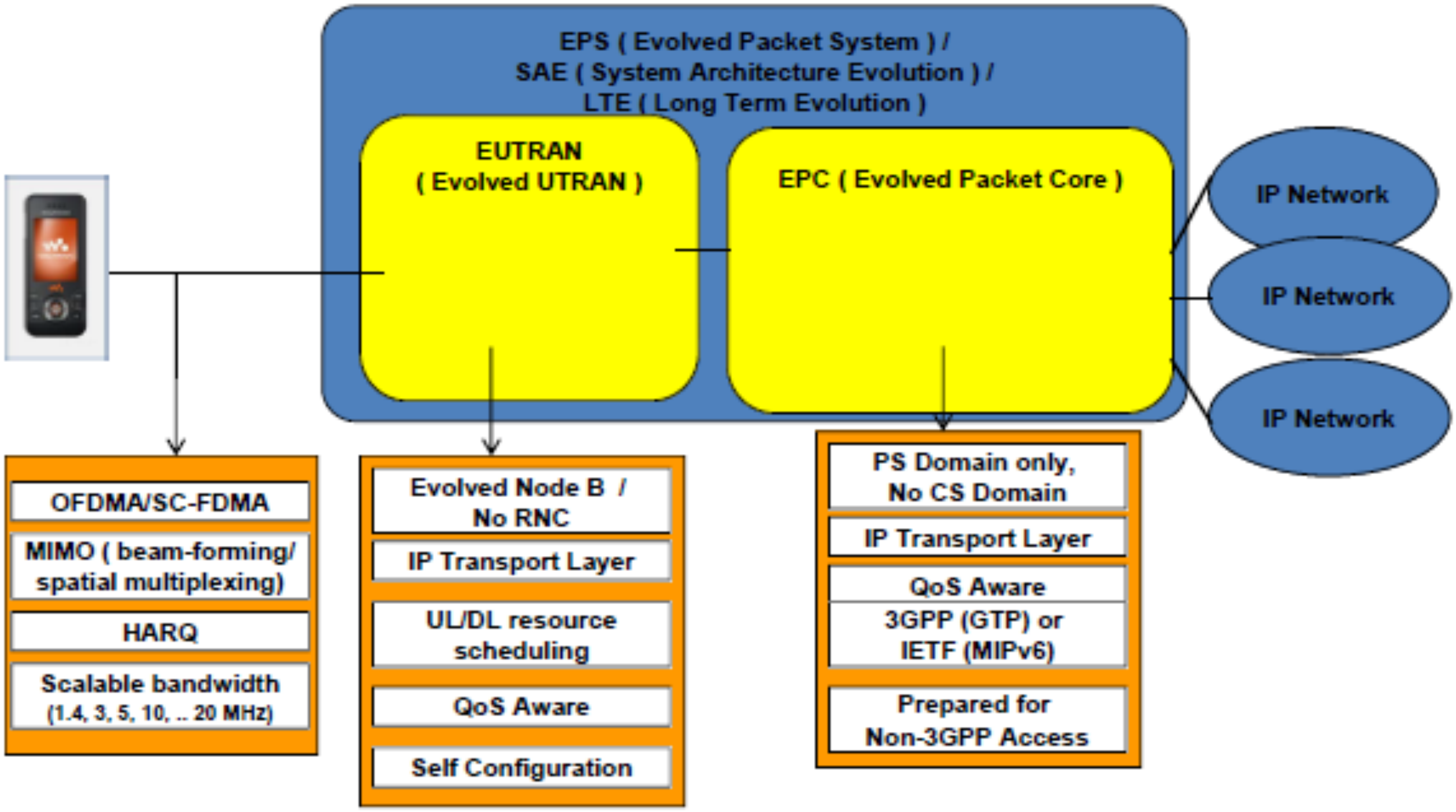


Figure 1. *LTE architecture: access network (eUTRAN) and core network (EPC) entities.*

LTE/SAE Key Features – Overview

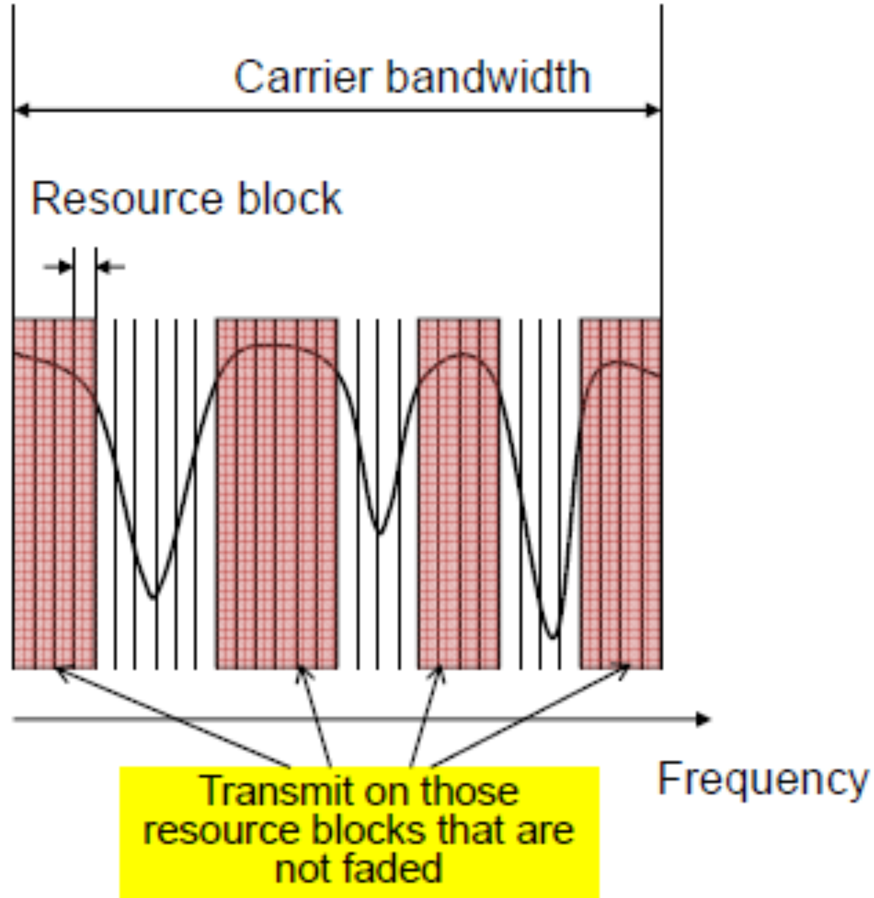


LTE/SAE Key Features

- Evolved NodeB
  - No RNC is provided anymore
  - The evolved Node Bs take over all radio management functionality.
  - This will make radio management faster and hopefully the network architecture simpler
- IP transport layer
  - EUTRAN exclusively uses IP as transport layer
- UL/DL resource scheduling
  - In UMTS physical resources are either shared or dedicated
  - Evolved Node B handles all physical resource via a scheduler and assigns them dynamically to users and channels
  - This provides greater flexibility than the older system

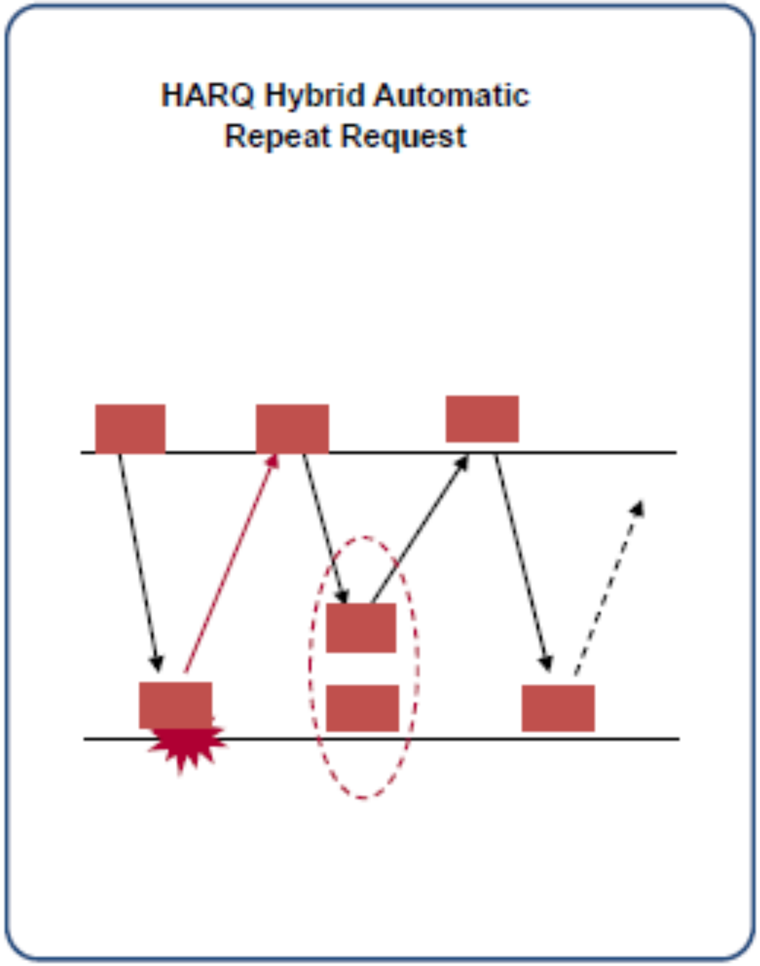
LTE/SAE Key Features – Cont.

- Frequency Domain Scheduling :
  - Frequency domain scheduling uses those resource blocks that are not faded
  - Not possible in CDMA based system



LTE/SAE Key Features – Cont.

- HARQ
  - Hybrid Automatic Retransmission on reQuest
  - HARQ has already been used for HSDPA and HSUPA.
  - HARQ especially increases the performance (delay and throughput) for cell edge users.
  - HARQ simply implements a retransmission protocol on layer 1/2 that allows to send retransmitted blocks with different coding than the 1st one.



LTE/SAE Key Features – Cont.

- QoS awareness
  - The scheduler must handle and distinguish different quality of service classes
  - Otherwise real time services would not be possible via EUTRAN
  - The system provides the possibility for differentiated service
- Self configuration
  - Currently under investigation
  - Possibility to let Evolved Node Bs configure themselves
- It will not completely substitute the manual configuration and optimization.

LTE/SAE Key Features – Cont.

- Packet Switched Domain only
  - No circuit switched domain is provided
  - If CS applications are required, they must be implemented via IP
- Non-3GPP access
  - The EPC will be prepared also to be used by non-3GPP access networks (e.g. LAN, WLAN, WiMAX, etc.)
  - This will provide true convergence of different packet radio access system

LTE/SAE Key Features – Cont.

- MIMO
  - Multiple Input Multiple Output
  - LTE will support MIMO as an option,
  - It describes the possibility to have multiple transmitter and receiver antennas in a system.
  - Up to four antennas can be used by a single LTE cell (gain: spatial multiplexing)
  - MIMO is considered to be the core technology to increase spectral efficiency.

LTE Overview – Design Targets and Multiple Access Technologies

LTE TECHNOLOGY BASICS

LTE key parameters

Frequency Range	UMTS FDD bands and UMTS TDD bands					
Channel bandwidth, 1 Resource Block=180 kHz	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
	6 RB	15 RB	25 RB	50 RB	75 RB	100 RB
Modulation Schemes	DL: OFDMA (Orthogonal Frequency Division Multiple Access) UL: SC-FDMA (Single Carrier Frequency Division Multiple Access)					
Multiple Access	DL: OFDMA (Orthogonal Frequency Division Multiple Access) UL: SC-FDMA (Single Carrier Frequency Division Multiple Access)					
MIMO technology	DL: Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset) UL: Multi user collaborative MIMO					
Peak Data Rate	DL: 150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz) UL: 75 Mbps (20 MHz)					

Scalable bandwidth → Easy to introduce in any frequency band:
Frequency refarming
(cost-efficient deployment on lower
Frequency bands supported)

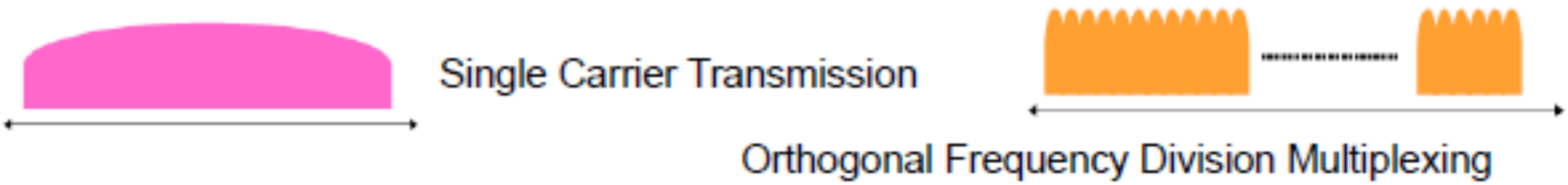
LTE Overview – Design Targets and Multiple Access Technologies

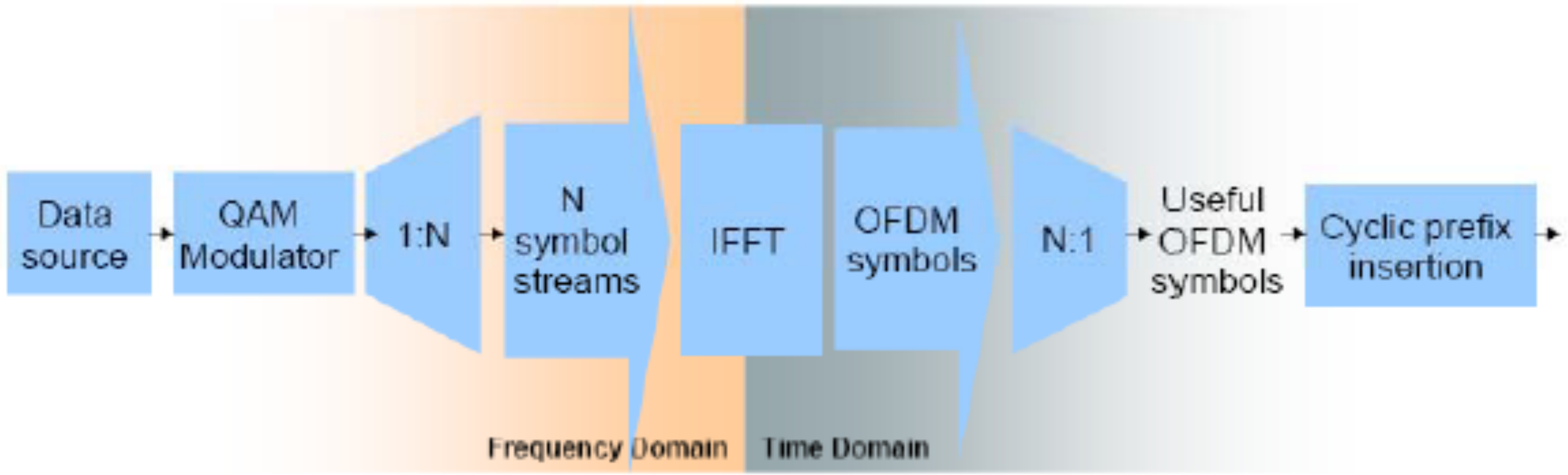
OFDM/OFDMA/SC-FDMA

OFDM: Orthogonal Frequency Division Multi-Carrier

- LTE uses OFDM for the DL– that is, from the base station to the terminal. OFDM meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for very wide carriers with high peak rates.
- The basic LTE downlink physical resource can be seen as a time-frequency grid. In the frequency domain, the spacing between the subcarriers, Δf, is 15kHz. In addition, the OFDM symbol duration time is $1/\Delta f$ + cyclic prefix. The cyclic prefix is used to maintain orthogonality between the sub-carriers even for a time-dispersive radio channel.
- One resource element carries QPSK, 16QAM or 64QAM.

OFDM – Cont.



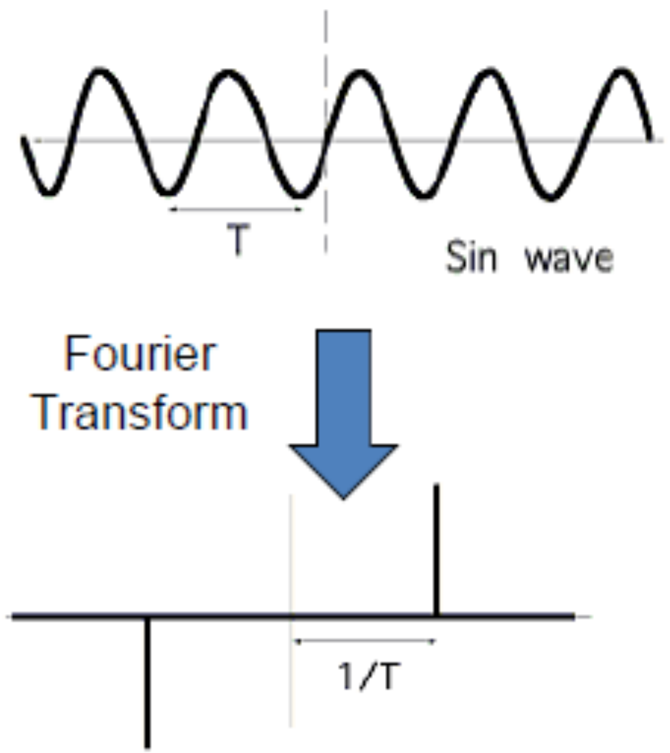


OFDM signal generation is based on Inverse Fast Fourier Transform (IFFT) operation on transmitter side. On receiver side, an FFT operation will be used.

Pulse shaping and Spectrum

- Two characteristics are important for a Signal:
  - The time domain presentation:
    - It helps recognize "how long the symbol lasts on air"
  - The frequency domain presentation:
    - to understand the required spectrum in terms of bandwidth

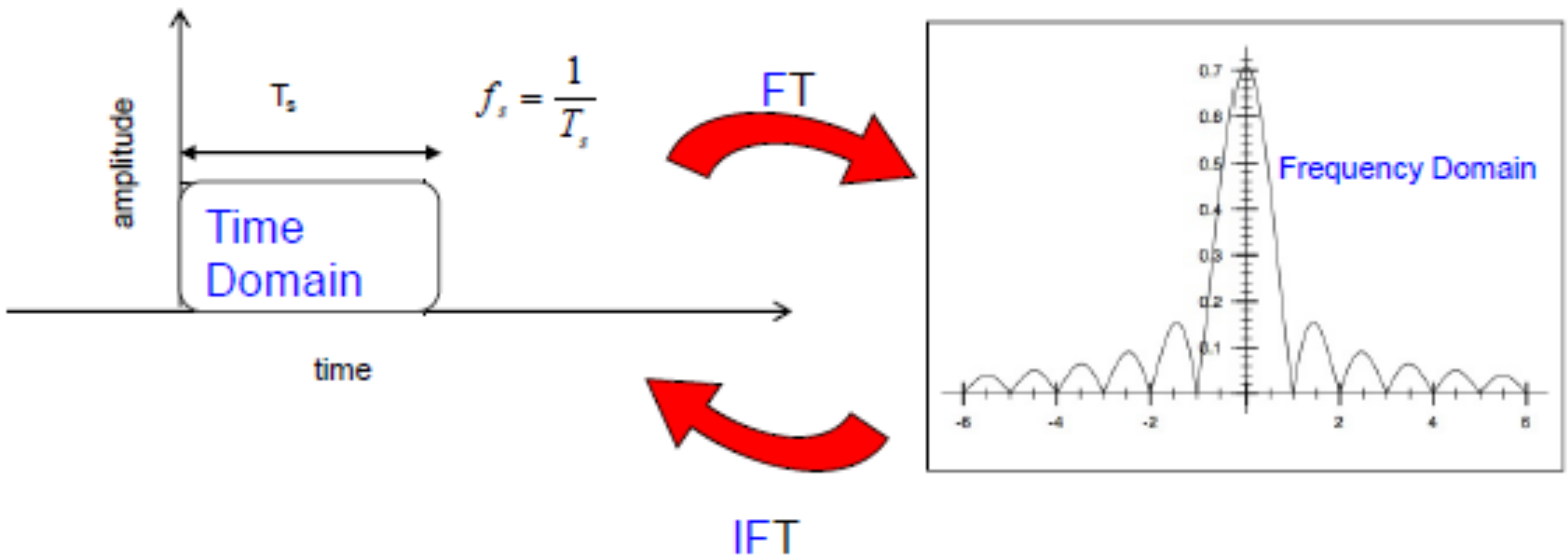
The time domain presentation



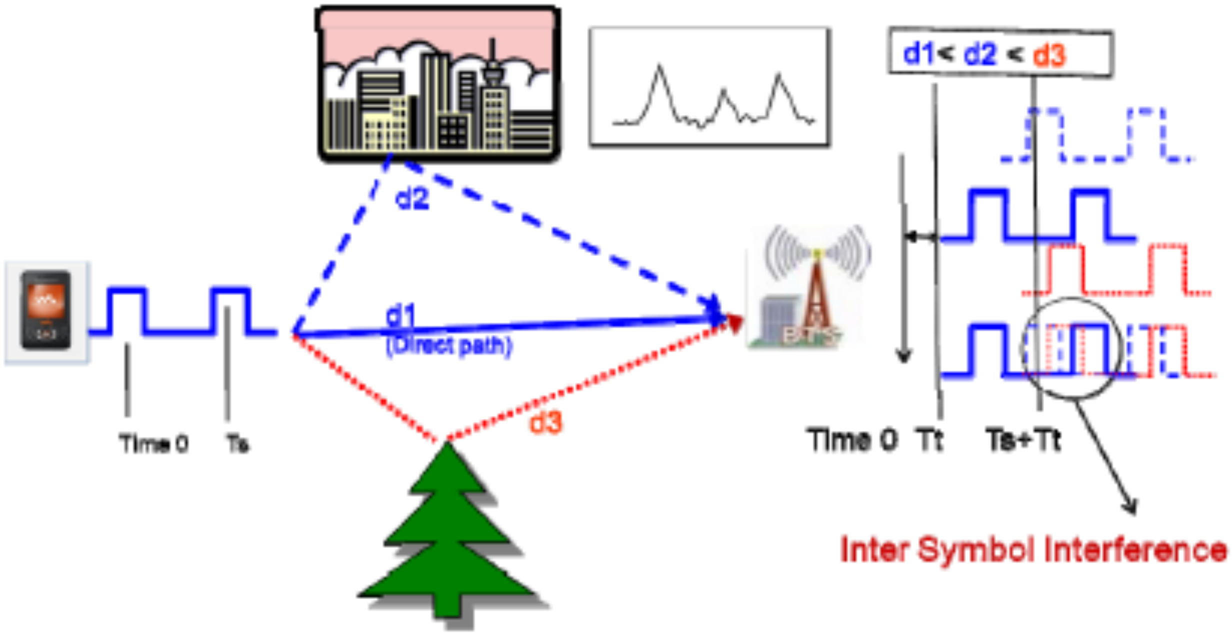
The frequency domain presentation

The rectangular Pulse

- It is one of the most simple time-domain pulses.
- It simply jumps at time t=0 to its maximum amplitude and after the pulse duration Ts just goes back to 0.



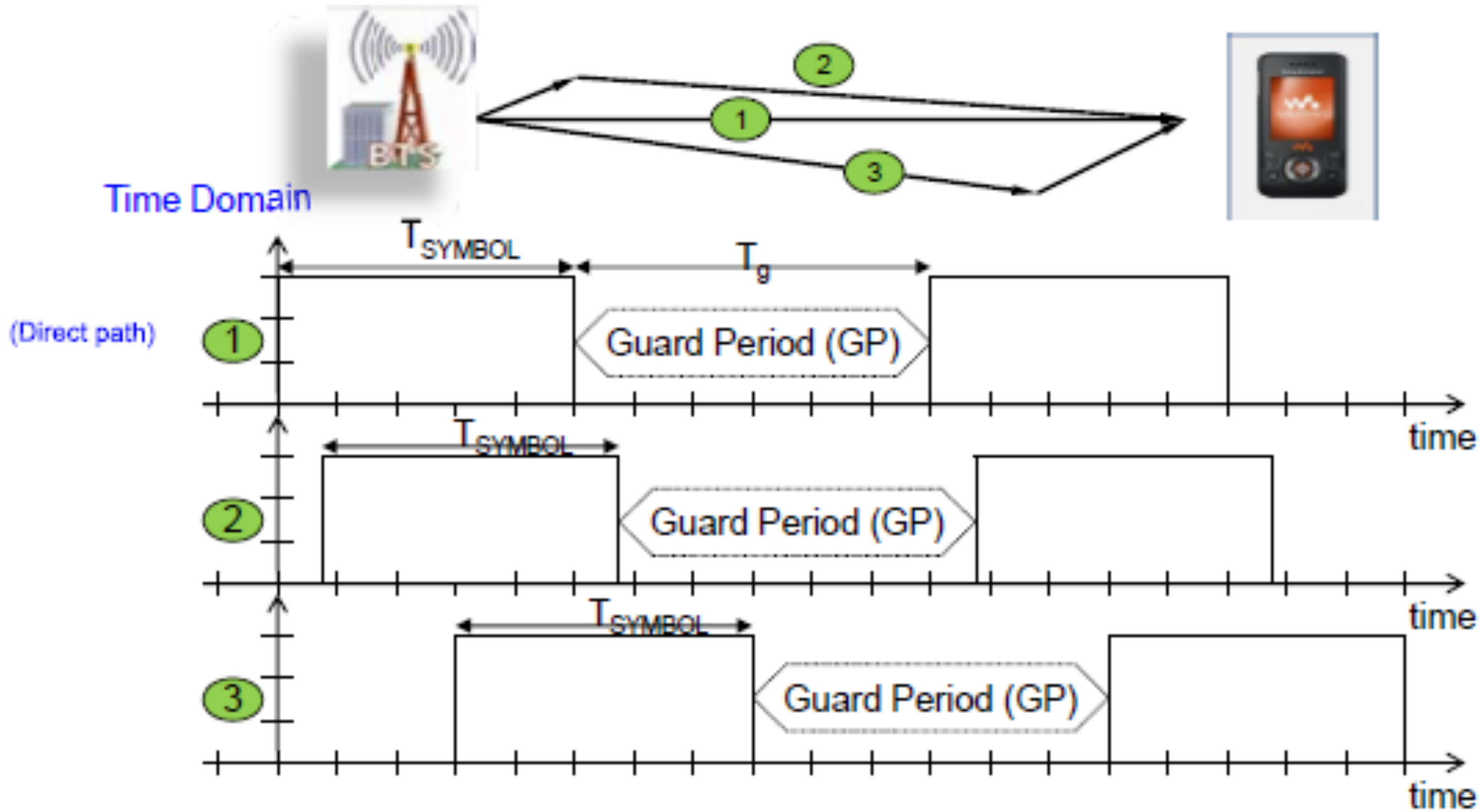
Multi-Path Propagation and Inter-Symbol Interference



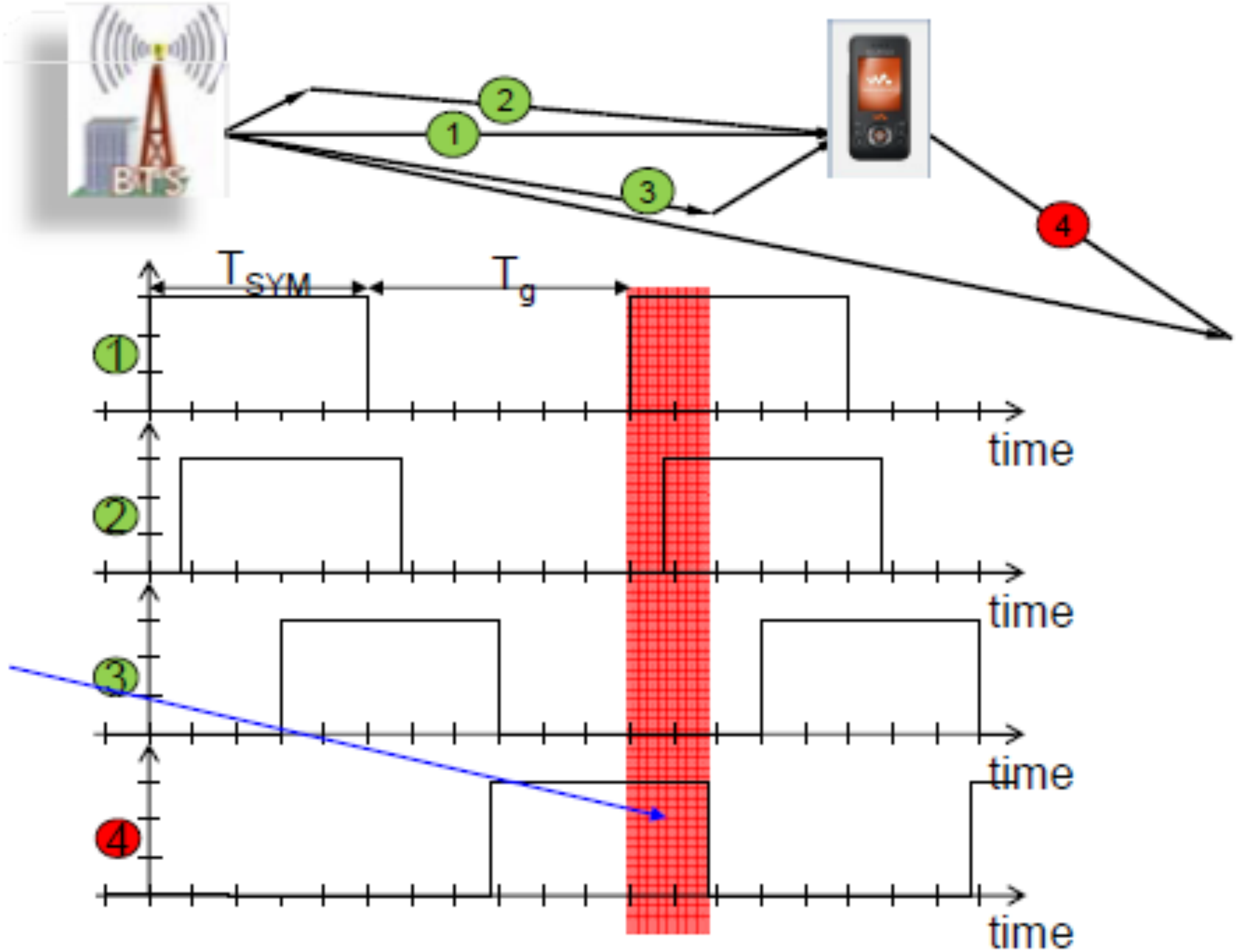
Multi-Path Propagation and Inter-Symbol Interference

- The cancellation of inter-symbol interference makes more complex the hardware design of the receivers.
- In WCDMA for instance the RAKE receiver requires a huge amount of DSP capacity.
- One of the goals of future radio systems is to simplify receiver design.
- Inter-symbol interference originating from the pulse form itself is simply avoided by starting the next pulse only after the previous one finished completely, therefore introducing a Guard Period (Tg) after the Pulse.
- There is no inter-symbol interference between symbols as long as the multi-path delay spread (e.g. delay difference between first and last detectable path) is less than the guard period duration Tg.

Multi-Path Propagation and the Guard Period



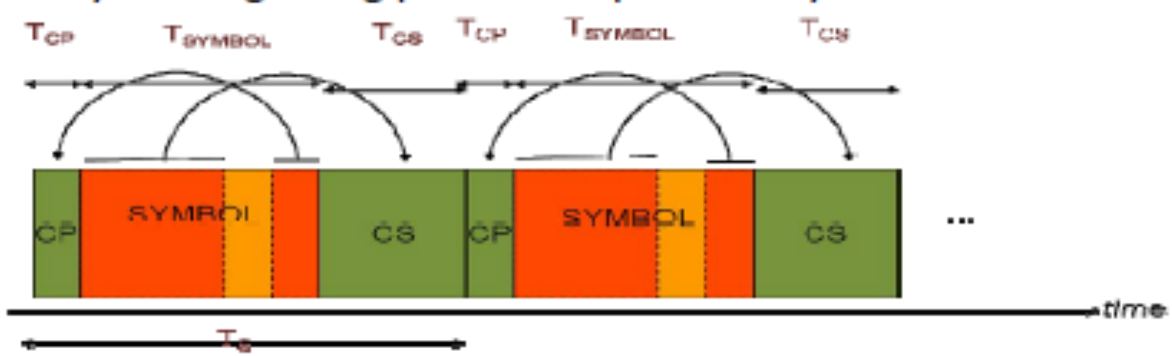
Multi-Path Propagation and the Guard Period



when the delay spread of the multi-path environment is greater than the guard period duration (Tg), then we encounter inter-symbol interference (ISI)

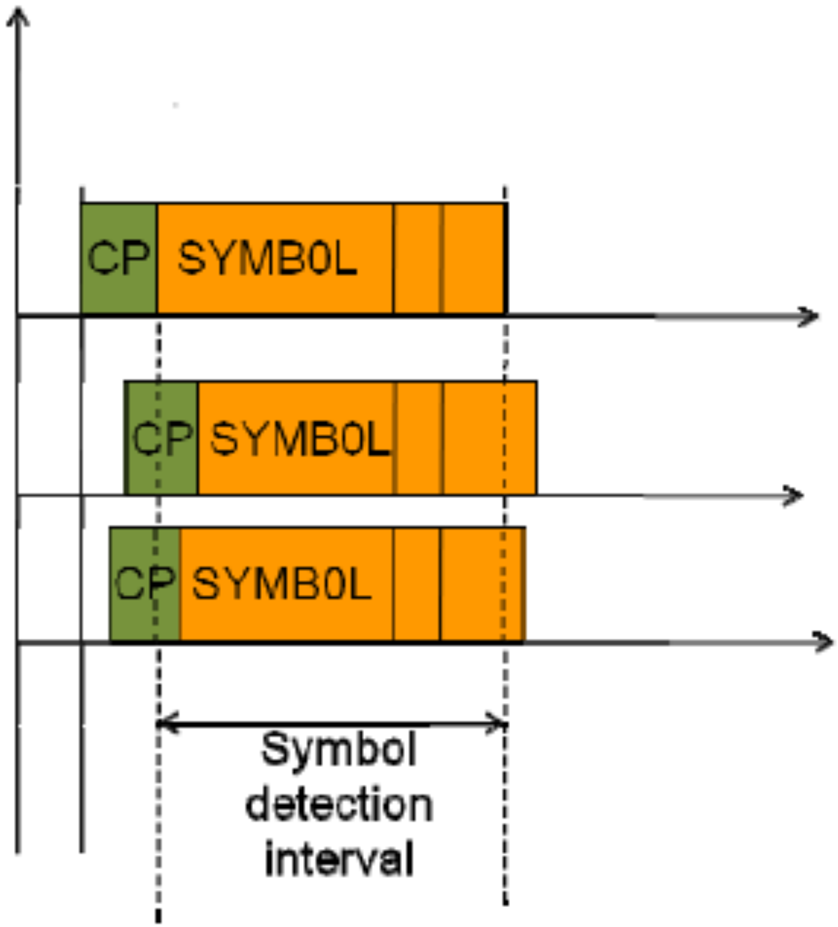
Reuse of the Guard Period

- There is the possibility to use the lost transmission time during the Guard Period by repeating part of the symbol during this period.
- This is achieved by filling the guard period with either one or both of the following two solutions: Cyclic Prefic (CP) and Cyclic Sufix (CS).
- CP: The cyclic prefix is filling the final part of the guard period. It simply consists of the last part of the following symbol. Cyclic prefixes are used by all modern OFDM systems and their sizes range from 1/4 to 1/32 of a symbol period.
- CS: The cyclic suffix fills the initial part of the guard period and it is simply occupied by the beginning part of the previous symbol.



Cyclic Prefix

- In multi-path propagation environments the delayed versions of the signal arrive with a time offset, so that the start of the symbol of the earliest path falls in the cyclic prefixes of the delayed symbols.
- As the CP is simply a repetition of the end of the symbol this is not a inter-symbol interference and can be easily compensated by the following decoding based on discrete Fourier transform.



Limitations of the Single-Carrier Modulation

- Using a single radio frequency carrier with rectangular pulse shaping has a major drawback:
- The cyclic prefix duration is fixed by the maximum expected delay spread over the multi-path propagation models for the system.

$$delay_{\max} = T_{CP}$$

- The symbol duration can be made as small as the cyclic prefix size, but then only one half of the time is used for data transmission, the other half is for the cyclic prefix, providing a very low efficiency (E)

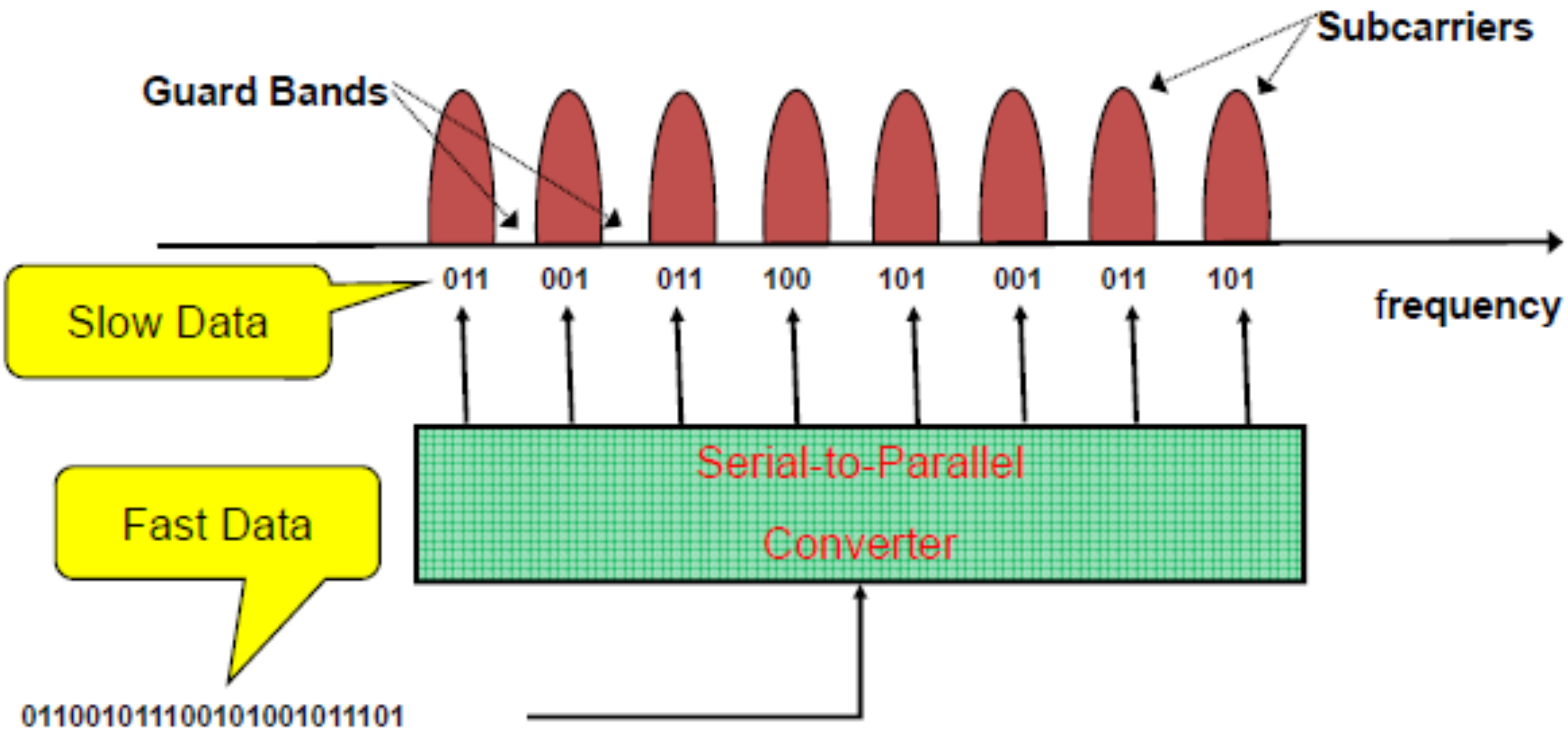
$$E = \frac{T_{SYMBOL}}{T_{SYMBOL} + T_{CP}}$$

- Also shorter symbol duration mean a broader spectrum bandwidth (f_S) to be used for a carrier.

$$f_S = \frac{1}{T_S} = \frac{1}{T_{SYMBOL} + T_{CP}}$$

- To increase efficiency the symbol duration must be made longer, but then the symbol rate is reduced.

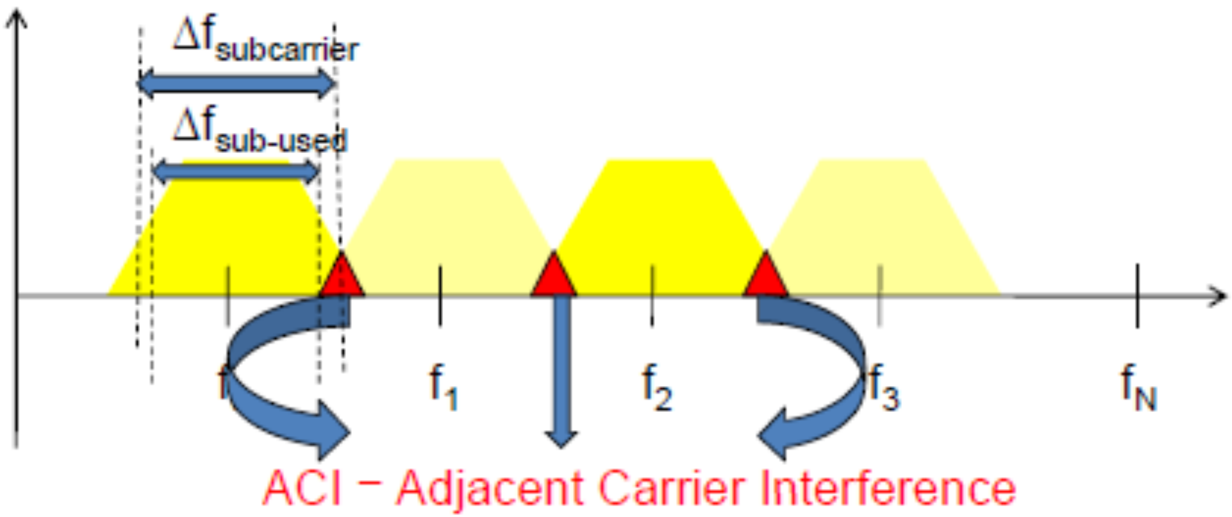
Multi-Carrier Modulation



Multi-Carrier Modulation –Cont.

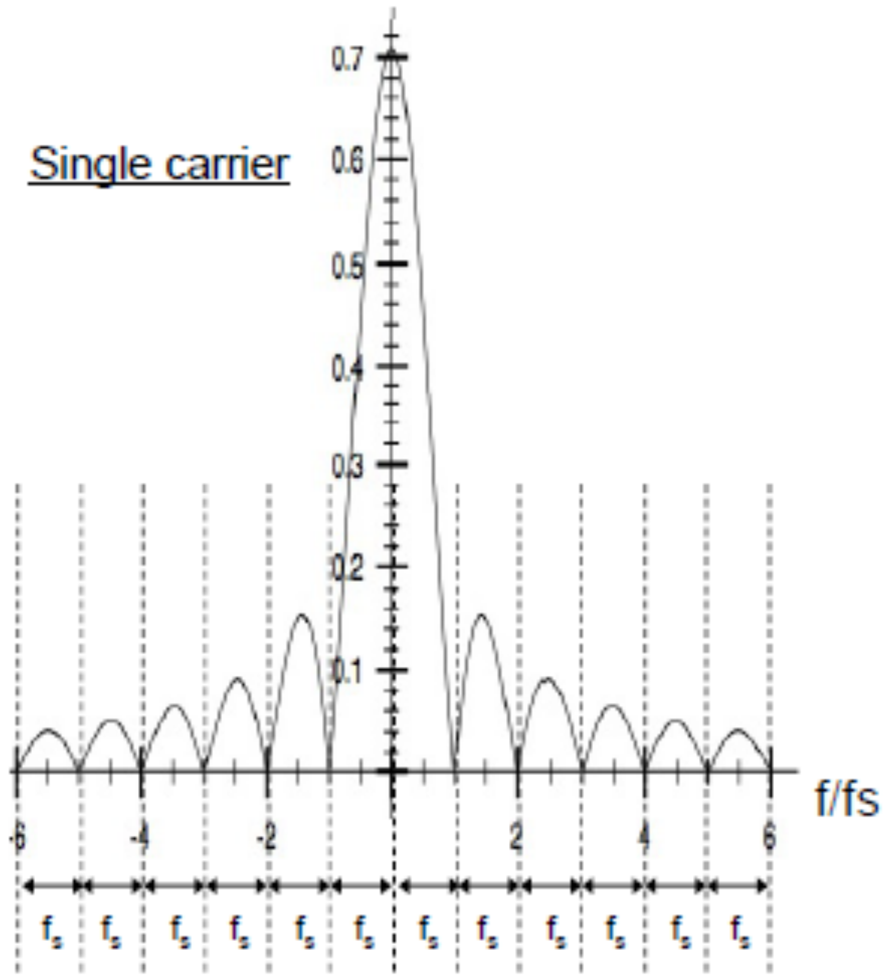
The center frequencies must be spaced so that interference between different carriers, known as **Adjacent Carrier Interference ACI,** is minimized; but not too much spaced as the total bandwidth will be wasted.

Each carrier uses an upper and lower guard band to protect itself from its adjacent carriers. Nevertheless, there will always be some interference between the adjacent carriers.



OFDM: Orthogonal Frequency Division Multi-Carrier

- For the rectangular pulse there is a better option possible and it is even easier to implement.
- We must just notice that the spectrum of a rectangular pulses shows null points exactly at integer multiples of the frequency given by the symbol duration.
- The only exception is the center frequency (peak power)

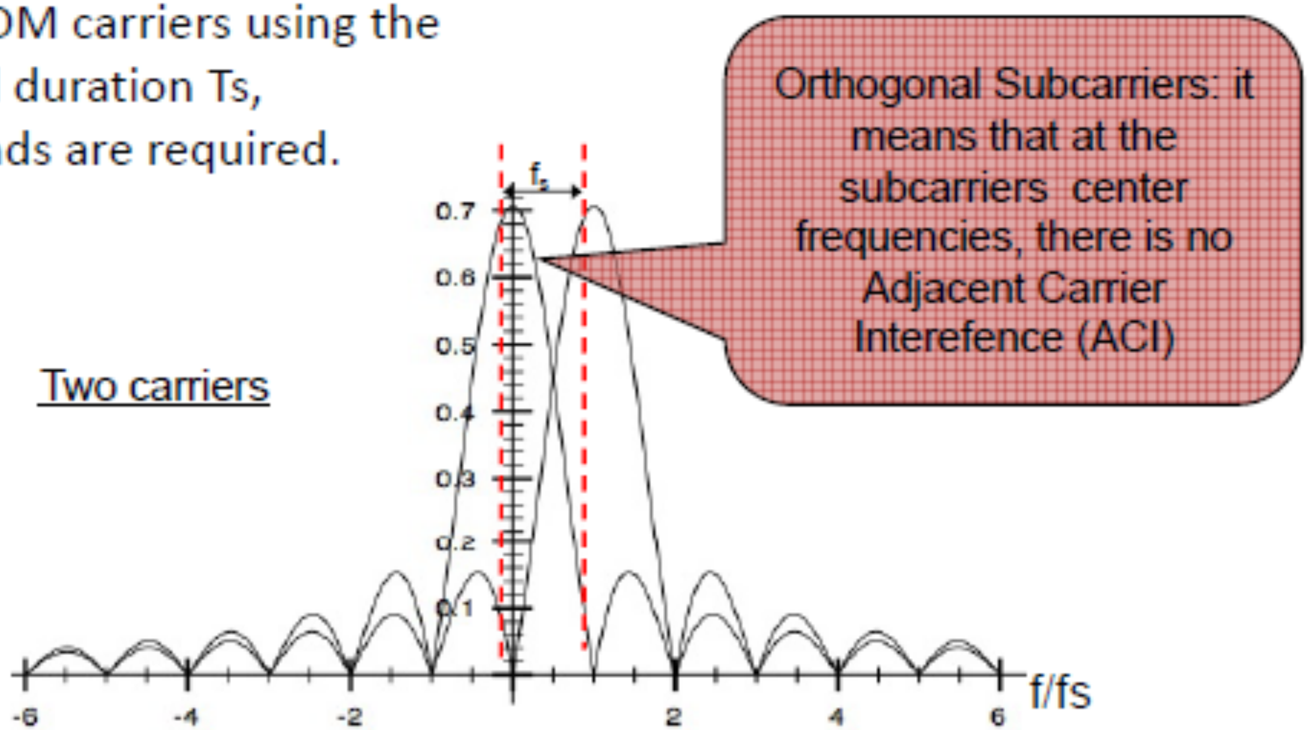


OFDM: Orthogonal Frequency Division Multi-Carrier

Thus OFDM simply places the next carrier exactly in the first null point of the previous one.

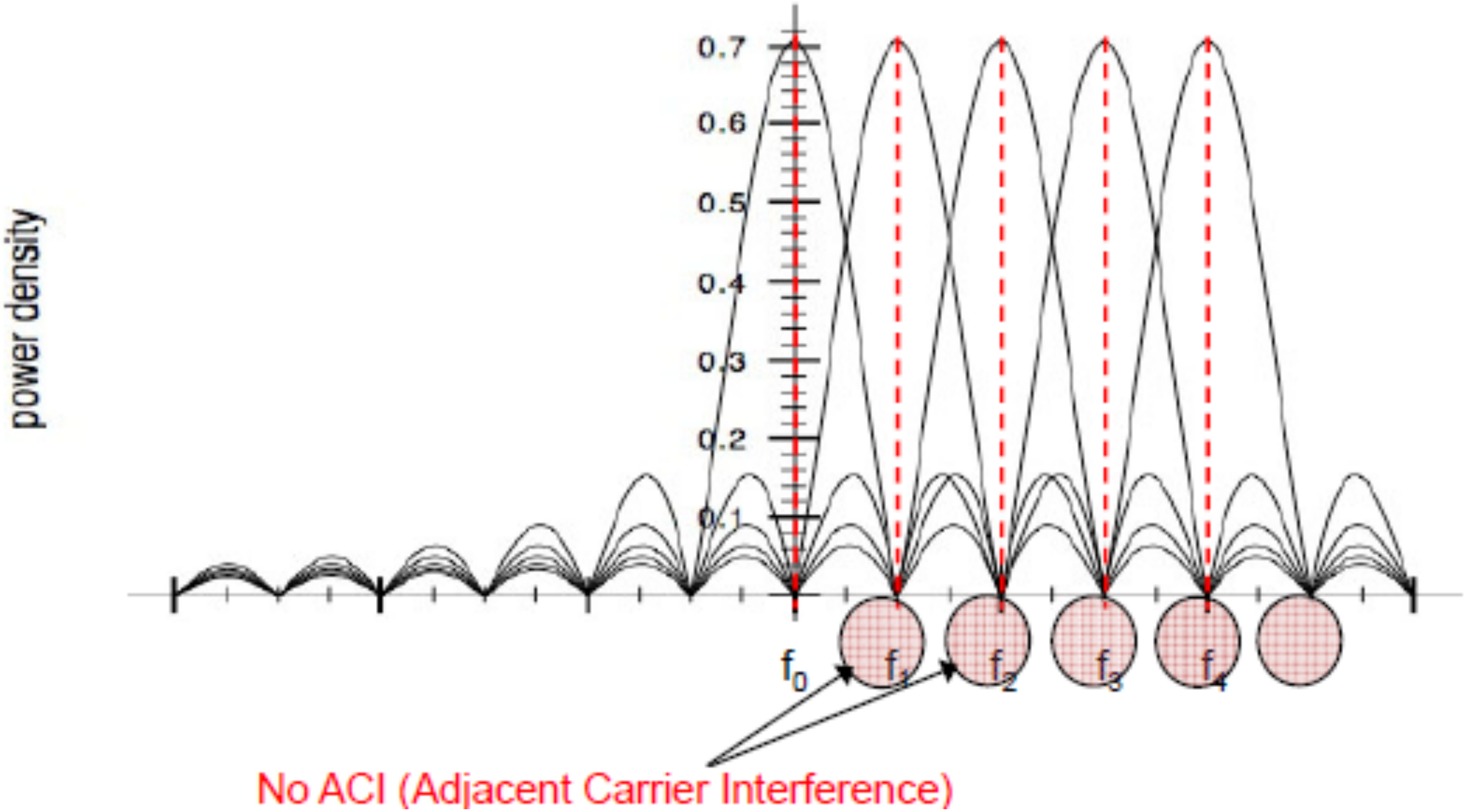
With this we don't need any pulse-shaping.

Between OFDM carriers using the same symbol duration Ts, no guard bands are required.



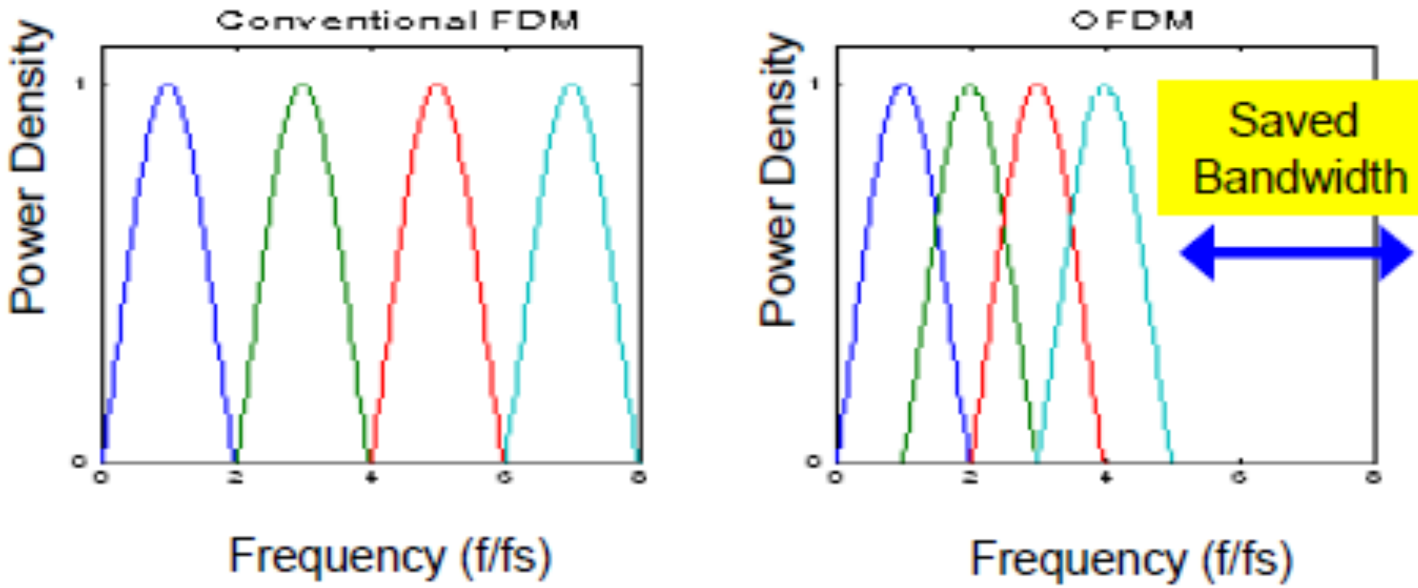
Spectrum Overlapping of multiple OFDM carriers

$$f_n = f_0 + n f_s = f_0 + n \frac{1}{T_s} \qquad n = \ldots -1, 0, 1, 2 \ldots$$

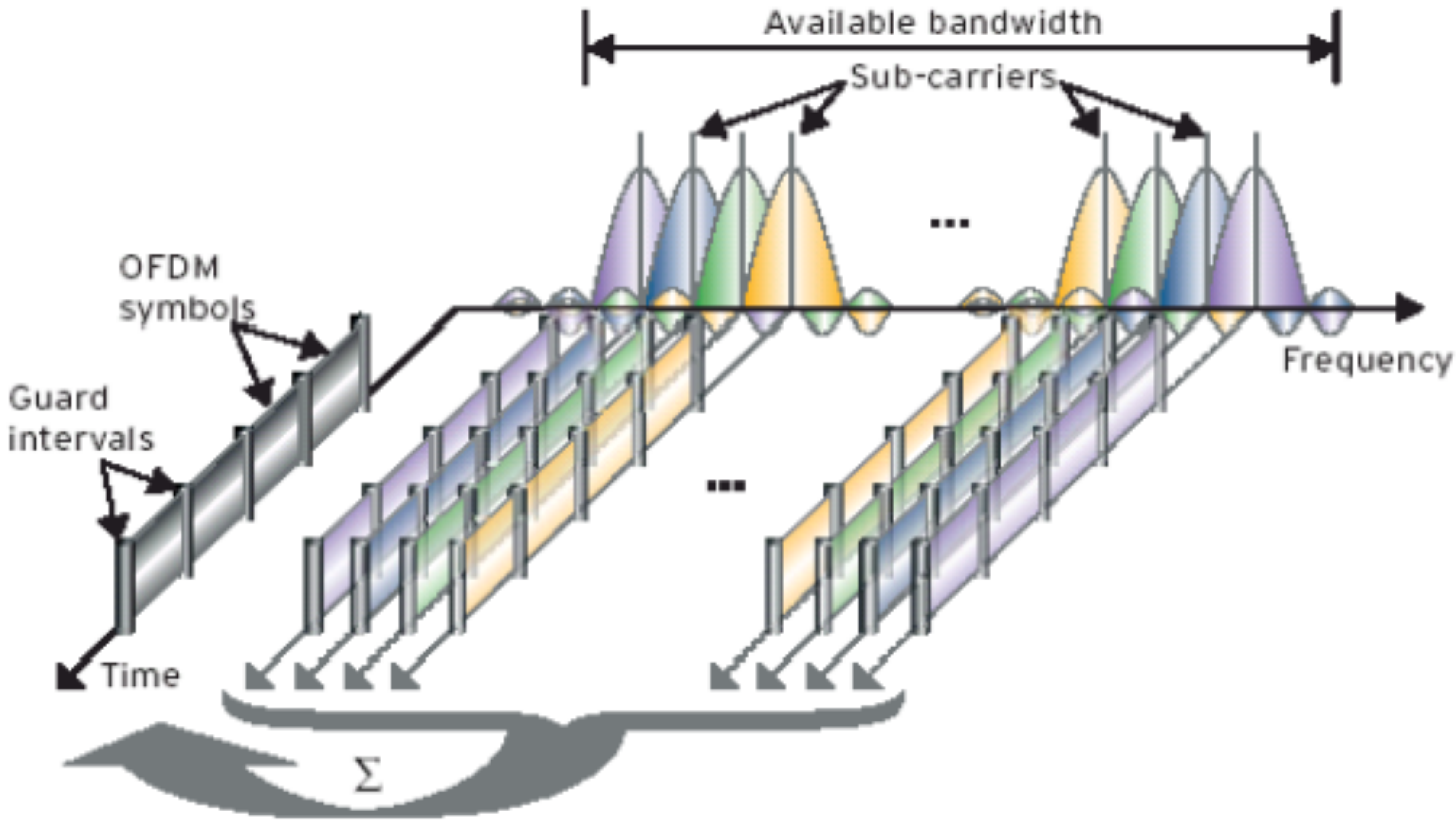


OFDM: Orthogonal Frequency Division Multi-Carrier

OFDM allows a tight packing of small carrier - called the **subcarriers** into a given frequency band.



The OFDM Signal



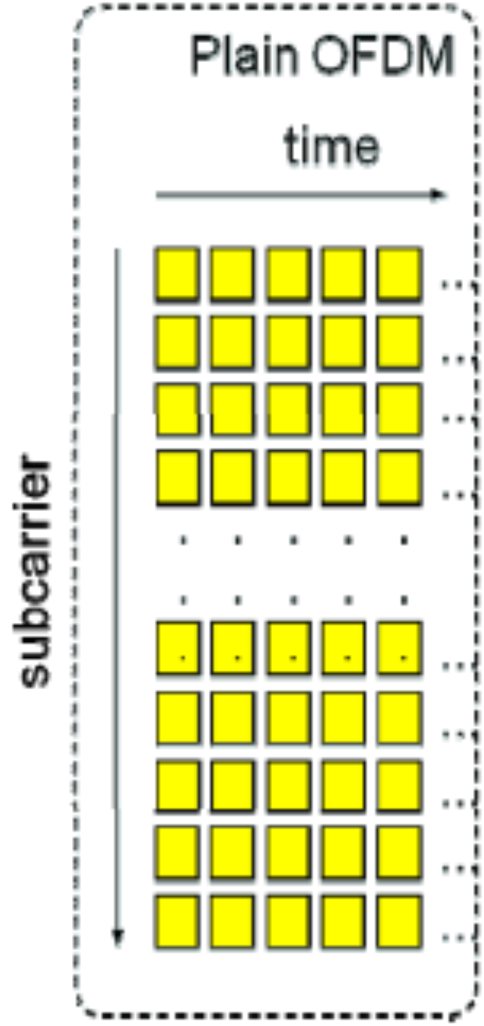
OFDM and Multiple Access

- Up to here we have only discussed simple point-to-point or broadcast OFDM.
- Now we have to analyze how to handle access of multiple users simultaneously to the system, each one using OFDM.
- OFDM can be combined with several different methods to handle multi-user systems:
  - Plain OFDM
  - Time Division Multiple Access via OFDM
  - Orthogonal Frequency Division Multiple Access OFDMA

Plain OFDM

- **Plain OFDM:** Normal OFDM has no built-in multiple-access mechanism.

- This is suitable for broadcast systems like DVB-T/H which transmit only broadcast and multicast signals and do not really need an uplink feedback channel (although such systems exist too).

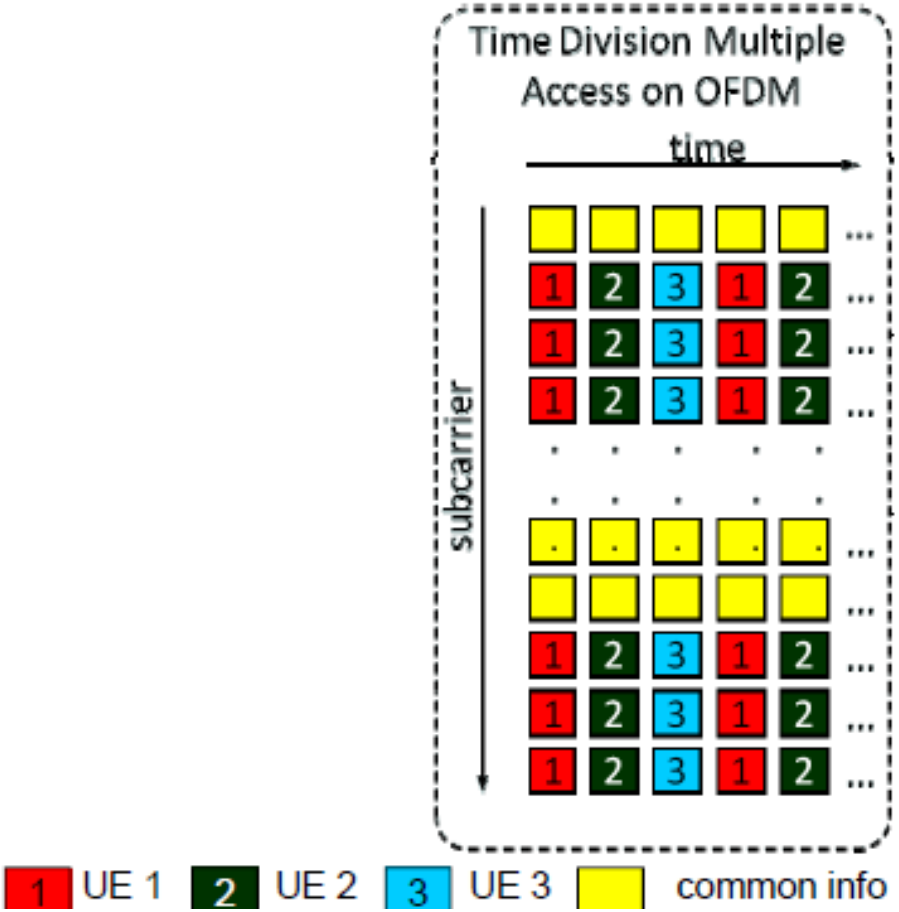


Time Division Multiple Access via OFDM

Time Division Multiple Access via OFDM: The simplest model to implement multiple access handling is by putting a time multiplexing on top of OFDM.

The disadvantage of this simple mechanism is, that every user gets the same amount of capacity (subcarriers) and it is thus rather difficult to implement flexible (high and low) bit rate services.

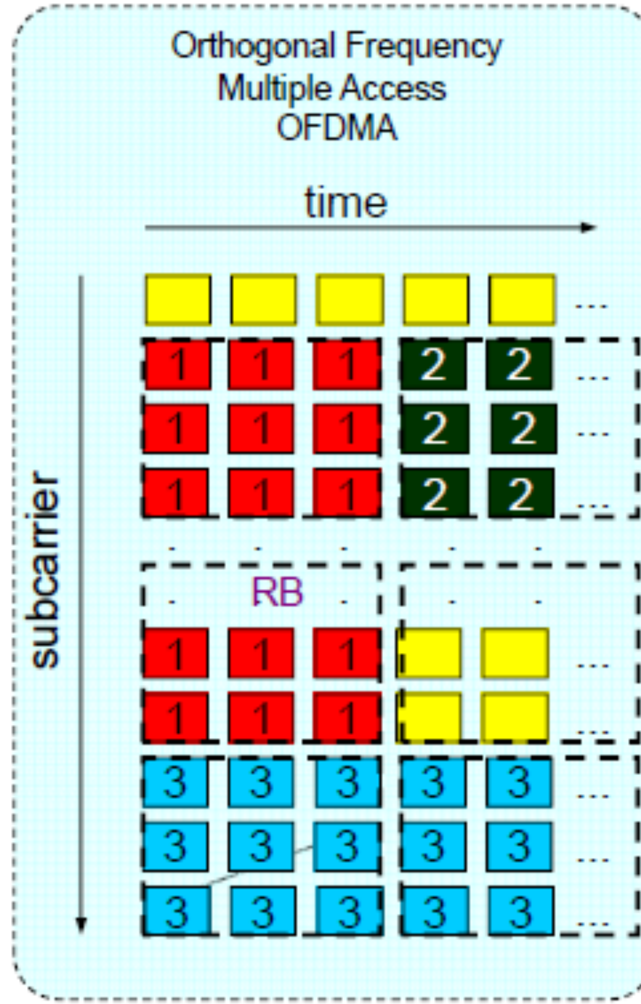
Furthermore it is nearly impossible to handle highly variable traffic (e.g. web traffic) efficiently without too much higher layer signaling and the resulting delay and signaling overhead.



Orthogonal Frequency Division Multiple Access OFDMA

The basic idea is to assign subcarriers to users based on their bit rate services.
With this approach it is quite easy to handle high and low bit rate users simultaneously in a single system.
But still it is difficult to run highly variable traffic efficiently.
The solution to this problem is to assign to a single users so called **resource blocks** or **scheduling blocks**.

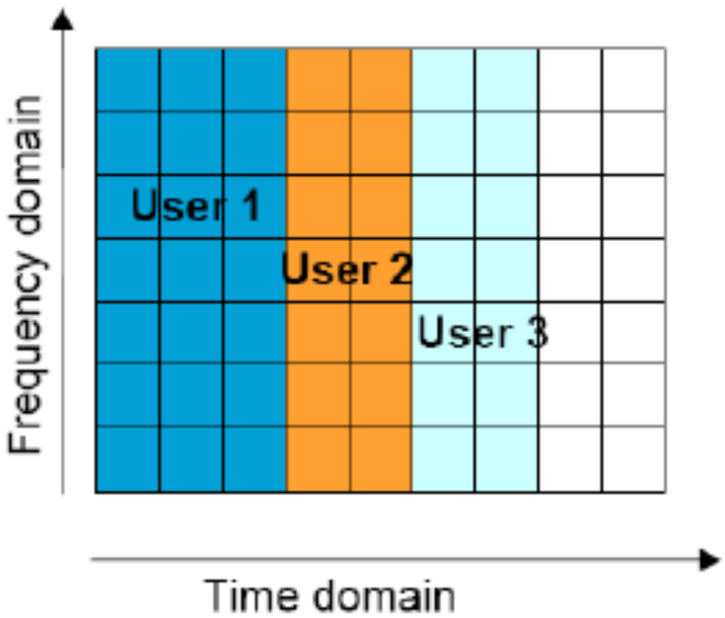
Such block is simply a set of some subcarriers over some time.
A single user can then use one or more Resource blocks.



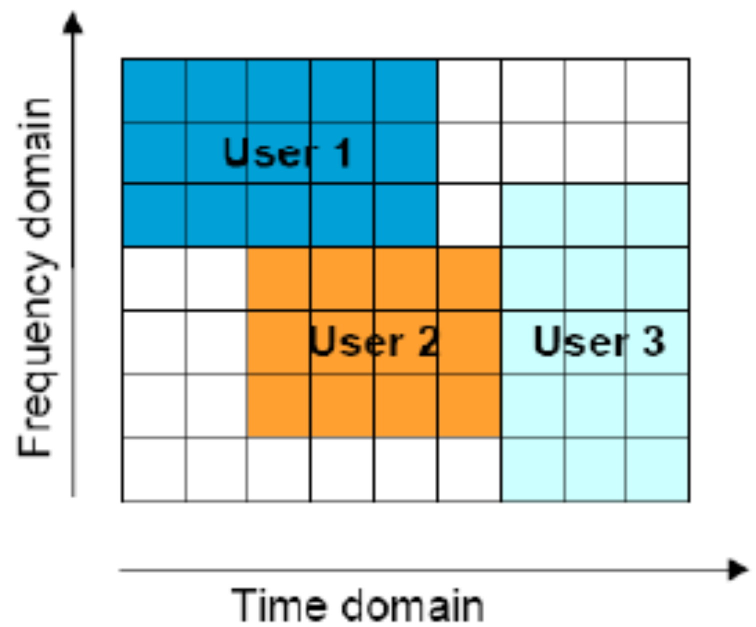
1 UE 1 | 2 UE 2 | 3 UE 3 | common info

Difference between OFDM and OFDMA

OFDM allocates users in time domain only



OFDMA allocates users in time and frequency domain

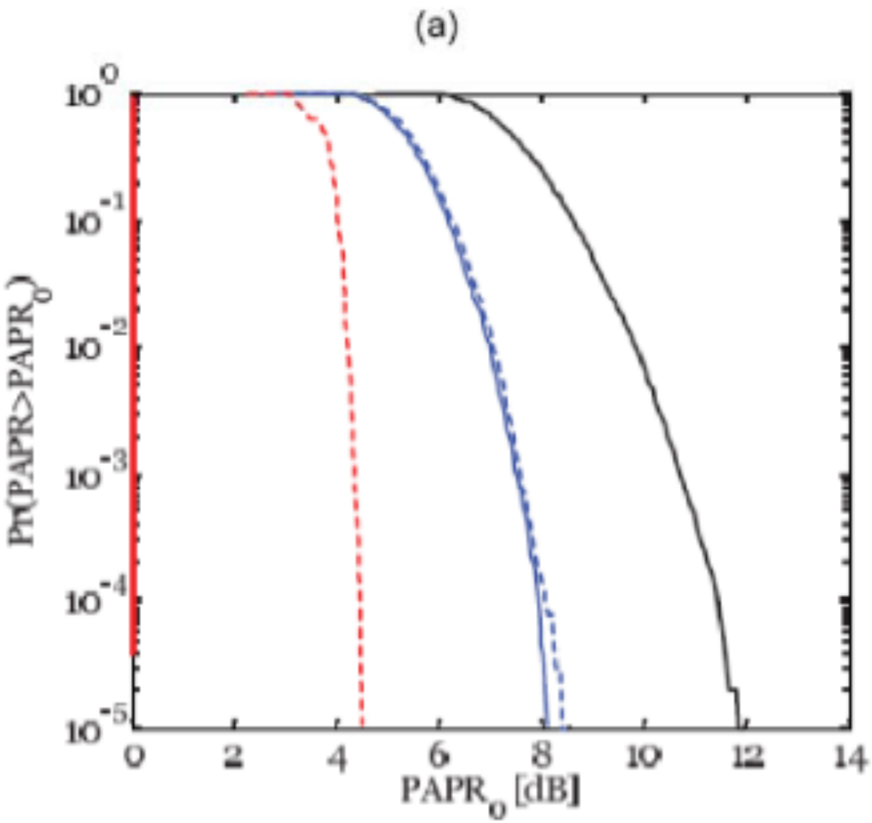


SC-FDMA

- SC-FDMA :Single Carrier Frequency Division Multiple Access
- SC-FDMA is a new hybrid modulation scheme that cleverly combines the low PAR of single-carrier systems with the multipath resistance and flexible subcarrier frequency allocation offered by OFDM.
- SC FDMA solves this problem by grouping together the resource blocks in such a way that reduces the need for linearity, and so power consumption, in the power amplifier. A low PAPR also improves coverage and the cell-edge performance.
- SC-FDMA signal processing has some similarities with OFDMA signal processing, so parameterization of DL and UL can be harmonized.
- SC-FDMA is one option in WiMAX (802.16d) and it is the method selected for LTE in the uplink direction.

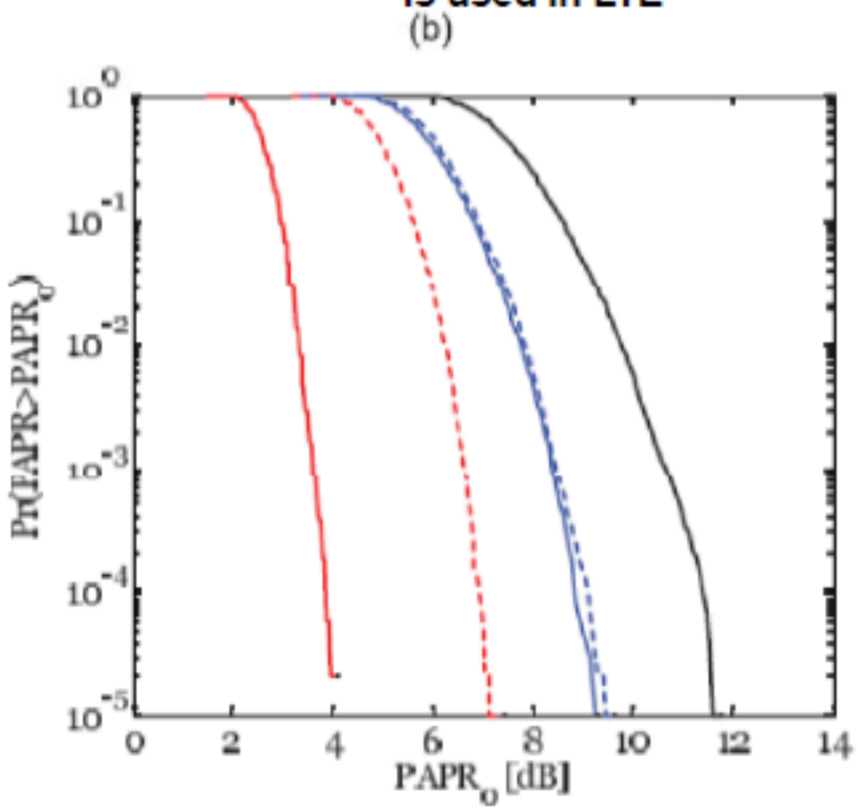
Comparaison of CCDF of PAPR for IFDMA, LFDMA and OFDMA

(a) :QPSK



(b) :16QAM

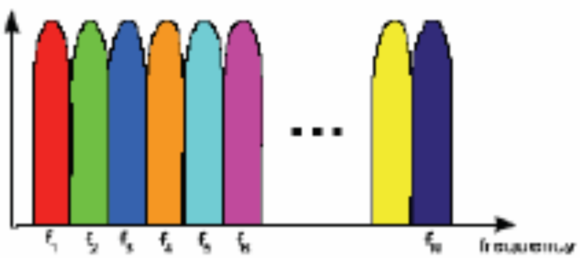
localized mode (LFDMA) is used in LTE



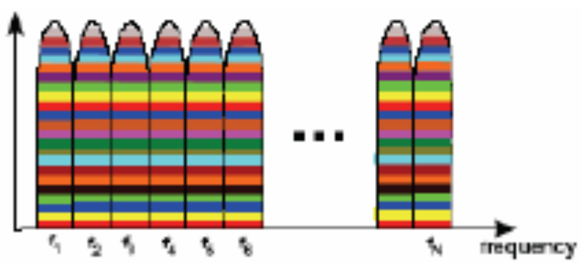
IFDMA = "Interleaved FDMA" = Distributed SC-FDMA
LFDMA = "Localized FDMA" = Localized SC-FDMA

How does a SC-FDMA signal look like?

- Similar to OFDM signal, but…
  - in OFDMA, each sub-carrier only carries information related to one specific symbol,
  - in SC-FDMA, each sub-carrier contains information of ALL transmitted symbols.

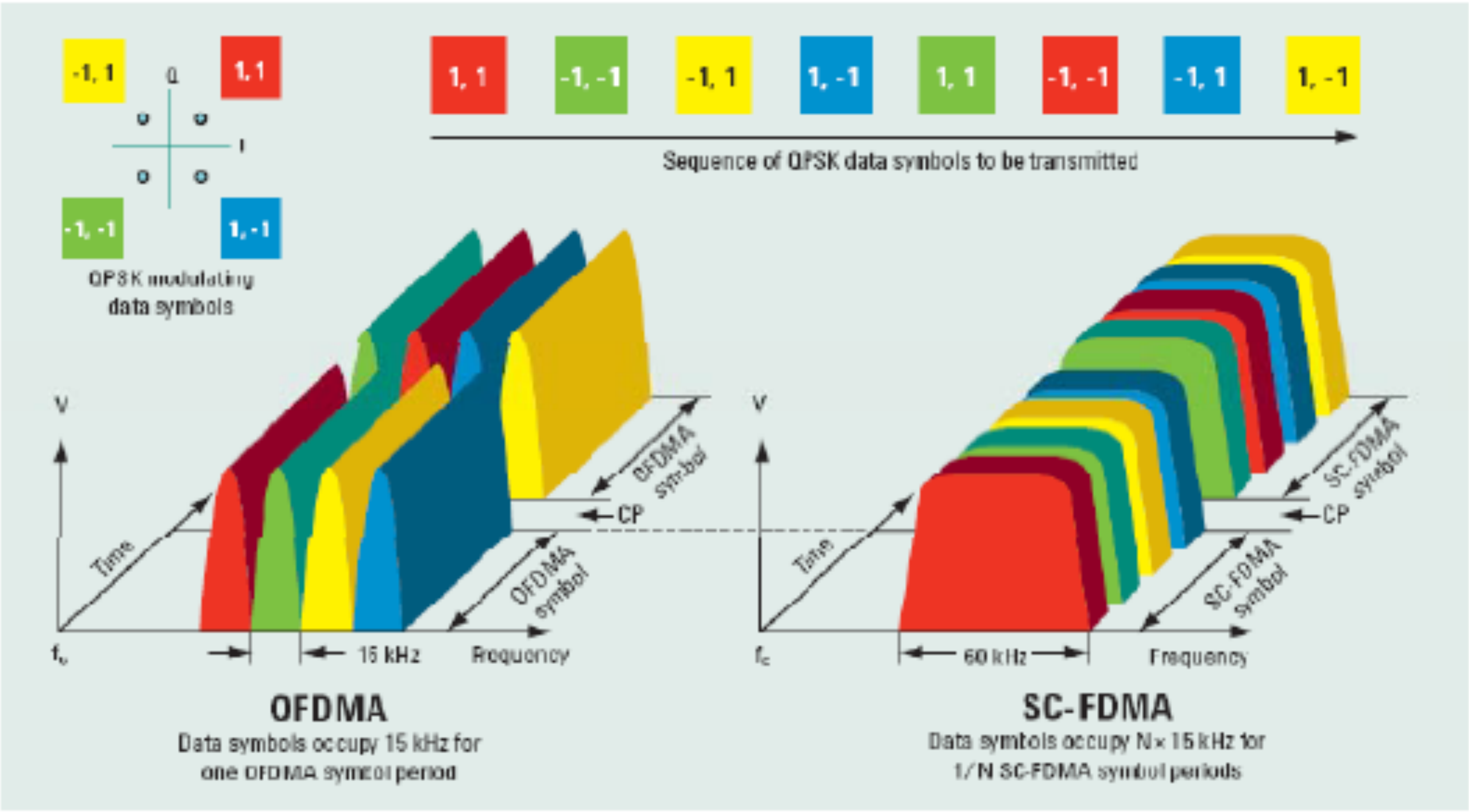


(a) OFDM subcarriers

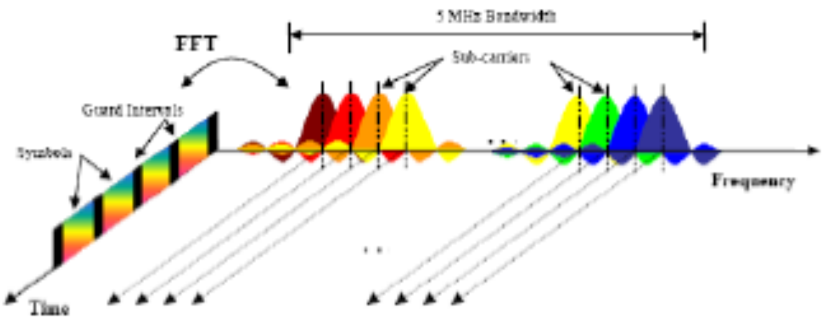


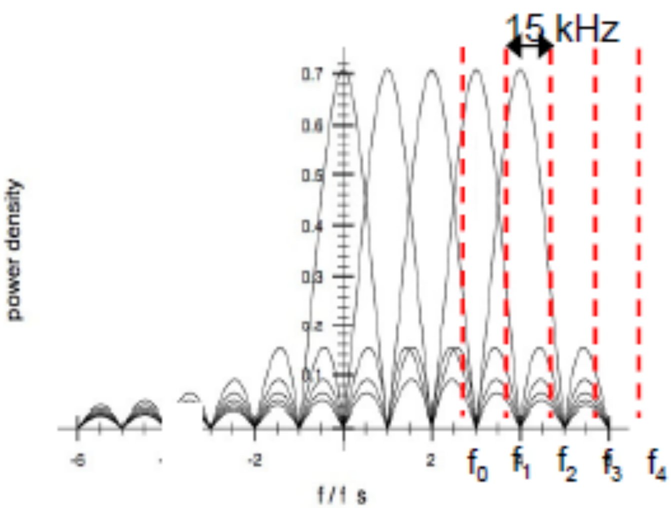
(b) DFT-s-OFDM subcarriers

Comparing OFDMA & SC-FDMA



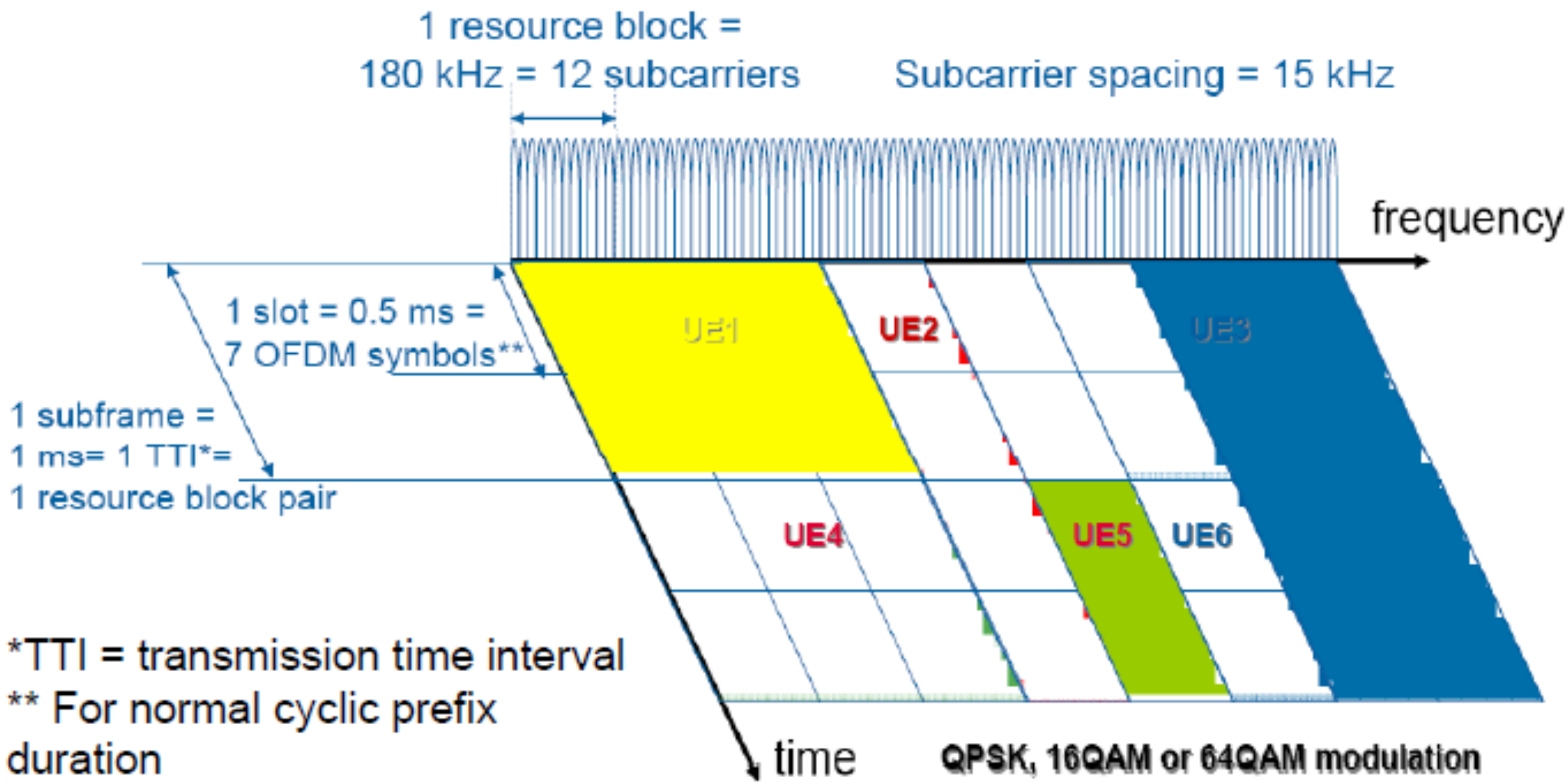
LTE downlink : conventional OFDMA





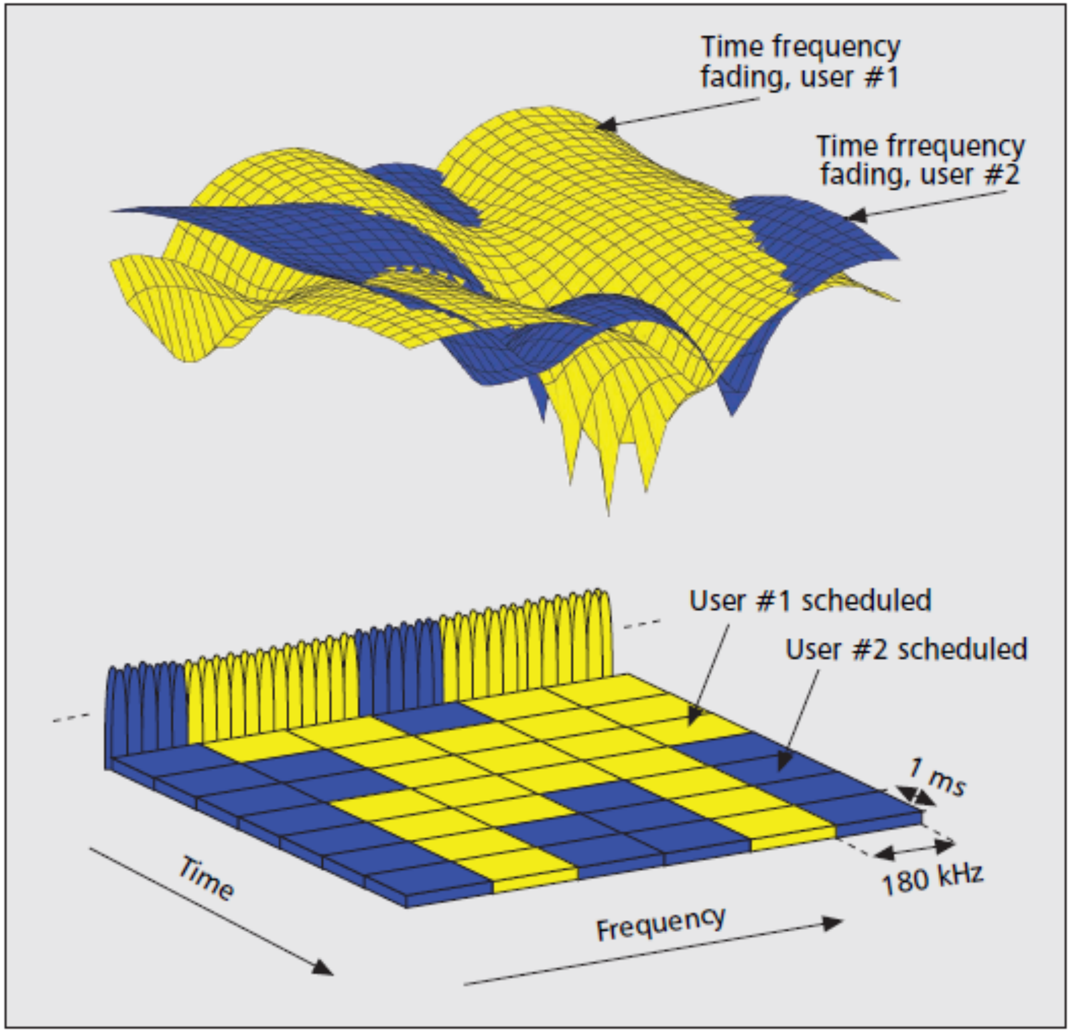
- LTE provides QPSK, 16QAM, 64QAM as downlink modulation schemes
- Cyclic prefix is used as guard interval, different configurations possible:
  - Normal cyclic prefix with 5.2 μs (first symbol) / 4.7 μs (other symbols)
  - Extended cyclic prefix with 16.7 μs
- 15 kHz subcarrier spacing
- Scalable bandwidth

OFDMA time-frequency multiplexing



*TTI = transmission time interval
** For normal cyclic prefix duration

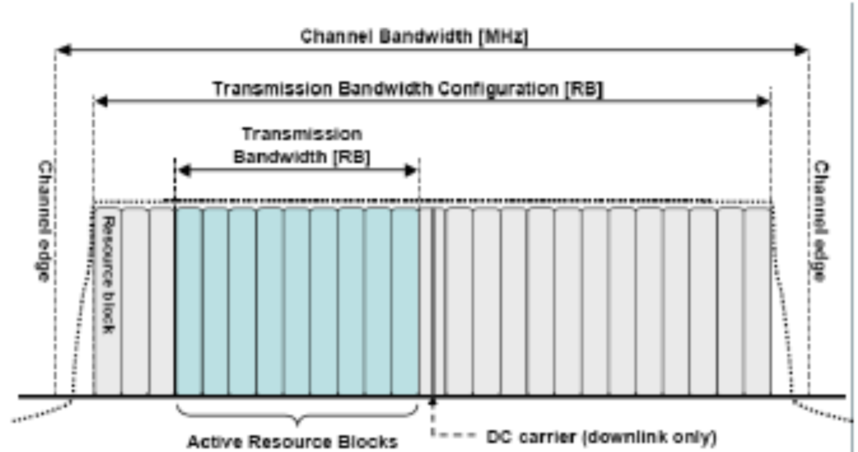
OFDMA: adapts to fading



■ **Figure 3.** *Channel-quality variations in frequency and time.*

Spectrum flexibility

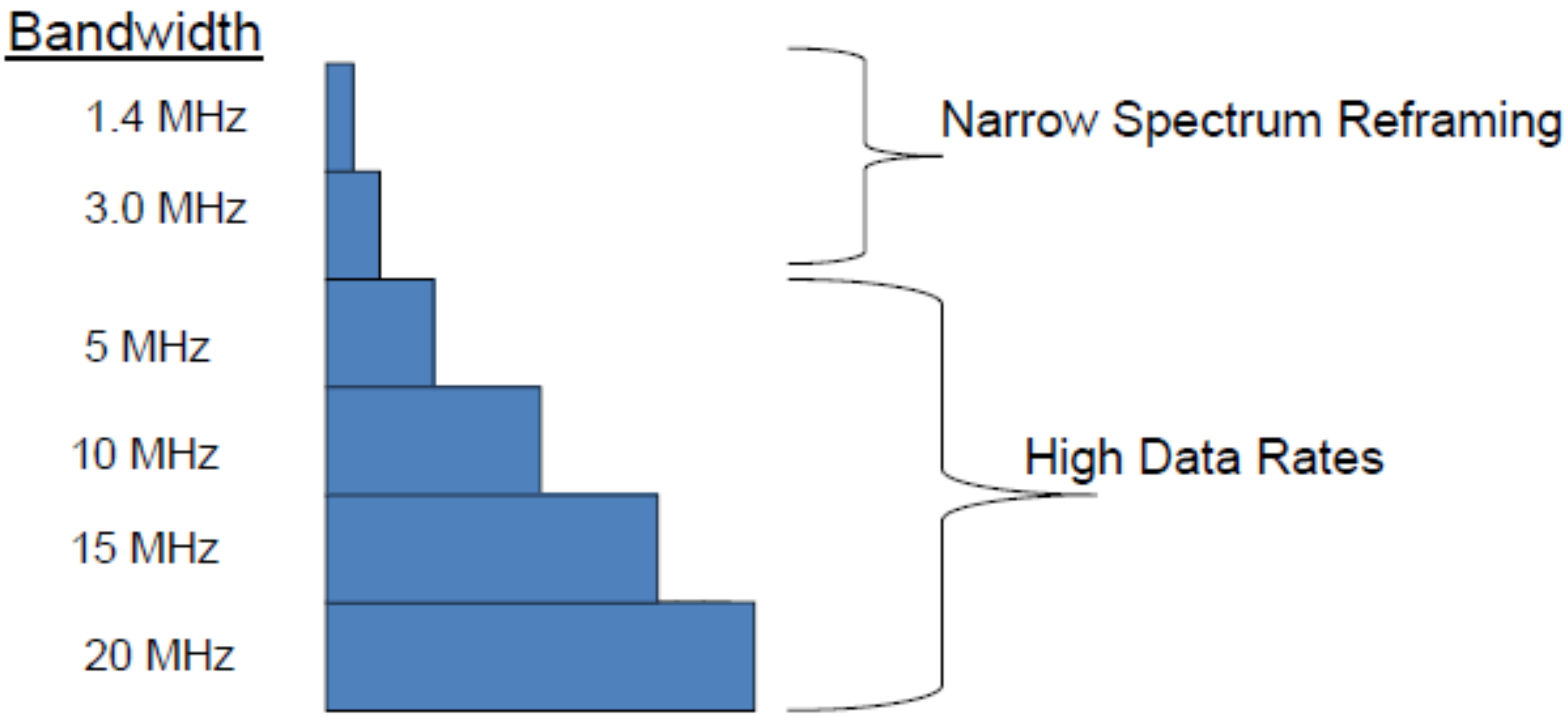
- LTE physical layer supports any bandwidth from 1.4 MHz to 20 MHz in steps of 180 kHz (resource block)
- Current LTE specification supports a subset of 6 different system bandwidths
- All UEs must support the maximum bandwidth of 20 MHz



Channel BW [MHz]	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100

Bandwidth Scalability

Scalable bandwidth 1.4 – 20 MHz using different number of subcarriers
Large bandwidth provides high data rates Small bandwidth allows simpler spectrum reframing, e.g. 450 MHz and 900 MHz

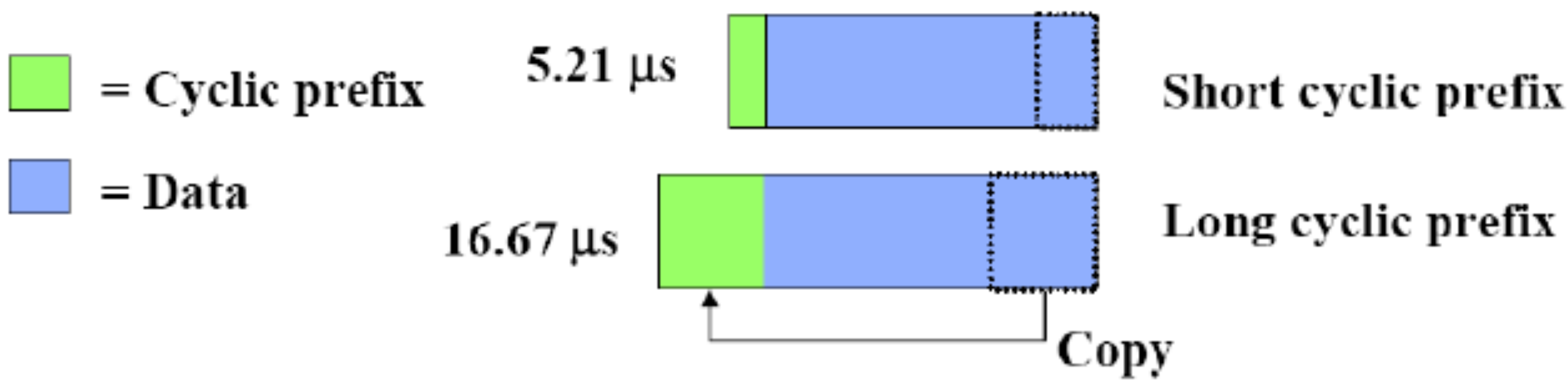


LTE Frame Structure

- LTE frames are 10 msec in duration. They are divided into 10 subframes, each subframe being 1.0 msec long. Each subframe is further divided into two slots, each of 0.5 msec duration. Slots consist of either 6 or 7 ODFM symbols, depending on whether the normal or extended cyclic prefix is employed

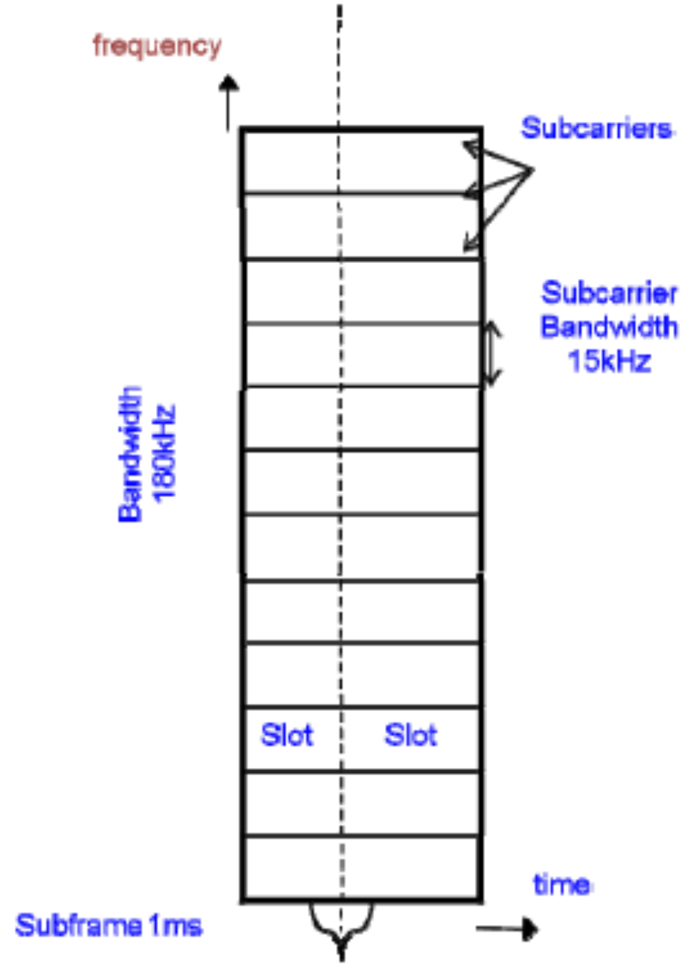
LTE Slot

- The LTE Slot carries:
  - 7 symbols with short cyclic prefix
  - 6 symbols with long prefix



OFDM Resource Block for LTE/EUTRAN

- EUTRAN combines OFDM symbols in so called resource blocks RB.
- A single resource block is always 12 consecutive subcarriers during one subframe (2 slots, 1 ms):
  - 12 subcarriers * 15 kHz= 180 kHz
- It is the task of the scheduler to assign resource blocks to physical channels belonging to different users or for general system tasks.
- A single cell must have at least 6 resource blocks (72 subcarriers) and up to 110 are possible (1320 subcarriers).

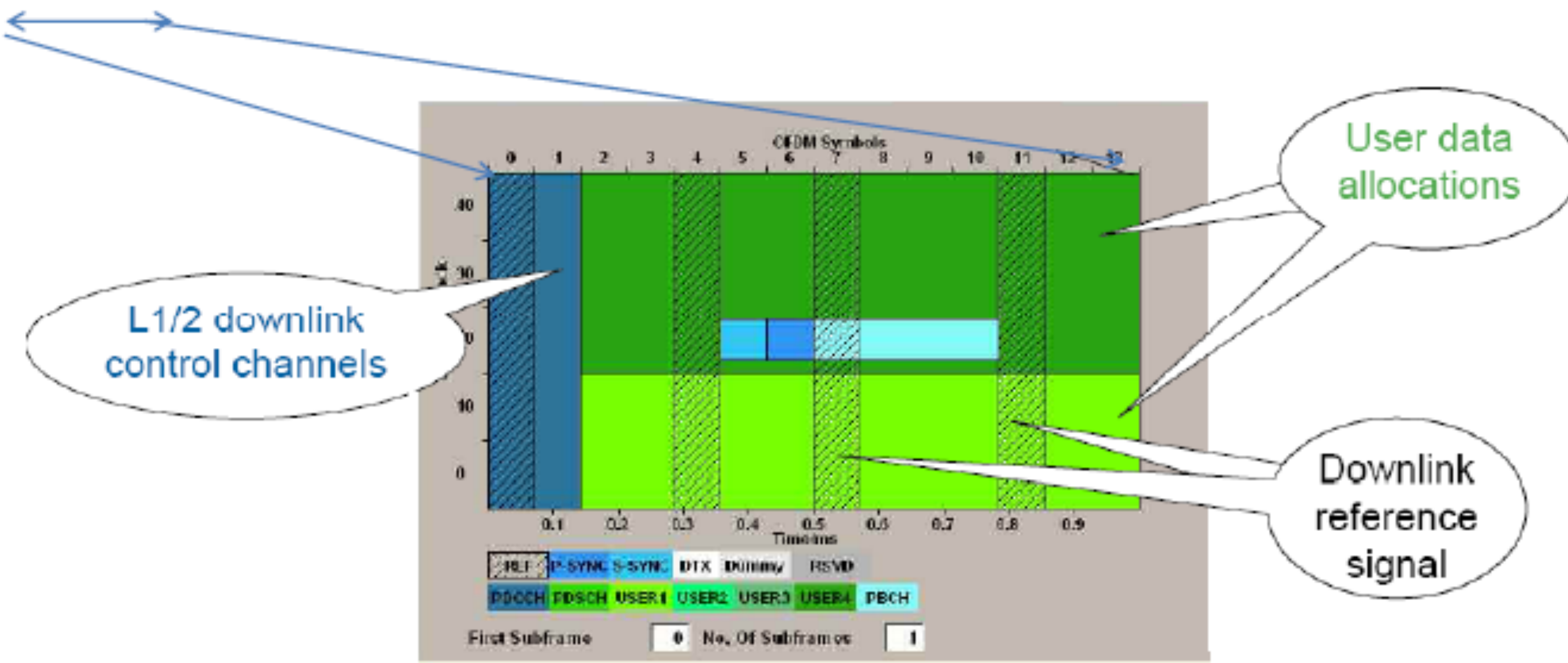


LTE DL frame structure type 1 (FDD), DL

# 00	# 01	# 02	# 03	# 04	# 05	# 06	# 07	# 08	# 09	# 10	# 11	# 12	# 13	# 14	# 15	# 16	# 17	# 18	# 19

↔ 1 slot = 0.5 ms

1 subframe = 1 ms

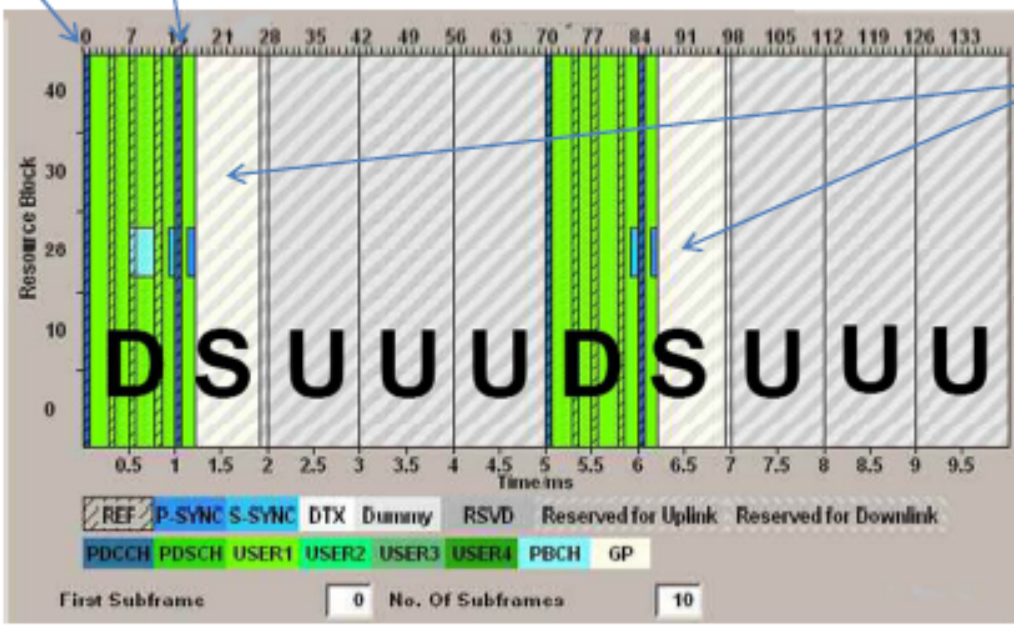


LTE DL frame structure type 2 (TDD)

1 subframe = 1 ms

1 slot = 0.5 ms

# 00	# 01	# 02	# 03	# 04	# 05	# 06	# 07	# 08	# 09	# 10	# 11	# 12	# 13	# 14	# 15	# 16	# 17	# 18	# 19



Special subframes containing:

DwPTS: downlink pilot time slot

UpPTS: uplink pilot time slot

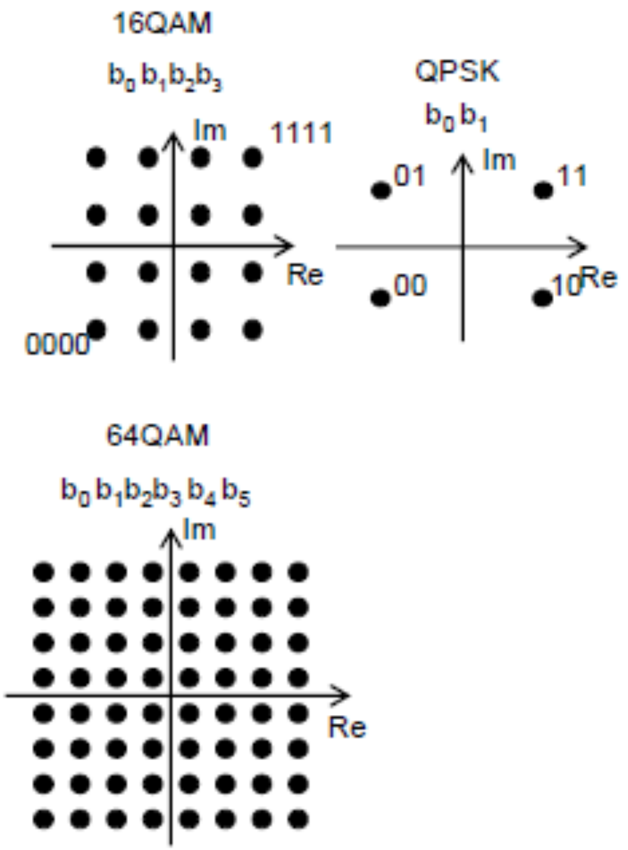
GP: guard period for TDD operation

Possible UL-DL configurations

UL-DL config	Subframe number									
0	0	1	2	3	4	5	6	7	8	9
1	D	S	U	U	U	D	S	U	U	U
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

Modulation Schemes for LTE/EUTRAN

- Each OFDM symbol even within a resource block can have a different modulation scheme.
- EUTRAN defines the following options: QPSK, 16QAM, 64QAM.
- Not every physical channel will be allowed to use any modulation scheme: Control channels to be using mainly QPSK.
- In general it is the scheduler that decides which form to use depending on carrier quality feedback information from the UE.



LTE Overview – Design Targets and Multiple Access Technologies

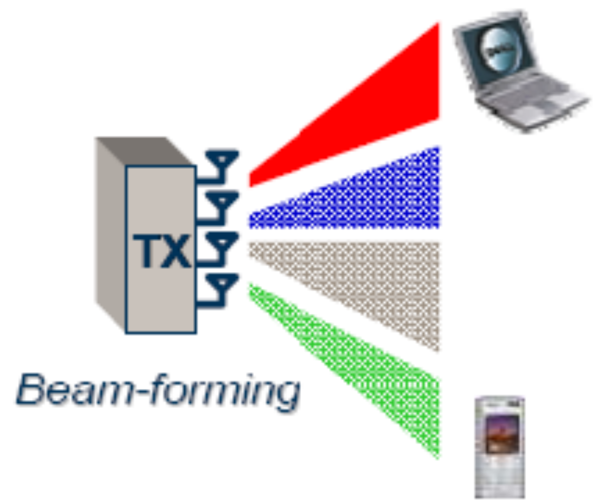
MIMO

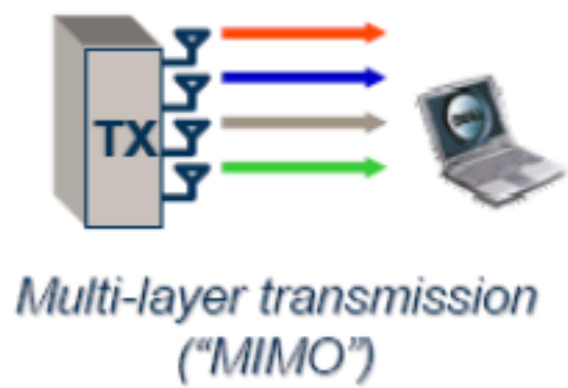
Multiple Antenna Techniques

- MIMO employs multiple transmit and receive antennas to substantially enhance the air interface.
- It uses space-time coding of the same data stream mapped onto multiple transmit antennas, which is an improvement over traditional reception diversity schemes where only a single transmit antenna is deployed to extend the coverage of the cell.
- MIMO processing also exploits spatial multiplexing, allowing different data streams to be transmitted simultaneously from the different transmit antennas, to increase the end-user data rate and cell capacity.
- In addition, when knowledge of the radio channel is available at the transmitter (e.g. via feedback information from the receiver), MIMO can also implement beam-forming to further increase available data rates and spectrum efficiency

Advanced Antenna Techniques

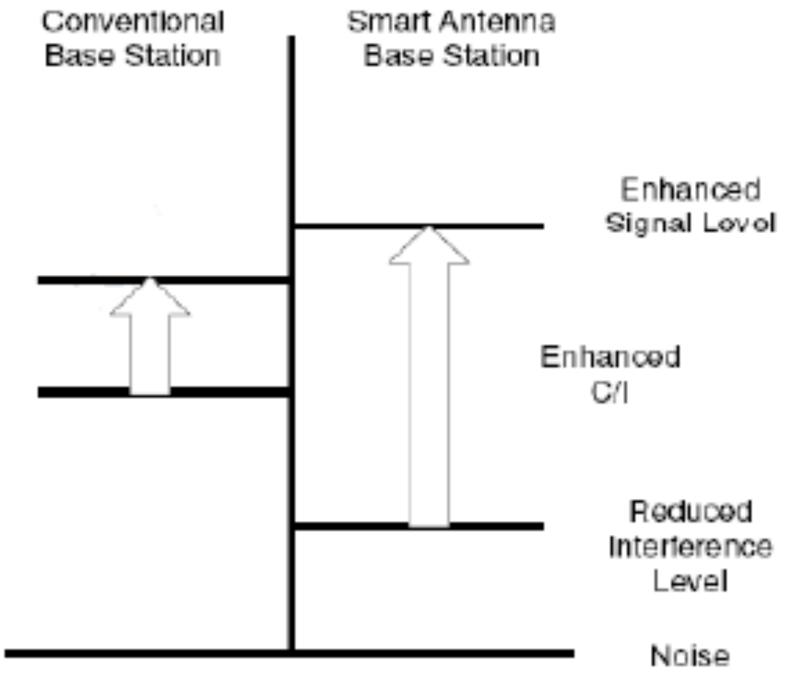
- Single data stream / user
- Beam-forming
  - Coverage, longer battery life
- Spatial Division Multiple Access (SDMA)
  - Multiple users in same radio resource
- Multiple data stream / user Diversity
  - Link robustness
- Spatial multiplexing
  - Spectral efficiency, high data rate support





MIMO – Beamforming

- Enhances signal reception through directional array gain, while individual antenna has omni-directional gain
- Extends cell coverage
- Suppresses interference in space domain
- Enhances system capacity
- Prolongs battery life
- Provides angular information for user tracking



LTE Overview – Design Targets and Multiple Access Technologies

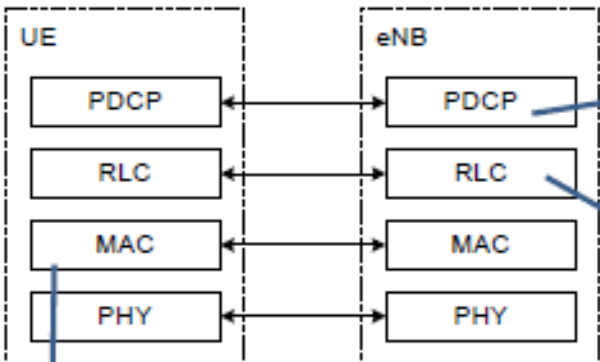
AIR INTERFACE PROTOCOLS

UNIVERSITÀ DI PARMA

Radio Protocols Architecture

- It is quite similar to the WCDMA protocol stack of UMTS.
- The protocol stack defines three layers:
- the physical layer (layer 1)
- data link and access layer (layer 2)
- layer 3 (hosting the AS, the NAS control protocols as well and the application level)

Radio Protocol architecture- User plane

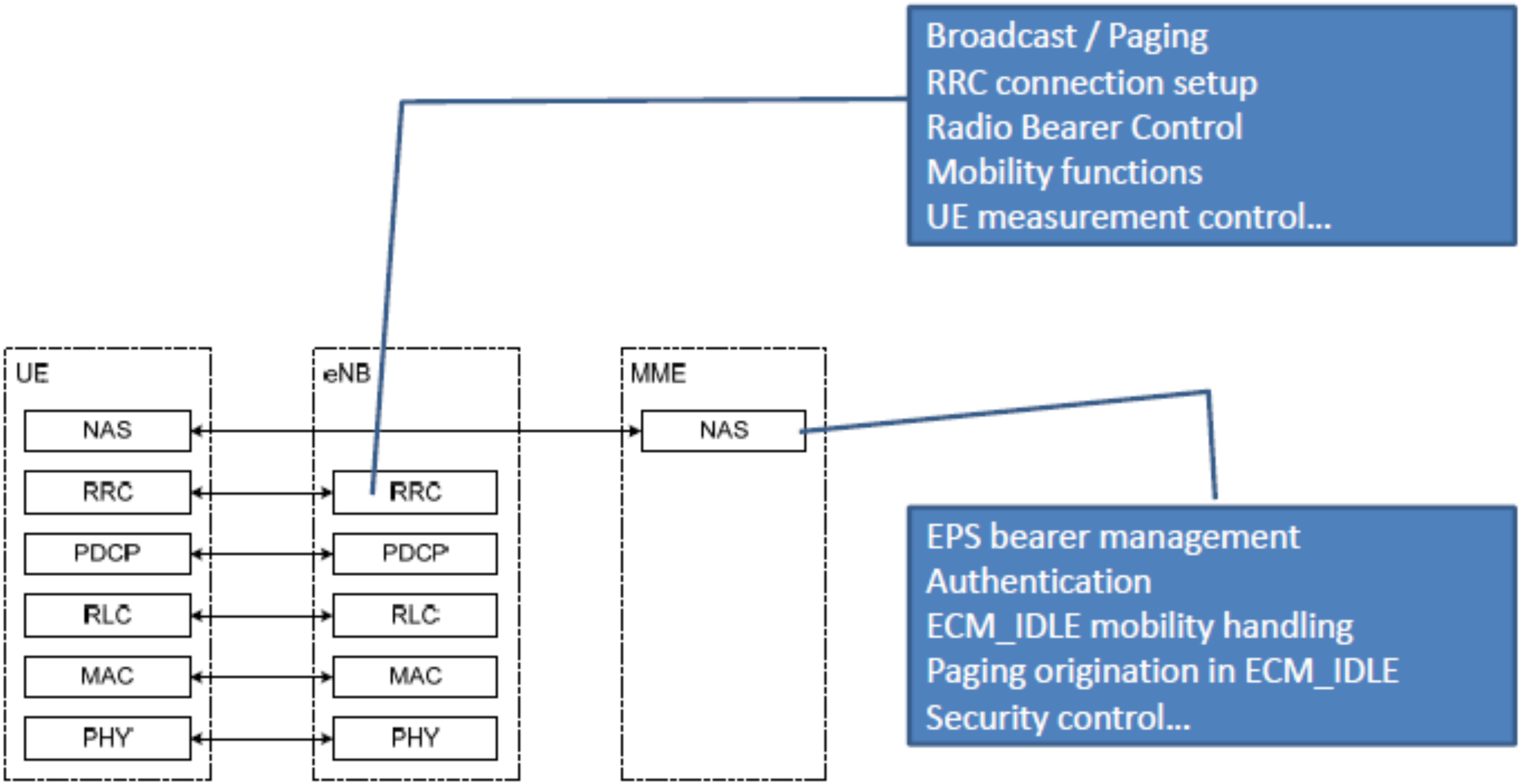


Header compression (ROHC)
In-sequence delivery of upper layer PDUs
Duplicate elimination of lower layer SDUs
Ciphering for user/control plane
Integrity protection for control plane
Timer based discard...

AM, UM, TM
ARQ
(Re-)segmentation Concatenation
In-sequence delivery
Duplicate detection
SDU discard
Re-establishment...

Mapping between logical and transport channels
(De)-Multiplexing
Scheduling information reporting
HARQ
Priority handling
Transport format selection...

Control-plane protocol stack



Physical Layer

- It provides the basic bit transmission functionality over air.
- the physical layer is driven by OFDMA in the downlink and SC-FDMA in the uplink.
- Physical channels are dynamically mapped to the available resources (physical resource blocks and antenna ports).
- To higher layers the physical layer offers its data transmission functionality via transport channels.
- Like in UMTS a transport channel is a block oriented transmission service with certain characteristics regarding bit rates, delay, collision risk and reliability.
- in contrast to 3G WCDMA or even 2G GSM there are no dedicated transport or physical channels anymore, as all resource mapping is dynamically driven by the scheduler.

Medium Access Control (MAC)

- MAC is the lowest layer 2 protocol.
- Its main function is to drive the transport channels.
- From higher layers MAC is fed with logical channels which are in one-to-one correspondence with radio bearers.
- Each logical channel is given a priority and MAC has to multiplex logical channel data onto transport channels (demultiplexing in reception)
- Further functions of MAC will be collision handling and explicit UE identification.
- An important function for the performance is the HARQ functionality which is official part of MAC and available for some transport channel types.

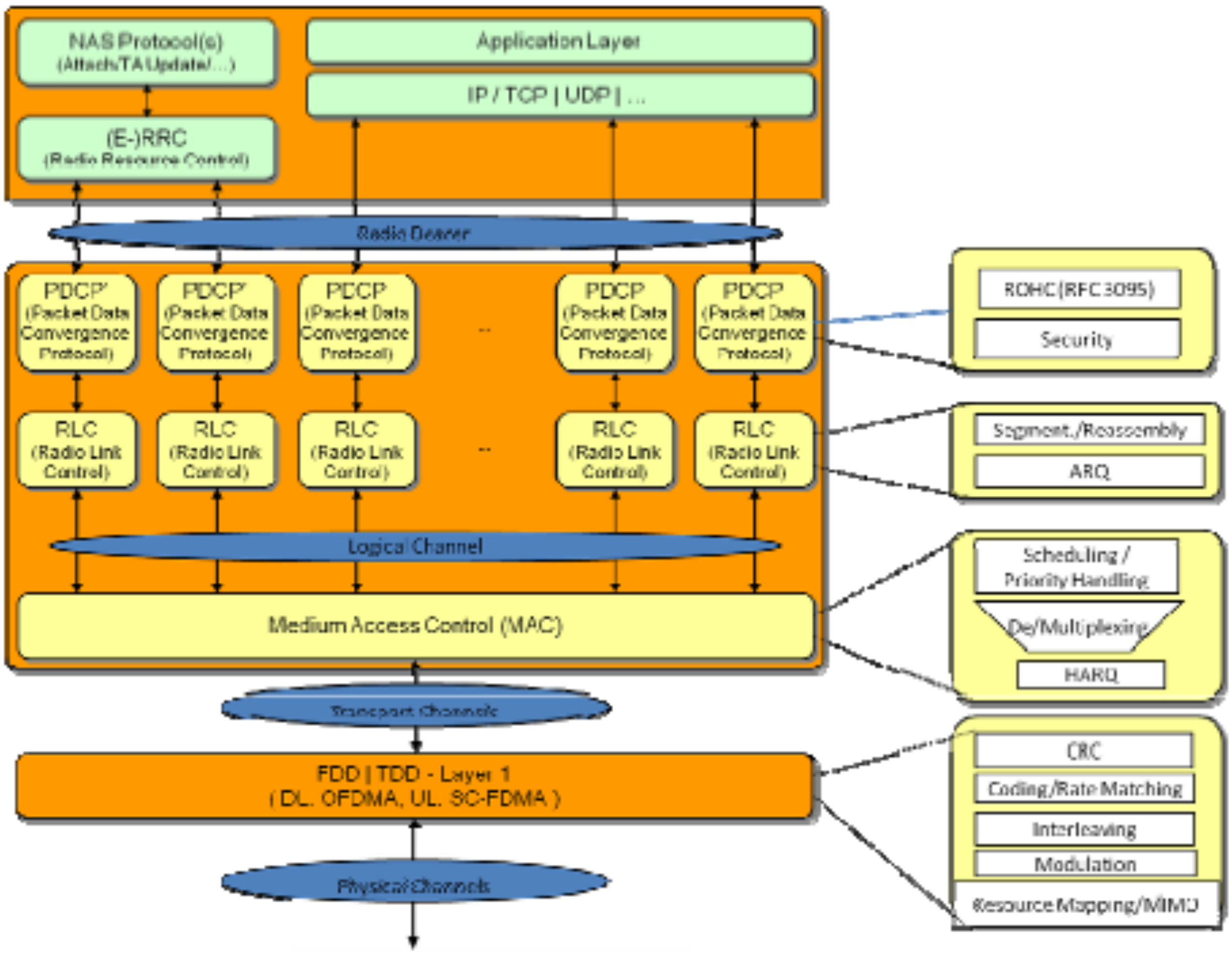
Radio Link Control (RLC)

- There is a one to one relationship between each Radio Bearer and each RLC instance
- RLC can enhance the radio bearer with ARQ (Automatic Retransmission on reQuest) using sequence numbered data frames and status reports to trigger retransmission.
- The second functionality of RLC is the segmentation and reassembly that divides higher layer data or concatenates higher layer data into data chunks suitable for transport over transport channels which allow only a certain set of transport block sizes.

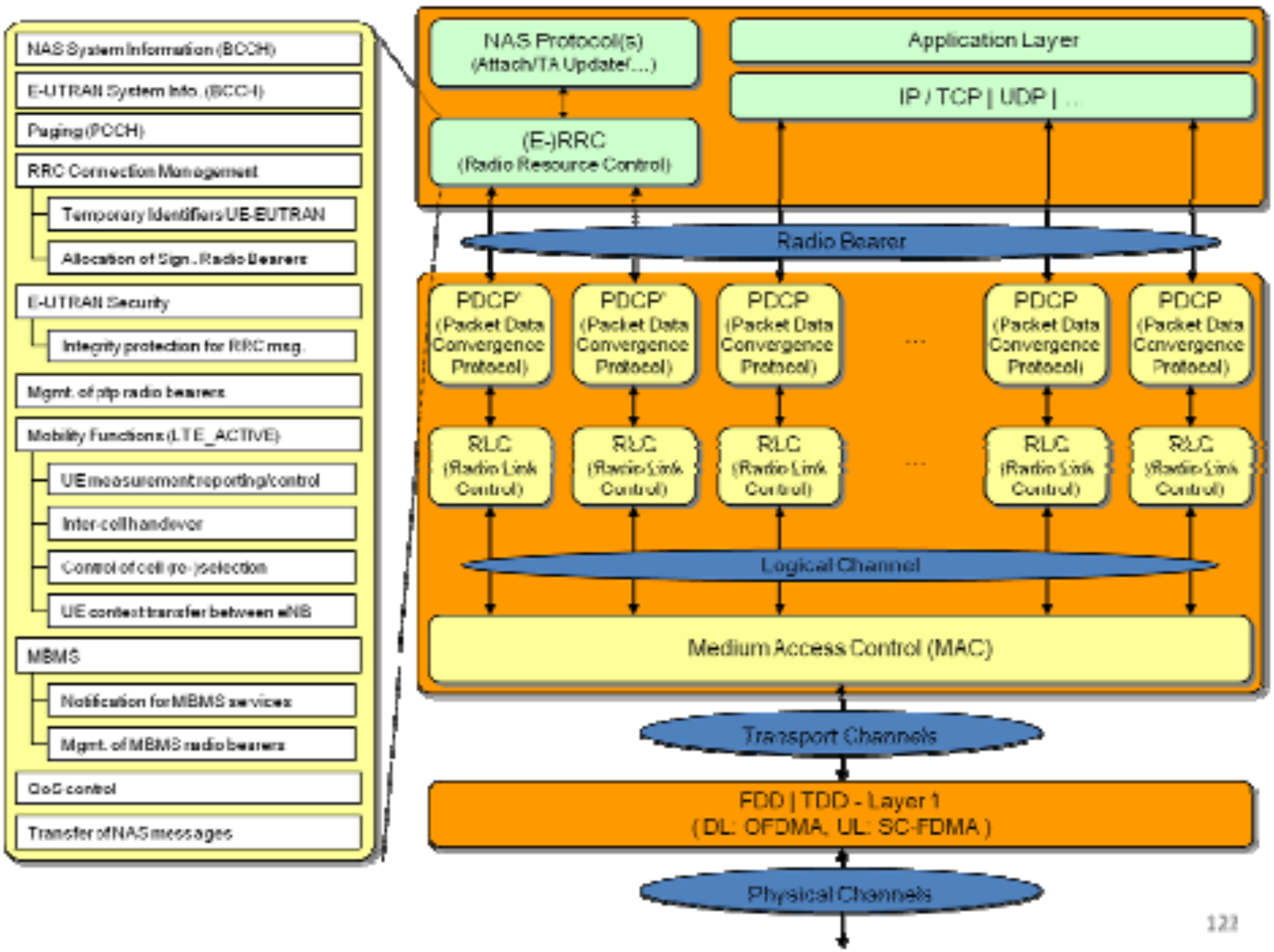
Layer 3 Radio Protocols

- PDCP (Packet Data Convergence Protocol)
  - Each radio bearer also uses one PDCP instance.
  - PDCP is responsible for header compression (ROHC: RObust Header Compression; RFC 3095) and ciphering/deciphering.
  - Obviously header compression makes sense for IP datagram's, but not for signaling. Thus the PDCP entities for signaling radio bearers will usually do ciphering/deciphering only.
- RRC (Radio Resource Control)
  - RRC is the access stratum specific control protocol for EUTRAN.
  - It will provide the required messages for channel management, measurement control and reporting, etc.
- NAS Protocols
  - The NAS protocol is running between UE and MME and thus must be transparently transferred via EUTRAN.
  - It sits on top of RRC, which provides the required carrier messages for NAS transfer

Layer 1/2 Radio Protocols – Summary



RRC Protocol



LTE MBMS Concept

- MBMS (Multimedia Broadcast Multicast Services) is an essential requirement for LTE. The so-called E-MBMS will therefore be an integral part of LTE.
- In LTE, MBMS transmissions may be performed as single-cell transmission or as multi-cell transmission. In case of multi-cell transmission the cells and content are synchronized to enable for the terminal to soft-combine the energy from multiple transmissions.
- The superimposed signal looks like multipath to the terminal. This concept is also known as Single Frequency Network (SFN).
- The E-UTRAN can configure which cells are part of an SFN for transmission of an MBMS service. The MBMS traffic can share the same carrier with the unicast traffic or be sent on a separate carrier.
- For MBMS traffic, an extended cyclic prefix is provided. In case of subframes carrying MBMS SFN data, specific reference signals are used. MBMS data is carried on the MBMS traffic channel (MTCH) as logical channel.

LTE vs WiMAX

- Both are designed to move data rather than voice and both are IP networks based on OFDM technology.
- WiMax is based on a IEEE standard (802.16), and like that other popular IEEE effort, Wi-Fi, it’s an open standard that was debated by a large community of engineers before getting ratified. The level of openness means WiMax equipment is standard and therefore cheaper to buy.
- As for speeds, LTE will is faster than the current generation of WiMax.
- However, LTE will take time to roll out, with deployments reaching mass adoption by 2012 . WiMax is out now, and more networks should be available later this year.
- The crucial difference is that, unlike WiMAX, which requires a new network to be built, LTE runs on an evolution of the existing UMTS infrastructure already used by over 80 per cent of mobile subscribers globally. This means that even though development and deployment of the LTE standard may lag Mobile WiMAX, it has a crucial incumbent advantage.

Summary

- The 3GPP Long Term Evolution (LTE) represents a major advance in cellular technology.
- LTE is designed to meet carrier needs for high-speed data and media transport as well as high-capacity voice support well into the next decade.
- LTE is well positioned to meet the requirements of next-generation mobile networks. It will enable operators to offer high performance, mass-market mobile broadband services, through a combination of high bit-rates and system throughput – in both the uplink and downlink – with low latency.

Summary– Cont.

- LTE infrastructure is designed to be as simple as possible to deploy and operate, through flexible technology that can be deployed in a wide variety of frequency bands.
- LTE offers scalable bandwidths, from from 1.4 MHz up to 20MHz, together with support for both FDD paired and TDD unpaired spectrum.
- The LTE–SAE architecture reduces the number of nodes, supports flexible network configurations and provides a high level of service availability.
- Furthermore, LTE–SAE will interoperate with GSM, WCDMA/HSPA, TD-SCDMA and CDMA.

Summary – Cont.

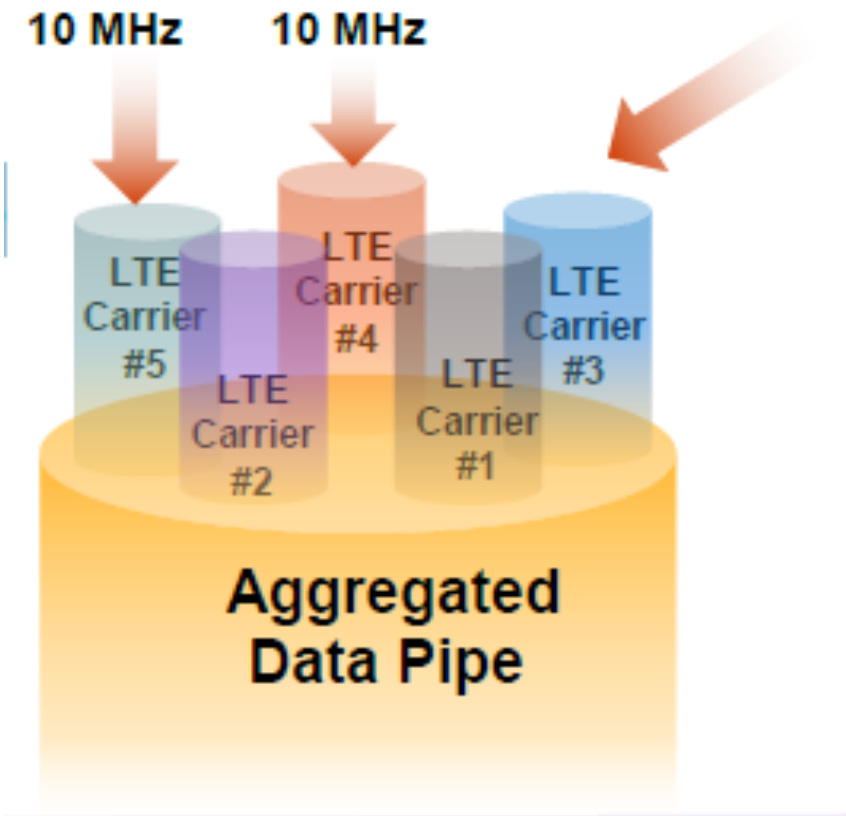
Technologies/Features		Benefits	Requirements
OFDMA with CP/SC-FDMA with CP	+	Equalizer simpler Scheduling time/frequency Better PAPR (SC-FDMA) ISI suppression (CP)	
QPSK, 16 QAM, 64 QAM	+	Higher bitrates Adaptative modulation	
Canaux communs	+	Variable traffic Better capacity	- Scheduling is needed
TTI = 1 ms	+	Better response to channel variation Higher bitrates	

Summary– Cont.

Technologies/Features		Benefits	
TTI = 1 ms	+	Better response to channel variation Higher bitrates	
Flat architecture	+	Simpler Architecture Better latency	
All IP	+	Architecture simpler Convergence	Scheduling with priorities is needed
MIMO	+	Higher bitrates	
Bande passante flexible(1.4 → 20 MHz)	+		
Universal frequency reuse (1/1)	+	Better spectral efficiency	ICIC

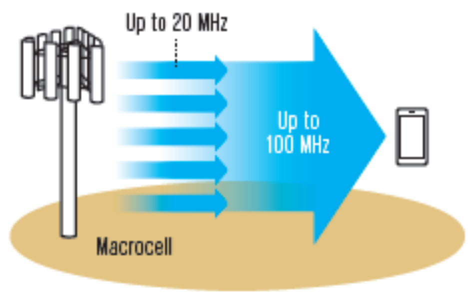
LTE Releases

- Release 8
  - Initial LTE release
  - Up to 4x4 MIMO
- Release 9
  - Minor enhancements
  - Currently built out by VZ, ATT & S
- Release 10, LTE Advanced
  - 2013 Commercial Availability
  - Channel bonding up to 5X
  - 8x8 MIMO, SON

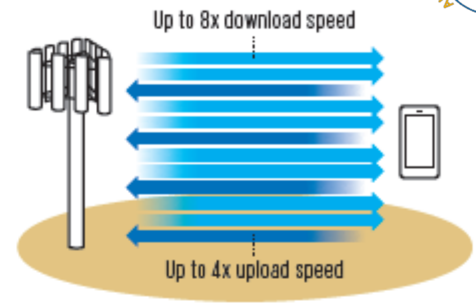


THE LTE-ADVANCED ADVANTAGE

Known as "true 4G," LTE-Advanced includes a menu of wireless technologies that will boost the capacity of current 4G LTE networks and make possible mobile download rates as high as 3 gigabits per second. Here are five key features that distinguish the new standard from its predecessors.

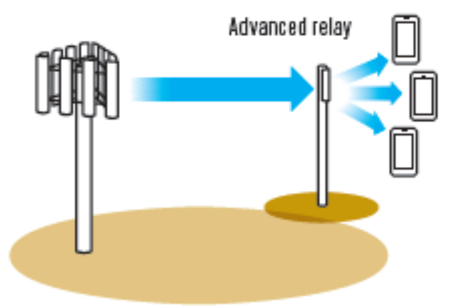


WIDER BANDWIDTH
Using a technology called **carrier aggregation**, operators can combine up to five LTE frequency channels, or carriers, as wide as 20 megahertz that reside in different parts of the radio spectrum.

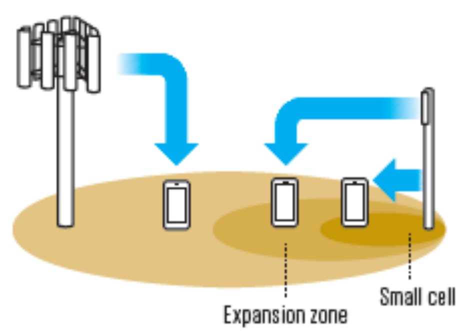


MORE DATA STREAMS
LTE-Advanced supports more sophisticated **multiple input, multiple output** (MIMO) techniques, which enable several antennas to send and receive data. One use of MIMO, called spatial multiplexing, separates transmissions into many parallel streams, increasing data rates in proportion to the number of antennas used.

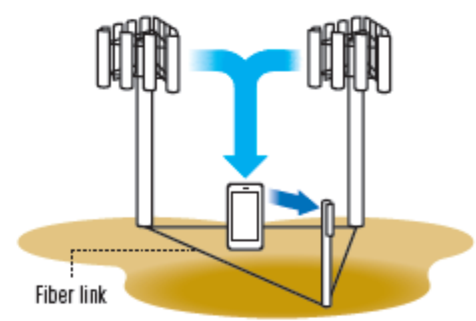
IEEE Spectrum, January 2014



SMARTER RELAYS
Conventional radio repeaters, such as those used in LTE networks, simply amplify transmissions from a base station. LTE-Advanced allows for more **advanced relays**, which first decode the signals and then forward only those meant for nearby users, increasing the total number each relay can serve.

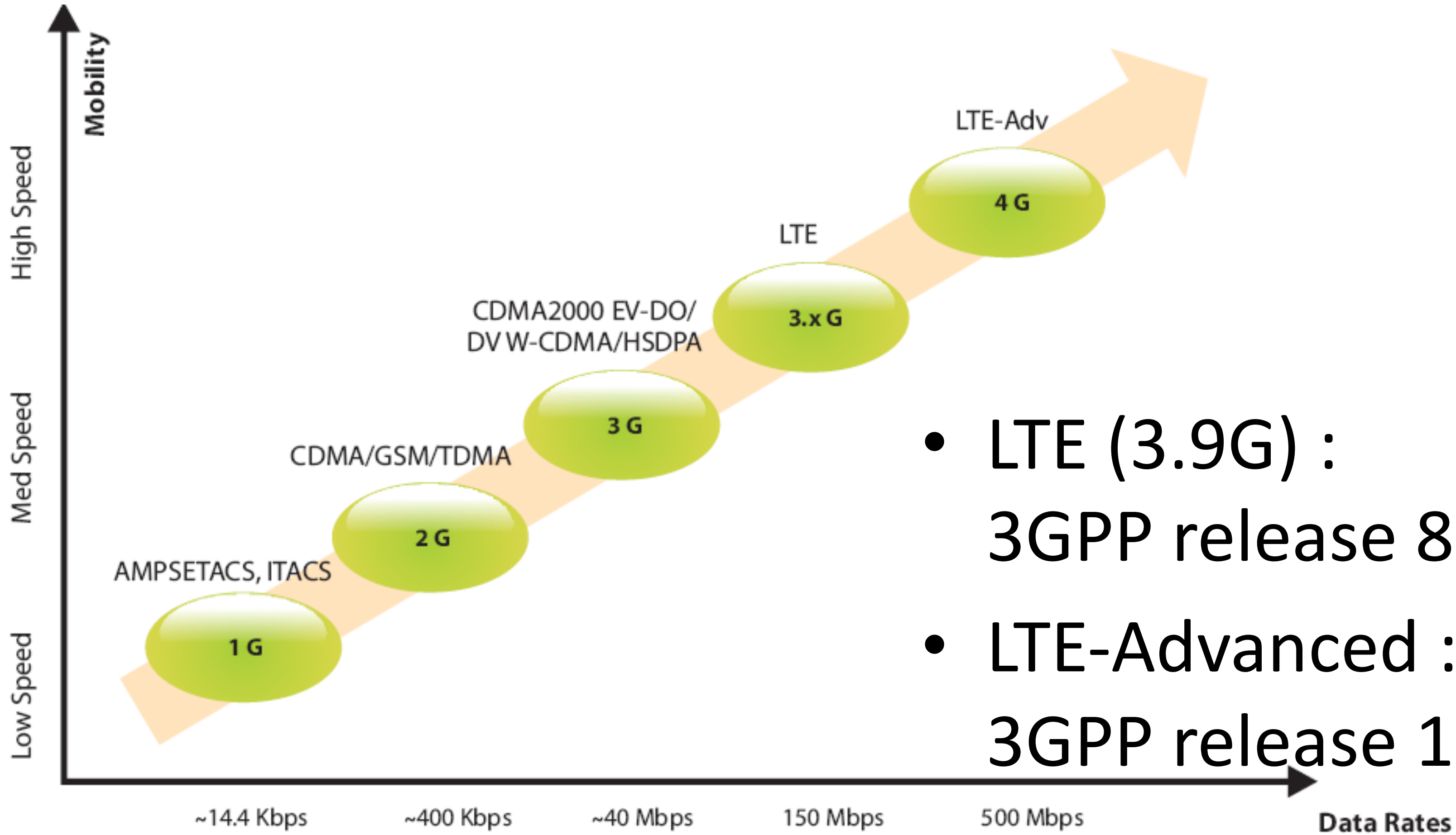


SUPPORT FOR SMALL CELLS
A protocol called **enhanced inter-cell interference coordination** (eICIC) alleviates interference to a small cell—a low-power base station whose coverage zone lies inside a traditional macrocell. The two cells can dynamically coordinate their use of spectrum, letting the small cell expand its transmission range.



COORDINATED TRANSMISSIONS
To improve reception, LTE-Advanced introduces **coordinated multipoint** (CoMP). It permits several base stations to form a single cell, allowing a mobile unit to connect with all of them at the same time. For example, the unit could receive downloads from high-power towers while uploading to a nearby small cell.

From the past to the future



- LTE (3.9G) : 3GPP release 8~9
- LTE-Advanced : 3GPP release 10+