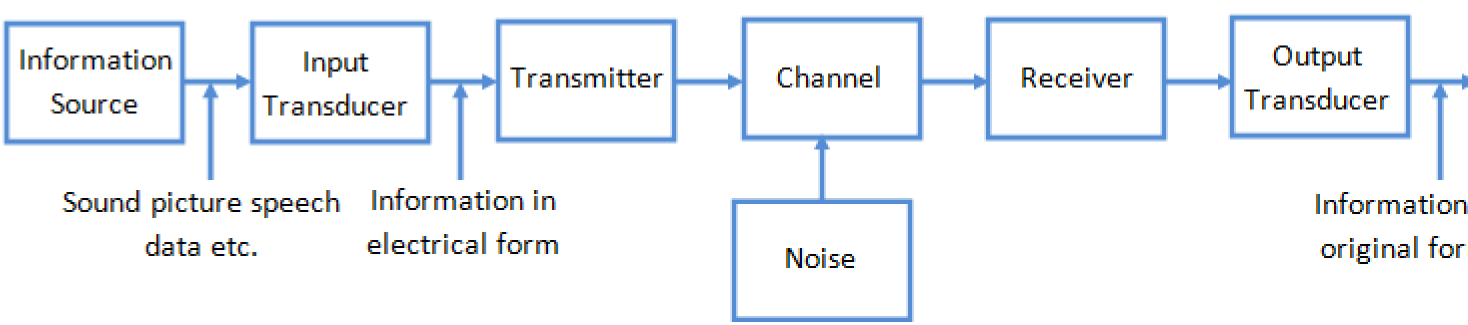
Data Networks
Physical Layer

M. R. Pakravan
Department of Electrical Engineering
Sharif University of Technology

Physical Layer

- Physical Layer is responsible for delivering a stream of symbols (usually a stream of 1's and 0's) from a source over a channel to a destination.
- Information theory shows that there are limitation for delivering information over a channel
- Maximum Data Rate of a band limited noiseless channel:
  $C=2W*\log_2(V)$ bits/sec
  where V is number of discrete signal levels, W is channel bandwidth
- For Noisy channels: $C=W\log_2(1+SNR)$ bits/sec
- Example: A channel with a bandwidth of 4kHz and SNR=30dB can carry 40kbps at most

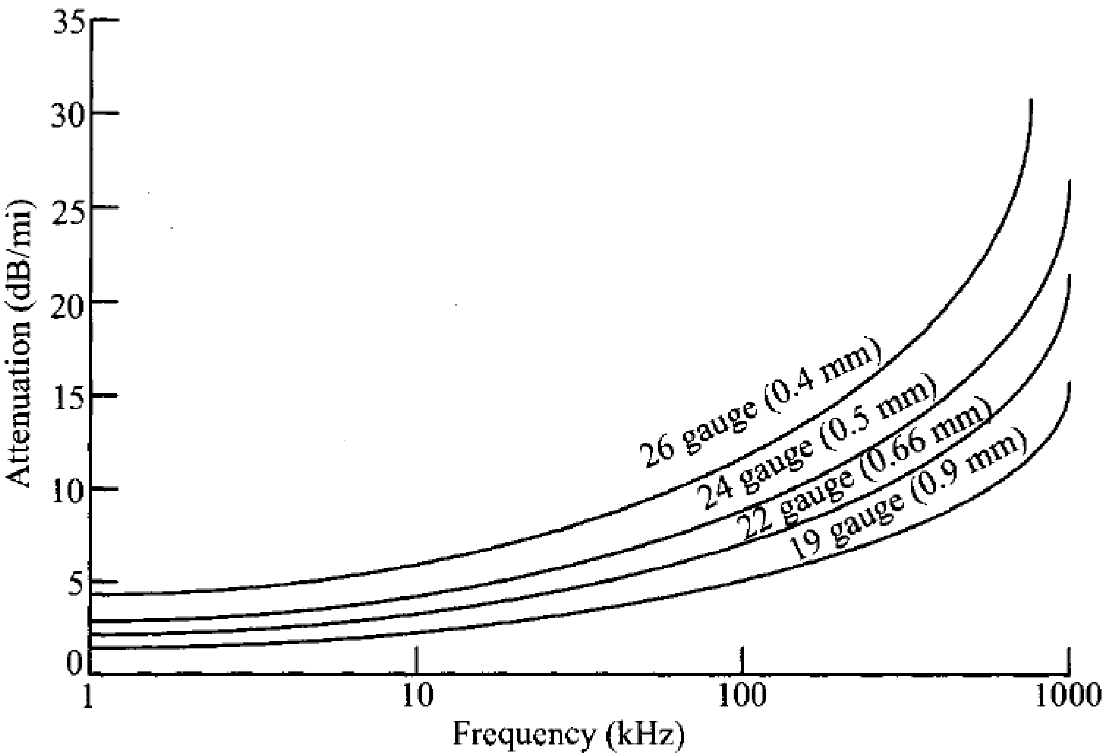


Physical Layer

- Important communication Media:
  - Guided Transmission Media
    - Twisted Pair
    - Coaxial Cable
    - Power Lines
    - Fiber Optics
  - Wireless Transmission
    - Radio/Microwave Transmission
    - Millimeter Wave Transmission
    - Light wave Transmission
    - Satellite Communication
      - Geostationary
      - Medium Orbit Satellites
      - Low Earth Orbit Satellites

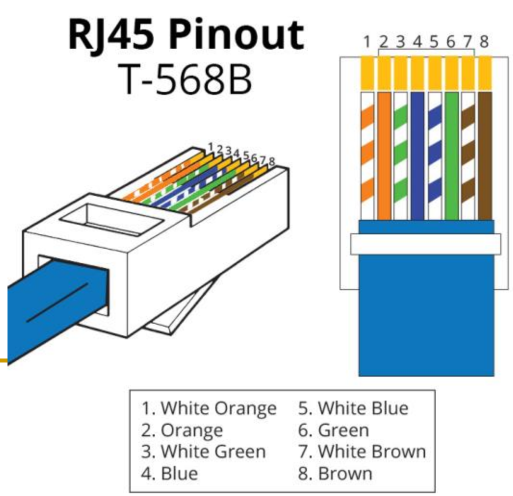
Twisted Pair

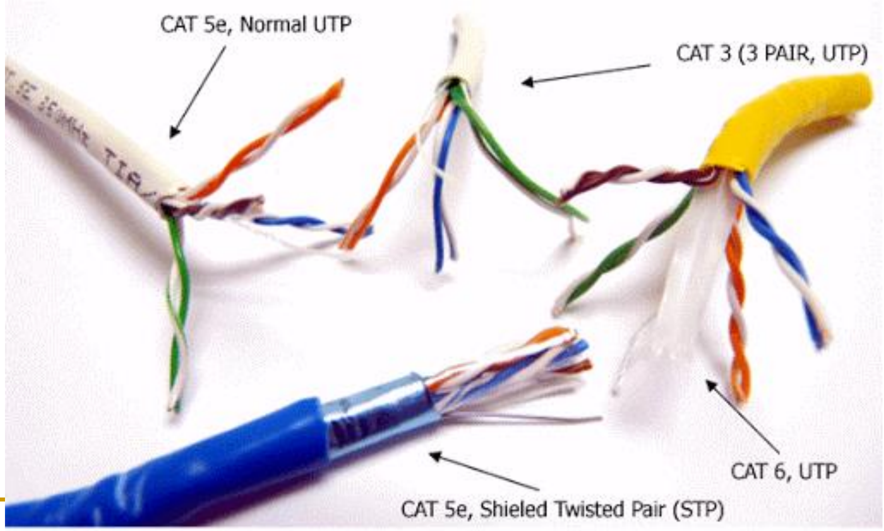
- Twisted Pair cable is used in telephone networks and data networks
- Attenuation depends on distance, frequency and cable type



Twisted Pair

- Twisted Pair is also used for LAN cabling



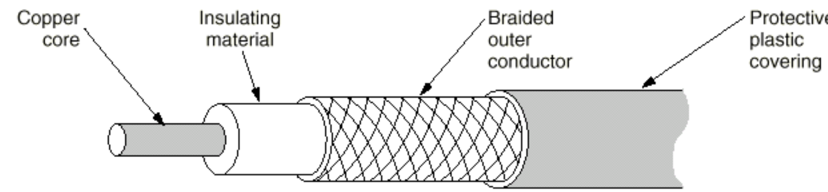


Twisted Pair

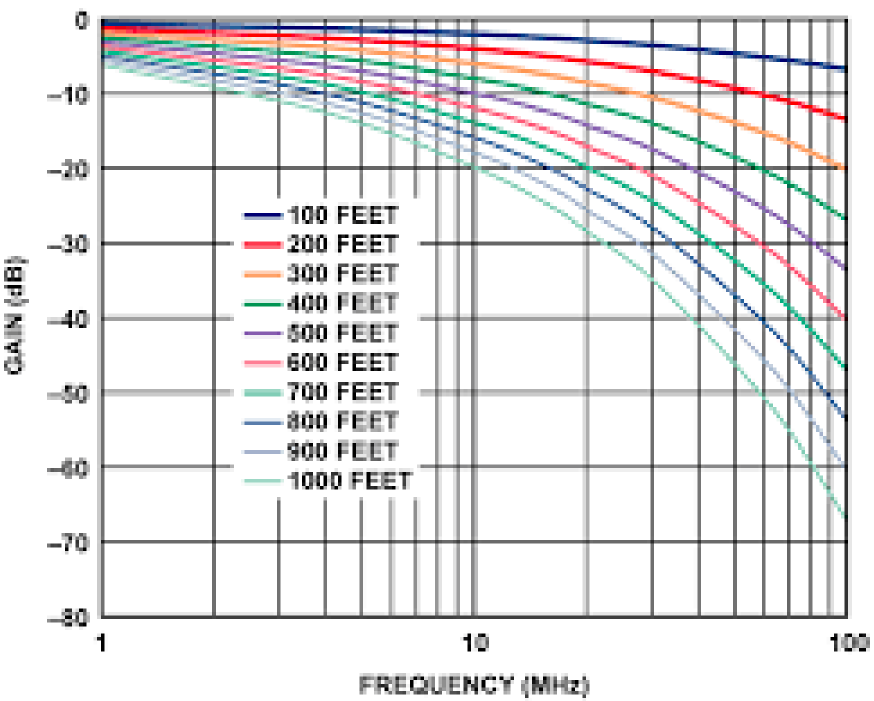
- Twisted pair cables are standardized and used in data networks

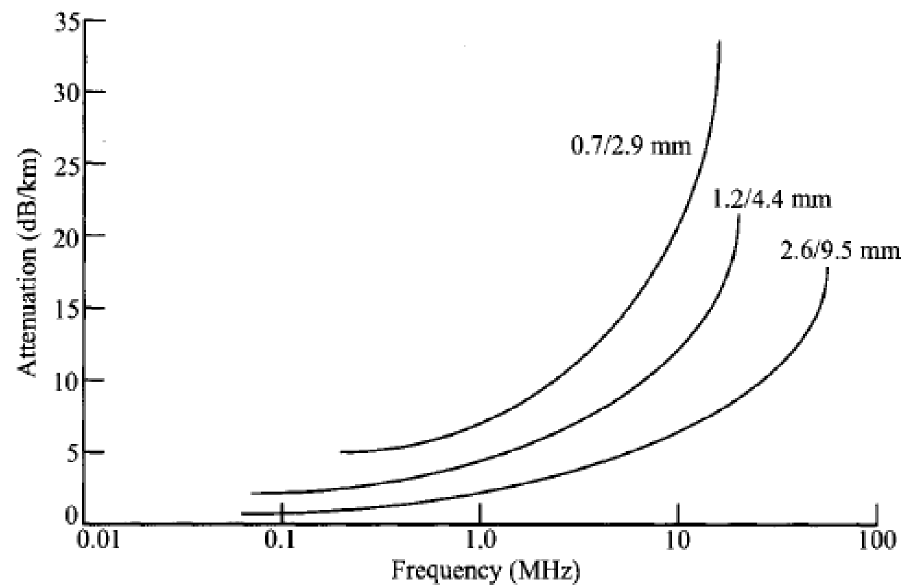
ategory	Max. Data Rate	Bandwidth	Max. Distance	Usage
Category 1	1 Mbps	0.4 MHz		Telephone and modem lines
Category 2	4 Mbps	4 MHz		LocalTalk & Telephone
Category 3	10 Mbps	16 MHz	100 m	10BaseT Ethernet
Category 4	16 Mbps	20 MHz	100 m	Token Ring
Category 5	100 Mbps	100 MHz	100 m	100BaseT Ethernet
Category 5e	1 Gbps	100 MHz	100 m	100BaseT Ethernet, residential homes
Category 6	1 Gbps	250 MHz	100 m (10Gb at 37 m)	Gigabit Ethernet, commercial buildings
Category 6a	10 Gbps	500 MHz	100 m	Gigabit Ethernet, commercial buildings
Category 7	10 Gbps	600 MHz	100 m	10 Gbps Core Infrastructure
Category 7a	10 Gbps	1000 MHz	100 m (40Gb at 50 m)	10 Gbps Core Infrastructure
Category 8	25 Gbps (Cat8.1) 40 Gbps (Cat8.2)	2000 MHz	30 m	25 Gbps/40 Gbps Core Infrastructure

Coaxial Cable

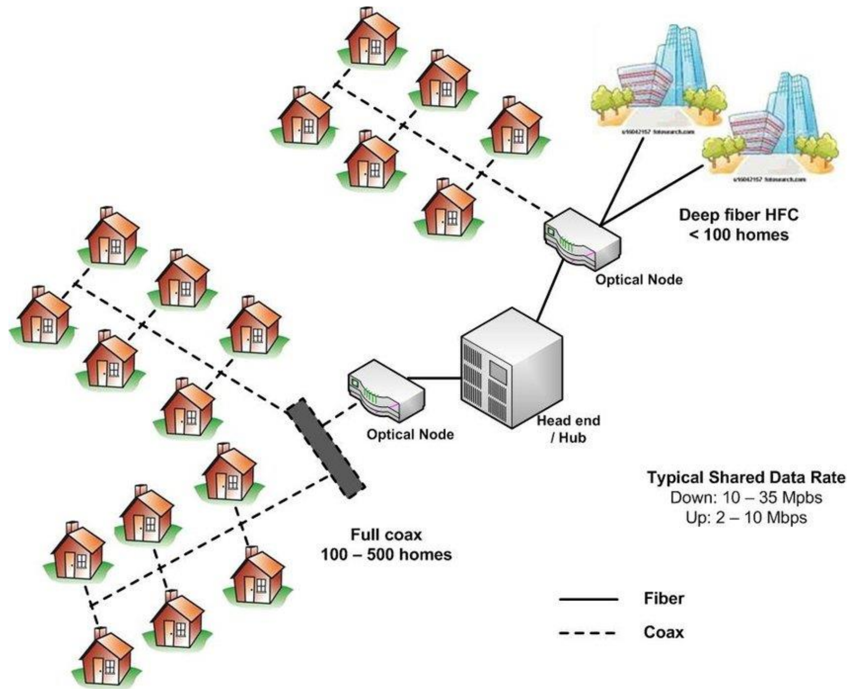


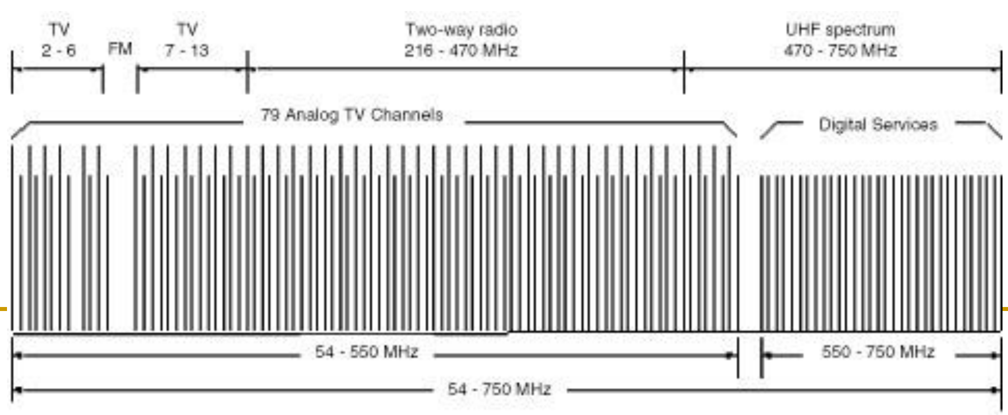
- Better shielding than twisted pair
- Lower attenuation & cross talk
- Can carry 1~2 Gbps in 1 km
- Telco's used it for their backbone communication. It is replaced by fiber optics.
- Cable TV companies use it for TV and data delivery services.





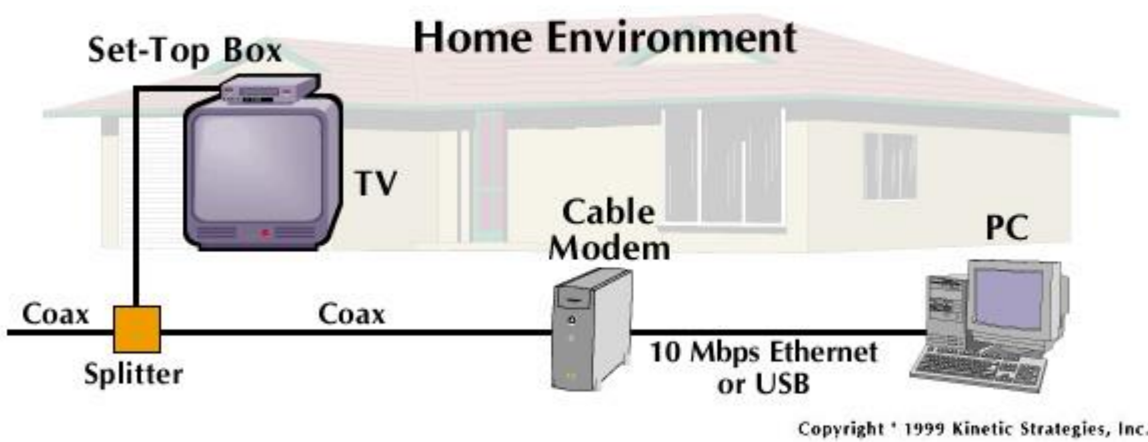
Cable TV Networks





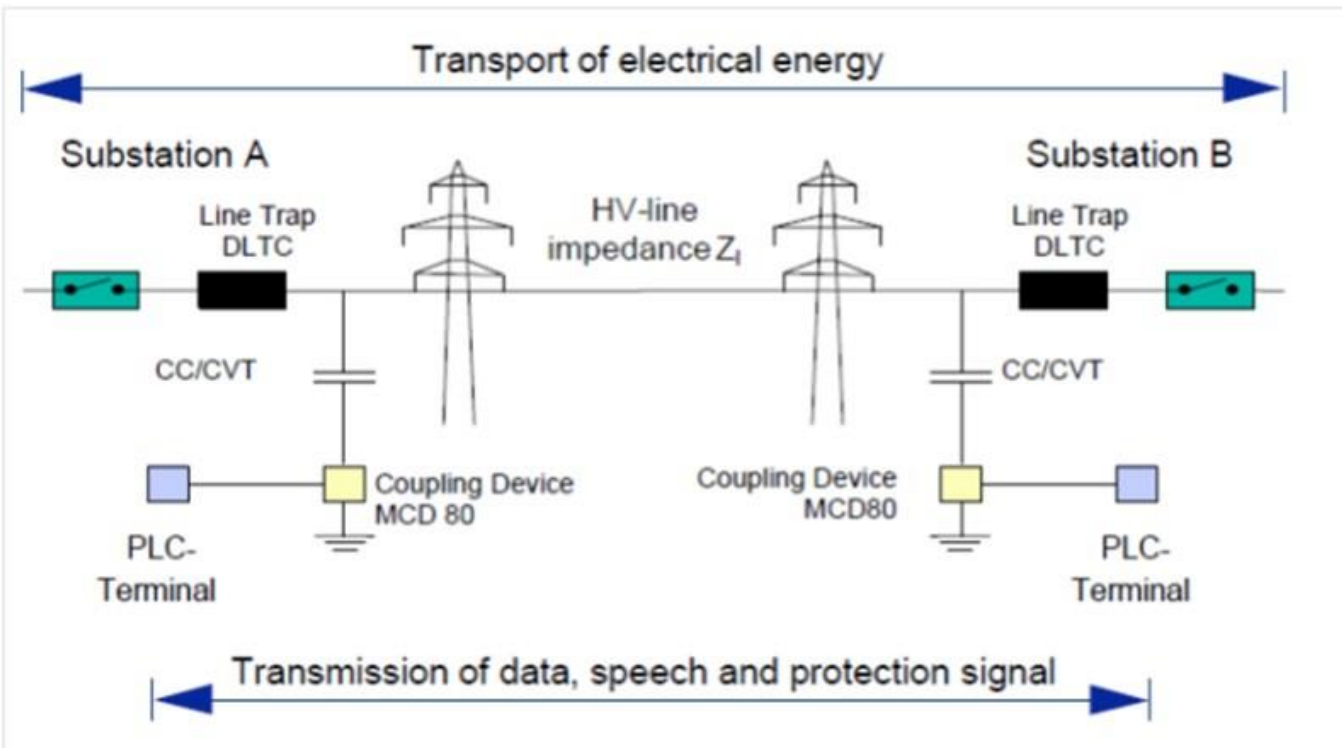
Hybrid Fiber Coax Architecture

- Combination of fibers and coaxes used to deliver the service
- Lasers are intensity modulated using the analogue RF signal
- Data Over Cable Service Interface Specification (DOCSIS) series of standards were developed to allow data service delivery over the TV cable network.
- DOCSIS 3.0 is the latest version of the standard (2007) which also supports QoS



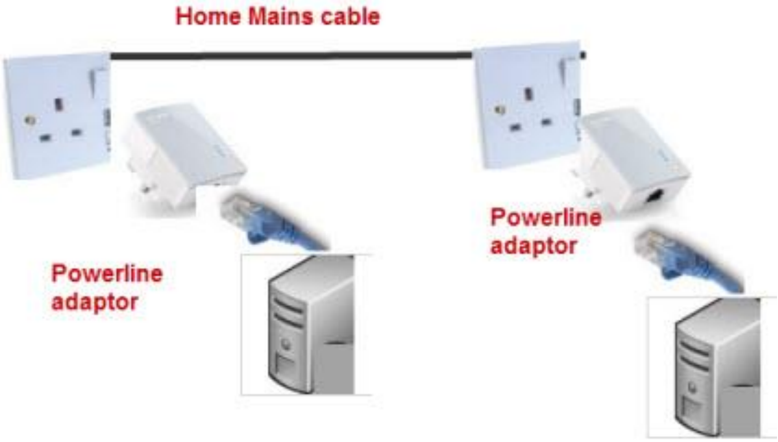
Power Lines

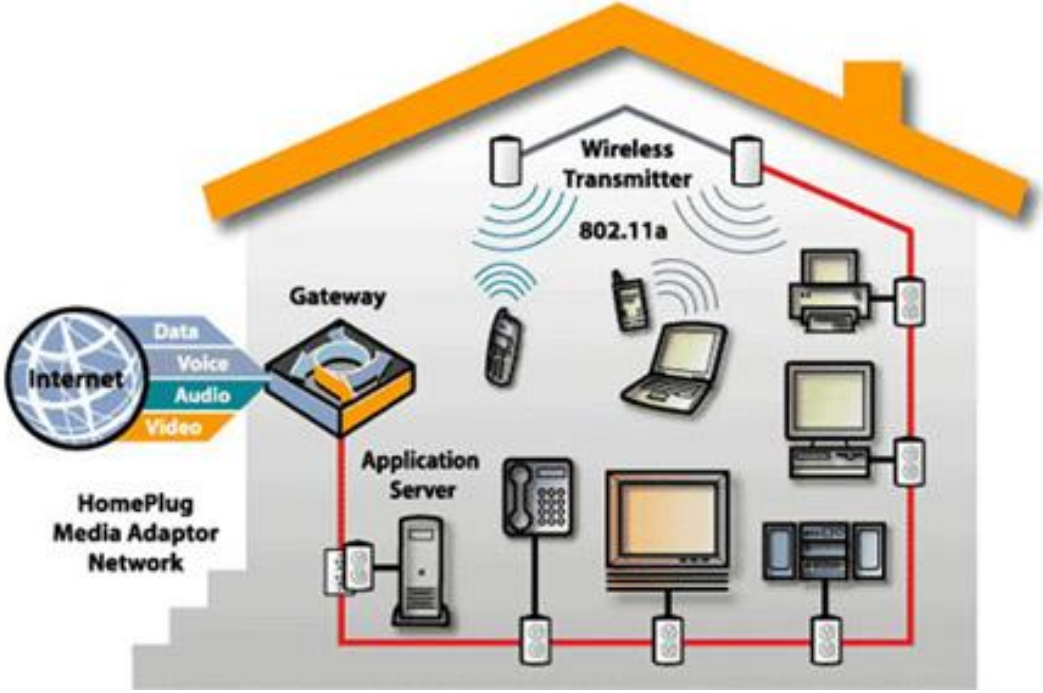
- Power Lines Carrier Communication Systems are used by Electric companies for transmission of control and dispatching data over power lines.



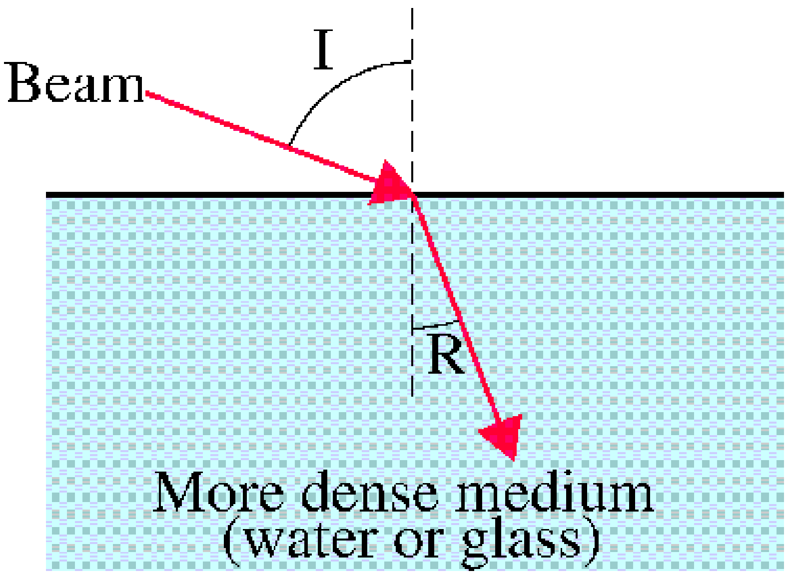
Power Lines

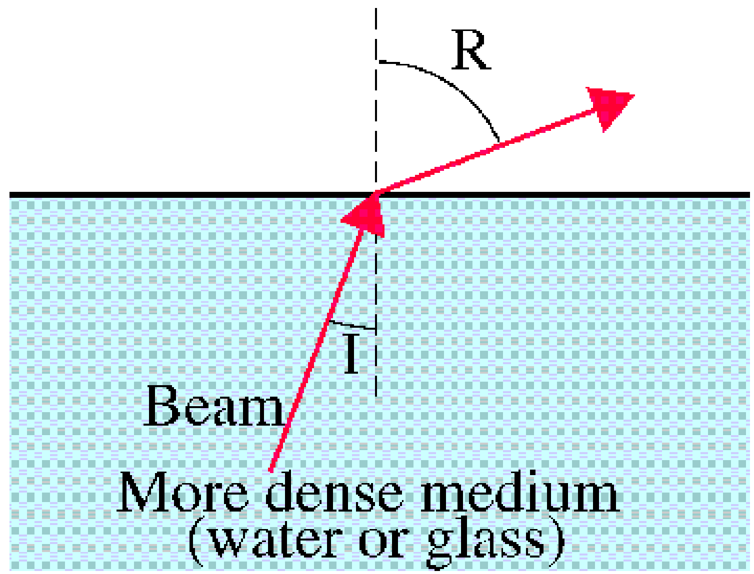
- Power Lines can be used for broadband data communication inside home.
- HomePlug AV2 standard supports up to 1Gbps





Light Refraction

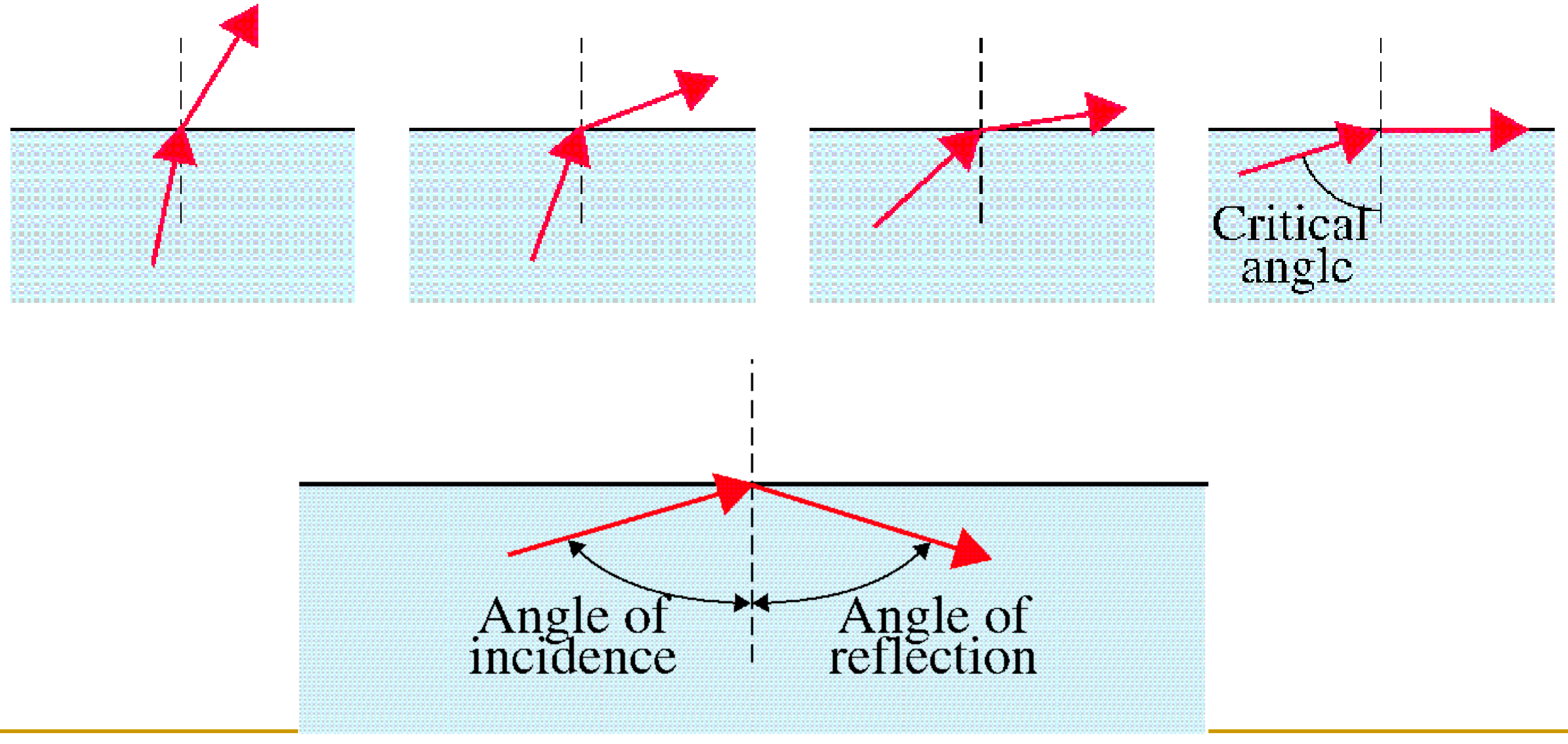




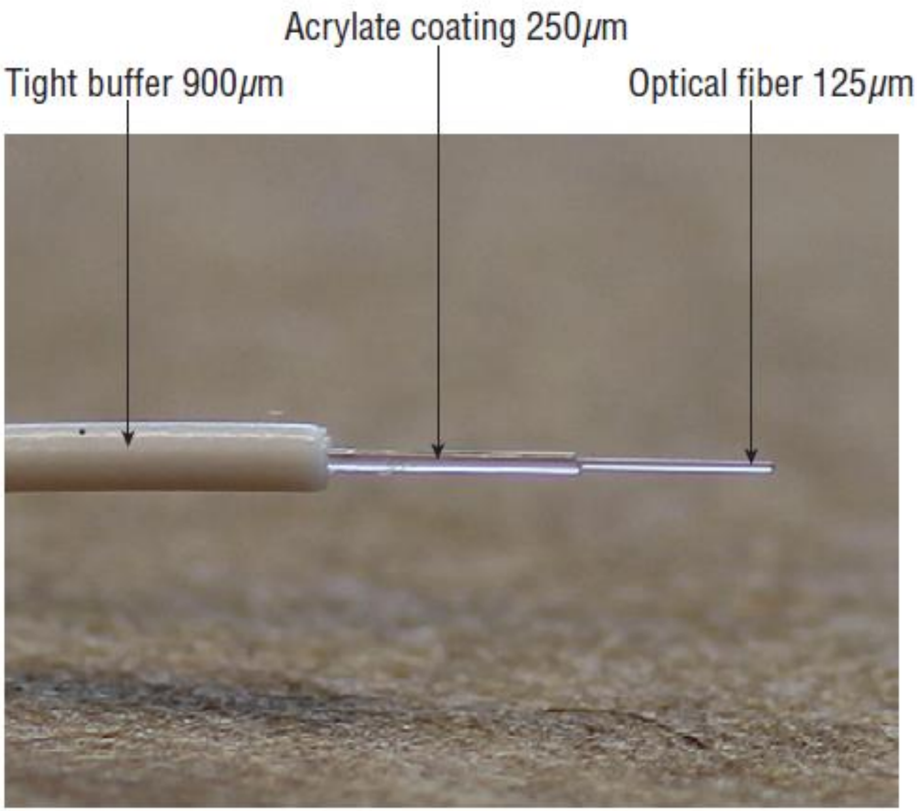
From less dense to more dense medium

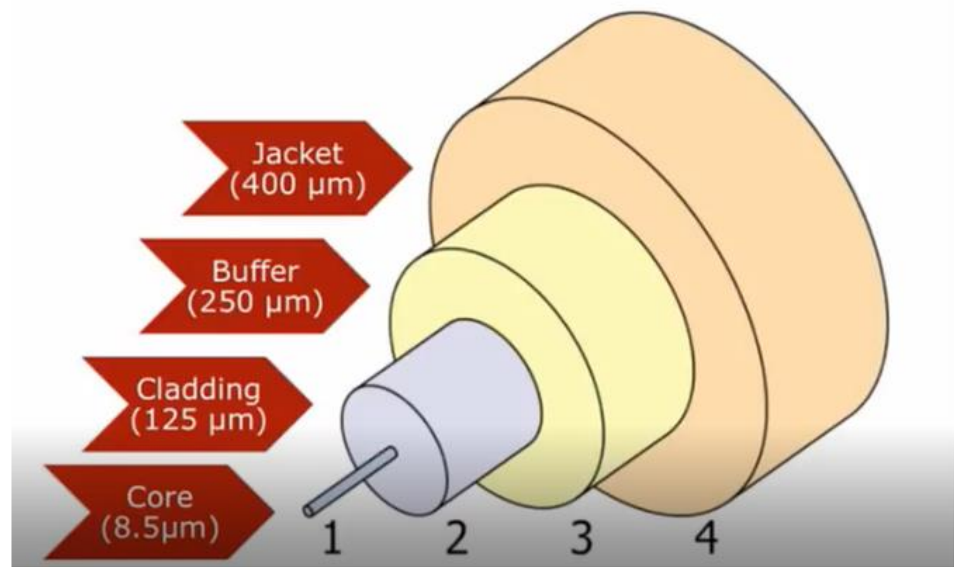
From more dense to less dense medium

Light Reflection

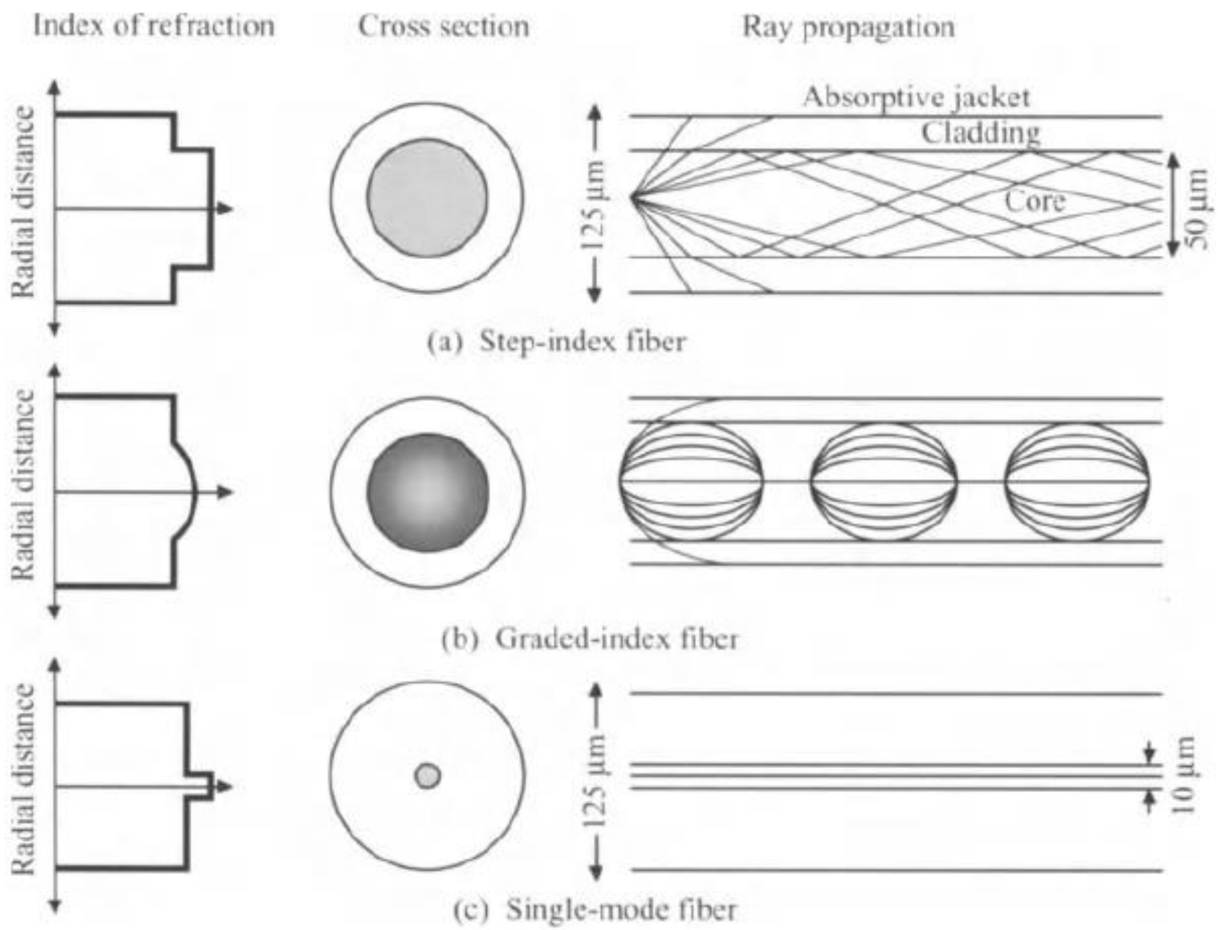


Optical Fiber Structure





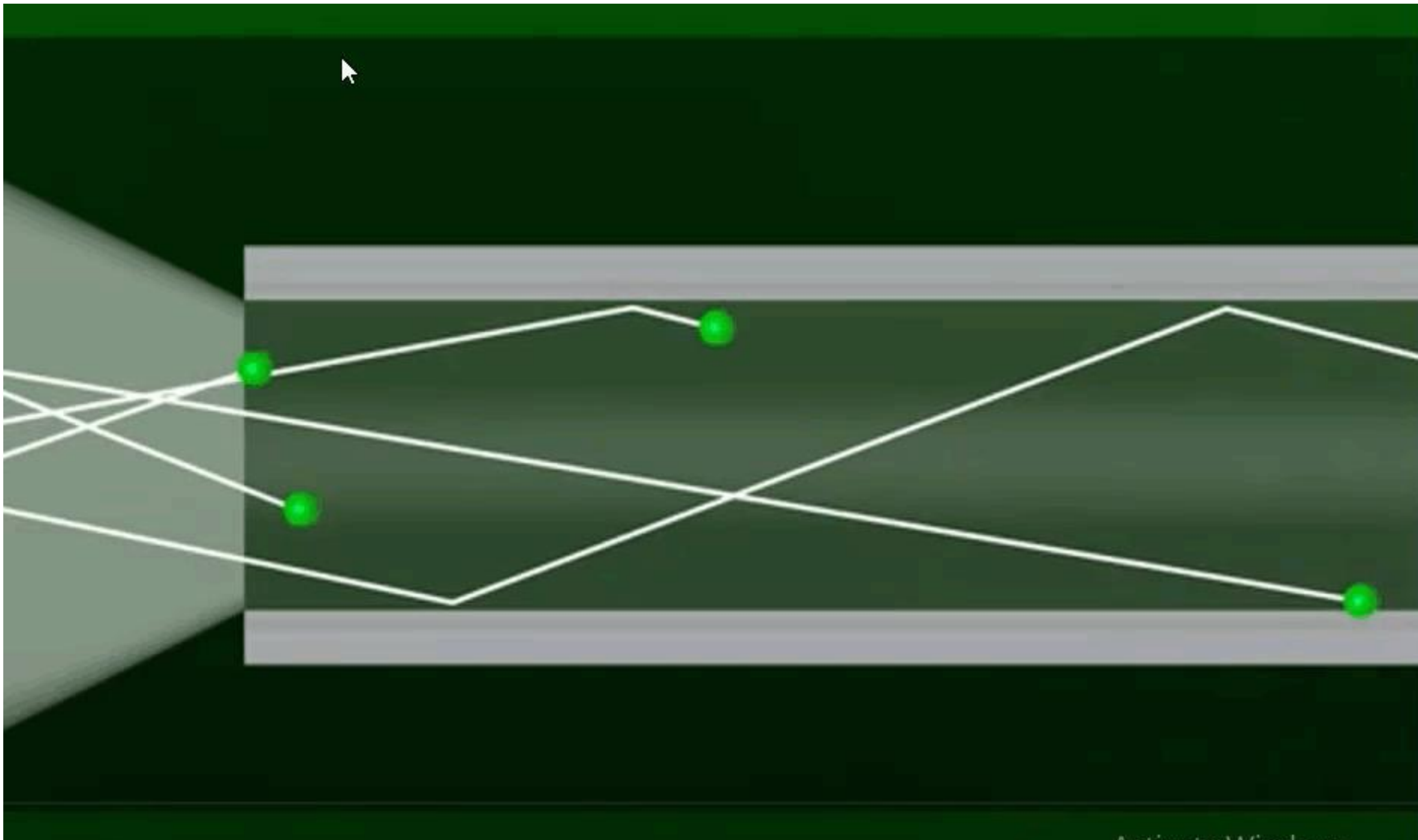
Fiber types



Multi-mode Fiber

Single-mode Fiber

Fiber Types:
Single Mode and Multi Mode



Fiber Optic Connector (LC/LC)

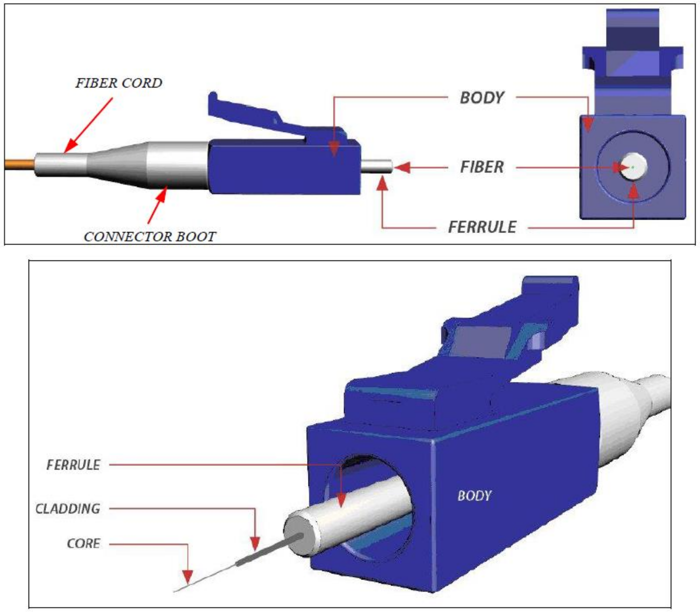
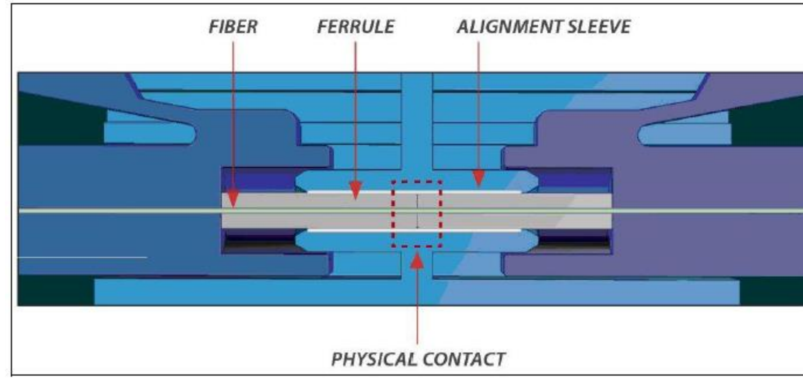
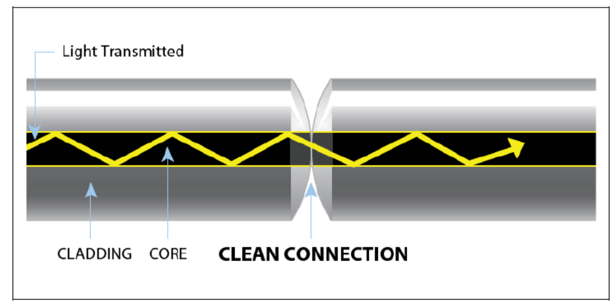
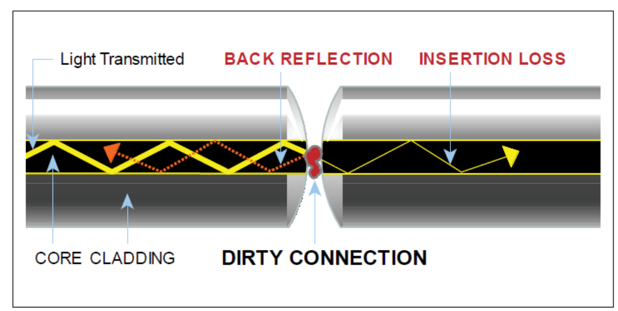


Figure 1 – Fiber Connector Components (LC Example)





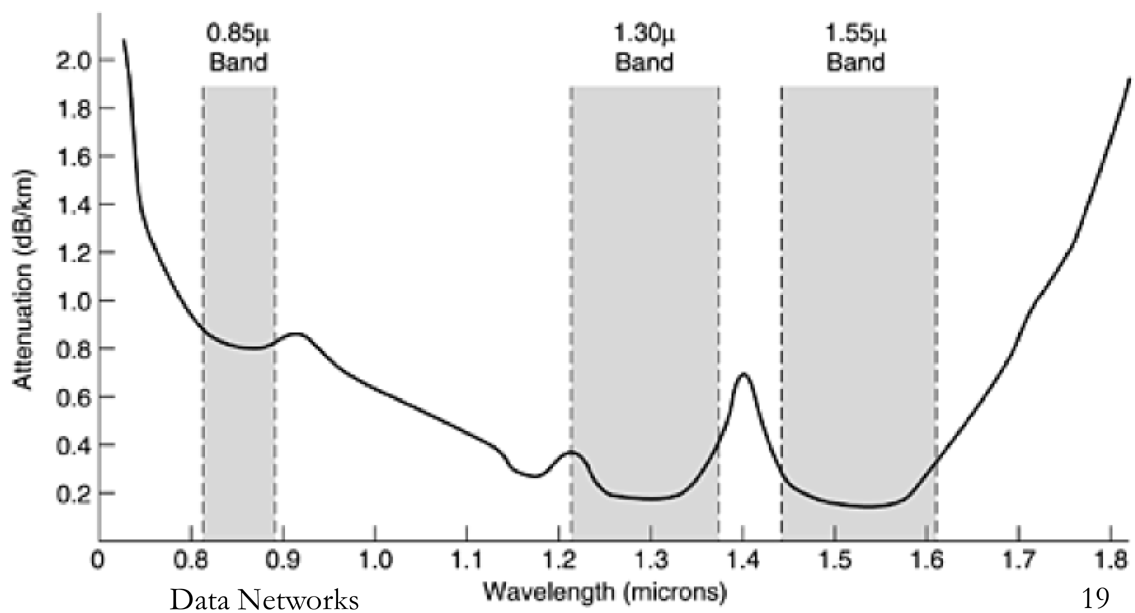


LC Adaptor

Types of fiber connectors

Attenuation

- Typical Attenuation for Multimode fiber:
  - 3 dB/km @ 850 nm
  - 1 dB/km @ 1300 nm
- Typical Attenuation for Single mode fiber:
  - 0.4 dB/km @ 1310 nm
  - 0.25 dB/km @ 1550 nm



Fiber Optic Cable: Advantages

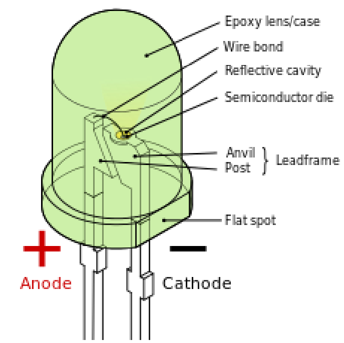
- Fiber can handle much higher data rates than copper
  - C-Band: 1530-1565 nm
  - Frequency Range: 191 THz to 196 THz => 5 THz of bandwidth
- Fiber has low loss of signal power (attenuation), so fewer repeaters are needed for fiber optic links compared to copper based links
- Fibers are difficult to tap and therefore excellent for security

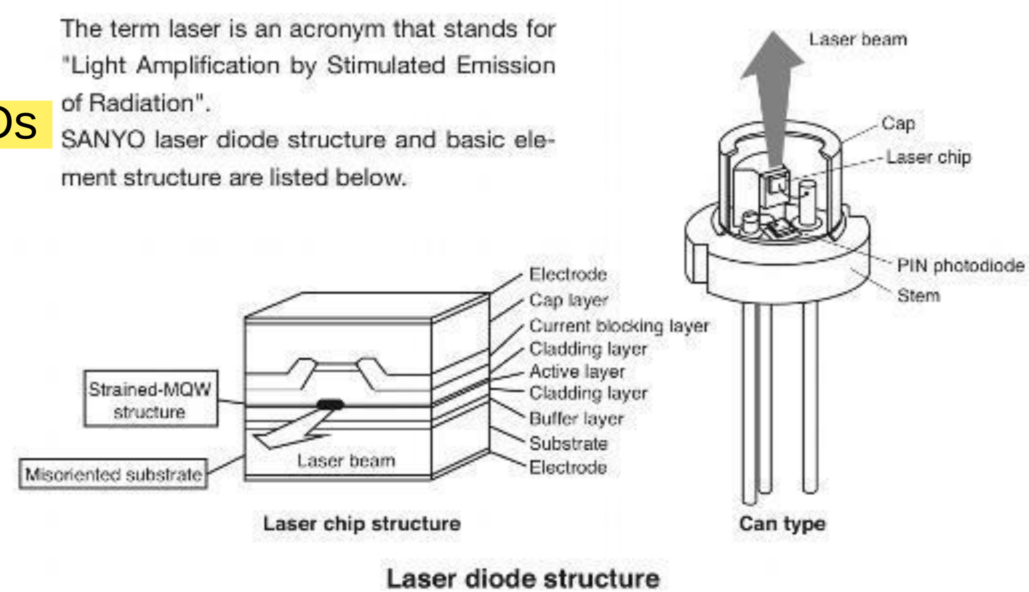
Fiber Optic Advantages

- Fiber is not affected by power surges, electromagnetic interference or power failure, or corrosive chemicals in the air
  - Photons of light in a fiber do not affect each other as they have no electrical charge, and they are not affected by stray photons outside the fiber
  - In the case of copper, electrons move through the cable and these are affected by each other and by electromagnetic fields outside the cable
- Fibers are thin and lightweight, allowing more cables to fit into a given area
  - 1000 twisted pair cables 1 km long = 800kg
  - 2 optical fiber cables 1km long = 100kg (allows transfer of much more data)

Light source

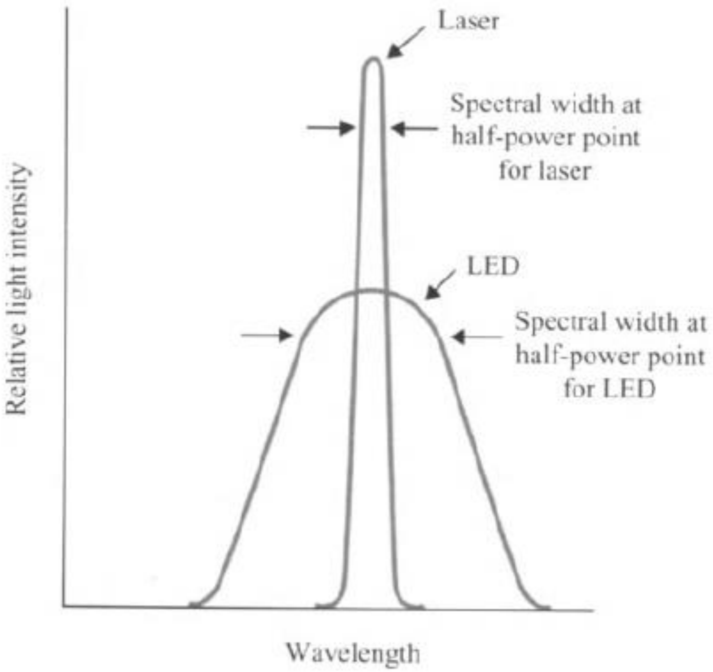
- Sending device called "light source"
- Light source
  - Light-emitting diode (LED)
    - Cheap but unfocused
    - Short distance
  - Laser diode (LD)
    - More expensive than LEDs but focused
    - Preserve the signal (long distance)
    - Most communication systems use LD





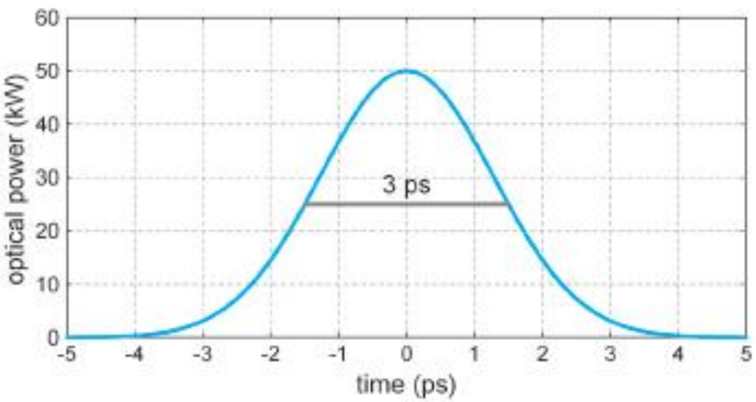
Light Sources

- Lasers produce light in a more confined region of spectrum



Light Sources

- Lasers can generate pulses with shorter duration in time. Therefore, higher modulation rates can be achieved with lasers.



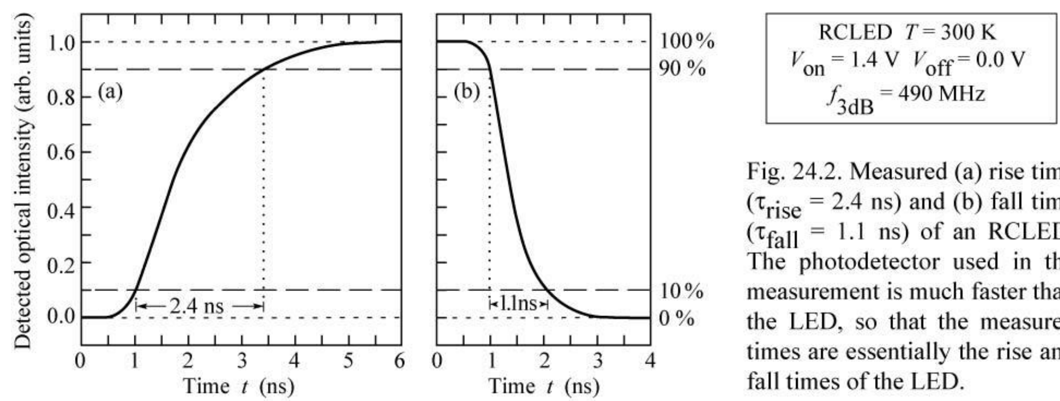
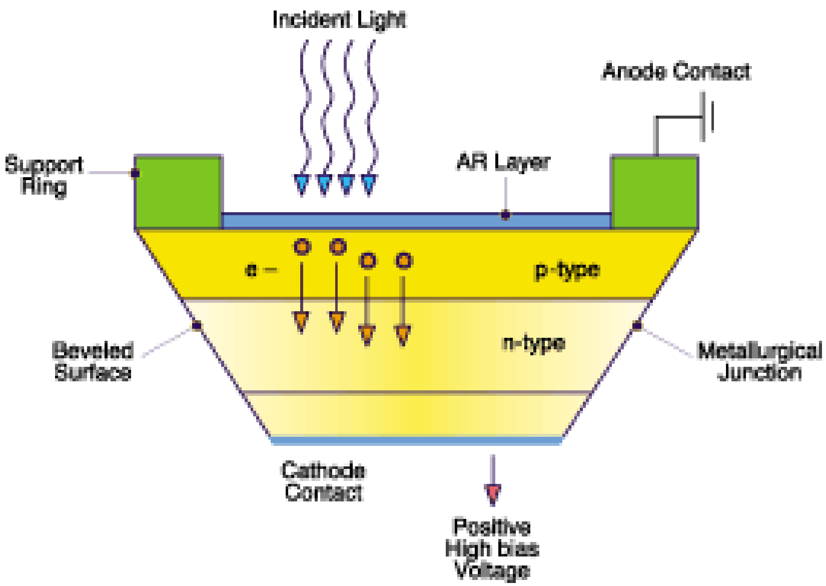


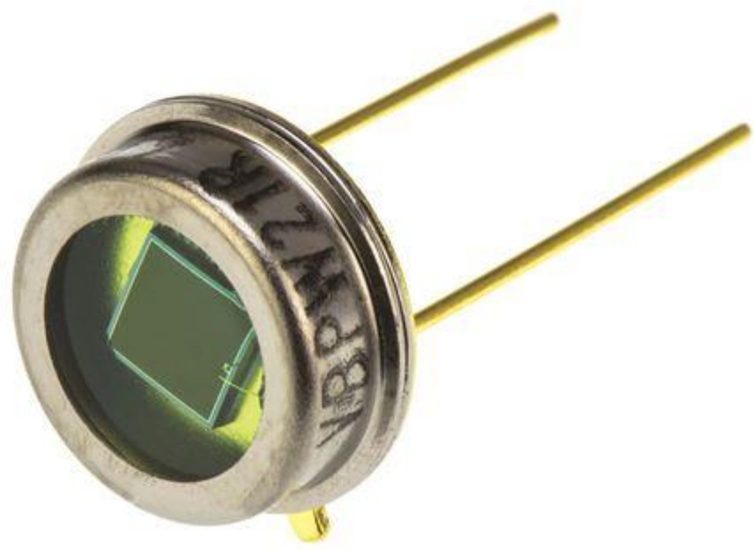
Fig. 24.2. Measured (a) rise time (τ_{rise} = 2.4 ns) and (b) fall time (τ_{fall} = 1.1 ns) of an RCLED. The photodetector used in the measurement is much faster than the LED, so that the measured times are essentially the rise and fall times of the LED.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

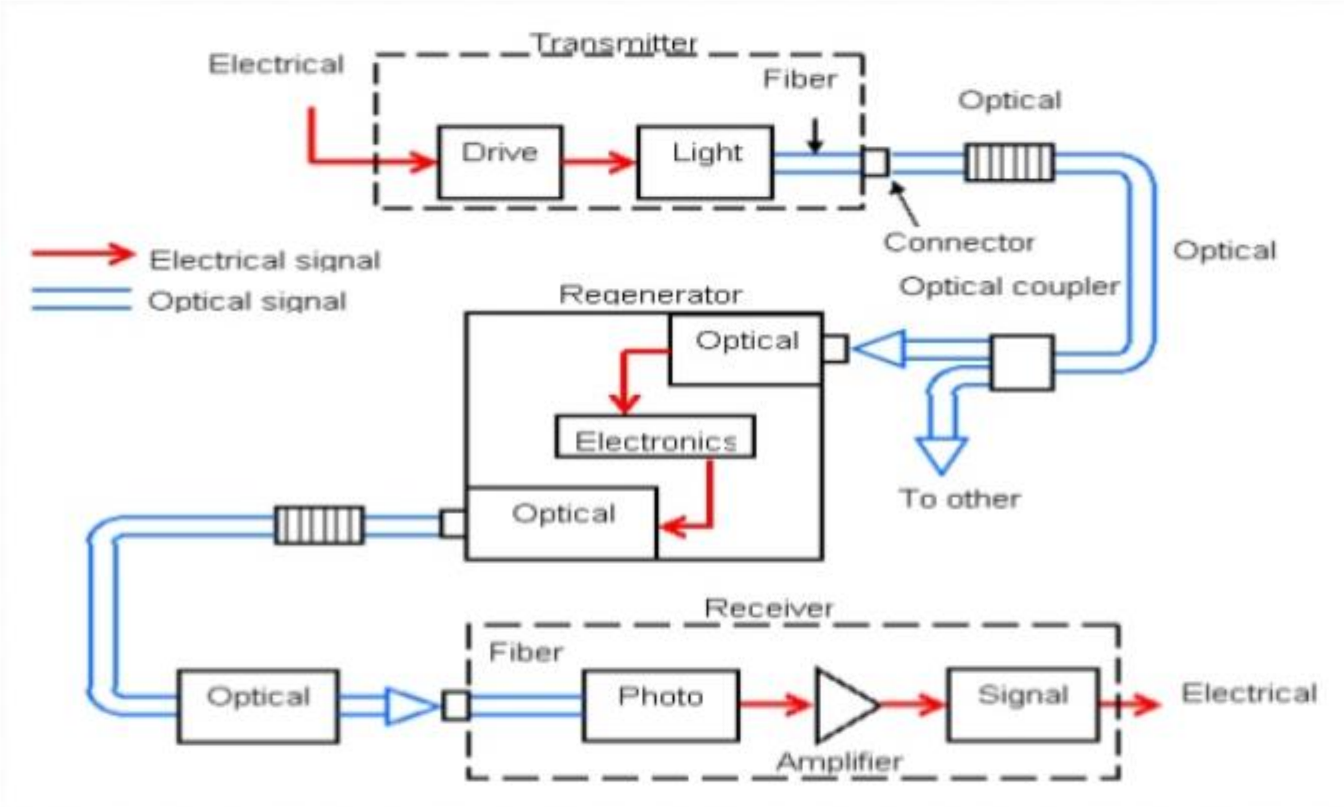
Light Receiver

- Receiving device called “photosensitive cell” (photodiode)
- Photodiode converts optical signal to electrical signal



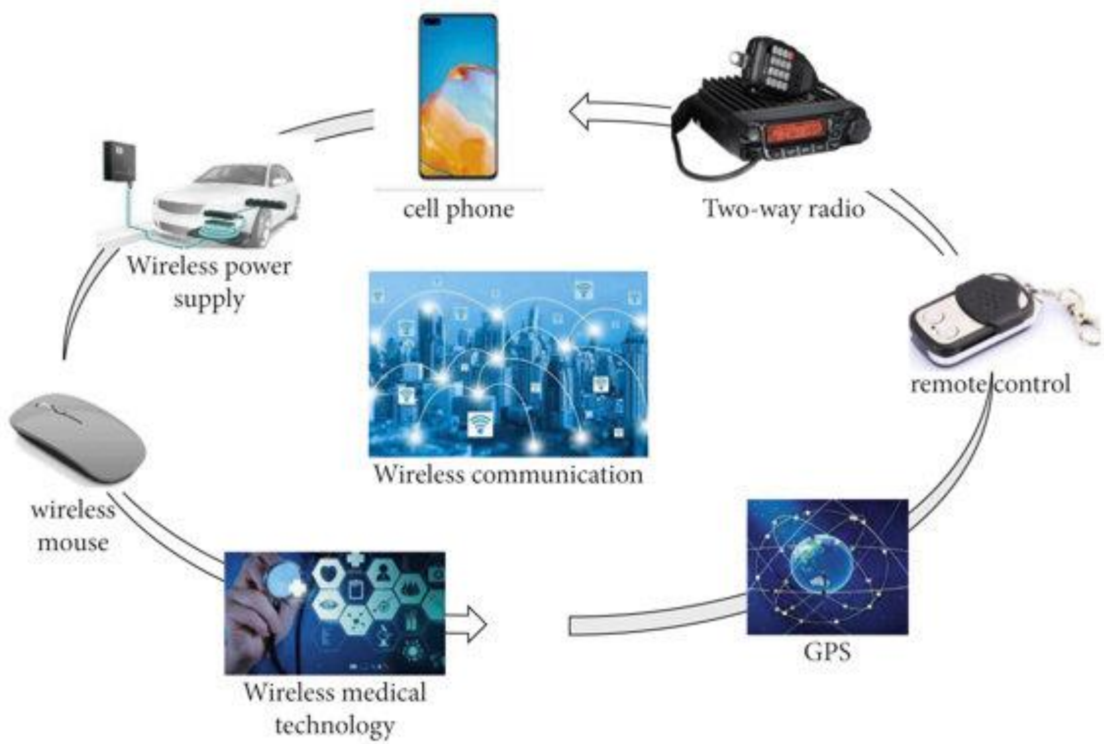


Light wave transmission system - overview

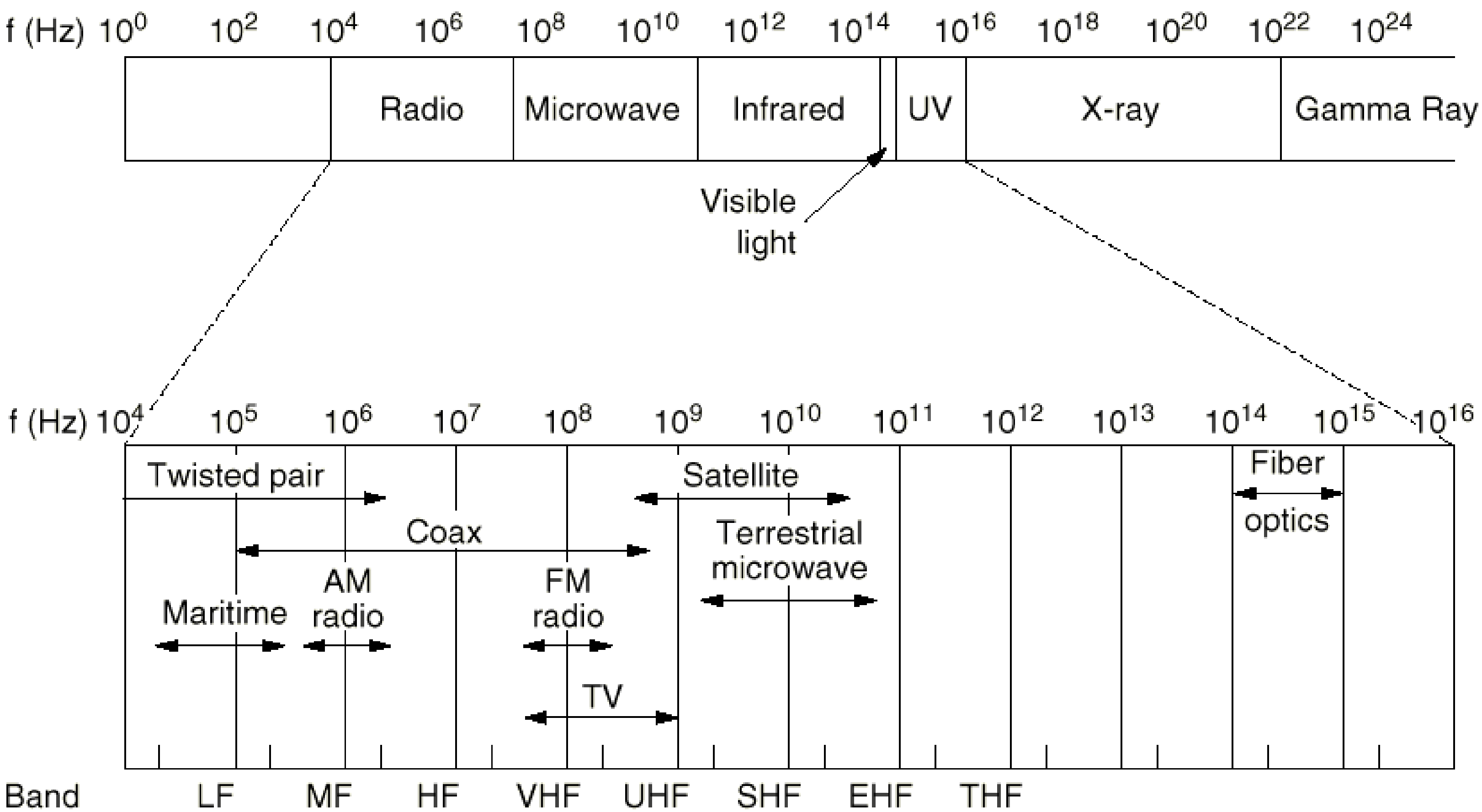


Wireless Communication

- Main Drivers
  - Communication without a physical attachment such as wires or fibers.
  - Mobility of users
  - Ease of deployment

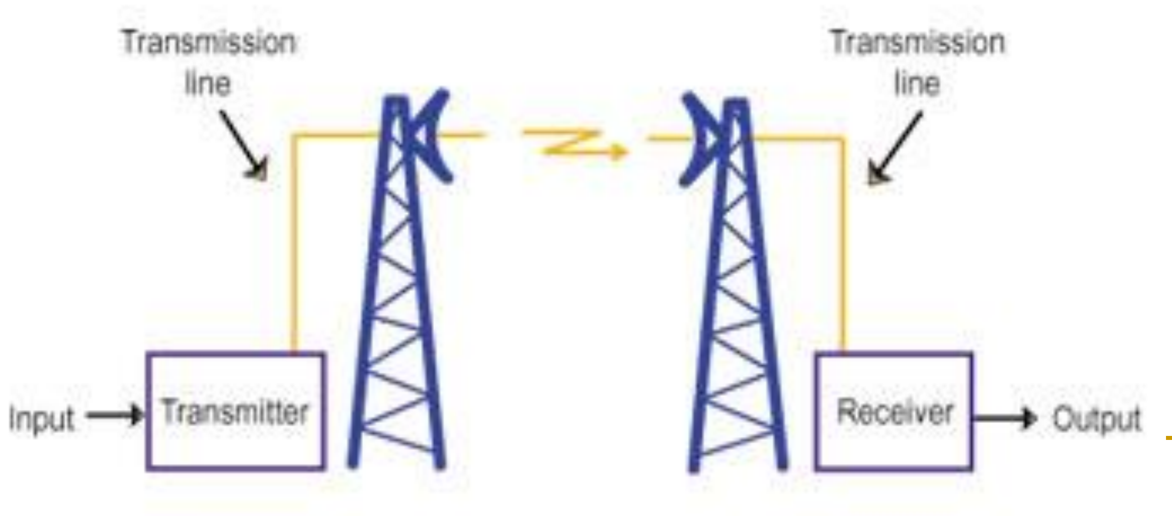


Electromagnetic Spectrum

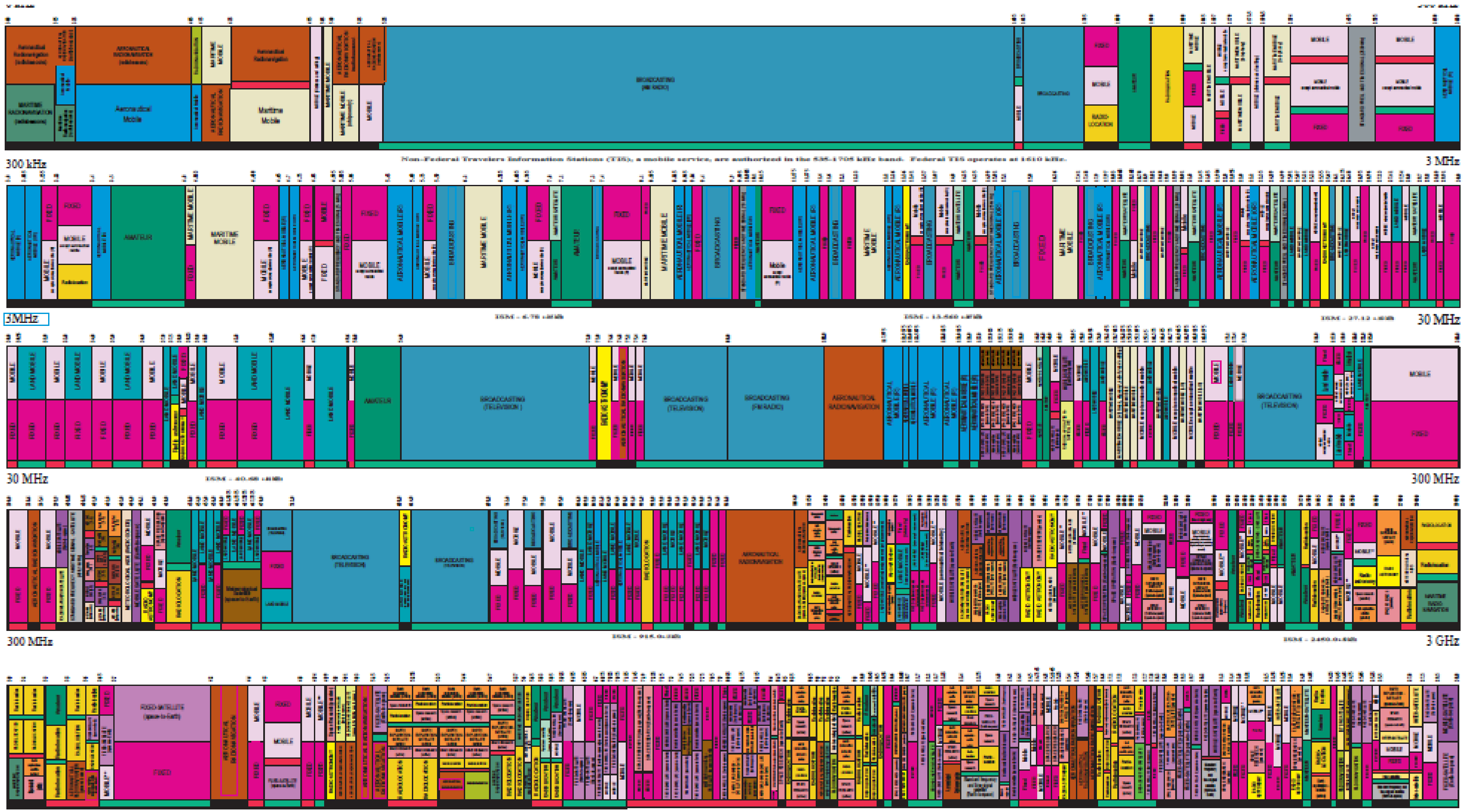


Wireless Communication

- Radio range of frequencies (10KHz to 10MHz) usually used for broadcast communication
  - Long range, low attenuation, reflection from ionosphere
- Microwave range of frequencies (10MHz to 10GHz) usually used for point to point long distance transmission and local two-way communications
  - Medium range, affected by rain and weather conditions. Subject to multipath fading.



Spectrum Allocation



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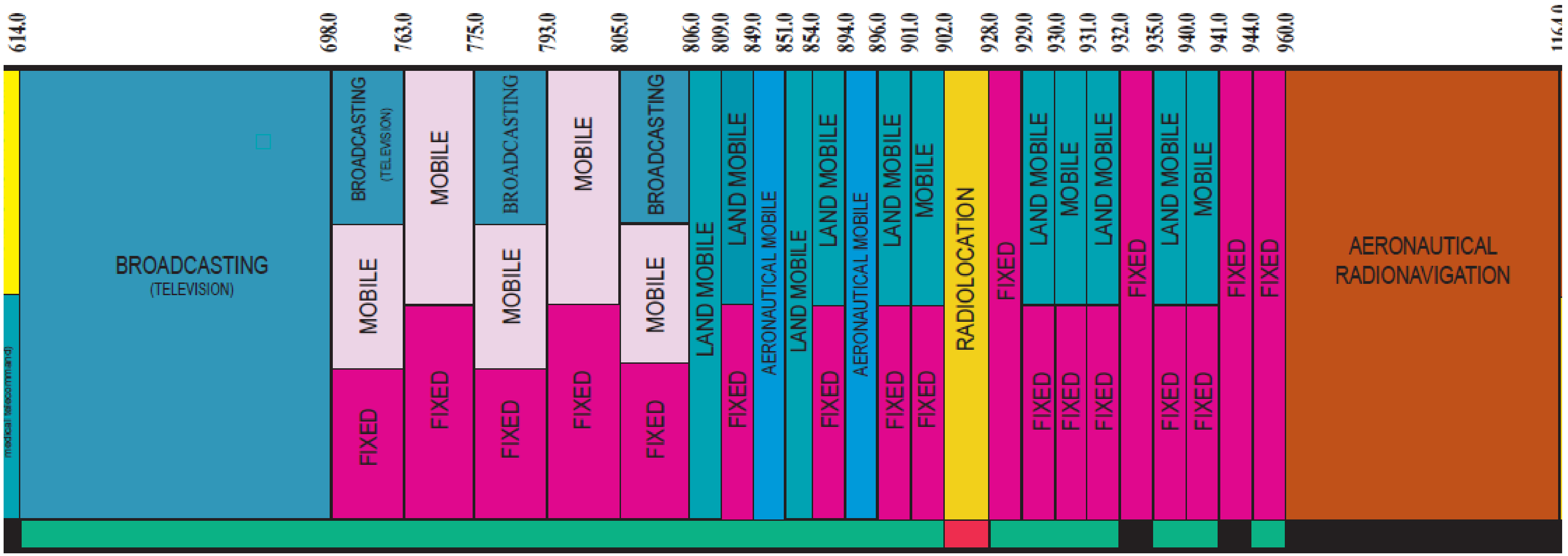
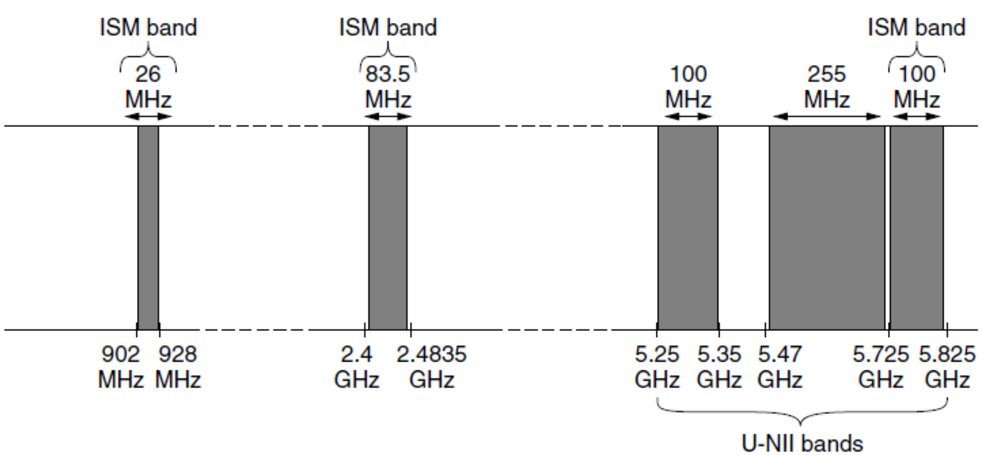


Spectrum Regulations

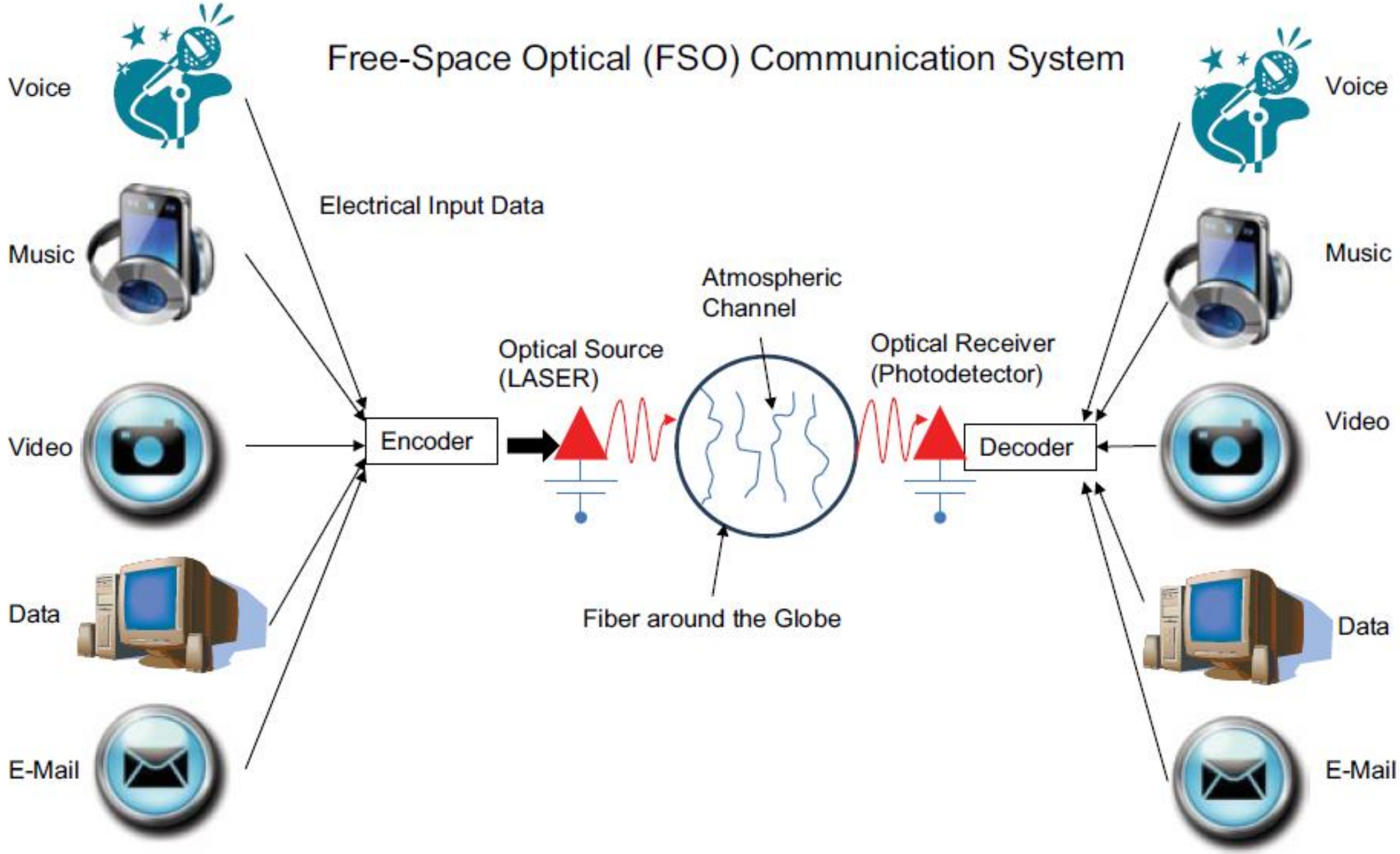
- Most radio frequency bands are regulated. Using frequency spectrum for commercial purposes is usually subject to a regulatory fee.
- There are license free bands available in most countries (ISM bands)



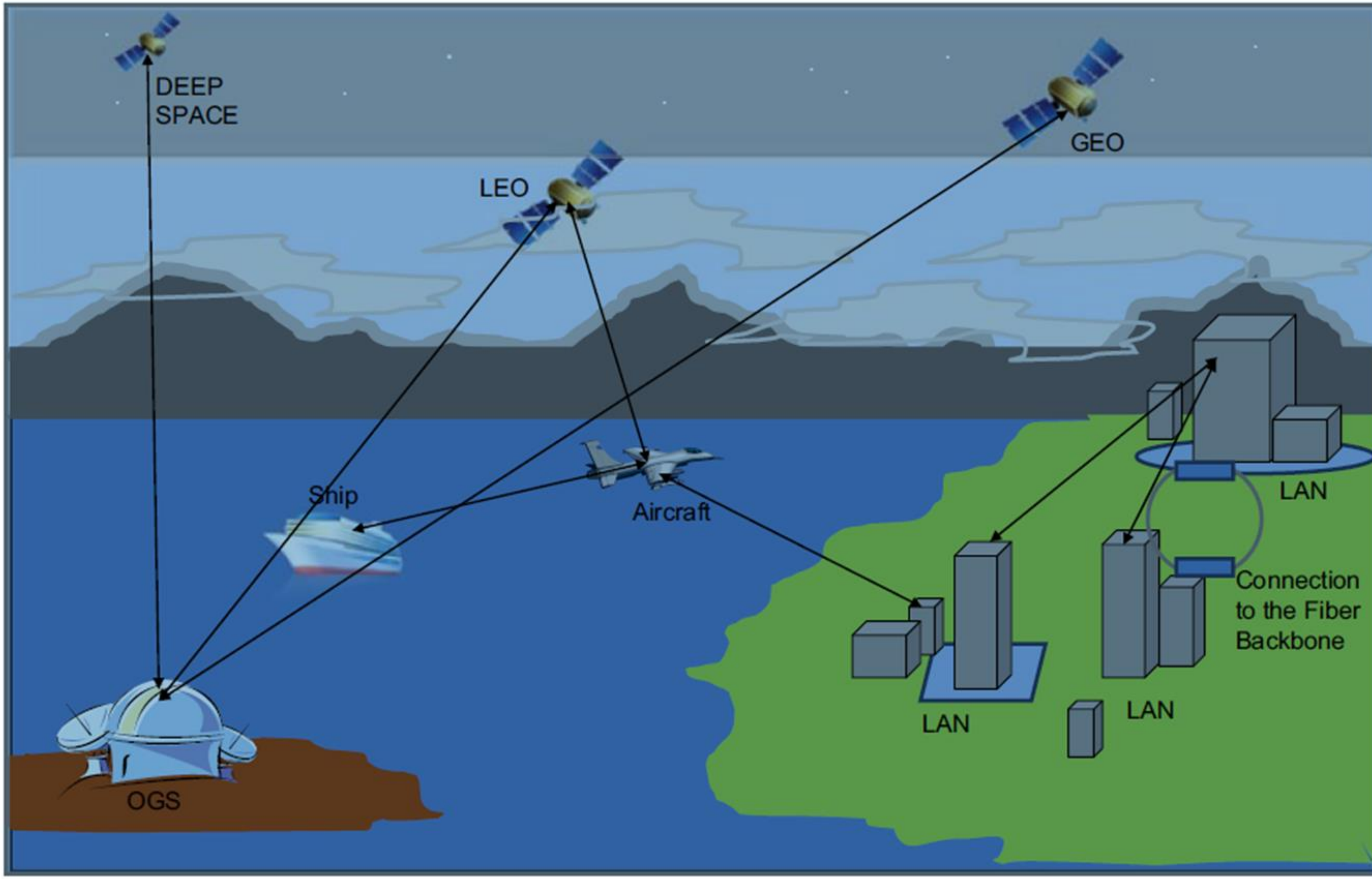
Range	Center Frequency	Bandwidth
6.765–6.795 MHz	6.78 MHz	30 kHz
13.553–13.567 MHz	13.56 MHz	14 kHz
26.957–27.283 MHz	27.12 MHz	326 kHz
40.66–40.7 MHz	40.68 MHz	40 kHz
433.05–434.79 MHz	433.92 MHz	1.84 MHz
902–928 MHz	915 MHz	26 MHz
2.4–2.5 GHz	2.45 GHz	100 MHz
5.725–5.875 GHz	5.8 GHz	150 MHz
24–24.25 GHz	24.125 GHz	250 MHz
61–61.5 GHz	61.25 GHz	500 MHz
122–123 GHz	122.5 GHz	1 GHz
244–246 GHz	245 GHz	2 GHz

Free Space Optical Communication

- Idea: Light as the information carrier for free space communication



FSO: Outdoor Applications



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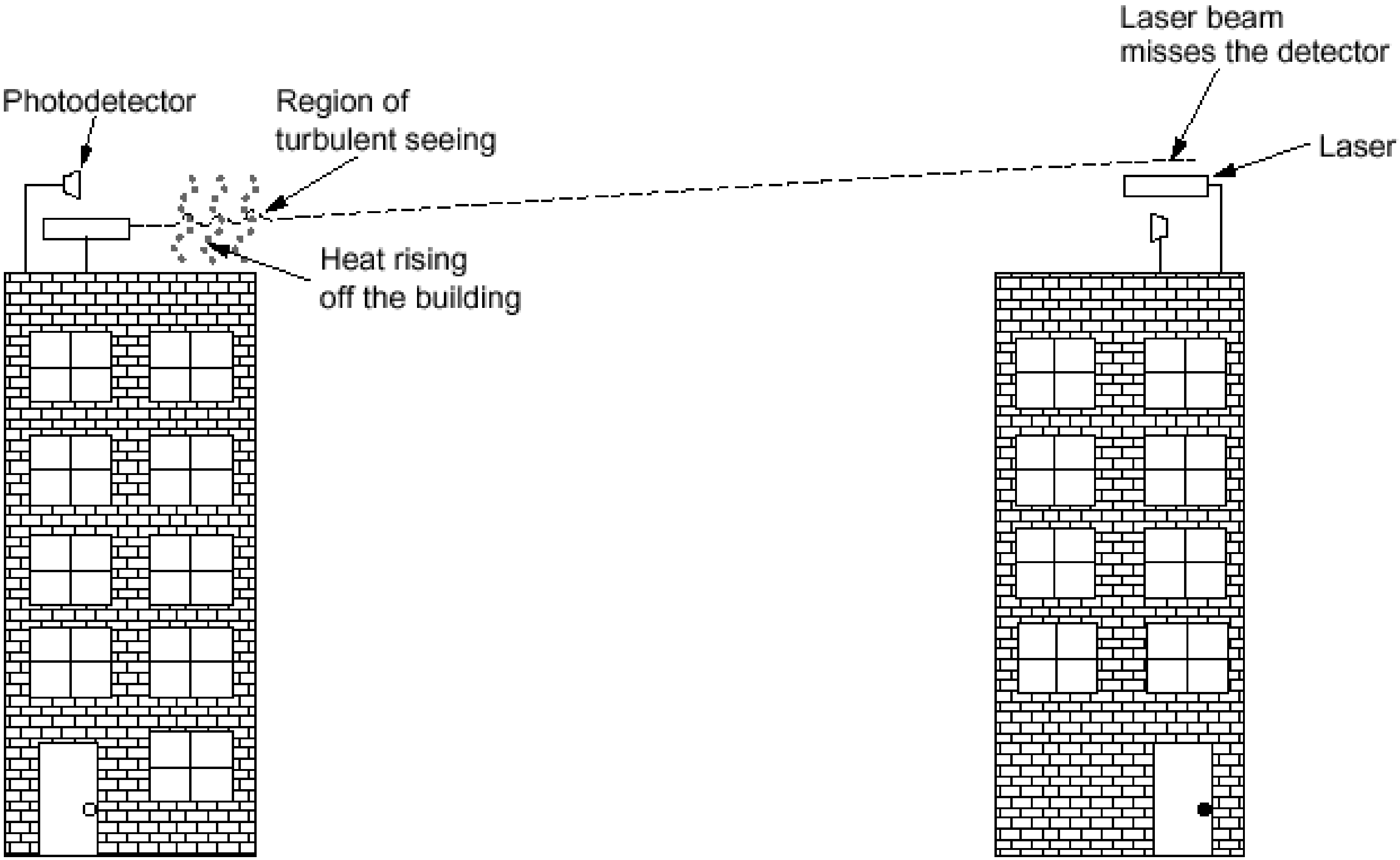
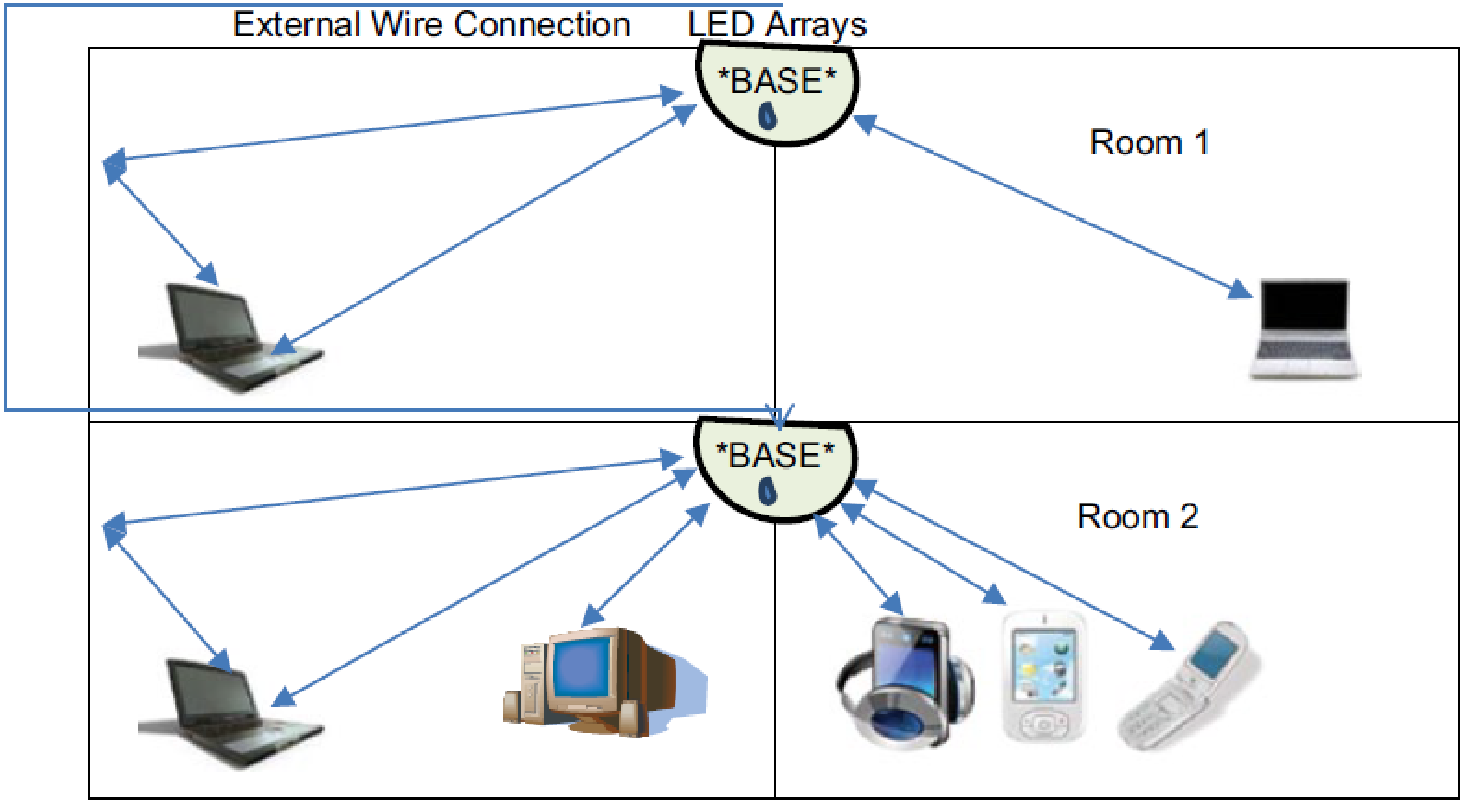


FSO: Indoor Applications

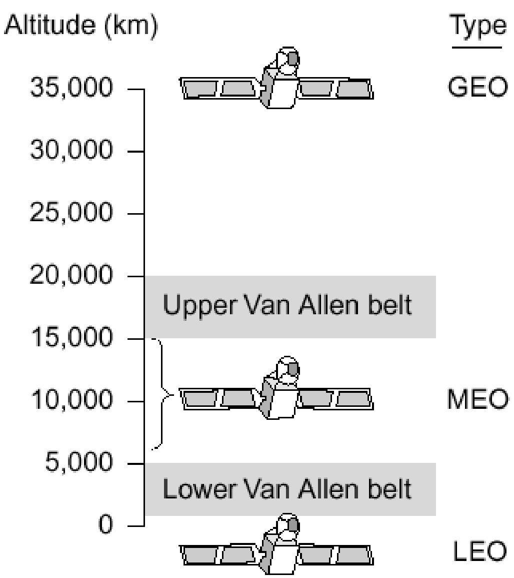


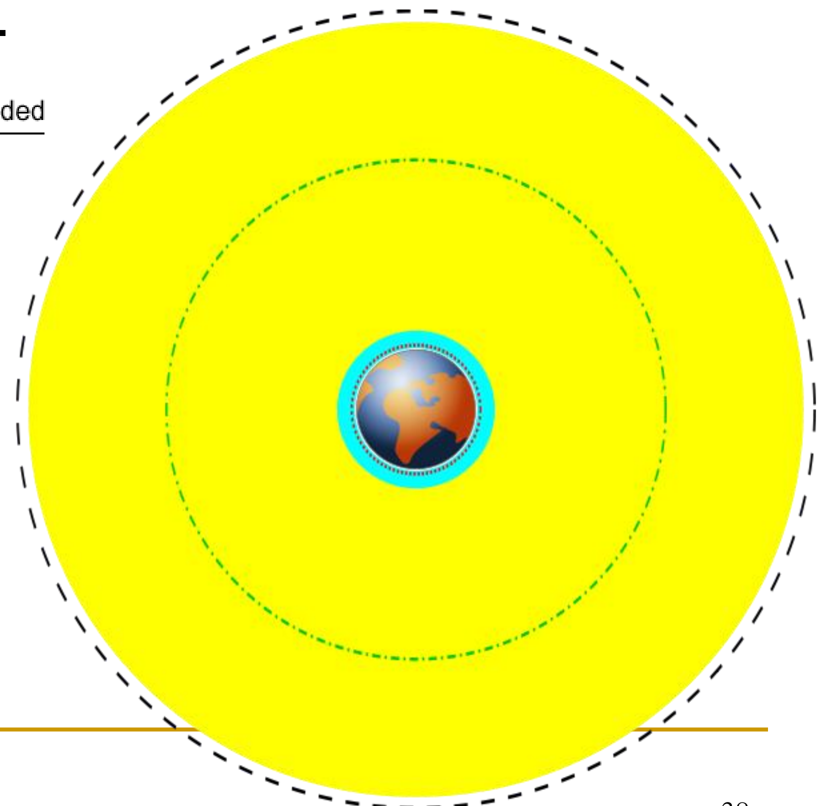
FSO: Indoor Applications

- Visible Light Communication (VLC)

Satellite Communication

- Satellites can be used as a wireless node in the sky that can receive, amplify, process and transmit communication signals
- They are mainly used in three orbit ranges and therefore have different rotation period around earth.





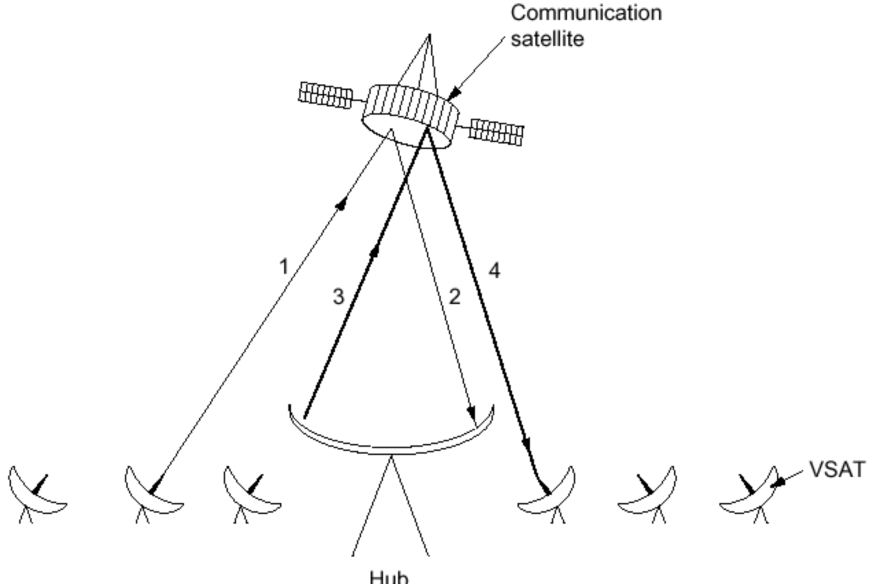
Satellite Communication

- Satellites generally have multiple transponders each with a given bandwidth/capacity for data transport
- They usually use "spot-beams" to focus their transmission on a given region.
- Most communication satellites are at Geostationary orbit
- Satellite operational frequency ranges:

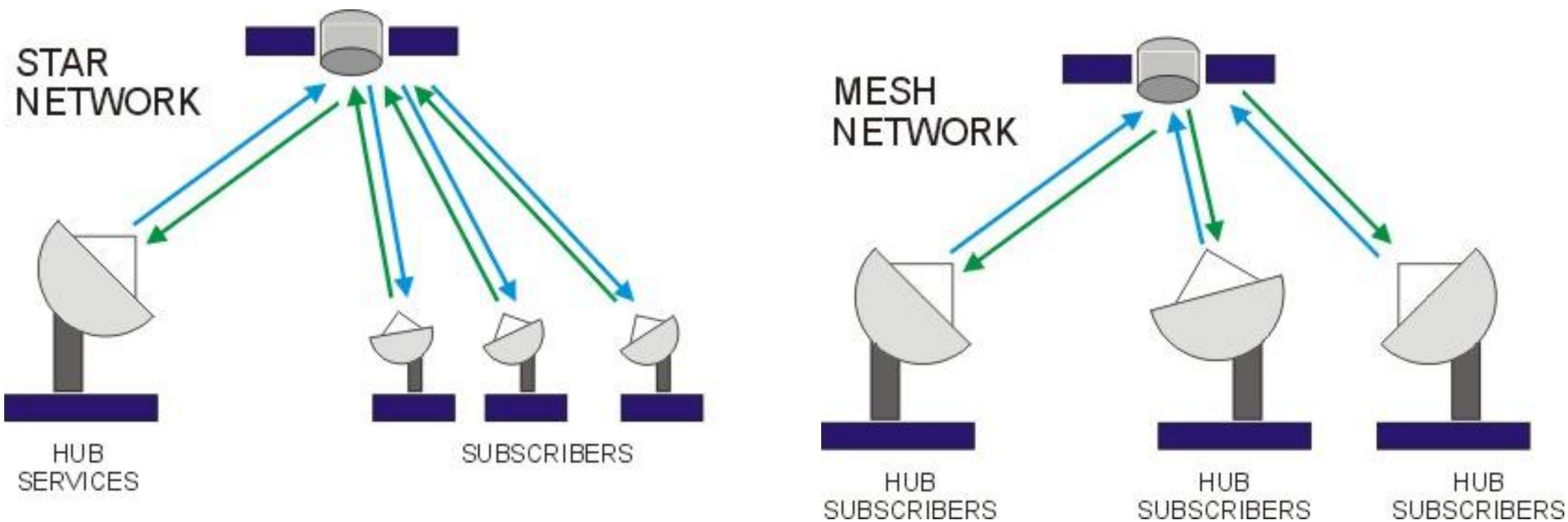
Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

Satellite Communication - VSAT

- Very Small Aperture Terminals (VSAT)
  - Small terminals that communicate to each other through a Geostationary satellite and a HUB.
  - VSAT can be used to provide voice and data connectivity to remote locations with no land-based telecommunication infrastructure
  - Data rate of links ranges from 4 kb/s to 100 Mb/s

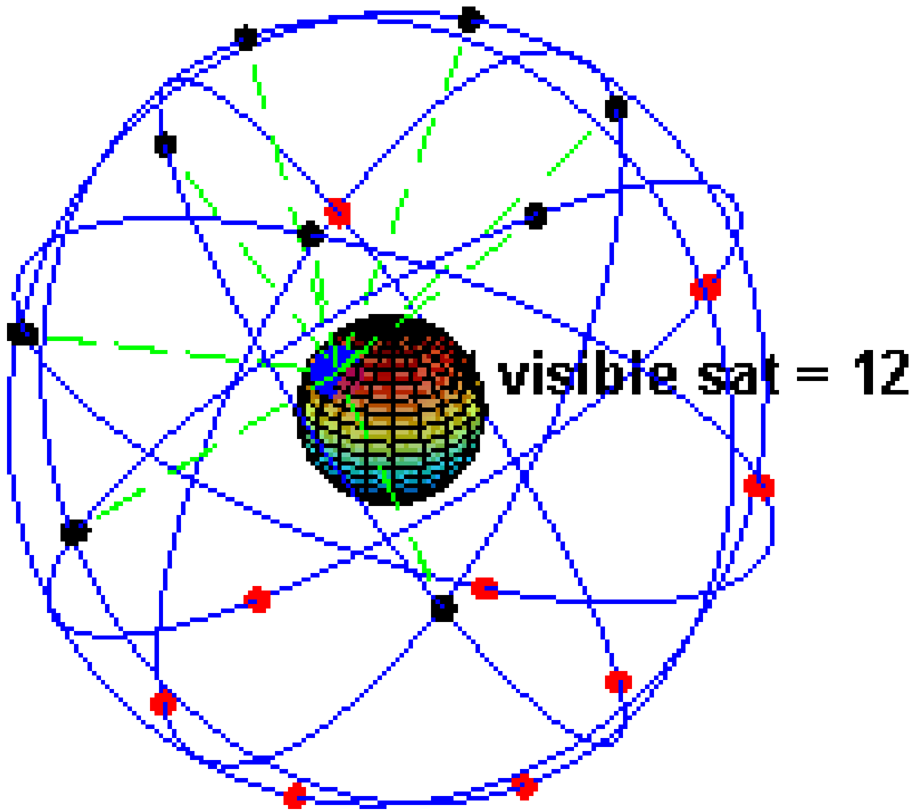


Satellite Communication - VSAT



Medium Earth Orbit Satellites (MEO)

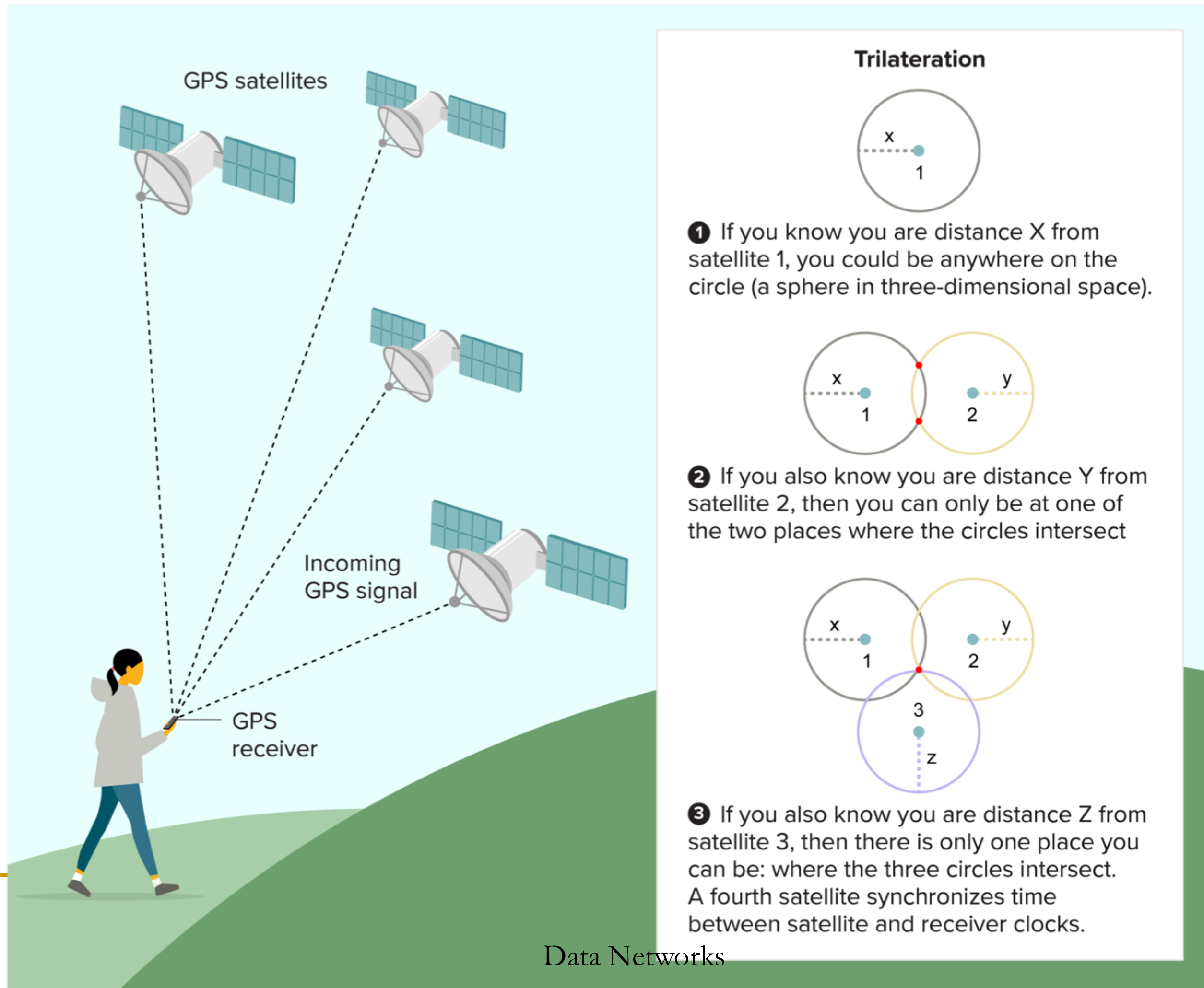
- Rotate at 6 hours or less around earth
- Global Positioning using 31 Satellites at about 20,000 km



How GPS works

How GPS works

A GPS receiver, like the one in your smartphone, pinpoints its location on Earth's surface by analyzing its distance to three GPS satellites; a fourth satellite synchronizes clocks in the receiver and satellites.

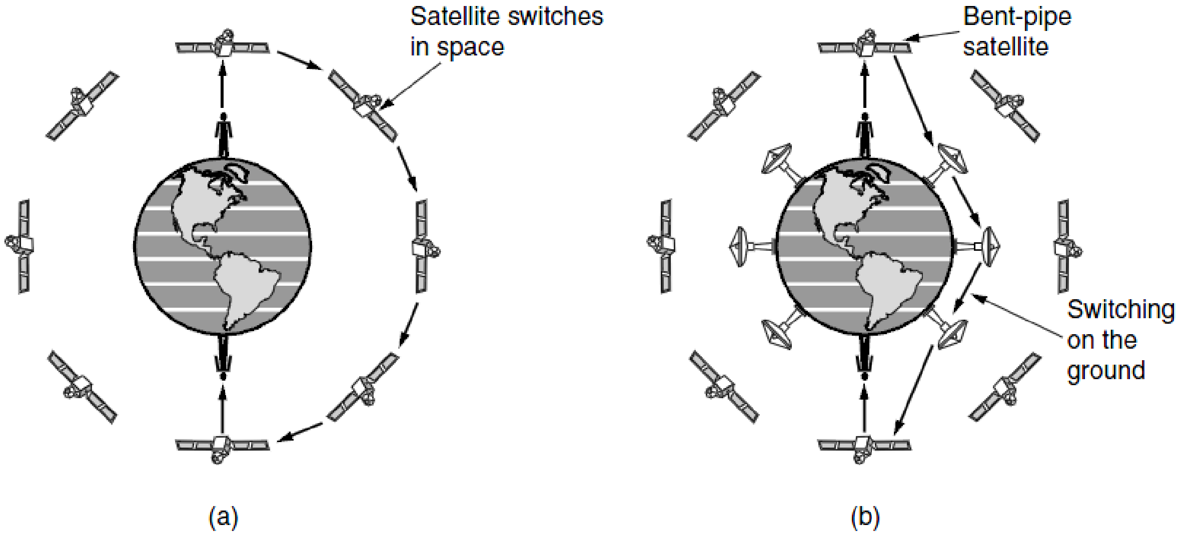


Low Earth Orbit Satellites (LEO)

- Satellites orbiting earth below 2000 km with a rotation time of 128 minutes or less
- Many satellites are needed to cover the earth for providing communication services (Mobile phone, Internet access)
- Starlink, Telesat, and Oneweb/Airtel are some of the companies that have satellite systems to provide global voice and data services.

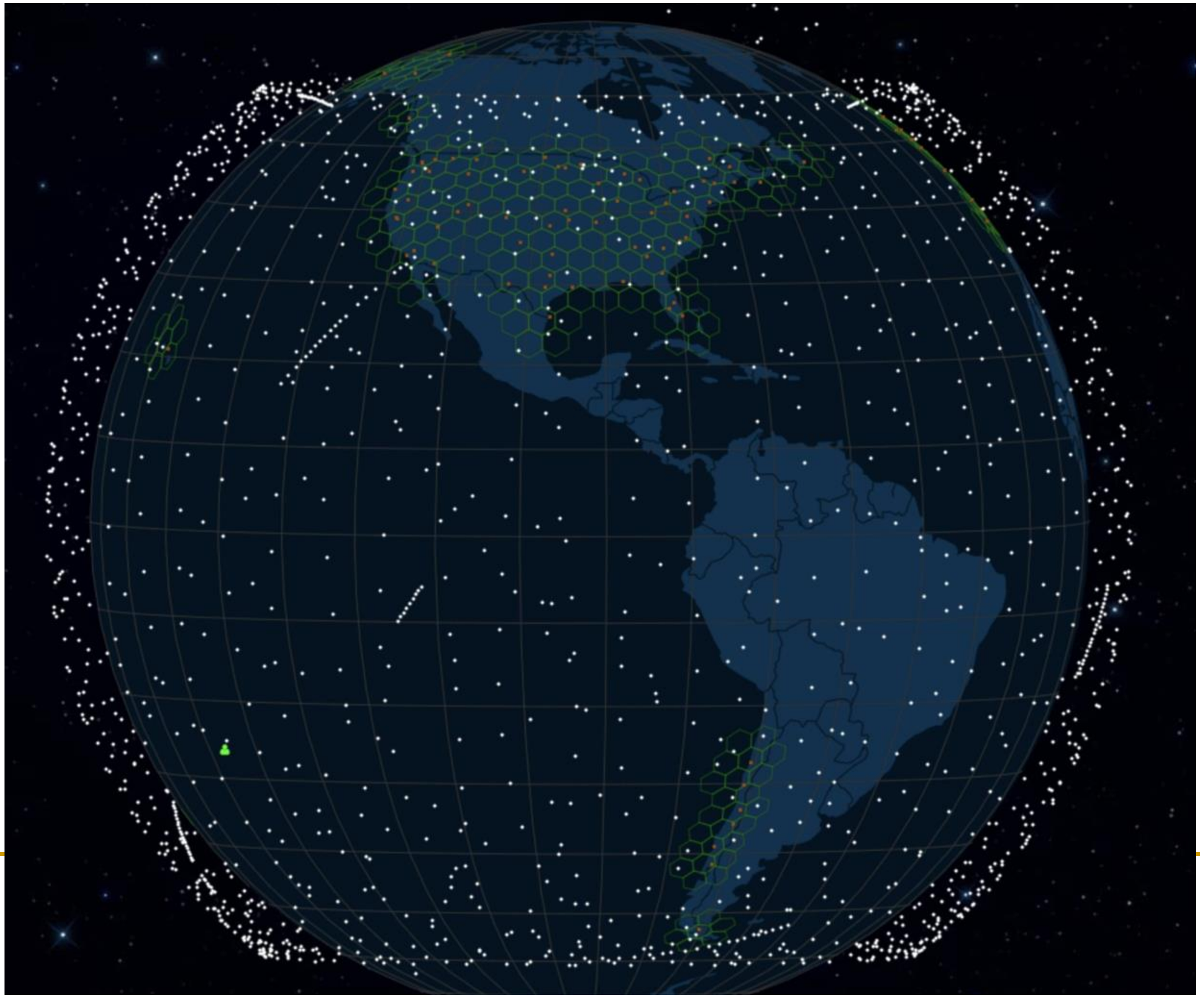
Satellite Communication

- In some LEO satellite systems such as Iridium, satellites are relaying and switching the data from source to destination
- In some other satellite systems such as Globalstar, satellites relay the signal to their ground station and switching is done by a terrestrial network. The advantage is that much of the complexity is on the ground and satellites are simpler.



LEO Satellites

- Starlink currently has more than 3500 satellites



Satellites Versus Fiber

- Optical communication is the dominant technology for transmission of voice and data.
- From office LANs to intercontinental communication networks, optical communication systems are used as a cost effective solution.
- Satellite communication serves some key demands
  - Networks that require rapid deployment (disaster recovery, military applications)
  - Communication in places where terrestrial networks are not well developed (jungles, countries with many islands, oil stations in the sea)
  - Broadcasting (TV, Radio)

Baseband Transmission

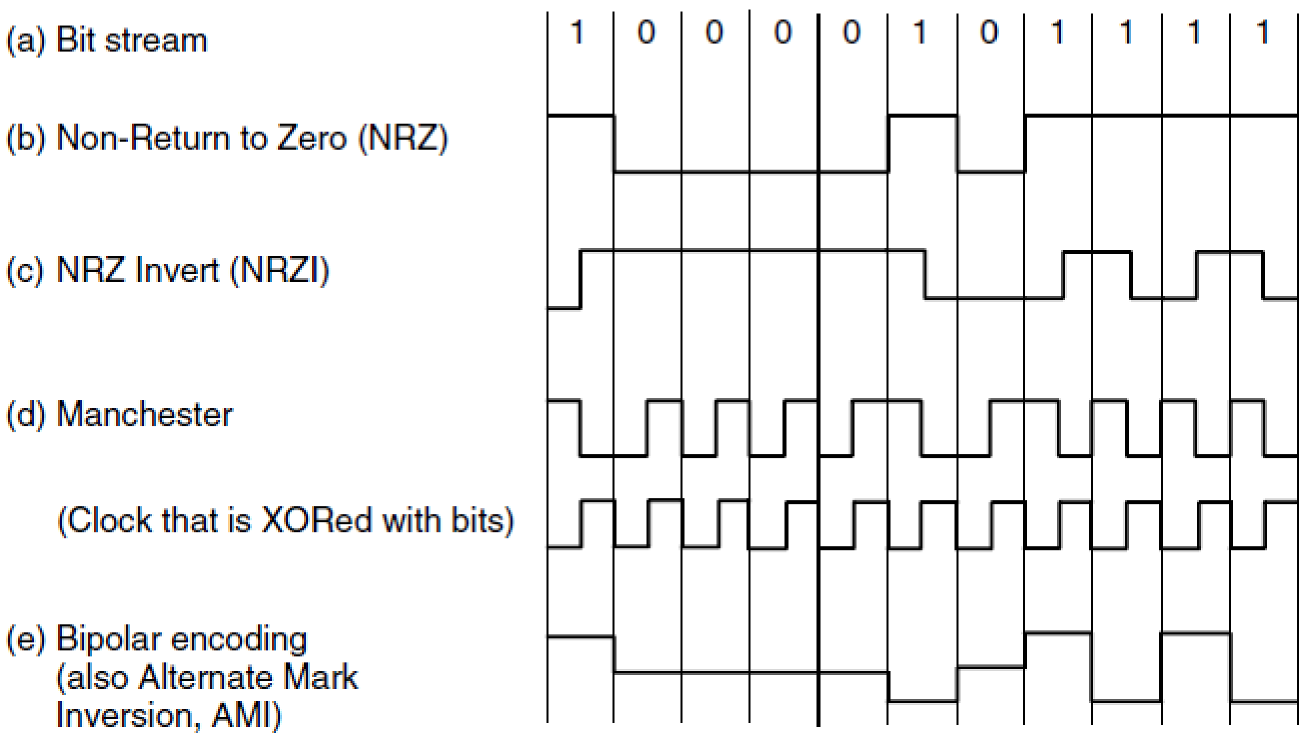


Figure 2-20. Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

Passband Transmission

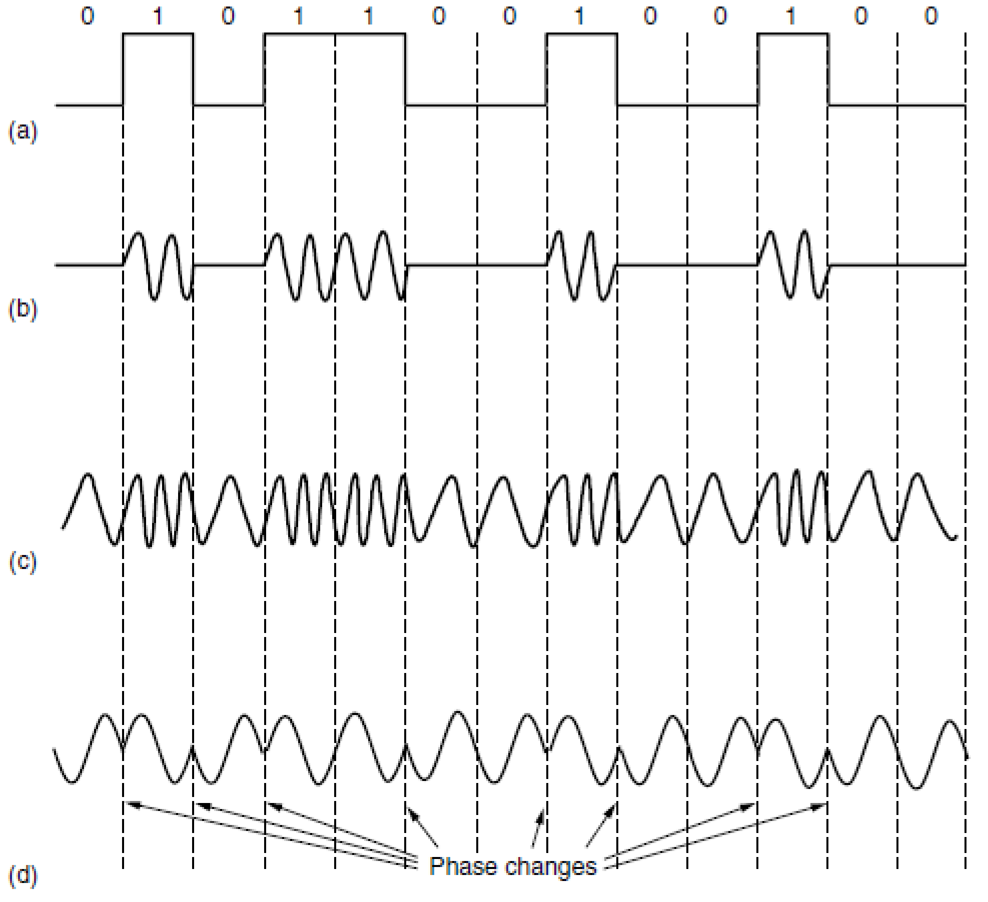
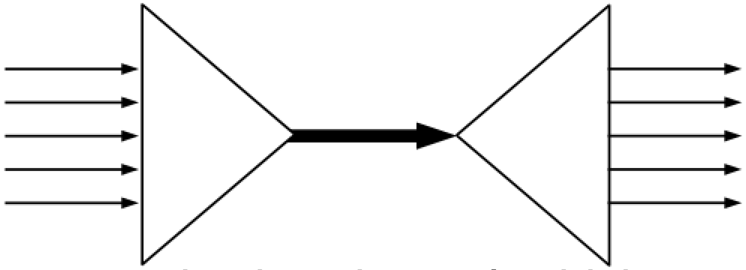


Figure 2-22. (a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Multiplexing

- In telecommunications and computer networks, multiplexing (sometimes contracted to muxing) is a method by which multiple analog message signals or digital data streams are combined into one signal over a shared medium.
- The aim is to share an expensive resource.
- Multiplexing originated in telegraphy in the 1870s, and is now widely applied in communications..



- The multiplexed signal is transmitted over a communication channel, which may be a physical transmission medium.
- The multiplexing divides the capacity of the high-level communication channel into several low-level logical channels, one for each message signal or data stream to be transferred.
- A reverse process, known as demultiplexing, can extract the original channels on the receiver side.
- A device that performs the multiplexing is called a multiplexer (MUX), and a device that performs the reverse process is called a demultiplexer (DEMUX).

Frequency Division Multiplexing

- Information from multiple sources can be multiplexed in frequency domain by assigning different carriers to different sources.
- Usually there is a guard band between different frequency bands
- Orthogonal Frequency Division Multiplexing (OFDM) allows us to use different frequency bands for transmission of data in a more efficient way
- OFDM is used in wireless networks, cable networks and twisted pair networks.

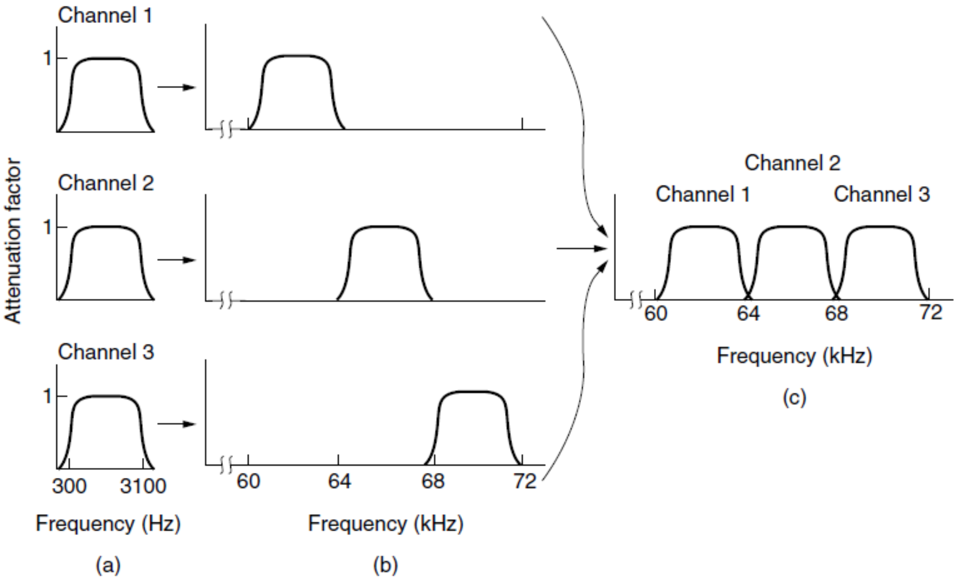


Figure 2-25. Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

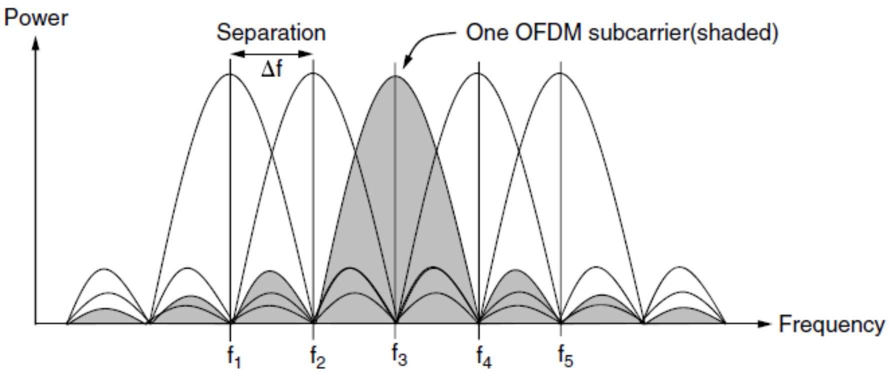
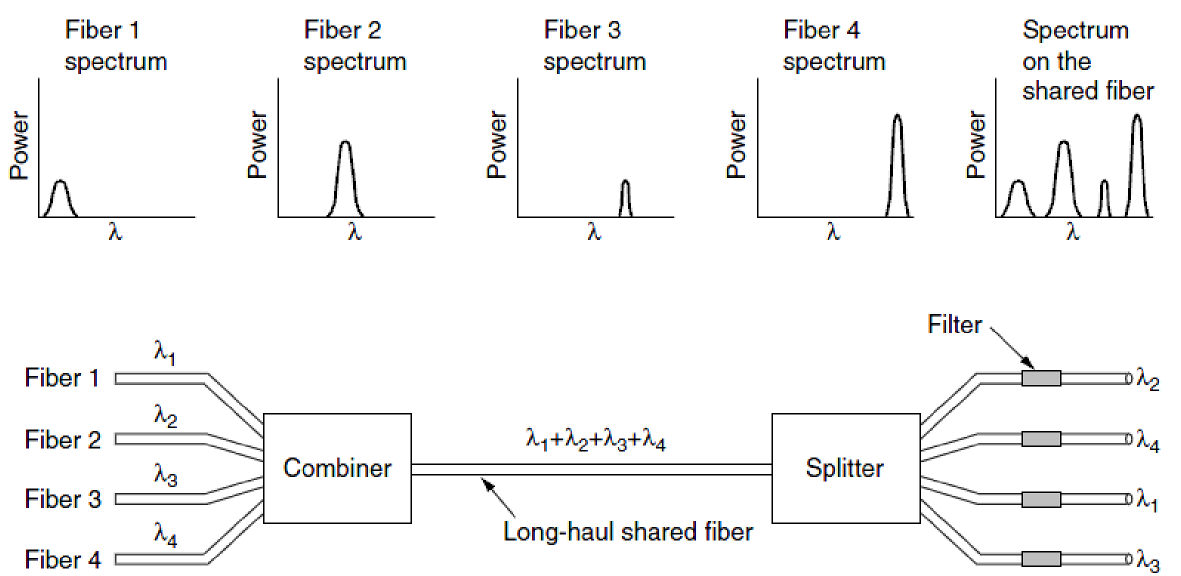


Figure 2-26. Orthogonal frequency division multiplexing (OFDM).

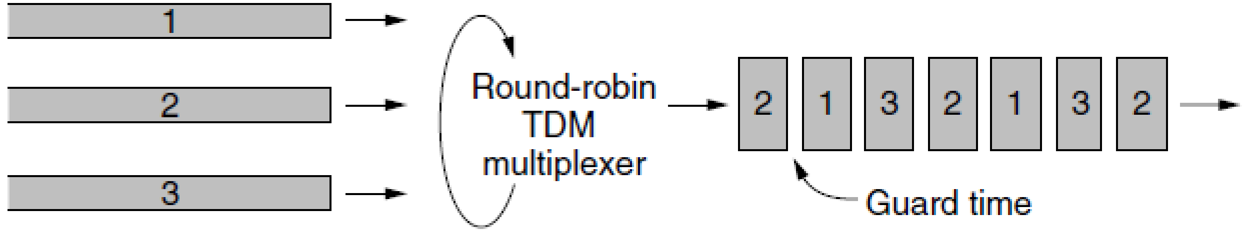
Wavelength Division Multiplexing

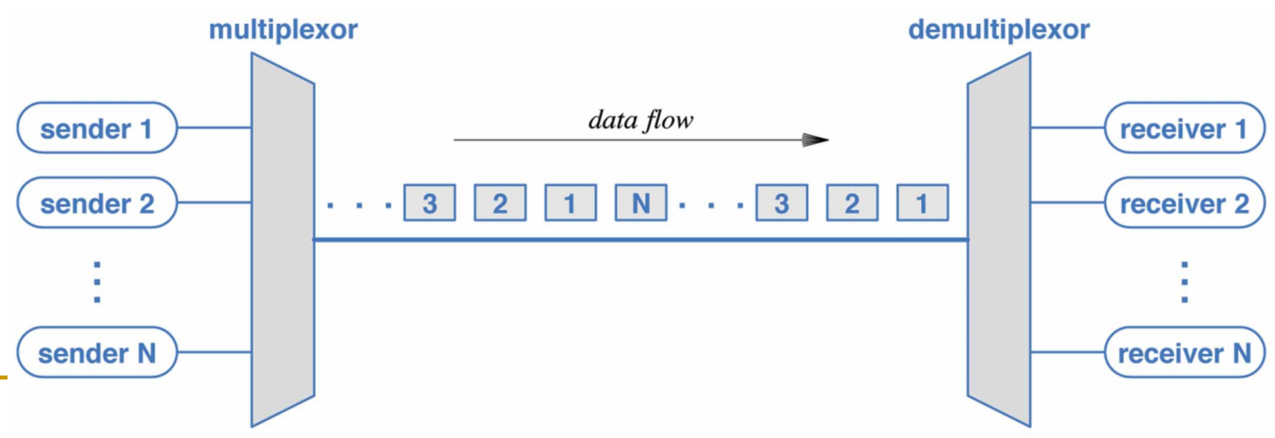
- Several independent streams of data each carried in a different wavelength can be multiplexed in optical domain and transmitted over a single fiber.
- This technology has drastically increased the capacity and lowered to cost of transmission networks



Time Division Multiplexing

- Different sources of data can be transmitted by dividing time into different slots and using each slot for a stream of data
- TDM is widely used in optical networks and wireless networks.

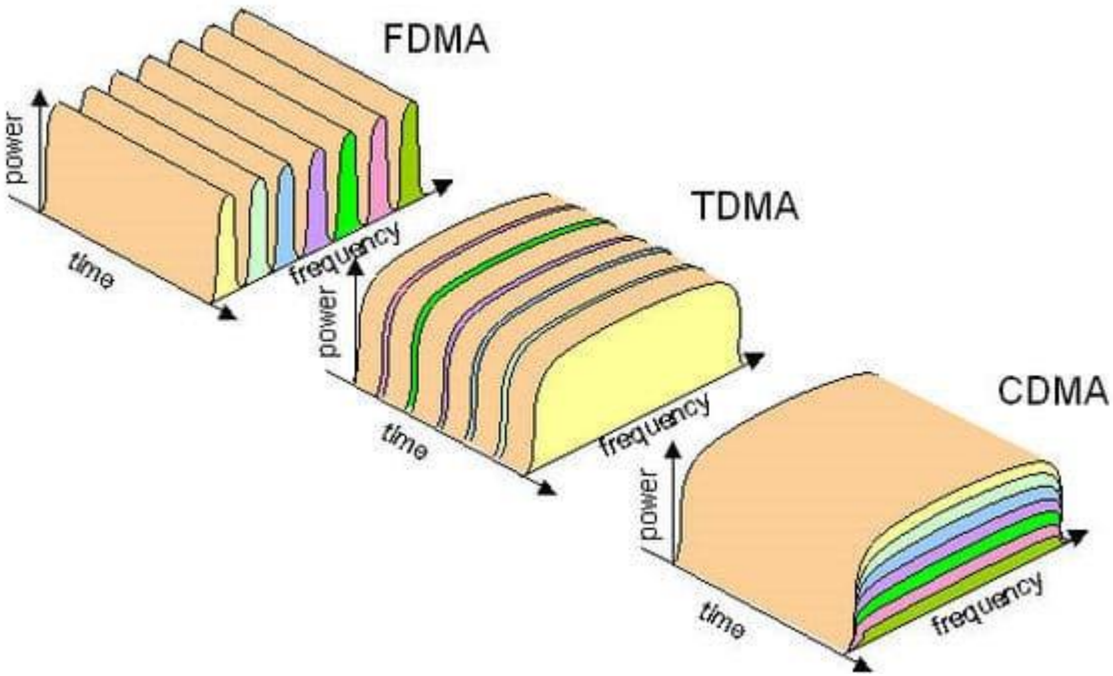




Code Division Multiplexing

- A techniques which allows for a new multiple access mechanism and is proving to be very effective for mobile communication. (Used in 2G and 3G mobile systems)
- Time division: TDM
  - each speaker gets its turn
- Frequency division: FDM
  - concurrent speakers separated far enough
- Code Division Multiplexing (CDM)
  - every speaker speaks a different language ***at the same time***
- Key idea:
  - Each station uses the entire frequency band but uses a different code.

Principles of CDMA



https://networkencyclopedia.com/code-division-multiple-access-cdma/

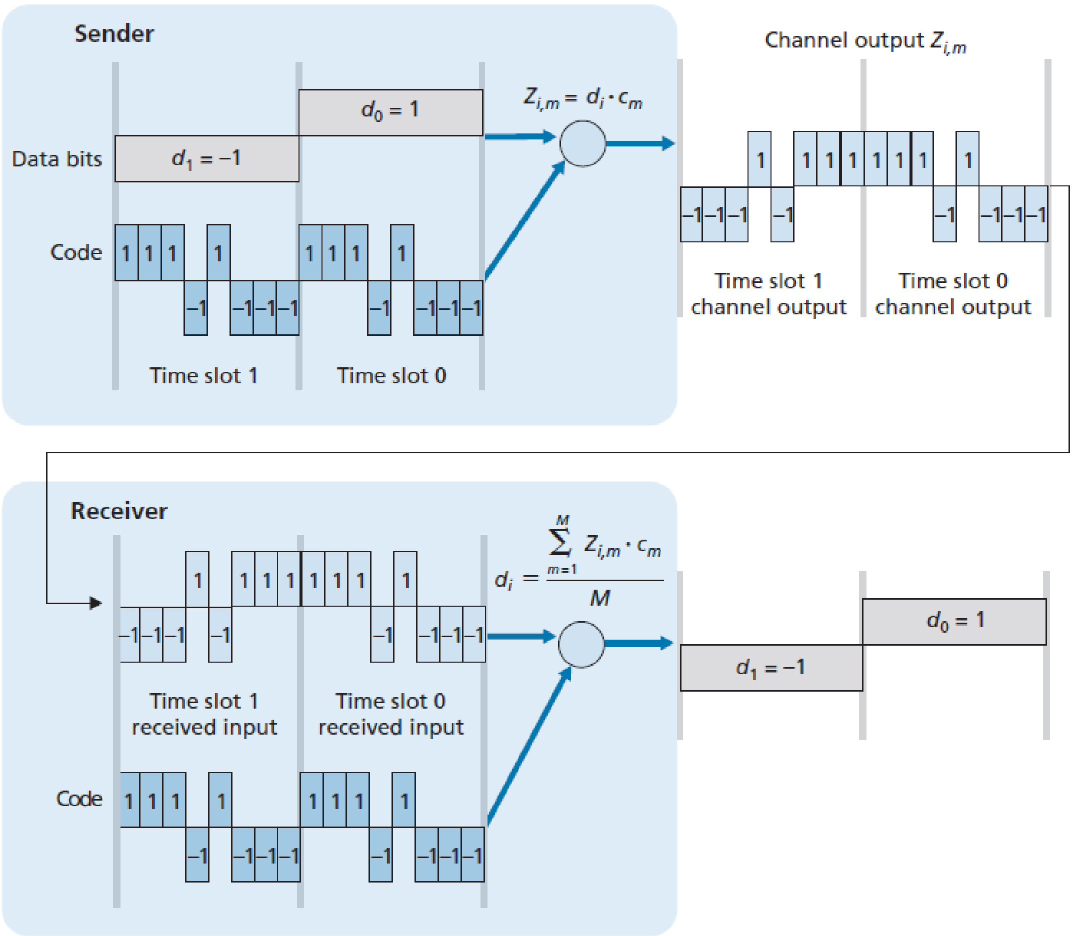
Code Division Multiplexing

- Each bit time interval is divided into m slots called chips
- Each transmitter uses a unique chip sequence to send 1 and its inverse to send 0.
  - Send 1 as: 1 1 -1 -1 1 -1 1 -1
  - Send 0 as: -1 -1 1 1 -1 1 -1 1
- Chips are chosen to have these properties:

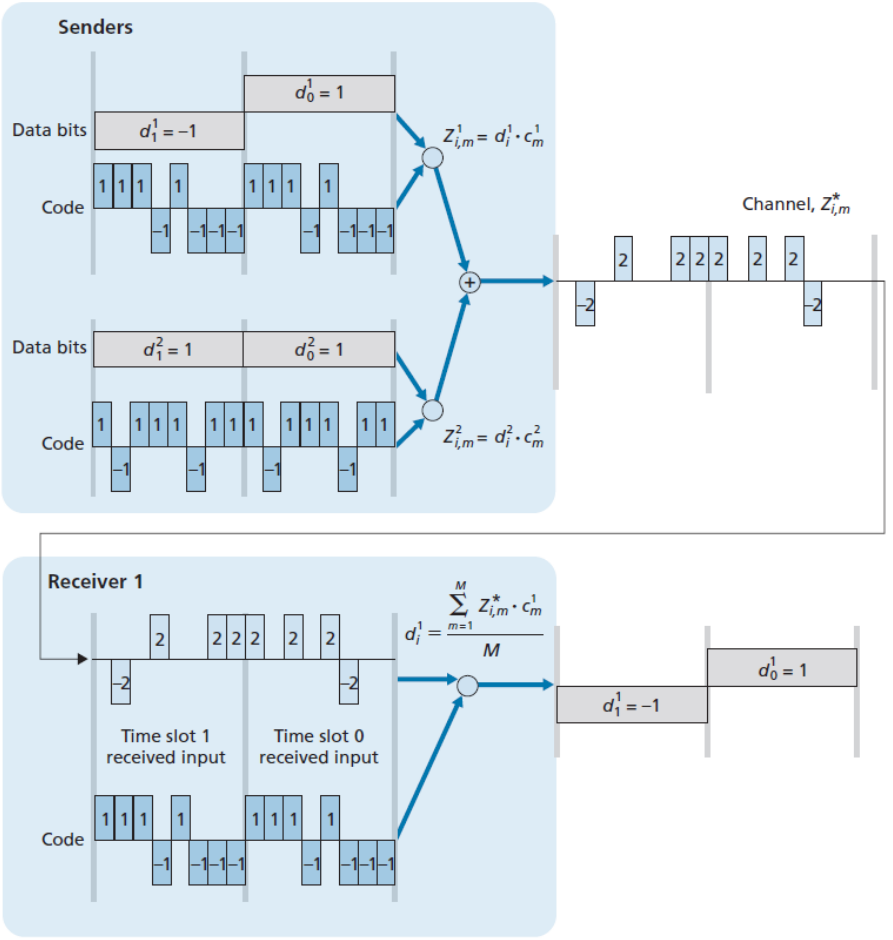
$$S \bullet T = \frac{1}{m} \sum_{i=1}^{m} s_i t_i = 0$$

$$S \bullet S = \frac{1}{m} \sum_{i=1}^{m} s_i^2 = 1$$

CDMA Example



CDMA Example



CDMA Example

- Example:

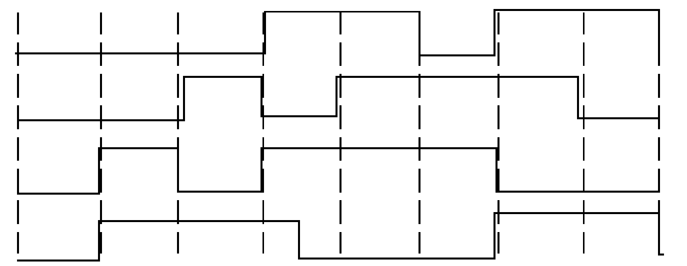
$A = (-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$

$B = (-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$

$C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$D = (-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$

(a)



(b)

$S_1 = C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$S_2 = B+C = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)$

$S_3 = A+\overline{B} = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)$

$S_4 = A+\overline{B}+C = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)$

$S_5 = A+B+C+D = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)$

$S_6 = A+B+\overline{C}+D = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)$

(c)

$S_1 \bullet C = [1+1-1+1+1+1-1-1]/8 = 1$

$S_2 \bullet C = [2+0+0+0+2+2+0+2]/8 = 1$

$S_3 \bullet C = [0+0+2+2+0-2+0-2]/8 = 0$

$S_4 \bullet C = [1+1+3+3+1-1+1-1]/8 = 1$

$S_5 \bullet C = [4+0+2+0+2+0-2+2]/8 = 1$

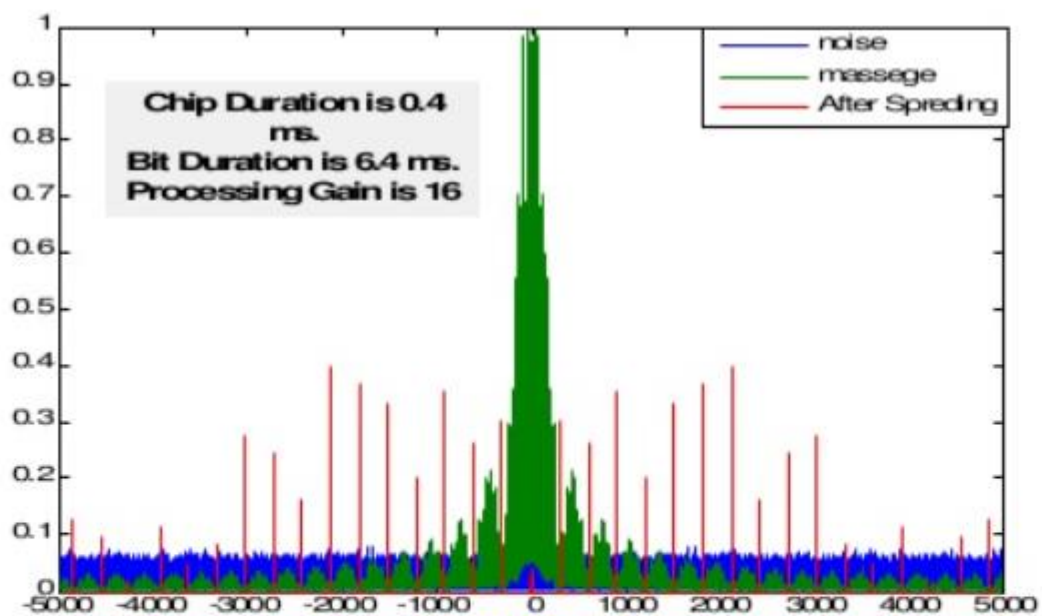
$S_6 \bullet C = [2-2+0-2+0-2-4+0]/8 = -1$

(d)

Code Division Multiplexing

- CDMA Spectrum

Spectrum of the CDMA:

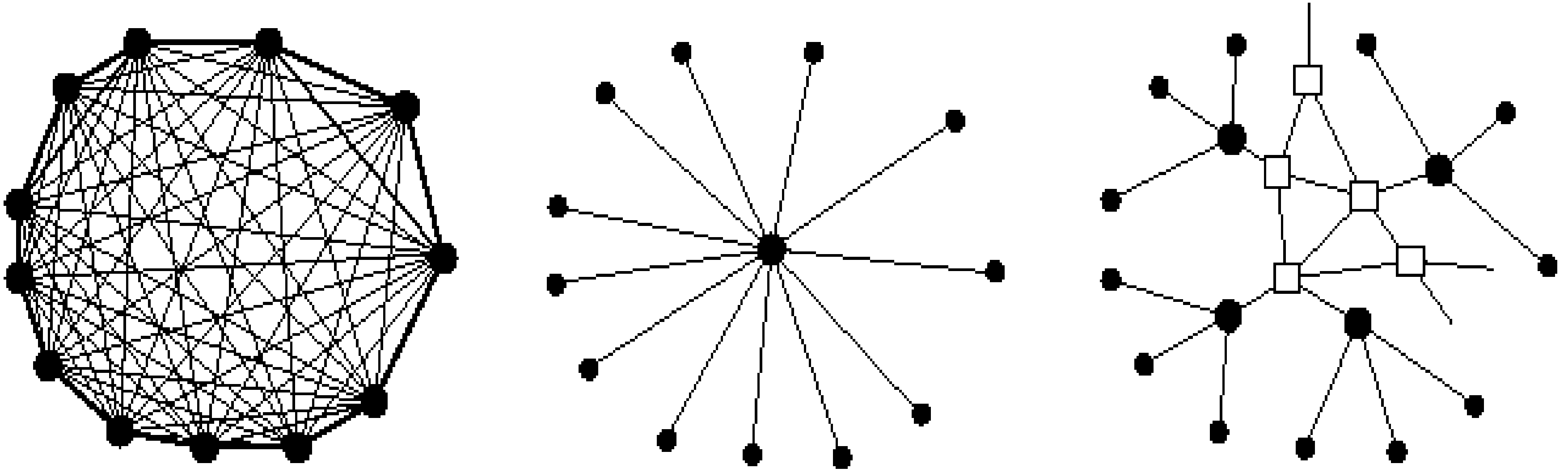


Code Division Multiplexing

- Practical issues:
  - Keys should be known in advance
  - Power Control:
    - Senders should be received with same power
    - Send with inverse power of received signal strength
  - Synchronization: what if senders are not synchronized:
    - Lock into the ‘wanted’ channel
    - Other channels will be received as background noise

Telephone system

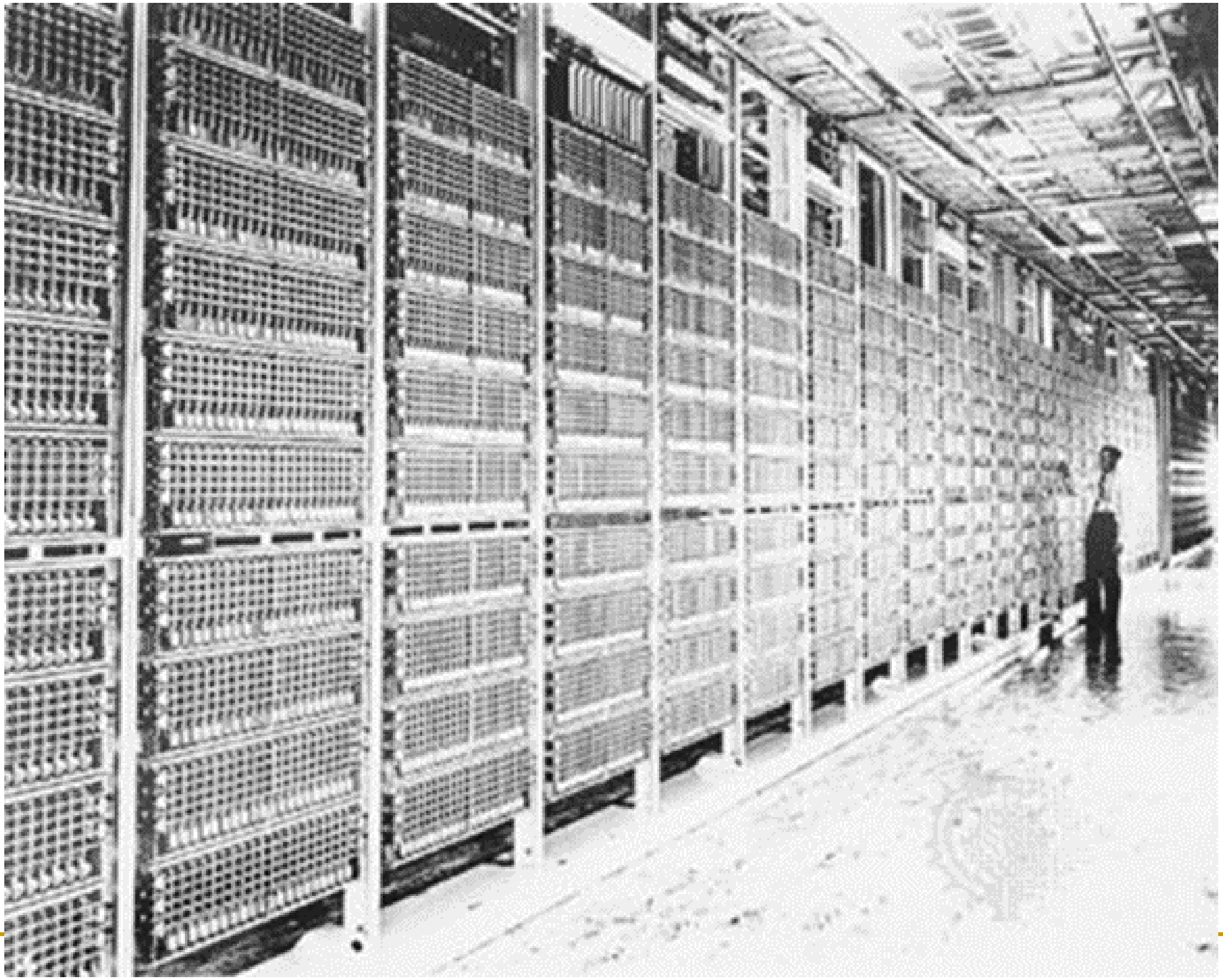
- Public Switched Telephone Network (PSTN)
  - A complex network that spans the globe and enables voice and data communication.



(a) (b) (c)

Old Telephone Switches

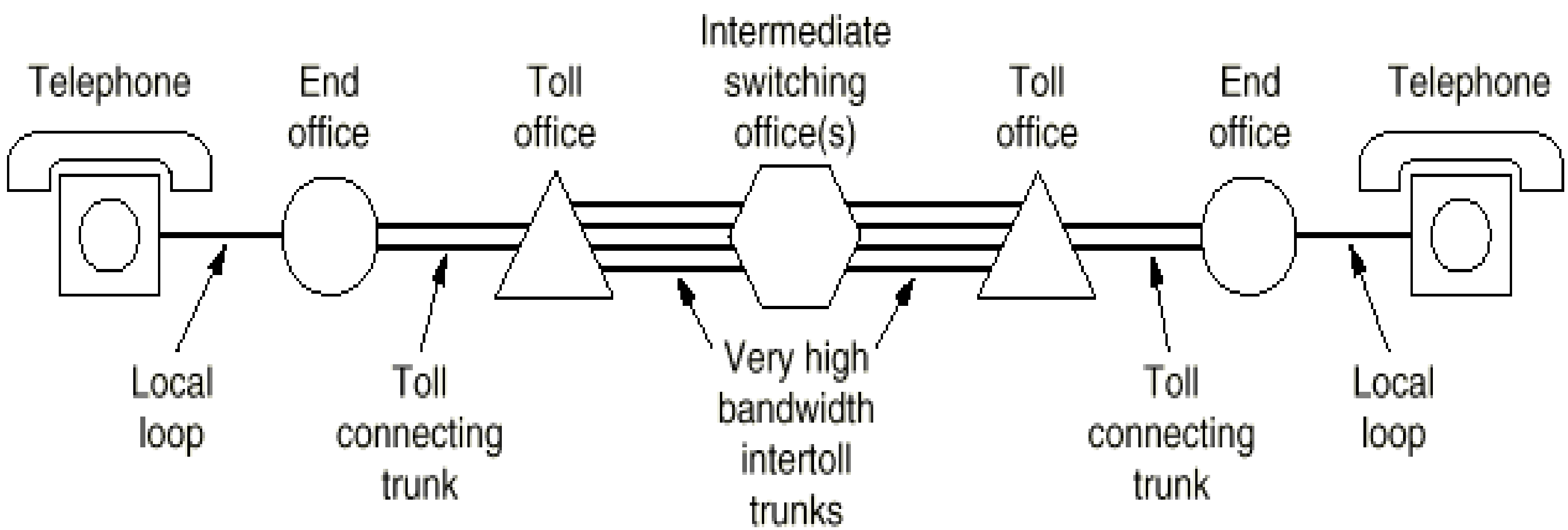
Elecrtromechanical Switching



Modern Switching Center

Telephone system

- Telephone system organization: hierarchical network with three important components:
  - Local loops:
  - Switching centers:
  - Trunks: connecting switching offices using various transmission technologies



Switch Hierarchy, an example

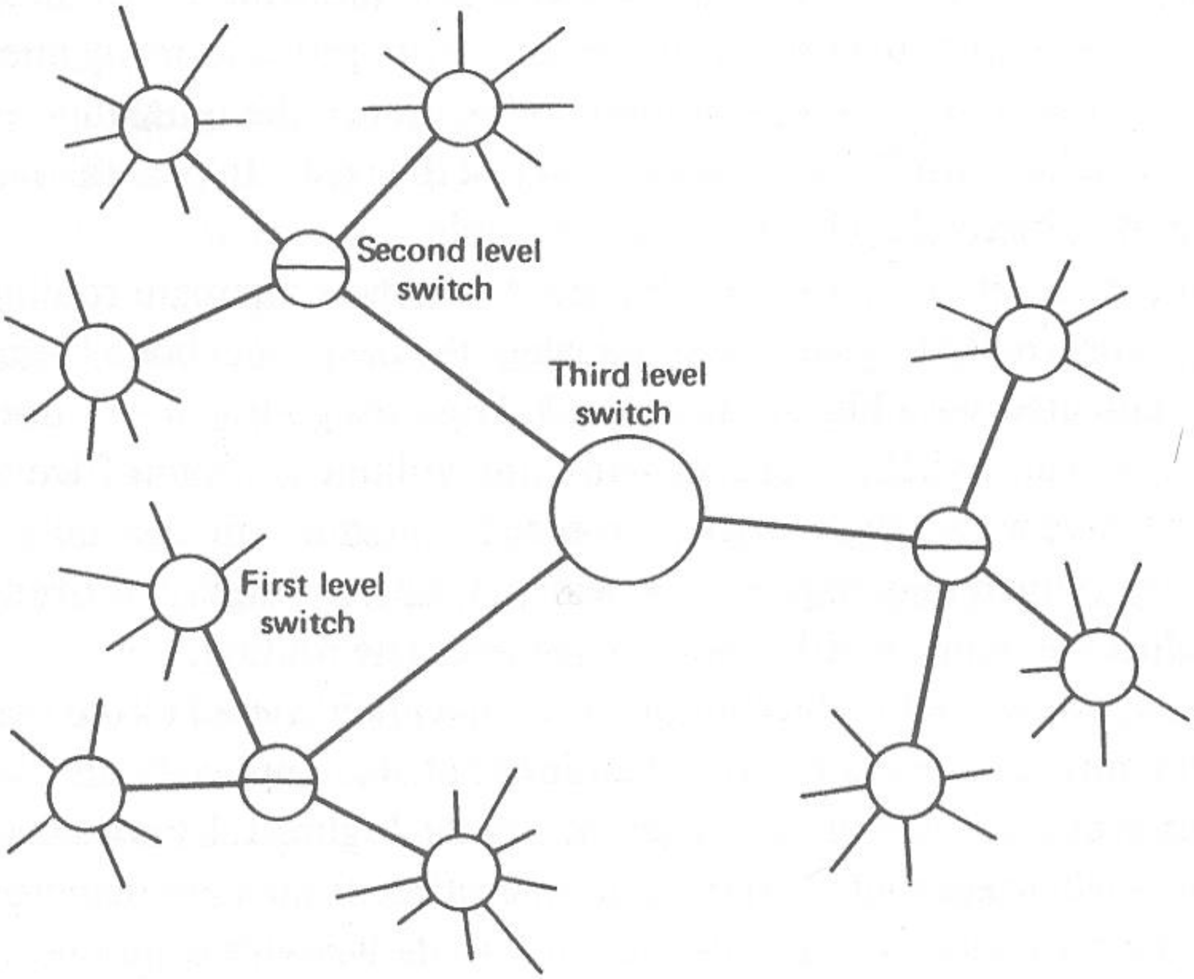
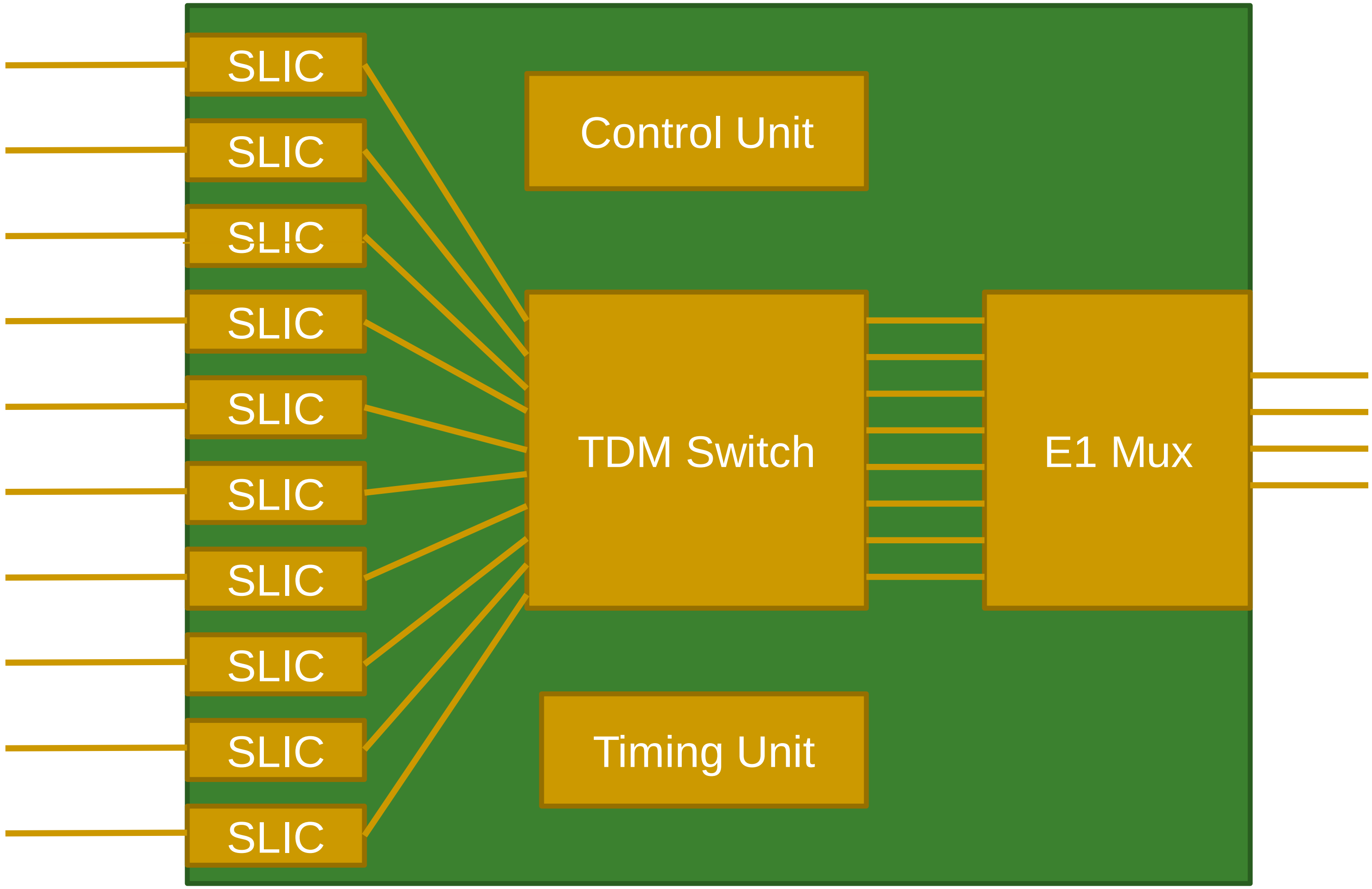


Figure 1.2 Three-level switching hierarchy.

Telephone Switch



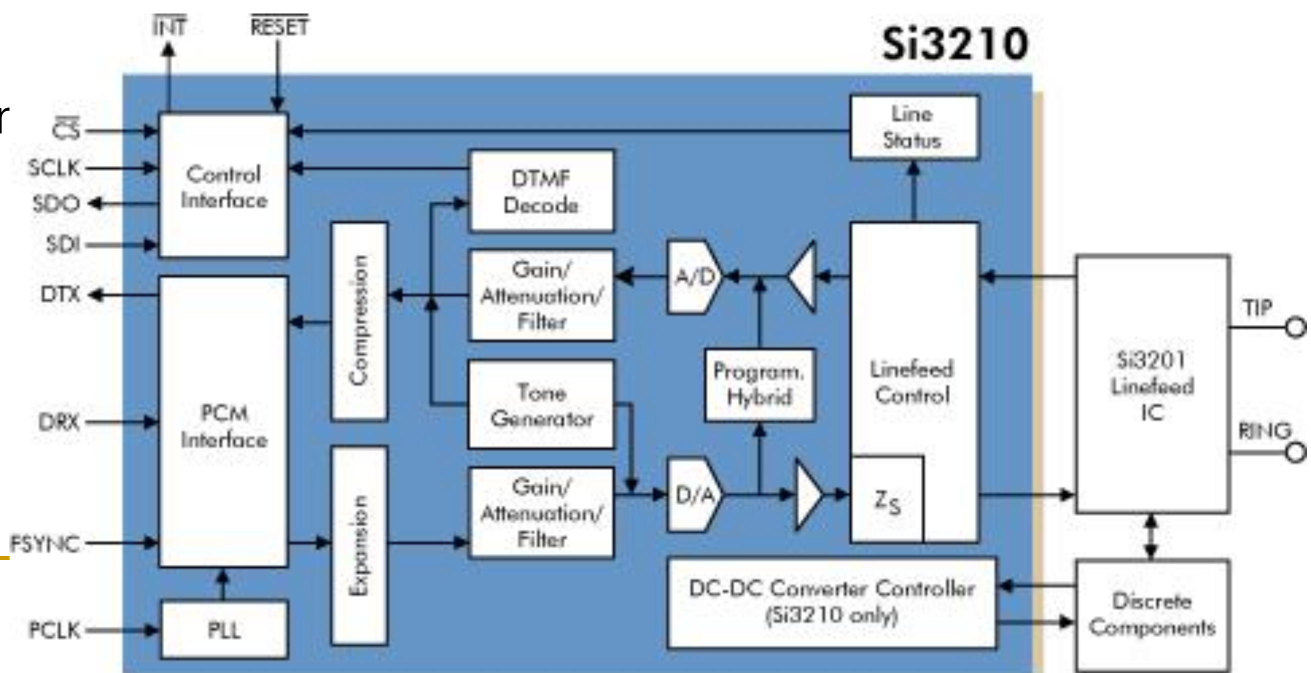
Dual-Tone Multi-Frequency Signaling

- DTMF is a telecommunication signaling system using the voice-frequency band over telephone lines between telephone equipment and other communications devices and switching centers.
- Pressing a key sends a combination of the row and column frequencies.
- Telephone switching centers detect the received tones to extract the pressed key.

	1209 Hz	1336 Hz	1477 Hz	1633 Hz
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	*	0	#	D

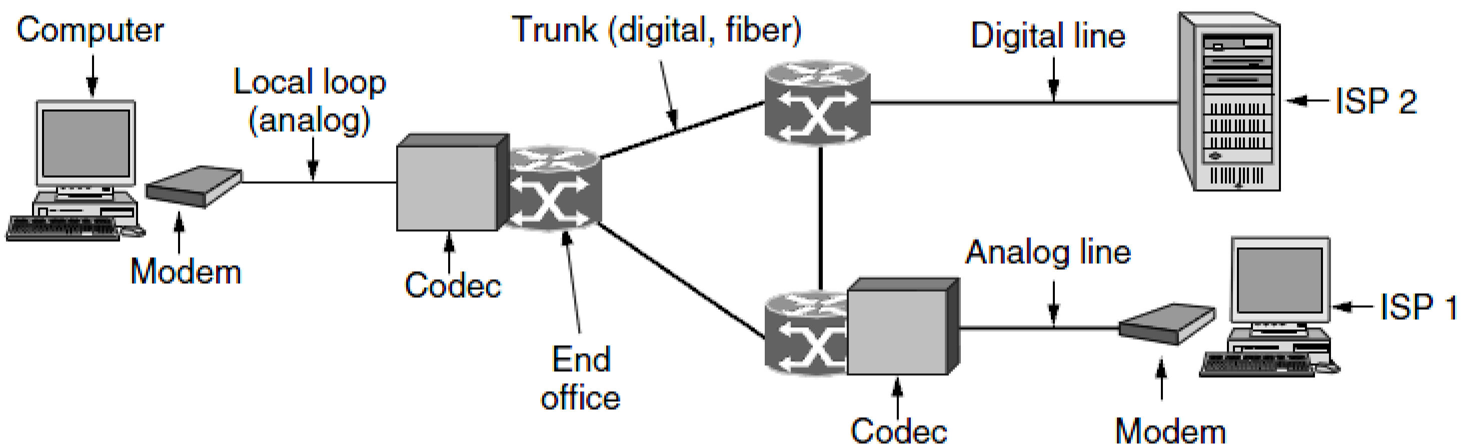
SLIC/CODEC

- Important User Side Functions
  - Battery supply to subscriber line
  - Overvoltage protection
  - Off/On hook detection
  - Ring Generation
  - Tone Detection
  - Tone Generation
  - Hybrid
  - Testing
- Important Network Side Function
  - PCM Coder/Decoder
  - Filtering and Amplification
  - Compression/Decompression



Telephone Modem

- Modem: A device that receives a stream of digital bits and sends/receives it properly from the transmission medium (such as twisted pair)
- Transmission problems:
  - Attenuation and Delays which are frequency dependent
  - Noise (Thermal Noise, Impulse Noise, etc)
  - Cross talk, caused by inductive coupling of wires
- For voice band modems, data rate is limited by PSTN sampling process and loop conditions

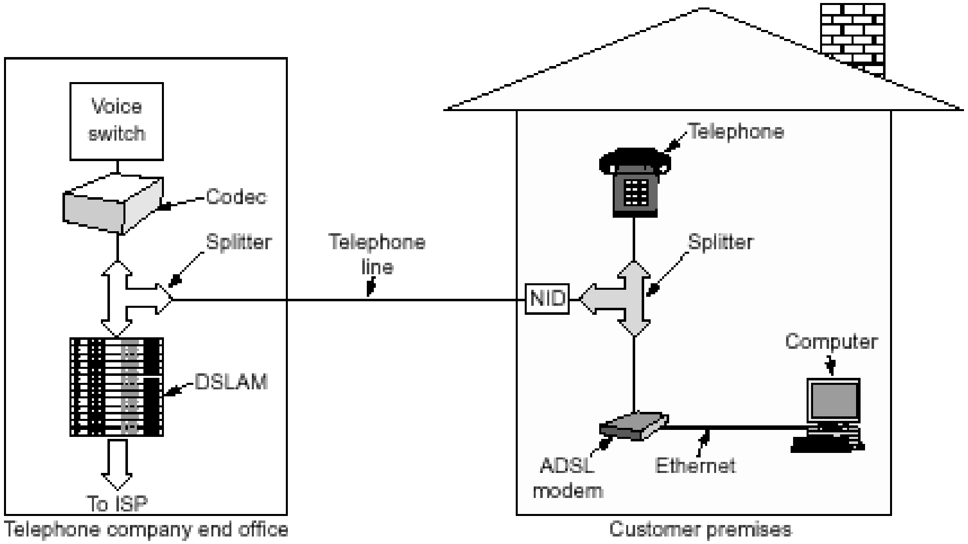


Voice band modem standards

- Important voice band modem standard:
  - V.32: 9600 bps : 4 bits / baud
  - V.32 bis: 14.4 kbps : 6 bits / baud
  - V.34: 28.8 kbps (Using QAM Constellation)
  - V.90: 56 kbps DS, 33.6 kbps US
  - V.92: 56 kbps DS, 48 kbps US
- Maximum modem data rate for connection over normal PSTN networks: 33.6kbps (limited by quantization noise)
- Rates achieved by V.90 and V.92 standards is achieved when connecting to ISPs with digital network connection
- Compression schemes:
  - MNPs : run-length encoding (runs of zero's may be very common)
  - V.42 bis : Ziv-Lempel compression

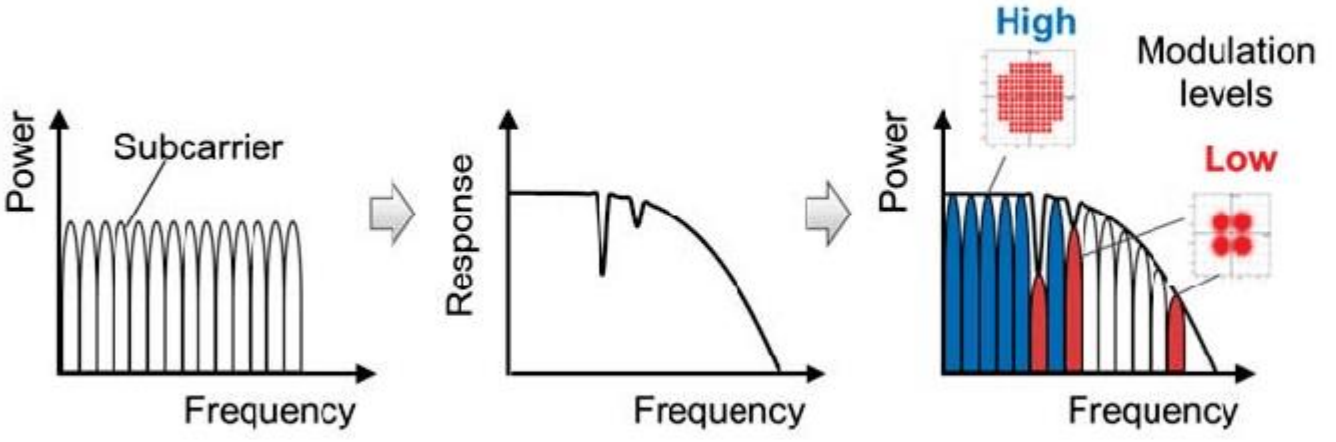
Asymmetric Digital Subscriber Line (ADSL)

- Objective: Offering data services without impacting the voice service on twisted pair
- Central Office (CO) side:
  - Use splitter to feed low pass part to the voice switch while the higher frequencies to the feed the DSLAM
- Customer Premise End (CPE)
  - Use splitter or in-line filters to feed the low pass part of the spectrum to the telephone and the high pass part to the CPE ADSL modem
- ADSL signal power spectrum is defined carefully to reduce cross talk into other services



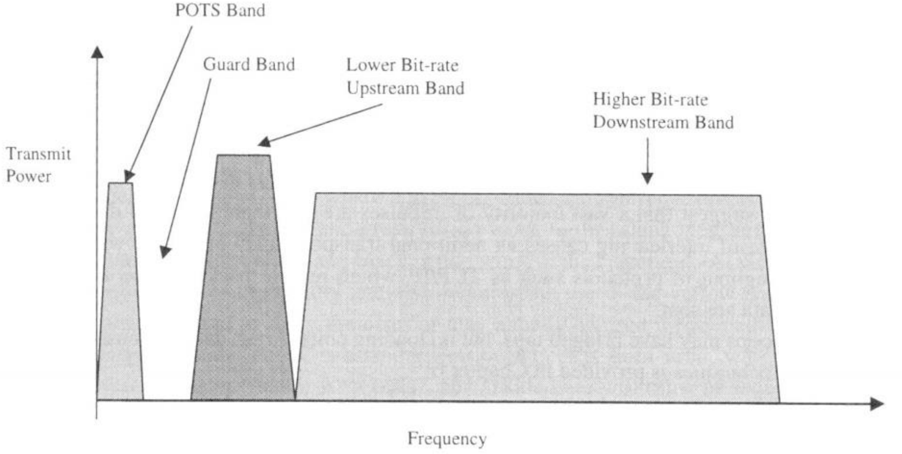
ADSL

- Uses Discrete Multi tone technique (DMT) as the modulation scheme.
- Idea: Divide frequency into small bins each carrying a separate QAM constellation
  - Better use of channel capacity
  - More resistance to noise
  - Rate adaptability



ADSL Spectrum

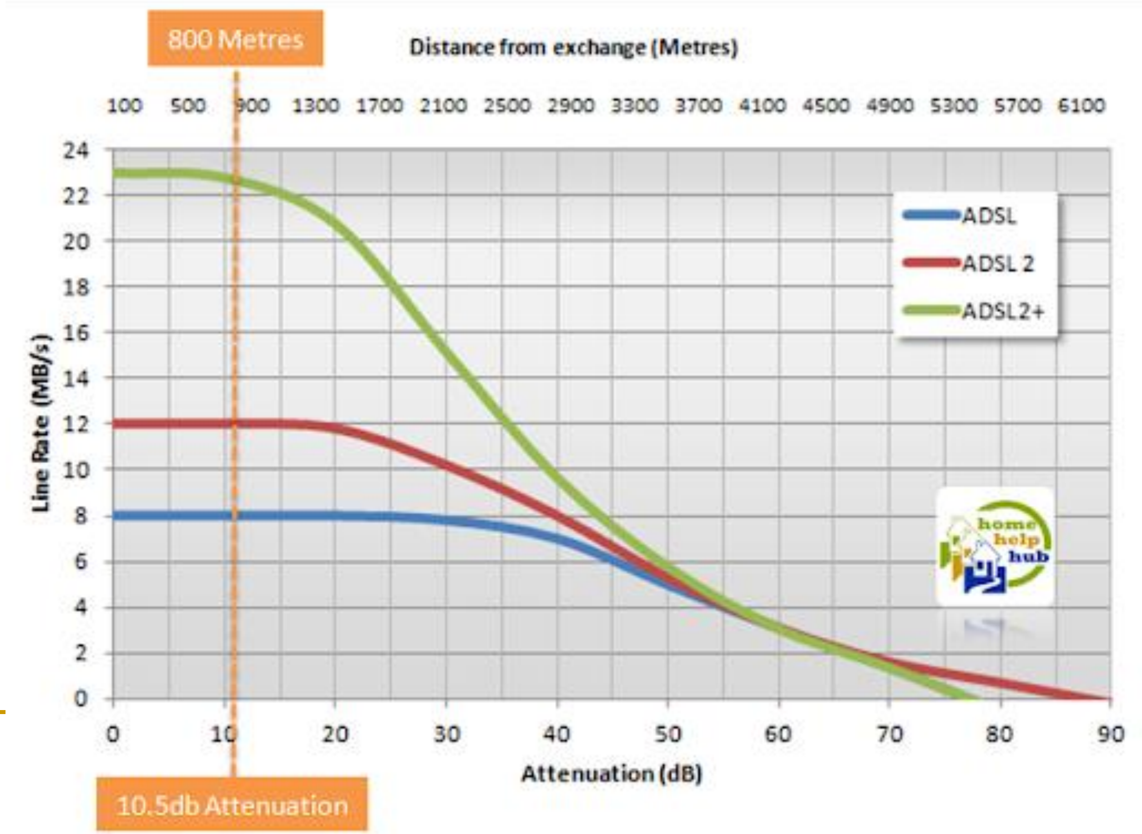
- ADSL Spectrum is designed to:
  - Allow higher download rate and lower upload rate at home
  - Co-exist with telephone service
- Most common mode of operation: Frequency Division Mode
  - Upstream (US) 25kHz to 130 kHz providing up to 3.5 Mbps
  - Downstream (DS) 140 kHz to 2.2 MHz providing up to 24 Mbps



FDM ADSL.

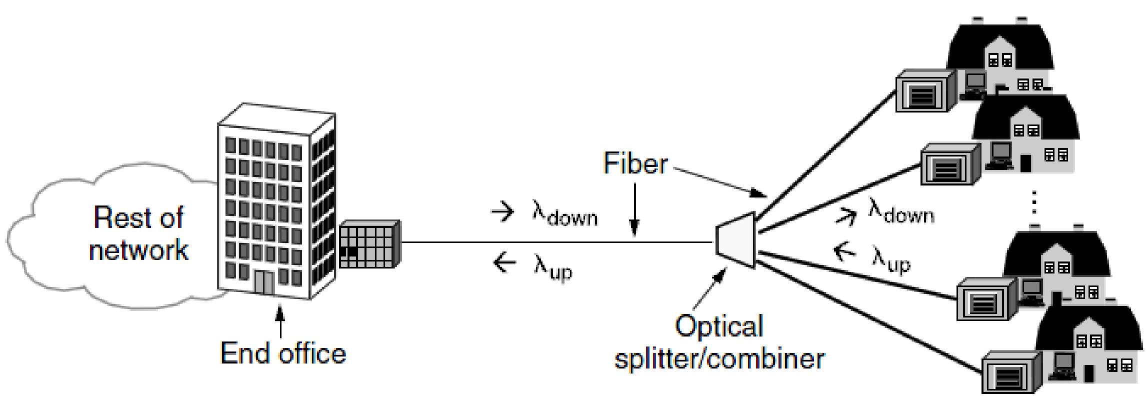
ADSL Rate

- ADSL downlink and uplink rate decrease with the distance between home and local exchange

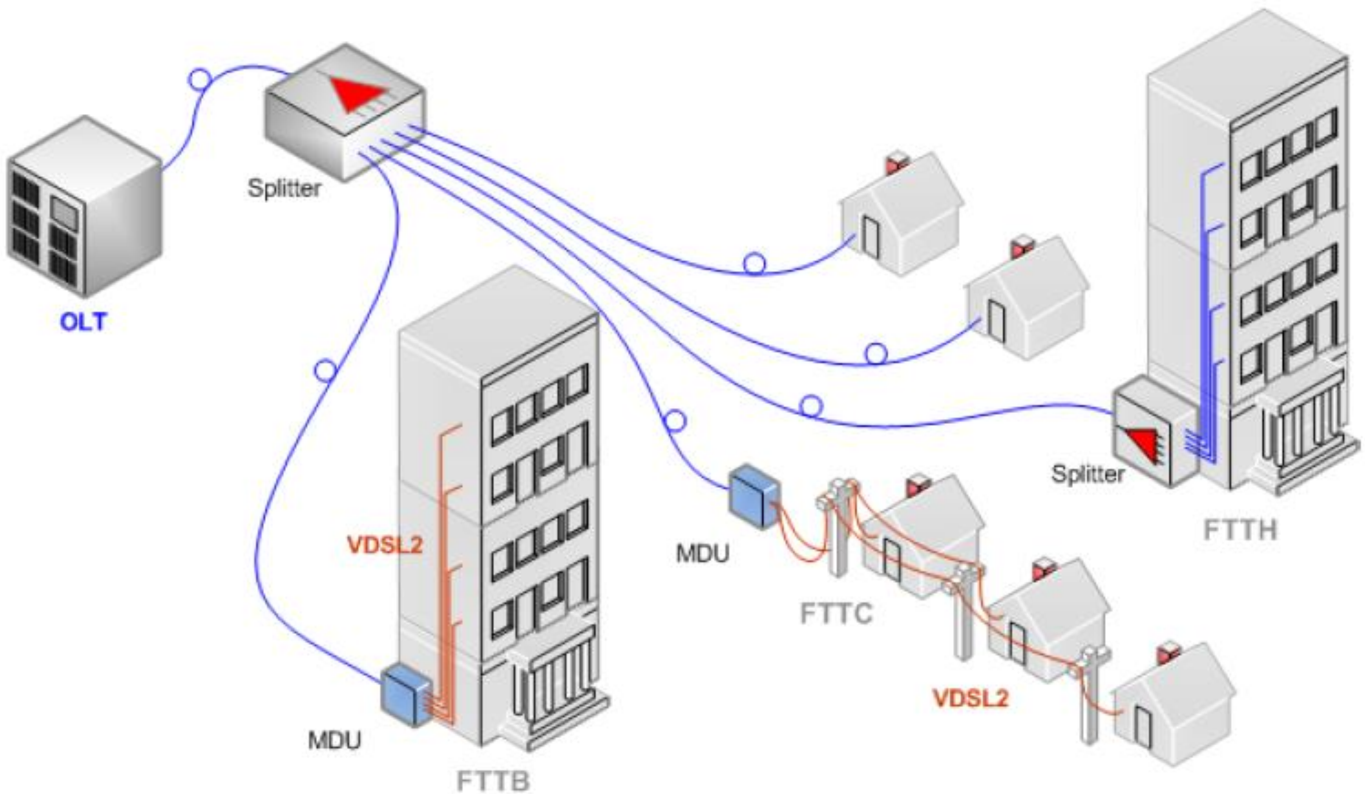


Fiber To The Home (FTTH)

- Fiber optic can provide a medium for providing very high speed data services.
- Bringing fiber deployment closer to the homes and businesses facilitates the deployment of higher speed data services for end
- Passive Optical Networks (PON) are becoming very popular and can run at around gigabits per second to provide different services such as
  - Ethernet PONs (EPON)
  - Gigabit capable PONs (GPON)



FTTH Application

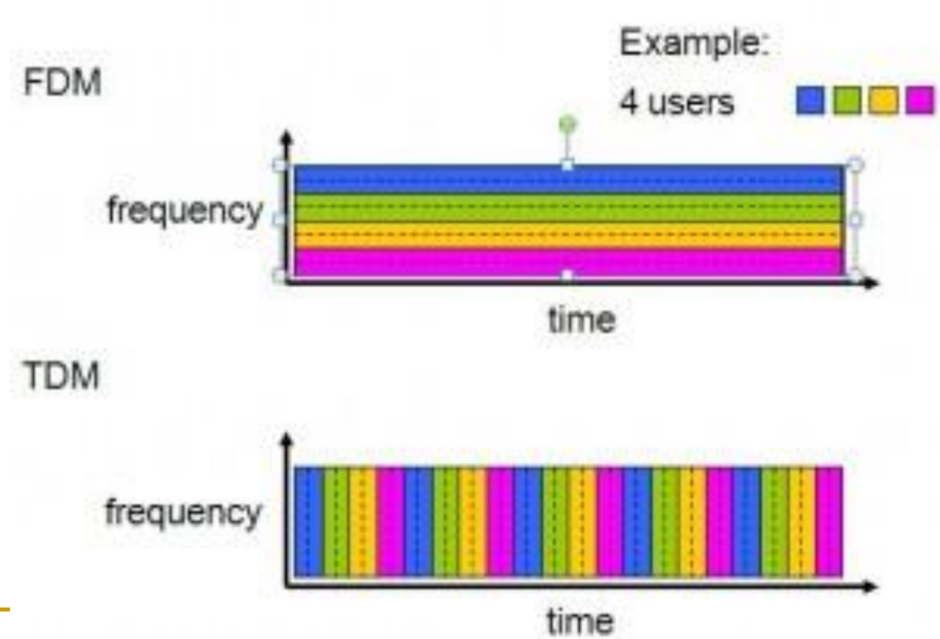


Source: FTTH Handbook
FTTH Council Europe

Figure 17: FTTH Applications

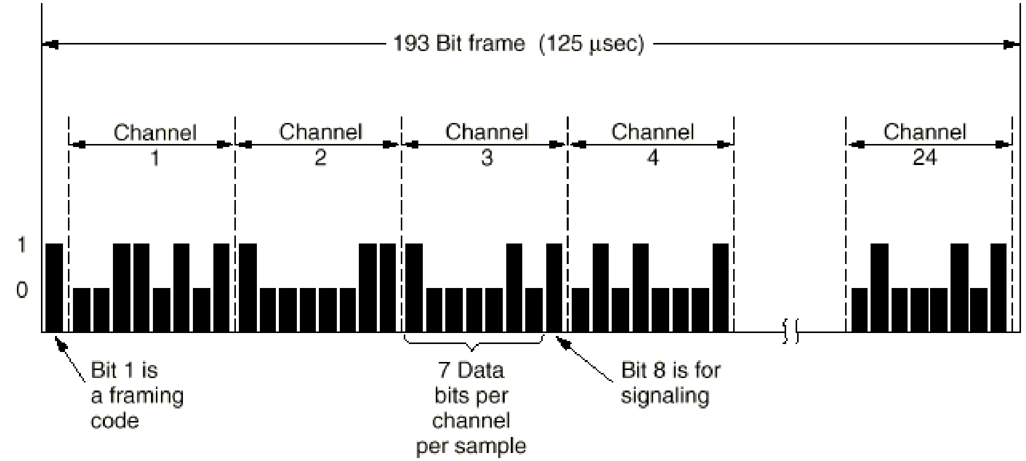
Trunks and Multiplexing

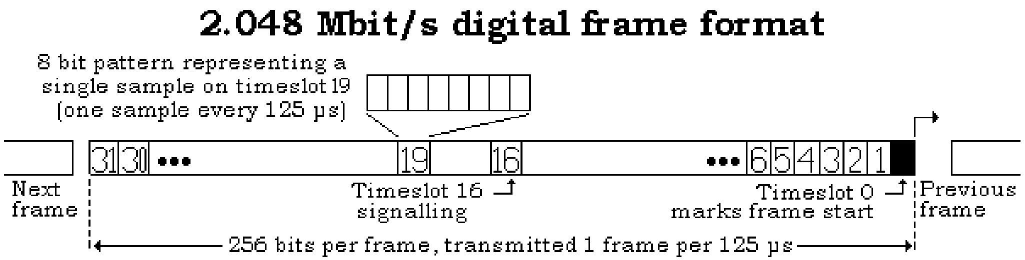
- TDM: time division multiplexing
  (can only be used in the digital domain)
  - Pulse Coded Modulation (PCM): Analog voice signals coming from local loop are sampled at 8000 samples/sec. Each sample is represented by 8 bits.
    $\Rightarrow$ 64 kbps representation of the voice signal
  - Several voice channels can be multiplexed in time to carry voice info between Telco offices.



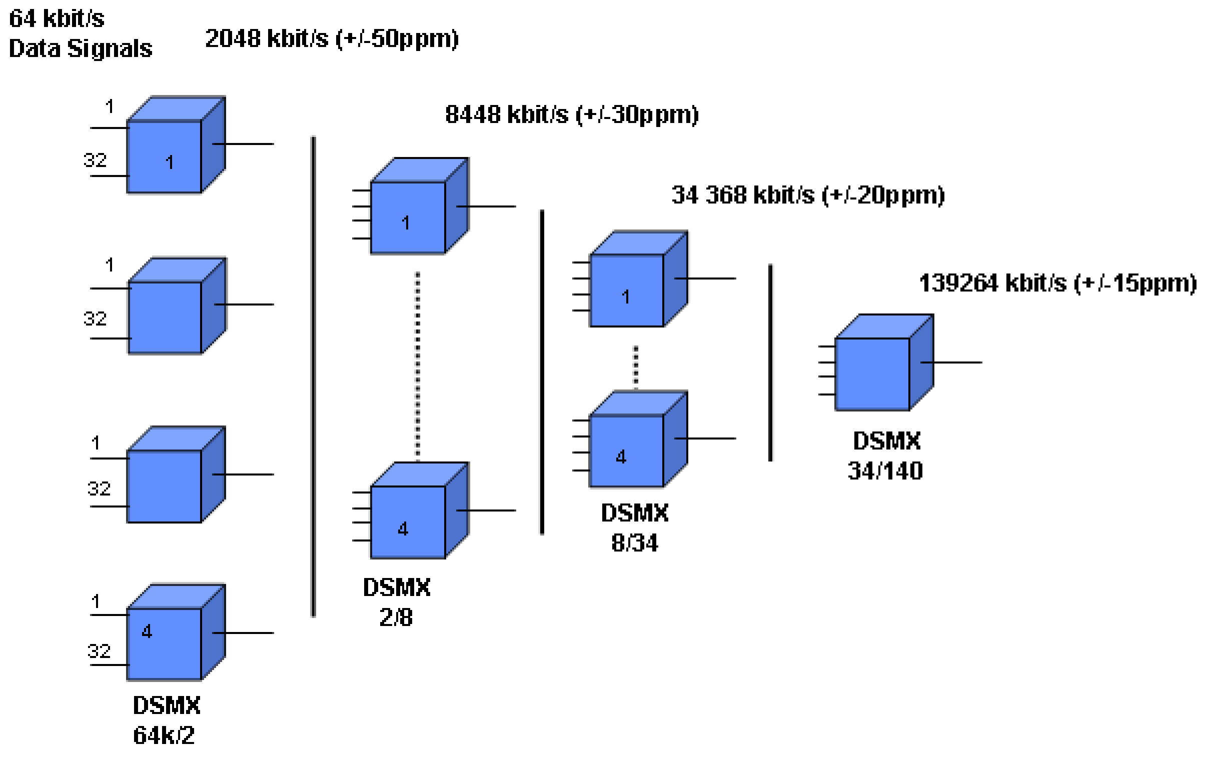
TDM carriers

- N. America : T1 carrier
  - 1.544 Mbps
  - 24 x 8 + 1 = 193 bits per frame
  - 1 frame per 125 microseconds
  - 8000 x 8 = 64 kbits/second per channel
  - 24 analog channels
  - AD-conversion: PCM 8-bit sampling at 8000 Hz
- Outside N. America : E1 carrier
  - 2.048 Mbps
  - 32 channels
  - 32 x 8 bits per frame
  - 30 data and 2 signaling channels
- Higher order rates are derived from multiplexing T1 or E1 signal streams



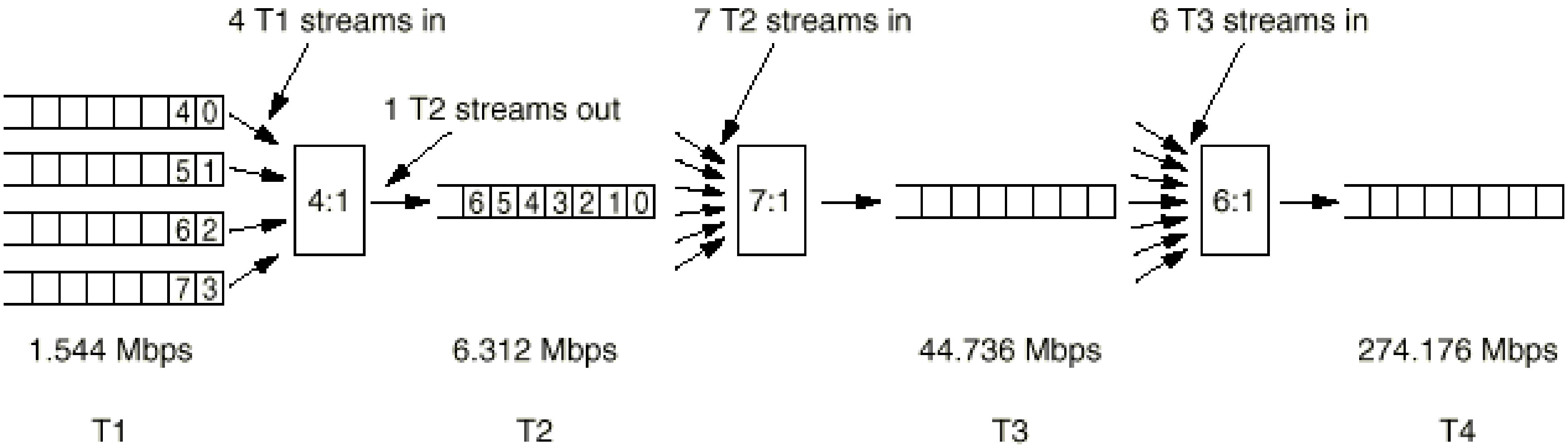


European PDH Hierarchy



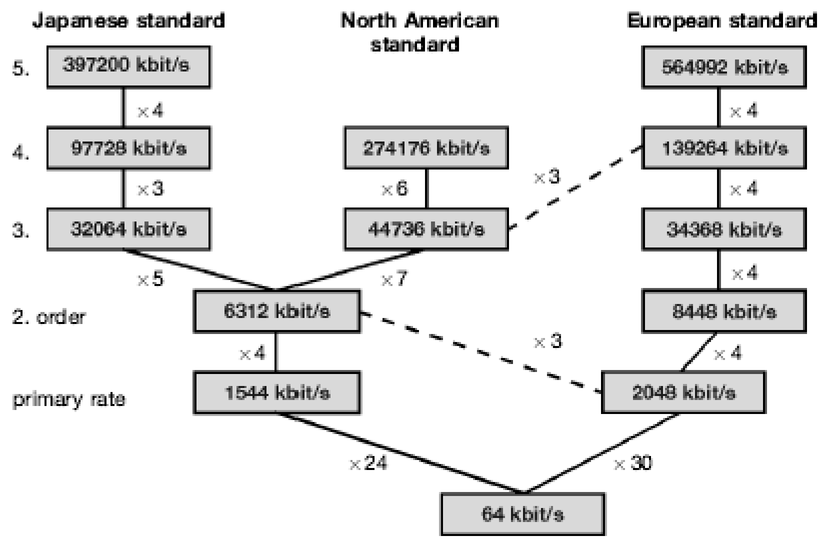
ITU-T Standard	Signal Bit Rate	Frame Size (bits)	Frame Per Second
G.704/732	E1 (2.048 Mbps +/-50ppm)	256	8000
G.742	E2 (8.448 Mbps +/-30ppm)	848	9962.2
G.751	E3 (34.368 Mbps +/-20ppm)	1536	22375
G.751	E4 (139.264 Mbps +/-15ppm)	2928	47562.8

US PDH Hierarchy

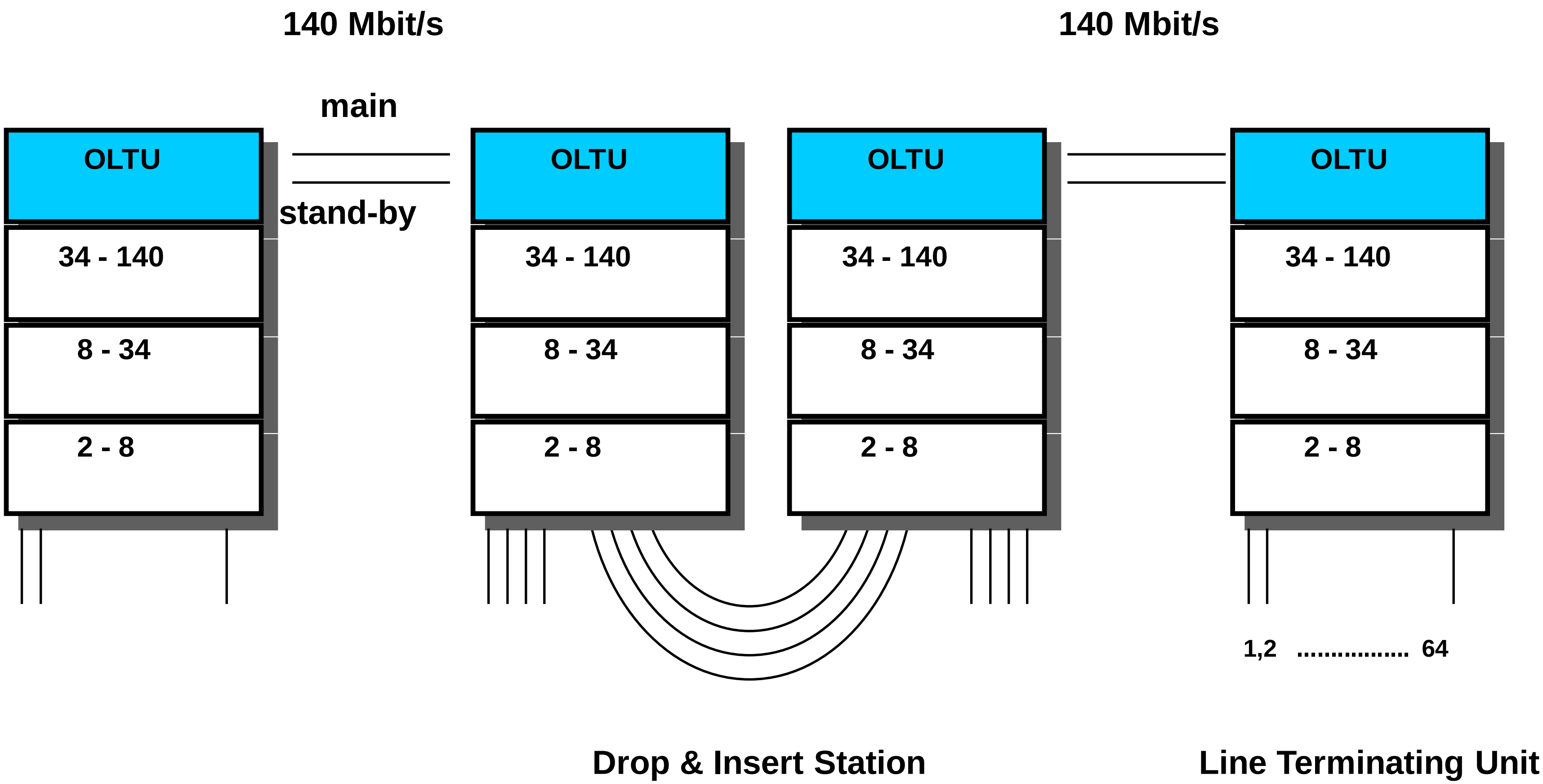


SONET/SDH

- SONET (Synchronous Optical Network) and SDH (Synchronous Digital Hierarchy) are the primary standards for all types of metro and long-haul transport of traffic over fiber networks.
- Design objectives:
  - Unify the US, European and Japanese digital transmission systems
  - Provide a multiplexing scheme or digital hierarchy
  - Provide OAM support
  - Direct access to low-level tributaries without the need to de-multiplex the entire signal



PDH Add/Drop

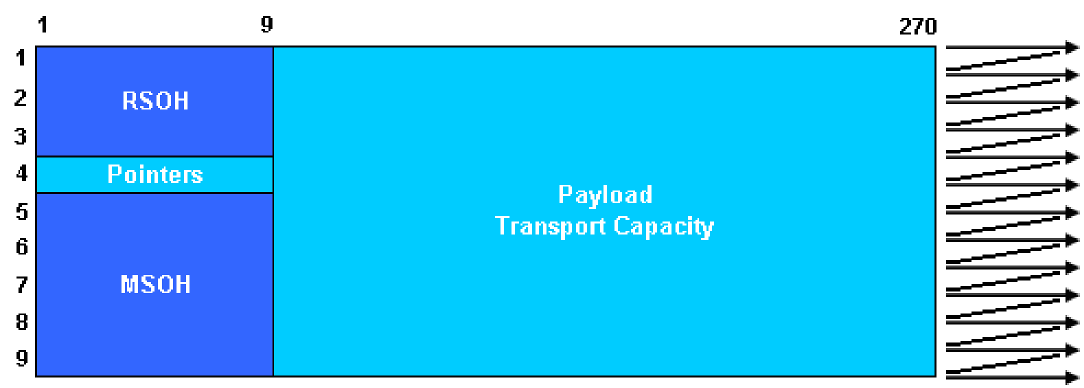

140 Mbit/s
140 Mbit/s
main
stand-by
OLTU
34 - 140
8 - 34
2 - 8
OLTU
34 - 140
8 - 34
2 - 8
OLTU
34 - 140
8 - 34
2 - 8
OLTU
34 - 140
8 - 34
2 - 8
1,2 64
Drop & Insert Station
Line Terminating Unit

SDH/PDH Comparison

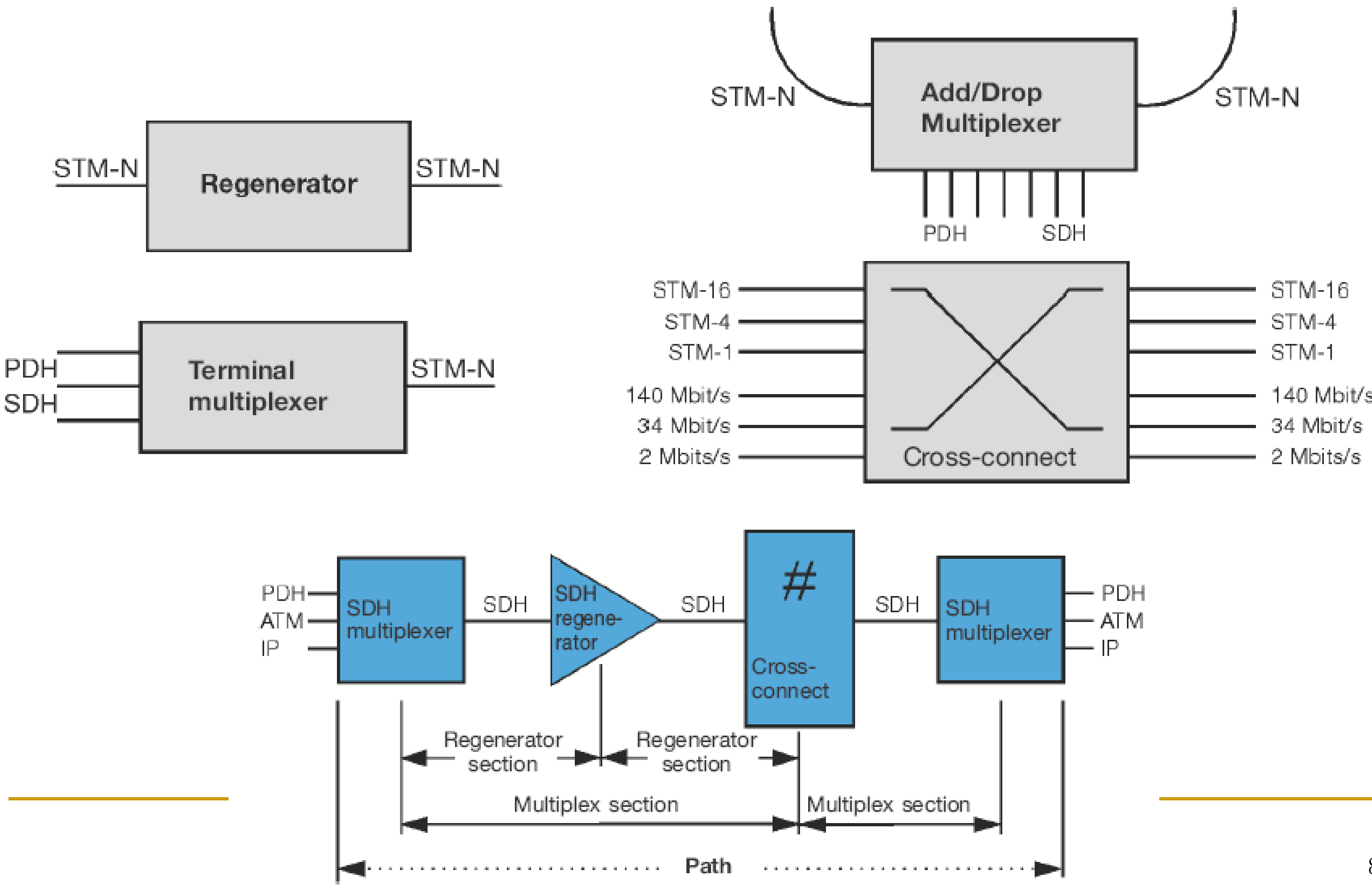
- PDH has some disadvantages.
  - Inability to identify individual channels in a higher order bit stream.
  - Insufficient capacity for network management.
  - There are different hierarchies in use around the world.
  - Specialized interface equipment is required to inter-work the two hierarchies.
- SDH has some advantages over PDH networks.
  - High transmission rates.
  - Simplified add & drop function.
  - Defined easy standard interconnection.
  - Reliability.
  - Future-proof platform for new services.

SONET/SDH

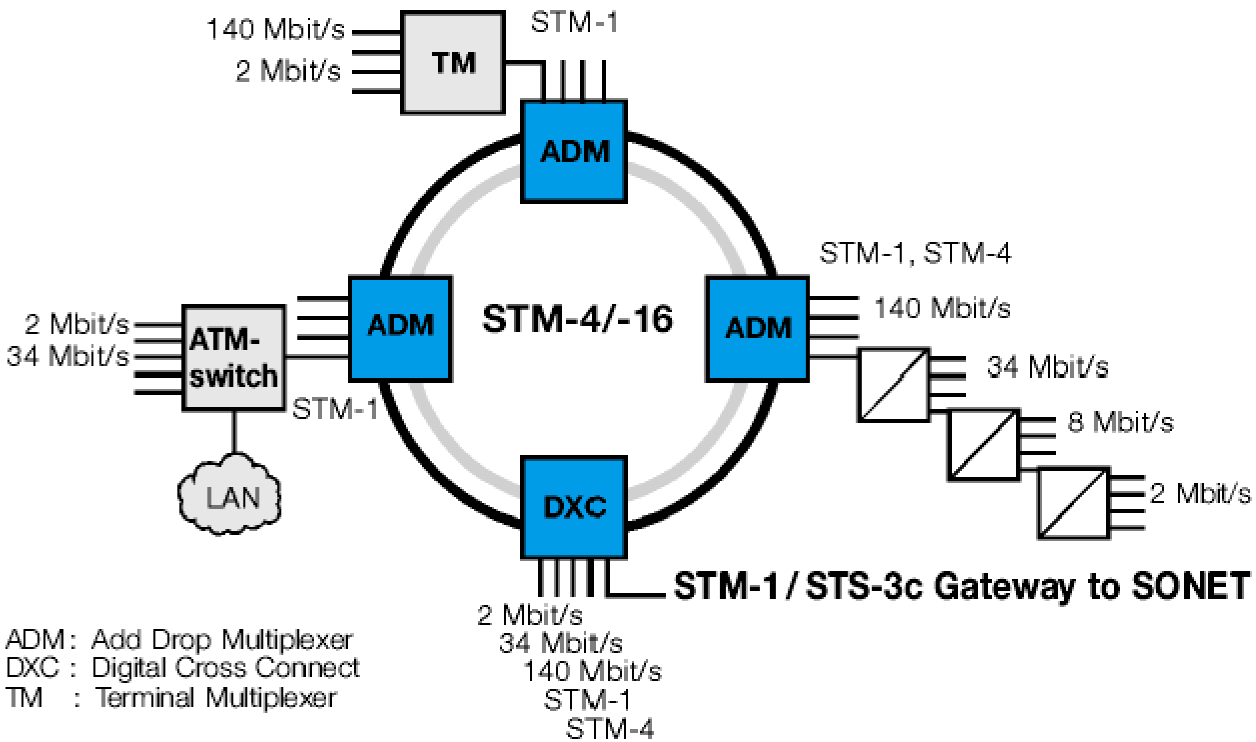
- SDH Rate and signaling
  - 155 Mbps or multiples
  - 270 x 9 x 8 bits per frame of 125 microseconds
- SDH multiplexing
  - 261 x 8 x 9 bits for synchronous payload envelope (SPE)
  - Payloads can carry many different types of traffic
  - Header bytes are used for framing, parity, voice channels, error monitoring, IDs, clocking and synchronization
- Standards: Multiples of 4nxSTM-1
  - STM-1: 155.52 Mbps
  - STM-4: 622.08 Mbps
  - STM-16: 2.5 Gbps
  - STM-64: 10 Gbps
  - STM-256: 40 Gbps



SDH Network Elements

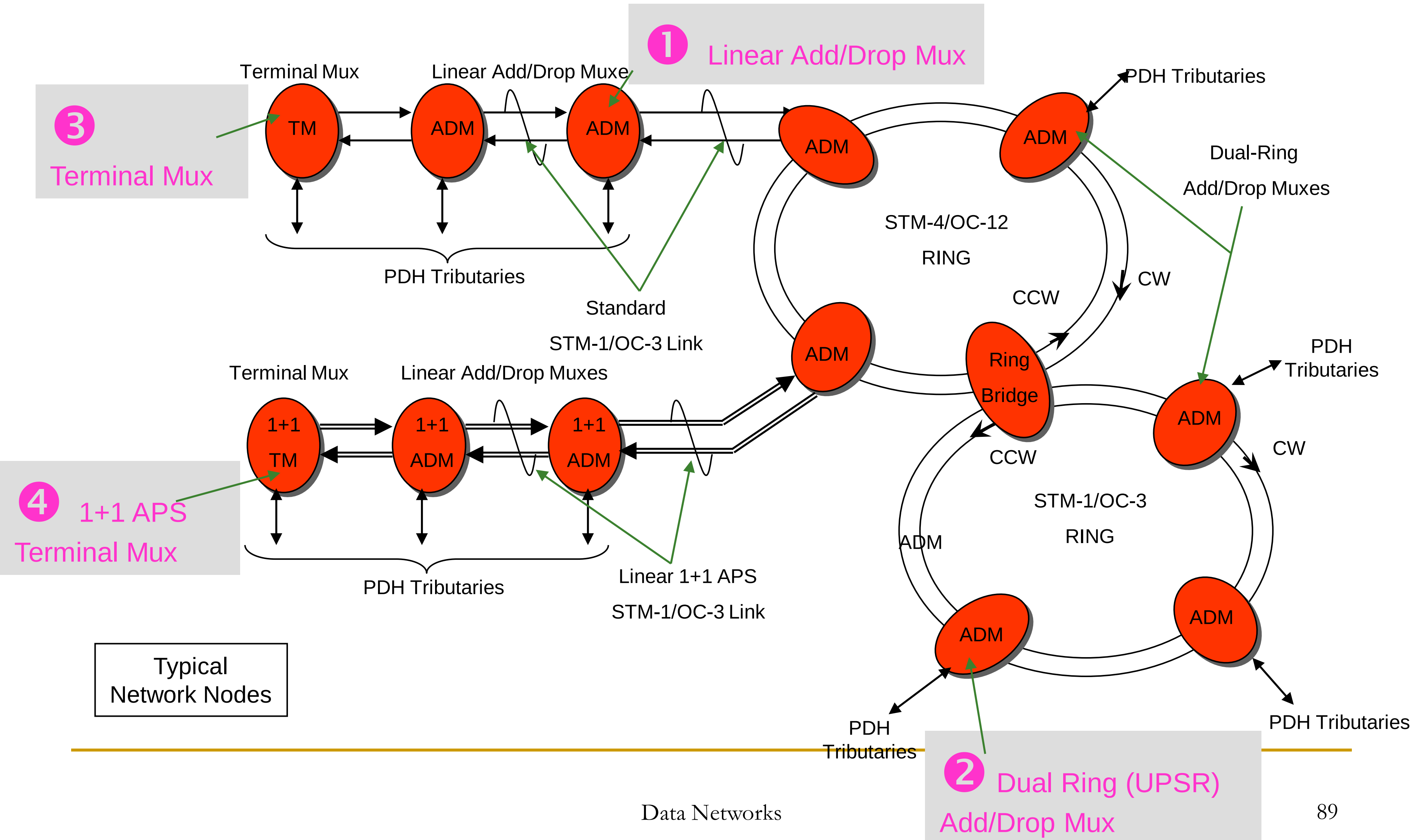


SDH Add/Drop



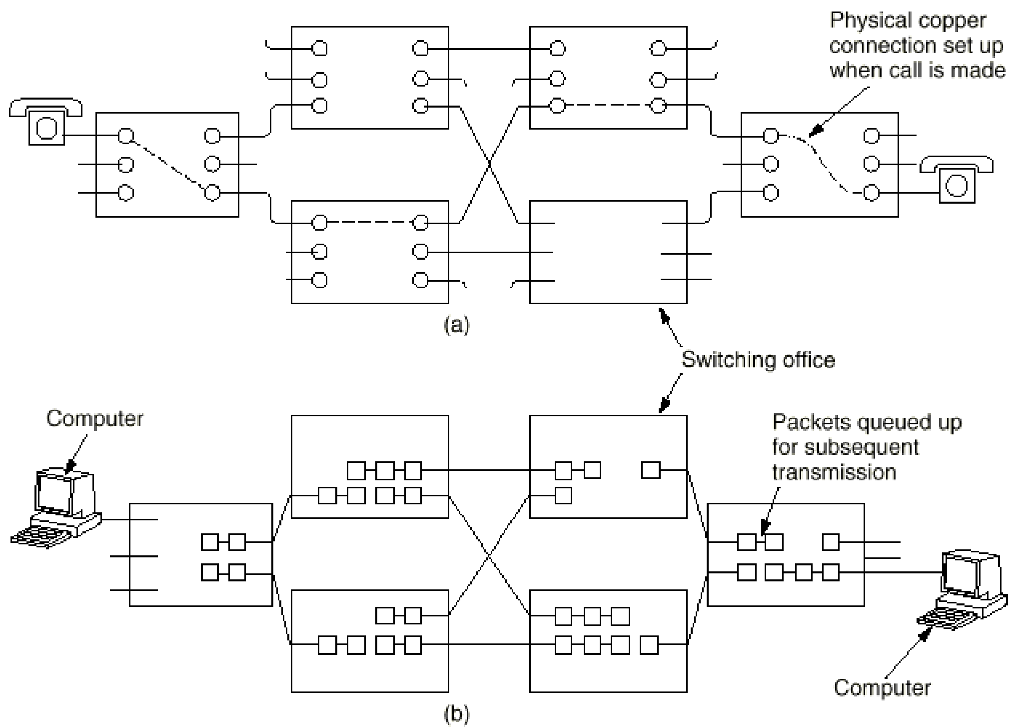
140 Mbit/s
2 Mbit/s
TM
STM-1
ADM
STM-1, STM-4
140 Mbit/s
2 Mbit/s
34 Mbit/s
ATM-switch
ADM
STM-4/-16
ADM
34 Mbit/s
STM-1
8 Mbit/s
LAN
DXC
2 Mbit/s
STM-1 / STS-3c Gateway to SONET
2 Mbit/s
34 Mbit/s
140 Mbit/s
STM-1
STM-4
ADM : Add Drop Multiplexer
DXC : Digital Cross Connect
TM : Terminal Multiplexer

Typical Network Architecture



Switching

- **Circuit switching**
  - Dedicated path established between source and destination
  - Long set-up time: O(10 sec)
  - No congestion change: guaranteed bandwidth
  - No extra random delay while call is established. Only transport delay
  - Unused bandwidth is wasted
  - Transparent to data format and framing mode. (road vs. railroad)



Switching

- **Packet switching**
  - Store-and-forward technique used
  - No dedicated path
  - Packet size should be limited in order not to block switches and/or overflow buffers
  - First packet is forwarded while second is received.
  - Rate conversion is easy
  - Delivery order may not be guaranteed

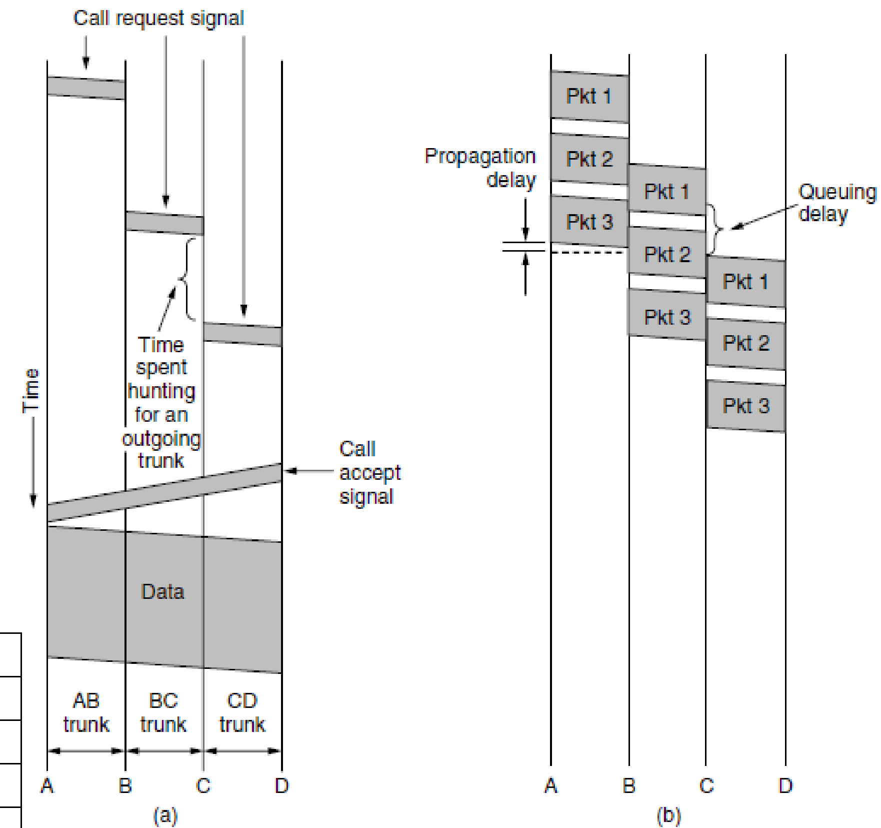


Figure 2-43. Timing of events in (a) circuit switching, (b) packet switching.

Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Charging	Per minute	Per packet

Mobile Economy

Unique mobile subscribers

2022 **5.4bn**

2030 **6.3bn**

68% 2022

73% 2030

Penetration rate
Percentage of population

CAGR 2022-2030 **2.0%**

Mobile internet users

2022 **4.4bn**

2030 **5.5bn**

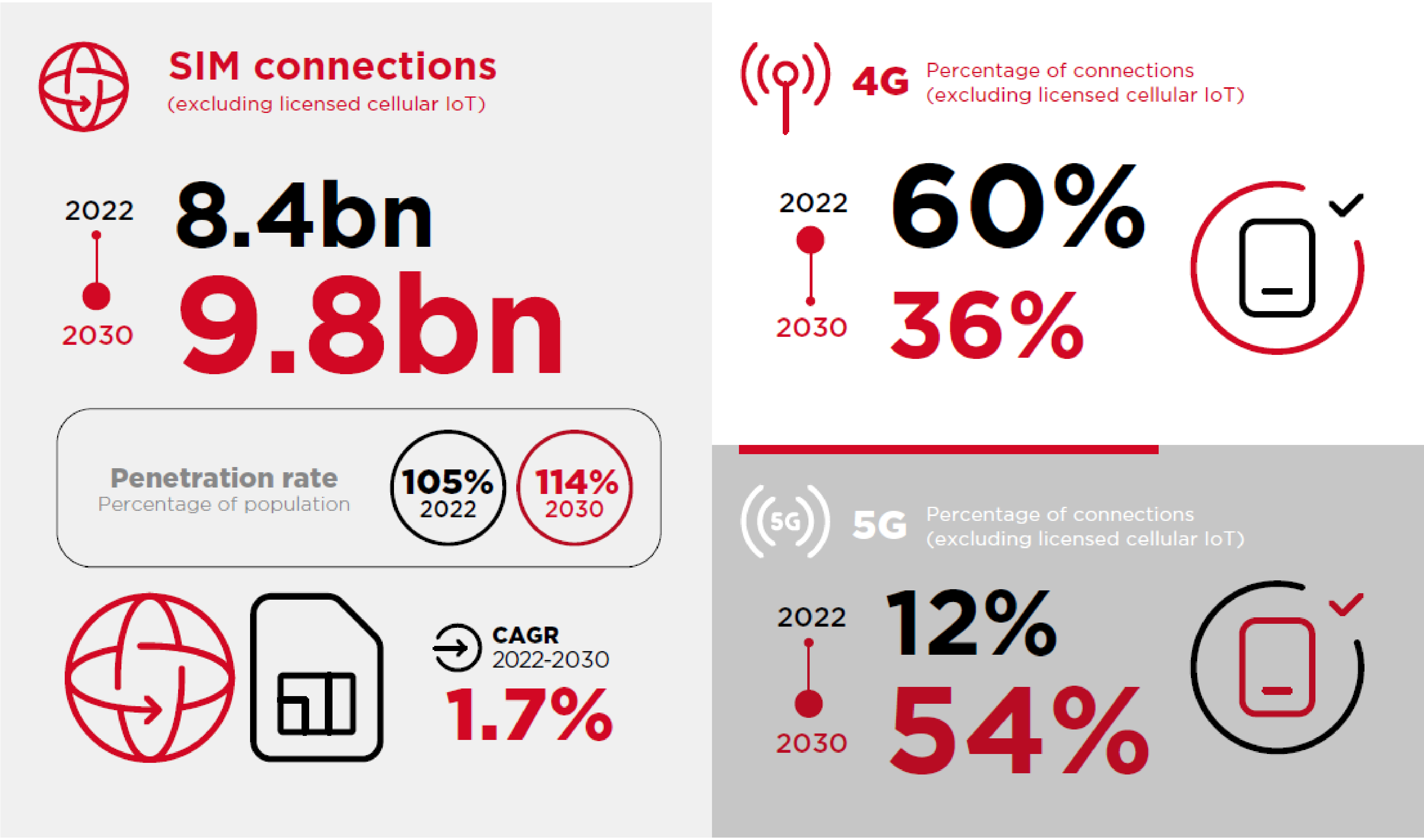
56% 2022

64% 2030

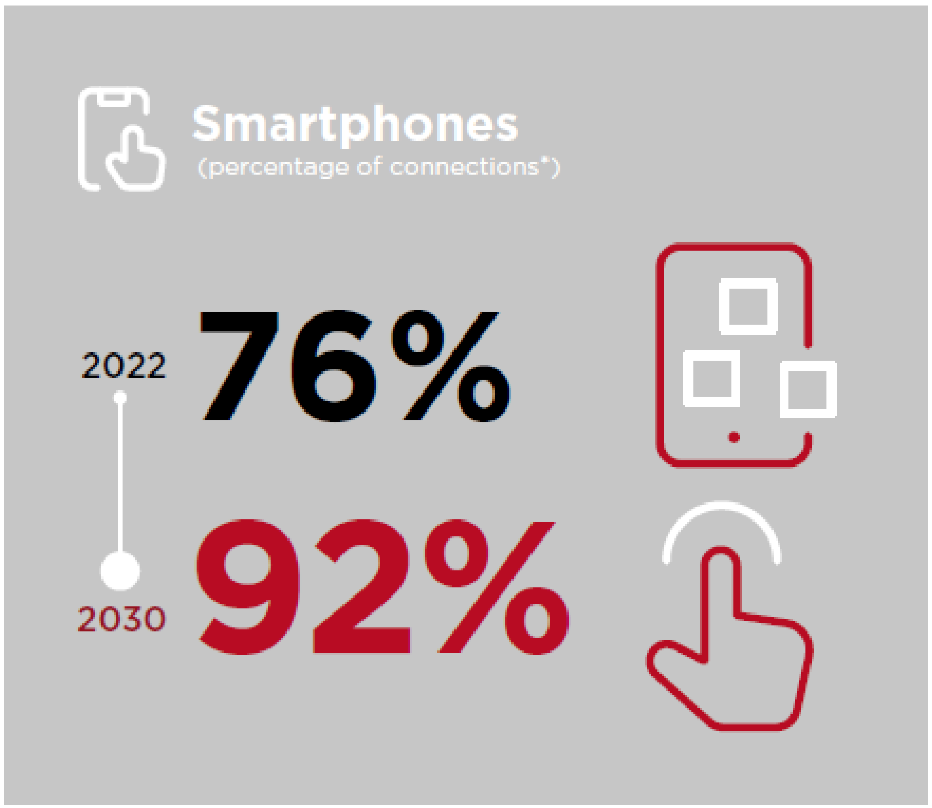
Penetration rate
Percentage of population

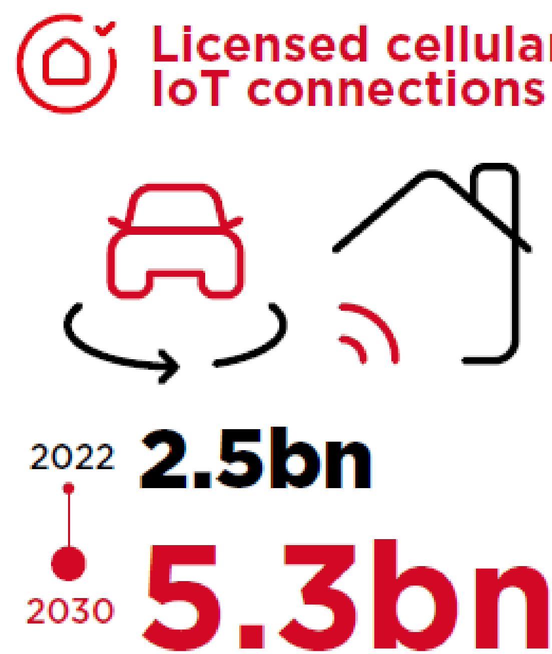
CAGR 2022-2030 **4.5%**

Mobile Economy

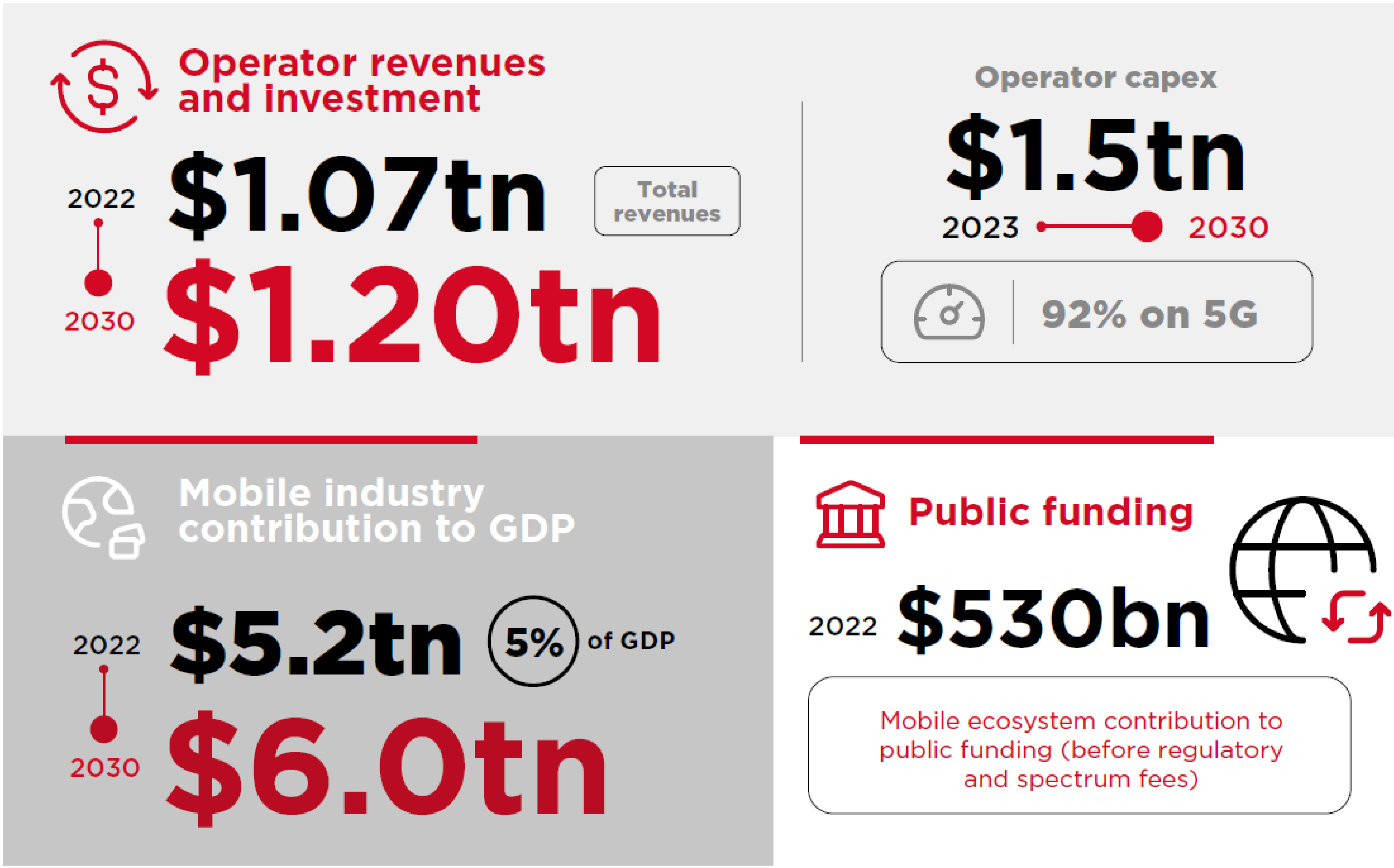


Mobile Economy

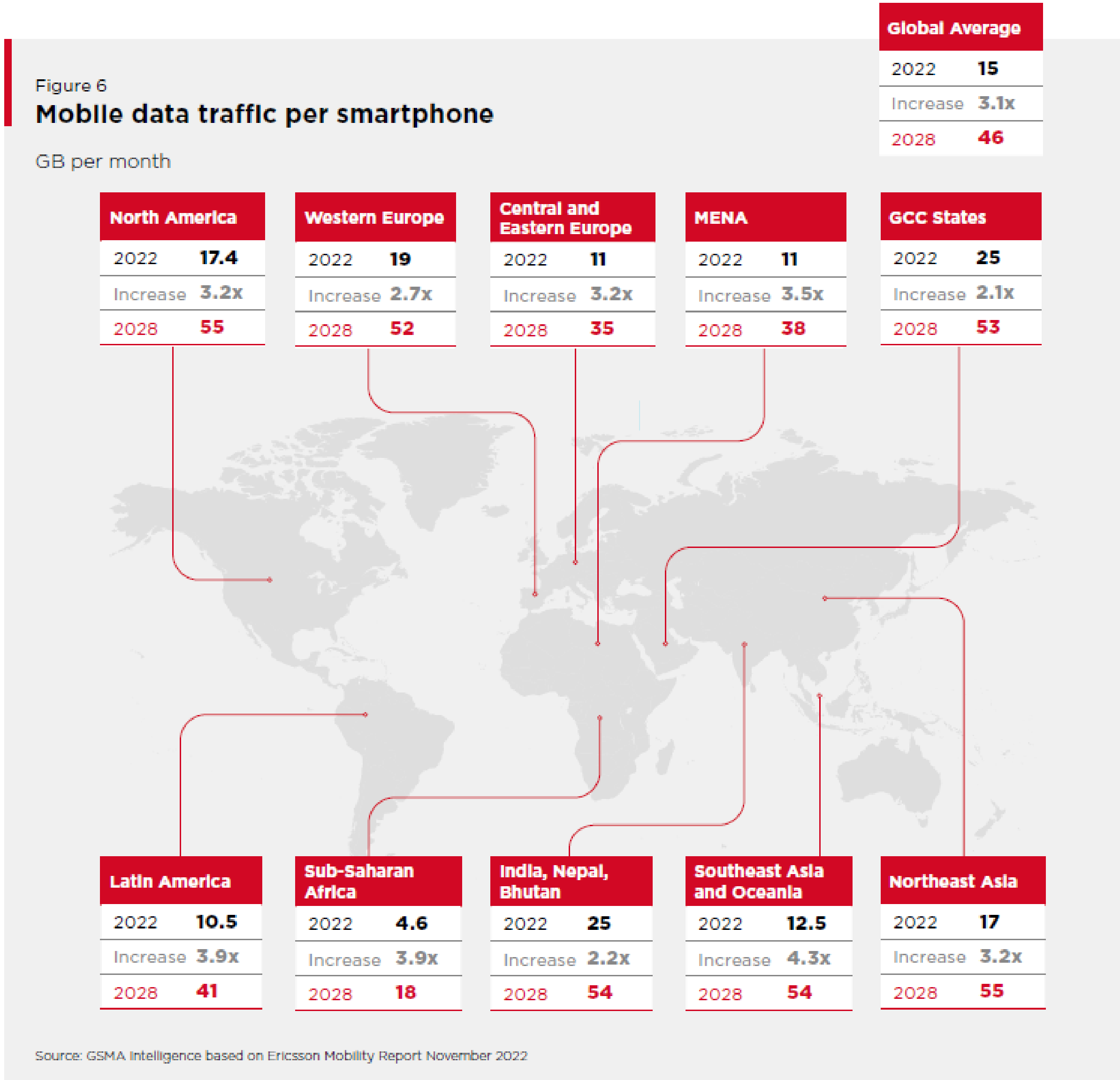




Mobile Economy

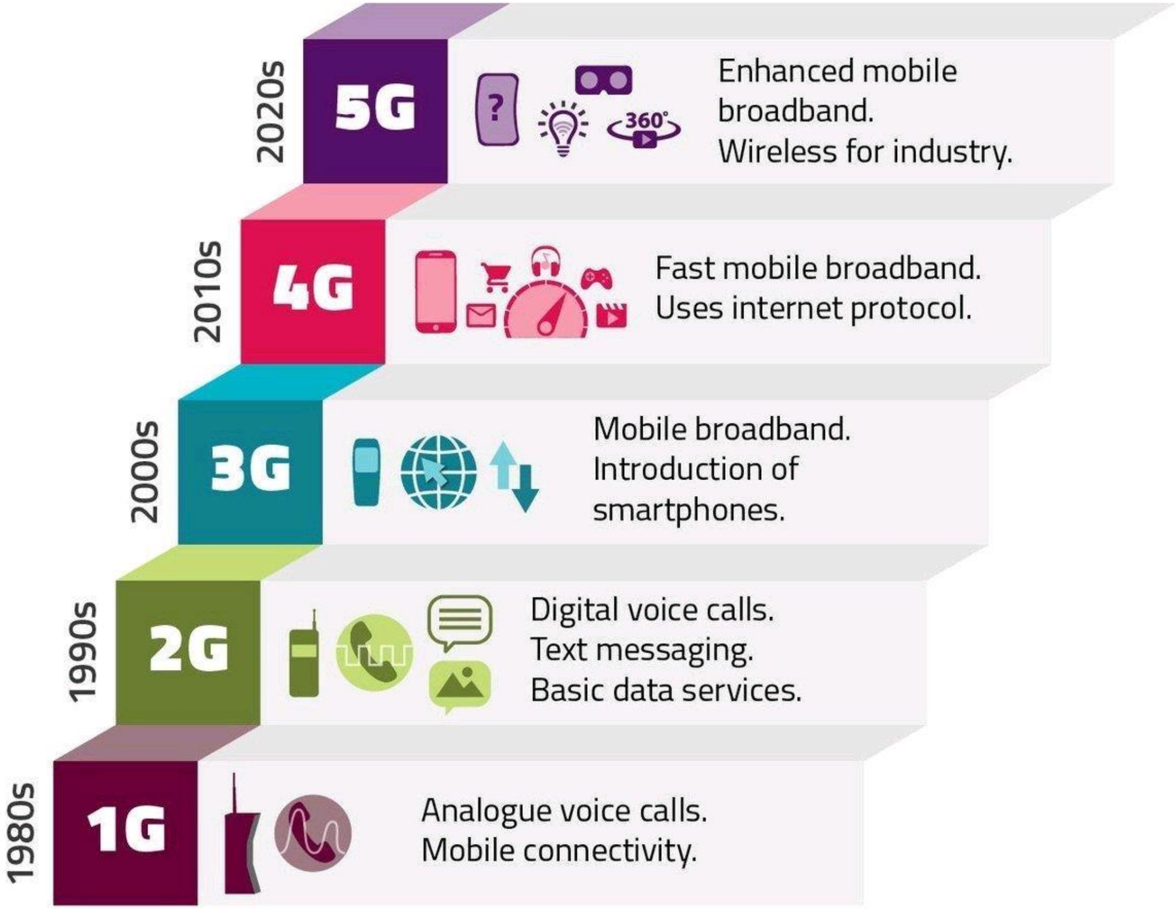


Trend of Data Usage



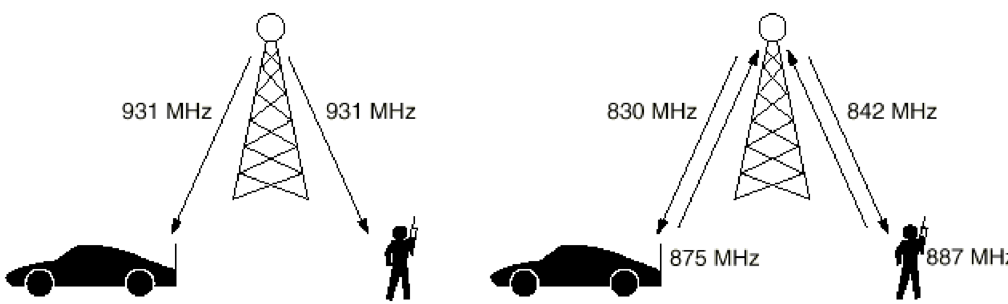
2. Ericsson Mobility Report November 2022
3. Analysing the behaviour of early 5G users: 10 things to know when planning consumer 5G strategies, GSMA Intelligence, 2021

Mobile Networks



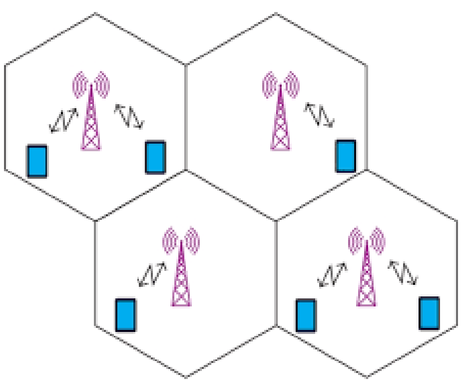
Mobile Phone System

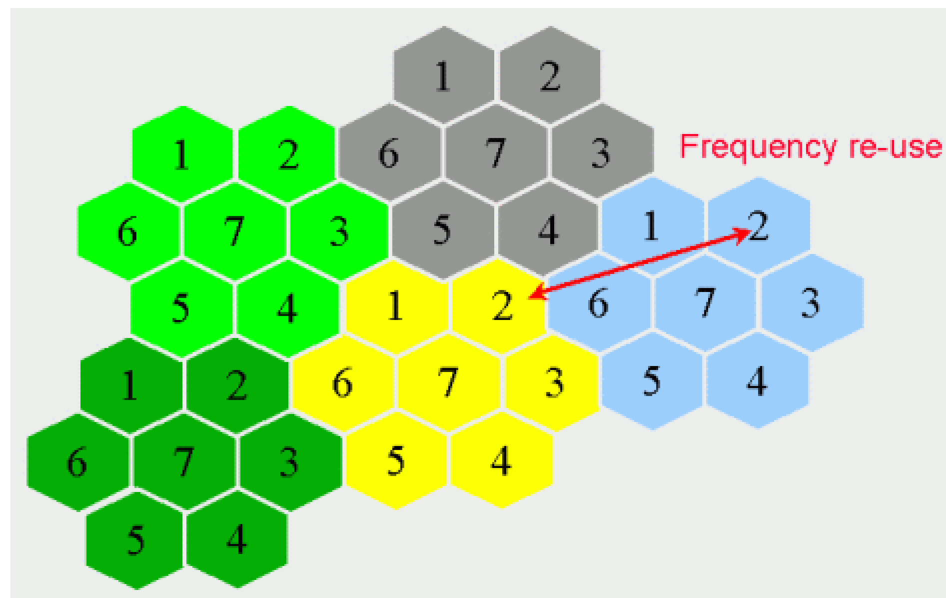
- First Generation:
  - Started from push to talk one to many systems (Police, Taxi's)
  - In 1960, Improved Mobile Telephone System (IMTS) was installed with separate US and DS channels
  - Had a high power transmitter with 23 channels from 150 MHz to 450MHz
  - Problems with channel capacity (Low number of channels) and interference



Concept of Cellular Networks

- Single hop wireless connectivity to the wired world
  - Space divided into cells
  - A base station is responsible to communicate with hosts in its cell
  - Mobile hosts can change cells while communicating
  - Hand-off occurs when a mobile host starts communicating via a new base station
- Factors for determining cell size
  - No. of users to be support
  - Multiplexing and transmission technologies





Mobile Phone System

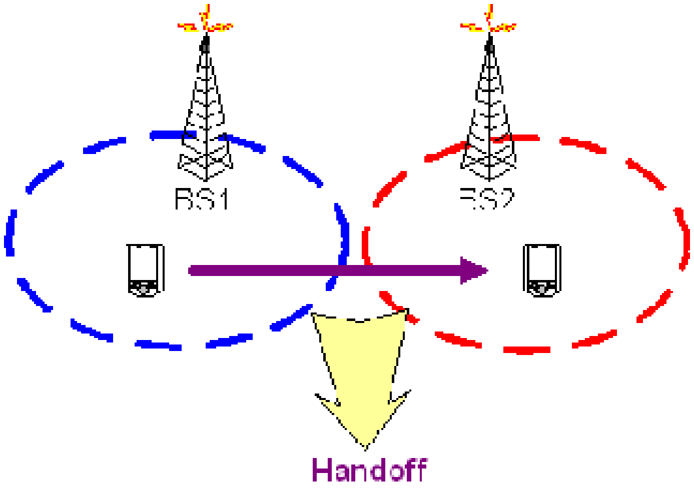
- Advanced Mobile Phone System (AMPS) (1982)
  - Divide area into radio cells to avoid interference and allow frequency re-use
  - Cells are around 10 km wide
  - Multiple base stations talk to a Base station switching center (BSC)
  - Multiple BSC's talk to a Mobile Switching Center (MSC) and then to the PSTN network
  - 832 upstream channels from 829-849 MHz, 832 downstream channels from 869-894 MHz each 30 kHz wide

Mobile Phone System

- Channels are used for
  - Control (Base to Mobile) to manage the system (21 channels)
  - Paging (Base to Mobile) to alert mobile users for a call
  - Access (Bi-directional) for call setup and channel assignment
  - Data (Bi-directional) for voice, fax and data (usually around 45 channels due to frequency re-use)

- Call handling
  - When handset is powered on, it scans control channels to find the most powerful signal
  - It then broadcasts its 32 bit serial number and phone number in digital format
  - BTS reports to MSC and it will decide if the user should be accepted for service
  - When mobile is dialing, MSC decides upon the channel and service availability and connects the call
  - MSC should also handle roaming and handoff
  - For incoming call, handset should continuously monitor the paging channel and respond through the control channel when a call request comes in

Hand off



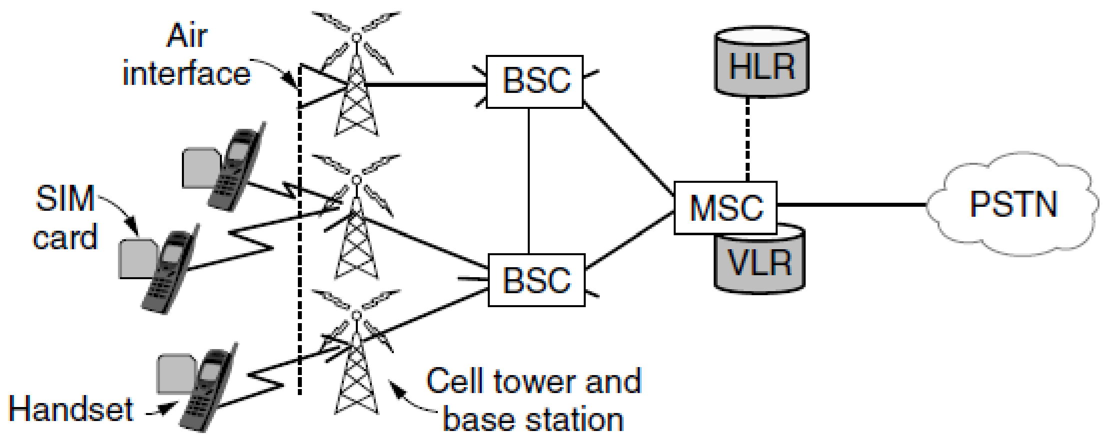
- Hand-off necessary when mobile moves from area of one BS into another
- BS initiated:
  - BS monitors the signal level of the mobile
  - Handoff occurs if signal level falls below threshold
  - Increases load on BS
  - Monitor signal level of each mobile
  - Determine target BS for handoff
- Mobile assisted:
  - Each BS periodically transmits beacon
  - Mobile, on hearing stronger beacon from a new BS, sends it a greeting
  - changes routing tables to make new BS its default gateway
  - sends new BS identity of the old BS
  - New BS acknowledges the greeting and begins to route mobile's call
- Intersystem:
  - Mobile moves across areas controlled by different MSC's
  - Handled similar to mobile assisted case with additional HLR/VLR effort

Mobile Phone System - 2G

- D-AMPS
  - IS-54, IS-135, backward compatible with AMPS.
  - Uses the same 30 kHz channels as AMPS. Therefore, D-AMPS (Sometimes call PCS) and AMPS can coexist in the same network.
  - A new band was opened for D-AMPS:
    - 1850-1910 MHz for US
    - 1930-1990 MHz for DS
  - Systems with much smaller phone size and longer battery life were developed
  - D-AMPS Vocoder can compress the voice down to 8kbps or less
  - Mobile Monitors the Rx quality and requests a handover to another base if there is a need

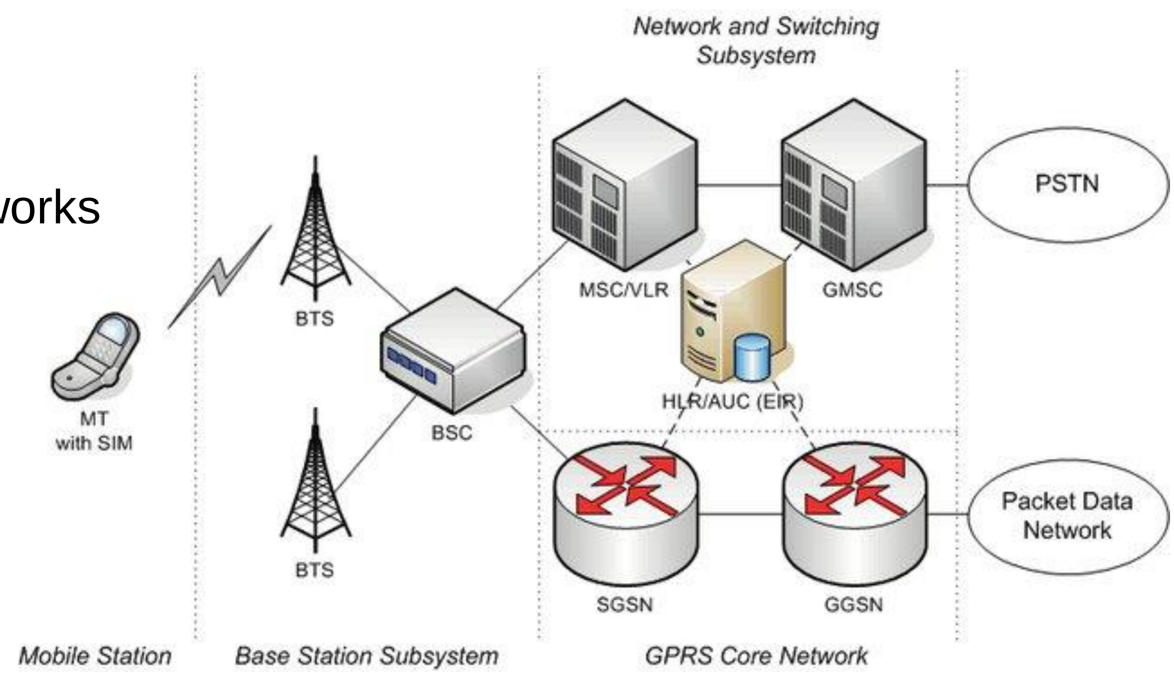
Mobile Phone System - GSM

- GSM: Global system for mobile communication
  - Developed in Europe in 1990s
  - Second generation mobile system
  - Can offer voice and data



Core Network

- Main tasks of core network
  - Call control
  - Routing
  - Locating
  - Mobility management
  - Signaling to other networks



Mobile Switching Center (MSC)

- Specific functions of a MSC
  - Switching of 64 kbit/s channels
  - Paging and call forwarding
  - Termination of SS7 (signaling system no. 7)
  - Mobility specific signaling
  - Location registration and forwarding of location information
  - Support of short message service (SMS)
  - Generation and forwarding of accounting and billing information
- Switching functions
  - Additional functions for mobility support
  - Interworking functions via Gateway MSC (GMSC)
  - Integration of several databases

Home Location Register (HLR)

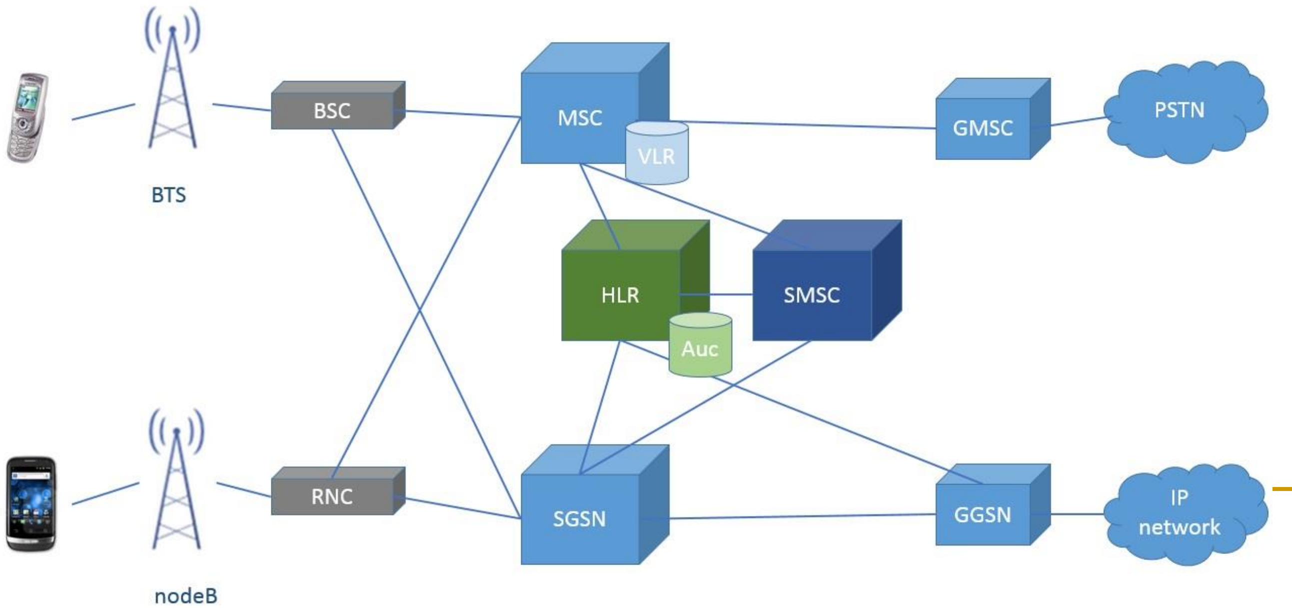
- Central master database that contains data from every user that has subscribed to the operator, includes:
  - Subscriber data
  - IMSI - International Mobile Subscriber Identity
  - List of subscribed services with parameters and restrictions
  - Location data
  - Current MSC/VLR address
- Responsibilities of the HLR include:
  - Management of service profiles
  - Mapping of subscriber identities (MSISDN, IMSI)
  - Supplementary service control and profile updates
  - Execution of supplementary service logic e.g. incoming calls barred.
  - Passing subscription records to VLR

Visitor Location Register (VLR)

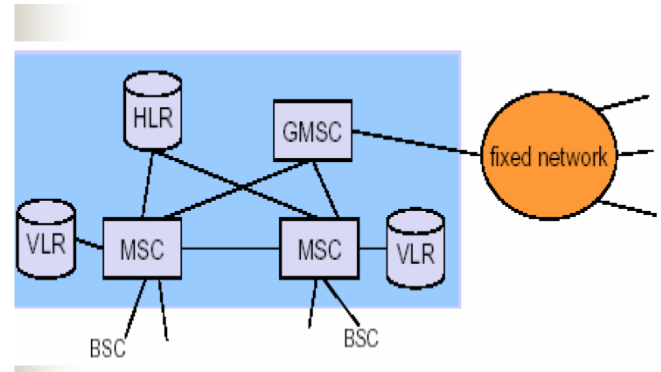
- Local database:
  - Data about all users currently in the domain of the VLR
  - Includes roamers and non-roamers
  - Associated to each MSC
- Responsibilities of the VLR include:
  - Executing supplementary service programs (outgoing calls barred)
  - Initiating authentication and ciphering
  - Initiating paging
  - Passing location information to HLR

SMS Center (SMSC)

- SMSC: stores and forwards messages to and from the SME (Short Message Entity)
- On receiving the short message from the short message center, MSC uses VLR (Visitor Location Register) which contains temporary information about the mobile, (mobile identification and the cell where the mobile is currently situated)
- Using information form the VLR the MSC is able to switch the information (short message) to the corresponding BSS (Base Station System, BSC + BTSs), which transmits the short message to the mobile.
- If the receiving mobile is not available, the message is stored in SMSC (based on operator policies) and will be delivered when it becomes available.



NSS Elements



- Gateway MSC
  - Connects mobile network to a fixed network
  - Request routing information from the HLR and routes the connection to the local MSC
- Authentication Center (AuC) (Associated to HLR)
  - Supports authentication and encryption mechanisms
  - Ki - subscriber secret authentication key
  - A3 - authentication algorithm
  - A8 - cipher key generation algorithm
- Equipment Identity Register (EIR)
  - Stores mobile stations IMEI (International Mobile Equipment Identity)
  - White-list - mobile stations allowed to connect without restrictions
  - Black-list - mobile stations locked (stolen or not type approved)
  - Gray-list - mobile stations under observation for possible problems

GSM Call Process

- GSM Channels:
  - Traffic Channels
  - Signaling Channels
- Signaling Channels:
  - Broadcast channel for:
    - Outputting identity of base station
    - Each mobile checks its signal strength to see if it has moved to another cell
  - Dedicated channel for:
    - Location updating
    - Registration
    - Call setup
  - Common Control channel for:
    - Paging (of incoming calls); each mobile monitors this channel
    - Random access channel, using slotted Aloha to request a slot on the dedicated channel, to set up a new call
    - Access grant channel

- Setting up a call:
  - Mobile requests a dedicated access channel# using random access channel; this is the only channel where we can get collisions; so it is used very shortly
  - Base grants channel# on access grant channel
  - Setup the call on dedicated channel
  - Start the conversation on one of the agreed regular channels

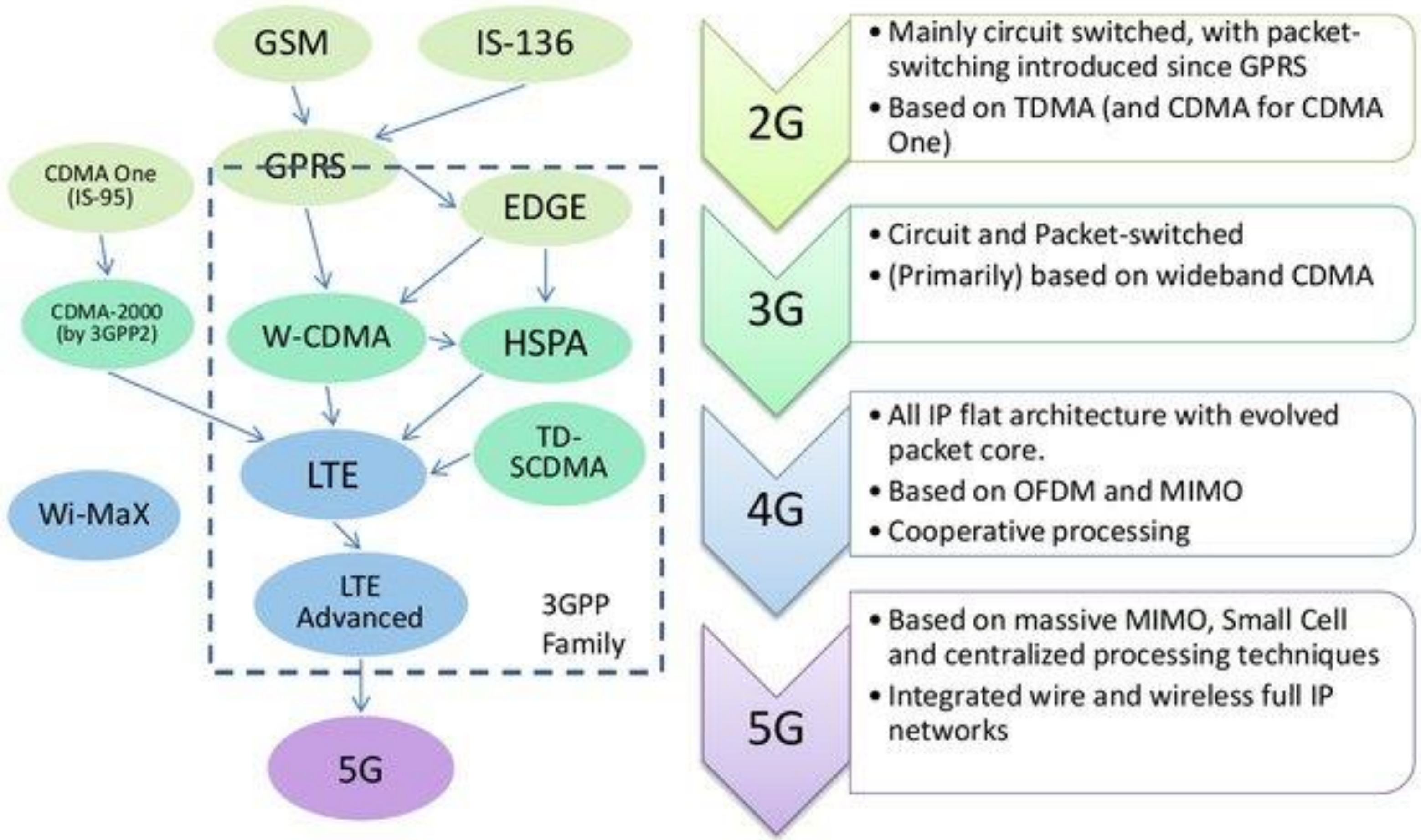
Evolution of 2G

- The demand for data connectivity in mobiles increased. Several steps were taken to define standards to support data networking in 2G networks.
- General Packet Radio Service (GPRS)
  - A packet oriented mobile data service on the 2G networks
  - GPRS provides data rates of 56–114 kbit/second by using unused time slots of GSM system.
  - Slots are reserved for IP data traffic based on demand.
  - GPRS is a best-effort service, implying variable throughput and latency that depend on the number of other users sharing the service concurrently
- Enhanced Data Rate for Global Evolution (EDGE)
  - EDGE is a digital mobile phone technology that allows improved data transmission rates as a backward-compatible extension of GSM
  - Peak bit-rates of up to 1 Mbit/s and typical bit-rates of 400 kbit/s can be expected.

Third Generation Mobile Systems (3G)

- Initial Objectives:
  - High quality voice
  - High speed data for messaging, multimedia and internet access.
  - Up to 2 Mbps rate to fixed users and up to 384 kbps to mobile users
- Three main standards:
  - Wideband CDMA
    - Developed mostly in Europe
    - Runs in a 5 MHz band
    - Can inter-work with GSM but not backward compatible
  - CDMA2000
    - Developed mostly in USA
    - Uses 5 MHz bandwidth
    - Designed to interwork with IS-95 which is a 2G CDMA standard used in North America
  - TD-SCDMA
    - Chinese version of 3G systems

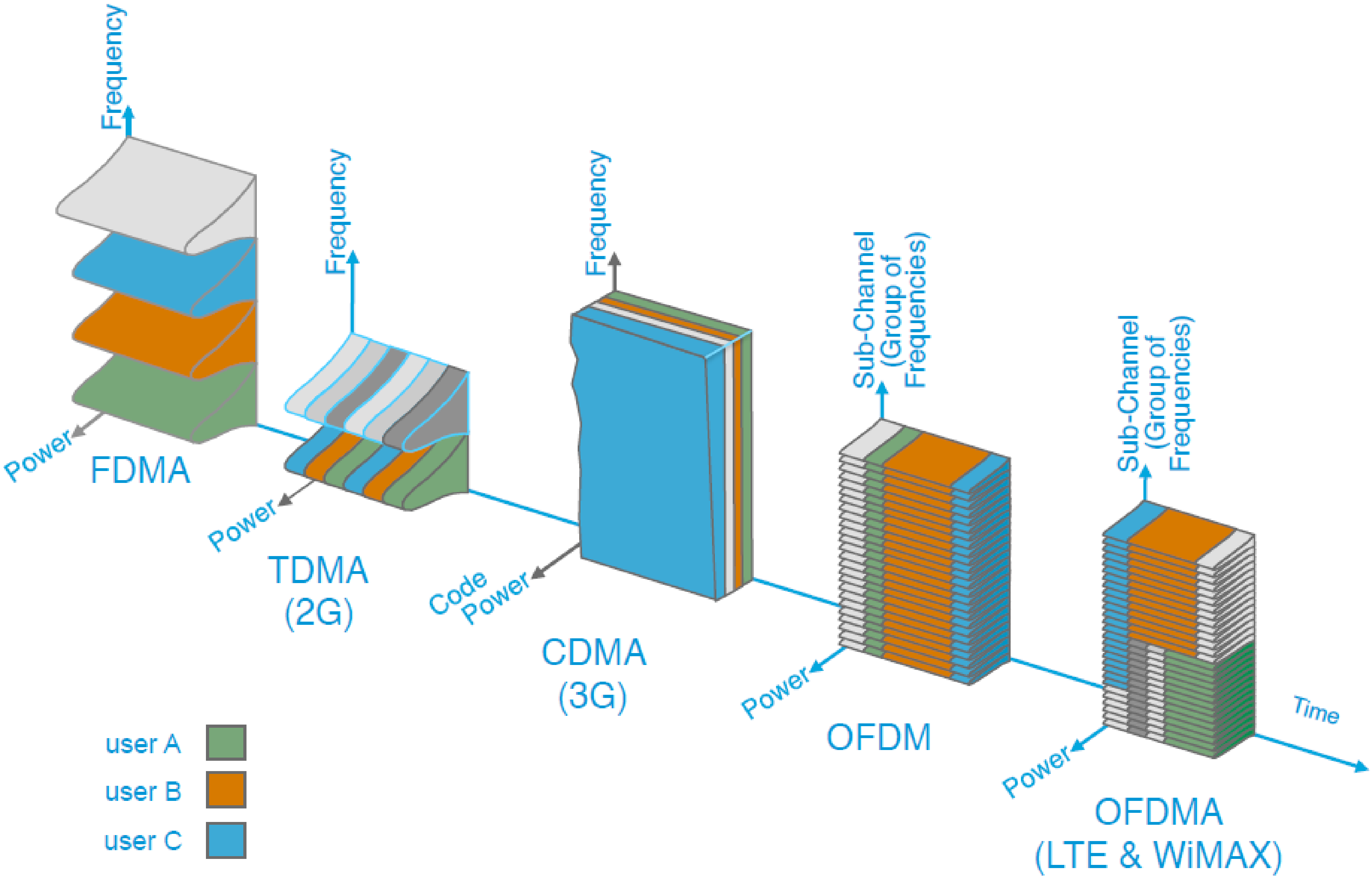
Evolution of Mobile Standards



Long Term Evolution (LTE)

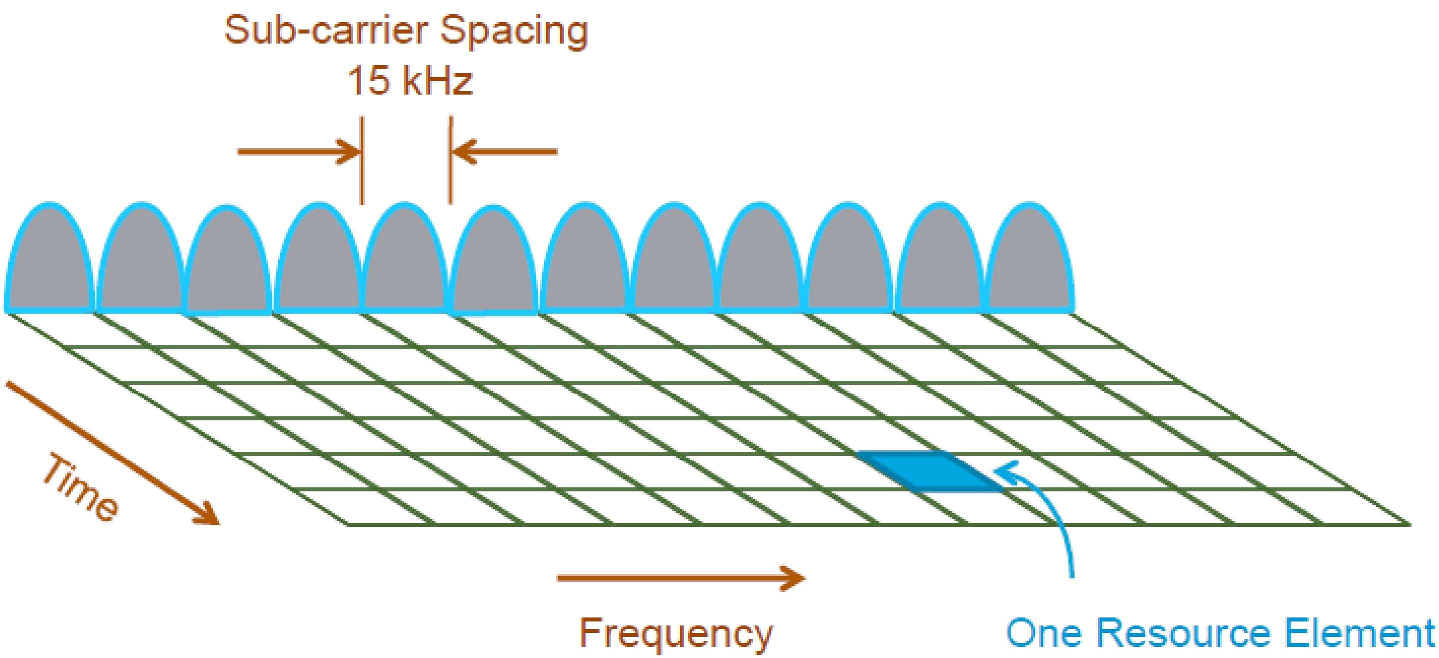
- The LTE specification:
  - Downlink peak rates of at least 100 Mbit/s for a single antenna, Peak download rates of 326.4 Mbit/s for 4x4 antennae, and 172.8 Mbit/s for 2x2 antennae (utilizing 20 MHz of spectrum)
  - Peak upload rates of 86.4 Mbit/s for every 20 MHz of spectrum using a single antenna
  - RAN round-trip times of less than 10 ms. Sub-5 ms latency for small IP packets
  - Scalable carrier bandwidths, from 1.4 MHz to 20 MHz
  - Five different terminal classes have been defined from a voice centric class up to a high end terminal that supports the peak data rates. All terminals will be able to process 20 MHz bandwidth
  - Supports both frequency division duplexing (FDD) and time division duplexing (TDD).
  - Simpler core network architecture resulting in low operating cost

Radio Access Technology Evolution

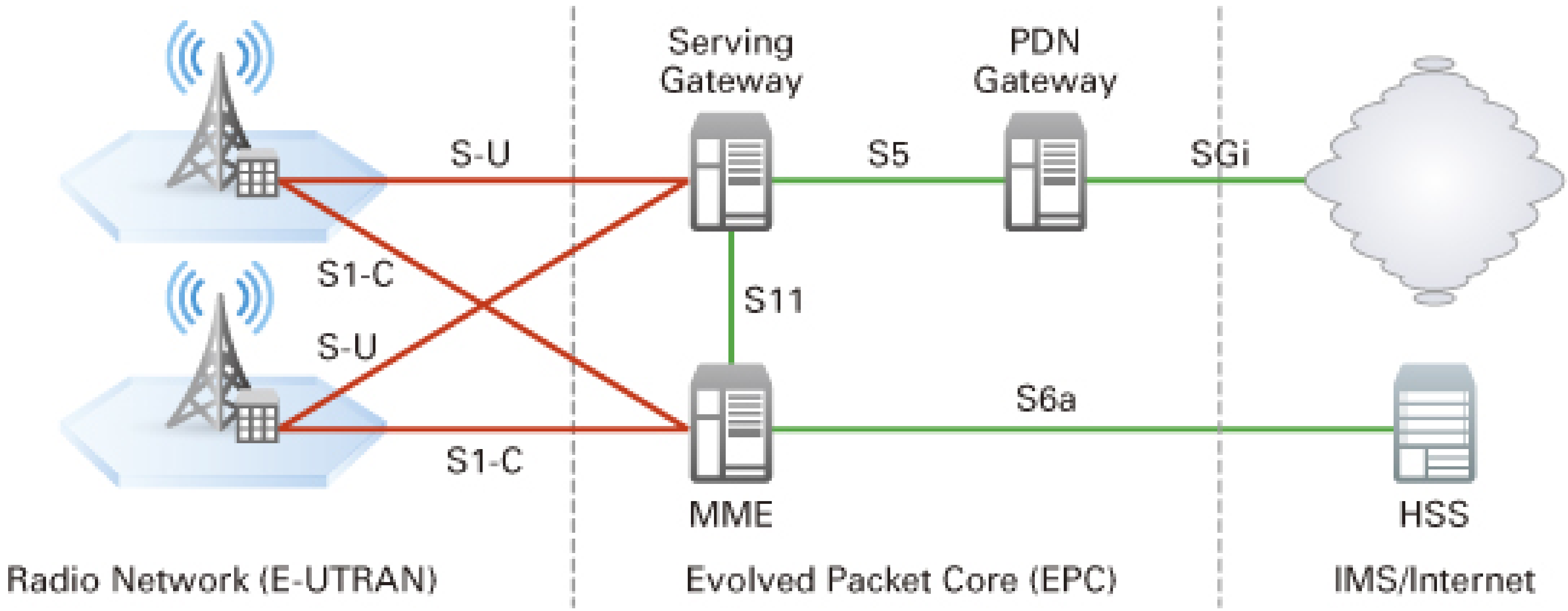


OFDMA

Resources Allocation in Time and Frequency



Evolved Packet Core (EPC)



Mobility Management Entity (MME)

- The MME is an important controller node in the LTE network. It is responsible for:
  - Idle mode UE (User Equipment) tracking
  - Paging procedure such as re-transmissions
  - Bearer activation and deactivation process
  - S-GW selection for a UE at the initial attach
  - Intra-LTE handover with Core Network node relocation
  - User authentication with HSS

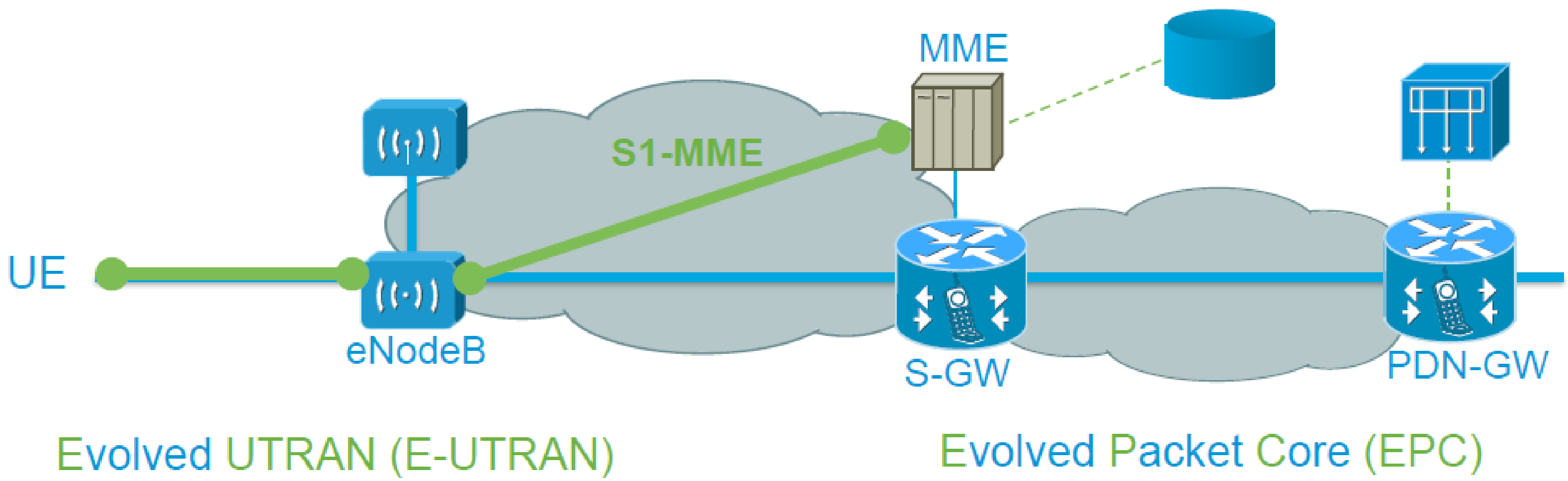
Serving Gateway (SGW)

- Main functions of the Serving Gateway:
  - Routing and forwarding of user data packets.
  - Inter-eNB handovers in the U-plane
  - Mobility between LTE and other types of networks, such as between 2G/3G and P-GW.
  - Replicating user traffic for lawful interception.
- The DL data from the UEs in idle state is terminated at the SGW, and arrival of DL data triggers paging for the UE.
- The SGW keeps context information such as parameters of the IP bearer and routing information, and stores the UE contexts when paging happens.

PDN Gateway (PGW)

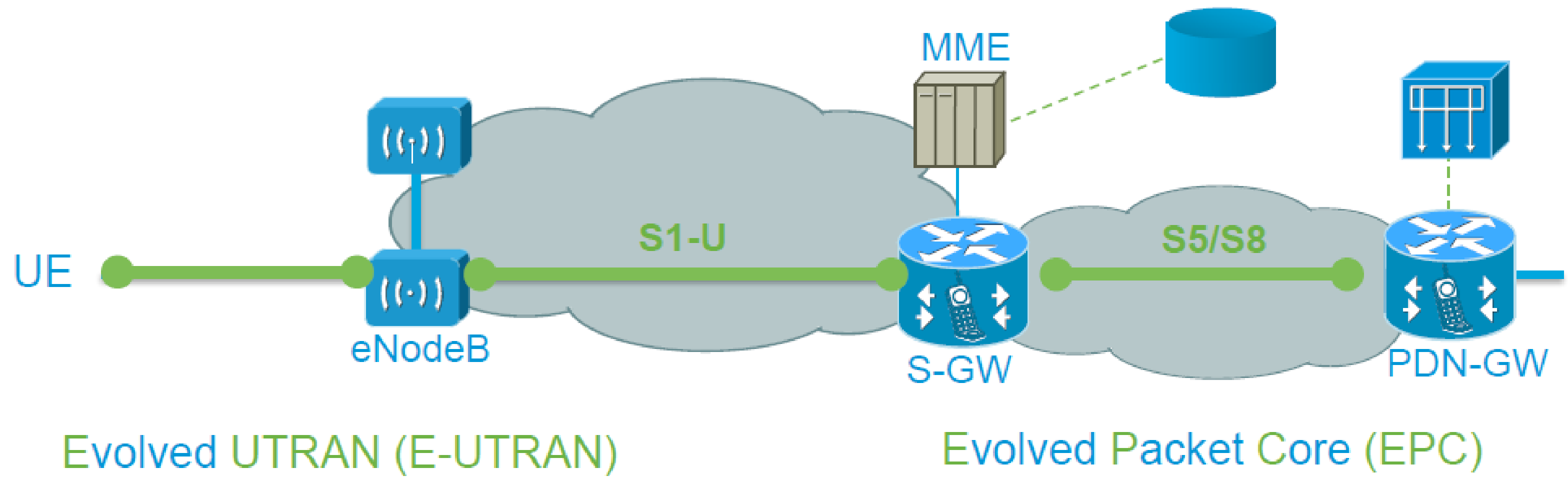
- The PDN Gateway is the connecting node between UEs and external networks. It is the entry point of data traffic for UEs.
- In order to access multiple PDNs, UEs can connect to several PGWs at the same time.
- The functions of the PGW include:
  - Policy enforcement
  - Packet filtering
  - Charging support
  - Lawful interception
  - Packet screening
  - Mobility between 3GPP and non-3GPP networks

EPC Protocol Stacks: Signaling



NAS				NAS
RRC	RRC	S1-AP	S1-MME	S1-AP
PDCP	PDCP	SCTP	36.413	SCTP
RLC	RLC	IP		IP
MAC	MAC	L2		L2
OFDMA	OFDMA	L1		L1

EPC Protocol Stacks: Data Plane



UE

IP (user)
PDCP
RLC
MAC
OFDMA

eNodeB

PDCP	GTP-U
RLC	UDP
MAC	IP
	L2
OFDMA	L1

S1-U
36.414

S-GW

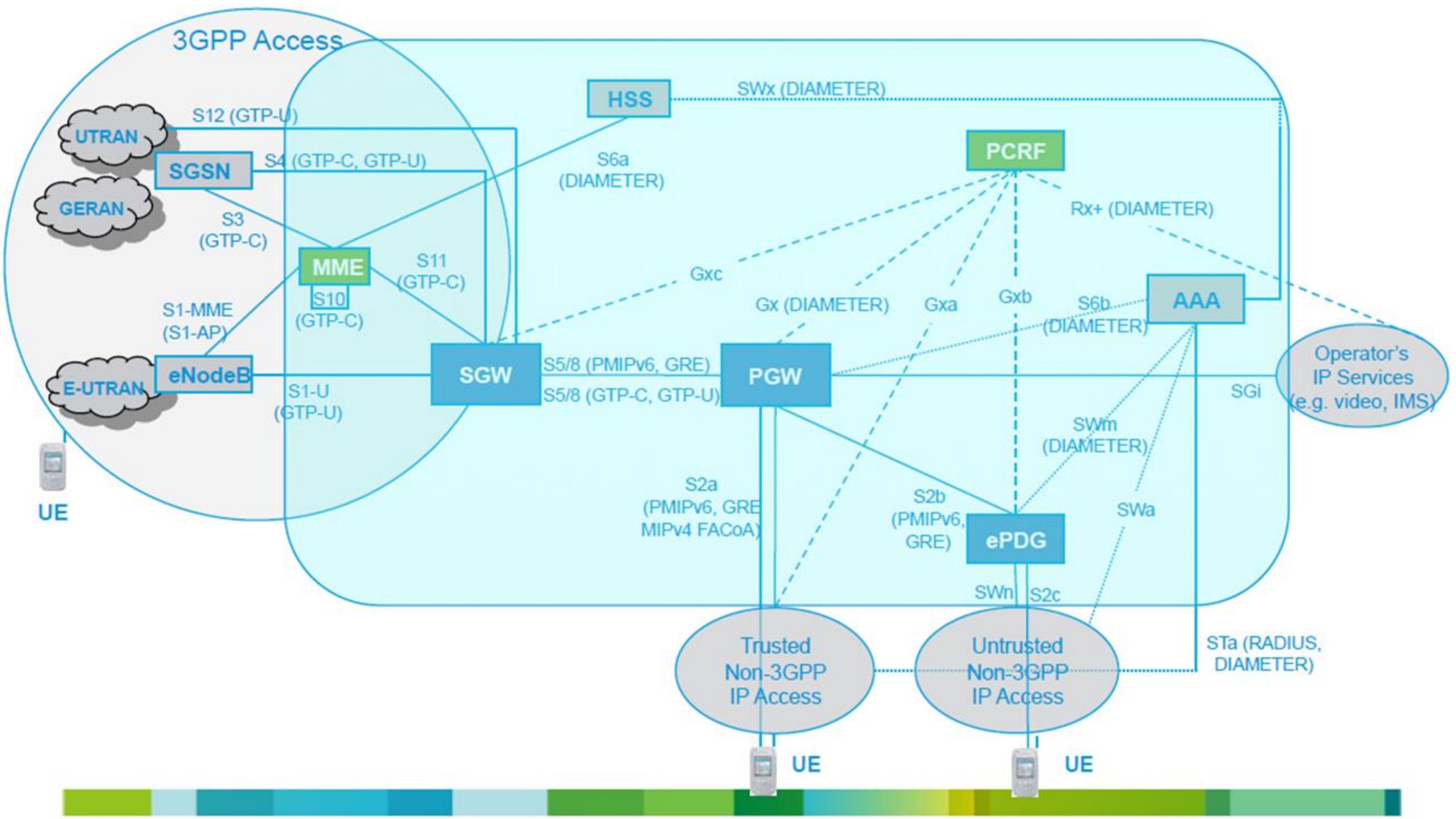
GTP-U	GTP-U	PMIP
UDP	UDP	GRE
IP	IP	
L2	L2	
L1	L1	

S5/S8
29.274 (GTP)
-
29.275 (PMIPv6)

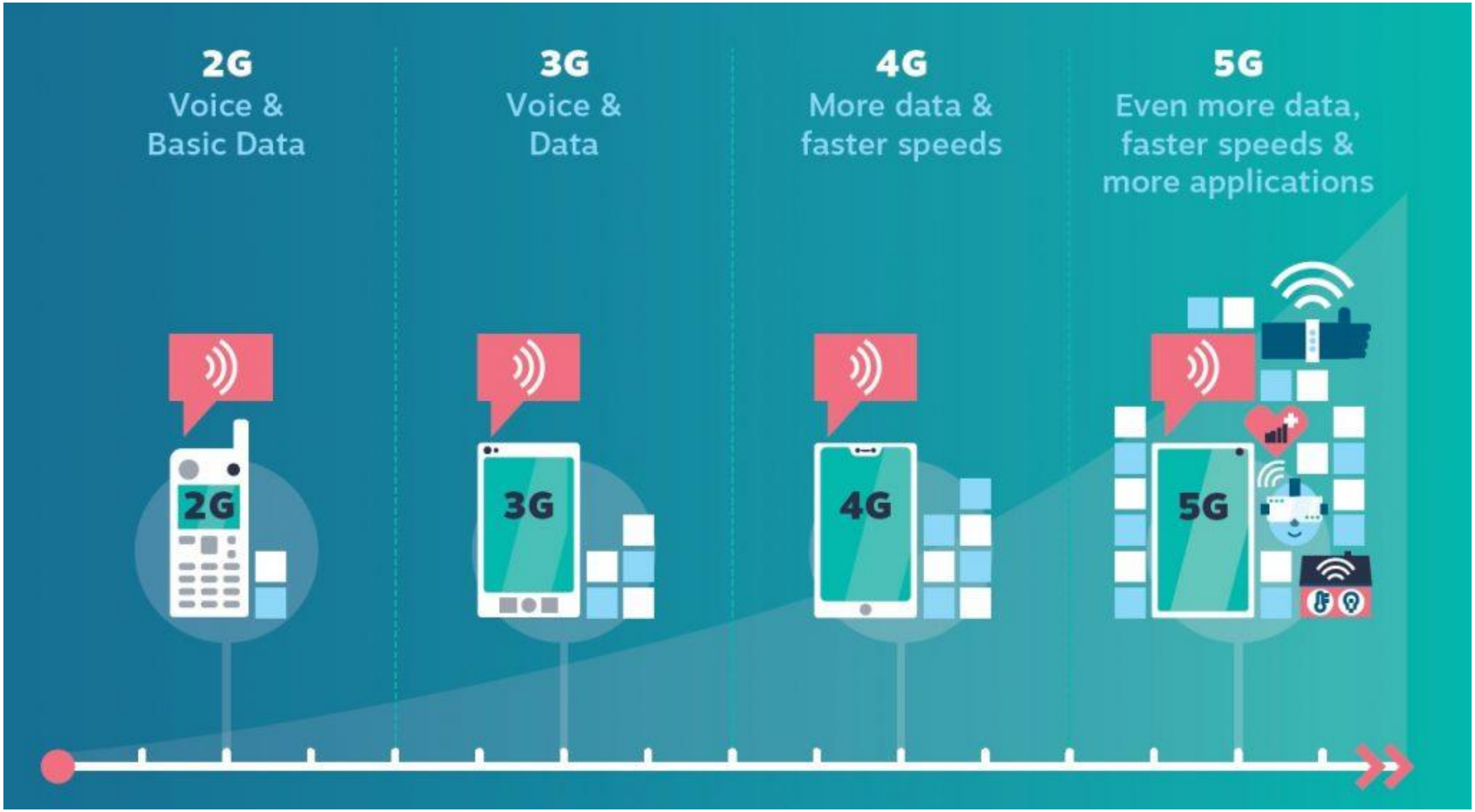
PDN-GW

IP (user)	
PMIP	GTP-U
UDP	GRE
IP	
L2	
L1	

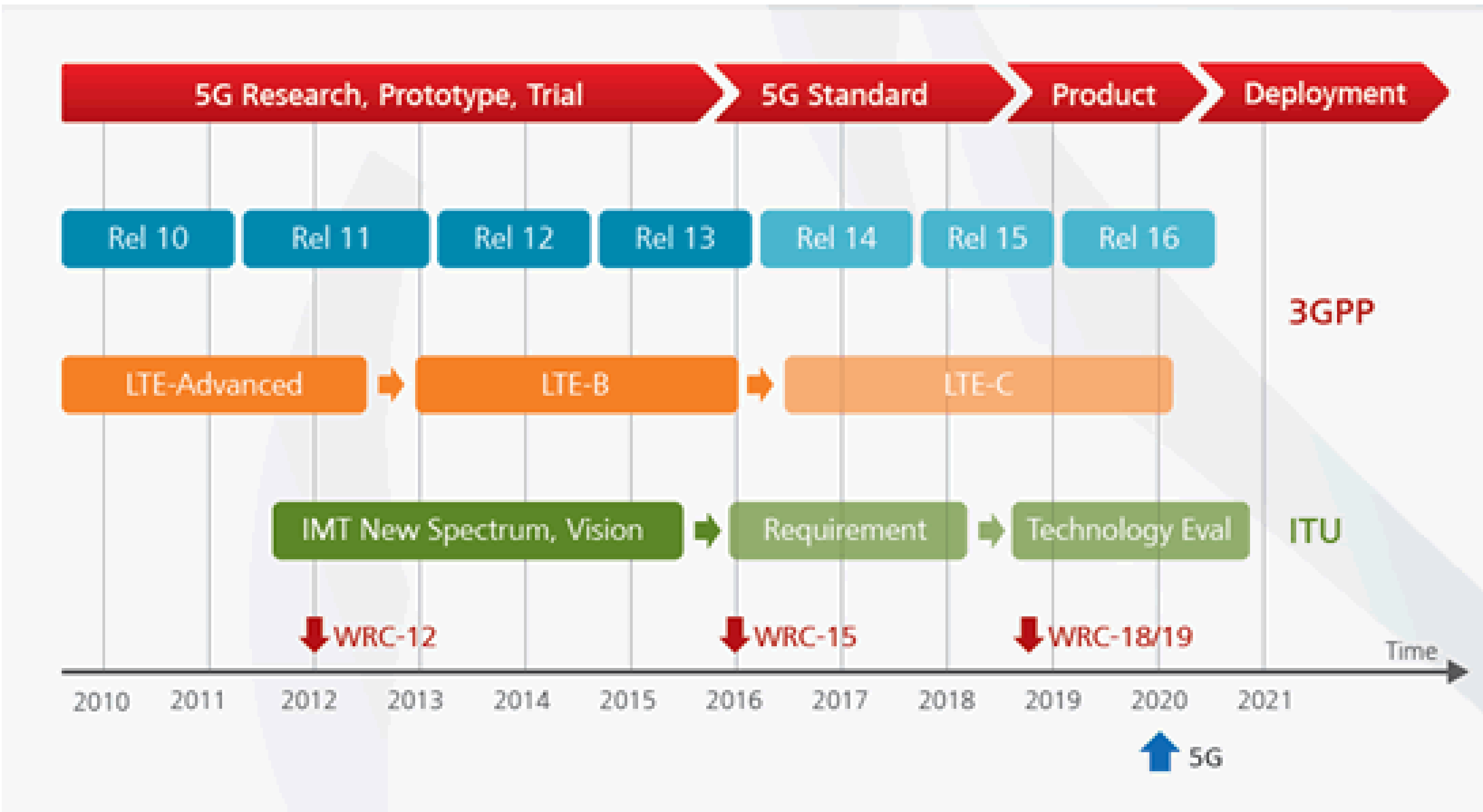
More Detailed EPC



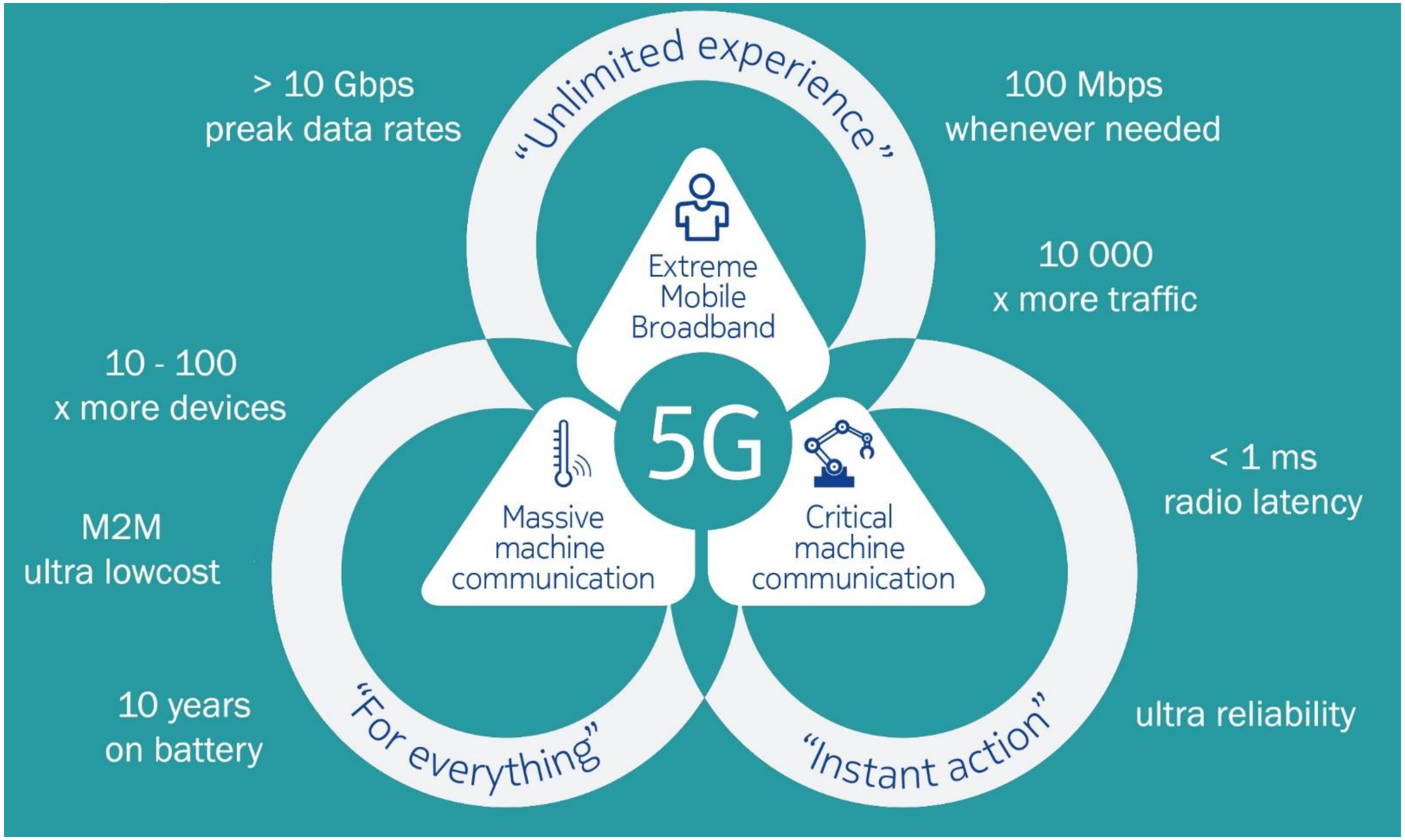
Evolution to 5G



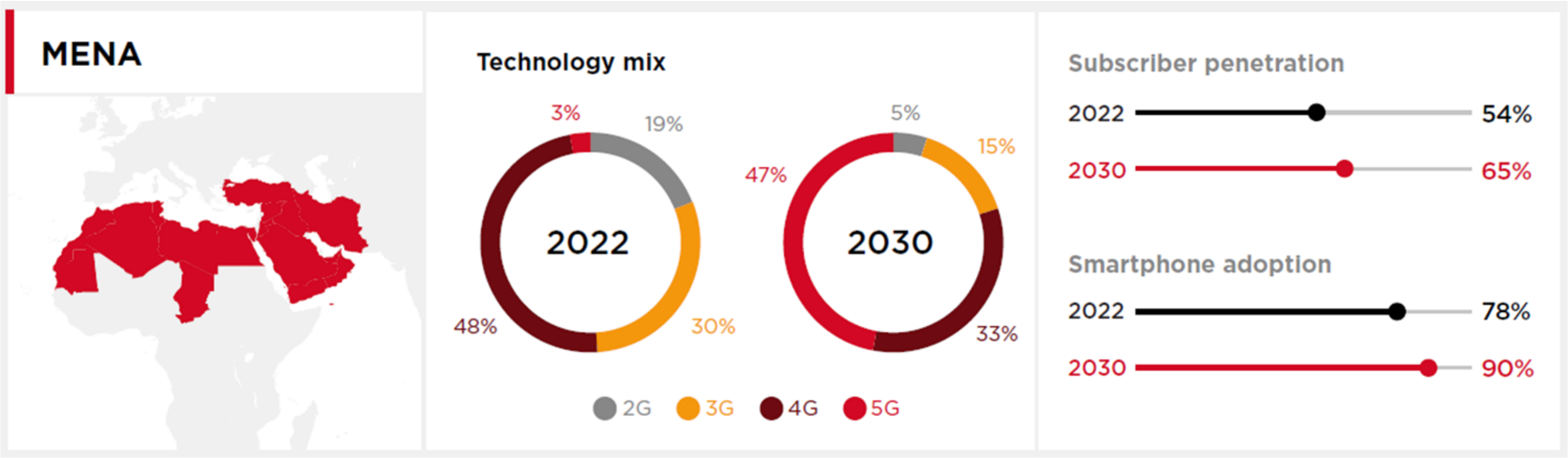
Evolution to 5G



Evolution towards 5G



Mobile Technology Trend



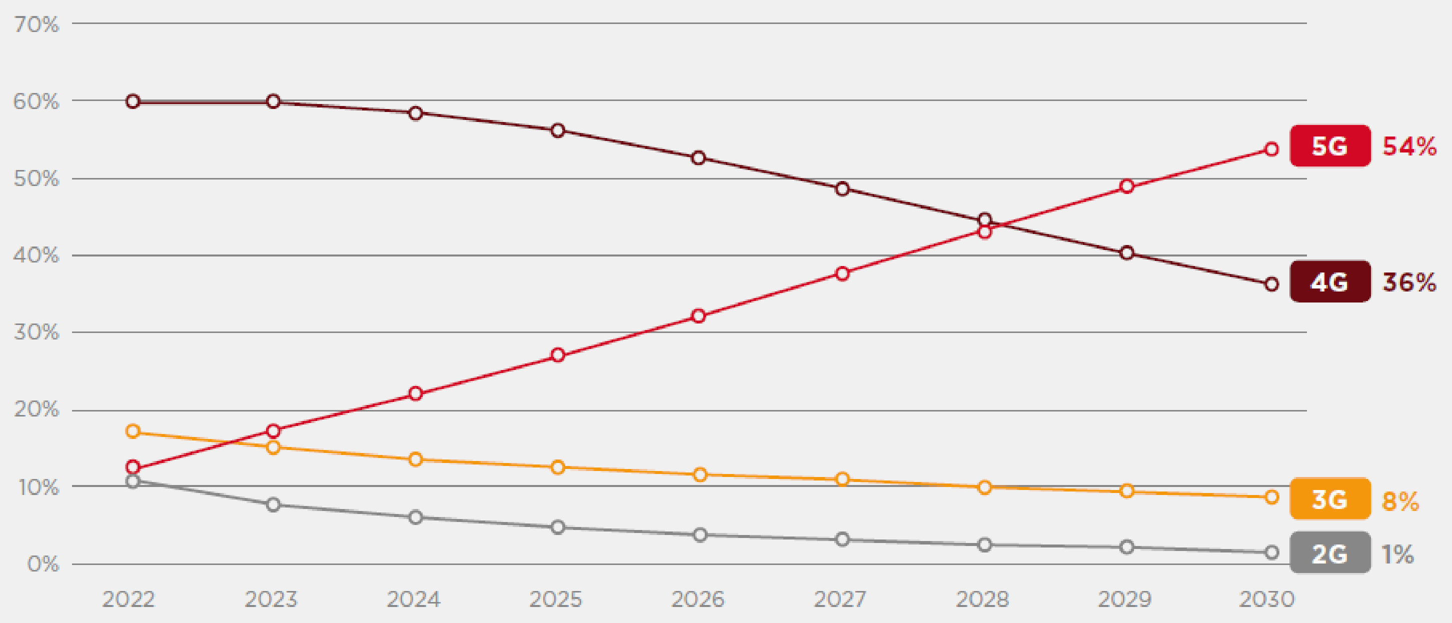
Source:

Mobile Technology Trend

Figure 3

Mobile adoption by technology

Percentage of total connections



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