DIPARTIMENTO DI INFORMATICA
Via Salaria 113 - 00198, Roma

SAPIENZA UNIVERSITÀ DI ROMA

Reti di Elaboratori

Corso di Laurea in Informatica
Università degli Studi di Roma "La Sapienza"
Canale A-L Prof.ssa Chiara Petrioli

Parte di queste slide sono state prese dal materiale associato al libro *Computer Networking: A Top Down Approach* , 5th edition.

Thanks also to Antonio Capone, Politecnico di Milano, Giuseppe Bianchi and Francesco LoPresti, Un. di Roma Tor Vergata

Info Utili: I docenti

Docente responsabile del Corso:

Prof.ssa Chiara Petrioli

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Campo di ricerca del docente: networked systems, con focus su reti wireless, Internet of Things ma anche QoS per Internet, Content Delivery Networks,…

Pagina web del gruppo di ricerca (SENSES lab): senseslab.di.uniroma1.it

Info Utili: I docenti

Esercitatori: Luca Iezzi

Dipartimento di Informatica

E-mail:{iezzi}ATdiag.uniroma1.it

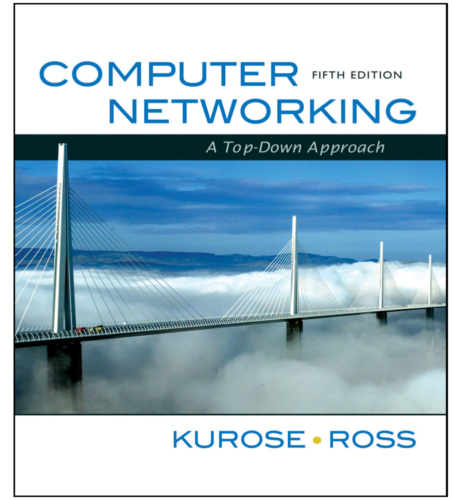
Divisione del corso verticale (per argomenti –es. lezioni frontali fatte dal docente tranne alcune lezioni su specifici argomenti+esercitazioni,introduzione al C-supporto esercitatore Luca Iezzi)

Materiale Didattico

Libro consigliato: *Computer Networking: A Top Down Approach* , Jim Kurose, Keith Ross, Addison-Wesley.

http://www.aw-bc.com/kurose_ross/

Versione italiana: Reti di calcolatori e internet. Un approccio top-down, James Kurose and Keith Ross, Pearson.



Altro materiale didattico (sul sito del corso): slide, articoli, RFC, riferimenti ad altri libri da usare per consultazione o per approfondire specifici argomenti.

Web page del corso:twiki.dsi.uniroma1.it→ Reti degli elaboratori→ Canale A-L

Orario di ricevimento: su appuntamento (per e-mail).

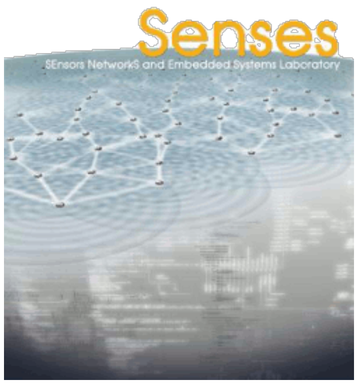
Modalità d’esame

- Scritto con domande aperte
  - Esonero previsti (da definire)
  - Si mantiene il voto per tutto l’anno accademico (e non oltre). Gli esonerati possono fare uno scritto solo sulla seconda parte del programma in tutti gli appelli di esame.
  - Domande sulle esercitazioni incluse nell’esame

Chiara Petrioli

FULBRIGHT

POLITECNICO DI MILANO



SEVENTH FRAMEWORK PROGRAMME

W • S E N S E
INTEGRATED CABLELESS SOLUTIONS

PATENTED

L'Università – il vostro momento

Caratteristica di (quasi) tutti i collaboratori/studenti che hanno lavorato con me in questi 15 anni e che si sono molto specializzati/hanno lavorato sui loro talenti: **Stanno facendo esattamente quello che desideravano nella vita (augurio per voi!)**

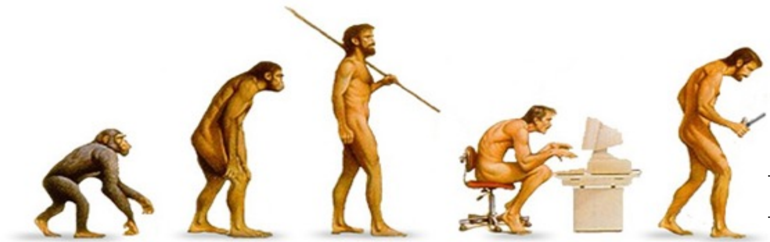
SAPIENZA
UNIVERSITÀ DI ROMA

Dipartimenti di Informatica e Ingegneria Informatica @Sapienza: Dipartimenti di eccellenza italiani

College experience

Facts on career development

Non avrete nessun problema a trovare un lavoro



Dovreste sviluppare la capacità, competenza e l'ambizione per ottenere lavori interessanti











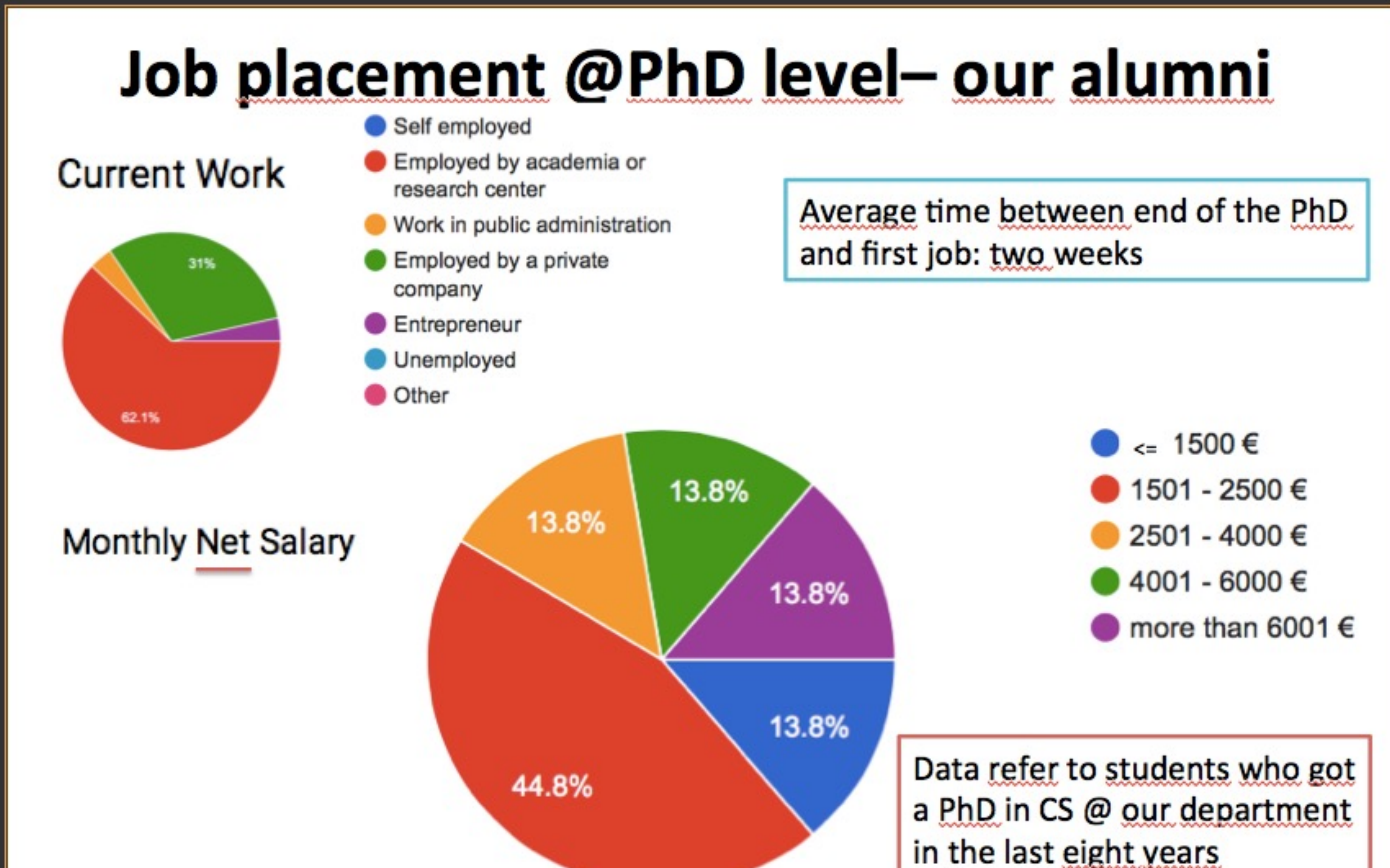


Perché proseguire (magistrale etc.)

Perché proseguire

Perché proseguire

Our alumni are professors, researchers, senior engineers and managers in some of the most prestigious international academic institutions, research centers and companies, including Google, Facebook, Microsoft, Amazon Lab, Digital Catapult, Telecom Paris Tech, NATO STO CMRE, Ericsson, INRIA, CNR, University of Padova, University of Rome La Sapienza, Università di Roma III, Missouri University of Science and Technology, Aalborg University, Cambridge University, UPC, IIT Bombay. Below the results of an anonymous questionnaire on job placement filled by our recent graduates (alumni graduated between two and eight years ago).



Perché proseguire

Scopo del corso

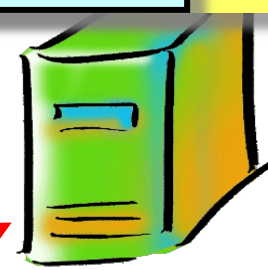
- Come sono in relazione le conoscenze della tecnologia di Internet con quelle relative alla scrittura di software?

Scopo del corso

Noi ci occuperemo:

- **Dei protocolli usati per i colloqui a tutti i livelli**
- **Delle infrastrutture di rete necessarie al funzionamento di INTERNET**

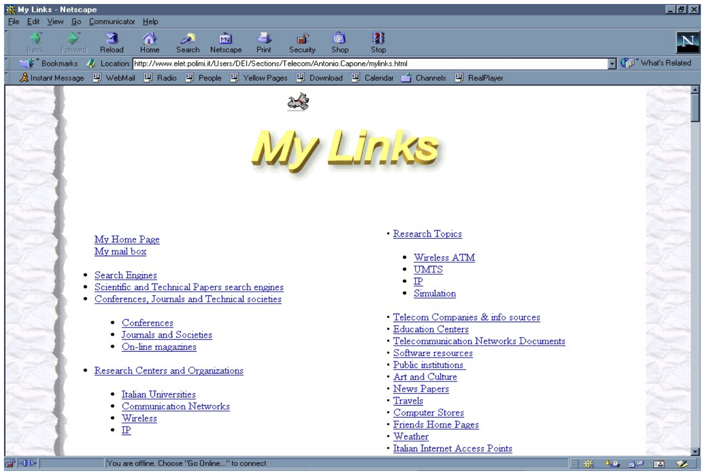
INTERNET



Molti software applicativi colloquiano con software remoti

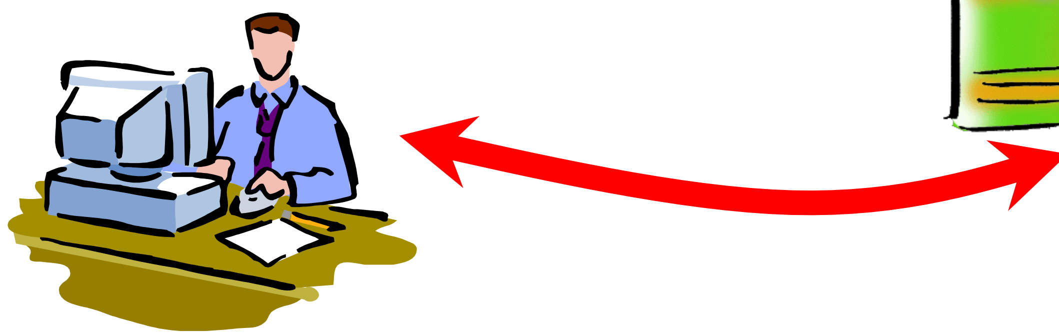
I colloqui sono soggetti a regole (protocolli)

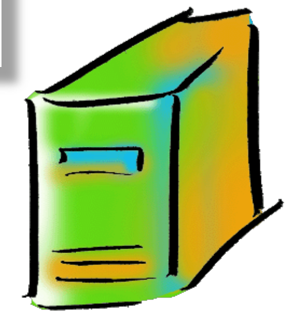
Perché top-down

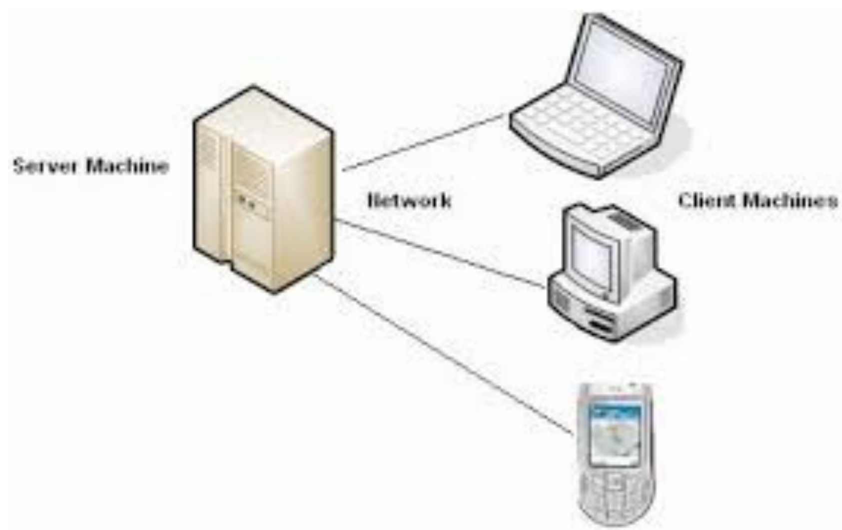


Chi di voi non ha mai navigato sul Web?

Ma chi di voi sa come tutto ciò sia possibile? MAGIC??

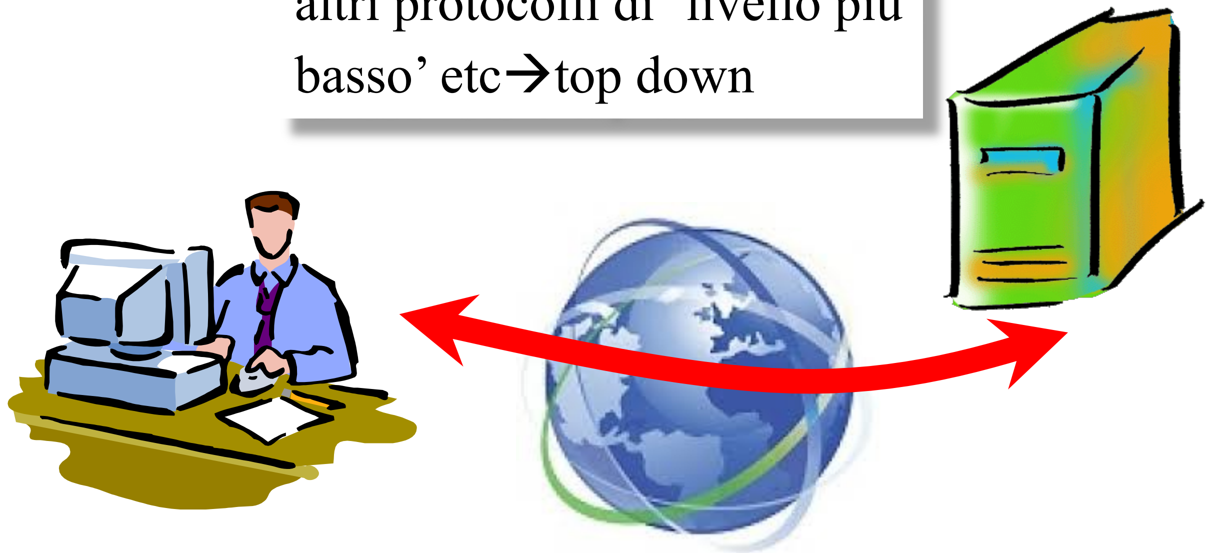






Perché top-down

Conoscere le applicazioni di rete aiuta a comprenderne il funzionamento, quindi i requisiti→ la necessità di altri protocolli di ‘livello più basso’ etc→top down



- OBIETTIVI DEL CORSO:
  - Comprendere come funziona Internet, perché i protocolli su cui si basa Internet funzionano efficacemente e quali problemi risolvono, le motivazioni alla base della loro introduzione e delle decisioni prese nella loro progettazione.
  - Sapere leggere gli standard e saper riconoscere le fonti da consultare quando vi si presenteranno problemi tecnici da risolvere.

Programma del corso

- Primi capitoli del Kurose-Ross. Dalle applicazione alla trasmissione dei segnali sul canale fisico
- Programmazione C e Hands on Experience (esercitazioni)
- Primo corso (sul quale è costruito un percorso formativo):
  - Pochissimo sul livello fisico
  - Descrizione dell’architettura TCP/IP classica →con alcune finestre su argomenti più avanzati o l’attuale evoluzione
  - Reti wireless, radio mobili e Sicurezza: solo alcune lezioni in questo corso. Sono aspetti estensivamente trattati in altri corsi (indirizzo Reti e Sicurezza), soprattutto alla specialistica.
  - Pillole su How to Develop your career

Linguaggi di programmazione di maggior utilità in ambito

Industriale, IEEE Spectrum, 2021

Language Types

- Web
- Enterprise
- Mobile
- Embedded

Rank	Language	Type	Score
1	Python	Web, Enterprise, Embedded	100.0
2	Java	Web, Mobile, Enterprise	95.4
3	C	Mobile, Enterprise, Embedded	94.7
4	C++	Mobile, Enterprise, Embedded	92.4
5	JavaScript	Web	88.1
6	C#	Web, Mobile, Enterprise, Embedded	82.4
7	R	Enterprise	81.7
8	Go	Web, Enterprise	77.7

Chapter 1: Introduction

Computer Networks and the Internet

Our goal:

- get context, overview, "feel" of networking
- more depth, detail *later* in course
- approach:
  - descriptive
  - use Internet as example

Overview:

- what's the Internet
- what's a protocol?
- network edge
- network core
- access net, physical media
- Internet/ISP structure
- performance: loss, delay
- protocol layers, service models
- history
- Standardization activities

Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

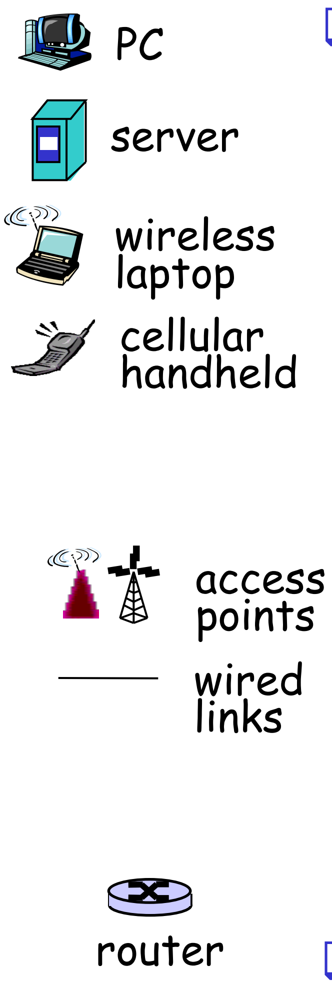
1.5 Internet structure and ISPs

1.6 Delay & loss in packet-switched networks

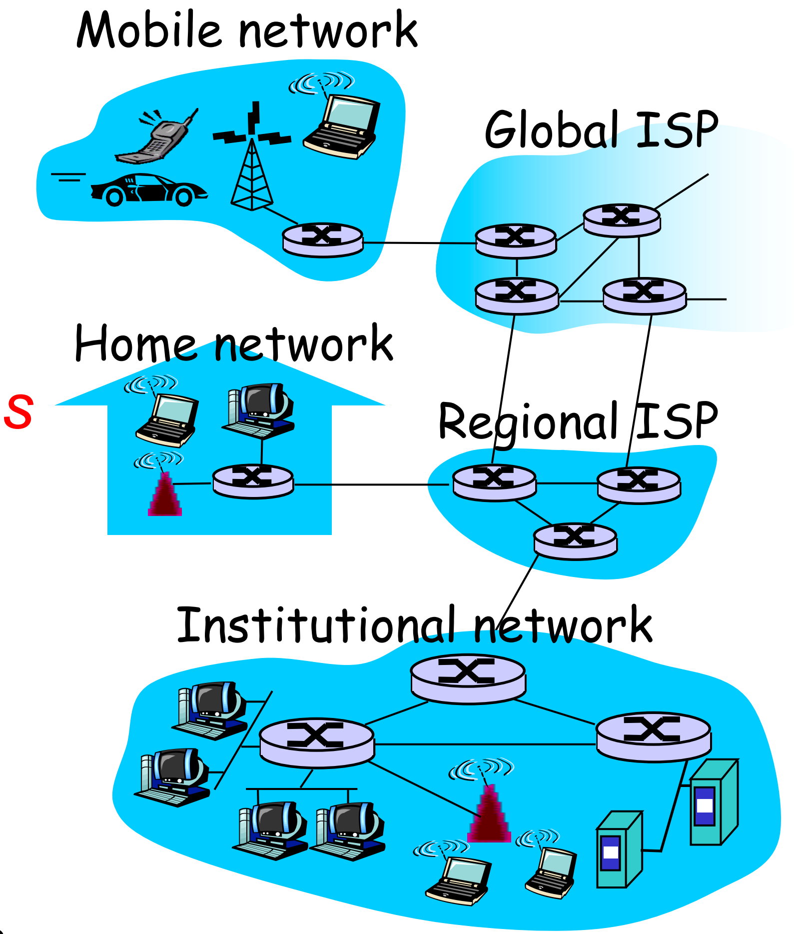
1.7 Protocol layers, service models

1.8 History

What's the Internet: "nuts and bolts" view

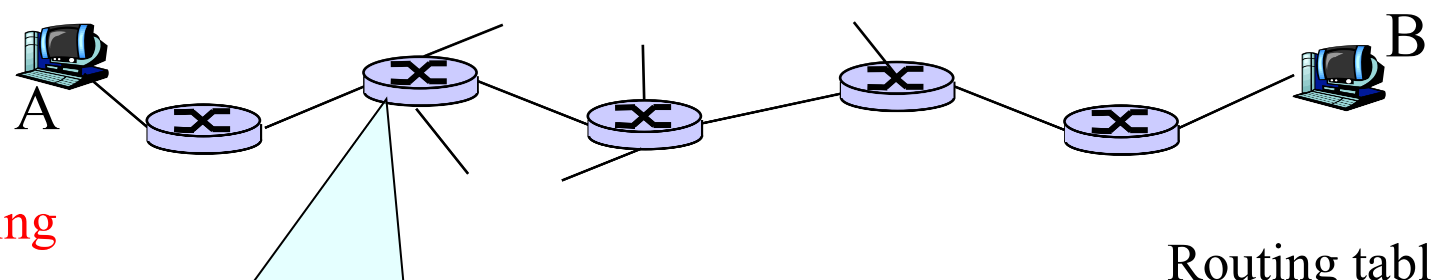


- Hundreds of millions/billions of connected computing devices: *hosts = end systems*
  - running *network apps*
- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate, *bandwidth*
- *routers:* forward packets (chunks of data)



Router

- Forward a chunk of information (called *packet*) arriving on one of its communication links to one of its outgoing communications link (the *next hop* on the source-to-destination path)



forwarding

-Receives the packet
-Based on a routing table and the destination address, computes the 'next hop' to the destination
-Forwards the packet to the next hop
-The process of computing and maintaining the routing table is called Routing

Routing table

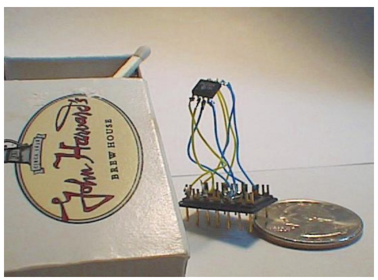
Dest. Address	Next Hop

“Cool” internet appliances

IP picture frame
http://www.ceiva.com/

Web-enabled toaster +
weather forecaster

Internet TV



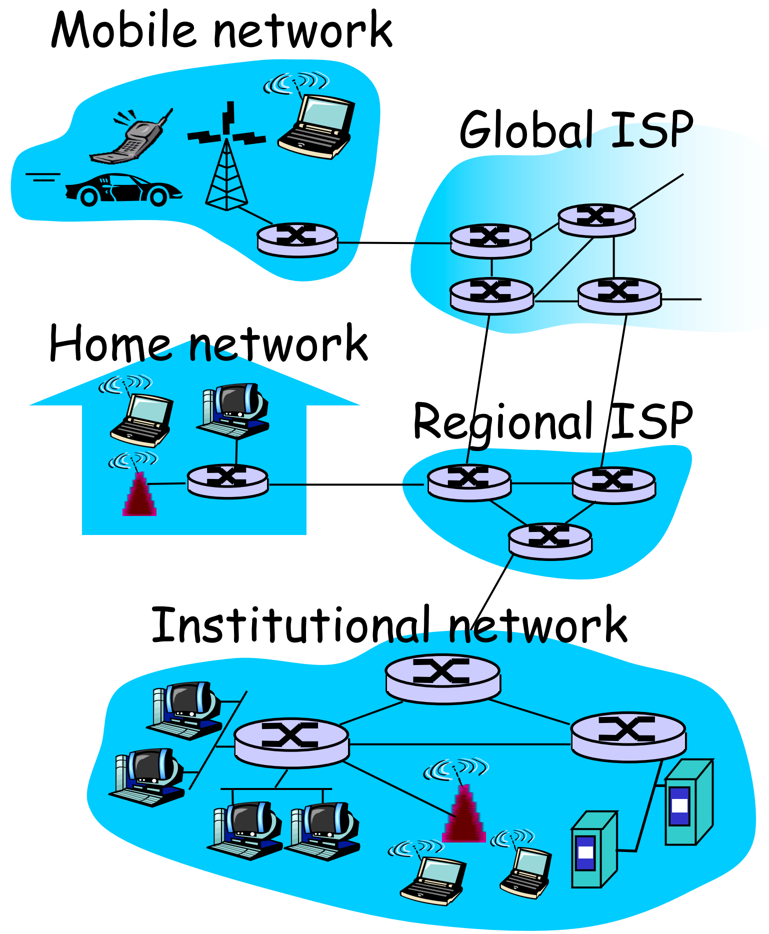
World’s smallest web server

Internet of Things

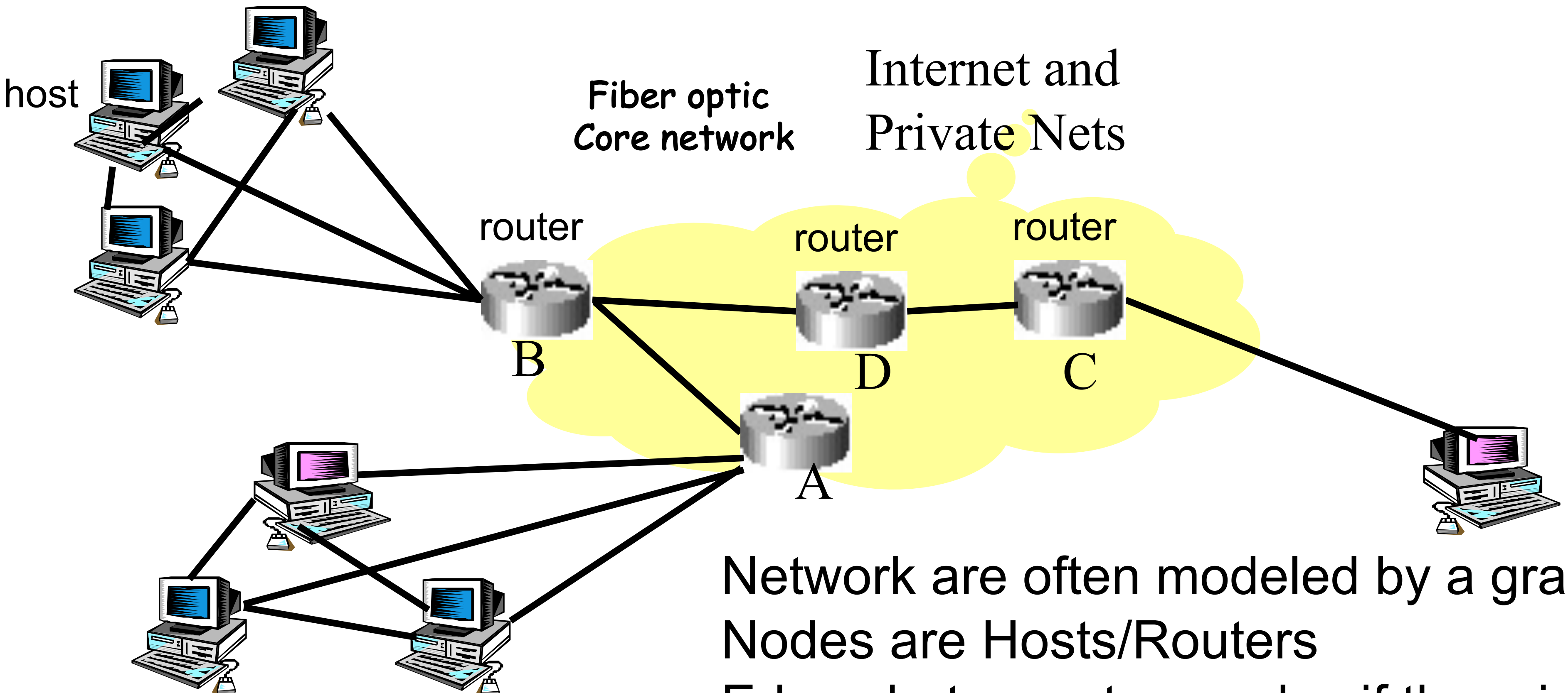
Wearable computing

What's the Internet: "nuts and bolts" view

- *protocols* control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, Skype, Ethernet
- *Internet: "network of networks"*
  - loosely hierarchical
  - public Internet versus private intranet
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force



Network Modeling: Network Physical Topology (a link to what you know)



Host = 1 interface
Router = 2+ interfaces

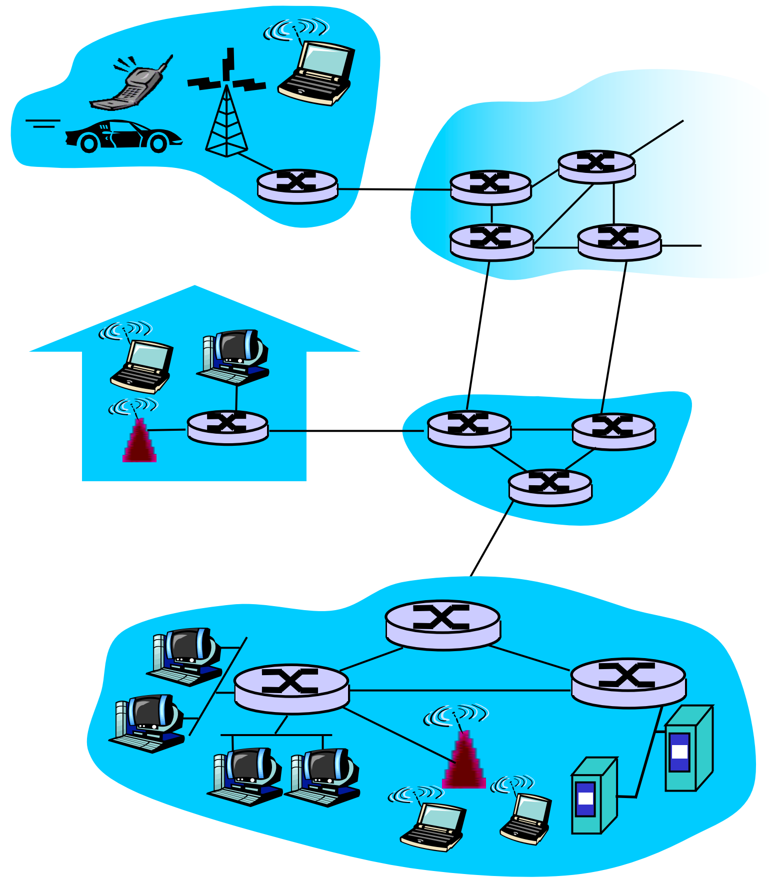
Network are often modeled by a graph
Nodes are Hosts/Routers
Edges between two nodes if there is a communication link between them
→ Network Physical topology

Rete logica e rete fisica

- Topologia fisica della rete
  - Un elemento di rete = un nodo
  - Esiste un arco tra due entità che sono collegate da un mezzo trasmissivo
- Topologia logica della rete
  - Un arco esprime un percorso diretto che l’informazione può seguire tra host ed un elemento di commutazione, o tra due elementi di commutazione
  - Nodo = elemento di commutazione, host

What's the Internet: a service view

- communication *infrastructure* enables distributed applications:
  - Web, VoIP, email, games, e-commerce, file sharing
- communication services provided to apps:
  - reliable data delivery from source to destination
  - "best effort" (unreliable) data delivery



What's a protocol?

human protocols:

- "what's the time?"
- "I have a question"
- introductions

… specific msgs sent

… specific actions taken when msgs received, or other events

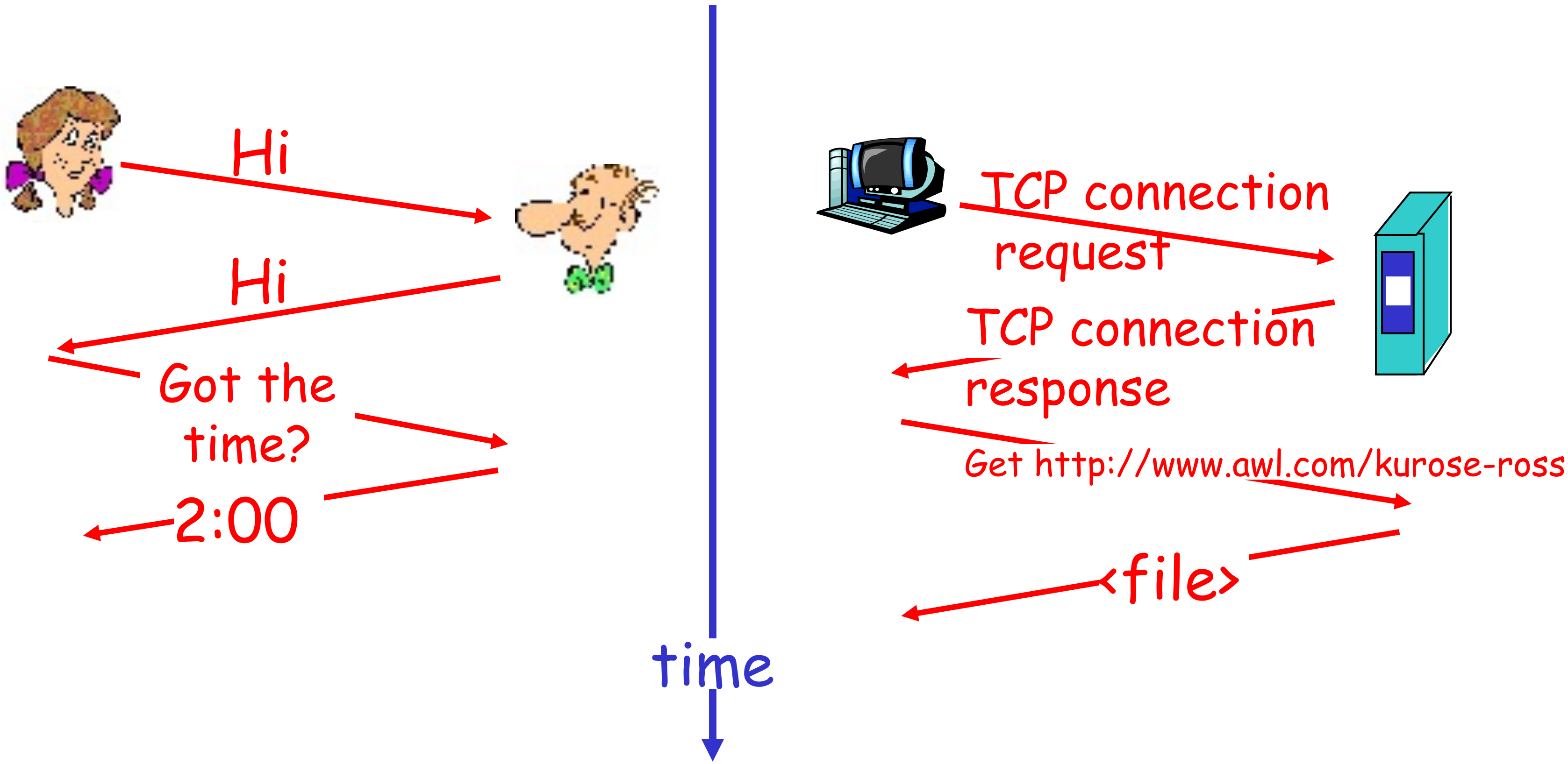
network protocols:

- machines rather than humans
- all communication activity in Internet governed by protocols

protocols define format, order of messages sent and received among network entities, and actions taken on msg transmission, receipt

What's a protocol?

a human protocol and a computer network protocol:



Q: Other human protocols?

What's the Internet: a service view

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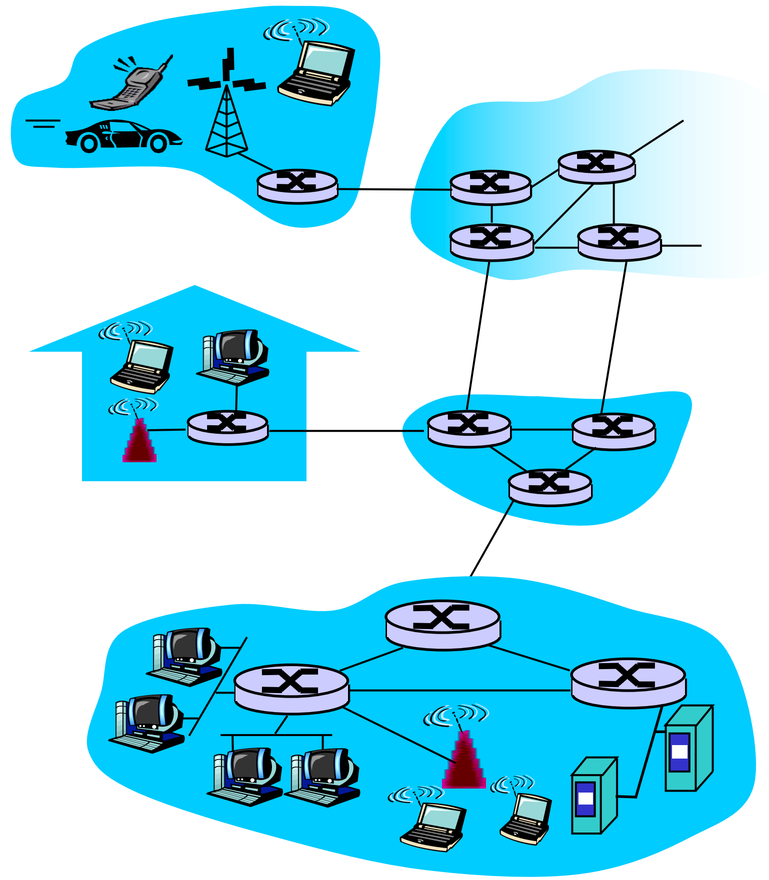


Network edge: connection-oriented service

Goal: data transfer between end systems
- *handshaking:* setup (prepare for) data transfer ahead of time
  - Hello, hello back human protocol
  - *set up "state"* in two communicating hosts

  (not in the network!!)
- TCP - Transmission Control Protocol
  - Internet's connection-oriented service

TCP service [RFC 793]

- *reliable, in-order* byte-stream data transfer
  - loss: acknowledgements and retransmissions
- *flow control:*
  - sender won't overwhelm receiver
- *congestion control:*
  - senders "slow down sending rate" when network congested

Network edge: connectionless service

Goal: data transfer between end systems
- same as before!

- UDP - User Datagram Protocol [RFC 768]: Internet's connectionless service
  - unreliable data transfer
  - no flow control
  - no congestion control

App's using TCP:

- HTTP (Web), FTP (file transfer), Telnet (remote login), SMTP (email)

App's using UDP:

- streaming media, teleconferencing, DNS, Internet telephony

Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

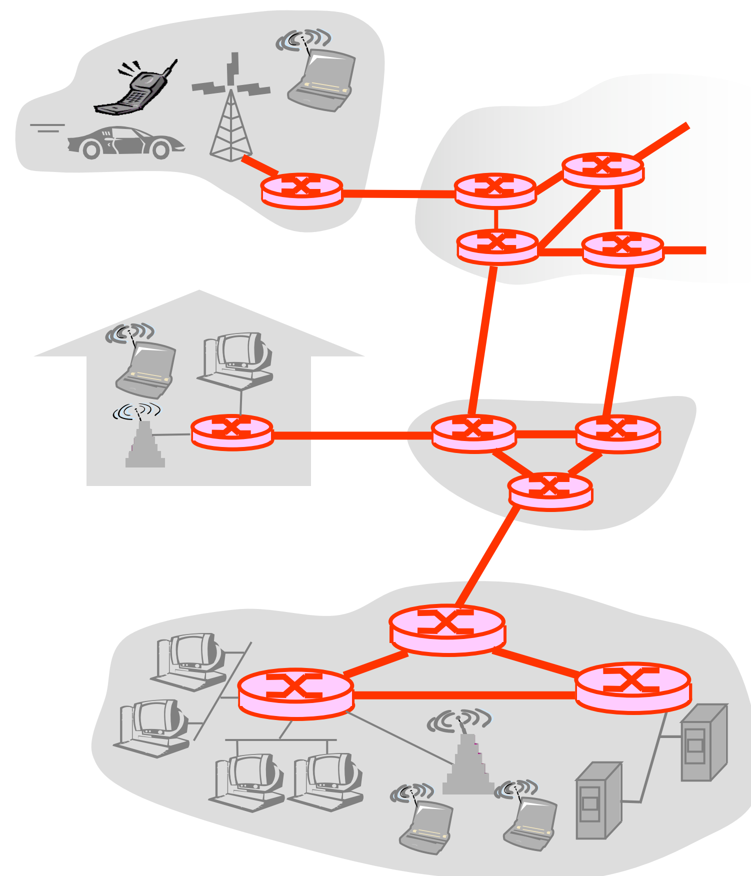
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

The Network Core

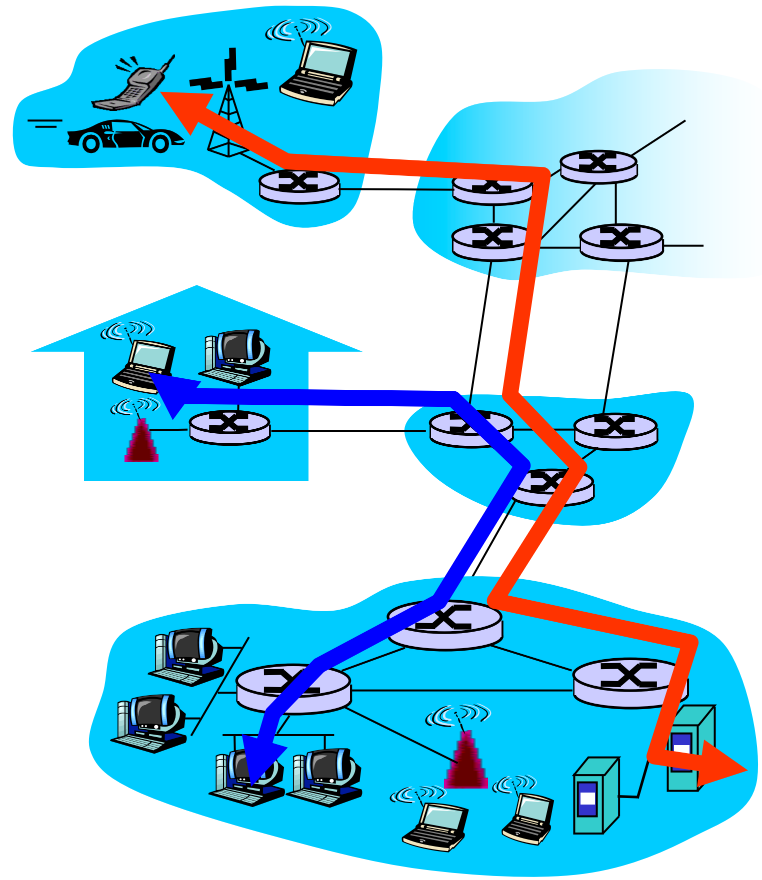
- mesh of interconnected routers
- *the* fundamental question: how is data transferred through net?
  - circuit switching: dedicated circuit per call: telephone net
  - packet-switching: data sent thru net in discrete "chunks"



Network Core: Circuit Switching

End-end resources reserved for "call"

- link bandwidth, switch capacity
- dedicated resources: no sharing
- circuit-like (guaranteed) performance
- call setup required



Network Core: Circuit Switching

network resources (e.g., bandwidth) divided into "pieces"

- pieces allocated to calls
- resource piece *idle* if not used by owning call *(no sharing)*

- dividing link bandwidth into "pieces"
  - frequency division
  - time division

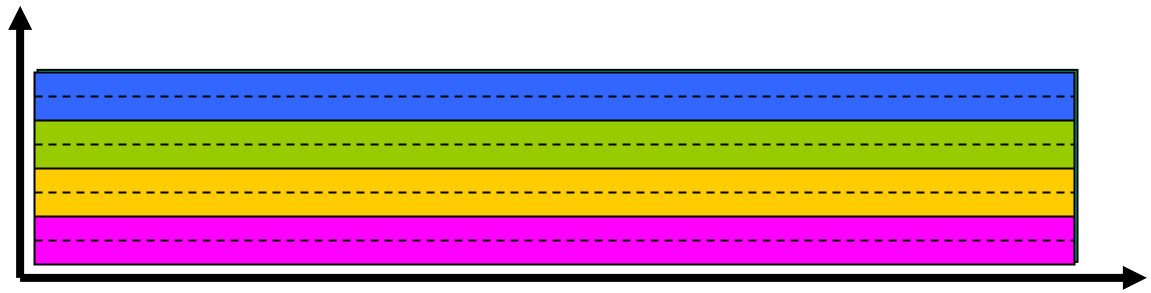
Circuit Switching: FDM and TDM

Example:

4 users

FDM

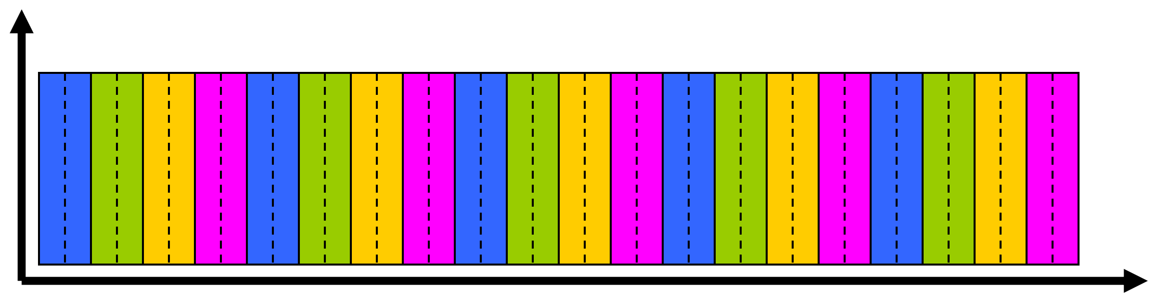
frequency



time

TDM

frequency



time

Numerical example

- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - All links are 1.536 Mbps
  - Each link uses TDM with 24 slots/sec
  - 500 msec to establish end-to-end circuit

Let's work it out!

..Numerical example

- Each circuit has a transmission rate of (1,536Mbps)/24=64Kbps
- 640000/64000=10s
- Plus the circuit establishment→10,5s

Network Core: Packet Switching

each end-end data stream divided into *packets*

- user A, B packets *share* network resources
- each packet uses full link bandwidth
- resources used *as needed*

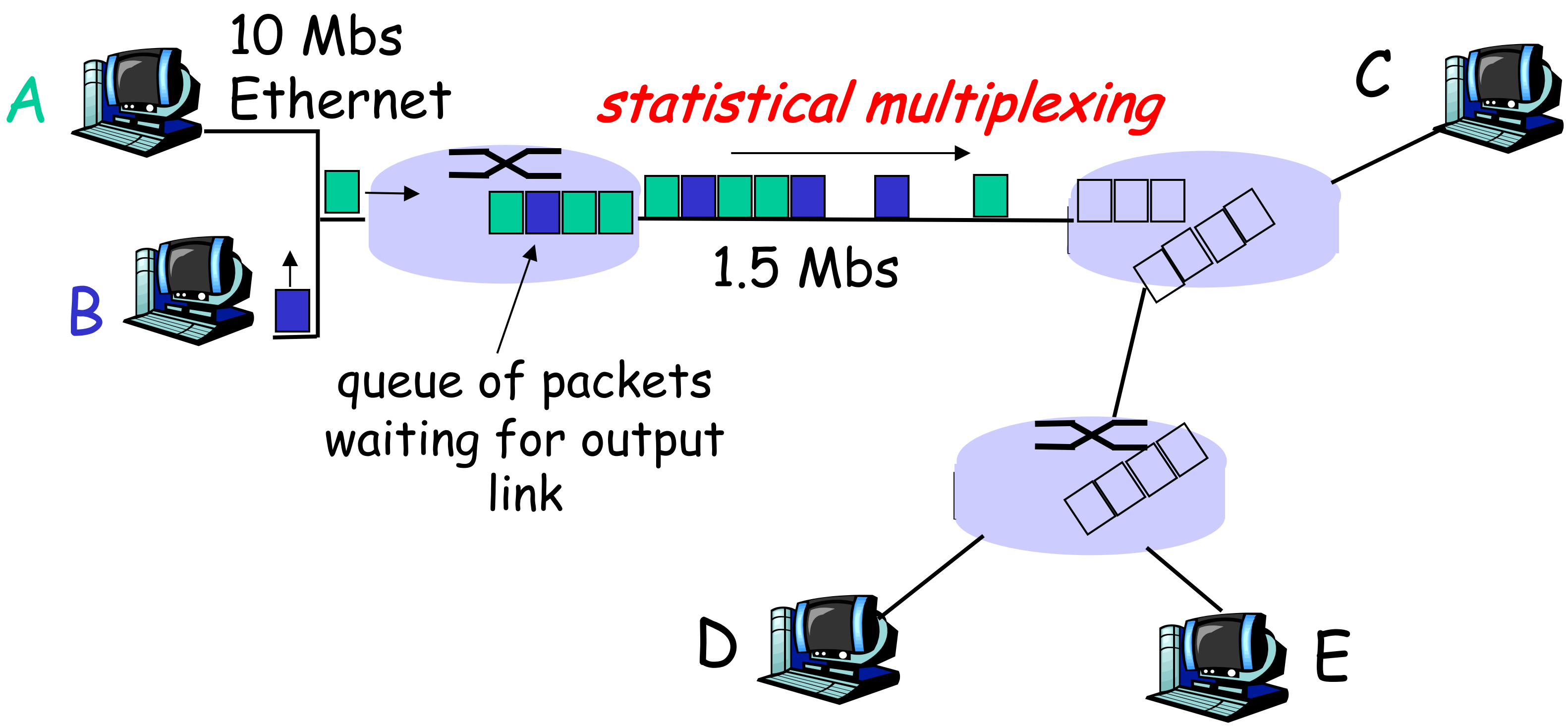
Bandwidth division into "pieces"
Dedicated allocation
Resource reservation

resource contention:

- aggregate resource demand can exceed amount available
- congestion: packets queue, wait for link use
- store and forward: packets move one hop at a time

Node receives complete packet before forwarding

Packet Switching: Statistical Multiplexing



Sequence of A & B packets does not have fixed pattern ➡ ***statistical multiplexing***.

In TDM each host gets same slot in revolving TDM frame.

Network Core: Packet Switching

each end-end data stream divided into *packets*

- user A, B packets *share* network resources
- each packet uses full link bandwidth
- resources used *as needed*

Bandwidth division into "pieces"

Dedicated allocation

Resource reservation

resource contention:

- aggregate resource demand can exceed amount available
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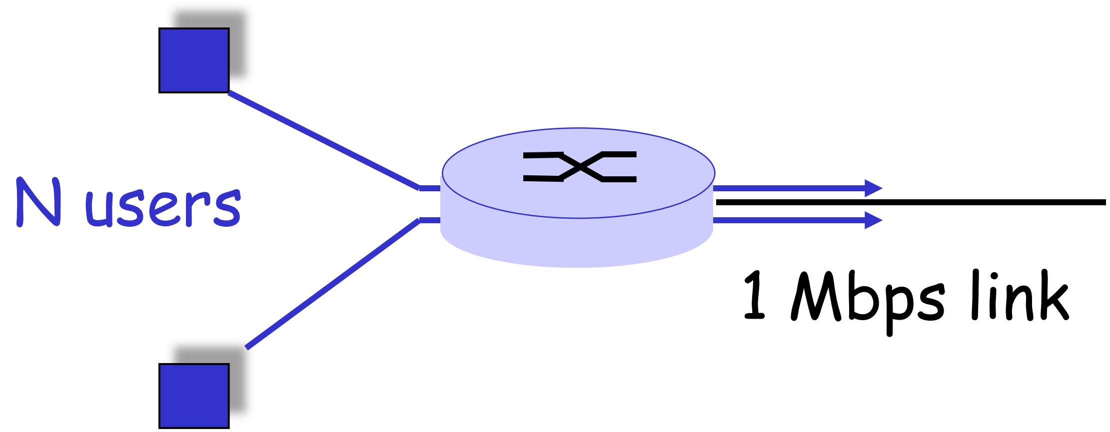
Packet switching versus circuit switching

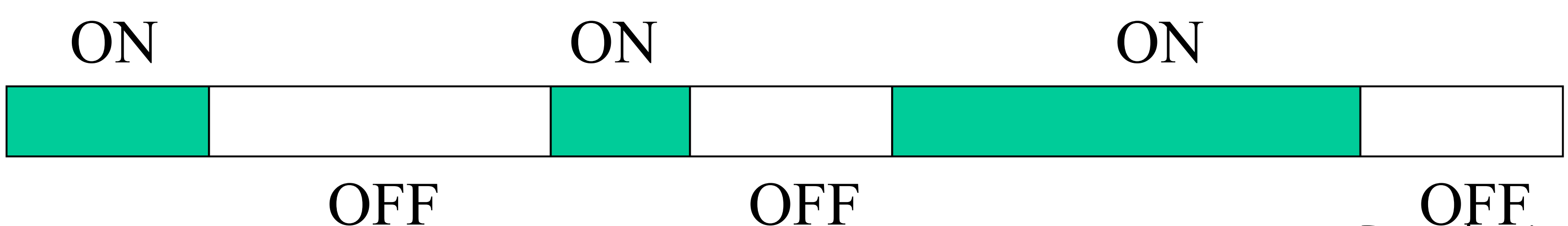
Packet switching allows more users to use network!

- 1 Mbit link
- each user:
  - 100 kbps when "active"
  - active 10% of time
- circuit-switching:
  - 10 users
- packet switching:
  - with 35 users, probability > 10 active less than .0004



Source types

- Constant Bit Rate (e.g. encoded voice without silence suppression→ voice packets have fixed size and are trasmitted periodically. Required bit rate: 64Kbps)
- Variable Bit Rate (e.g. Video encoding, voice with silence suppression, file downloading etc.)
    - The bit rate varies with time
    - Source behavior characterized by min/max transmission rate, and average bit rate. Source burstiness = max bit rate/ average bit rate.
    - Example: CBR ON/OFF



Packet switching versus circuit switching

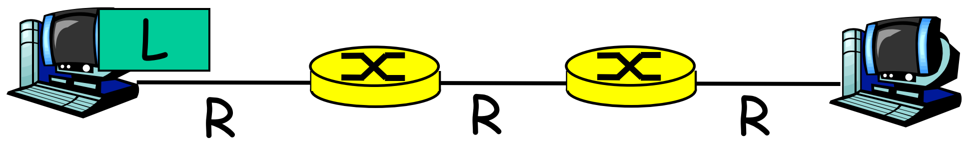
Is packet switching a "slam dunk winner?"

- Great for bursty data
  - resource sharing
  - simpler, no call setup
- Excessive congestion: packet delay and loss
  - protocols needed for reliable data transfer, congestion control

Packet switching

- Perche’ dividere i messaggi trasmessi dall’applicazione in pacchetti di dimensione limitata.
  - Nelle prossime slides pro e contro….

Packet-switching: store-and-forward



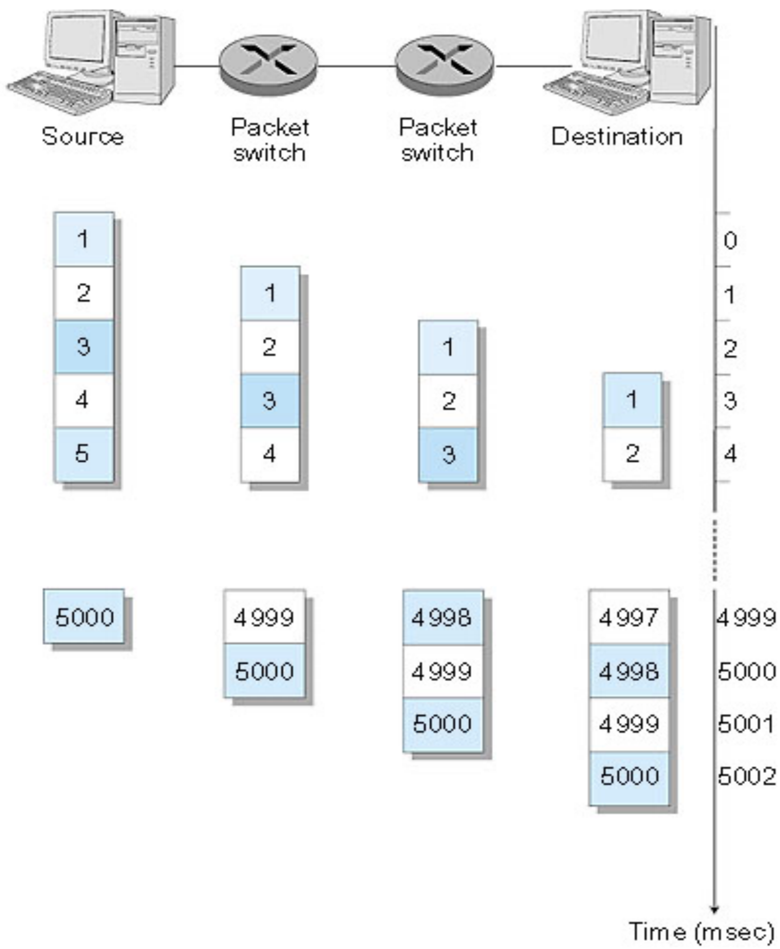
- Takes L/R seconds to transmit (push out) packet of L bits on to link or R bps
- Entire packet must arrive at router before it can be transmitted on next link: *store and forward*
- delay = 3L/R

Example:

- L = 7.5 Mbit
- R = 1.5 Mbps
- delay = 15 sec

(only transmission delay considered here)

Packet Switching: Message Segmenting



Now break up the message into 5000 packets

- Each packet 1,500 bits
- 1 msec to transmit packet on one link
- *pipelining:* each link works in parallel
- Delay reduced from 15 sec to 5.003 sec

Message switching iff dim pacchetti= dim. messaggio originale applicativo

See packet-switching vs. message switching (no segmentation) and the effect of queueing delay through the Java applets on the Kurose-Ross website.

Effect of packet sizes

Packet format

- A longer packet (more data transmitted in a single packet) leads to a lower overhead
- Longer packets result in a higher chance to be corrupted (critical especially for wireless transmission)
- When a packet is corrupted all the data are lost and need to be retransmitted
- Longer packets might decrease the parallellsm of transmission

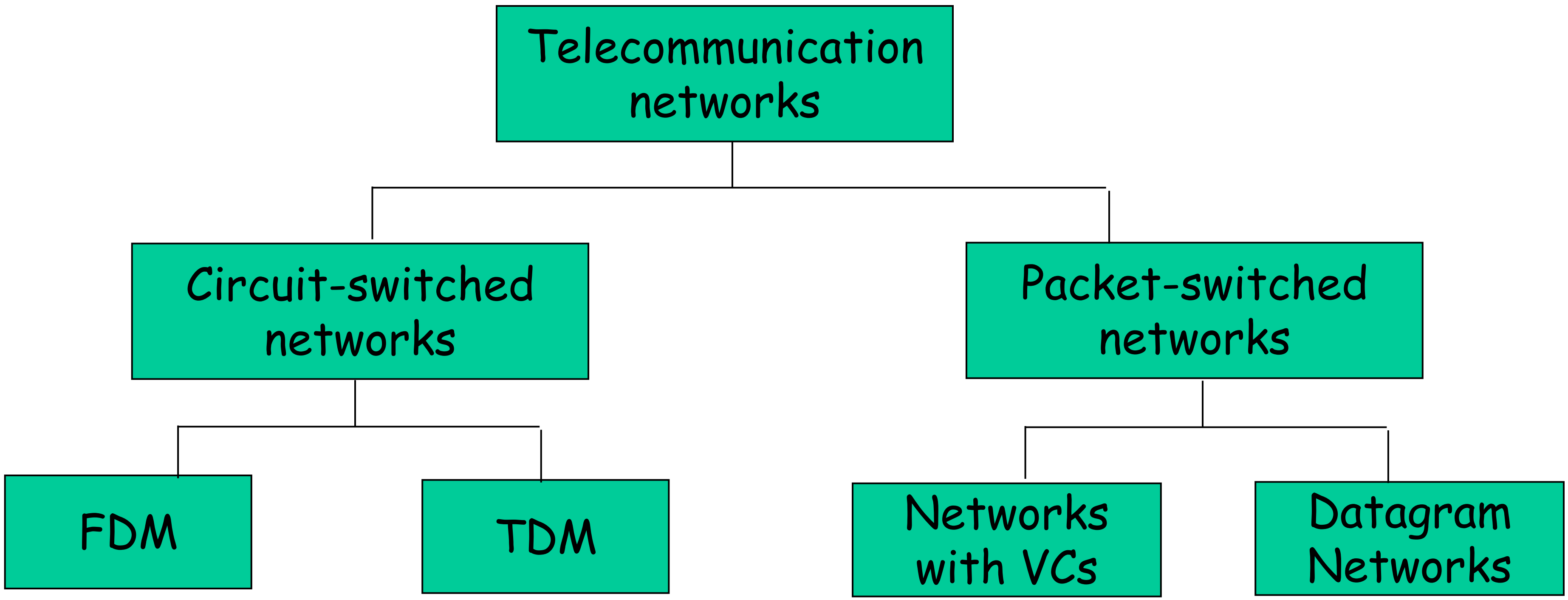
Packet-switched networks: forwarding

- *Goal:* move packets through routers from source to destination
  - we'll study several path selection (i.e. routing)algorithms (chapter 4)
- datagram network:
  - *destination address* in packet determines next hop
  - routes may change during session
  - analogy: driving, asking directions
- virtual circuit network:
  - each packet carries tag (virtual circuit ID), tag determines next hop
  - fixed path determined at *call setup time*, remains fixed thru call; VC share network resources
  - *routers maintain per-call state (the link on which a packet with a VC tag arriving to a given inbound link has to be forwarded and its VC tag on the next hop)*
  - Virtual circuit number changes from hop to hop. Each router has to map incoming interface, incoming VC # in outgoing interface, outgoing VC #
    - Why? (what would be the size of the VC number field and the complexity of the VC number assignment in case the same VC # had to be used over the whole path??)

Internet L3 protocol: IP

MPLS

Network Taxonomy



Chapter 1: roadmap

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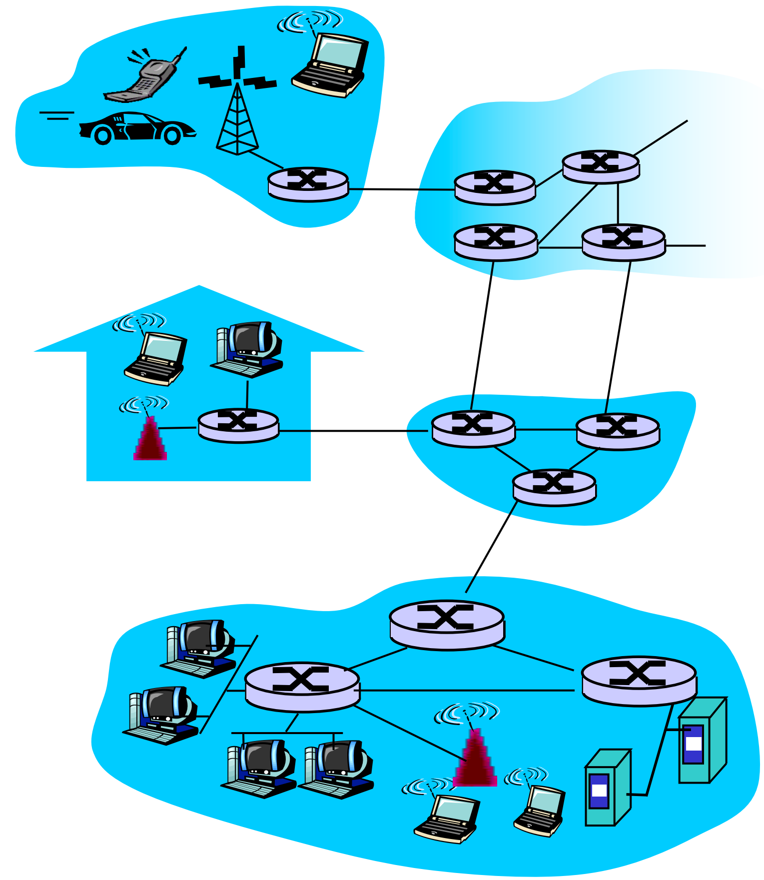
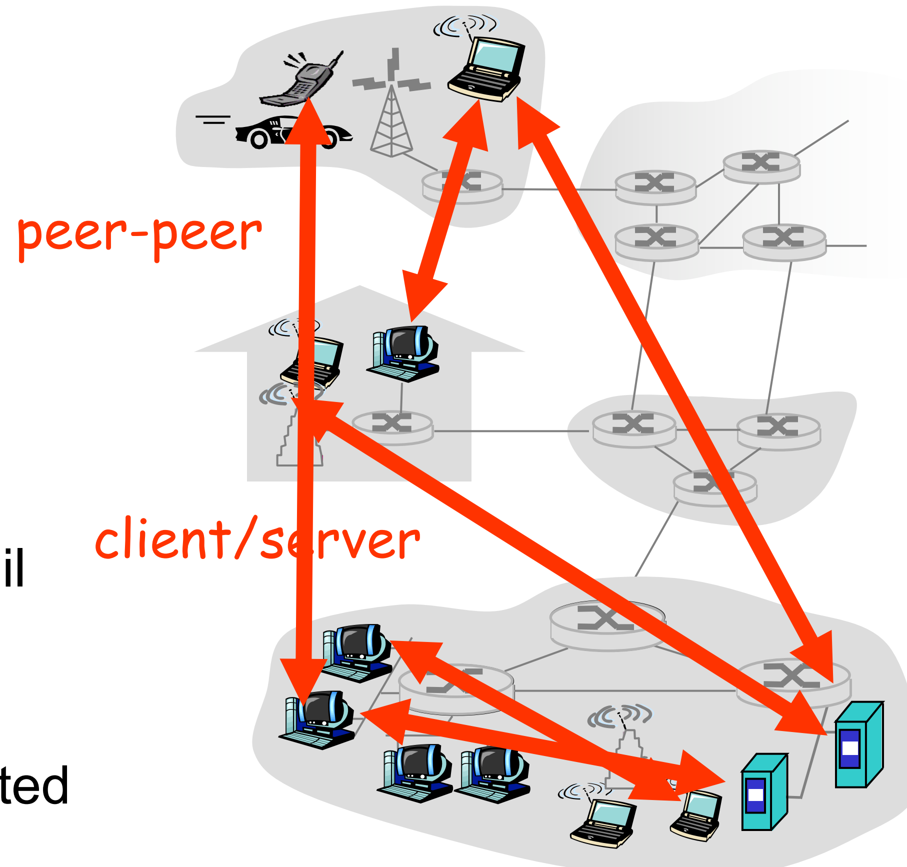
A closer look at network structure:

- network edge: applications and hosts
- access networks, physical media: wired, wireless communication links
- network core:
  - interconnected routers
  - network of networks



The network edge:

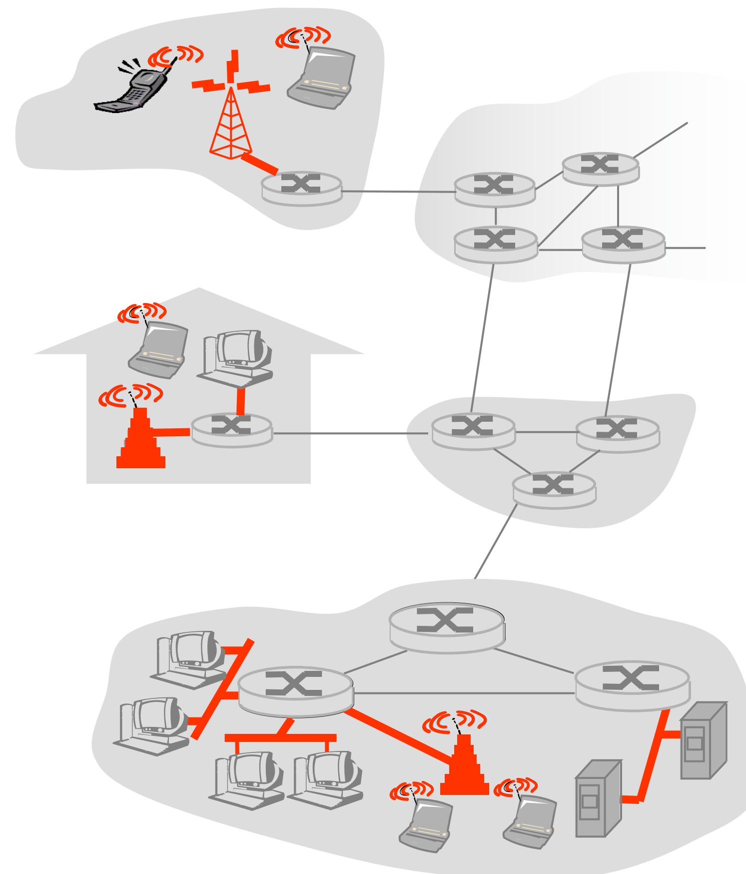
- end systems (hosts):
  - run application programs
  - e.g. Web, email
  - at "edge of network"
- client/server model
  - client host requests, receives service from always-on server
  - e.g. Web browser/server; email client/server
- peer-peer model:
  - minimal (or no) use of dedicated servers
  - e.g. Skype, BitTorrent



Access networks and physical media

Q: How to connect end systems to edge router?

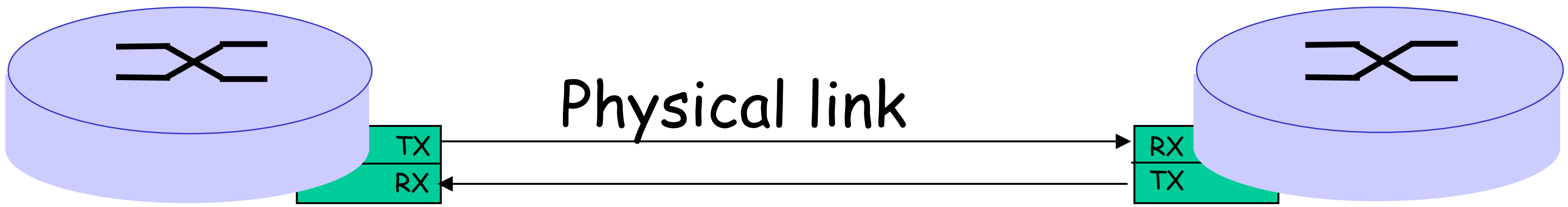
- residential access nets
- institutional access networks (school, company)
- mobile access networks



Keep in mind:

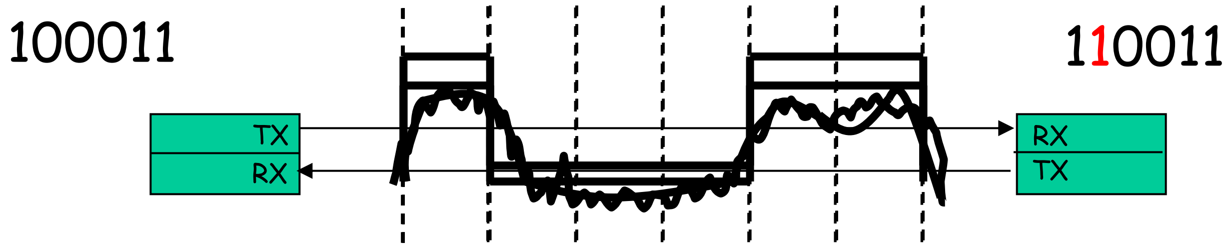
- bandwidth (bits per second) of access network?
- shared or dedicated?
- reliable/unreliable (bit error rates)

Transmission across a physical link



- Bits: propagate between transmitter and receiver
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio

Transmission across a physical link

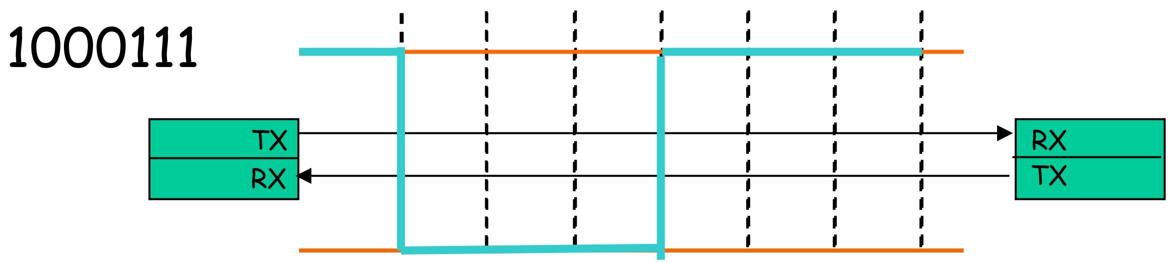


- Bit sequence modulates a suitable waveform which is sent across the link
  - How and which depends on the medium
- As the signal travels it experiences
  - Attenuation (absorption)
  - Distortion (limited bandwidth (frequency))
  - Noise (interference, thermal noise)
  - Influenced by medium, bit rate and distance
- Received sequence may be incorrect!!!

Codifica NRZ

- Codifica NRZ (Non Return to Zero)

Ogni bit ha associato un valore stabile per la sua intera durata (1: High; 0: Low)

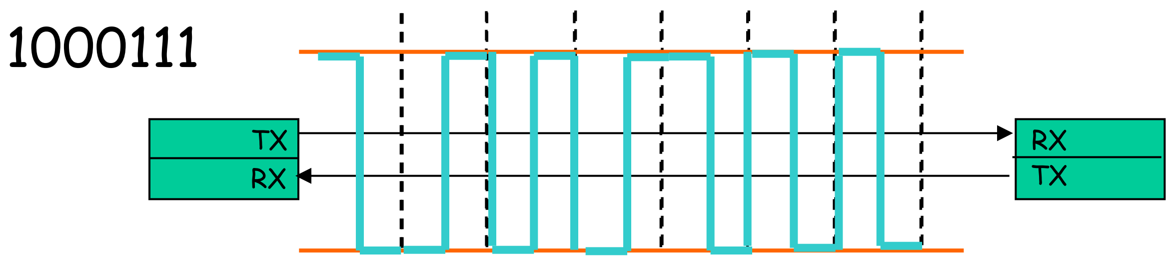


Problemi di sincronizzazione del ricevitore (nessuna transizione nel caso di sequenze di zeri o di uni)→ NRZ 5B6B o 4B5B

Codifica Manchester

- Codifica Manchester

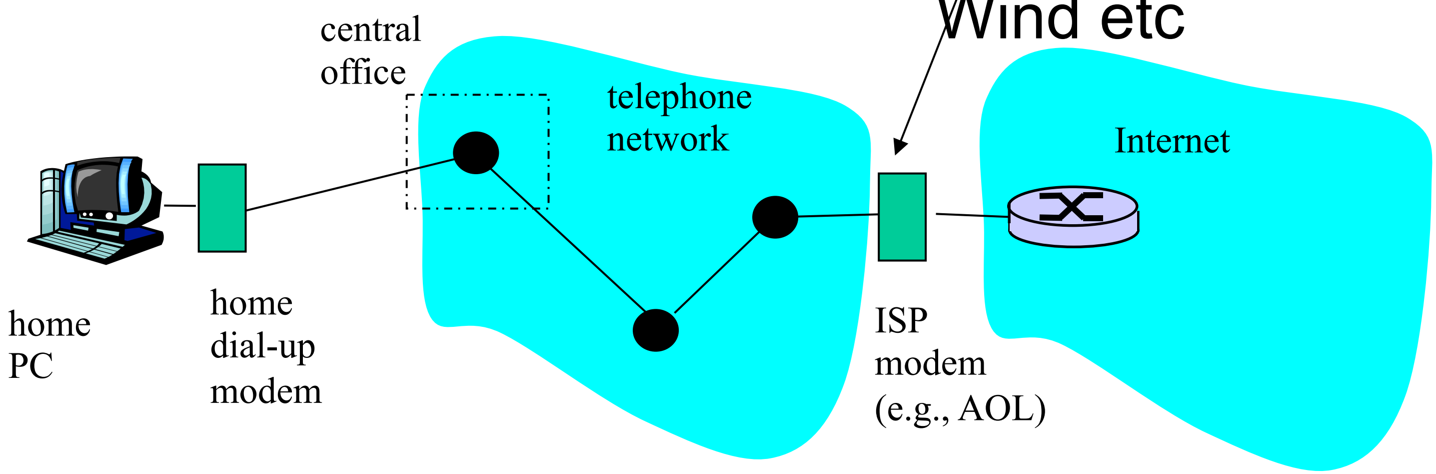
Una transizione basso-alto (codifica dello zero) o alto-basso (codifica del valore uno) in corrispondenza di ogni bit



Usato in Ethernet 10Mbps e Token Ring

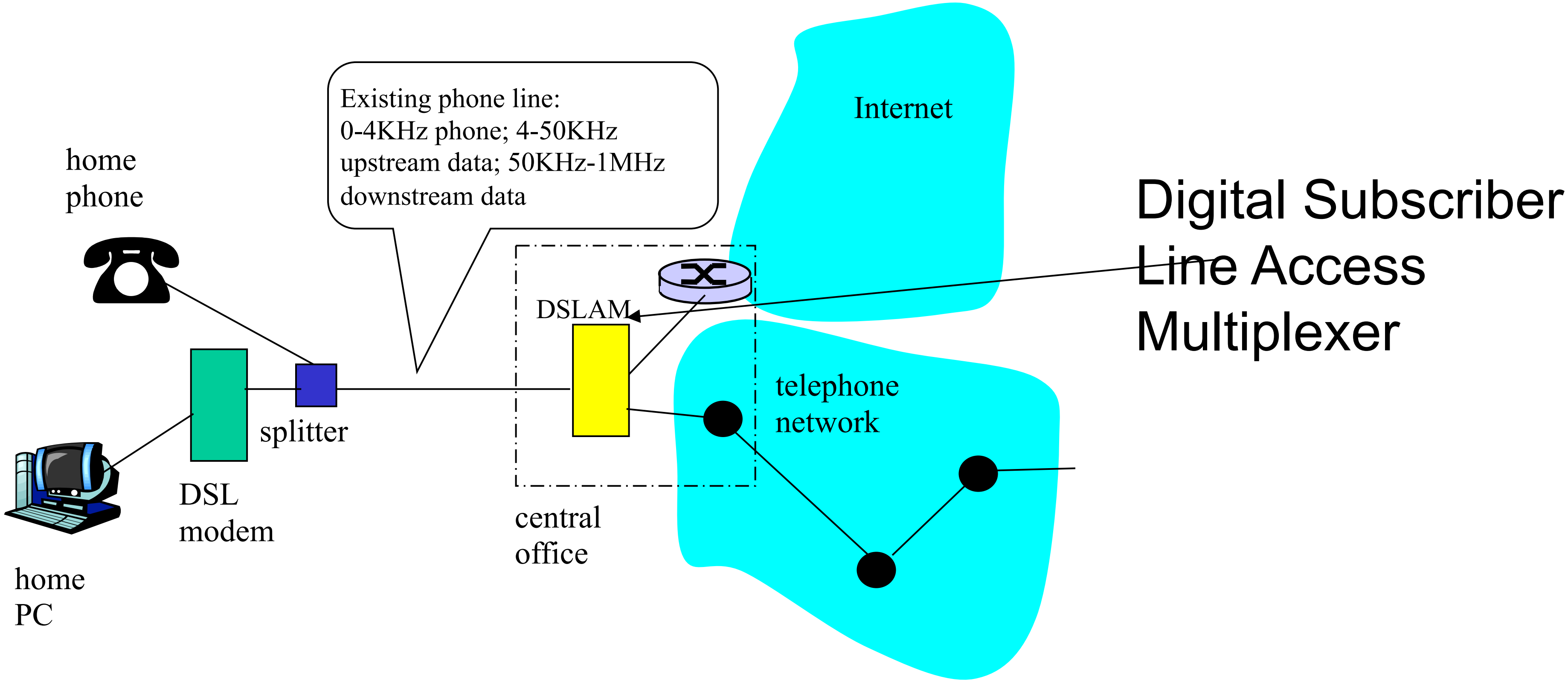
Dial-up Modem

ISP=Internet Service Provider
Es. Telecom, Tiscali, Fastweb, Wind etc



- Uses existing telephony infrastructure
  - Home is connected to central office
- up to 56Kbps direct access to router (often less)
- Can't surf and phone at same time: not "always on"

Digital Subscriber Line (DSL)

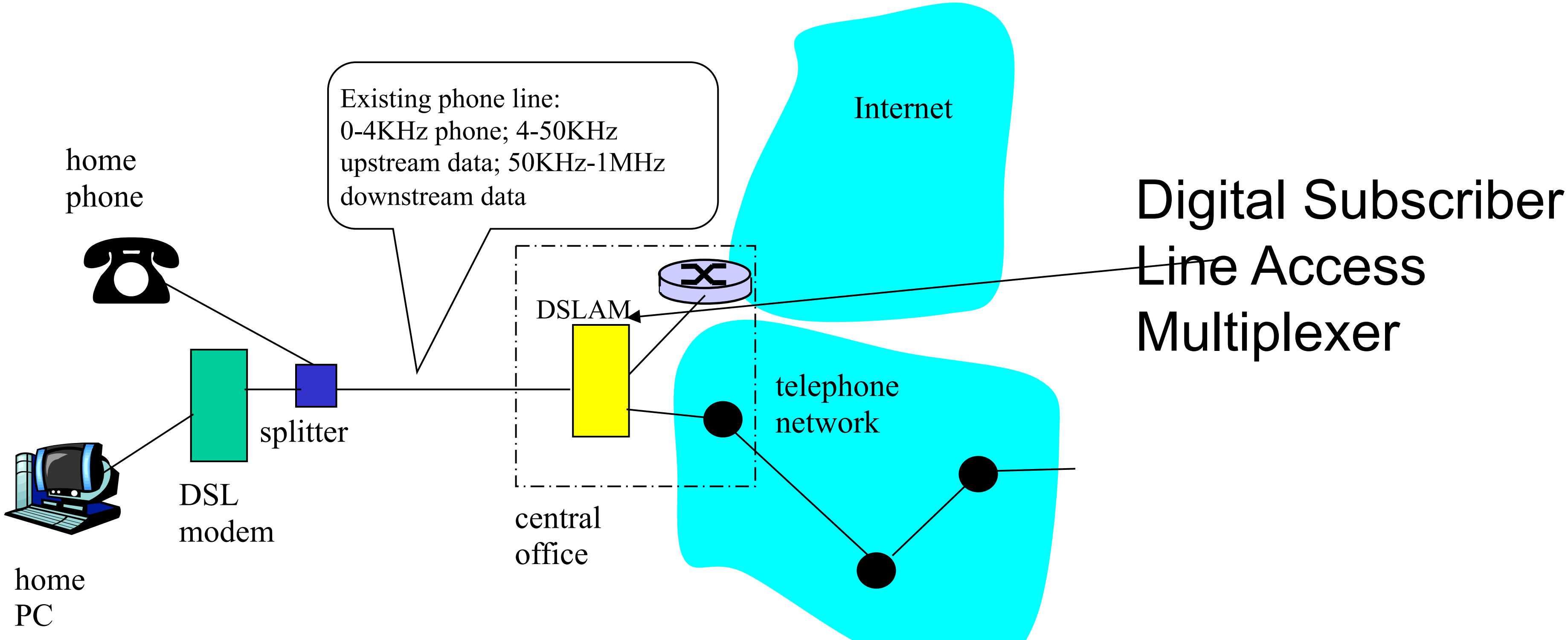


- Also uses existing telephone infrastruture
- up to 1 Mbps upstream (typically < 256 kbps)
- up to 8 Mbps downstream (typically < 1 Mbps)
- If distance of Km, higher data rate if shorter distance between DSL and DSLAM
- dedicated physical line to telephone central office

ADSL loops extender

- An **ADSL loop extender** or **ADSL repeater** is a device placed midway between the subscriber and central office by the telephone company to extend the distance and increase the channel capacity of their DSL connection.
- In some cases, service can now be established as far as 10 miles from the Central Office (factor of 2 improvement)

Digital Subscriber Line (DSL)



- Also uses exi
- up to 1 Mbps
- up to 8 Mbps
- dedicated phy

Speed significantly increased in the last few years

- **technologies more robust to interference;**
- **lower distance from DSM modem to DSLAM**

Residential access: cable modems

- Does not use telephone infrastructure
  - Instead uses cable TV infrastructure
- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream, 2 Mbps upstream
- network of cable and fiber attaches homes to ISP router
  - homes share access to router
  - unlike DSL, which has dedicated access

Residential access: cable modems

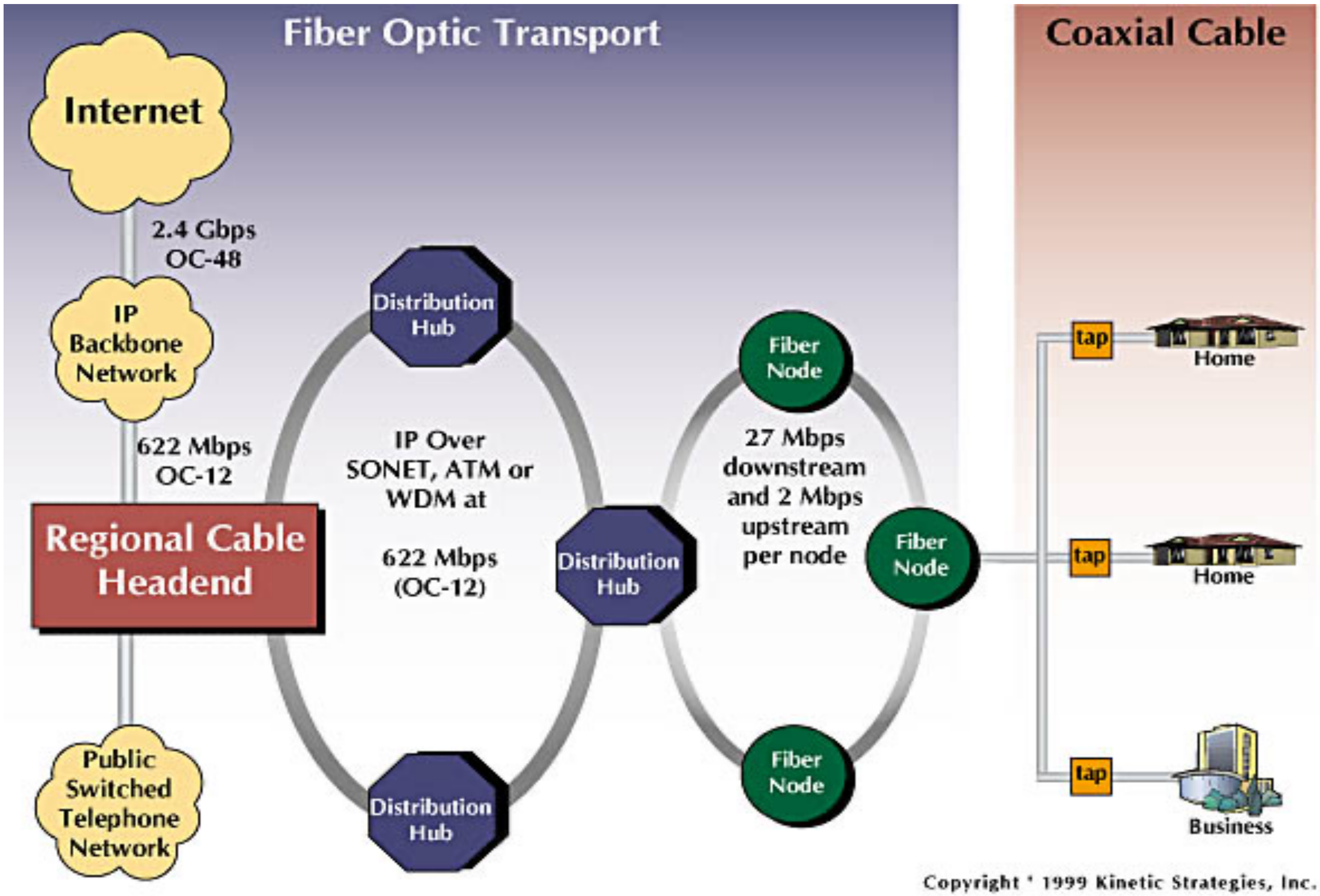
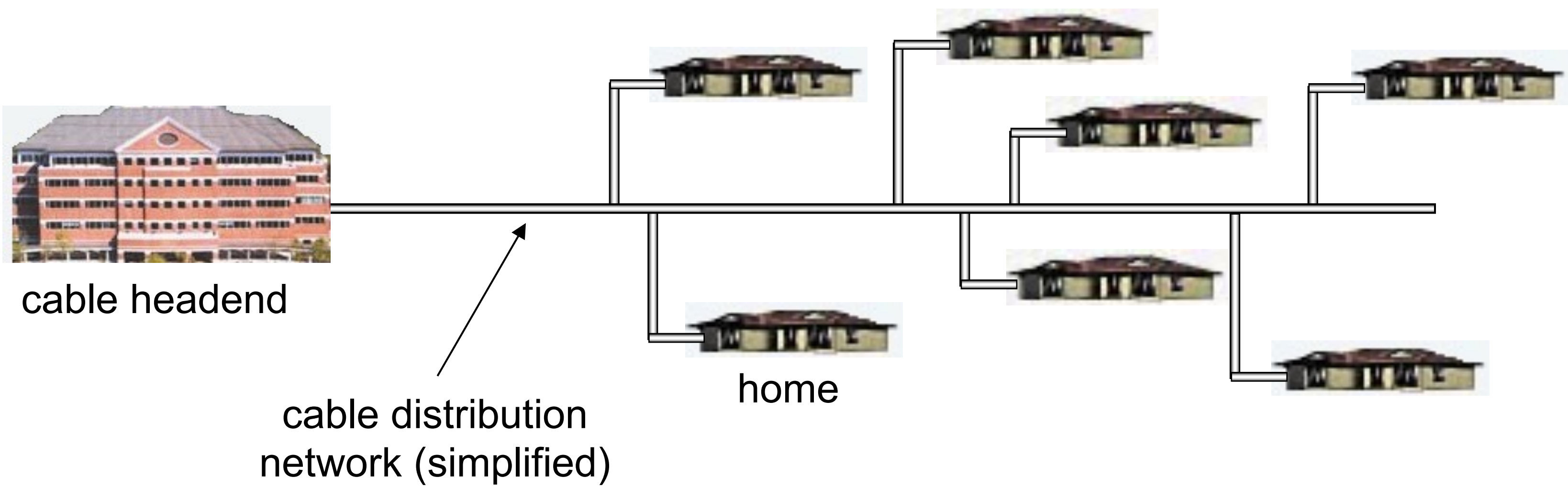


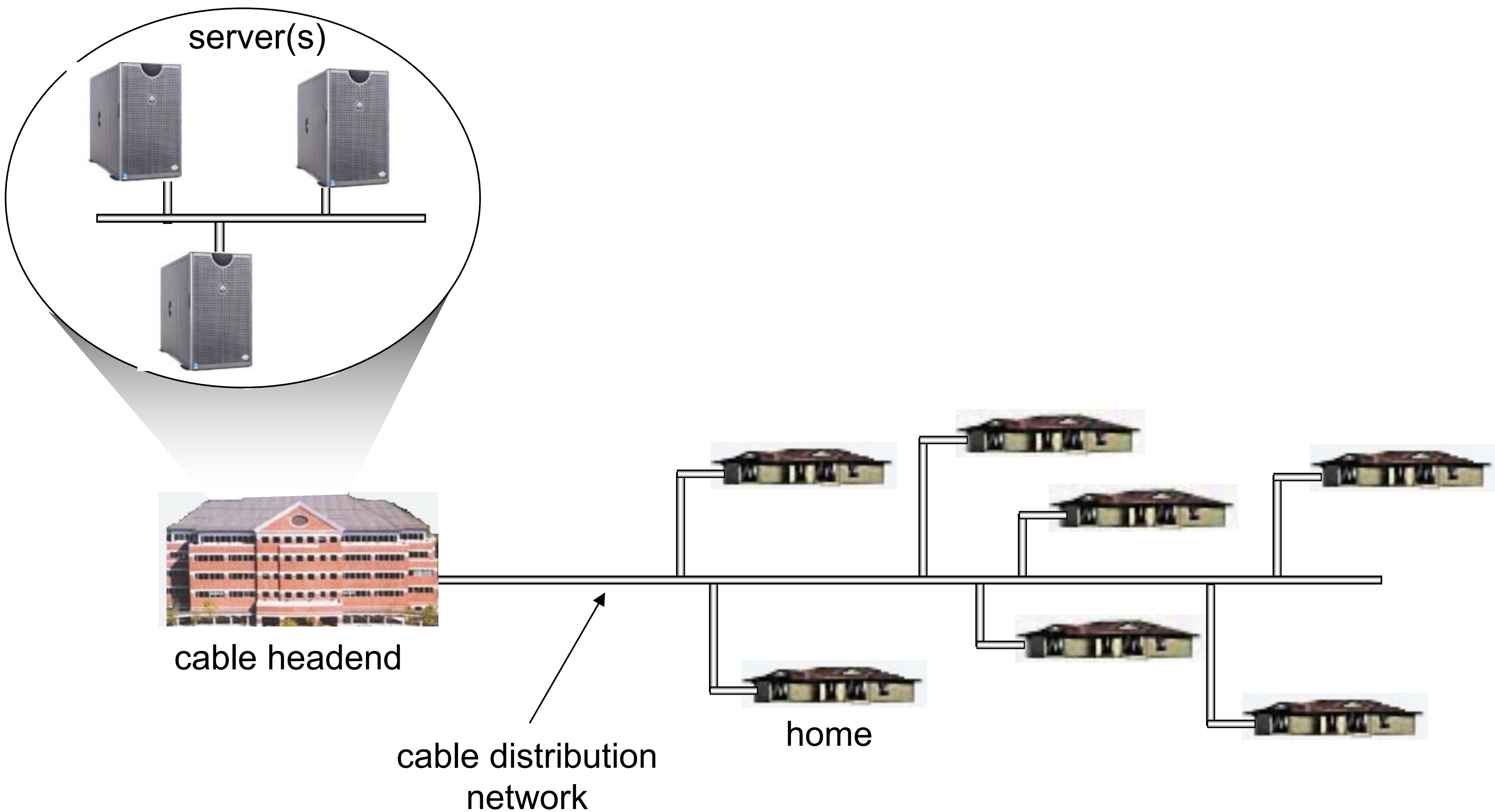
Diagram: http://www.cabledatacomnews.com/cmic/diagram.html

Cable Network Architecture: Overview

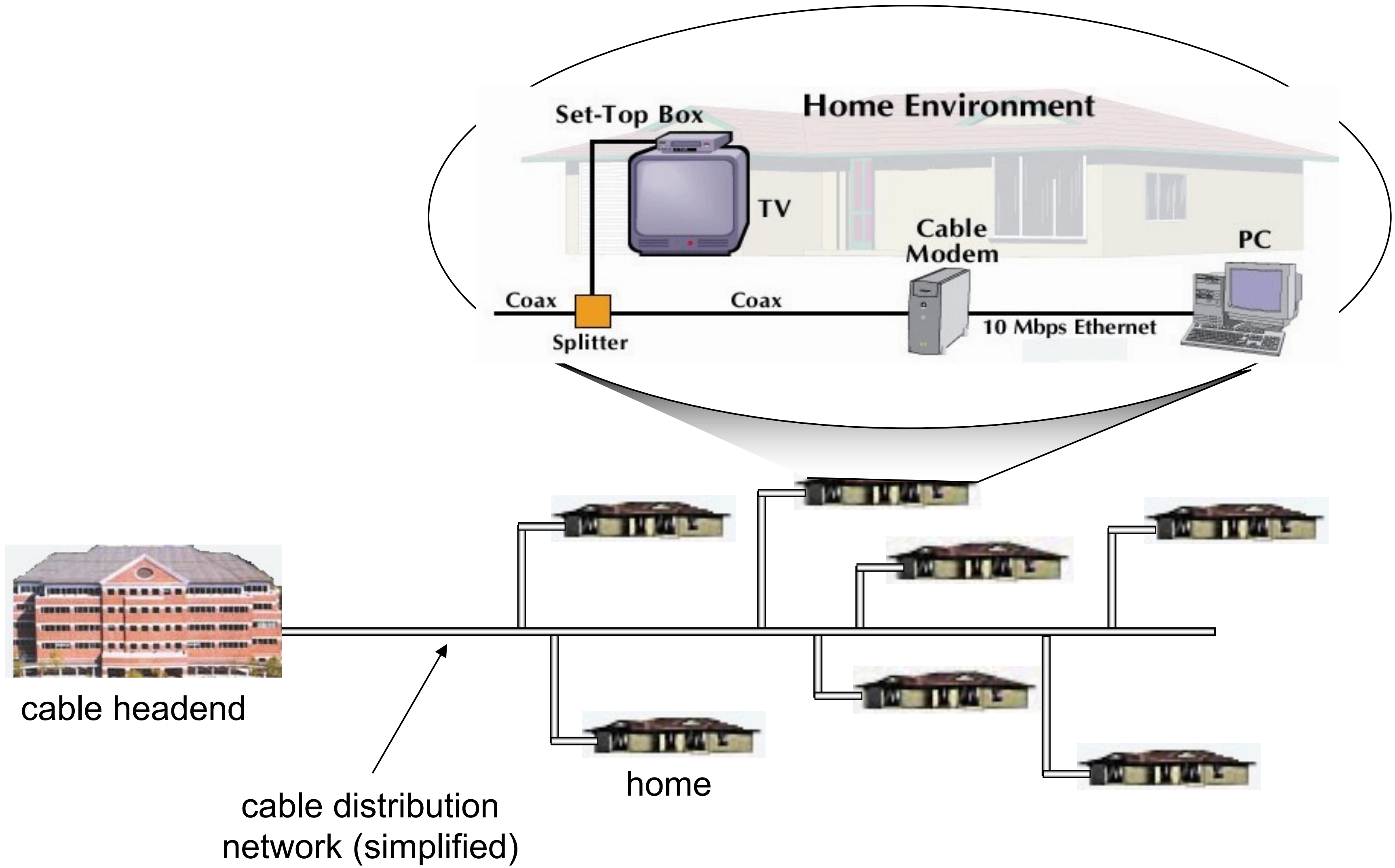
Typically 500 to 5,000 homes



Cable Network Architecture: Overview

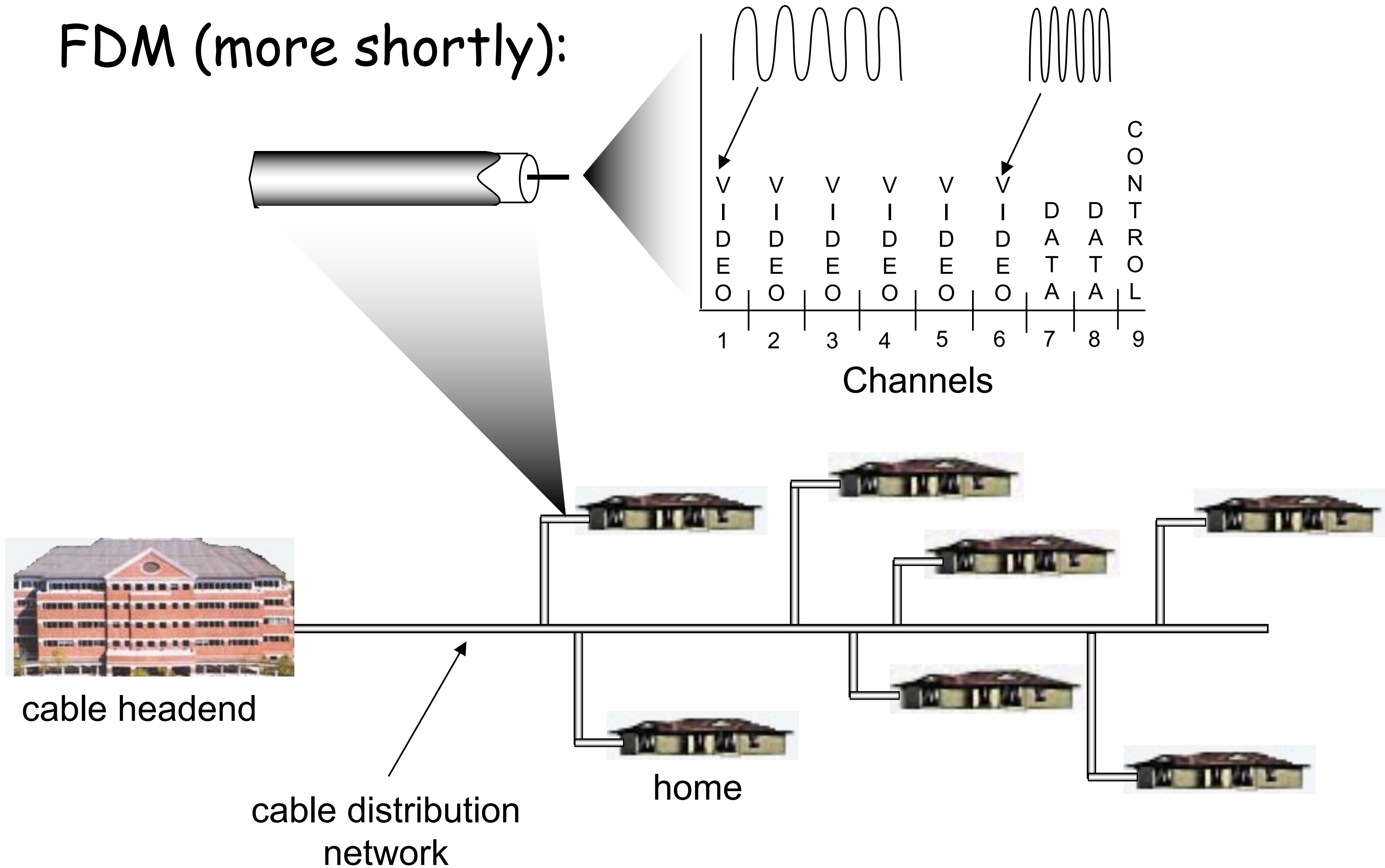


Cable Network Architecture: Overview

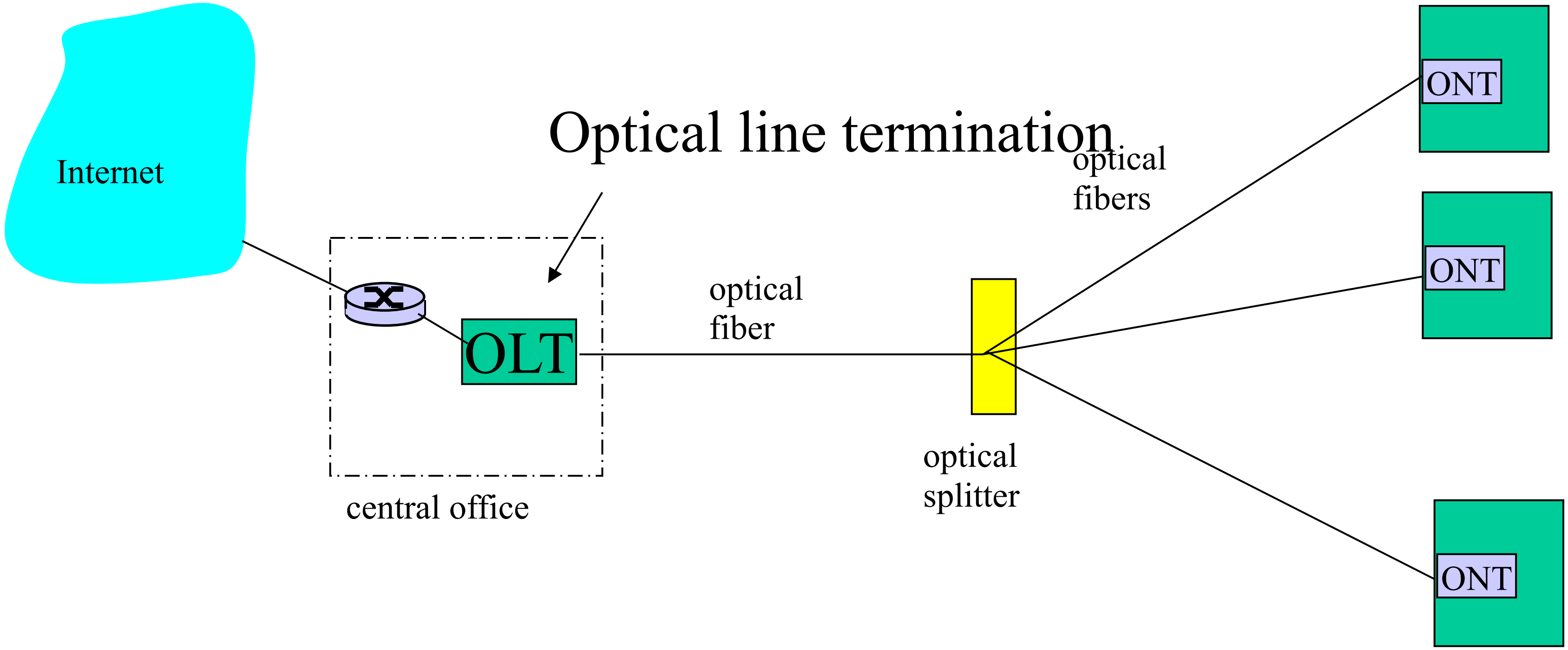


Cable Network Architecture: Overview

FDM (more shortly):



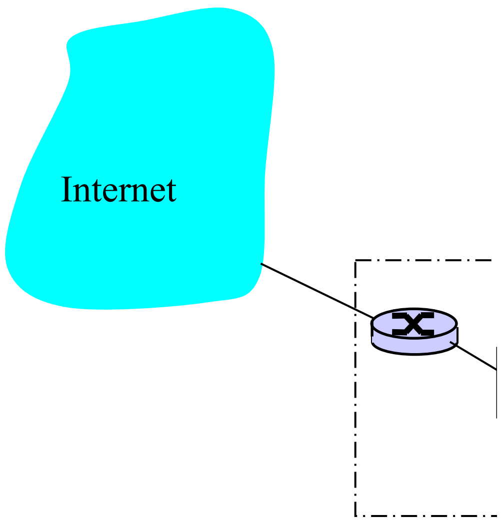
Fiber to the Home

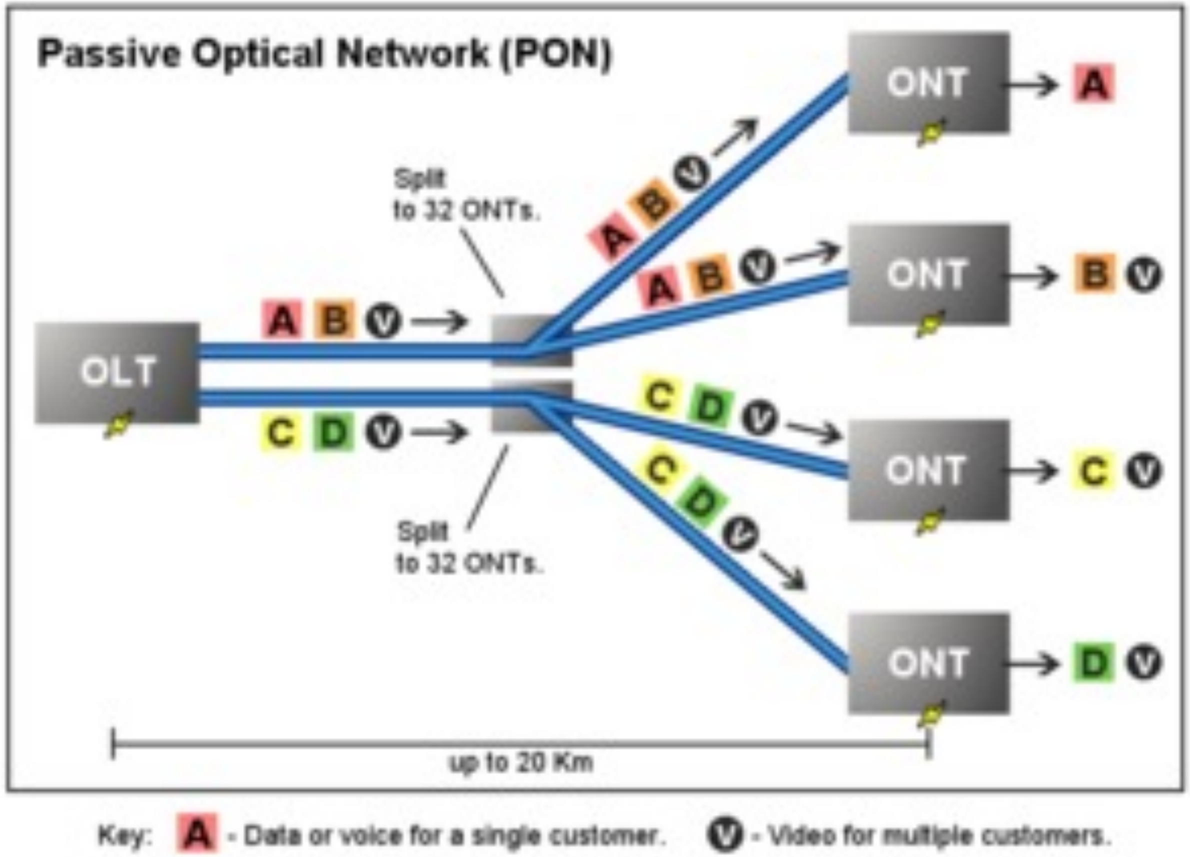


- Optical links from central office to the home
- Two competing optical technologies:
  - Passive Optical network (PON)
  - Active Optical Network (PAN)
- Much higher Internet rates; fiber also carries television and phone services

Optical Network unit

Fiber to the Home



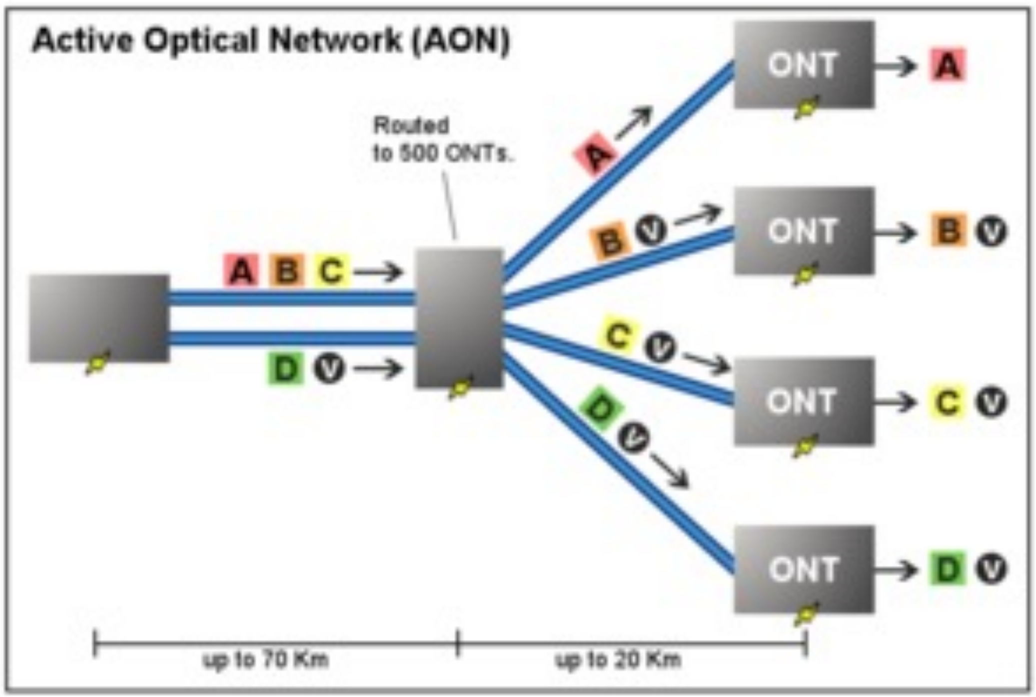


- Optical links fro
- Two competing
  - Passive Optical network (PON)
  - Active Optical Network (PAN)
- Much higher Internet rates; fiber also carries television and phone services

cal
Network
unit

Active Optical Networks

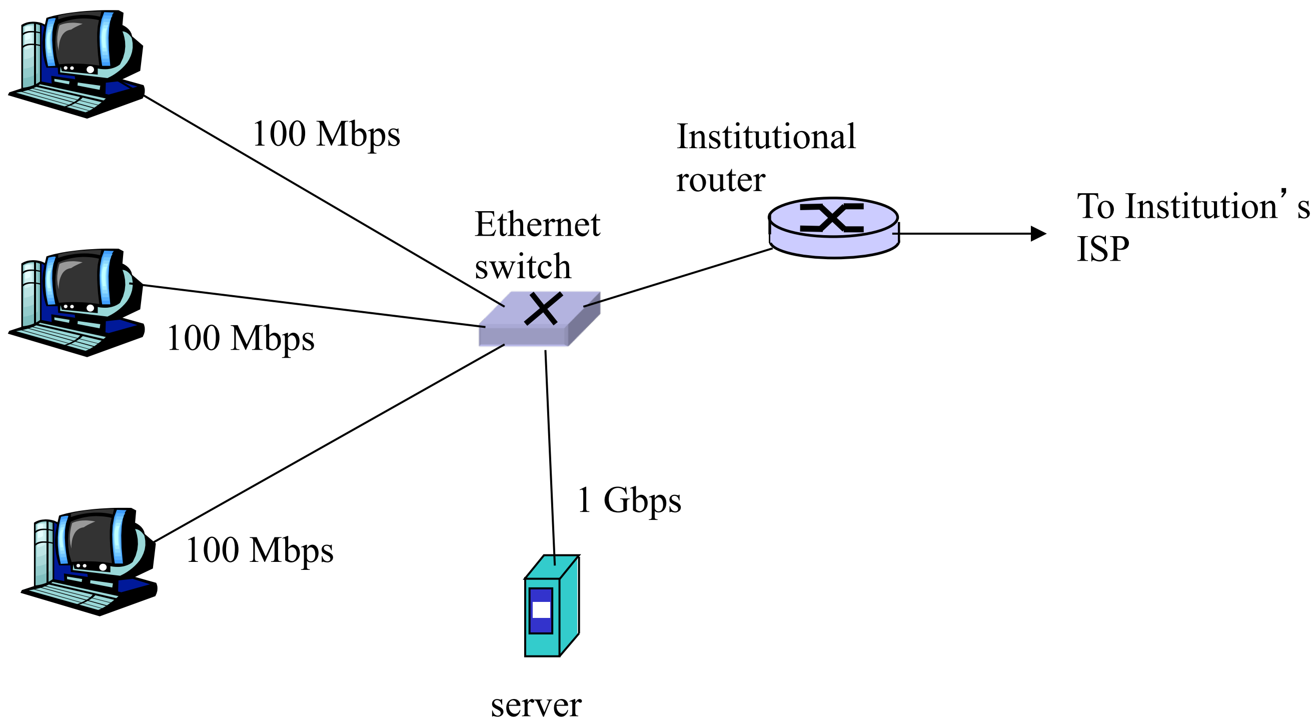
- An active optical system uses electrically powered switching equipment, such as a router or a switch aggregator, to manage signal distribution and direct signals to specific customers.
- In such a system, a customer may have a dedicated fiber running to his or her house.



Active vs Passive Optical Networks

- Passive optical networks, or PONs, have some distinct advantages.
  - They're efficient, in that each fiber optic strand can serve up to 32 users
  - PONs have a low building cost relative to active optical networks along with lower maintenance costs. In active optical networks one aggregator is required every 48 subscribers.
- Passive optical networks also have some disadvantages.
  - They have less range than an active optical network.
  - PONs also make it difficult to isolate a failure when they occur.
  - Because the bandwidth in a PON is not dedicated to individual subscribers, data transmission speed may slow down during peak usage times.

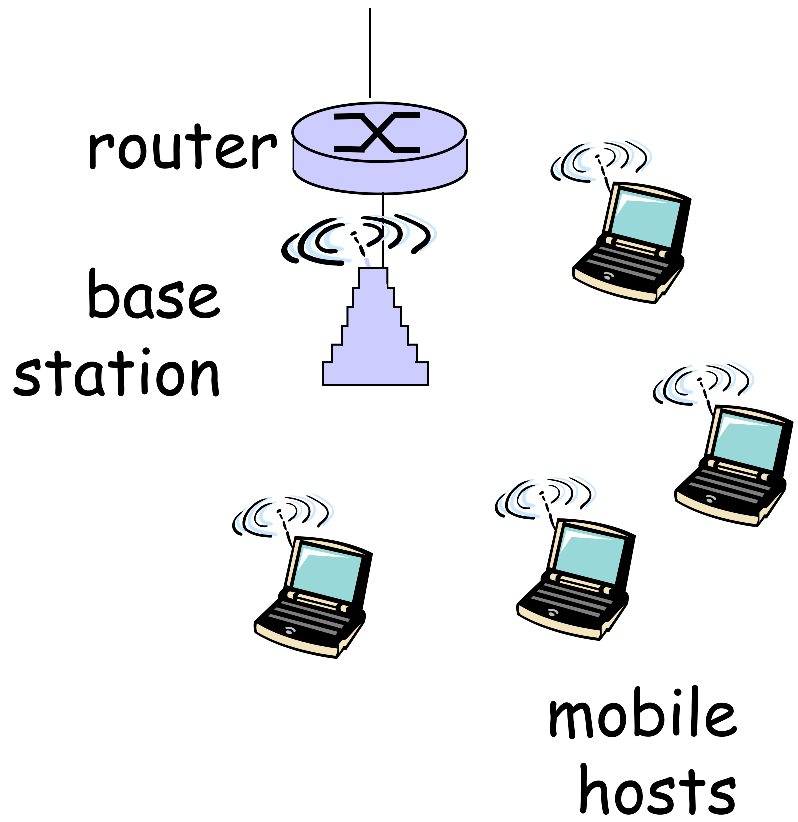
Ethernet Internet access



- Typically used in companies, universities, etc
- 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
- Today, end systems typically connect into Ethernet switch

Wireless access networks

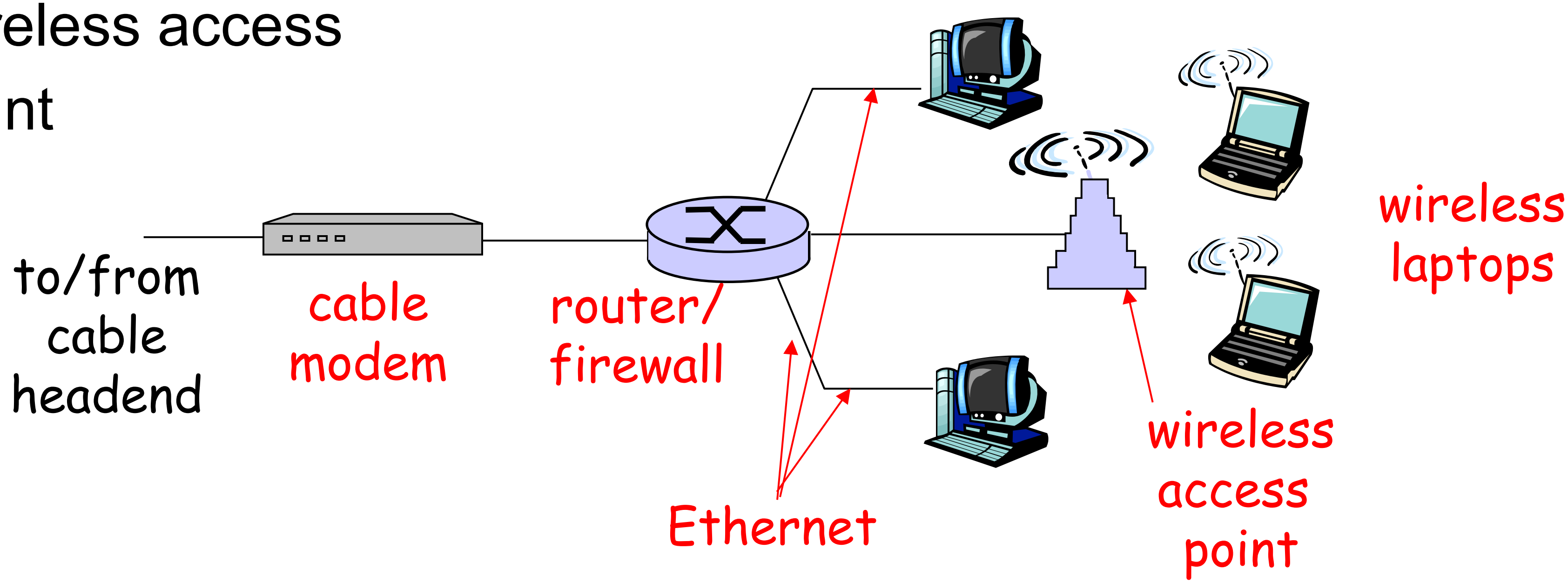
- shared *wireless* access network connects end system to router
  - via base station aka “access point”
- wireless LANs:
  - 802.11b/g (WiFi): 11 or 54 Mbps
- wider-area wireless access
  - provided by telco operator
  - ~1Mbps over cellular system (EVDO, HSDPA), several tens Mbps LTE
  - WiMAX (10’s Mbps) over wide area
  - Next to come: 5G systems



Home networks

Typical home network components:

- DSL or cable modem
- router/firewall/NAT
- Ethernet
- wireless access point

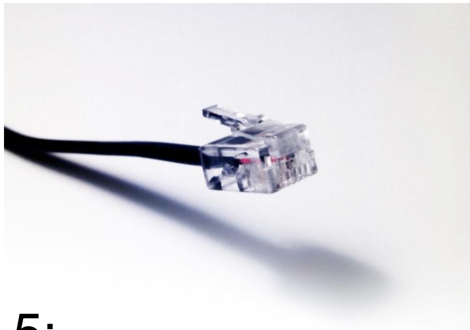


Physical Media

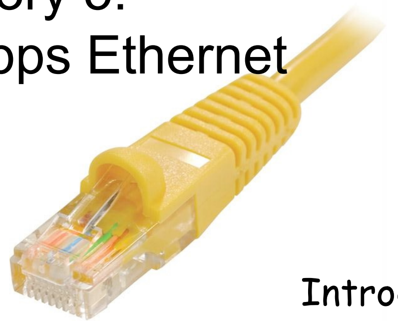
- Bit: propagates between transmitter/rcvr pairs
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio

Twisted Pair (TP)

- two insulated copper wires
  - Category 3: traditional phone wires, 10 Mbps Ethernet



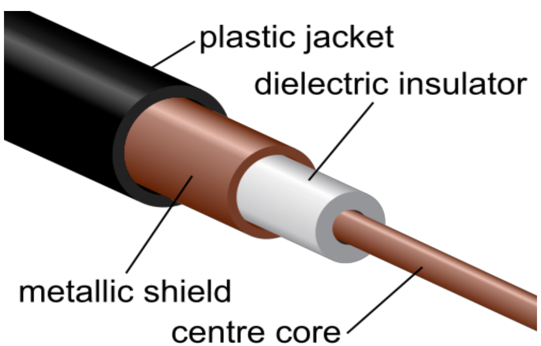
  - Category 5: 100Mbps Ethernet



Physical Media: coax, fiber

Coaxial cable:

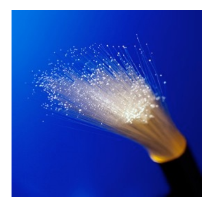
- two concentric copper conductors
- bidirectional
- baseband:
  - single channel on cable
  - legacy Ethernet
- broadband:
  - multiple channels on cable
  - HFC



http://commons.wikimedia.org/wiki/File:Coaxial_cable_cutaway.svg

Fiber optic cable:

- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
  - high-speed point-to-point transmission (e.g., 10's-100's Gps, but experimented up to tens of terabps)
- low error rate: repeaters spaced far apart ; immune to electromagnetic noise



http://www.macmynd.com/storage/misc-pics/fiber_optic_cable.jpg

Physical media: radio

- signal carried in electromagnetic spectrum
- no physical "wire"
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

Radio link types:

- terrestrial microwave
  - e.g. up to 45 Mbps channels
- LAN (e.g., Wifi)
  - 11Mbps, 54 Mbps
- wide-area (e.g., cellular)
  - 3G cellular: ~ 1 Mbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
    - (500 Km dalla superficie terrestre, servono costellazioni di satelliti)

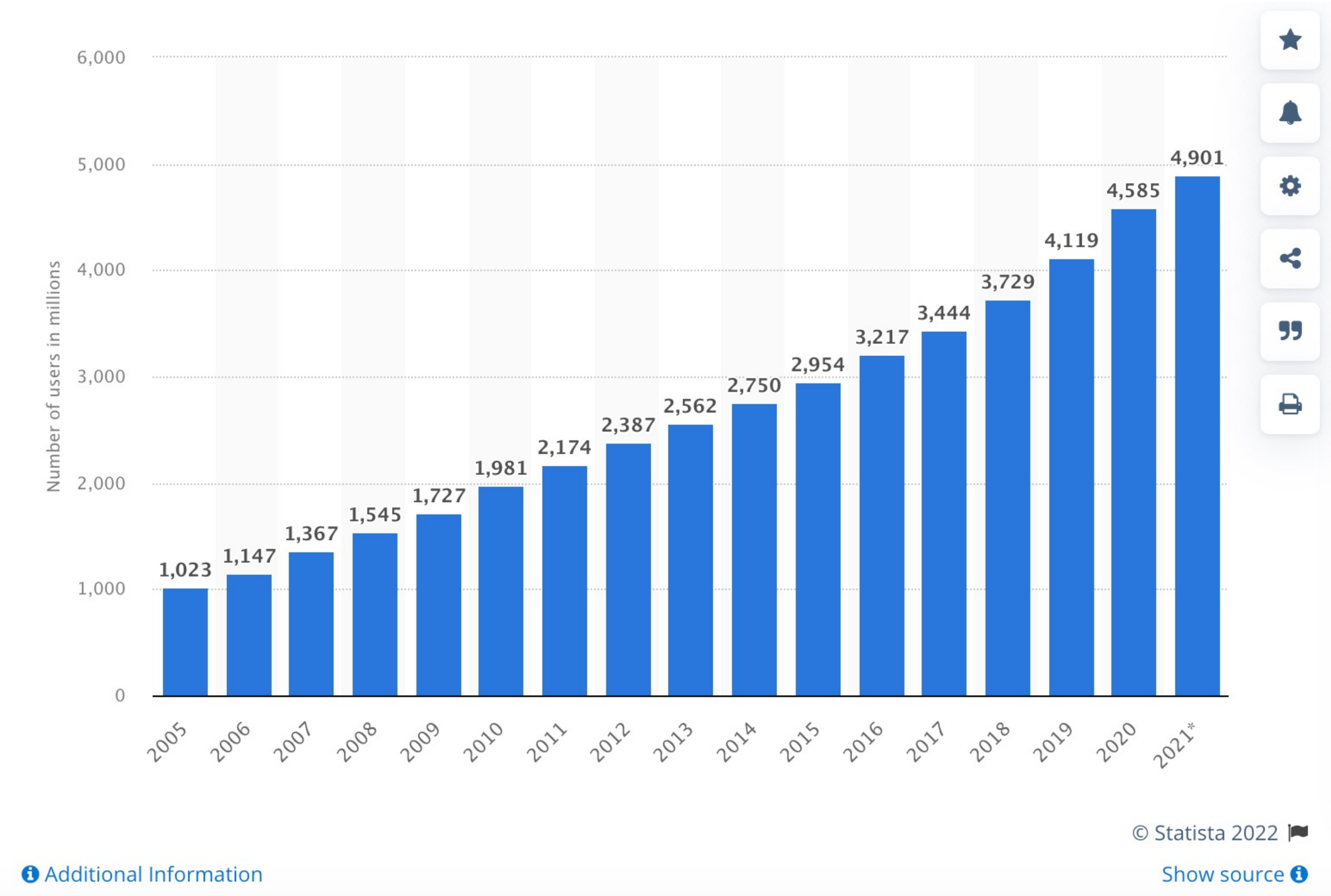
Physical media performance evolution (update: 2014) –Access technologies

WiFi, Ethernet, Fiber to the "home", DSL…Maximum current speeds or technologies tested to enter the market within a couple of years

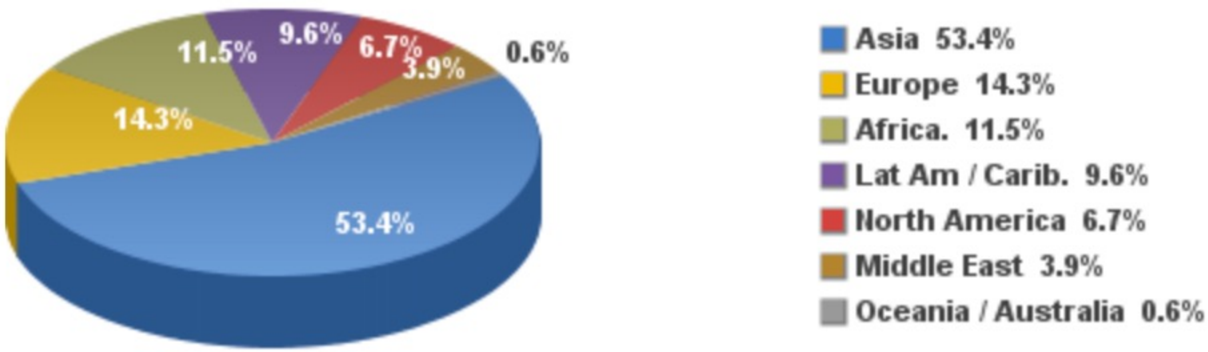
- DSL (G.Fast technology) 1Gbps
  - Combined with fiber; access to broadband network within 50m to reach such speeds
- Ethernet: 25Gbps (40Gbps under standardization). With more lines: currently 100Gbps, standards towards 400Gbps
- WiFi IEEE 802.11ac Up to 1Gbps to come
- Fiber
  - Technologies tested up to few tens of terabps
  - 1Gbps per home more than enough (current threshold per user satisfaction >10Mbps)
- Cellular systems evolution
  - Tens-hundred of Mbps

To conclude general introduction: Why is Internet So Important-- Some Statistics

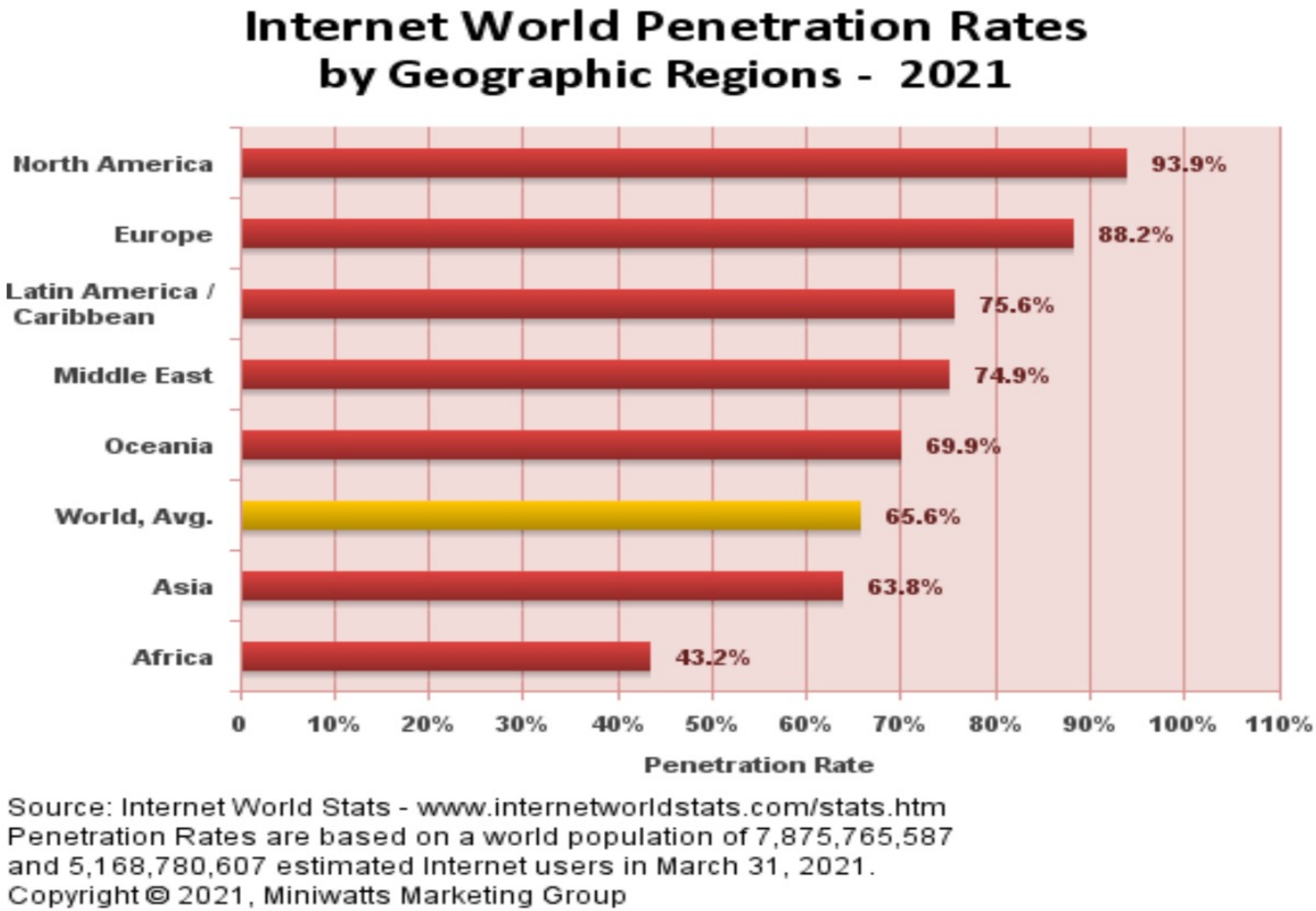
Today: over 4 billions



Internet Users Distribution in the World - 2021



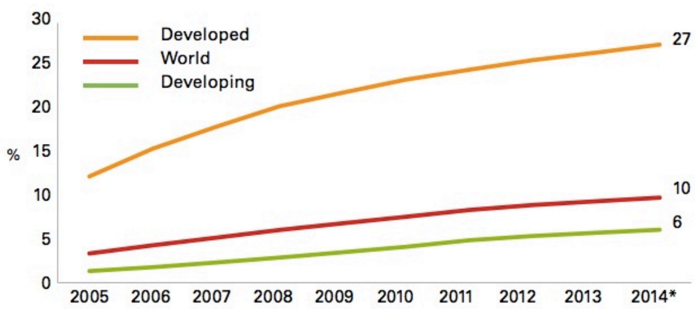
Source: Internet World Stats - www.internetworldstats.com/stats.htm
Basis: 5,168,780,607 Internet users in March 31, 2021


Internet World Penetration Rates
by Geographic Regions - 2021
North America
Europe
Latin America / Caribbean
Middle East
Oceania
World, Avg.
Asia
Africa
93.9%
88.2%
75.6%
74.9%
69.9%
65.6%
63.8%
43.2%
0
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
110%
Penetration Rate
Source: Internet World Stats - www.internetworldstats.com/stats.htm
Penetration Rates are based on a world population of 7,875,765,587
and 5,168,780,607 estimated Internet users in March 31, 2021.
Copyright © 2021, Miniwatts Marketing Group

A changing Internet…

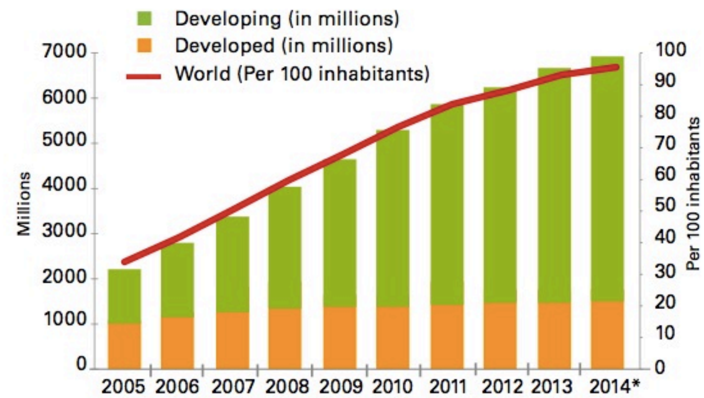
Wired broadband subscription (for 100 users)

Active mobile broadband subscription



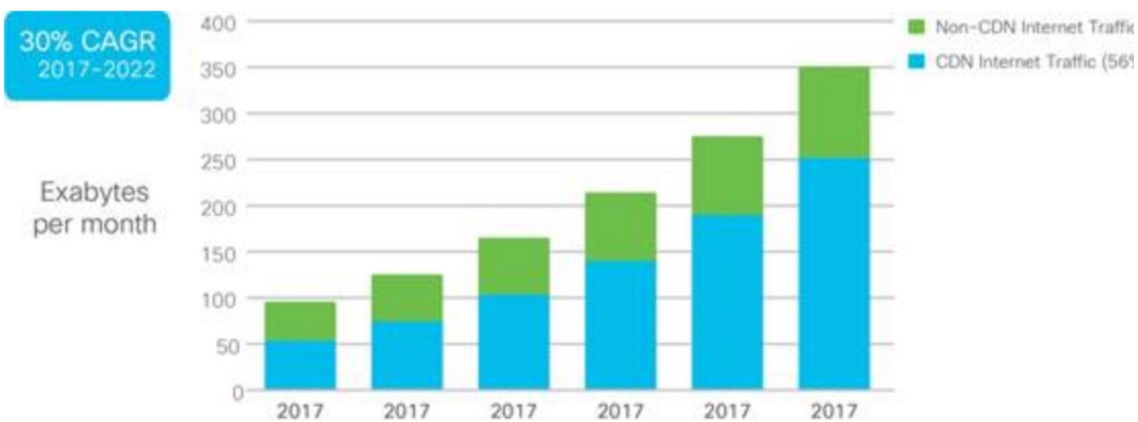
Note: * Estimate
Source: ITU World Telecommunication/ICT Indicators database

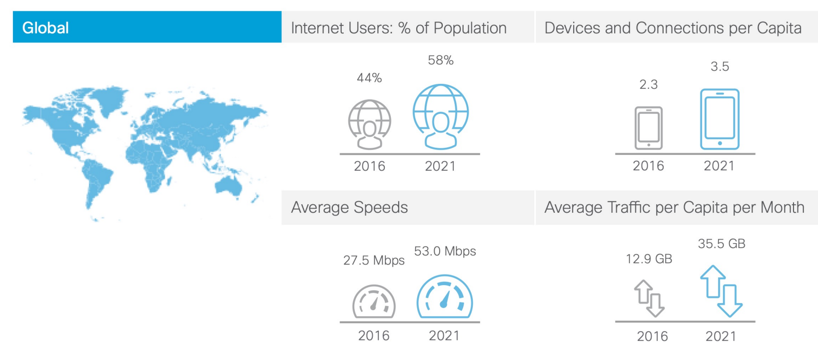
Mobile cellular subscription



Note: * Estimate
Source: ITU World Telecommunication/ICT Indicators database

Figure 24. Global content delivery network Internet traffic, 2017 and 2022





* Figures (n) refer to 2017, 2022 traffic share
Source: Cisco VNI Global IP Traffic Forecast, 2017-2022

A changing Internet…

CISCO forecasting

Consumer Internet Traffic,2017-2022	2017	2018	2019	2020	2021	2022	CAGR 2017-2022
By Network (EB per Month)							
Fixed	67	86	111	141	179	225	27%
Mobile	10	16	25	36	50	68	47%
By Subsegment (EB per Month)							
Internet video	56	77	105	140	184	240	34%
Web, email, and data	12	15	19	23	27	31	22%
Online gaming	1	3	4	7	11	15	59%
File sharing	8	7	7	7	7	7	-3%

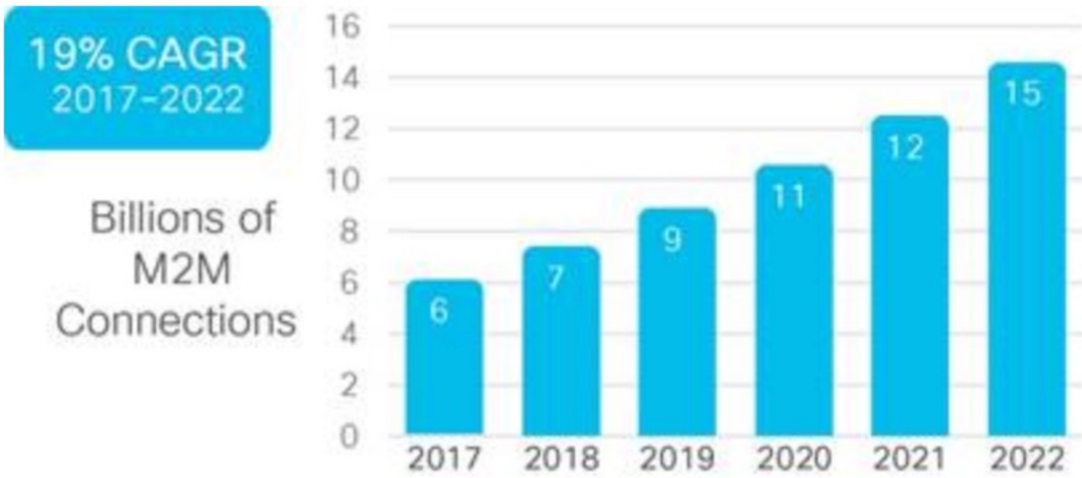
A changing Internet…

CISCO forecasting

Consumer Internet Traffic,2017-2022	2017	2018	2019	2020	2021	2022	CAGR 2017-2022
By Network (EB per Month)							
Fixed	67	86	111	141	179	225	27%
Mobile	10	16	25	36	50	68	47%
						240	34%
						31	22%
						15	59%
						7	-3%

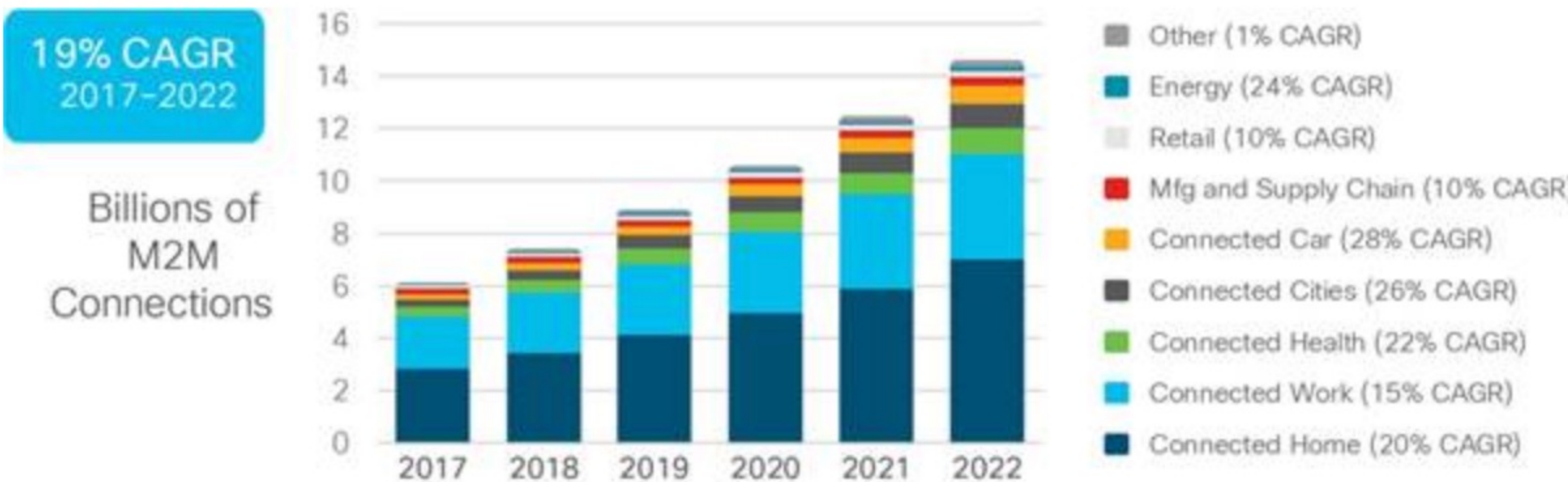
Changes in trends:
IoT
Multimedia support
Network devices reconfigurability and virtualization
Cloud vs. Edge computing

Figure 10. Global M2M connection growth

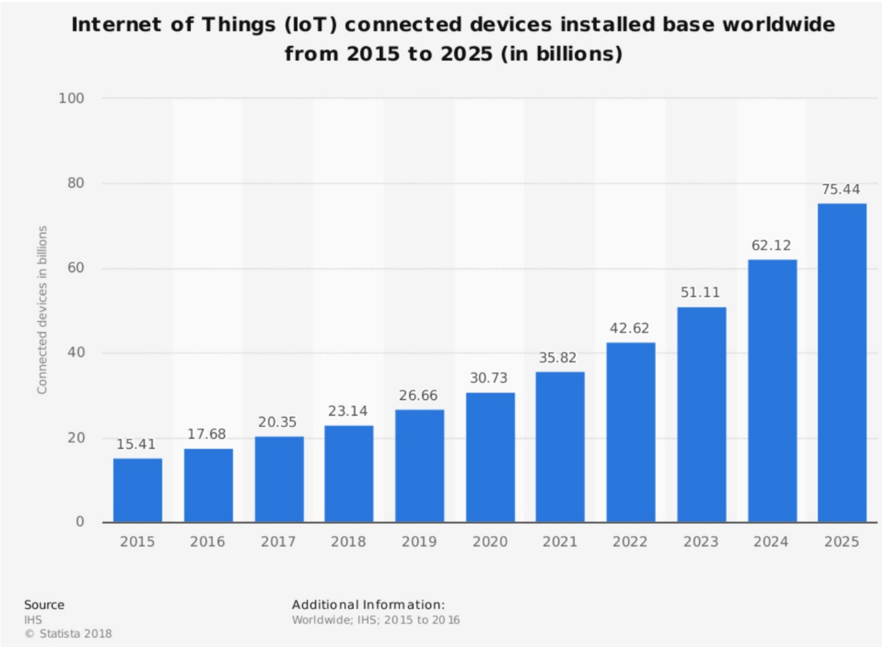


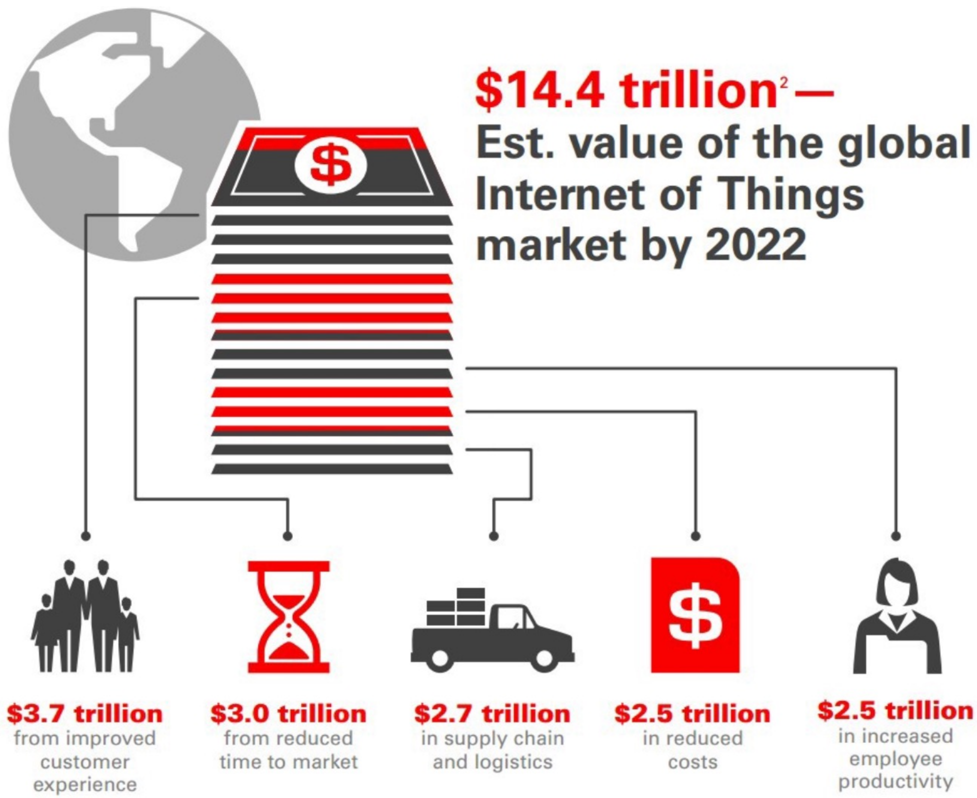
Source: Cisco VNI Global IP Traffic Forecast, 2017-2022

Figure 11. Global M2M connection growth by industries

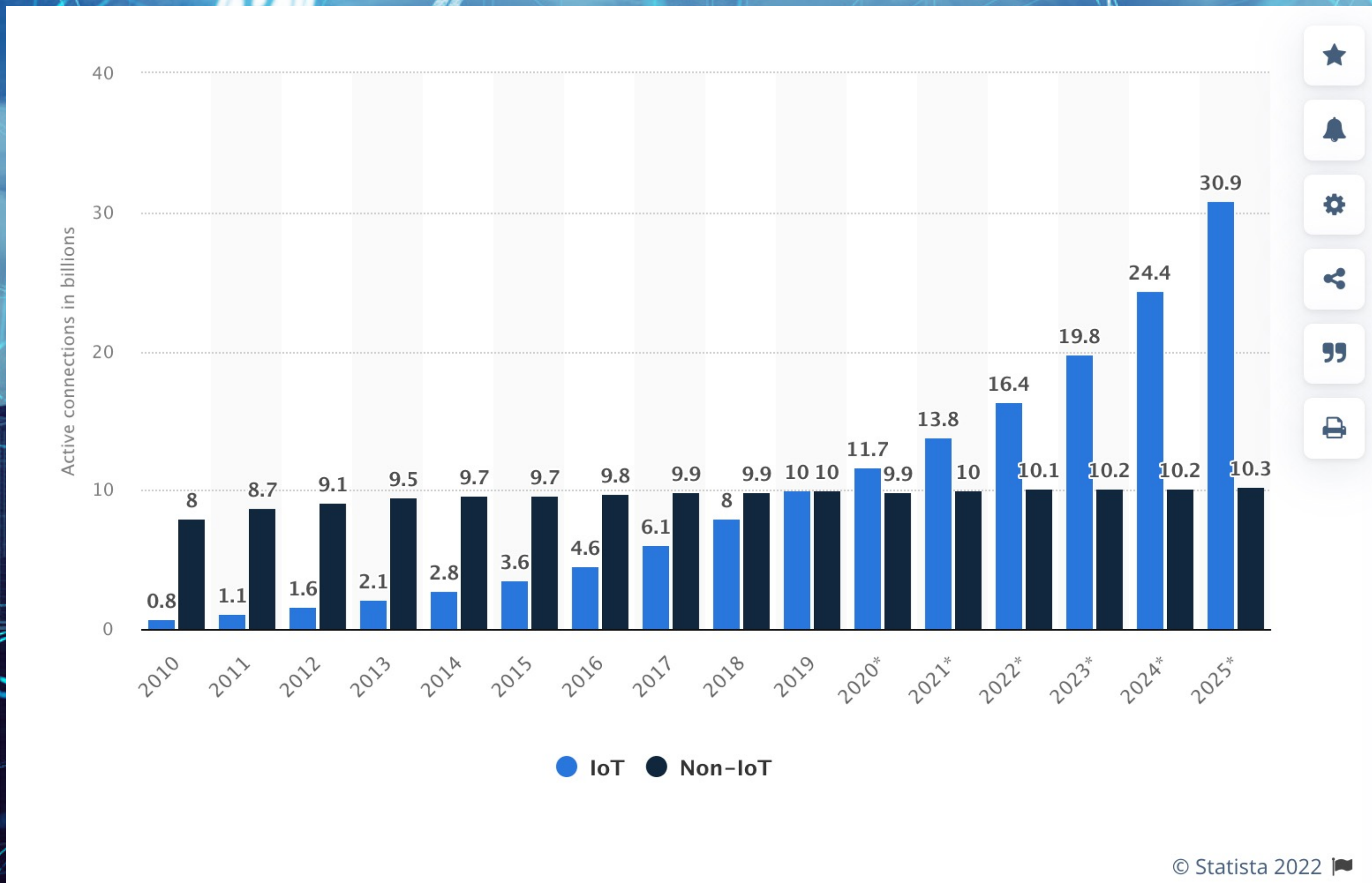


Il mondo dell'IoT

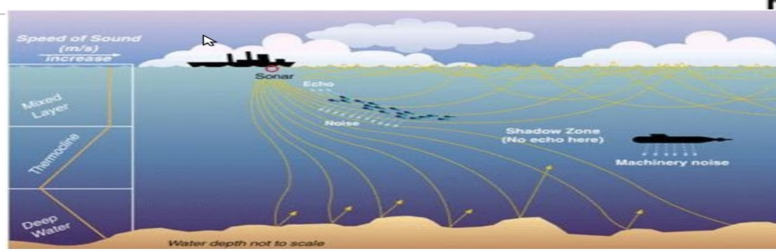




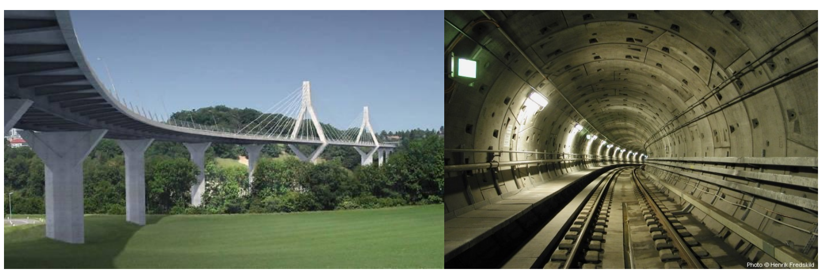
Internet of Things (IoT) and non-IoT active device connections worldwide from

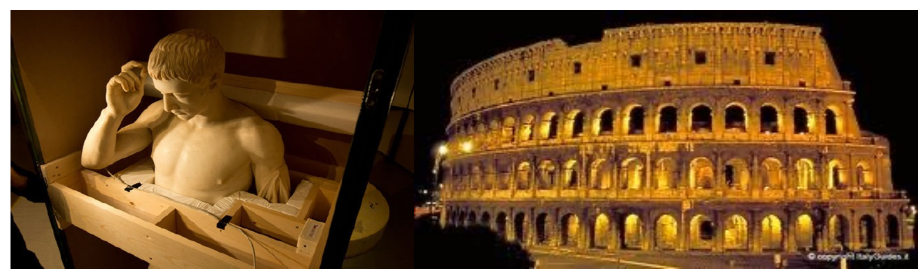


SENSES lab: IoT & Systems for Smarter City/Smarter Planet



Underwater monitoring & control systems





Structural health monitoring

Cultural Heritage

In Sapienza è possibile un percorso di specializzazione su IoT