Wireless Network Security and Privacy

Wireless Network Basics

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Outline

- Network Basics
  - A high level perspective
- Wireless Fundamentals
  - Important Terms
  - Modulation
  - MAC layer
  - Physical layer
- Popular standards and the corresponding wireless networks:
  - 802.11 Wi-Fi
  - 802.15 Bluetooth
  - 802.15 Zigbee
  - 5G☺☹
- New emerging wireless communications and applications
  - 60G Hz
  - Li-Fi
  - Low power wide area network: NB-IoT, Lora

Part 1: Network Basics

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

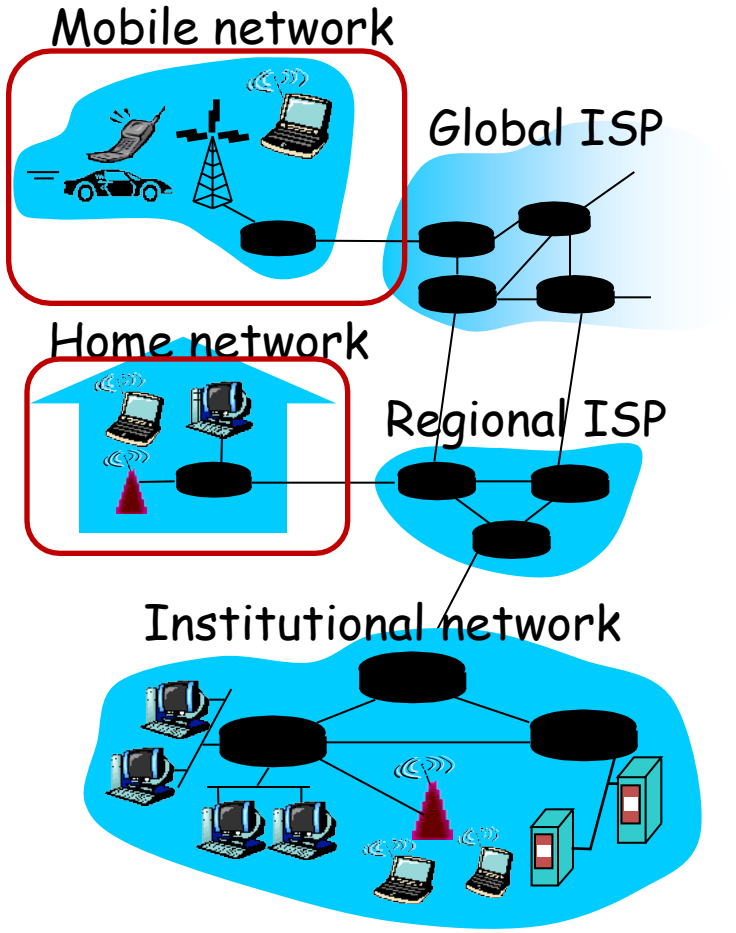
PC

server

wireless laptop

cellular handheld

- millions of connected computing devices:
  - *hosts = end systems*
  - running *network apps*



access points

wired links

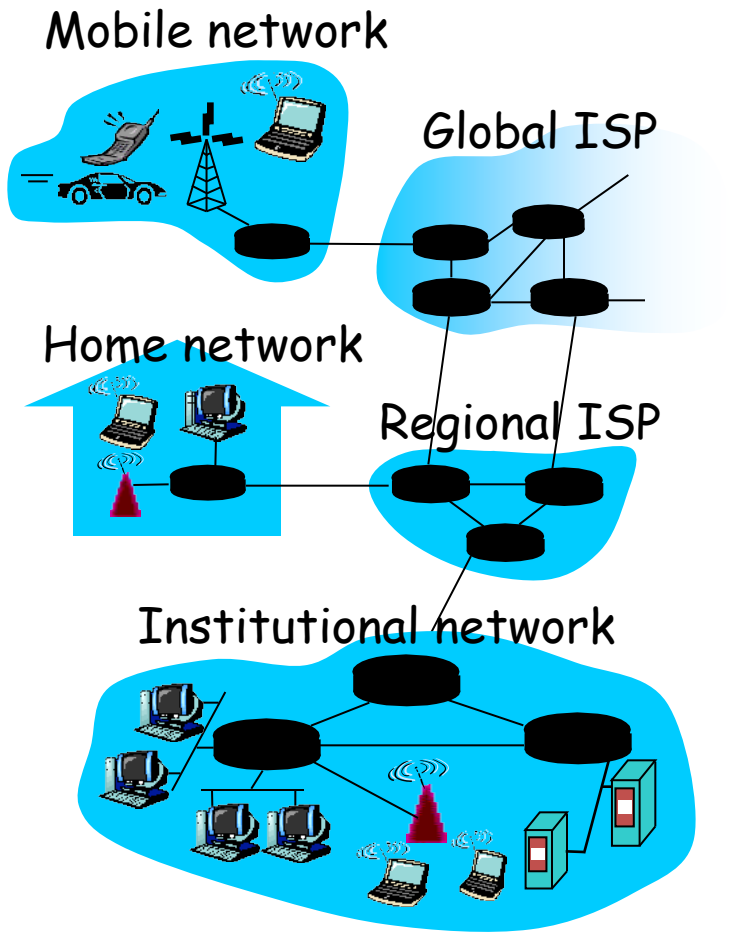
- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate = *bandwidth*

router

- *routers:* forward packets (chunks of data)

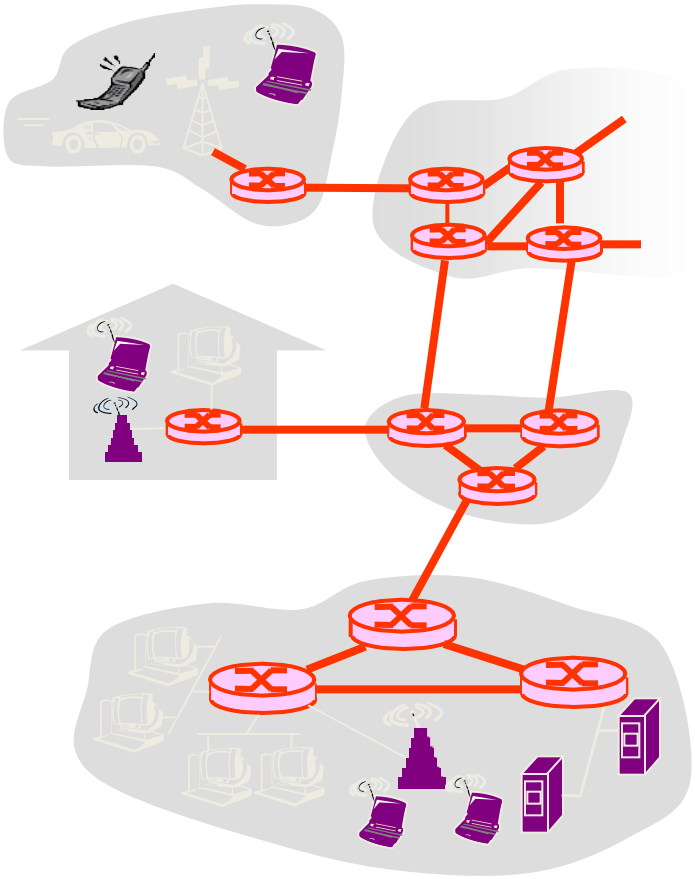
What's the Internet: "nuts and bolts" view

- *protocols* control sending, receiving of messages
  - 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



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”

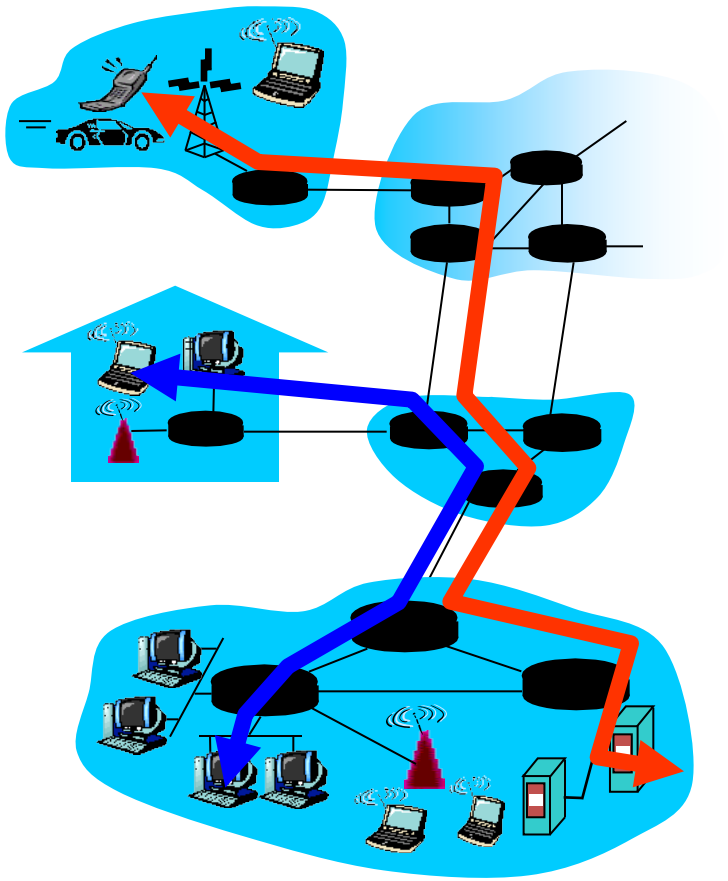


Network Core: Circuit Switching

End-end resources reserved for "call"

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

Q: Cons and Pros?

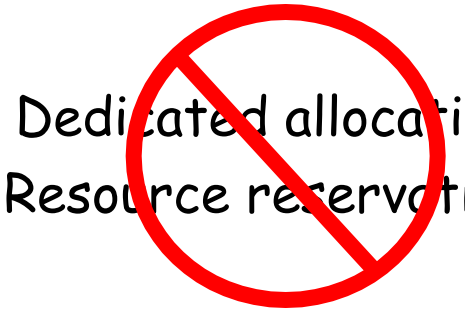


Network Core: Packet Switching

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"

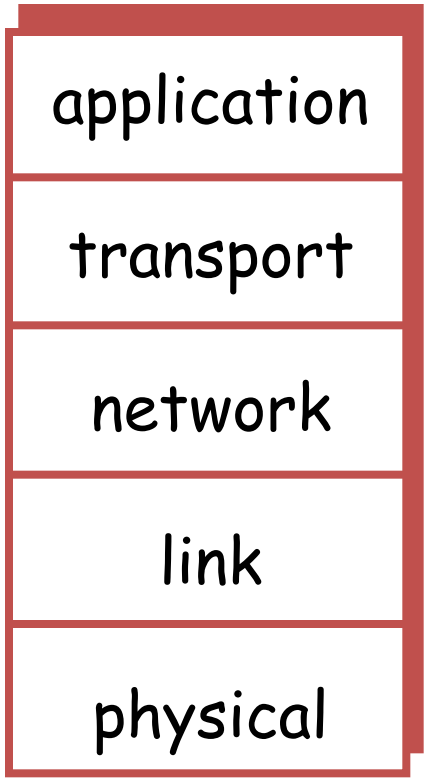


resource contention:

- 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

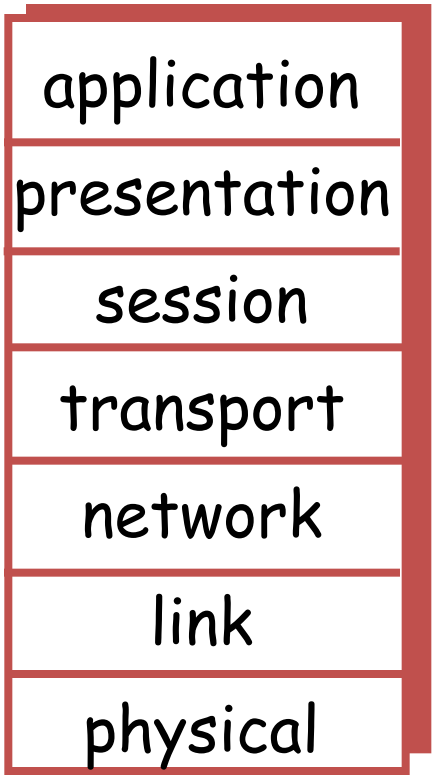
Internet protocol stack

- application: supporting network applications
  - FTP, SMTP, HTTP
- transport: process-process data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bits “on the wire”

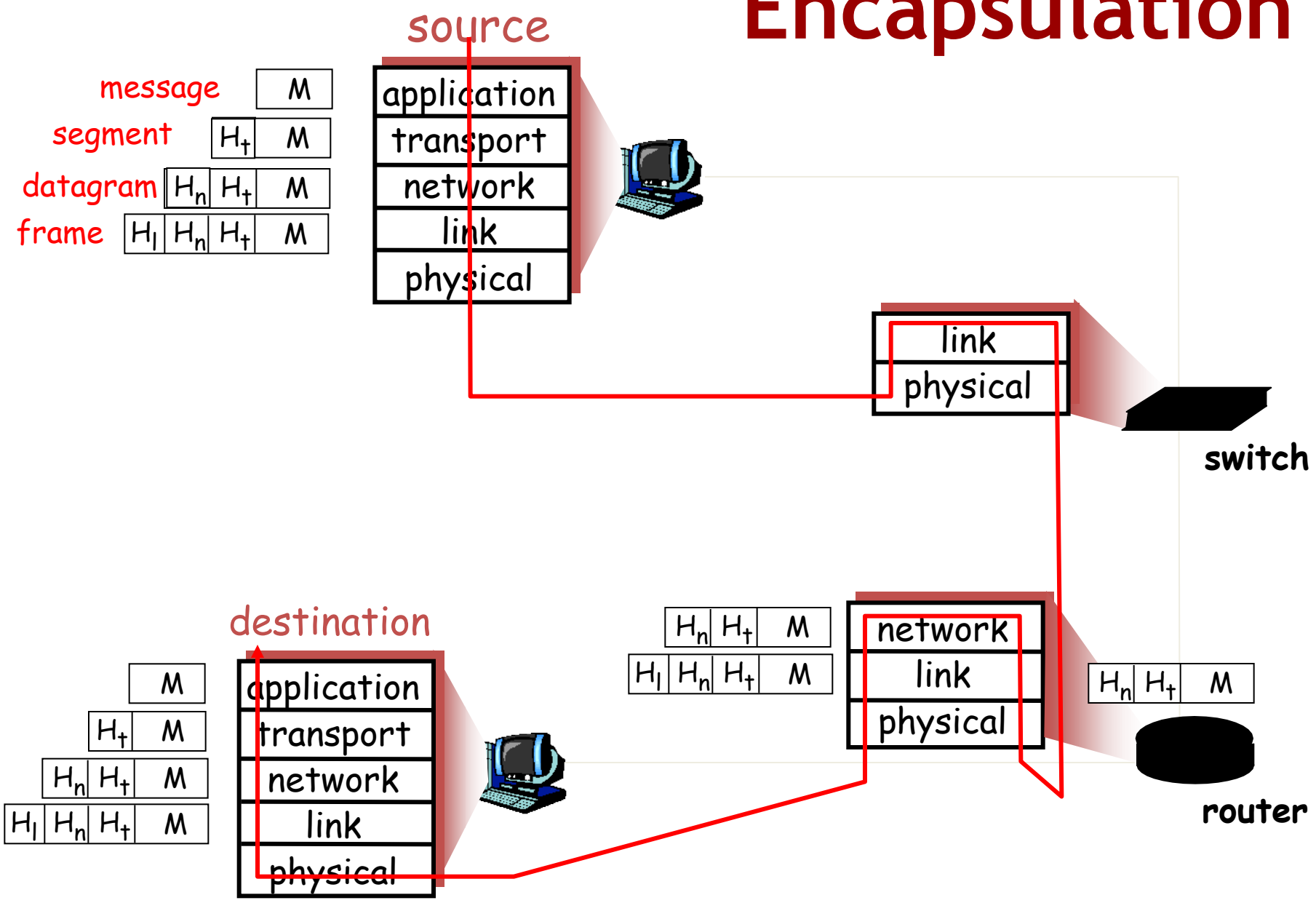


ISO/OSI reference model

- presentation: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- *session:* synchronization, checkpointing, recovery of data exchange
- Internet stack "missing" these layers!
  - these services, *if needed,* must be implemented in application
  - needed?



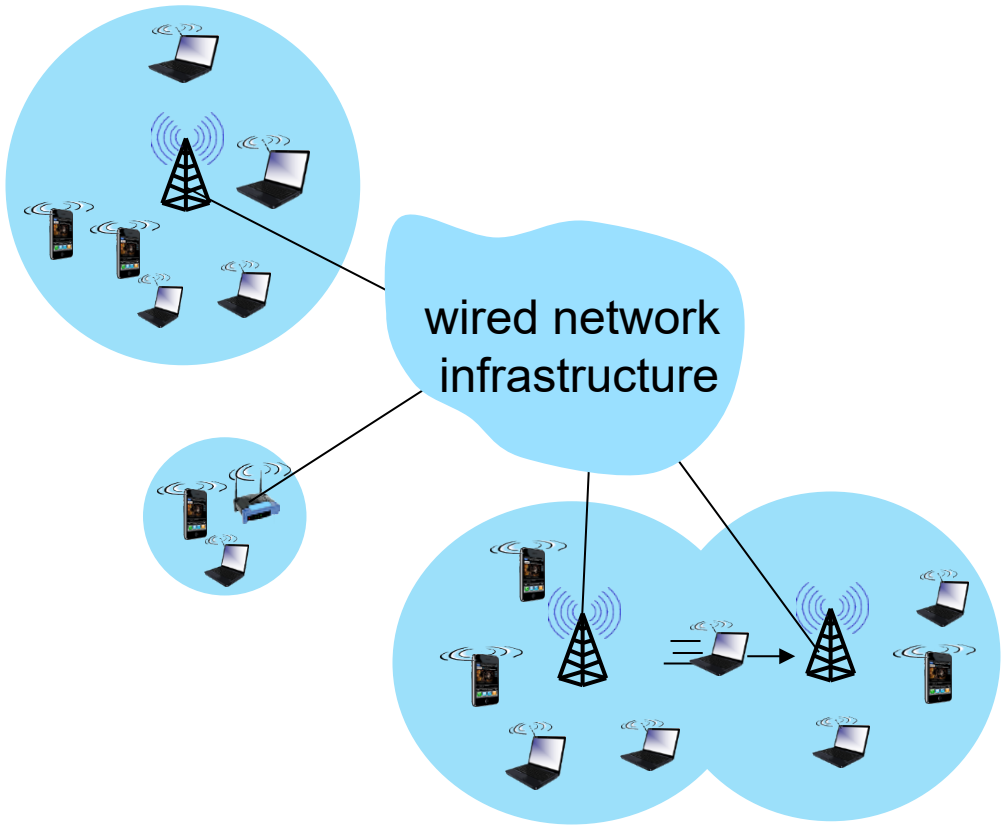
Encapsulation



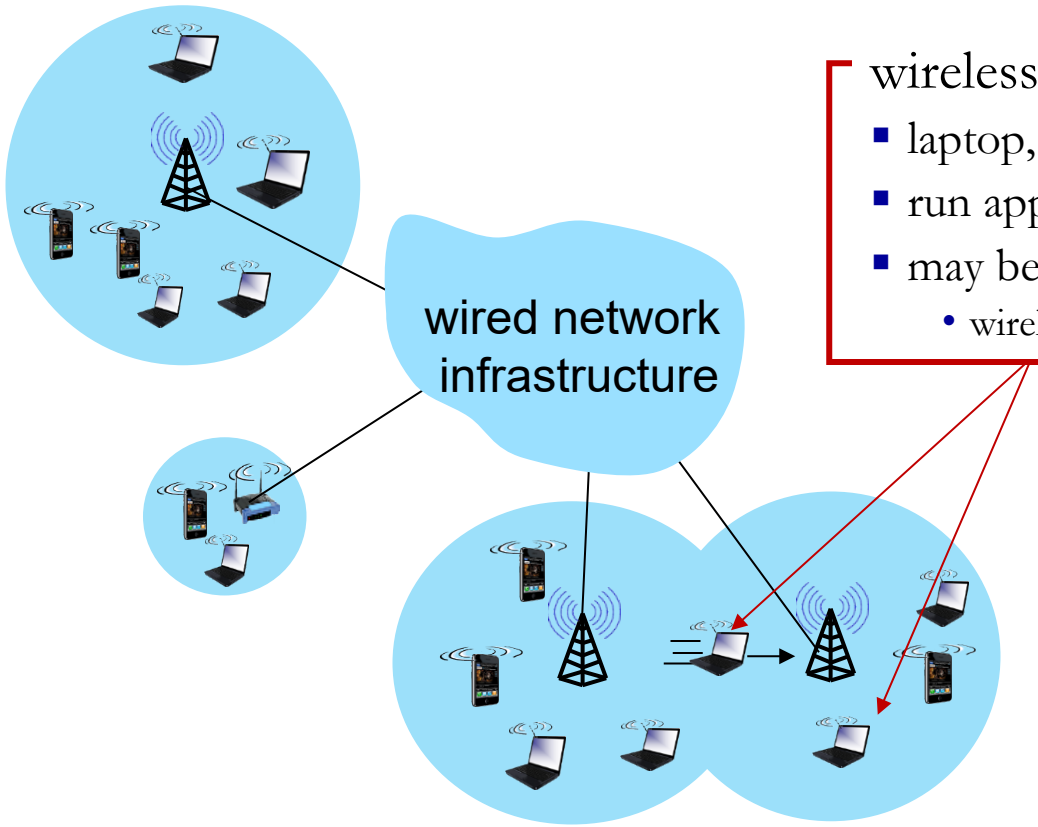
Part 2: Wireless Network Basics

INTRODUCTION TO WIRELESS NETWORK

Elements of a wireless network



Elements of a wireless network

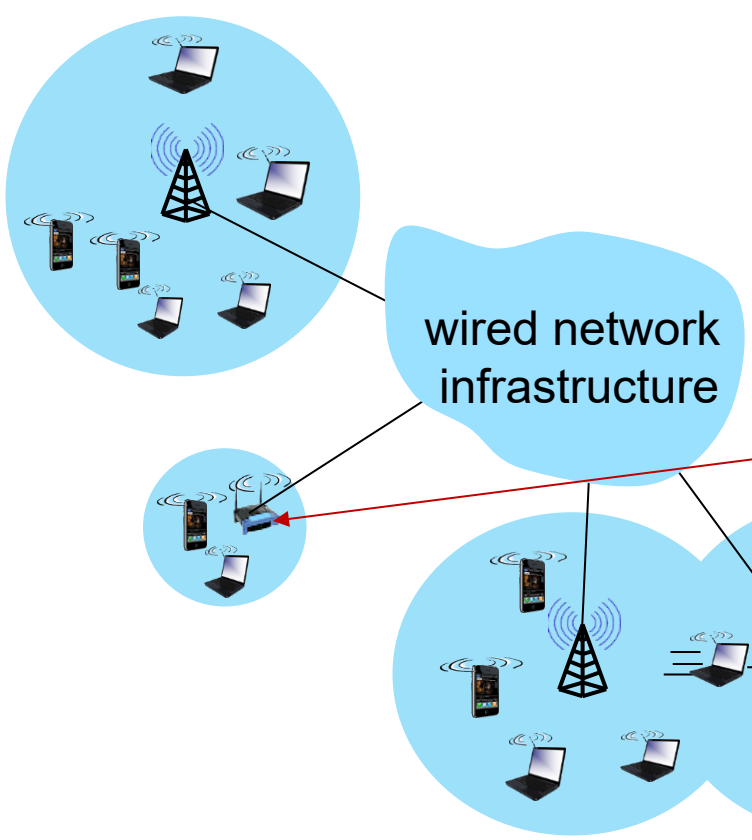


wireless hosts

- laptop, smartphone, IoT
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility!



Elements of a wireless network

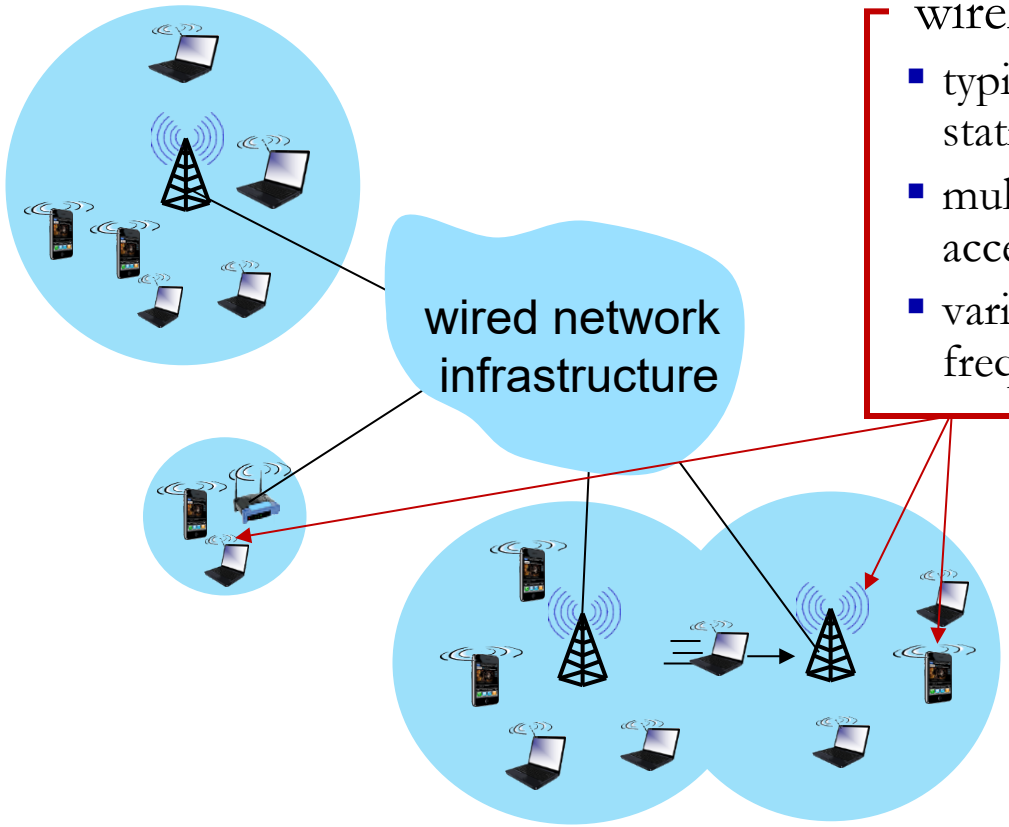


base station



- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

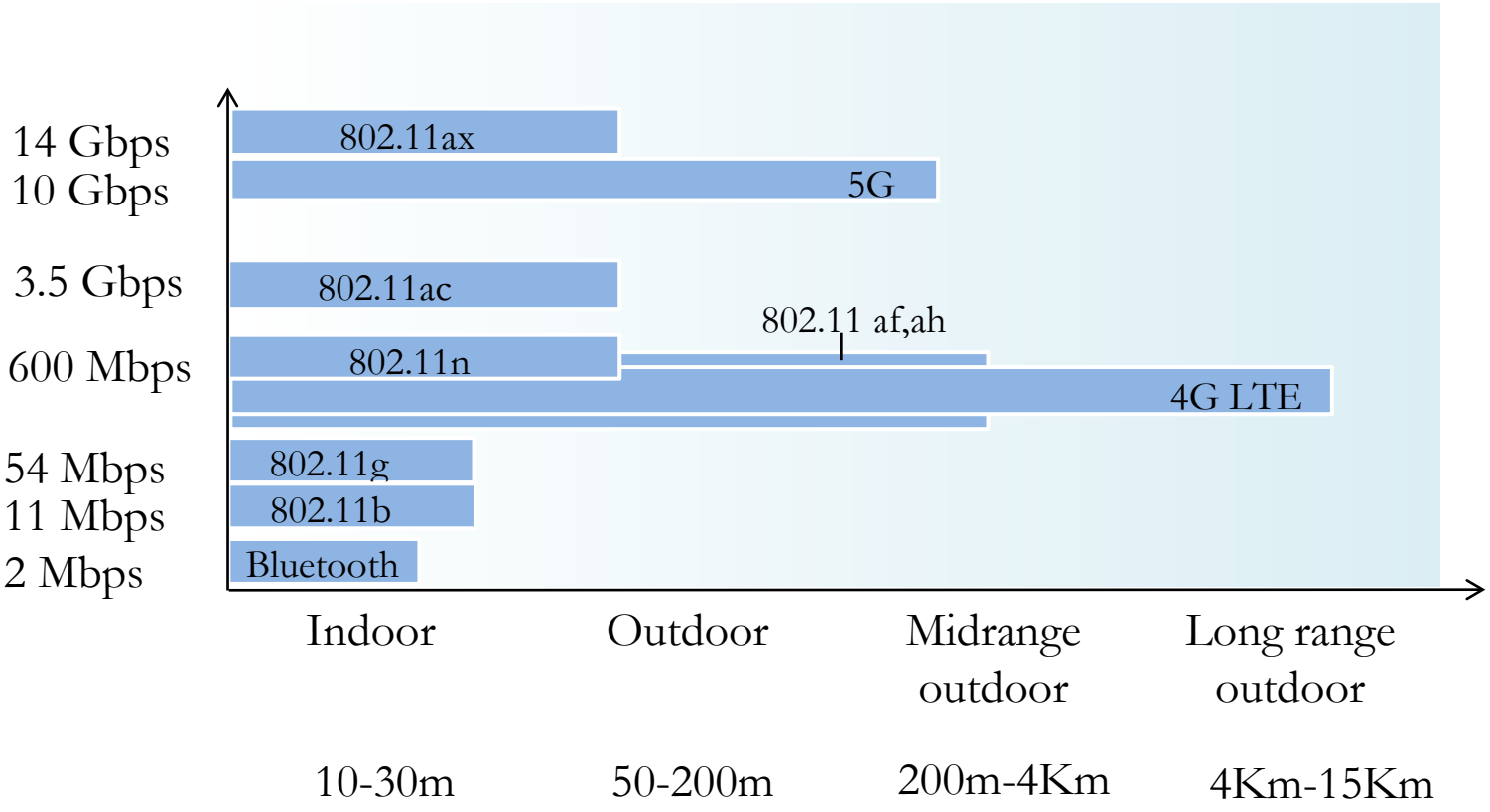
Elements of a wireless network



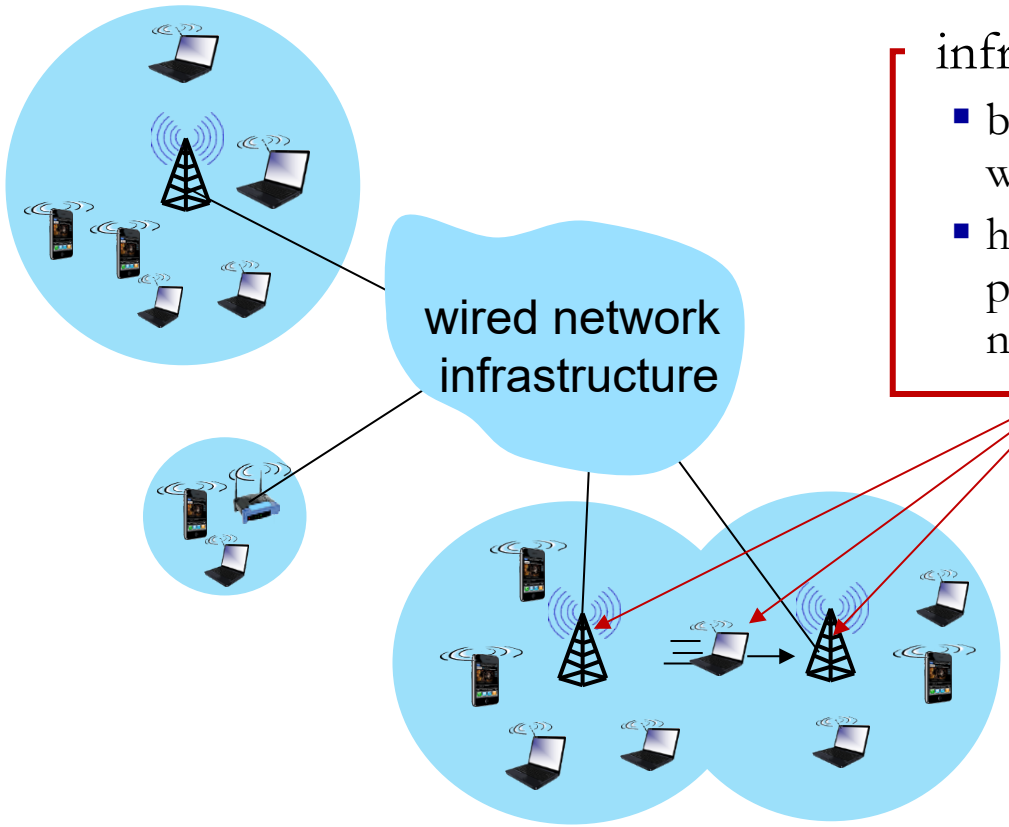
wireless link

- typically used to connect mobile(s) to base station, also used as backbone link
- multiple access protocol coordinates link access
- various transmission rates and distances, frequency bands

Characteristics of wireless links



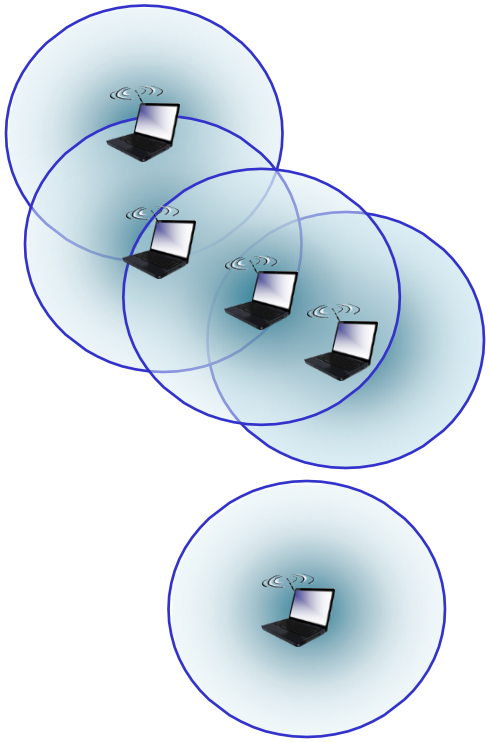
Elements of a wireless network



infrastructure mode

- base station connects mobiles into wired network
- handoff: mobile changes base station providing connection into wired network

Elements of a wireless network



ad hoc mode

- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves
- Example: wireless sensor networks

Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET(车联网)

Wireless networks

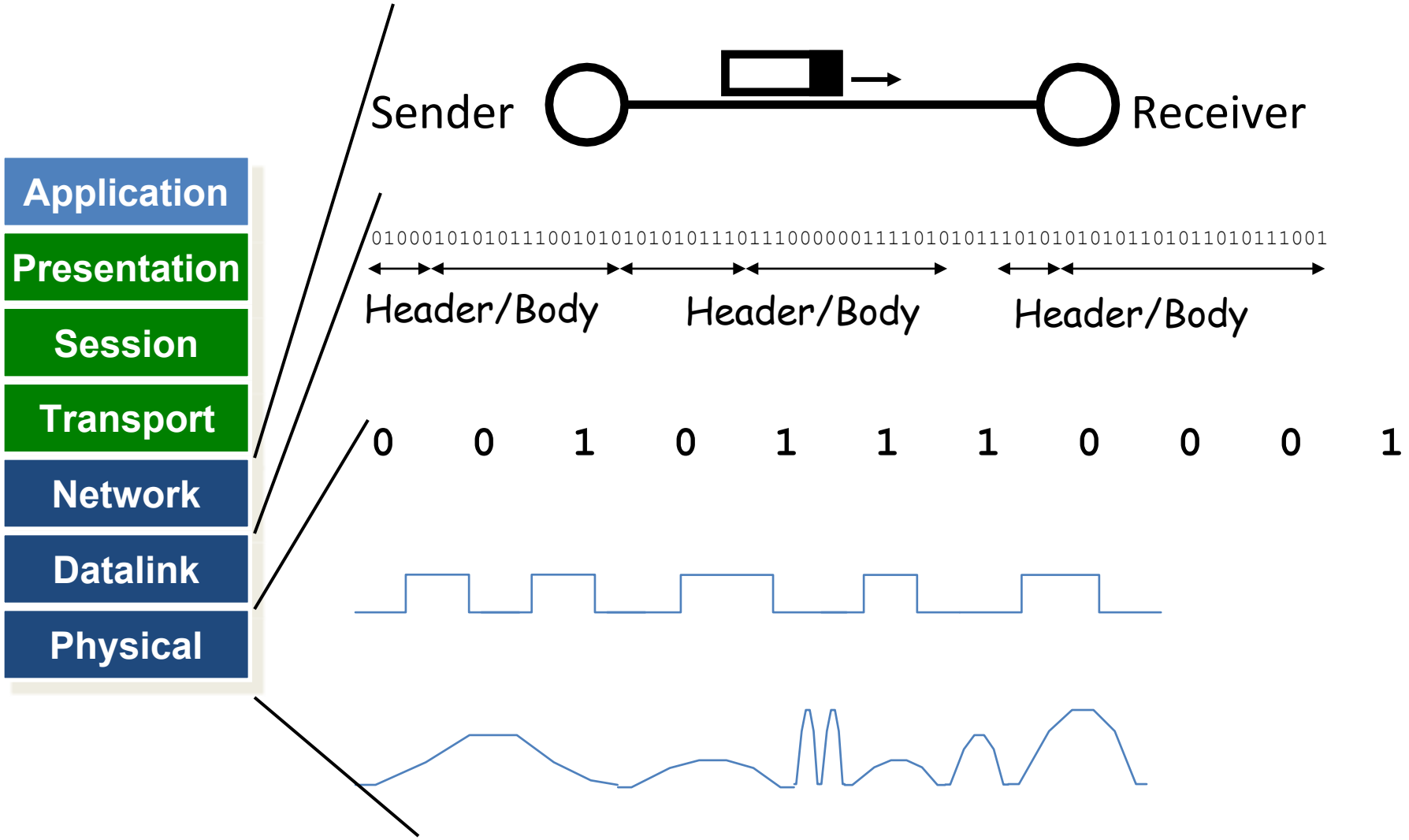
- Why wireless?
- **Wireless networks**
  - "*any* type of network whose interconnections between nodes is implemented without the use of wires."
  - "generally implemented with some type of remote information transmission system



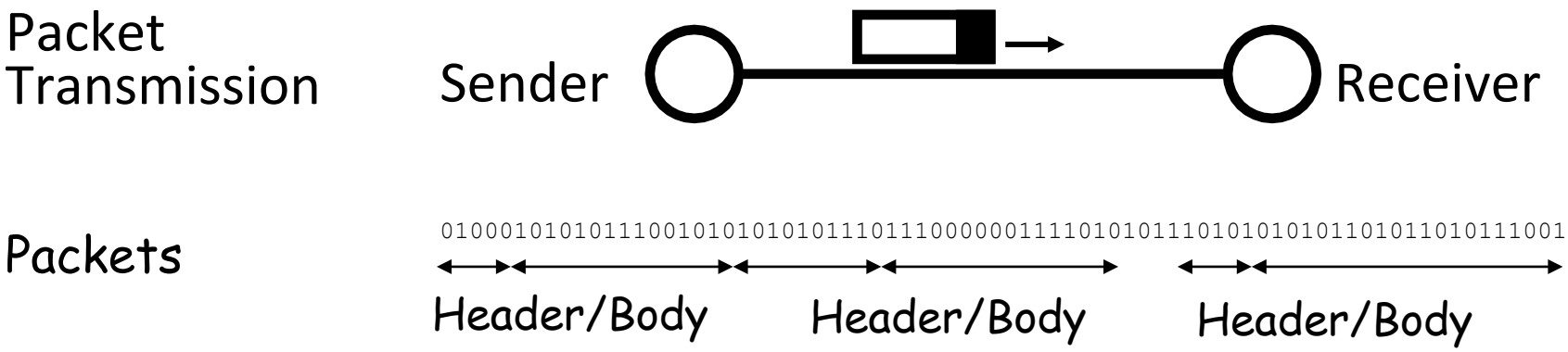
Transferring Information

- Information transfer is a physical process
- In this class, we generally care about
  - Electrical signals (on a wire)
  - Optical signals (in a fiber)
  - More broadly, EM waves
- Information carriers can also be
  - Sound waves
  - Quantum states
  - Proteins
  - Ink & paper, etc.

From Signals to Packets



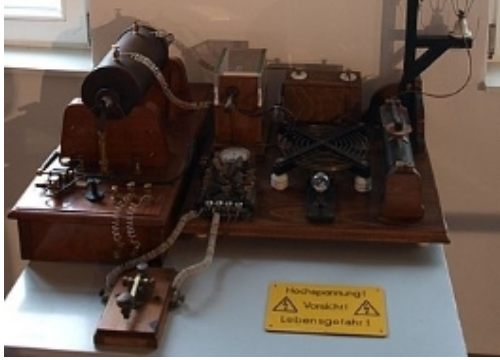
From Signals to Packets



Radio Frequency Communication

- RF = “portion of the electromagnetic spectrum in which electromagnetic waves can be generated by alternating current fed to an antenna”

Some History



- 1873 – "*A Dynamical Theory of the Electromagnetic Field*." by James Clerk Maxwell
- 1887 - Heinrich Hertz demonstrates spark-gap transmitter – didn't think it is very useful!
- 1890 - Edouard Branly demonstrates practical coherer
- 1893-97 - Nikola Tesla, Oliver Lodge, Jagdish Chandra Bose, Alexander Popov, Guglielmo Marconi demonstrated "lab" models of their "wireless devices"
- 1897 - Wireless Telegraph and Signal Company, Ltd. In London
- 1901 – successful transmission across the Atlantic Ocean ("a bit more" power and bigger antennas)

Some History (contd)

Q: What do they have to do with radio?

A: Nothing but after Titanic, spark-gap transmitters quickly became universal on large ships

- Radio Act of 1912 – all ships must maintain 24-hour radio watch and keep in contact with nearby ships and coastal radio stations
  - → interference → tuning → modulation
- Radio Act of 1927 – created Federal Radio Commission to regulate radio use "as the public convenience, interest, or necessity requires."
- Communications Act of 1934 – established Federal Communications Commission (FCC)
- Telecommunications Act of 1996, 2006

IMPORTANT TERMS

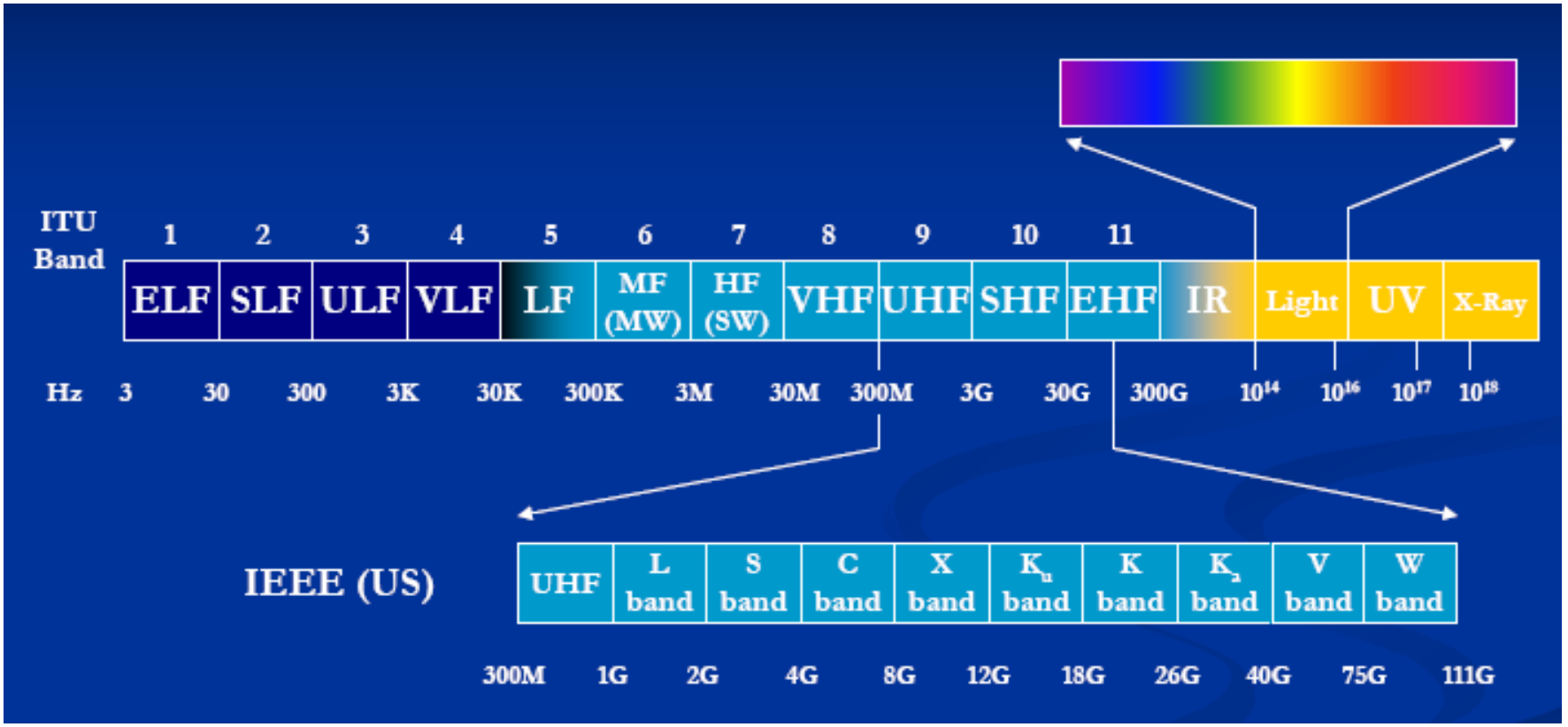
Spectrum

- EM waves have medium dependent properties such as: speed (refraction折射), resonance (absorption吸收), reflection反射, scattering散射
- Propagation in atmosphere:
  - f < 2 MHz: ground-waves (waves follow the contour of the earth)
  - 2 MHz < f < 30 MHz: sky-wave propagation (reflections from ionosphere)
  - f > 30 MHz: line-of-sight (atmospheric scattering)
- Jamming can happen
- In vacuum:



atmospheric scattering

Spectrum Classification



查 • 论 • 编 — 无线电波 — [隐藏]

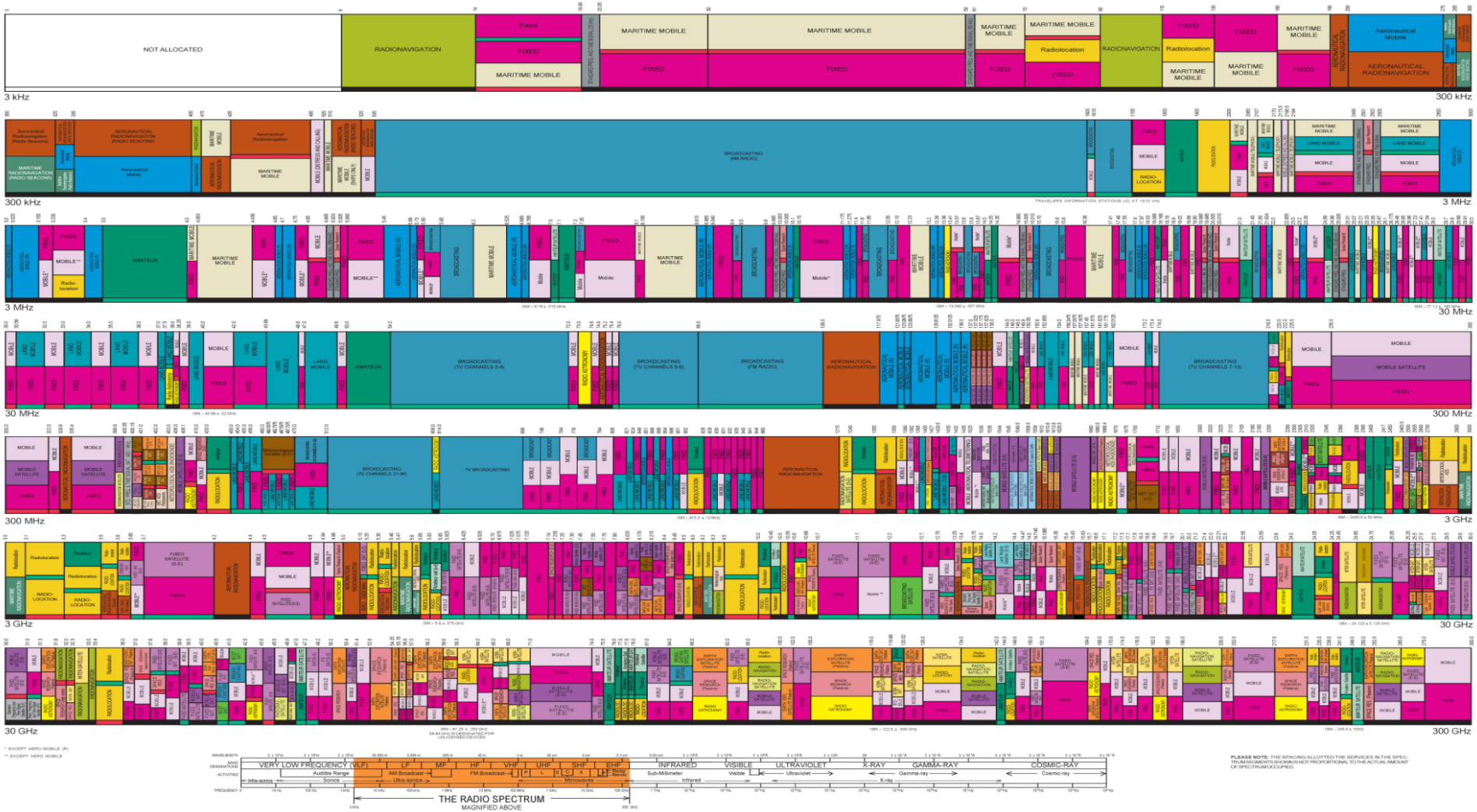
无线电波名	极低频	超低频	特低频	甚低频	低频	中频	高频	甚高频	特高频	超高频	极高频
英文缩写	ELF	SLF	ULF	VLF	LF	MF	HF	VHF	UHF	SHF	EHF
频率下限	3 Hz	30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz
频率上限	30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz	300 GHz
最大波长	100000 km	10000 km	1000 km	100 km	10 km	1 km	100 m	10 m	1 m	10 cm	1 cm
最小波长	10000 km	1000 km	100 km	10 km	1 km	100 m	10 m	1 m	10 cm	1 cm	1 mm

规范控制 GND: 4719942-8

Spectrum Allocation

- Spectrum – national resource under government control (usually split between commercial and military)
  - US: Federal Communications Commission (**FCC**) and Office of Spectral Management (**OSM**) in US
  - EU: European Conference of Post and Telecommunications Administrations (**CEPT**)
    - European Communications Office (ECO) -> Electronic Communications Committee (ECC)
  - Japan: Ministry of Public Management, Home Affairs, Posts and Telecommunications (**MPHPT**)
  - China:无线电管理局（国家无线电办公室）
- International Telecommunications Union (**ITU**: ITU-T,ITU-R)
- Commercial allocation
  - Fixed
  - Auctions
  - Unlicensed
  - Secondary market and spectrum leasing
- Policy shift: Cognitive radio - a transceiver can intelligently detect which communication channels are in use and which ones are not
- EM LLM

Spectrum Allocation (cont'd)



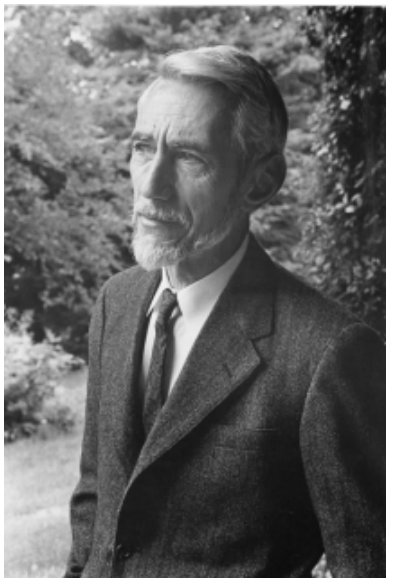
Spectrum Allocation

- Unlicensed spectrum (US)

ISM band I*	902 - 928 MHz
ISM band II	2.4-2.4835 GHz
ISM band III (Wireless PBX)	5.725-5.850 GHz
ISM	59-64 GHz
U-NII band I (indoor systems, WLAN)	5.15-5.25 GHz
U-NII band I (short-range outdoor, WLAN)	5.25-5.35 GHz
U-NII band I (indoor/outdoor)	5.47-5.725 GHz
U-NII band III (long-range outdoor, WLAN)	5.725-5.825 GHz

ISM = Industrial, Scientific and Medical
U-NII = Unlicensed National Information Infrastructure

Shannon Capacity



- **Claude Shannon**（克劳德·艾尔伍德·香农）(1916-2001)

$$C = B \log_2(1 + \frac{S}{N})$$

- Upper bound on achievable communication rate in AWGN environments (1948)
  - *C* is the channel capacity in bits per second;
  - *B* is the bandwidth of the channel in hertz;
  - *S* is the signal power, measured in watt or volt^2;
  - *N* is the noise power
  - *S/N* is the signal-to-noise ratio (SNR)
- Example:
  - Local loop bandwidth: 3200 Hz
  - Typical S/N: 1000 (30db)
  - What is the upper limit on capacity?
    - 3200 x $\log_2(1 + 1000)$ = 31.895 kbits/s

Bandwidth

- Bandwidth is **width of the frequency range** in which the Fourier transform of the signal is non-zero. (At what frequencies is there energy)

- Sometimes referred to as the channel width. Or, where it is above some threshold value (Usually, the half power threshold, e.g., -3dB)

- dB
  - Short for decibel
  - Defined as $10 * \log_{10}(P_1/P_2)$
  - When used for signal to noise: $10 * \log_{10}(P_S/P_N)$

Noise

- "Any unwanted input" that limits systems ability to process weak signals
- Measure of the signal "noisiness" = signal-to-noise ratio (frequency dependant)
- Noise sources:
  - External
  - Atmospheric
  - Interstellar
- Receiver internal
  - Thermal
  - Flicker noise (low frequency)
  - Shot noise
- Noise is not always bad!

EXAMPLES:
- Random noise in resistors and transistors
- Mixer noise
- Power supply noise

Antennas

- "Interface" between the transmitter (receiver) and channel

- Can the wires inside devices be antennas?

Multipath

- Non Line-of-sight

- Objects in the environment
  - Reflection
  - Diffraction
  - Scattering

- Multiple signal copies added together
  - Attenuated
  - Delayed
  - Phase shifted

$$d(t) = h_1 s(t - \Delta_1) + h_2 s(t - \Delta_2) + \ldots + h_m s(t - \Delta_m)$$

- Frequency selective fading
- Flat fading
- Ultimately causes inter symbol interference (ISI) which limits performance

Wireless link characteristics (1)

important differences from wired link ….

- decreased signal strength*:* radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
  - Cross-technology communication (CTC)
  - E.g., WiFi and Zigbee/Bluetooth
- multipath propagation: radio signal reflects off objects ground, arriving at destination at slightly different times

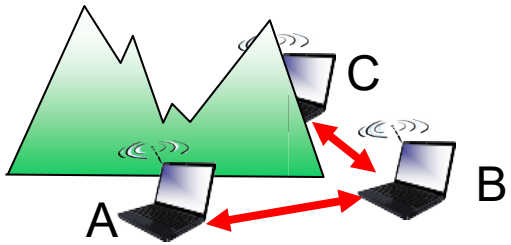




…. make communication across (even a point to point) wireless link much more “difficult”

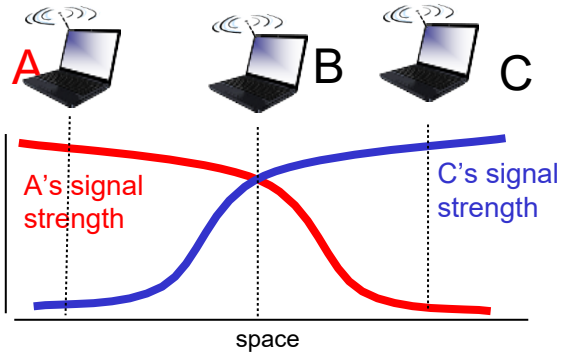
Wireless link characteristics (2)

- Multiple wireless senders, receivers create additional problems (beyond multiple access):



Hidden terminal problem

- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B



Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C can not hear each other, resulting in interfering at B

Wireless Access Control

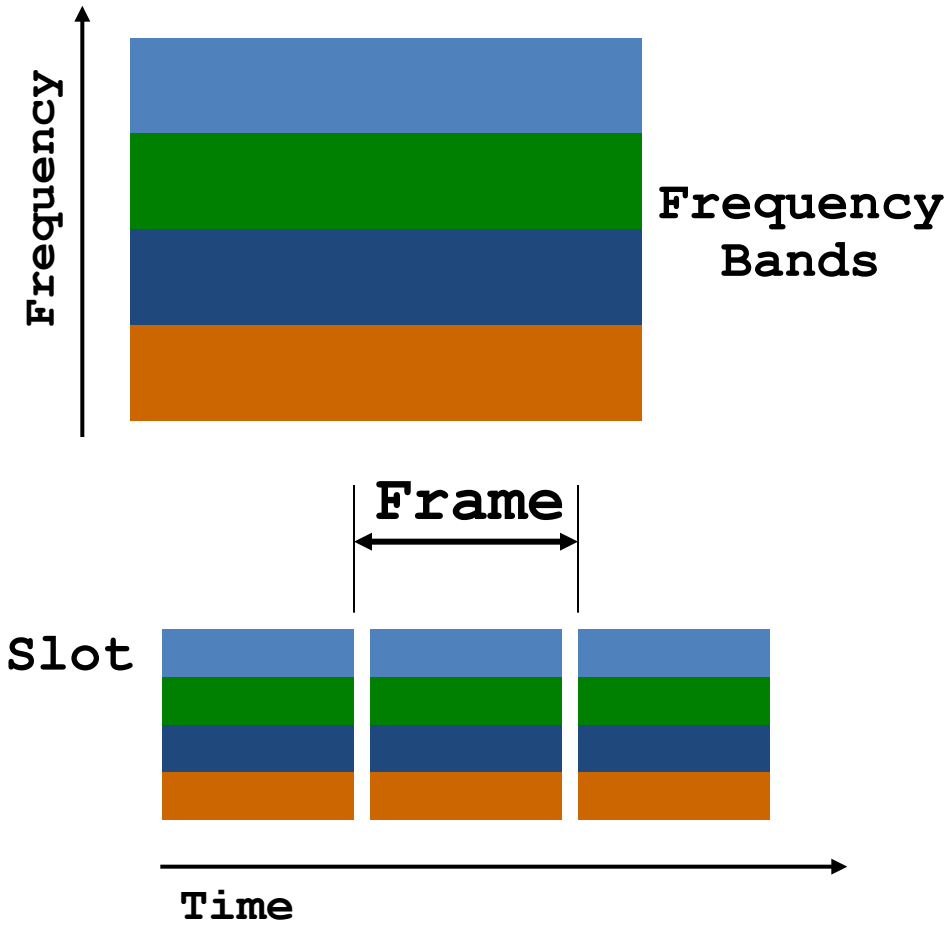
- Recall packet switch: Sharing instead of dedicated resource

- Data is divided into chunks – packets:
  - Each packet fights for resources
  - Each packet can be routed independently

- Resource allocation (switching)
  - DMA: TDMA, FDMA
  - ALOHA:
    - unslotted (pure), slotted
  - Carrier-sense :
    - non-persistent, p-persistent, CD, CA

Frequency vs. Time-division Multiplexing

- With FDM different users use different parts of the frequency spectrum.
  - I.e. each user can send all the time at reduced rate
- With TDM different users send at different times.
  - I.e. each user can send at full speed some of the time
  - Example: time-share condo
- The two solutions can be combined.



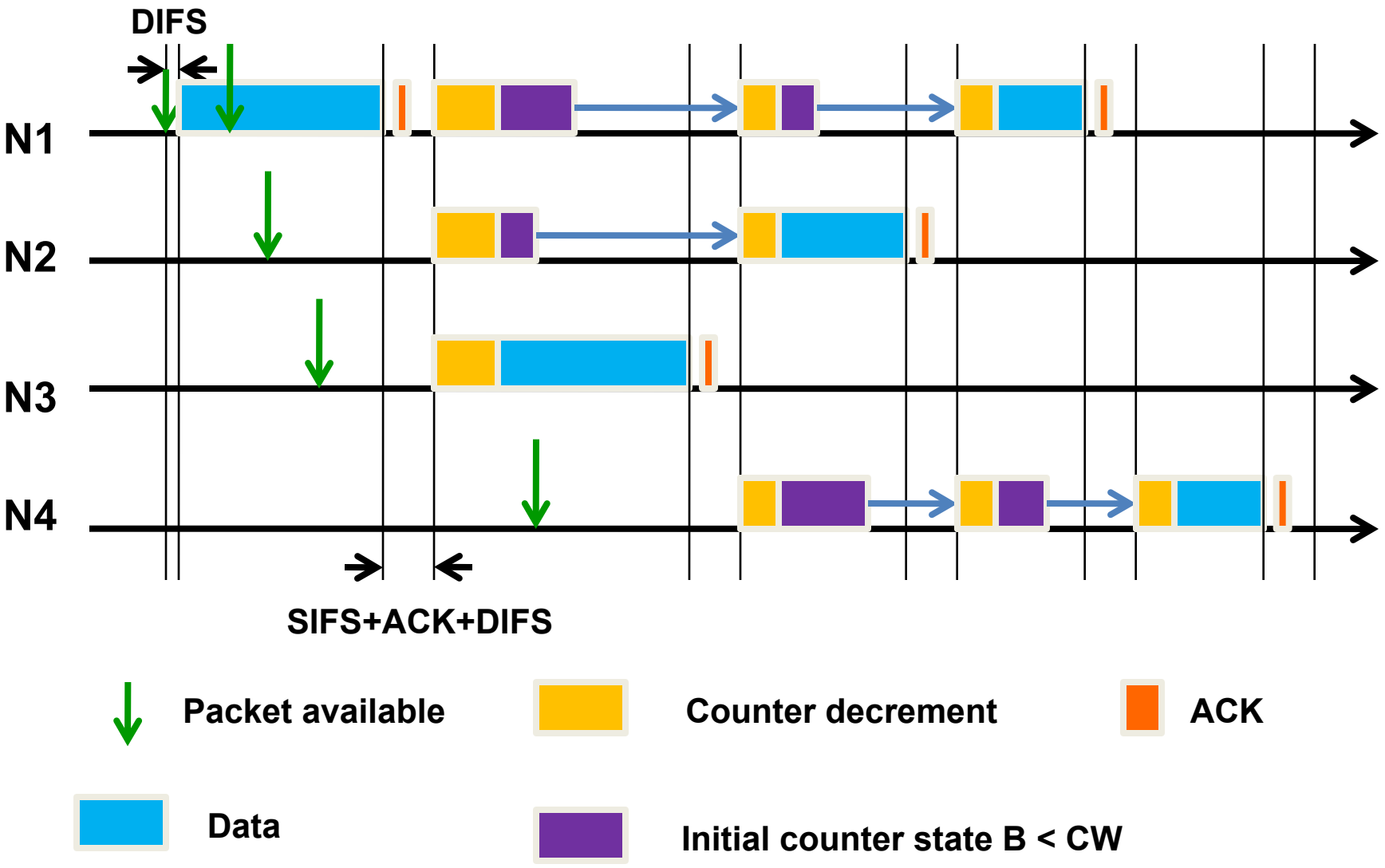
CSMA/CA

- Use CSMA with Collision Avoidance
  - Based on carrier sense function called Clear Channel Assessment (CCA)
- Why not collision detection in wired networks?
- Reduce collision probability where mostly needed
- Possible to implement different Efficient backoff algorithm stable at high loads

1-Persistent CSMA (Ethernet)

- Sense the channel
  - If busy, keep listening to the channel and transmit immediately when the channel becomes idle.
  - If idle, transmit a packet immediately.
- If collision occurs
  - Wait a random amount of time and start over again.
- Greedy algorithm

Basic access in absence of collisions



Q: Why is your Wi-Fi always slow?

Binary random backoff

- initial counter state:
  $B = U[0, CW - 1]$
- contention window size:
- k: # of contentions
- example: 802.11b DSSS
  $CW_{min} = 32$, $\hat{k} = 5$, and $CW_{max} = 1024$

Discussion and Quick

- How LLM can influence the communication, e.g., to its performance, security…
- Use your GPT, Fable, Deepseek, etc.,
- 10 mins

Wireless Network Threat Model

Welcome to the Party



Wireless networking is analogous to a cocktail party

Open Invitation

- Anyone can “talk”, anyone nearby can “listen”
  - We can control connectivity in wired networks, but not in wireless





A Dynamic Occasion

- Everyone is free to move around as they please
  - Physical mobility - that's why we lost the wires, right?
  - Logical mobility – connecting with different peers at different times
- Conversation quantity/load/demand varies
  - Nobody really talks constantly all the time...
- Party conditions change over time
  - Noise, humidity/temperature, obstacles, reflections
- Others: services, roles, energy, …

Limited Engagement

- Each attendee has a limited amount of energy
  - Wireless devices are ideally battery-powered, otherwise why go wireless?

- Not all attendees have the same capabilities:
  - Some are less capable of processing what others say (e.g., less computation capability, 8-bit processors)
  - Some have limited memory (e.g., less storage)
  - Some have a limited vocabulary or speak a different language (e.g., different communication standards)
  - Some are quieter than others (e.g., shorter range of communication)

Coordination?

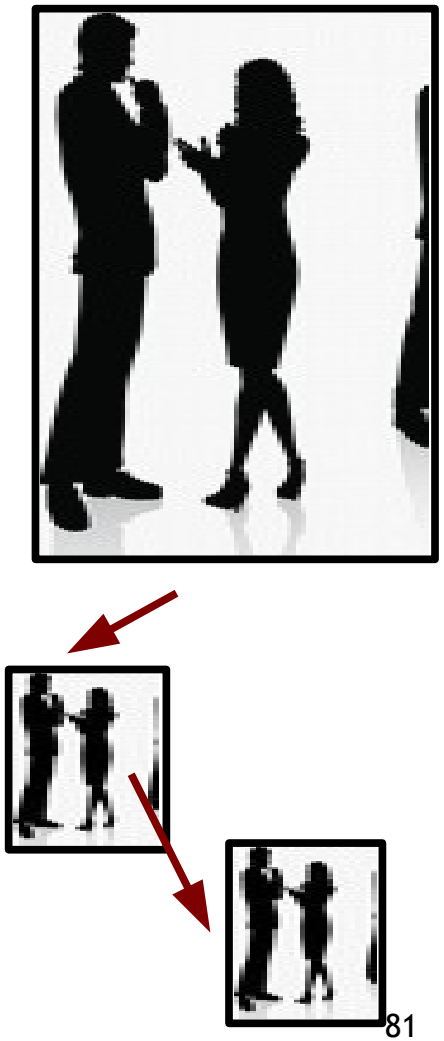
- Larger social gatherings probably don't have a single coordinator in charge of controlling conversations
  - This type of control is usually more distributed, if existent at all
  - In wireless, APs and gateways act as local controllers, providing access to the cloud, but not controlled by it
- Competition among (in)dependent sub-groups
  - Think of how many WiFi APs you've seen at once...

How do we deal with these challenges?

“Simplify, Simplify, Simplify”

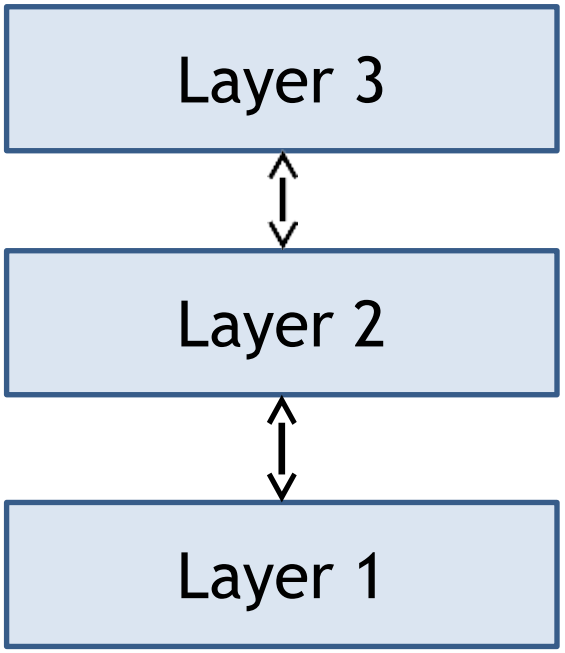
- Thoreau

- Instead of trying to solve all of the possible problems of cocktail party conversation, we decompose the problem into manageable steps
  - Communicating efficiently and effectively to a neighbor
  - Correcting mistakes, repeating, or re-stating
  - Relaying messages to a distant person
  - Making sure messages reach the intended recipient quickly, correctly, efficiently, etc. without annoying the messenger



Layering

- **Layering simplifies network design**
- Layered model:

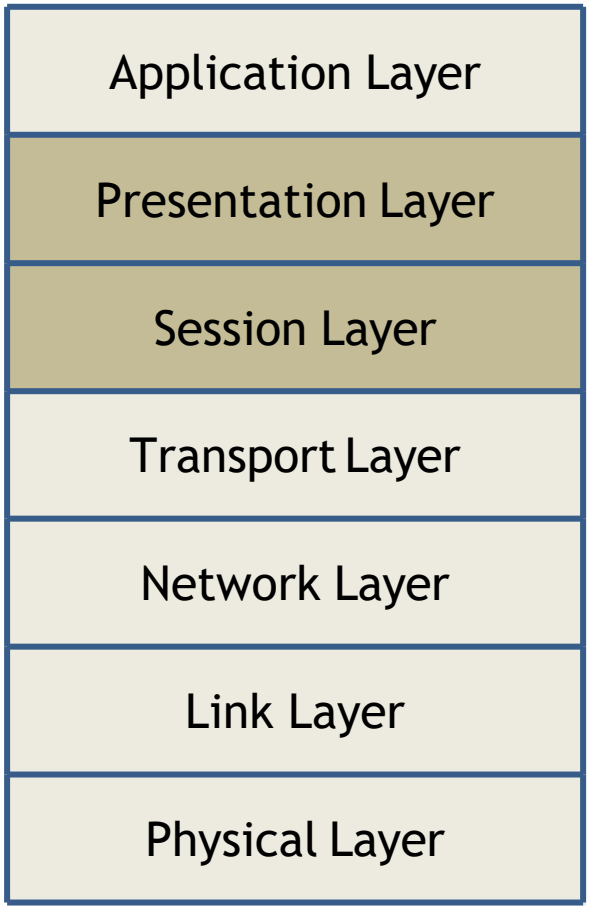


Lower layer provides a service to higher layer

Higher layer doesn't care (or even know, sometimes) how service is implemented: **lack of transparency**

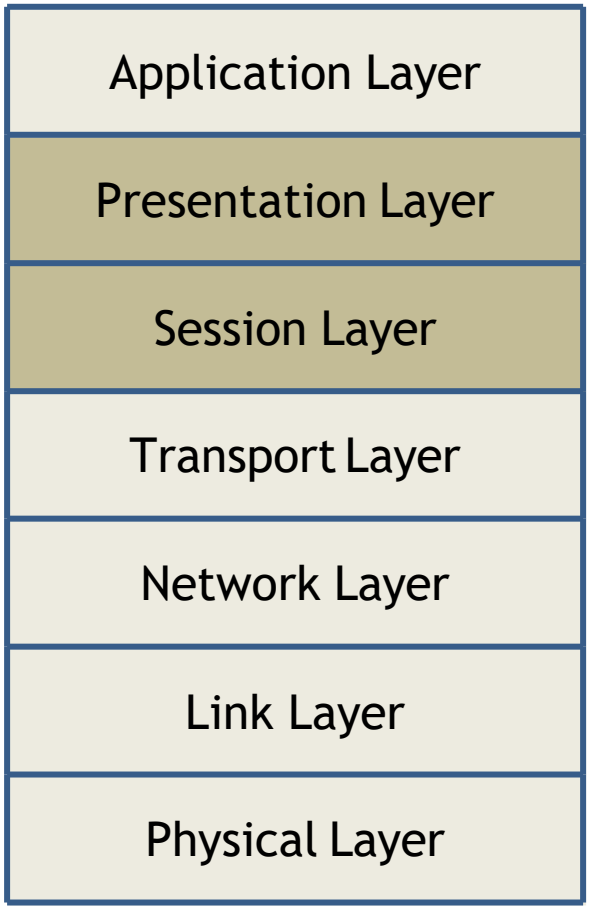
Layering Standards

- Standard layered model
  - Typically we talk about network layering using the 7-layer ISO Open Standards Interconnection (OSI) Model
  - Other models exist, but everyone seems to like ISO OSI



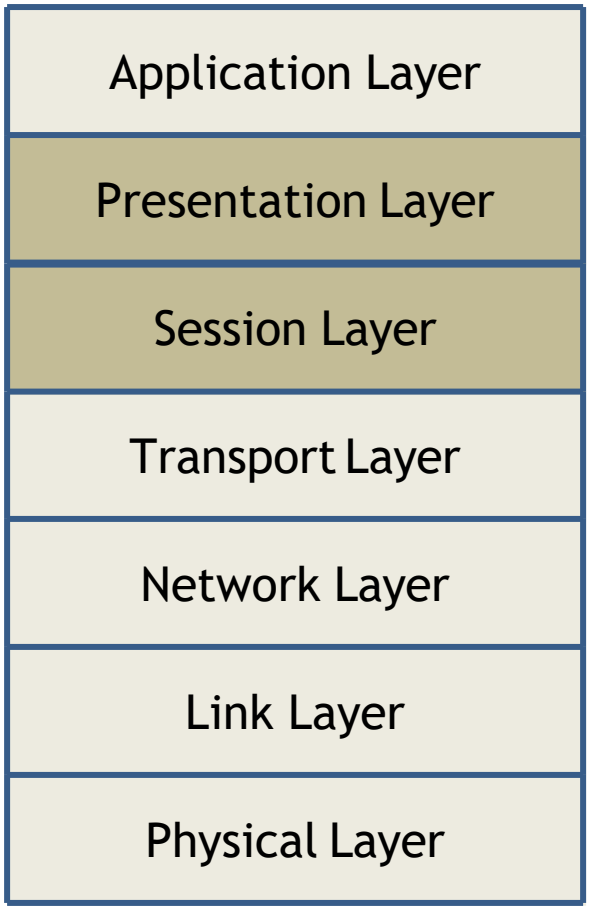
Layer Functionality

- Application Layer – support network applications
  - Presentation Layer – Compression, encryption, data conversion
  - Session Layer – Establish & terminate sessions
- Transport Layer – *Reliable* end-to-end data transfer
  - Multiplexing, error control, flow and congestion control



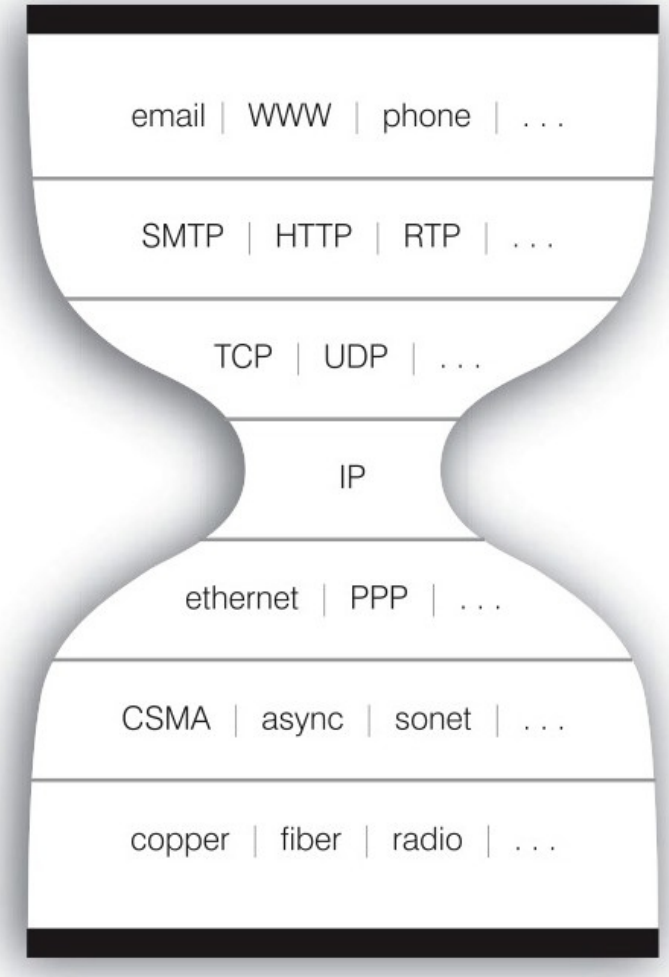
Layer Functionality

- Network Layer – Addressing and routing
- Link Layer – *Reliable* single-hop data transfer
  - Framing, error detection, medium access control (MAC) sub-layer
- Physical Layer – Moves bits
  - Bit synchronization, modulation & demodulation, physical connections



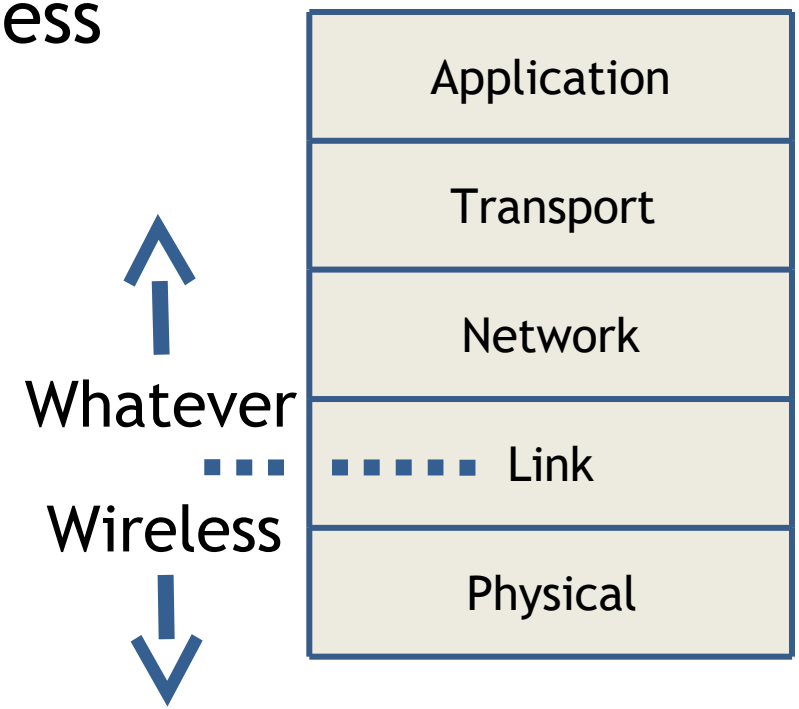
Internet Layering

- Layered protocols have been the basis of network design for decades
- Layers work great in some scenarios



Layering in Wireless

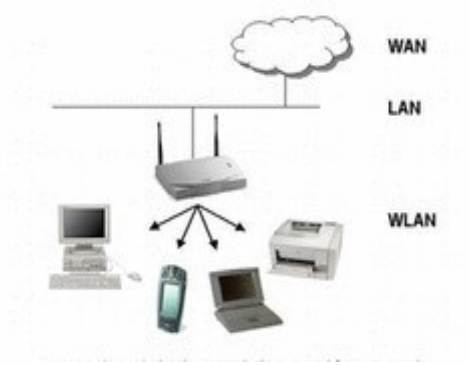
- Below a certain point, things can be designed for wireless communication
- Above that point, the medium doesn't matter…
  - Or does it?
  - Or should it?
- Trade-offs...



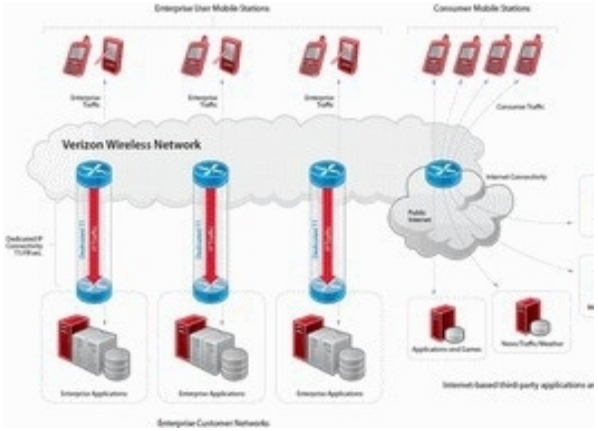
What types of wireless networks are we going to talk about?

Wireless Networks

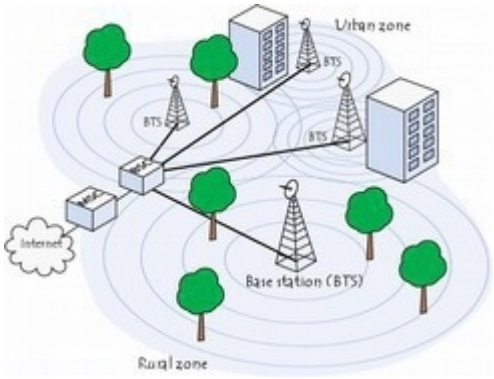
Wireless Internet

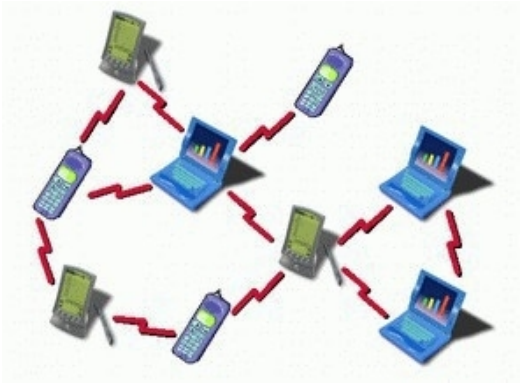


Enterprise Wireless

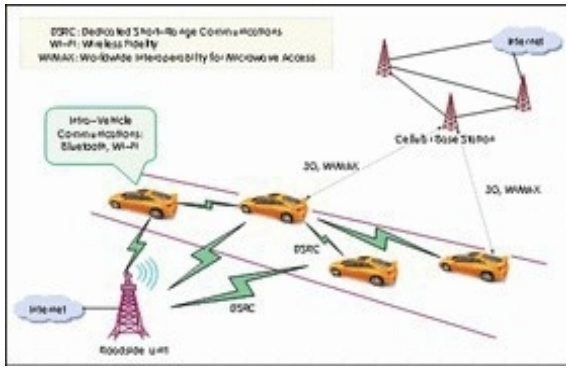


Telecommunications

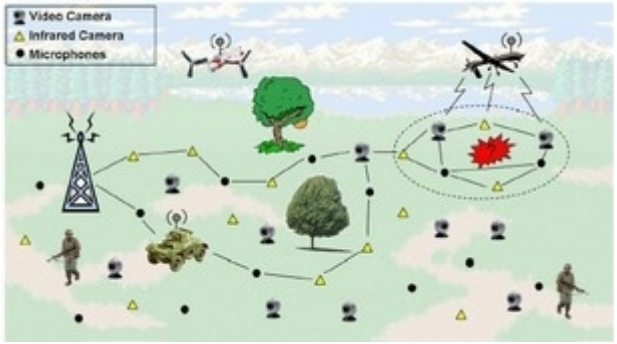




Ad Hoc / Mesh



Vehicular Networks

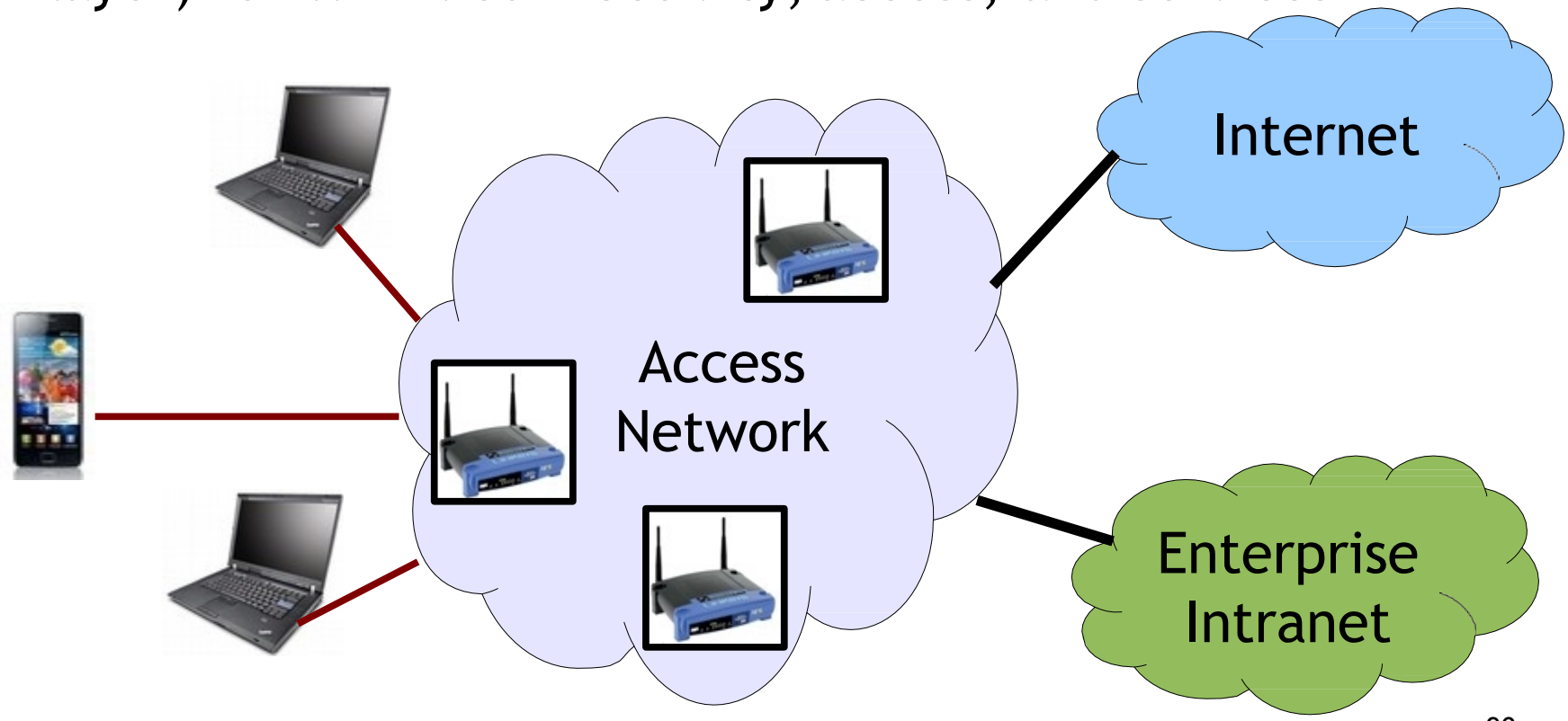


Sensing / Control Systems

And more...

WLAN Systems

- Almost every WLAN system in existence uses the IEEE 802.11 “WiFi” standard
  - 802.11 defines lower-layer services (physical, link, MAC layer) for WLAN connectivity, access, and services



Telecom/Mobile Networks

- Mobile networks have evolved from providing voice connectivity to the PSTN to providing all forms of connectivity to the Internet
  - AMPS first introduced in 1978
  - GSM developed through the 1990s- 2000s
  - 3G/4G standards emerged with full data support, looking more like a WLAN/WMAN

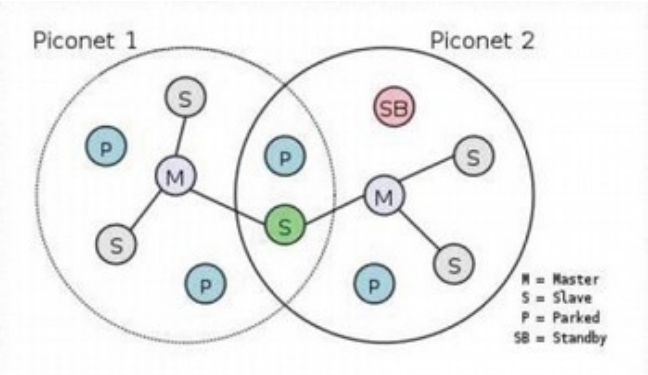






Personal Area Networks

- Local “device-to-device” networking using the 802.15 family of standards
- Typically short range, few devices, low power
- Commonly used for home, personal, office

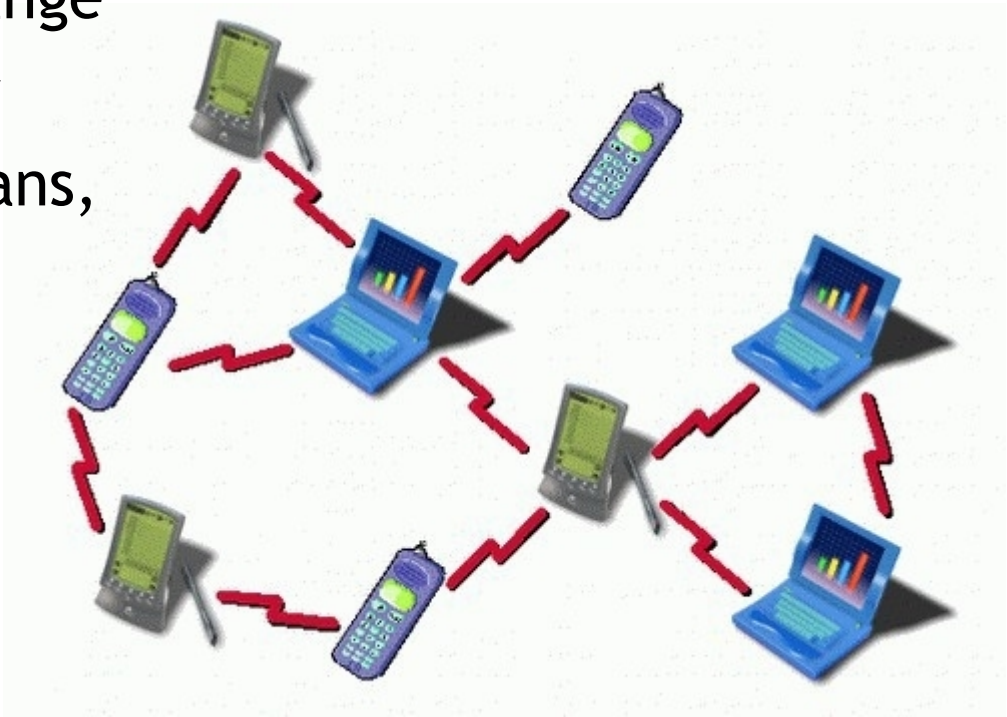






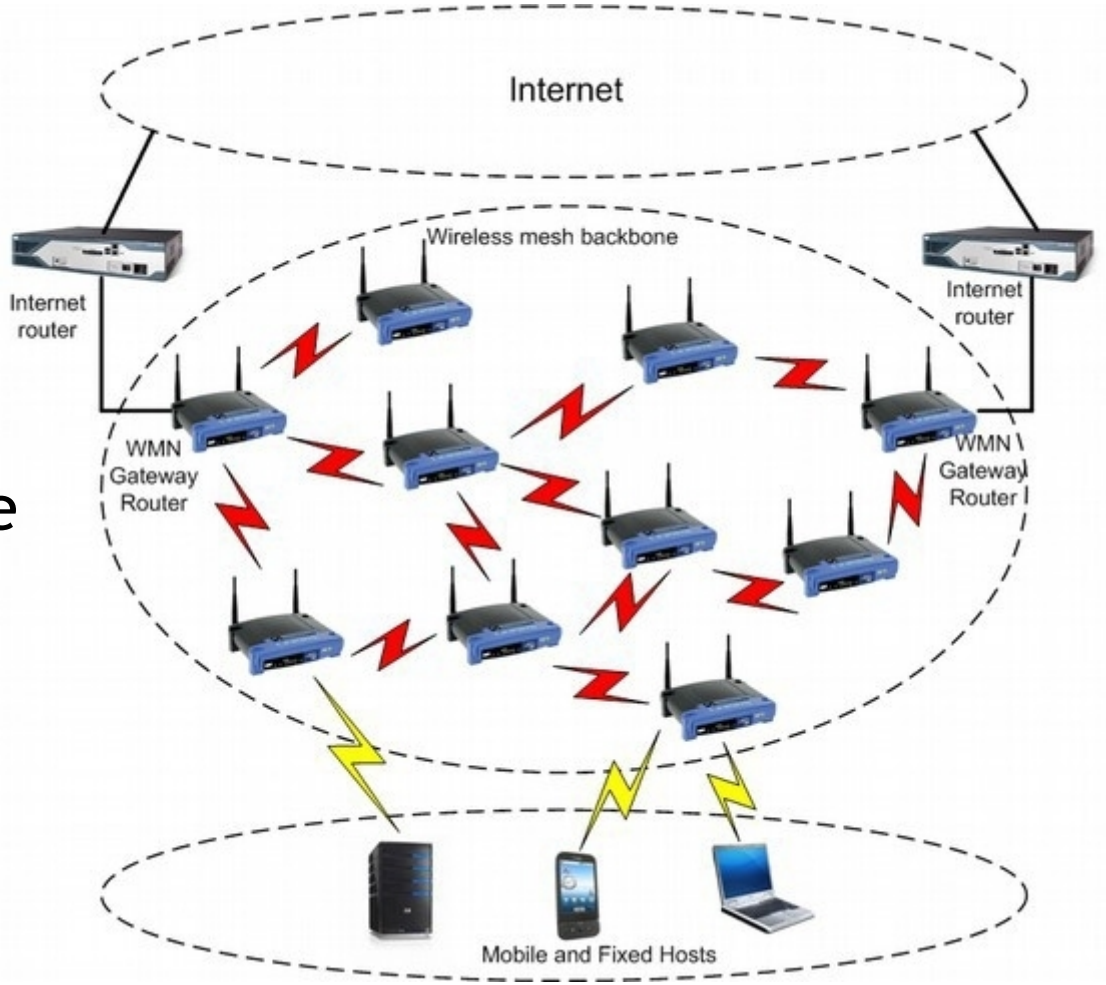
Mobile Ad Hoc Networks

- Mobile ad hoc networks (MANETs) typically connect local/offline devices with no Internet connection
  - Device-to-device, no APs
  - Peer-to-peer data exchange
  - In-network services only
  - Sometimes involve humans, but sometimes don't
  - No central server
  - No authority
  - No backhaul



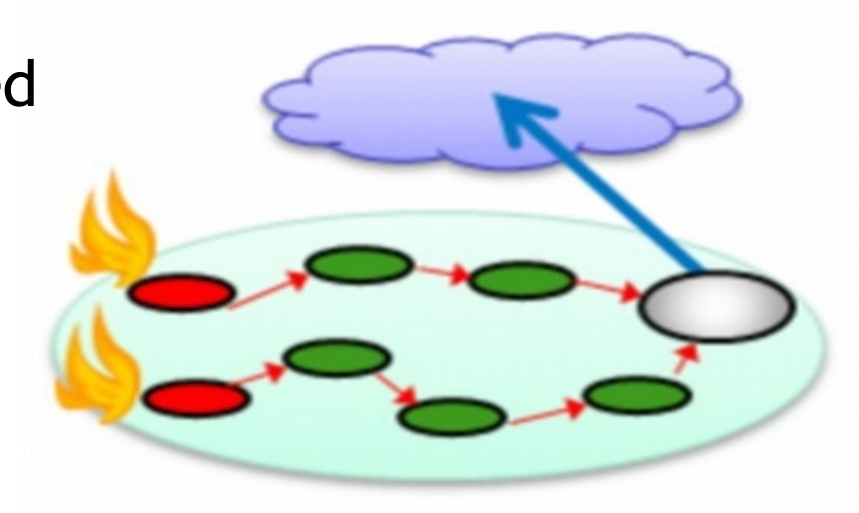
Wireless Mesh Networks

- Mesh networks provide multi-hop wireless connections to a backhaul
  - Mesh routers can be fixed or mobile, serve as multi-hop Internet connectivity
  - Hosts are typically mobile, hand-off to mesh routers



Sensor Networks

- Mostly use ZigBee (based on 802.15.4) or WiFi depending on requirements
  - Sensor networks are typically closer to a mesh architecture: multi-hop to one/many APs
  - Intermittent low-rate traffic, mostly sensor readings from nodes back to APs
  - Heavily resource-constrained
  - Designed for life-time



Home Networks

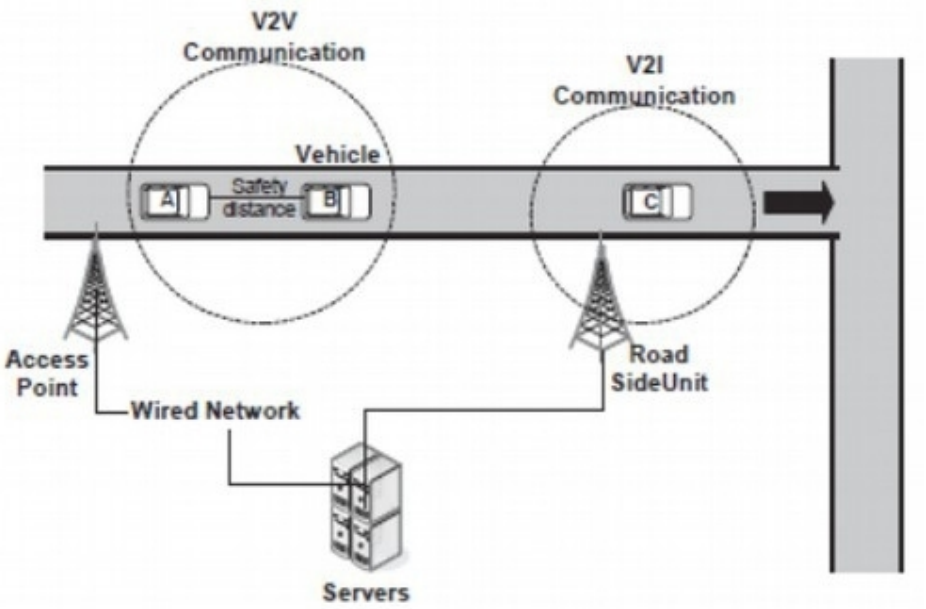
- In-home networked systems (Smart Home)
  - Entertainment/media
  - Appliances, etc.
- Home energy networks
  - The home side of the smart grid, between the smart meter and user
  - Mostly wireless (802.15.4, etc.)





VANETs

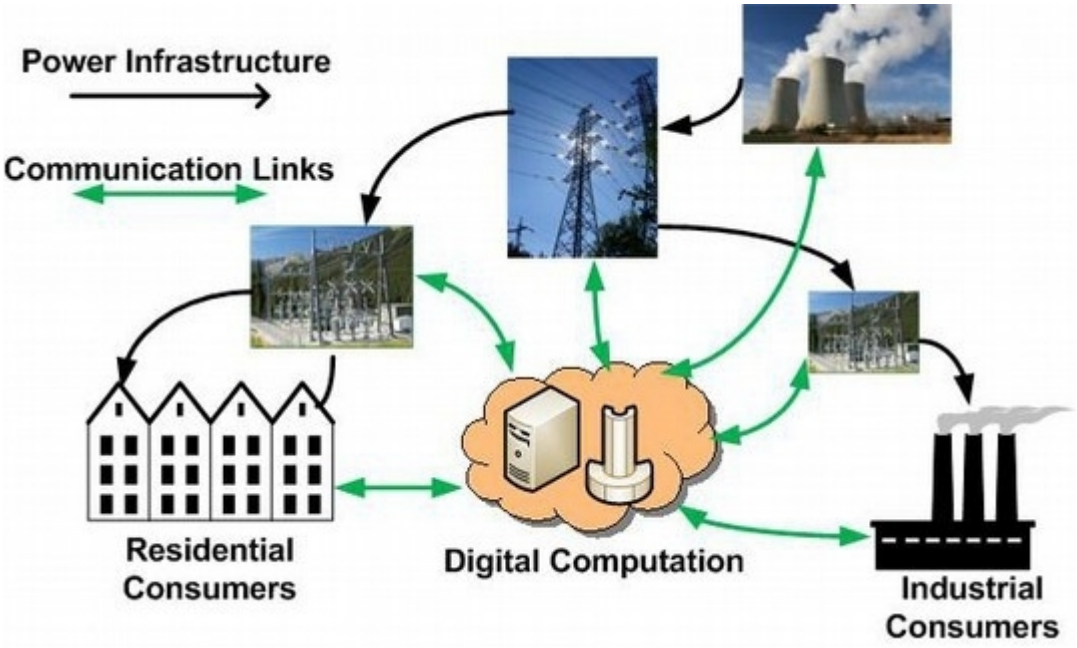
- VANET = Vehicular ad hoc network
  - Cars talk among each other and with roadside infrastructure



- Applications of interest:
  - Automated driver safety management
  - Passive road quality / condition monitoring
  - In-car entertainment
  - Navigation services
  - Context-aware rec's:
    - "This alternate route would be faster, and it would go past your favorite Primanti Bros."

Smart Grid

- The Smart Grid incorporates hybrid wired/wireless communications into the energy grid
- Applications of interest:
  - Dynamic pricing
  - Improved efficiency
  - Home energy mgmt.
  - Disaster/outage recovery



What is Wireless Network Security?

A probabilistic guarantee that a wireless network does a particular job as expected, even when faced with a variety of threats.

E.g., Confidentiality, Integrity, Authenticity…

Threats of Interest

- Many different types of threats faced in wireless
- Including (but not limited to) threats to:
  - Information content, source, etc.
  - Availability of wireless connectivity
  - Performance of network protocols
  - Proper use of scarce resources (energy, bandwidth, …)
  - Proper use of command/control messages
  - Correct representation of devices
  - …
- All of these are composed of certain primitives

Eavesdropping



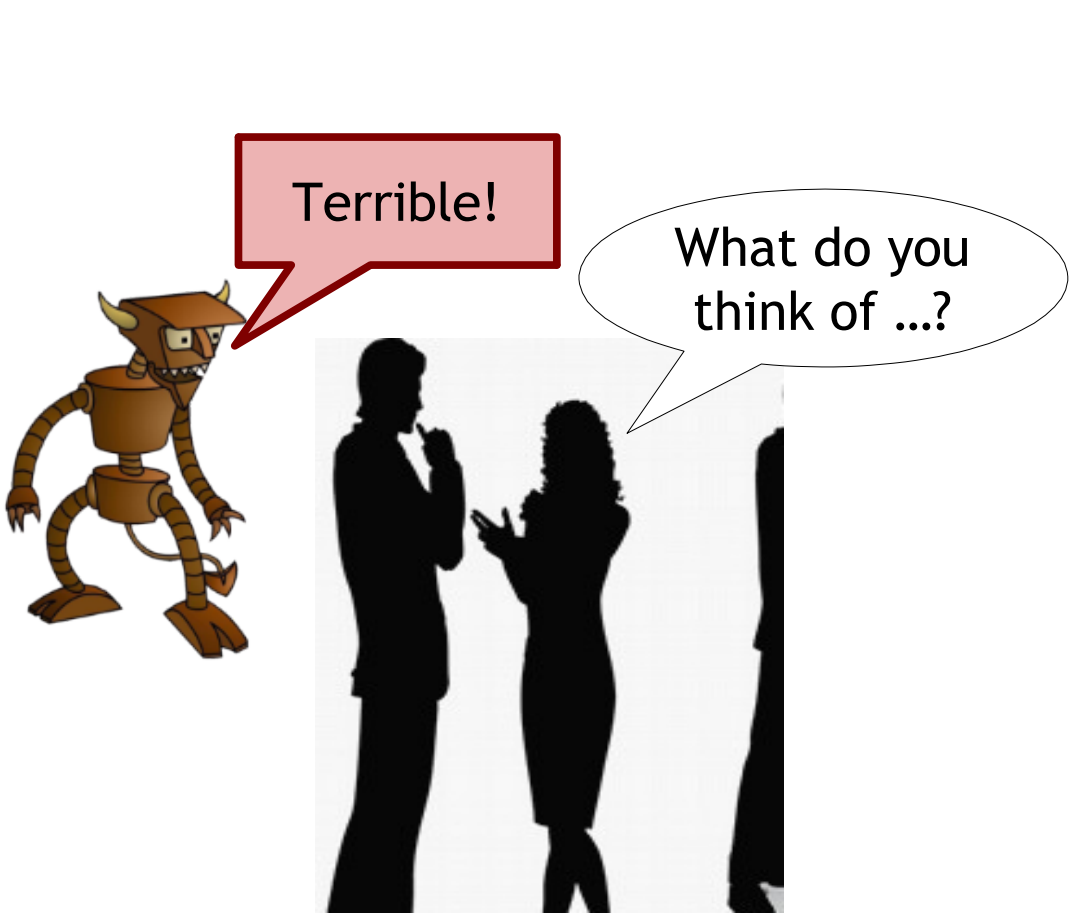


Interference





Msg/Pkt/Signal Injection/Replay



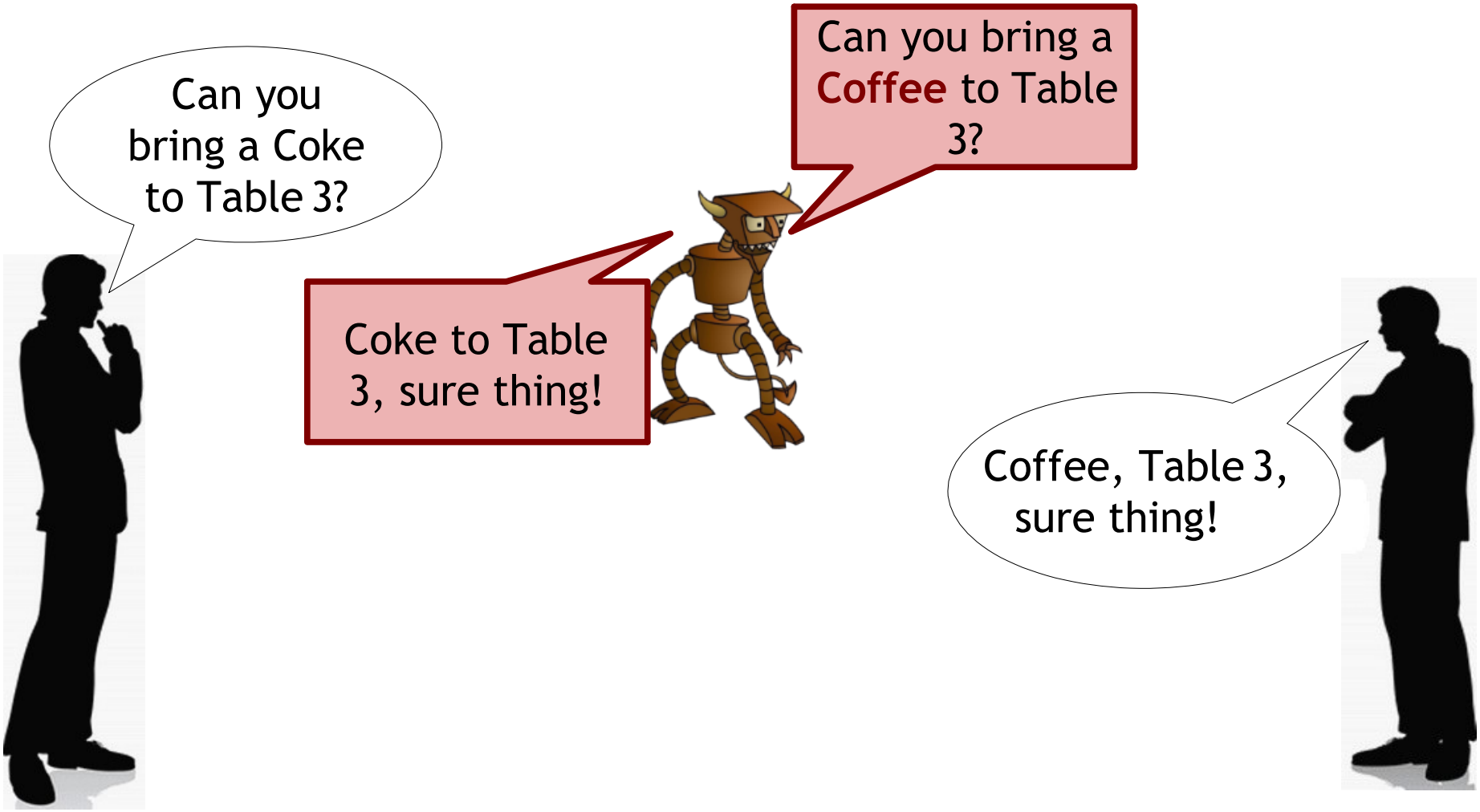


Spoofing





Man-in-the-Middle Attack



Byzantine Threats



- Byzantine threat is sort of like insider threat
- Basically, an authenticated / valid / trusted group member stops following the rules

And Many More...

- Denial/Degradation of Service
- Exploiting Composition Issues
- Context Manipulation
- …

Our plan.

We'll study how these various threats manifest at different layers and in different types of wireless systems.