Outline

- Introduction to Networked Embedded Systems
  - Embedded systems ➜ Networked embedded systems ➜ Embedded Internet
  - Network properties
- Layered Network Architectures
  - OSI framework – descriptions of layers
  - Internet protocol stack
- Physical Layer Options
  - Guided transmission media
  - Wireless transmission media
- Data Link Layer Services and MAC Protocols
- Embedded System Communication Protocols
  - Wired protocols: Ethernet, CAN, TTP, BACnet
  - Wireless protocols: Wi-Fi, ZigBee, WirelessHART
- TCP/IP Stack and 6LoWPAN Stack
- Modeling and Analysis of Communication Protocols

NETWORKS FOR ALL SIZES AND SCALES

- NoCs – connecting processors inside MPSoCs
- SPI, I2C, UART... – connecting discrete components inside boards
- USB, FireWire... – connecting peripherals around a PC
- Bluetooth, RFID, NFC... – connecting peripherals or sensors in small areas (BANs, PANs ...)
- CAN, fieldbuses... – connecting sensors, actuators and controlling equipment in a monitoring or control system (DCS)
- Zigbee, WirelessHART... – connection of self-organized wireless sensors (WSNs)
- Ethernet, WiFi... – connection of PCs and equipment in local areas (LANs)
- 10G Ethernet, ATM... – connection of large systems in large areas (MANs, WANs)
- GSM, LTE, WiMax… – wide area communications (MANs,WANs)

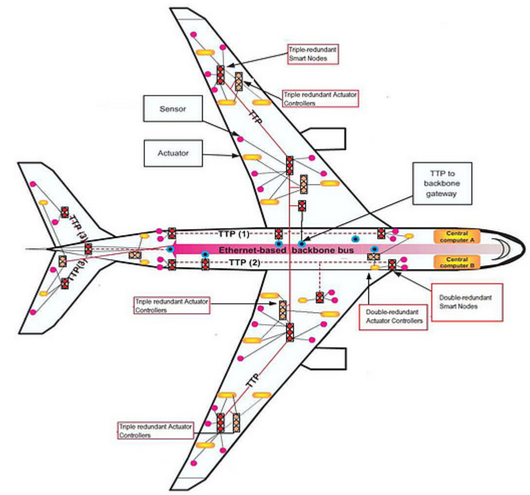
WHY NETWORKED AND DISTRIBUTED ARCHITECTURE

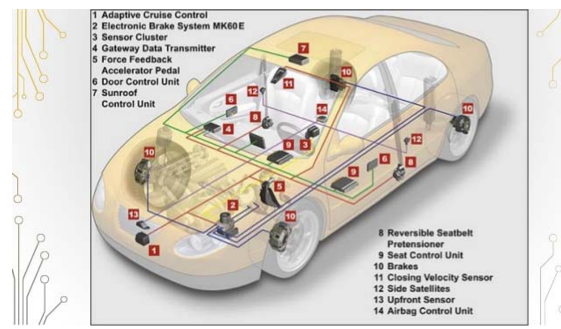
- Processing closer to data source / sink
  - Intelligent sensors and actuators
  - Reduce the computational overhead on the central processing node
- Dependability
  - Error-containment within nodes
- Composability
  - System composition by integrating components and subsystems
- Scalability
  - Easy addition of new nodes with new or replicated functionality
  - Especially for wireless
- Maintainability
  - Modularity and easy node replacement
  - Simplification of the cabling, especially for wireless

DISTRIBUTED VS. NETWORKED EMBEDDED SYSTEMS

Distributed Embedded Systems

- System-centered (designed as a whole)
  - Confined in space (despite possibly large)
  - Normally fixed set of components
  - Preference for wired networks w/ fixed topology
- Most common non-functional requirements
  - Real-time
    - End-to-end constraints on response to stimuli
    - Jitter constraints on periodic activities
  - Dependability
    - Ultra high reliability and safety, high availability
  - Composability
  - Maintainability

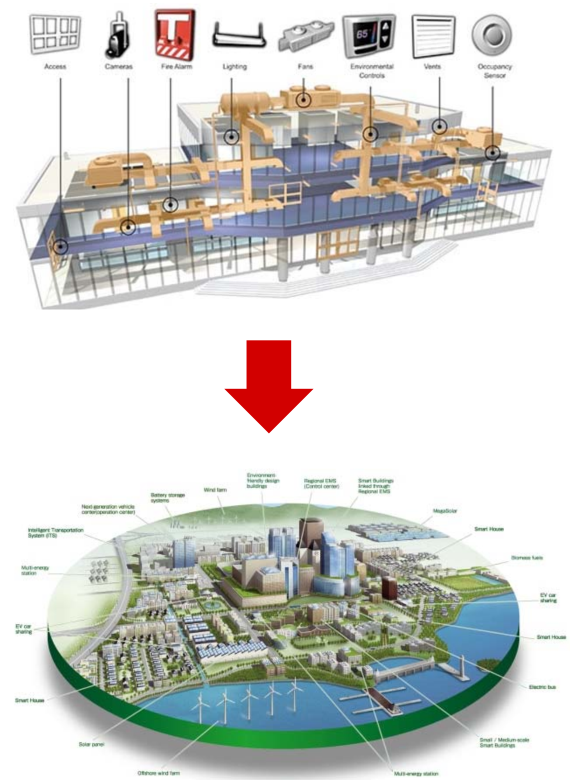




DISTRIBUTED VS. NETWORKED EMBEDDED SYSTEMS

Networked Embedded Systems

- Interconnected stand-alone equipment or systems for extra functionality (communication-centered)
  - Fuzzy notion of global system
  - Variable set of components
  - A combination of wireless/wired networks
    - Structured / Ad-hoc connections
    - Varying topology
    - Multi-hop communication
- Most common non-functional requirements
  - Scalability
  - Heterogeneity
  - Self-configuration
  - (Soft) real-time



NETWORK PROPERTIES

- Supported topologies
  - star, line, tree, mesh, bus, ring…
- Media access mechanisms
  - controlled access vs. uncontrolled access
- Network performance metrics
  - Bandwidth, throughput and goodput
- Network real-time performance
  - latency, jitter, coherent notion of time
- Network Security
  - Cryptosecurity, Emission, Transmission and Physical security

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LAYER ARCHITECTURE

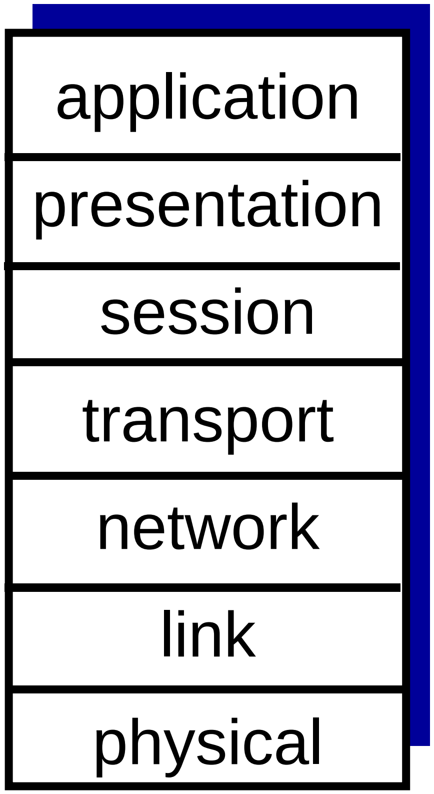
- Layer architecture simplifies the network design.
  - Explicit structure allows identification, relationship of complex system's pieces.
  - Modularization eases maintenance, updating of system.
  - Change of implementation of layer's service transparent to rest of system.
- It is easy to debug network applications with a layered architecture.
- The network management is easier due to the layered architecture.
- Network layers follow a set of rules, called protocol.
- The protocol defines the format of the data being exchanged, and the control and timing for the handshake between layers.

WHY LAYERING CONSIDERED HARMFUL?

- Structured layering implies that the functions of each layer are carried out completely before the protocol data unit is passed to the next layer.
- This means that the optimization of each layer has to be done separately.
- Such ordering constraints are in conflict with efficient implementation of data manipulation functions.

ISO/OSI REFERENCE MODEL

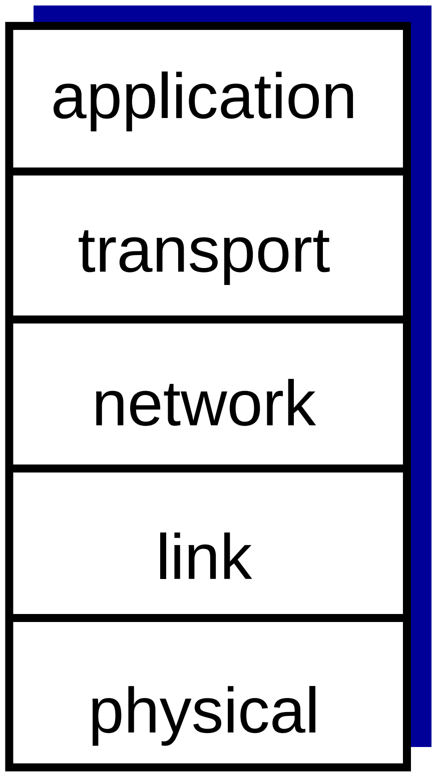
- Application: Network processes to applications
  - FTP, SMTP, HTTP…
- Presentation: Data representation
  - encryption, compression, machine-specific conventions
- Session: Interhost communication
  - synchronization, checkpointing, recovery of data exchange
- Transport: End-to-end connections
  - TCP, UDP
- Network: Addressing and routing
  - IP, routing protocols
- Link: Access to media
  - Ethernet, 802.111 (WiFi), PPP
- Physical: bits “on the wire”



INTERNET PROTOCOL STACK

- Internet stack “missing” presentation and session layers.
  - These services, if needed, must be implemented in applications.

- Application: supporting network applications
  - FTP, SMTP, HTTP
- Transport: process data transfer
  - TCP, UDP
- Network: routing of datagrams from source to destination
  - IP, routing protocols
- Link: data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP
- Physical: bits “on the wire”



EMBEDDED / REAL-TIME PROTOCOL STACK

- The OSI 7 layers impose a considerable overhead
  - Time to execute the protocol stack
  - Time to transmit protocol control information
  - Memory requirements (for all intermediate protocol invocations)
- Many embedded / real-time networks
  - are dedicated to a well defined application
  - use single broadcast domain (no need for routing)
  - use short messages (no need to fragment/reassemble)

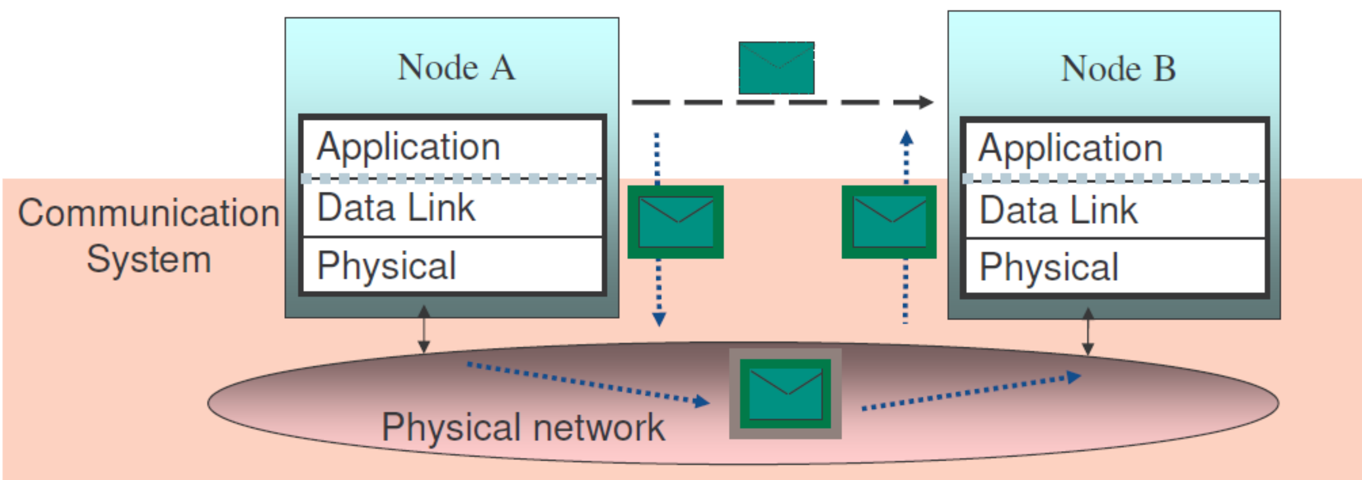


Figure from Dr. Luis Almeida

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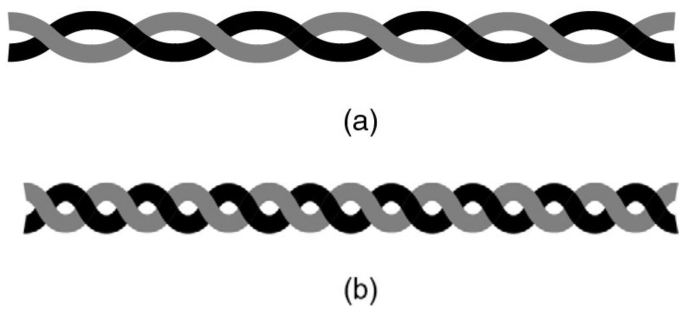
GUIDED TRANSMISSION MEDIA

Magnetic Media

- HP Ultrium tape =100GB. A box 60x60x60 holds 2000 tapes =>200 Tera bytes=1600 Tbits.
- A box can be delivered in 24 hours anywhere in USA => throughput: 1600 Tbits/86400 sec = 19 Gbps!

Twisted Pair/ Unshielded TP (UTP)

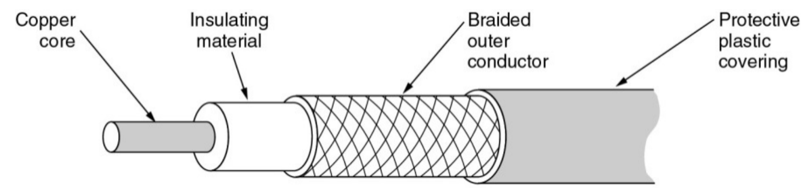
- Classic telephone lines
  - Category 3 (a) – 16MHz
  - Category 5 (b) – 100 MHz
  - Category 6 – 250 MHz
  - Category 7 – 600 MHz
- Throughput : a few Mbit/sec – Gbits/sec.
- Works up to 100m, afterwards repeaters needed.



GUIDED TRANSMISSION MEDIA (CONT.)

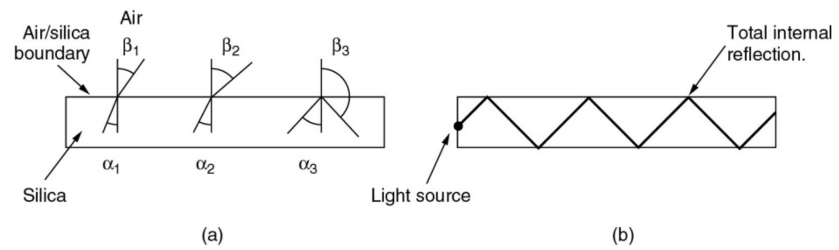
Coaxial Cable

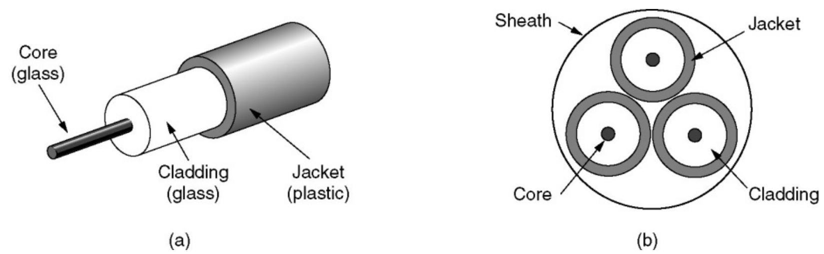
- Bandwidth ~ 1 GHz (better shielding)
- Up to 200m



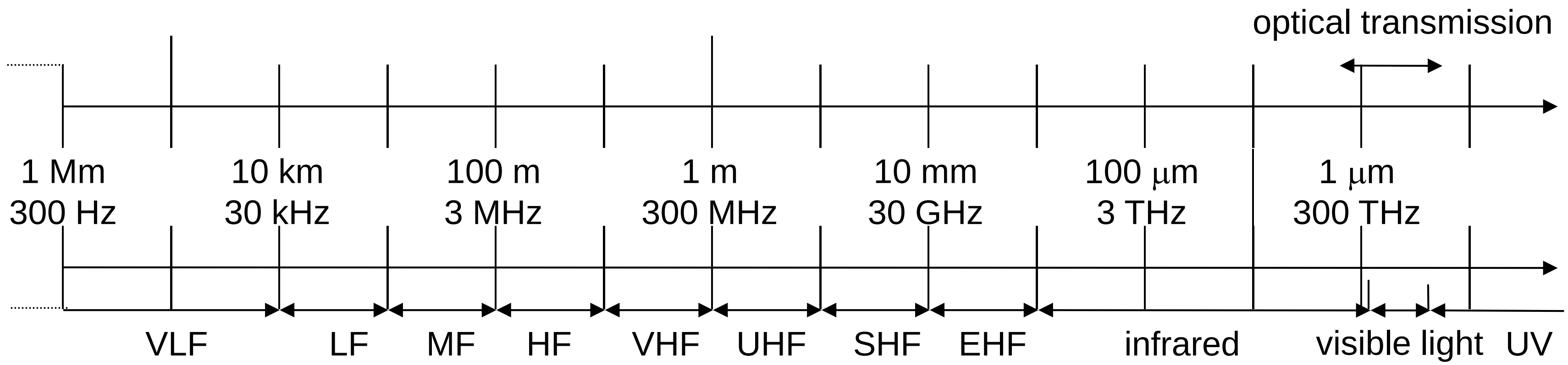
Fiber Optics

- Rather used at higher bandwidths
- Invulnerable to electric and electromagnetic signals
- Could be very long
- Hard to tamper with -> Security
- Usually simplex transmission





THE ELECTROMAGNETIC SPECTRUM



VLF = Very Low Frequency

LF = Low Frequency

MF = Medium Frequency

HF = High Frequency

VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

- Frequency and wave length: $\lambda = c/f$, wave length λ, speed of light $c \cong 3x10^8 m/s$, frequency f
- Radio spectrum is part of the electromagnetic spectrum from 1Hz to 3THz: http://en.wikipedia.org/wiki/Radio_spectrum

DATA LINK LAYER SERVICES

- Framing, link access:
  - encapsulate datagram into frame, adding header, tailer
  - channel access if shared medium
  - "MAC" addresses used in frame headers to identify source, destination
- Reliable delivery between adjacent nodes
  - Seldom used on low bit-error link (fiber, some twisted pair)
  - wireless links: high error rates
- Flow control:
  - Pacing between adjacent sending and receiving nodes
- Error detection:
  - Errors caused by signal attenuation, noise.
  - Receiver detects presence of errors: signals sender for retransmission or drops frame
- Error correction:
  - Receiver identifies and corrects bit error(s) without resorting to retransmission
- Half-duplex and full-duplex
  - with half duplex, nodes at both ends of link can transmit, but not at same time

MULTIPLE ACCESS PROTOCOLS

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

Multiple Access Protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit.
- communication about channel sharing must use channel itself.
  - no out-of-band channel for coordination

AN IDEAL MULTIPLE ACCESS PROTOCOL

given: broadcast channel of rate *R* bps

desiderata:

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

MAC PROTOCOLS: TAXONOMY

Three broad classes:

- Channel partitioning
  - divide channel into smaller “pieces” (time slots, frequency, code)
  - allocate piece to node for exclusive use
- Random access
  - channel not divided, allow collisions
  - “recover” from collisions
- “Taking turns”
  - nodes take turns, but nodes with more to send can take longer turns

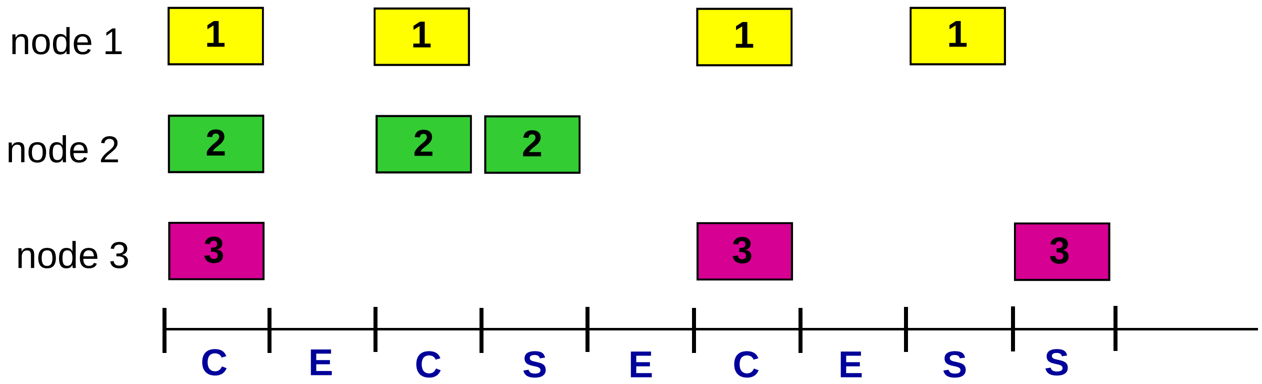
RANDOM ACCESS PROTOCOLS

- When node has packet to send:
  - Transmit at full channel data rate R.
  - No *a priori* coordination among nodes
  - Two or more transmitting nodes ➜ "collision"

- Random access MAC protocol specifies:
  - How to detect collisions
  - How to recover from collisions (e.g., via delayed retransmissions)

- Examples of random access MAC protocols:
  - Slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA

SLOTTED ALOHA



Pros:

- Single active node can continuously transmit at full rate of channel
- Highly decentralized: only slots in nodes need to be in sync
- Simple

Cons:

- Collisions, wasting slots
- Idle slots
- Nodes may be able to detect collision in less than time to transmit packet
- Clock synchronization

SLOTTED ALOHA: EFFICIENCY

efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)

- suppose: N nodes with many frames to send, each transmits in slot with probability p
- prob that given node has success in a slot = $p(1-p)^{N-1}$
- prob that any node has a success = $Np(1-p)^{N-1}$

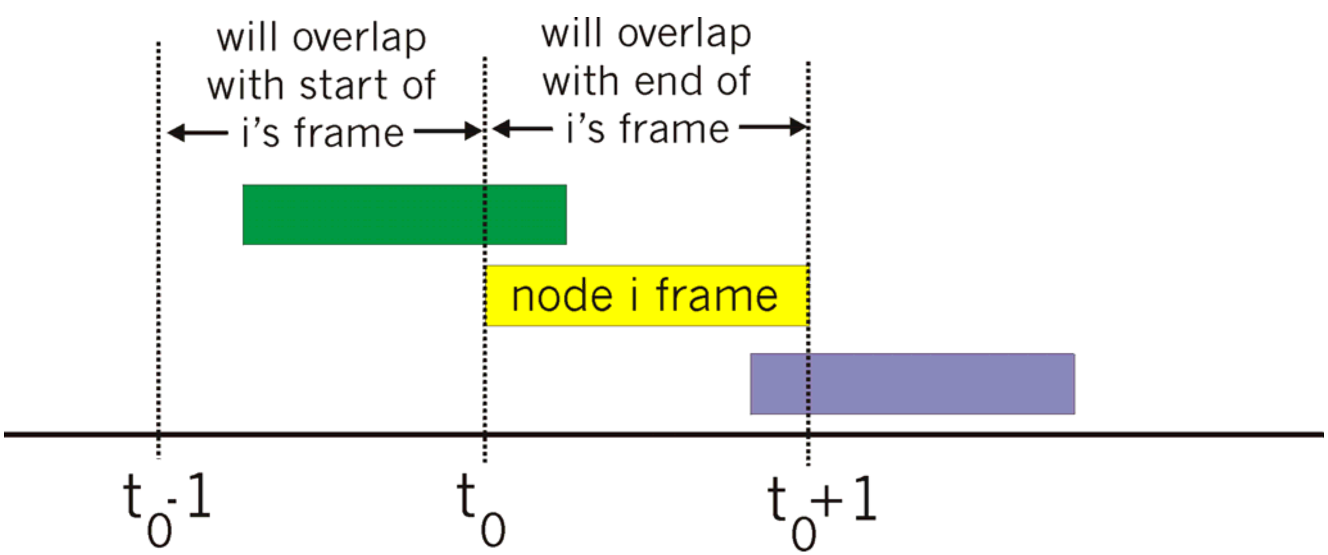
- max efficiency: find p* that maximizes $Np(1-p)^{N-1}$
- for many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives:

max efficiency = 1/e = .37

at best: channel used for useful transmissions 37% of time!

PURE (UNSLOTTED) ALOHA

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



PURE ALOHA EFFICIENCY

P(success by given node) = P(node transmits) $\cdot$

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

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

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

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

… choosing optimum p and then letting n $\longrightarrow \infty$

$$= 1/(2e) = .18$$

even *worse* than slotted Aloha!

CSMA (CARRIER SENSE MULTIPLE ACCESS)

CSMA: listen before transmit

- If channel sensed idle: transmit entire frame
- If channel sensed busy: defer transmission
- Human analogy: don’t interrupt others!

CSMA/CD: carrier sensing, deferral as in CSMA

- collisions detected within short time
- colliding transmissions aborted, reducing channel wastage

- Collision detection:
  - easy in wired media: measure signal strengths, compare transmitted, received signals
  - difficult in wireless media: received signal strength overwhelmed by local transmission strength
- Human analogy: the polite conversationalist

CSMA/CA (COLLISION AVOIDANCE)

- CSMA/CA:
  - Wireless MAC protocols often use collision avoidance techniques, in conjunction with a (physical or virtual) carrier sense mechanism
  - To be discussed more in WiFi and ZigBee protocols
- Collision avoidance
  - Nodes hearing RTS or CTS stay silent for the duration of the corresponding transmission.
  - Once channel becomes idle, the node waits for a randomly chosen duration before attempting to transmit.
- Carrier sense
  - Nodes stay silent when carrier sensed (physical/virtual)
  - Physical carrier sense: carrier sense threshold
  - Virtual carrier sense using Network Allocation Vector (NAV): NAV is updated based on overheard RTS/CTS/DATA/ACK packets

"TAKING TURNS" MAC PROTOCOLS

Channel partitioning MAC protocols:

- Share channel *efficiently* and *fairly* at high load
- Inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

Random access MAC protocols

- Efficient at low load: single node can fully utilize channel
- High load: collision overhead

"taking turns" protocols

- Look for best of both worlds.

SUMMARY OF MAC PROTOCOLS

- Channel partitioning, by time, frequency or code
  - Time Division, Frequency Division
- Random access (dynamic)
  - ALOHA, S-ALOHA, CSMA, CSMA/CD
  - Carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in 802.11
- Taking turns
  - Polling from central site, token passing
  - Bluetooth, FDDI, token ring

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EMBEDDED SYSTEM COMMUNICATION PROTOCOLS

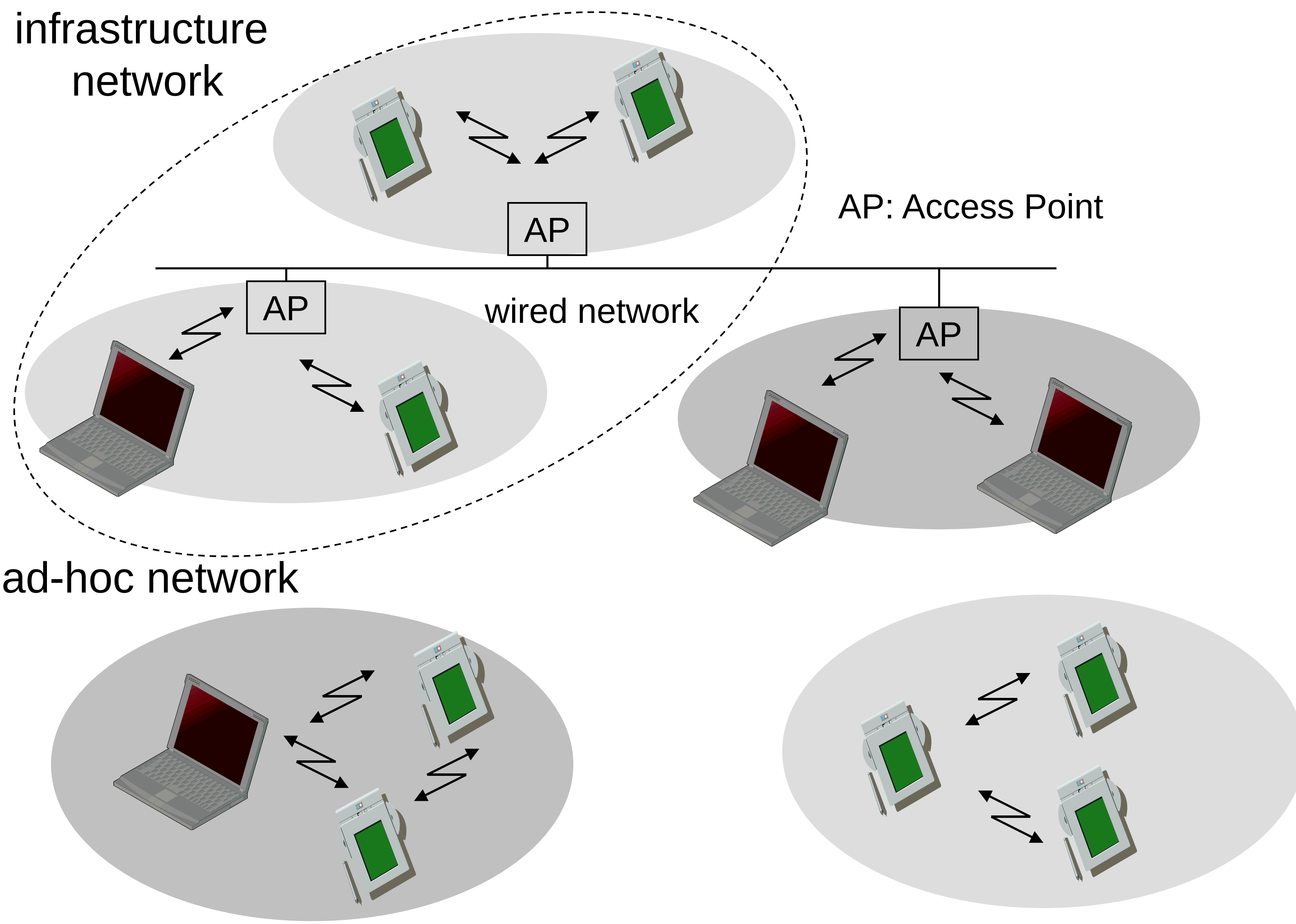
Wired communication protocol examples:

- Ethernet (802.3)
- CAN
- TTP
- BACnet

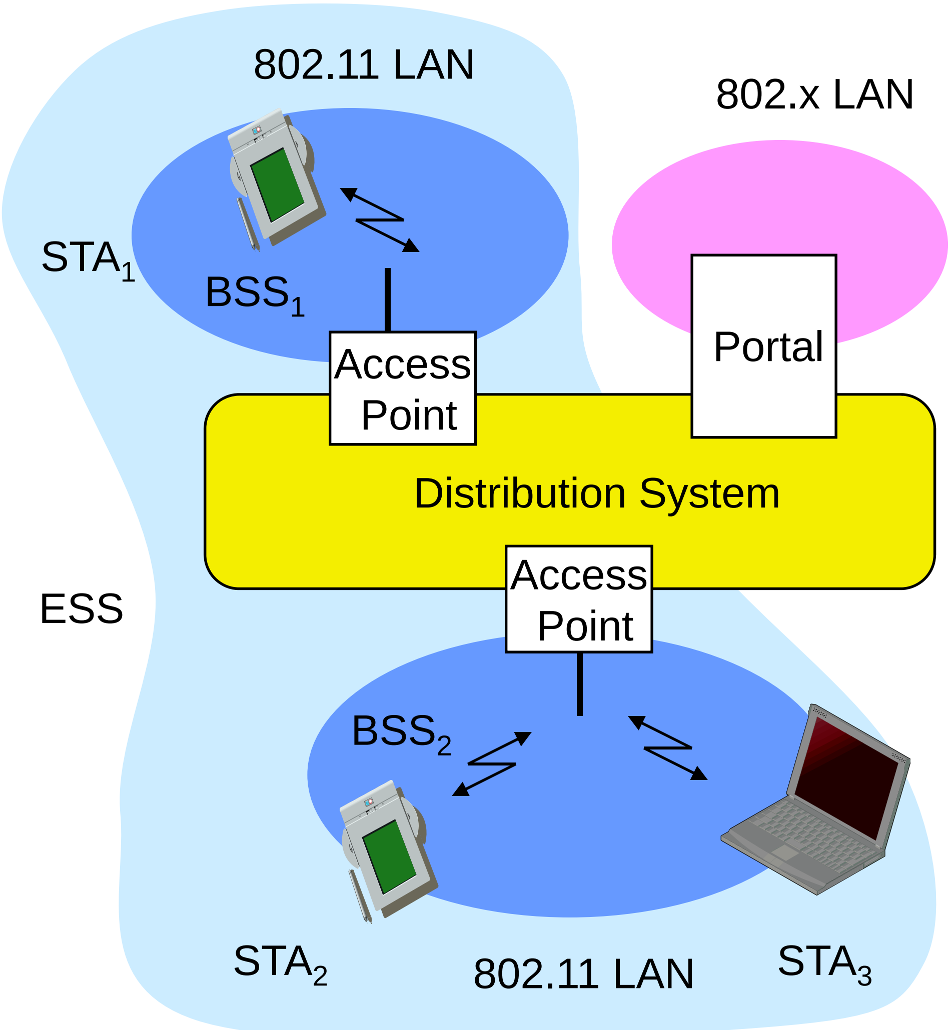
Wireless communication protocol examples:

- Wi-Fi (802.11)
- ZigBee (based on 802.15.4 PHY and MAC)
- WirelessHART (Not discussed in this lecture)

INFRASTRUCTURE VS. AD-HOC NETWORKS

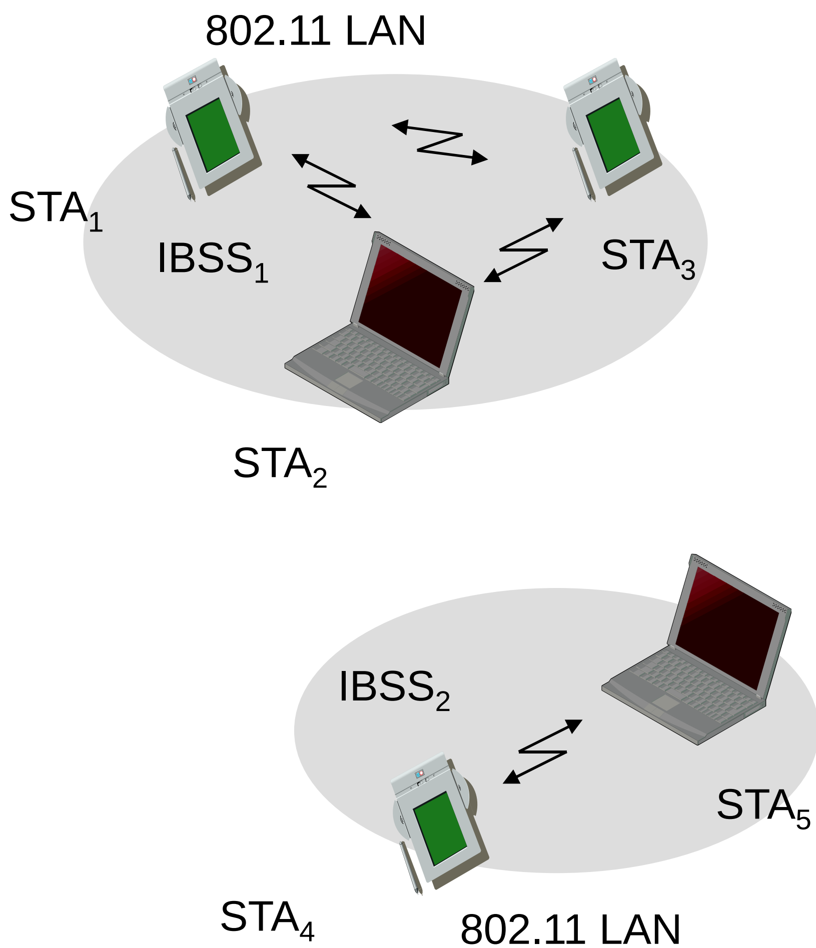


802.11: INFRASTRUCTURE



- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Basic Service Set (BSS)
  - group of stations using the same AP
- Portal
  - bridge to other (wired) networks
- Distribution System
  - interconnection network to form one logical network (EES: Extended Service Set) based on several BSS

802.11: AD HOC MODE



Direct communication within a limited range

- Station (STA): terminal with access mechanisms to the wireless medium
- Independent Basic Service Set (IBSS): group of stations using the same network

WLAN: IEEE 802.11B

- Data rate
  - 1, 2, 5.5, 11 Mbit/s, depending on SNR
  - User data rate max. approx. 6 Mbit/s
- Transmission range
  - 300m outdoor, 30m indoor
  - Max. data rate ~10m indoor
- Frequency
  - Free 2.4 GHz ISM-band
- Availability
  - Many products and vendors
- Quality of Service
  - Best effort, no guarantees (unless polling is used, limited support in products)
- Pros
  - Many installed systems and vendors
  - Available worldwide
  - Free ISM-band
- Cons
  - Heavy interference on ISM-band
  - No service guarantees
  - Relatively low data rate

WLAN: IEEE 802.11A

- Data rate
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s, depending on SNR
  - User throughput (1500 byte packets): 5.3 (6), 18 (24), 24 (36), 32 (54)
  - 6, 12, 24 Mbit/s mandatory
- Transmission range
  - 100m outdoor, 10m indoor
  - E.g., 54 Mbit/s up to 5 m, 48 up to 12 m, 36 up to 25 m, 24 up to 30m, 18 up to 40 m, 12 up to 60 m
- Frequency
  - Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band
- Availability
  - Some products, some vendors
- Quality of Service
  - Best effort, no guarantees (same as all 802.11 products)
- Pros
  - Fits into 802.x standards
  - Free ISM-band
  - Available, simple system
  - Uses less crowded 5 GHz band
  - Higher data rates
- Cons
  - Shorter range

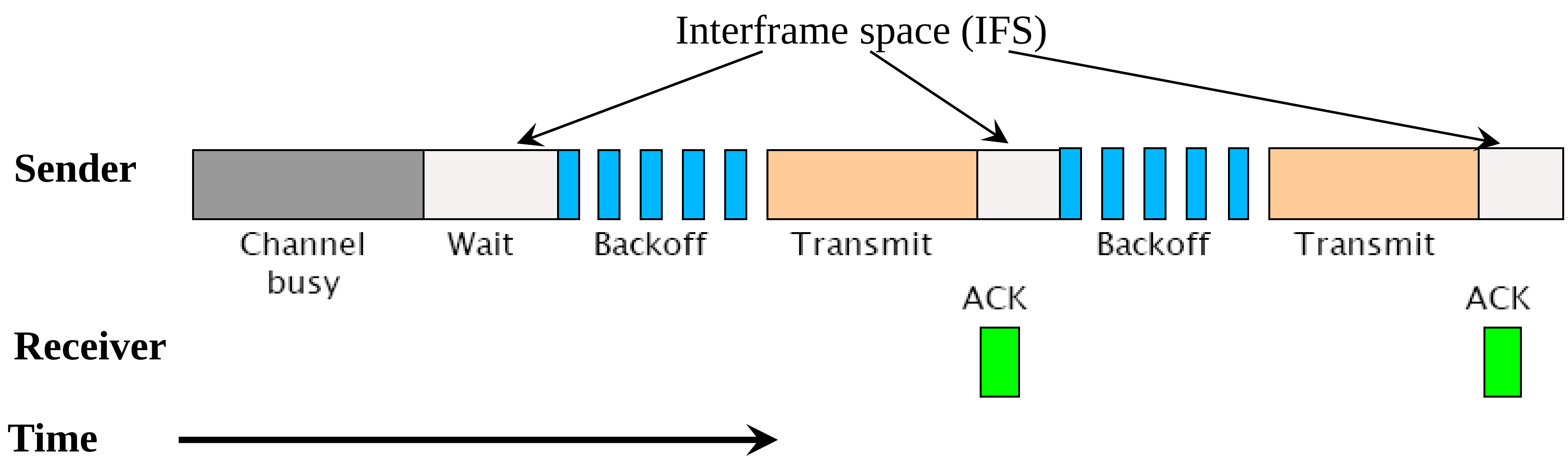
WLAN: IEEE 802.11N

- Data rate
  - 7.2, 14.4, 21.7, 28.9, …, 72.2 Mbit/s, depending on SNR
- Multiple input multiple output (MIMO)
- 20MHz and 40MHz bands
- Transmission range
  - Increase range by several factors due to MIMO
- Frequency
  - Free 2.4GHz ISM-band
  - Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band
- Availability
  - Some products, some vendors
- Quality of Service
  - Best effort, no guarantees (same as all 802.11 products)
- Pros
  - Fits into 802.x standards
  - Free ISM-band
  - Available, simple system
  - Uses dual band
  - Higher data rates
- Cons
  - Interference on ISM-band

Distributed and centralized access methods

- DCF CSMA/CA (mandatory)
  - Collision avoidance via randomized “back-off“ mechanism
  - Minimum distance between consecutive packets
  - ACK packet for acknowledgements (not for broadcasts)
- DCF w/ RTS/CTS (optional)
  - Distributed Foundation Wireless MAC
  - Avoids hidden terminal problem
- PCF (optional)
  - Access point polls terminals according to a list

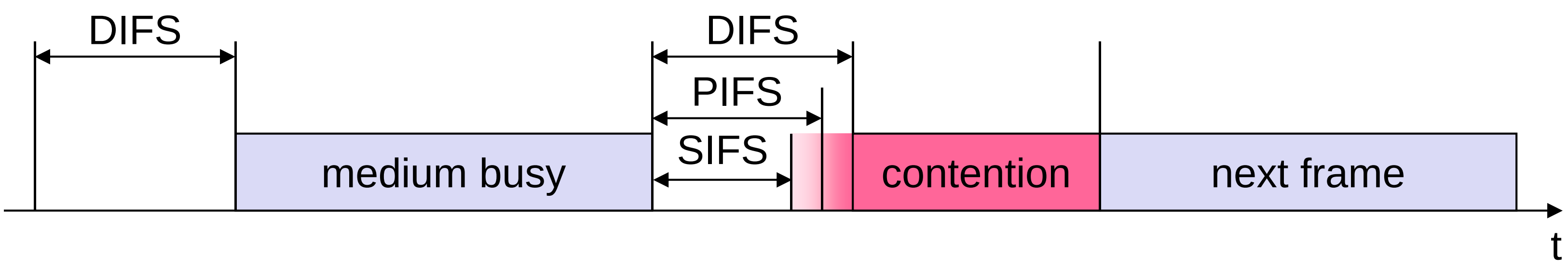
DCF ILLUSTRATION



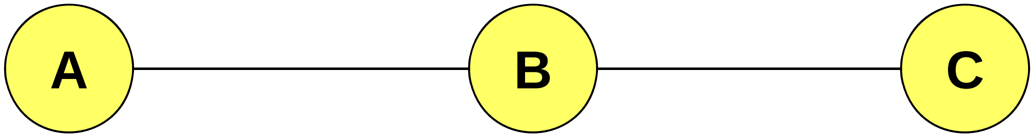
- Before a node transmits, it listens for activity on the network
- If medium is busy, node waits to transmit
- After medium is clear, don't immediately start transmitting...
- Otherwise all nodes would start talking at the same time!
- Instead, delay a random amount of time (random backoff)

Priorities defined through different inter frame spaces

- No guarantee, hard priorities
- SIFS (Short Inter Frame Spacing)
  - Highest priority, for ACK, CTS, polling response
- PIFS (PCF IFS)
  - Medium priority, for time-bounded service using PCF
- DIFS (DCF, Distributed Coordination Function IFS)
  - Lowest priority, for asynchronous data service

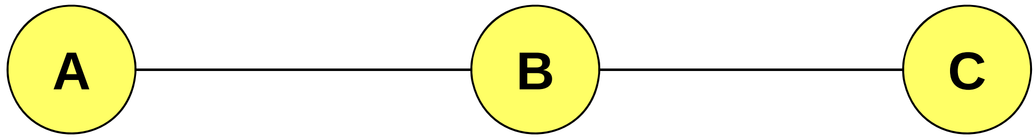


HIDDEN TERMINAL PROBLEM



- B can communicate with both A and C
- A and C cannot hear each other
- Problem
  - When A transmits to B, C cannot detect the transmission using the carrier sense mechanism
  - If C transmits, collision will occur at node B
- Solution
  - Hidden sender C needs to defer

SOLUTION FOR HIDDEN TERMINAL PROBLEM: MACA



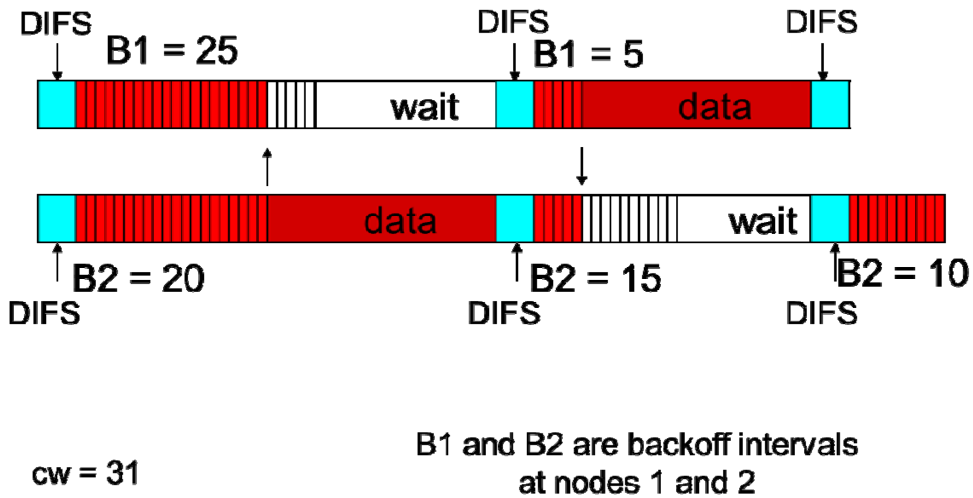
- When A wants to send a packet to B, A first sends a Request-to-Send (RTS) to B

- On receiving RTS, B responds by sending Clear-to-Send (CTS), provided that A is able to receive the packet

- When C overhears a CTS, it keeps quiet for the duration of the transfer
  - Transfer duration is included in both RTS and CTS

BACKOFF INTERVAL

- Collision avoidance
  - Backoff intervals used to reduce collision probability
- When transmitting a packet, choose a backoff interval in the range [0, CW]
  - CW is contention window
- Count down the backoff interval when medium is idle
  - Count-down is suspended if medium becomes busy
- Transmit when backoff interval reaches 0



BACKOFF INTERVAL

- The time spent counting down backoff intervals is a part of MAC overhead
- Important to choose CW appropriately
  - large CW ➔ large overhead
  - small CW ➔ may lead to many collisions (when two nodes count down to 0 simultaneously)
- How to choose an appropriate CW?

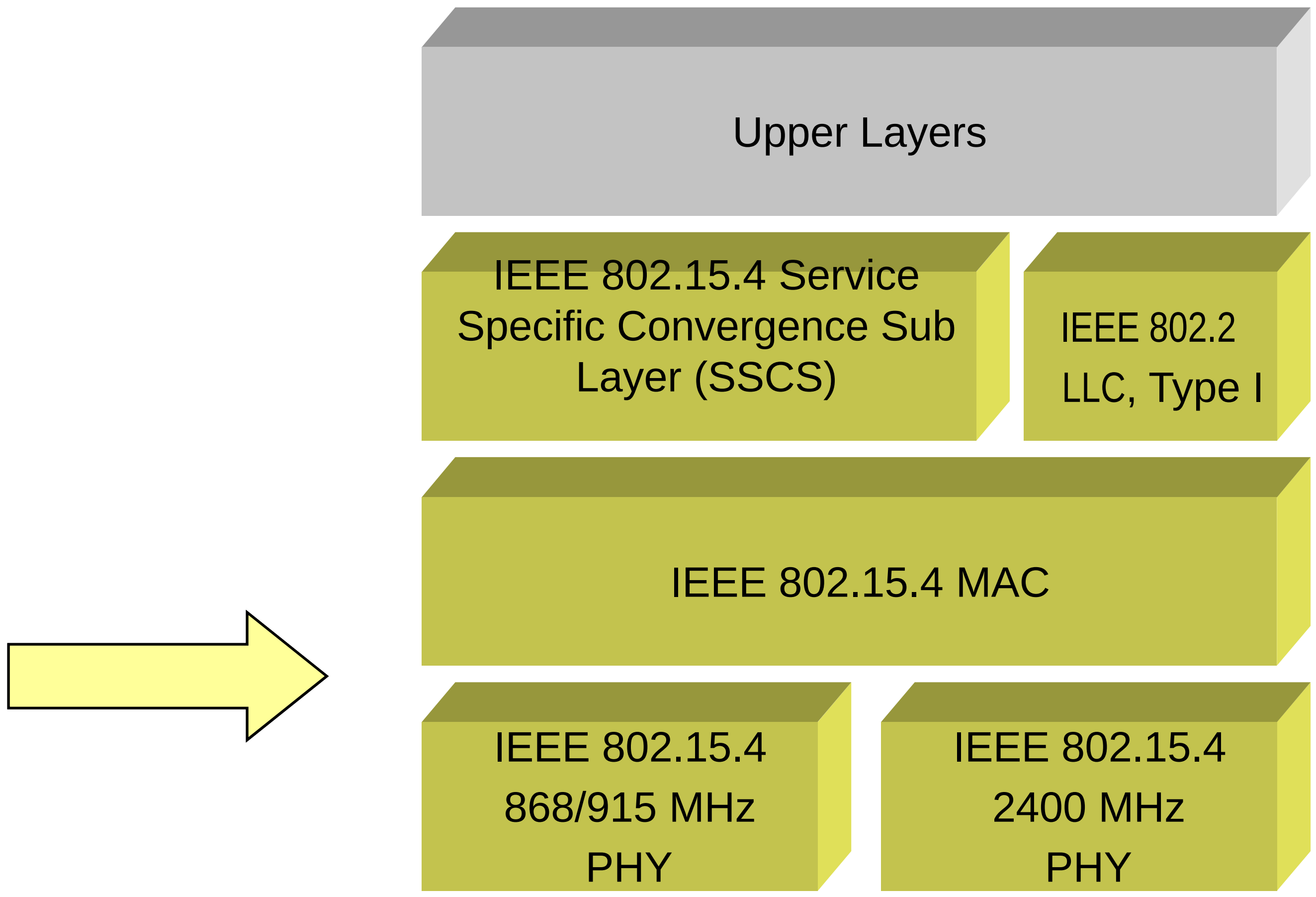
802.11 - FRAME FORMAT

- Types
  - control frames, management frames, data frames
- Sequence numbers
  - important against duplicated frames due to lost ACKs
- Addresses
  - Sender, receiver, BSS identifier
- Miscellaneous
  - sending time, checksum, frame control, data

bytes	2	2	6	6	6	2	6	0-2312	4
	Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	CRC

bits	2	2	4	1	1	1	1	1	1	1	1
	Protocol version	Type	Subtype	To DS	From DS	More Frag	Retry	Power Mgmt	More Data	WEP	Order

802.15.4 ARCHITECTURE

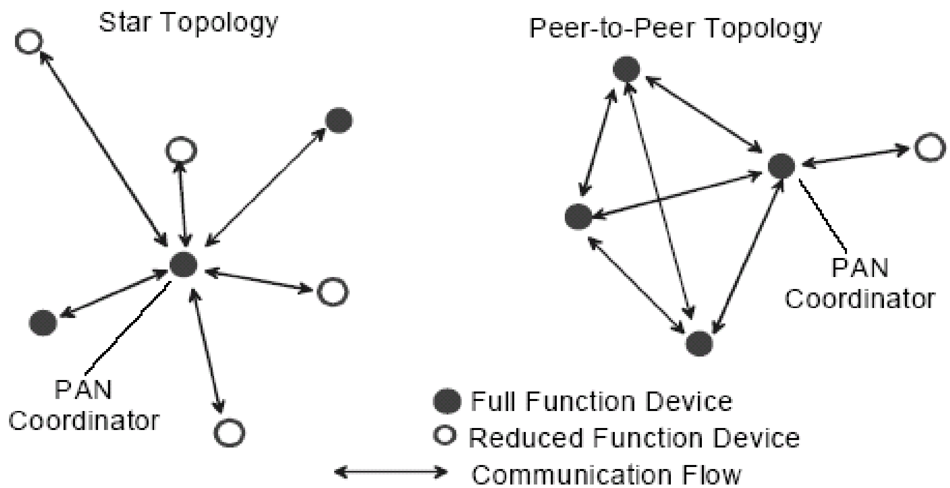


DEVICE ADDRESSING

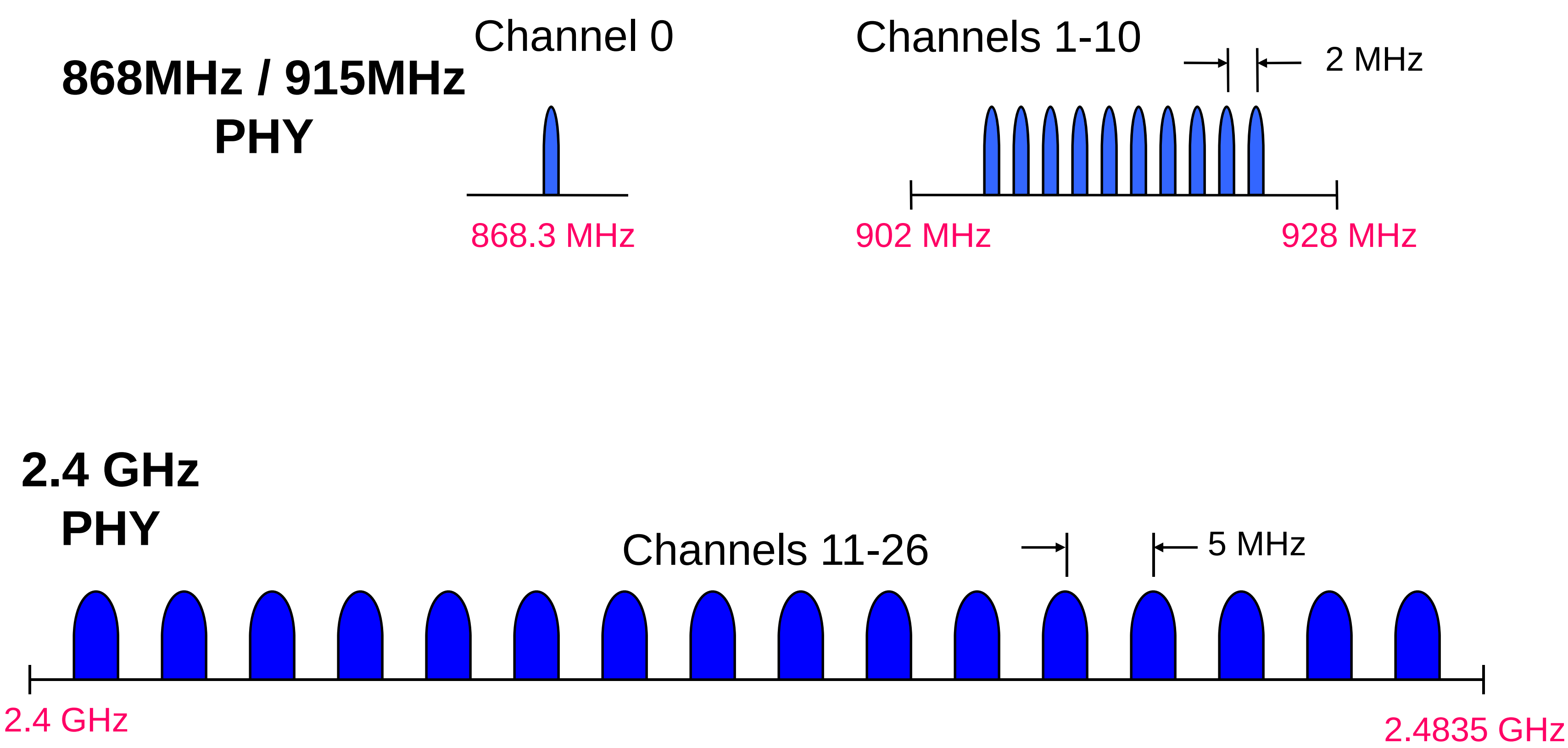
- Two or more devices communicating on the same physical channel constitute a WPAN which includes at least one FFD (PAN coordinator).
- Each independent PAN will select a unique PAN identifier.
- All devices operating on a network shall have unique 64-bit extended address. This address can be used for direct communication in the PAN.
- An associated device can use a 16-bit short address, which is allocated by the PAN coordinator when the device associates.

IEEE 802.15.4 SUPPORTED TOPOLOGIES

- MAC supports 2 topologies: star and peer-to-peer
- Star topology supports beacon and no-beacon structure
  - All communication done through PAN coordinator

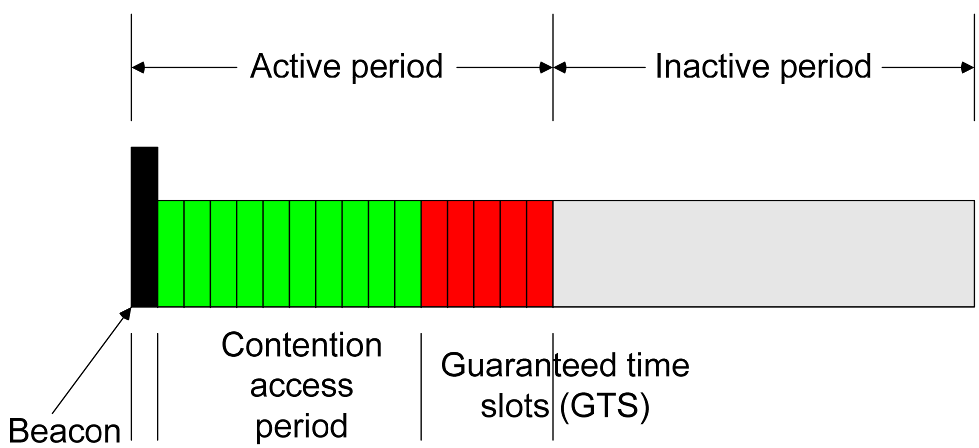


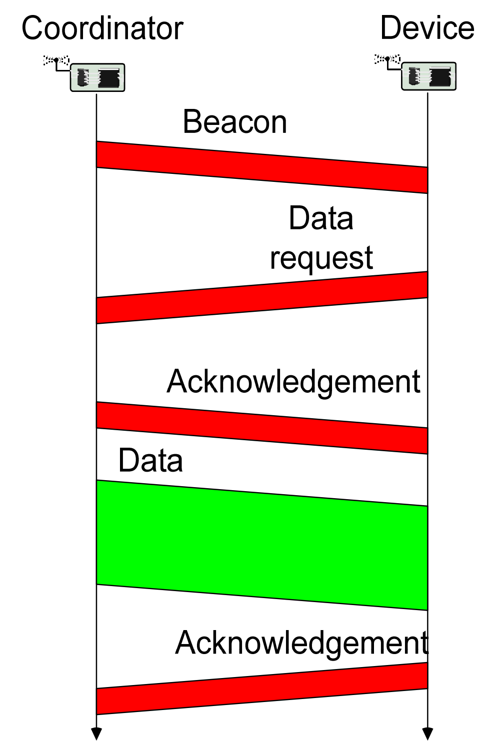
PHYSICAL FREQUENCIES AND CHANNELS



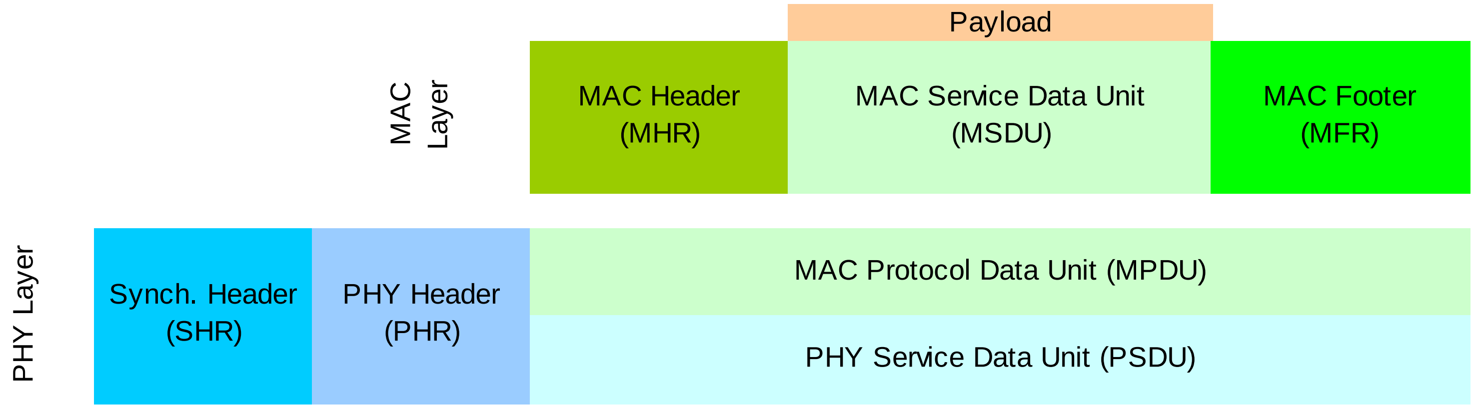
IEEE 802.15.4 MAC OVERVIEW

- Star networks: devices are associated with coordinators
  - Forming a PAN, identified by a PAN identifier
- Coordinator
  - Bookkeeping of devices, address assignment, generate beacons
  - Talks to devices and peer coordinators
- Beacon-mode superframe structure
  - GTS assigned to devices upon request





IEEE 802.15.4 GENERAL FRAME STRUCTURE



Four Types of MAC Frames:

- Data Frame
- Beacon Frame
- Acknowledgment Frame
- MAC Command Frame

EMBEDDED SYSTEM COMMUNICATION PROTOCOLS

Wired communication protocol examples:

- Ethernet (802.3)
- CAN
- TTP
- BACnet

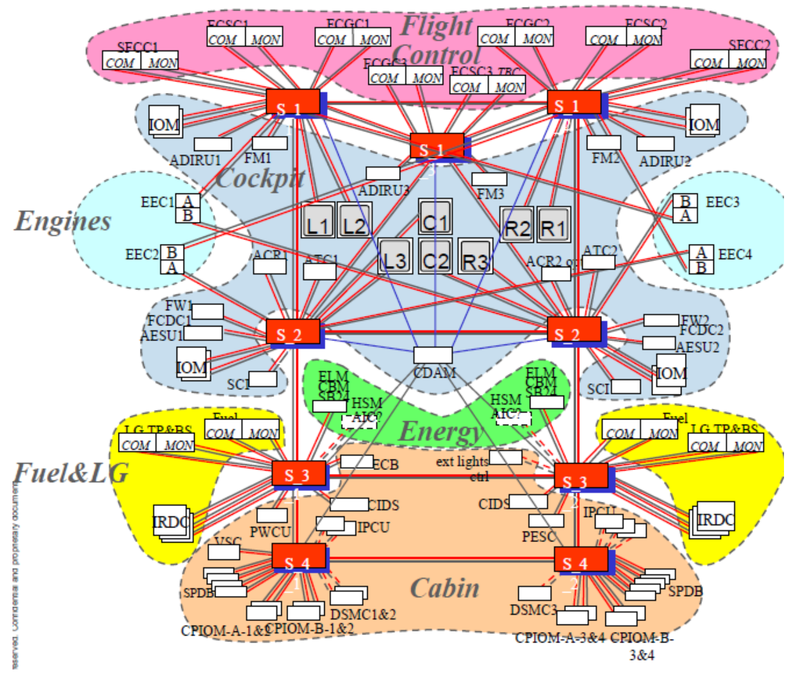
Wireless communication protocol examples:

- Wi-Fi (802.11)
- ZigBee (based on 802.15.4 PHY and MAC)
- WirelessHART (Not discussed in this lecture)

EMBEDDED SYSTEM COMMUNICATION PROTOCOL: ETHERNET

"dominant" wired LAN technology:

- cheap $20 for NIC
- first widely used LAN technology
- simpler, cheaper than token LANs and ATM
- kept up with speed race: 10 Mbps – 10 Gbps



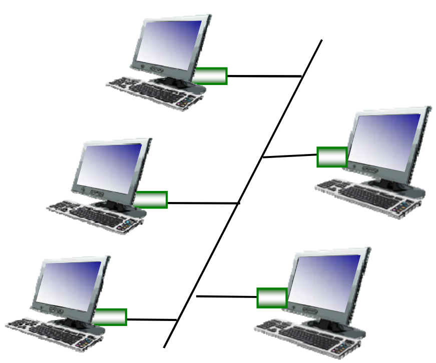
An example avionics communication network: AFDX network (Avionics Full Duplex Ethernet

(Figure from Airbus, more details can be found at: http://www.artist-embedded.org/docs/Events/2007/IMA/Slides/ARTIST2_IMA_Itier.pdf)

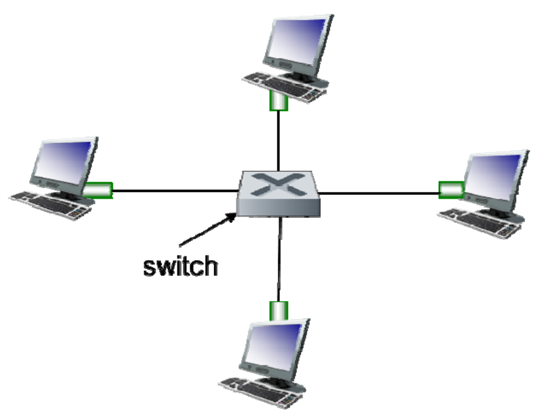
ETHERNET: PHYSICAL TOPOLOGY

- Bus: traditional topology
  - All workstations are connected on a single cable.
  - All transmissions go to all the connected workstation.

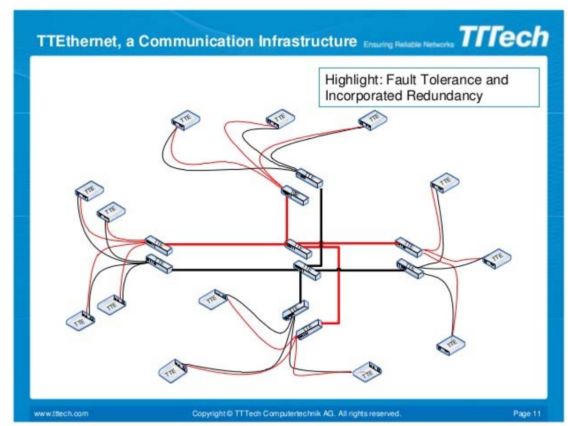
- Star: the most common solution today
  - Active switch in center
  - Each "spoke" runs a (separate) Ethernet protocol



bus: coaxial cable



star



TTEthernet

ETHERNET FRAME STRUCTURE

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

Preamble:

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

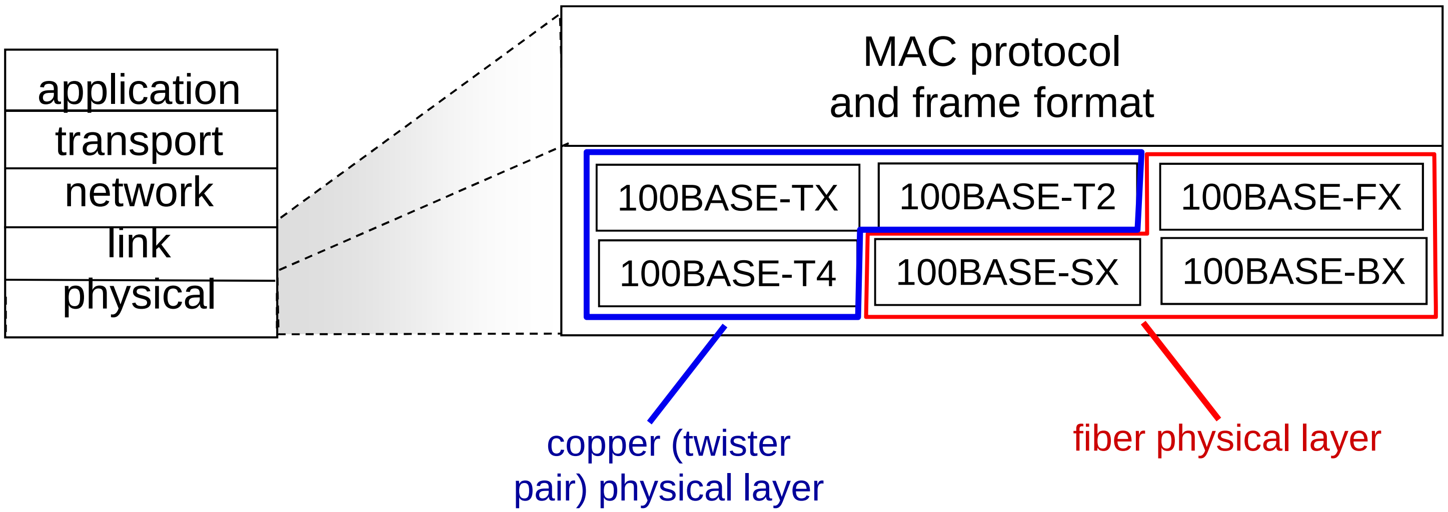
ETHERNET: UNRELIABLE, CONNECTIONLESS

- Connectionless: no handshaking between sending and receiving NICs
- Unreliable: receiving NIC doesn't send ACKs or NACKs to sending NIC
    - data in dropped frames recovered only if initial sender uses higher layer reliable data transfer (e.g., TCP), otherwise dropped data lost
- Ethernet's MAC protocol: unslotted CSMA/CD with binary backoff

802.3 ETHERNET STANDARDS: LINK & PHYSICAL LAYERS

Many different Ethernet standards

- Common MAC protocol and frame format
- Different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10G bps
- Different physical layer media: fiber, cable



https://en.wikipedia.org/wiki/Ethernet_physical_layer