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Computer Networks

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Class 5: Link Layer

[K] Chapter 6
[T] Chapters 3 and 4

Roadmap

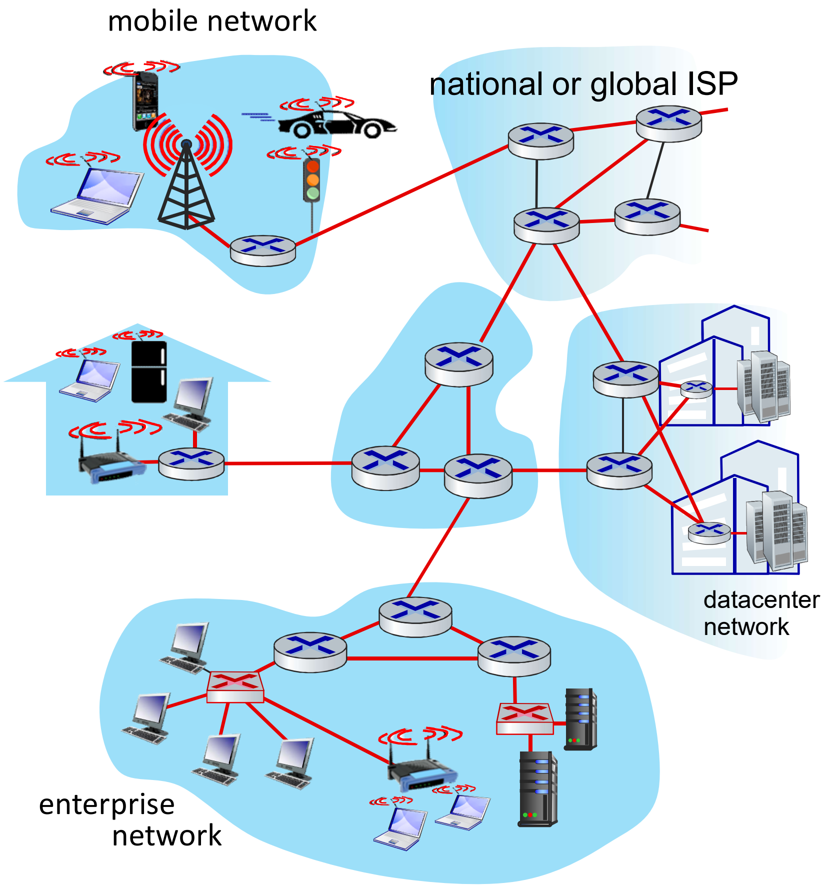
- **Introduction**
  - **Goals**
  - **Terminology**
  - **The Trip Analogy**
  - **Services**
  - **Implementation**
  - **Communication**
- Error Control
- Medium Access Control
- LANs

Introduction – Goals

- Understand principles behind link layer services:
  1. Error detection, correction
  2. Sharing a broadcast channel: multiple access
  3. Link layer addressing
- Practice: implementation of various link layer technologies:
  - Ethernet
  - VLANs
  - MPLS
  - Data center networks

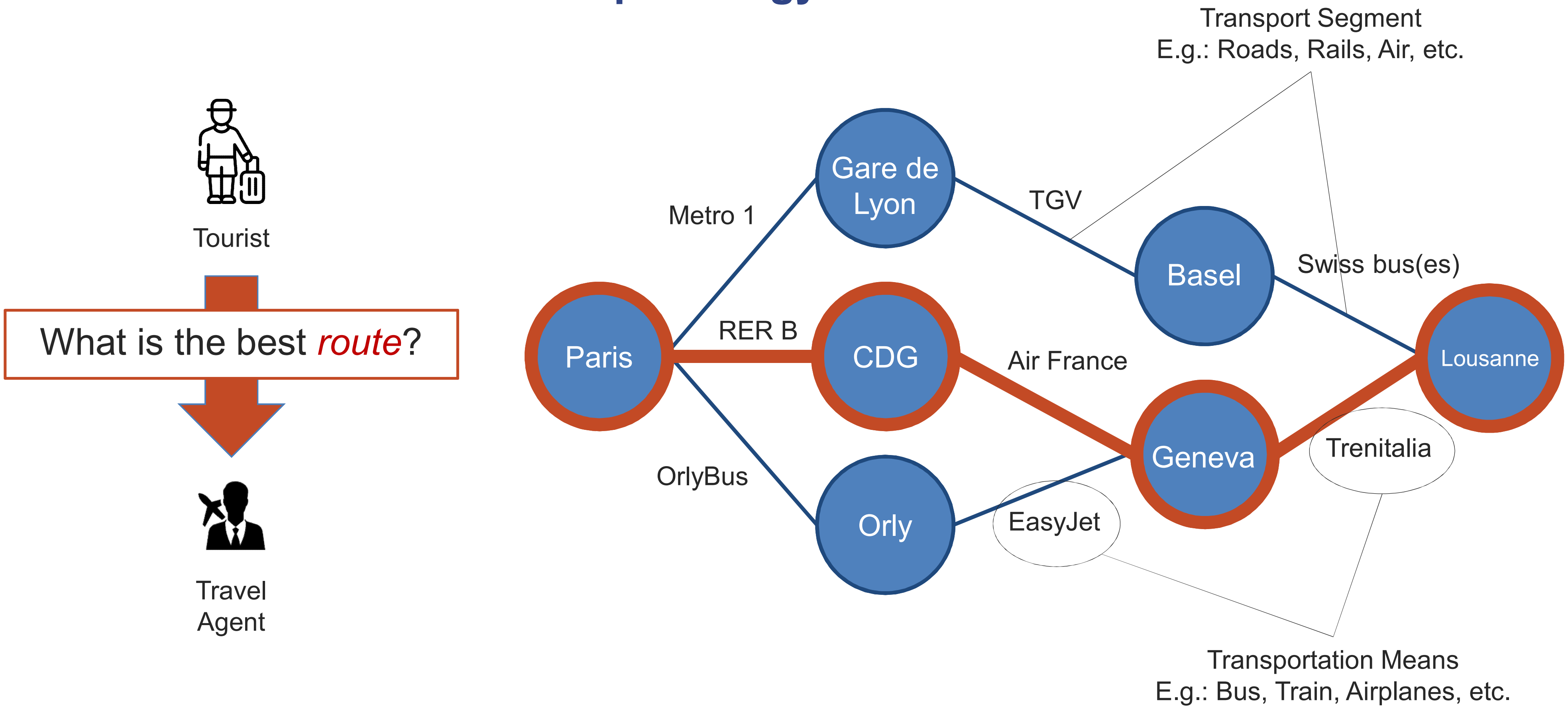
Introduction – Terminology

- Nodes: Hosts, routers, switches, etc.
- Links: Logical communication channels that connect adjacent nodes along a communication path
- Frame: Layer-2 packet that encapsuates datagrams

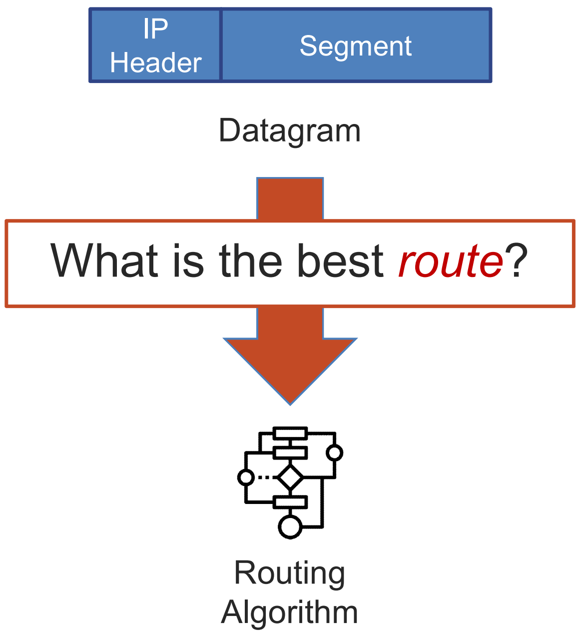


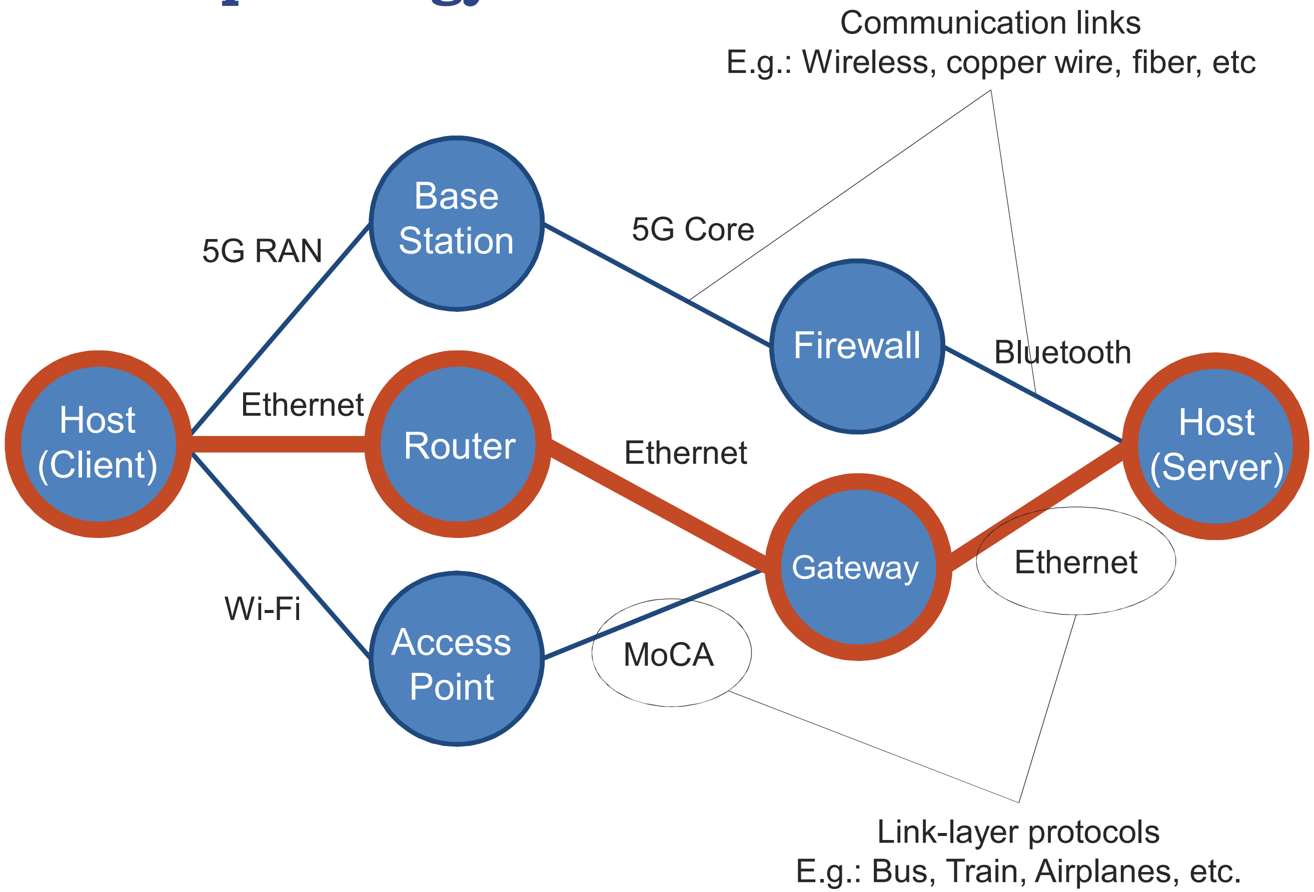
Definition: **Link layer** is a bundle of hardware, algorithms, and protocols in charge of transferring datagrams from one node to a physically adjacent node over a link.

Introduction – Context: The Trip Analogy



Introduction – Context: The Trip Analogy





Introduction – Context: Overview

The “Trip” Analogy

- Datagram = Tourist
- Routing algorithm = Travel Agent
- Communication link = Transport segment
  - E.g.: Wireless, Copper, Fiber Optics, etc.
- Link-layer protocol = Transportation mean
  - E.g.: Ethernet, Wi-Fi, 5G, ARP, etc.

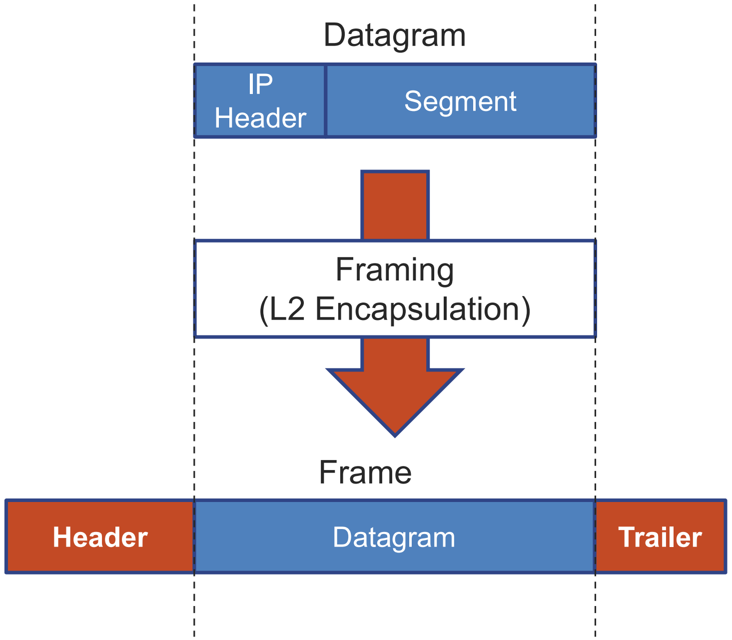
Characteristics

- Datagram is transferred by different link-layer protocols over different links:
  - E.g.: Wi-Fi on first link, Ethernet on next link, etc.
- Each link-layer protocol provides one or more among the following services:
  - Reliable data transfer over link
  - Flow control
  - Fragmentation and sequence integrity
  - Duplex transmissions
  - **Error detection and correction**
  - **Multiple access control**
  - **Framing and addressing**

Introduction – Link Layer Primary Services

Framing and Link Access

- Definition: Encapsulates datagrams (layer-3 packets) in a frame by adding header and trailer.
- Q: Why is it important?
- A: It adds pieces of information used by a given link-layer protocol.
- Examples of added information:
  - Channel access instructions if the physical medium is shared (Physical layer)
  - Headers contain MAC addresses identifying source and destination nodes
  - Trailers may contain information helping bit error detection and correction



Introduction – Link Layer Primary Services

Error Detection

- Definition: Identify bits that were swaped during the transmission process due to bad channel conditions.
- Q: Why is it important?
- A: It helps the receiver to make a decision based on the frame error status.
- Examples of decisions:
  - If frame is OK, then accept frame and
    - forward to next network node (e.g.: L2 switches)
    - send datagram to layer 3 (e.g.: hosts and routers)
  - If frame contains errors, then
    - **correct** bit errors **without** retransmissions
    - **drop** frame and signal retransmission

Error Correction

- Definition: Correct bits that were misidentified due to bad channel conditions **without** requiring frame's retransmission.
- Q: Why is it important?
- A: For an efficient channel usage, retransmissions must be avoided.
- Suitability of Error Correction:
  - OK for guided and other low-error physical media
  - In high-error physical media, such as wireless, correction becomes an unfeasbile service

    (we discuss wireless link layer services later in the course)

Introduction – Link Layer Primary Services

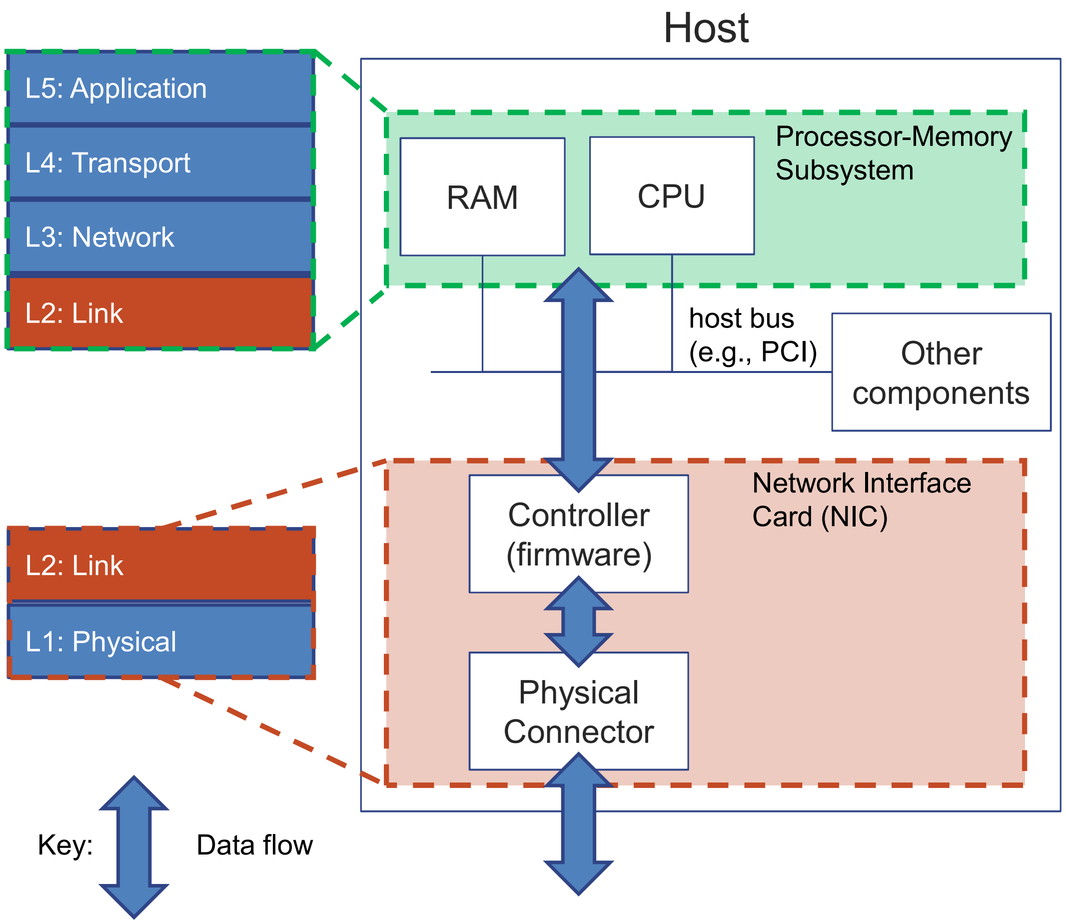
Medium Access Control (MAC) *Sublayer*

- <u>Definition</u>: Enable simultaneous multiple transmissions in a shared-medium network.
- Q: Why is it important?
- A: It allows media reuse for multiple transmissions
  - Allow scalable deployment of guided media
  - Enable deployment of wireless media
- Q: Haven't we discussed this in L1?
- A: Multiplexing techniques are examples of MAC service implementation in L1.
  - FDM, TDM, CDMA

Introduction – Link Layer Secondary Services

Sequence Integrity: Guarantee that frames arrive in order at the receiver. Flow Control: Bound throughput by receiver's service rate.	Services usually delegated to Layer 4 (e.g.,TCP)
Reception Acknowledgement: Signal transmitter that frame was successfuly received. Virtual Connection: Ensure that sender and receiver have a dedicated, synchronized logical channel	Used in ATM networks Not used in the Internet
Duplex Transmissions: Allow channel with two-way transmissions.	Advanced Telecom. Courses

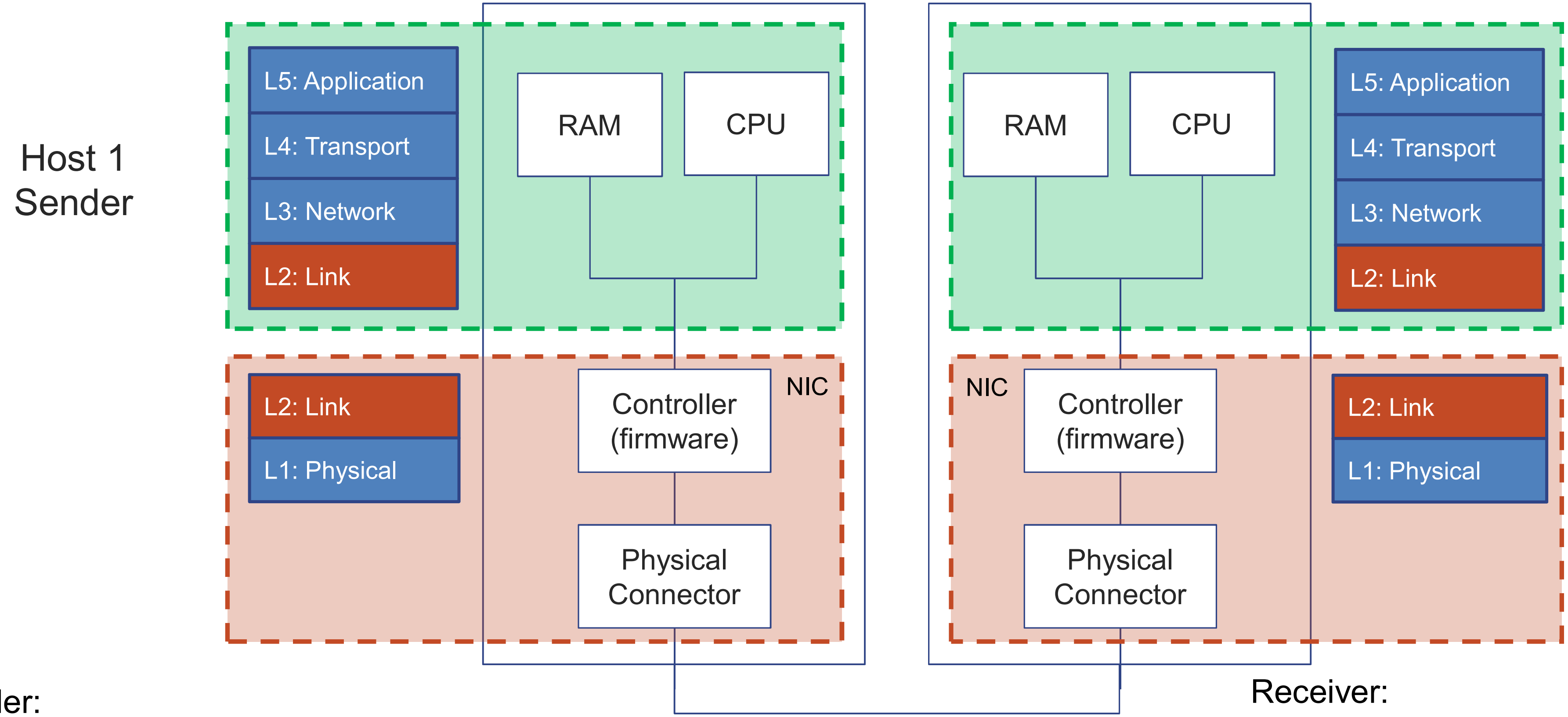
Introduction – Where is the link layer implemented?



Ethernet NIC

Wi-Fi NIC

Introduction – End-to-End Interface Communication



Sender:
- encapsulates datagram in frame
- adds error checking bits, flow control, etc.

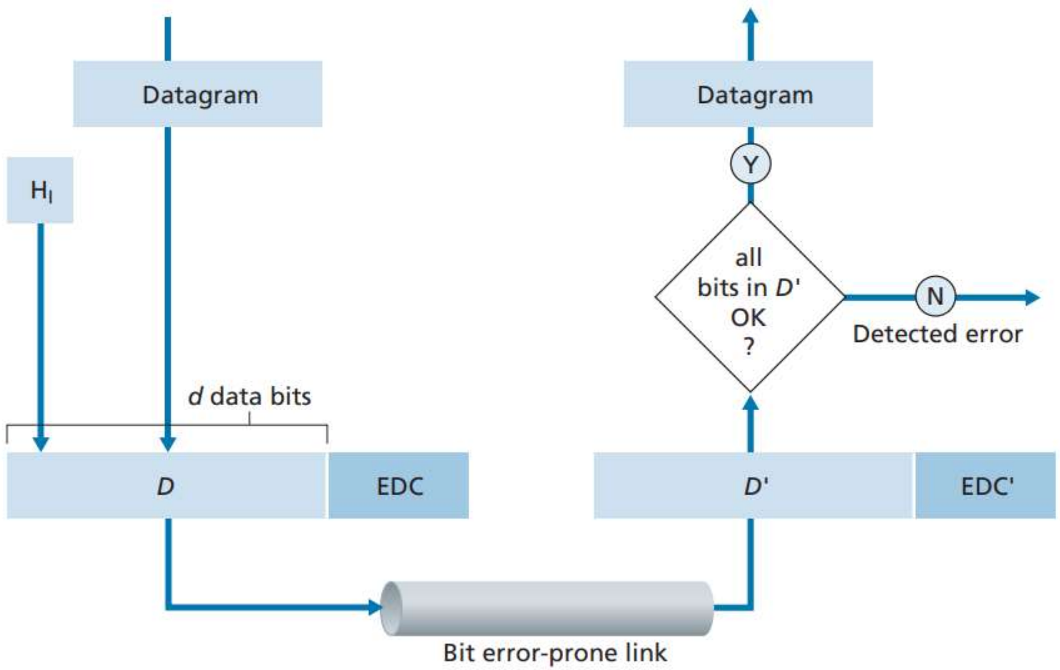
Receiver:
- looks for errors, flow control, etc.
- extracts datagram, passes to upper layer at receiving side

Roadmap

- Introduction
- **Error Control**
  - **Parity Checking**
  - **Cyclic Redundancy Checking**
  - **Examples and Exercises**
- Medium Access Control
- LANs

Error Control – Introduction

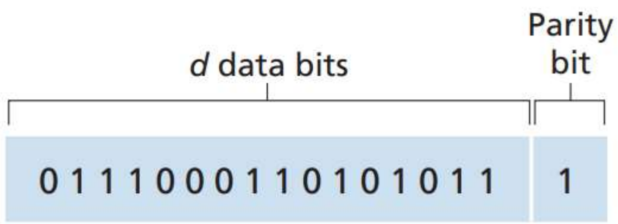
- Definition: The error control service provides mechanisms for bit errors detection and, if possible, their correction.
- Error Detection and Correction (EDC) bits are added to the trailler
  – independent of the L2 header.
- The decision on what to do if error is detected depends on the L2 protocol.
- Detection is not fully reliable!
  – Error control techniques with better performance may require larger EDC fields.



Error Control – Parity Checking

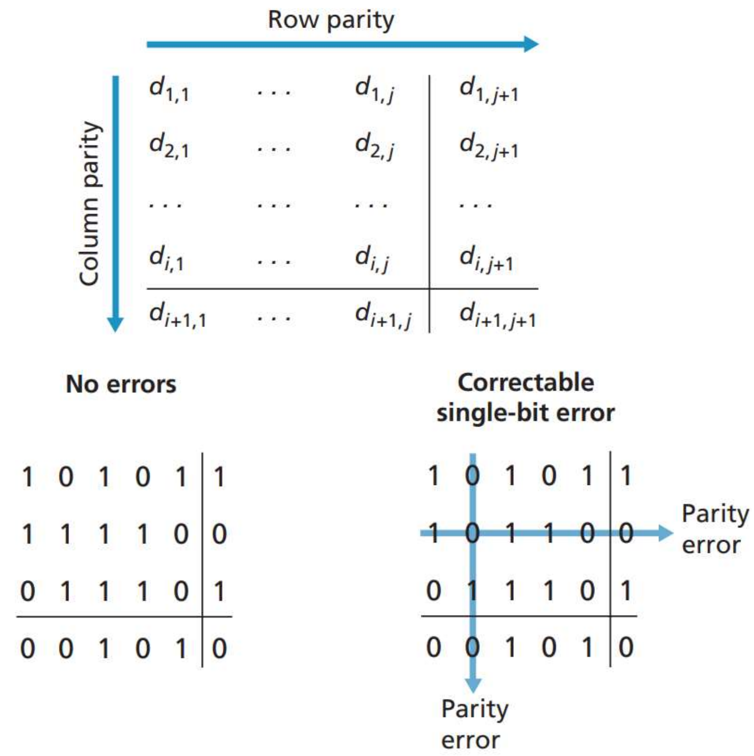
Single Bit Parity

Adds a single bit to the trailer of a frame to obtain a total number of 1s of a parity agreed by all communicating nodes.



Even parity: set parity bit so there is an even number of 1's

Two-Dimensional (2D) Bit Parity



Error Control – 2D Parity Examples

What are the parity bits and the parity frame for the following 4 frames?

```
Frame 1:       10100110
Frame 2:       00011000
Frame 3:       00000011
Frame 4:       11100101
```

Can you detect and correct error bit(s) in the following sequences of frames?

Sequence 1

```
Frame 1:       10100110 0
Frame 2:       00011000 0
Frame 3:       00010011 0
Frame 4:       11100101 1
Parity Frame:  01011000 1
```

Yes! Detect and correct.

Sequence 2

```
Frame 1:       10100110 0
Frame 2:       00011000 0
Frame 3:       00010001 0
Frame 4:       11100101 1
Parity Frame:  01011000 1
```

We can detect, but not correct.

Sequence 3

```
Frame 1:       10100110 0
Frame 2:       00011000 0
Frame 3:       10010001 0
Frame 4:       11100101 1
Parity Frame:  01011000 1
```

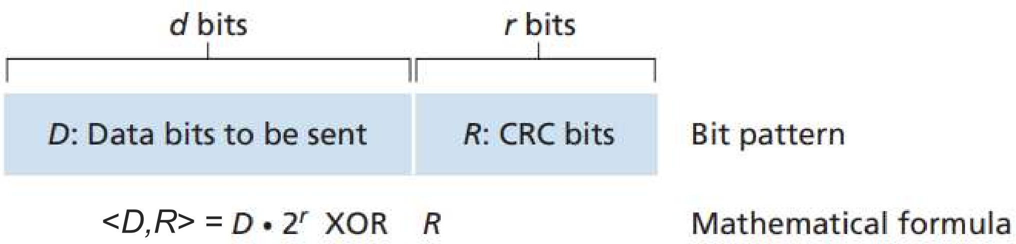
We can detect, but not correct.

Error Control – Cyclic Redundancy Checking (CRC)

Description

CRC adds redundancy bits to the trailler of the frame in order to provide a more efficient error control service.

How the frame is built in CRC?



Example

Input:

D = 10100101 d = 8
R = 011 r = 3

CRC Frame Computation:

D	= 00010100101
D . 2^r	= 10100101000
(D . 2^r) XOR R	= 10100101011

Result:

<D,R> = 10100101011

Error Control – Cyclic Redundancy Checking (CRC)

How does CRC work?

- Let G be a bit pattern of r+1 bits called **generator**.
- Sender and receiver define a **shared** G.
- When receiver gets a frame <D,R>, it checks:
  - If <D,R> is exactly divisible by G (mod 2), then frame is OK.
  - Otherwise, error detected.
- Division operation does not consider carry!

Efficiency and Applicability

- CRC can detect error bursts no longer than r+1
- Widely used in practice (e.g., Ethernet, Wi-Fi)

How are the redundancy bits R computed?

- "<D,R> is exactly divisible by G (mod 2)" means:
  - <D,R> = n G, for some integer n>1
- By the def. of the CDC frame, we have:
  - D . 2^r XOR R = n G
- By applying XOR on both sides, we have:
  - D . 2^r = n G XOR R
- By applying division operation, we have:
  - R = D . 2^r % G

Error Control – CRC Example

The transmitter node wants to send bits D=101110.

It was agreed among all network nodes that the generator is G=1001.

For data bits D and generator G, how the transmitter can calculate the redundancy bits R?

```
    G
                     1 0 1 0 1 1
          ________________________
1 0 0 1  ) 1 0 1 1 1 0   0 0 0        D * 2^r
           1 0 0 1
               1 0 1
               0 0 0
               1 0 1 0
               1 0 0 1
                   1 1 0
                   0 0 0
                   1 1 0 0
                   1 0 0 1
                     1 0 1 0
                     1 0 0 1
                       0 1 1
                         R
```

EXERCISE: Error Control – CRC

A network node received the following CRC frame: <D,R> = 10011100101
Receiver and sender agreed on the following generator: G = 1001

<u>Question 1</u>: What are the data bits D and the redundancy bits R?

Since |G| = r+1, we have that r = 3 and, consequently, d = 8.
Therefore, D = 10011100 and R = 101.

<u>Question 2</u>: Is there an error with the CRC frame?

No! The frame is OK because <D,R> is divisible by G, i.e., the remainder between <D,R> and G is zero.

```
               10001101
1001 |      10011100101
            1001
            00001100
                1001
                01011
                 1001
                 001001
                   1001
                   0000
```

Roadmap

- Introduction
- Error Control
- **Medium Access Control (MAC)**
  - **Introduction**
  - **Channel Partitioning Protocols**
    - **TDMA, FDMA, CDMA**
  - **“Taking Turns” Protocols**
    - **Polling, Token Passing**
  - **Random Access Protocols**
    - **ALOHA, Slotted ALOHA**
    - **CSMA, CSMA/CD**
  - **Examples**
- LANs

MAC – Introduction

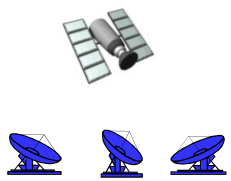
two types of “links”:

- point-to-point
  - point-to-point link between Ethernet switch, host
  - PPP for dial-up access
- broadcast (shared wire or medium)
  - old-fashioned Ethernet
  - upstream HFC in cable-based access network
  - 802.11 wireless LAN, 4G/4G. satellite

shared wire (e.g., cabled Ethernet)

shared radio: 4G/5G

shared radio: WiFi



shared radio: satellite

humans at a cocktail party (shared air, acoustical)

MAC – Definition

- 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

MAC – Ideal Protocol

given: multiple access channel of rate *R* bps

desired characteristics:

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 – Taxonomy

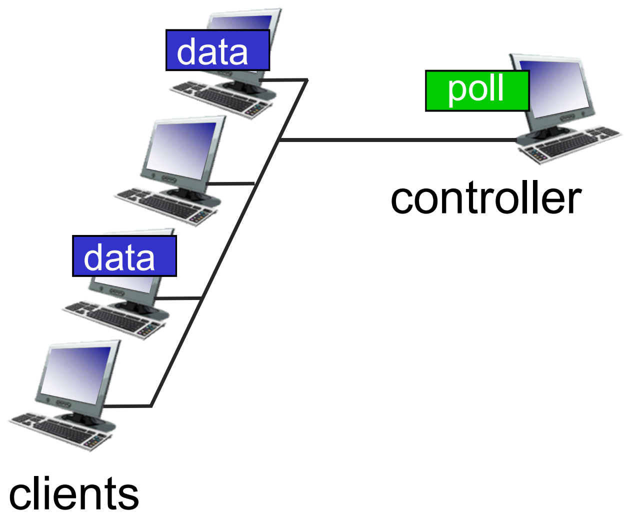
three broad classes:

- 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

MAC – “Taking Turns” Protocols: Polling

polling:

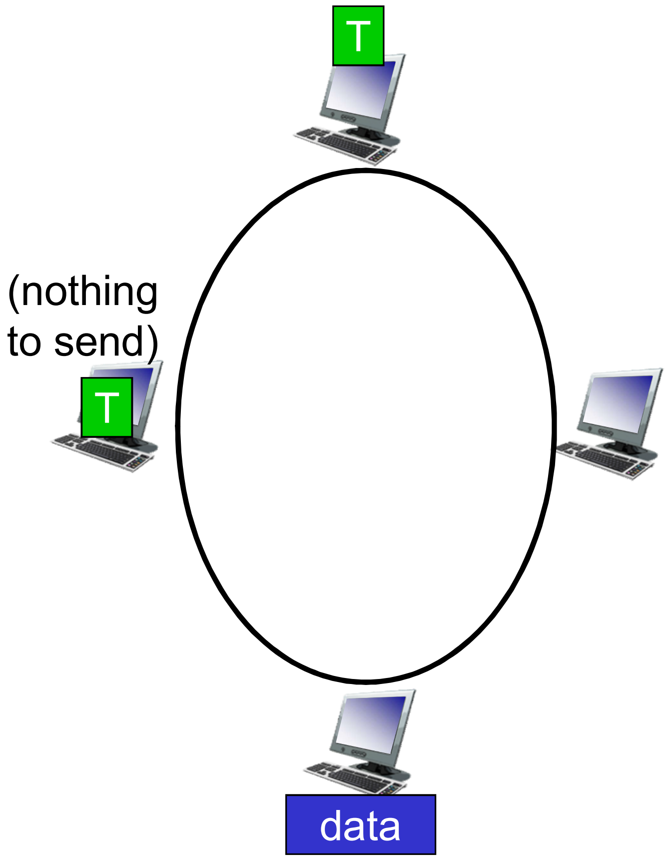
- controller node “invites” other nodes (clients) to transmit in turn
- typically used with “dumb” devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (controller)



MAC – “Taking Turns” Protocols: Token Passing

token passing:

- control *token* passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)



MAC – Random Access Protocols: Introduction

- 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:
  - ALOHA, slotted ALOHA
  - CSMA, CSMA/CD, CSMA/CA

MAC – Random Access Protocols: Slotted ALOHA

assumptions:

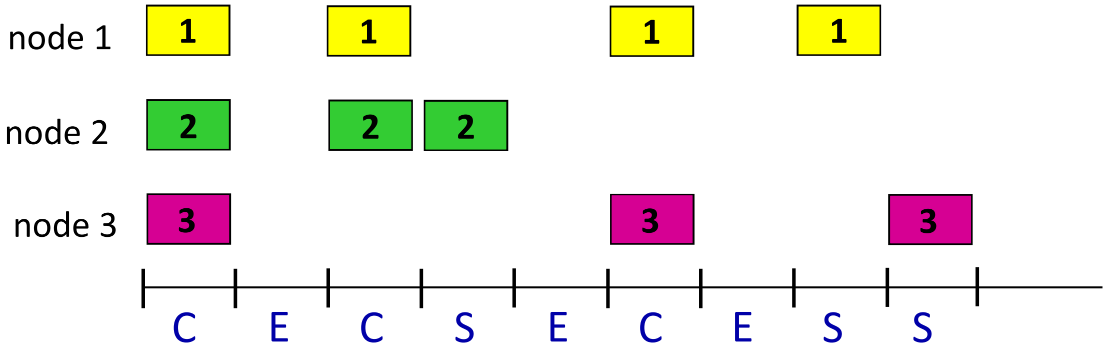
- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

operation:

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

randomization – *why*?

MAC – Random Access Protocols: Slotted ALOHA



C: collision
S: success
E: empty

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

MAC – Random Access Protocols: Slotted ALOHA (S-ALOHA)

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

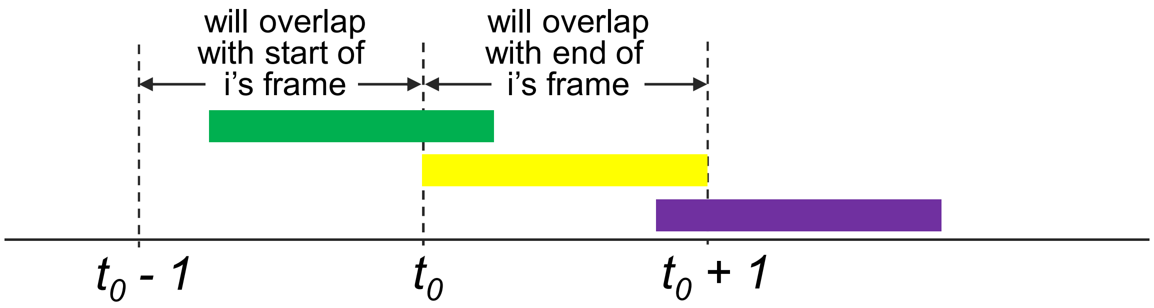
- *suppose: N* nodes with many frames to send, each transmits in slot with probability *p*
  - prob that given node has success in a slot = $p(1-p)^{N-1}$
  - prob that *any* node has a success = $Np(1-p)^{N-1}$
  - max efficiency: find p^* that maximizes $Np(1-p)^{N-1}$
  - for many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives:

Maximum Efficiency = $1/e = .37$

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

MAC – Random Access Protocols: Pure ALOHA

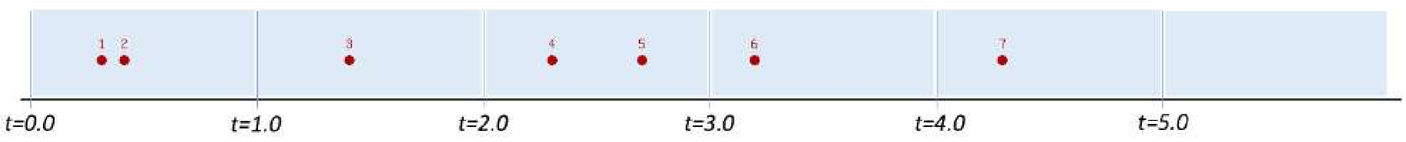
- unslotted Aloha: simpler, no synchronization
  - when frame first arrives: transmit immediately
- collision probability increases with no synchronization:
  - frame sent at t_0 collides with other frames sent in $[t_0-1,t_0+1]$



- pure Aloha efficiency: 18% !

EXERCISE: MAC – Random Access Protocols: ALOHA

Consider the figure below, which shows the arrival of 7 messages for transmission at different multiple access wireless nodes at times t = <0.3, 0.4, 1.4, 2.3, 2.7, 3.2, 4.3> and each transmission requires exactly one time unit.



Question 1: Suppose all nodes are implementing the Aloha protocol. For each message, indicate the time at which each transmission begins.

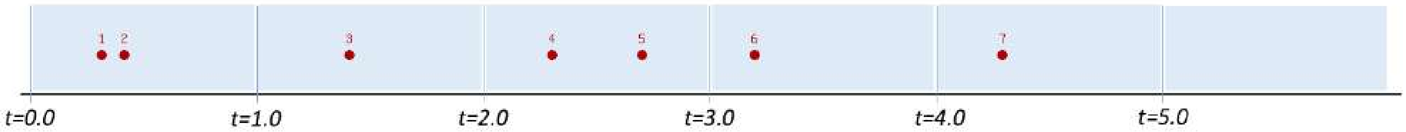
Answer:
1. t=0.3
2. t=0.4
3. t=1.4
4. t=2.3
5. t=2.7
6. t=3.2
7. t=4.3

Question 2: Which messages transmit successfully?

Answer: Message 7

EXERCISE: MAC – Random Access Protocols: S-ALOHA

Consider the figure below, which shows the arrival of 7 messages for transmission at different multiple access wireless nodes at times t = <0.3, 0.4, 1.4, 2.3, 2.7, 3.2, 4.3> and each transmission requires exactly one time unit.



Question 1: Suppose all nodes are implementing the Slotted Aloha protocol. For each message, indicate the time at which each transmission begins.

Answer:
1. t=1.0
2. t=1.0
3. t=2.0
4. t=3.0
5. t=3.0
6. t=4.0
7. t=5.0

Question 2: Which messages transmit successfully?

Answer: Messages 3, 6, and 7

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