The Medium Access Control Sublayer

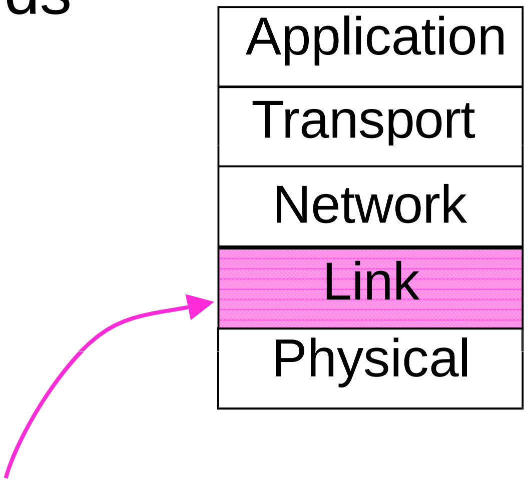
Chapter 4

- Networks links can be divided into two categories:
  - Point-to-point connections
    - WAN is point-to-point links
  - Broadcast channels/multiaccess channels or random access channels
    - For fixed channel and traffic from N users
    - Wireless is a broadcast channel
  - Analogy
    - Conference call with six people with different telephones
- Medium access control sublayer is a sublayer in data link layer
- Multi-access channels and LANs are closely related
  - So, we discuss about LANs
- MAC sublayer is the bottom of the datalink layer

The MAC Sublayer

Responsible for deciding who sends next on a multi-access link

- An important part of the link layer, especially for LANs



Application

Transport

Network

Link

Physical

MAC is in here!

Medium Access Control Sublayer

- Channel Allocation Problem
- Multiple Access Protocols
- Ethernet
- Wireless LANs
- Broadband Wireless
- Bluetooth
- RFID
- Data Link Layer Switching

Channel Allocation Problem

- Channel connects one user to other user/users
    - Portion of wireless spectrum, single wire, optical fiber
- Two options:
    - Static Channel allocation
    - Dynamic channel allocation
- Static allocation
    - For fixed channel and traffic from N users
    - Divide up bandwidth using FTM, TDM, CDMA, etc.
    - This is a static allocation, e.g., FM radio
    - The static allocation performs poorly for bursty traffic
    - Allocation to a user will sometimes go unused

Static Allocation: Performance of FDM

- FDM
  - If there are N users, the bandwidth is divided into N equal-sized portions, with each user being assigned one portion.
  - Issues
    - When number of senders increase, FDM suffers
- If the spectrum is cut up into N regions and fewer than N users are communicating, a large portion is wasted.
- Analysis: single channel
  - Channel capacity=C bps;
  - Mean time delay= T;
  - frame arrival rate = λ frames/sec,
  - the frames vary with the average length of= $1/\mu$ bits.
  - With this the service rate of the channel is μC frames/sec.
  - As per the standard queuing theory $T= 1/(\mu C- \lambda)$
  - https://en.wikipedia.org/wiki/Queueing_theory
- Allocation for dividing the channel into N channels
  - If we divide the channel into N channels, each can transmit with the capacity of C/N bps; the mean arrival rate is λ/N frames/sec. Then,
  - $T_N=1/(\mu(C/N)- (\lambda/N))= N/(\mu C- \lambda)=NT$
- Same arguments will apply for other modes of dividing the channel

Dynamic Channel Allocation

Dynamic allocation gives the channel to a user when they need it. Potentially N times as efficient for N users.

Schemes vary with assumptions:

Assumption	**Description**	**Implication**
Independent traffic	The expected number of frames per unit time is constant. After generation the station is blocked till the frame is delivered.	Often not a good model, but permits analysis
Single channel	A single channel is available for all stations. All stations can send and receive	No external way to coordinate senders
Observable collisions	If two frames are transmitted simultaneously, the signal is garbled. All stations can detect.	Needed for reliability; mechanisms vary
Continuous or slotted time	Time may be continuous or slotted. Frame transmissions can begin at the beginning of the slot.	Slotting may improve performance
Carrier sense	Stations can tell if the channel is in use	Can improve performance if available

Multiple Access Protocols

- ALOHA »
- CSMA (Carrier Sense Multiple Access) »
- Collision-free protocols »
    - $1/(\mu C- \Lambda)$
- Limited-contention protocols »
- Wireless LAN protocols »

PURE ALOHA

- **ALOHAnet**, also known as the **ALOHA System,** or simply **ALOHA**, was a pioneering computer networking system developed at the University of Hawaii.

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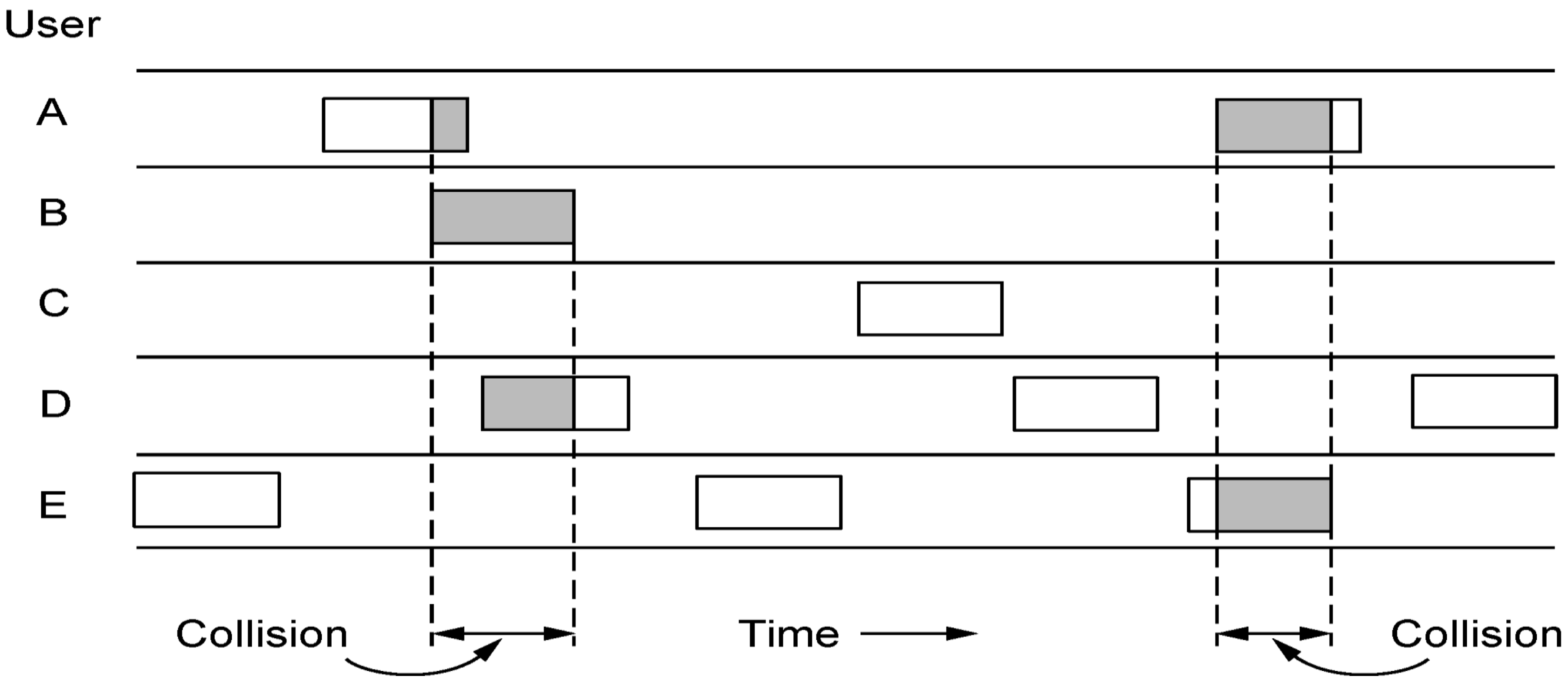
- ALOHAnet became operational in June, 1971, providing the first public demonstration of a wireless packet data network.

- ALOHA originally stood for “Additive Links On-line Hawaii Area”

PURE ALOHA

- Pure ALOHA
  - Users transmit frames whenever they have data;
  - If the frame is destroyed (Collison occurs), users waits a random amount of time and sends it again.



In pure ALOHA, frames are transmitted at completely arbitrary times.

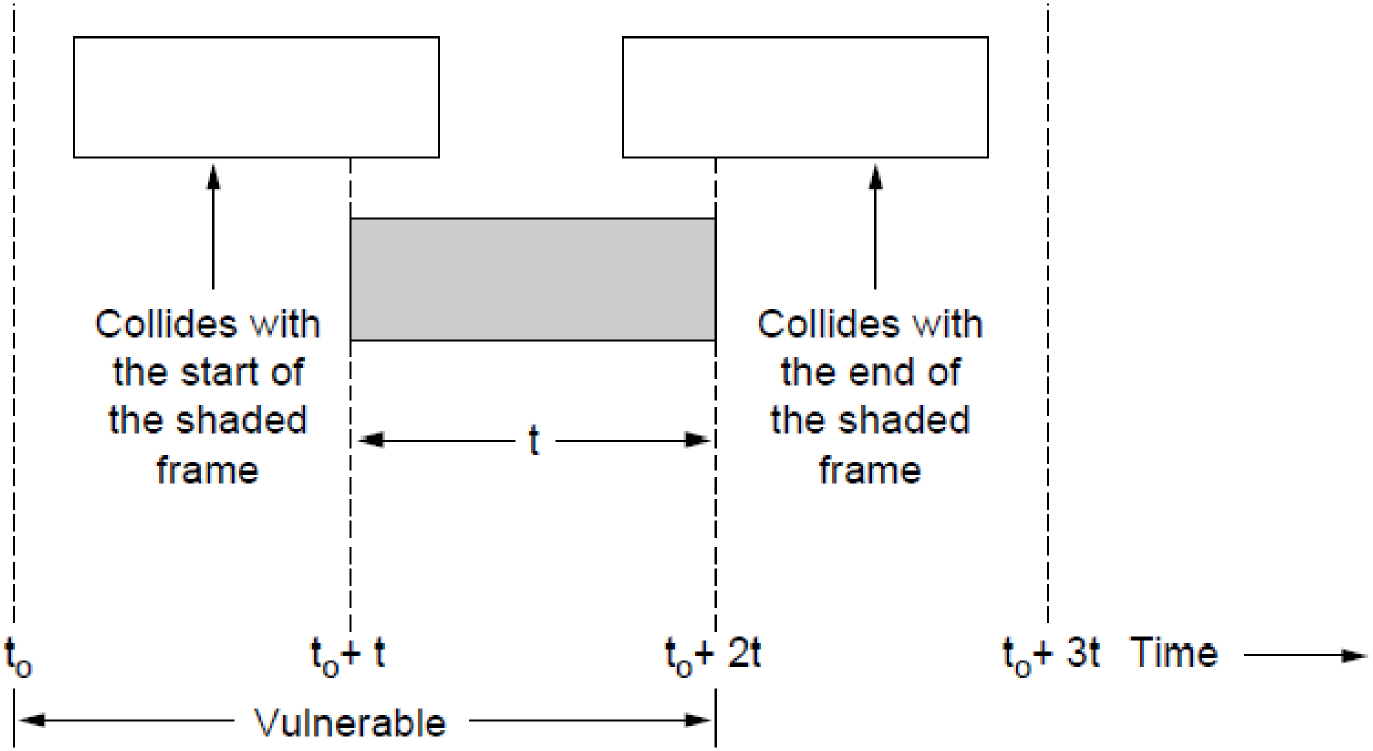
Efficiency of Pure ALOHA

- What fraction of frames escape collisions in chaotic situation?
  - Consider N users typing at the terminals, when the line is finished, user waits for the response.
- Let “frame time” denote the time to transmit the frame.
- Frame generation is modelled with a Poisson distribution with a mean of N frames per frame time (https://en.wikipedia.org/wiki/Poisson_distribution)
- If N >1, user is generating frames higher rate than the channel can handle.
- For reasonable throughput we expect that 0 < N < 1.
- Station also generated retransmissions
- Old and new frames are modeled by a Poisson distribution with a mean of G frames per frame time.
- Clearly, G >= N, So, at high load there will be many collisions.
- Throughput= G*P_0 , where P_0 is the probability that a frame does oot suffer a collision.
- Question: Under what conditions, the frame arrive undamaged?
- The probability that k frames are generated during the given frame time in which G frames are expected is given by Poisson distribution
  - Pr[k]=$\frac{G^k e^{-G}}{k!}$
  - The probability of 0 frames is e^{-G}
- The probability of no frames being initiated during the entire vulnerable period is thus given by $P_0 = e^{-2G}$; Using S= GP_0, we get S=G e^{-2G}

ALOHA (2)

Collisions happen when other users transmit during a vulnerable period that is twice the frame time

- Synchronizing senders to slots can reduce collisions


Collides with the start of the shaded frame
t
Collides with the end of the shaded frame
t_o
t_o+ t
t_o+ 2t
t_o+ 3t
Time
Vulnerable

Slotted ALOHA

- Divide the time into discrete intervals. Each interval corresponding to one frame.
  - Allow a special station to emit a pip at the start of the each interval.
  - Station is not permitted to send at any time. It has to wait for the slot.

Efficiency of Slotted ALOHA

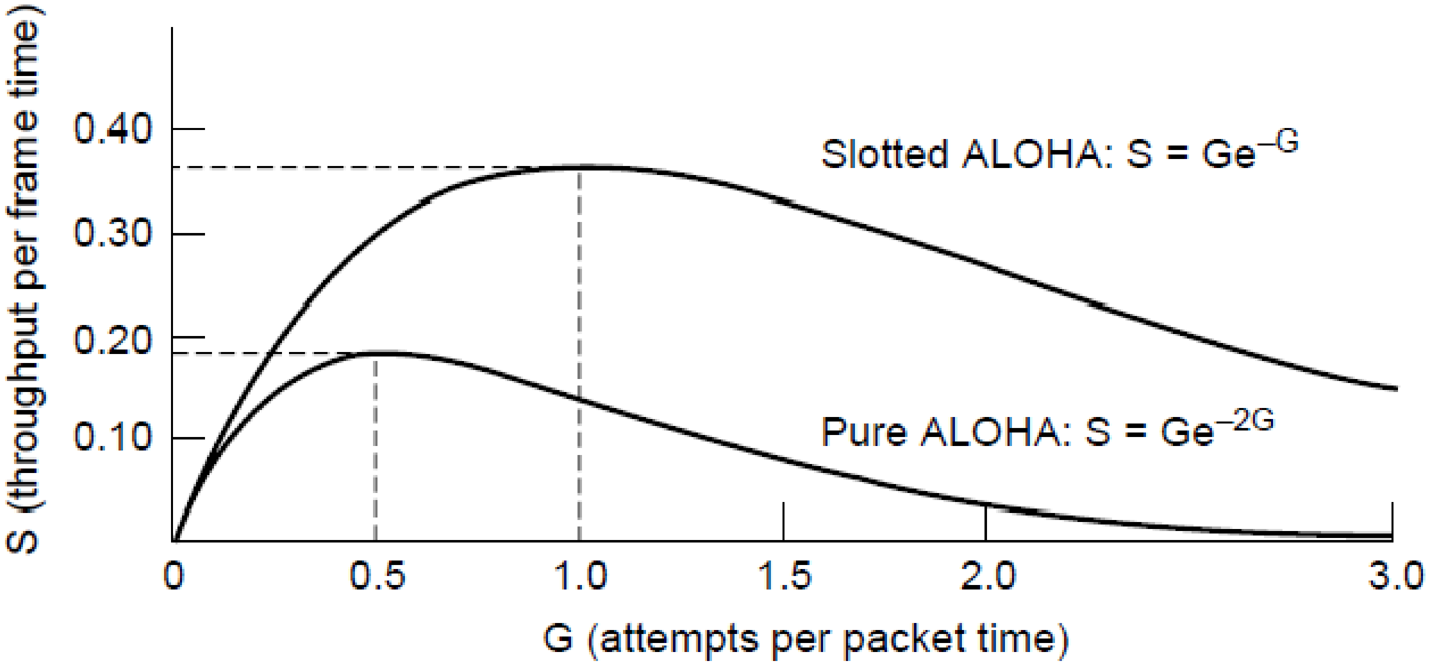
- In Slotted ALOHA, in contrast to Pure ALOHA, a station is not permitted to send whenever user types a line, it is required to wait for the beginning of the next slot. This halves the vulnerability period.
- The probability of no other traffic during the same slot as our test frame is there is then e^{-G}, which leads to S=G e^{-G}
- Slotted ALOHA peaks at G=1, the throughout is 1/e= about 0.368
- The probability of a transmission requiring exactly k attempts (i.e., k-1 collisions and one success) $P_k = e^{-G}(1- e^{-G})^{k-1}$
- The expected number of retransmissions, E, per line types at a terminal is them

  E$= \sum_{k=1}^{\infty} k\, P_k = \sum_{k=1}^{\infty} ke^{-G}(1- e^{-G})^{k-1}$= e^{G}
- A small increase in the channel load can drastically reduce the performance.

ALOHA

Slotted ALOHA is twice as efficient as pure ALOHA

- Low load wastes slots, high loads causes collisions
- Efficiency up to 1/e (37%) for random traffic models



Carrier Sense Multiple Access (CSMA)

- CSMA (Carrier Sense Multiple Access) improves on ALOHA by sensing the channel!
- User doesn’t send if it senses someone else

Variations on what to do if the channel is busy:

- 1-persistent (greedy) sends as soon as idle
- Nonpersistent waits a random time then tries again
- p-persistent sends with probability p when idle

1-Persistent CSMA Protocol

- When a station has data to send, it listens to the channel
- If the channel is idle, the station sends the data
- If the channel is busy, the station waits until it becomes idle.
- If the collision occurs, the station waits for random amount of time and starts over again.
- It is called 1-persistent, because, the station transmits with a probability of 1 when it finds the channel idle.
- Issues: when two stations ready, collisions occur, if they are not so impatient.

Nonpersistent CSMA Protocol

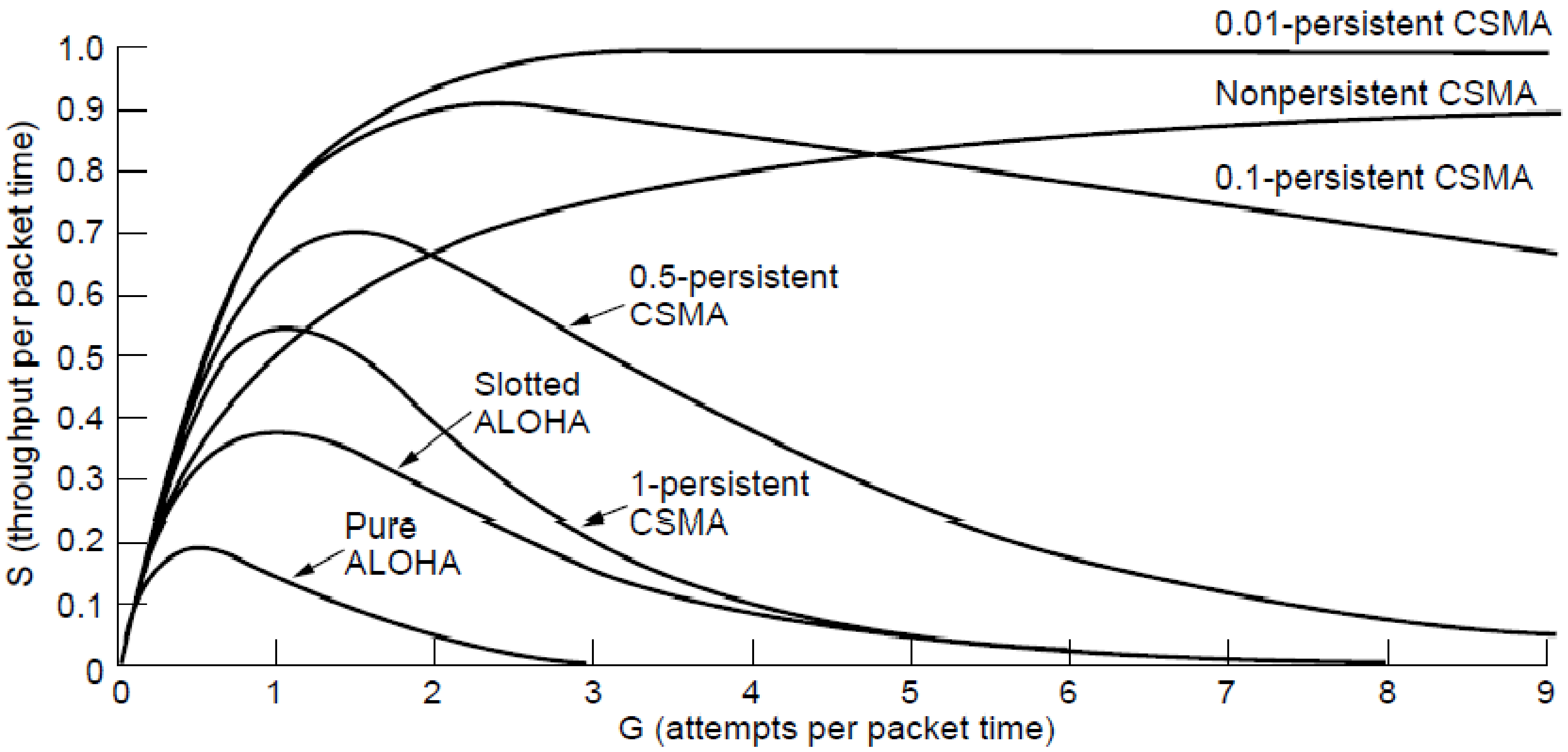
- Attempt has been made to be less greedy than 1-persistent
- When a station has data to send, it listens to the channel
- If the channel is idle, the station sends the data
- If the channel is busy,
  - the station does not make effort to seize it immediately after detecting the end of transmission. Instead, it waits for random period of time and repeats the algorithm
- Advantages: It has better utilization than 1-persistent CSMA

p-persistent CSMA Protocol

- Applies to slotted channels
- When a station has data to send, it listens to the channel
- If the channel is idle, the station sends the data with probability p. With a probability q=1-p, it defers until the next slot. If that slot is idle it either transmits or defers with probability p and q. this step repeats until either the frame has transmitted or other station has begun transmitting.
- If the slot is busy, it considers as a Collison, that it, it waits for random time and starts again.
- If the station initially senses that the slot is busy, it waits until the next slot and applies the above algorithm
- Advantages: Improved Utilization over nonpersistent CDMA

CSMA – Persistence

CSMA outperforms ALOHA, and being less persistent is better under high load



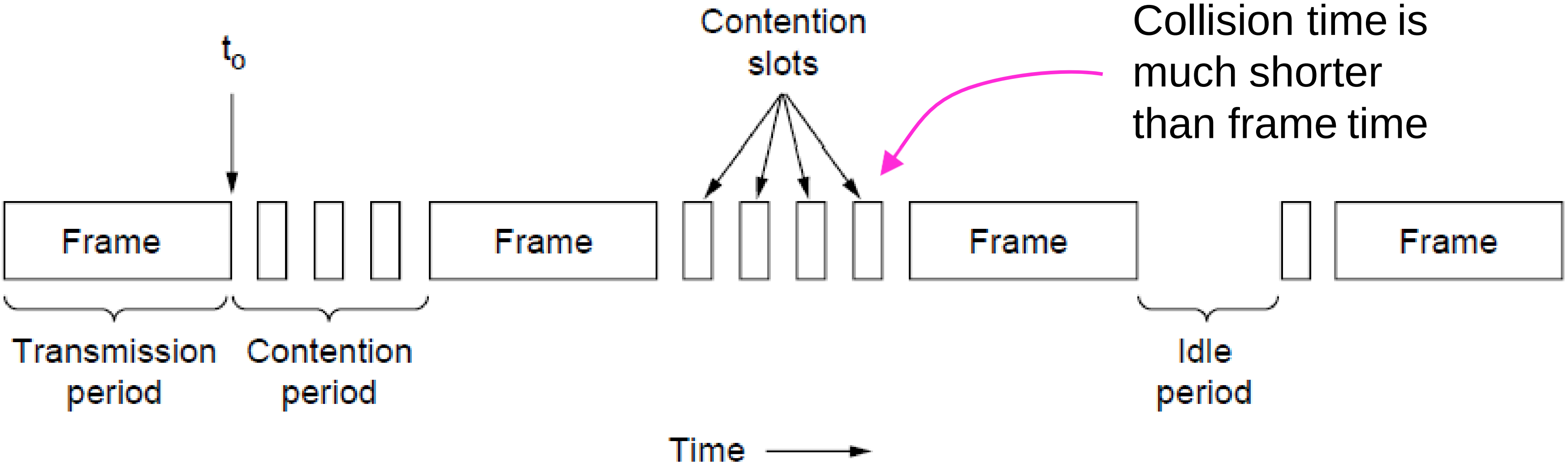
CSMA with Collision detection

- In CSMA, if two stations sense a channel to be idle and begin transmitting, the signals will collide.
- Alternative: Stations quickly detect collision and abruptly stop transmitting.
  - It saves time and bandwidth
- If a station detects collision, it aborts its transmission, waits a random period of time and tries again.
- CSMA/CD consists of alternating contention and transmission periods and idle periods (when all stations are quiet).
- If the channel transmits 2*t, whether t is the signal propagation time between the two farthest stations. (for 1KM co-axial cable, t=5 µsec).
- Performance is greatly improved if frame time is much larger than the propagation time.

CSMA (3) – Collision Detection

CSMA/CD improvement is to detect/abort collisions

- Reduced contention times improve performance



Collision time is much shorter than frame time

Collision-Free Protocols

- In CSMA/CD, collisions still occur during the contention period.
- It will effect the performance with large t (cable is long)

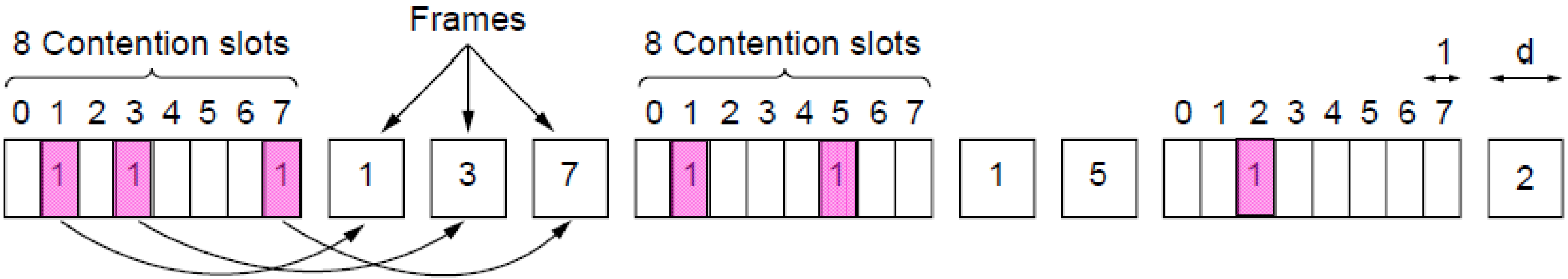
Bitmap Collision-free protocol

Collision-free protocols avoid collisions entirely

- Senders must know when it is their turn to send

The basic bit-map protocol:

- Contention period consists of N slots.
- Sender set a bit in contention slot if they have data
- Senders send in turn; everyone knows who has data
- Stations transmit data in the numerical order.



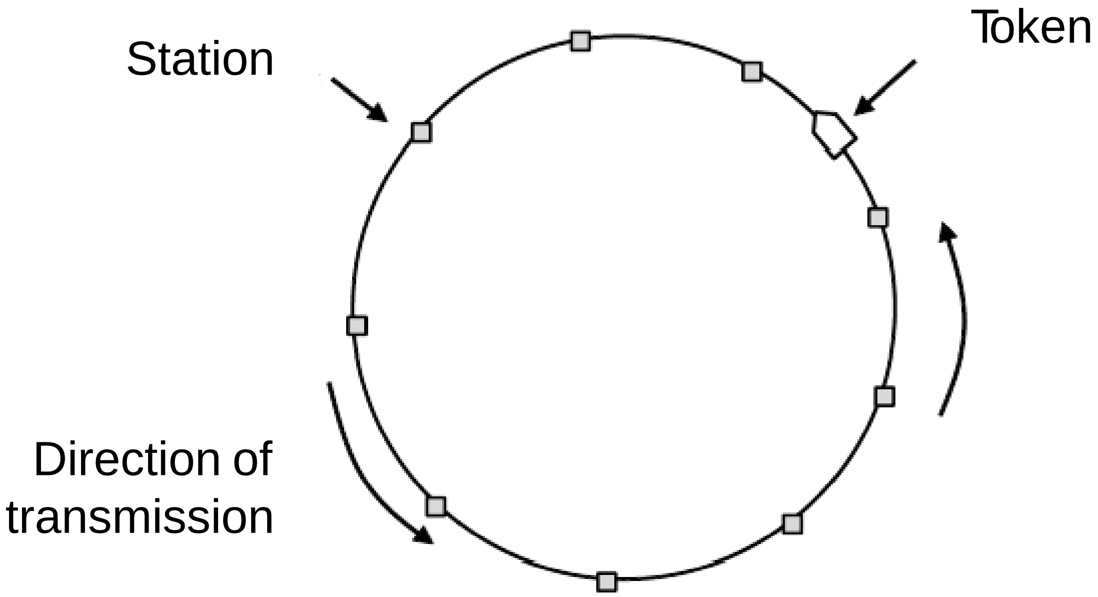
Performance:

- Low load: bit-map gets repeated. On an average, the station has to wait N/2 slots.
- High numbers slots rarely have to wait for next scan.
- Lower numbers channels have to wait for 1.5N slots and higher numbered channels have to wait for 0.5N slots.

Token Ring-Collision free protocol

Token sent round ring defines the sending order

- Station with token may send a frame before passing
- Idea can be used without ring too, e.g., token bus

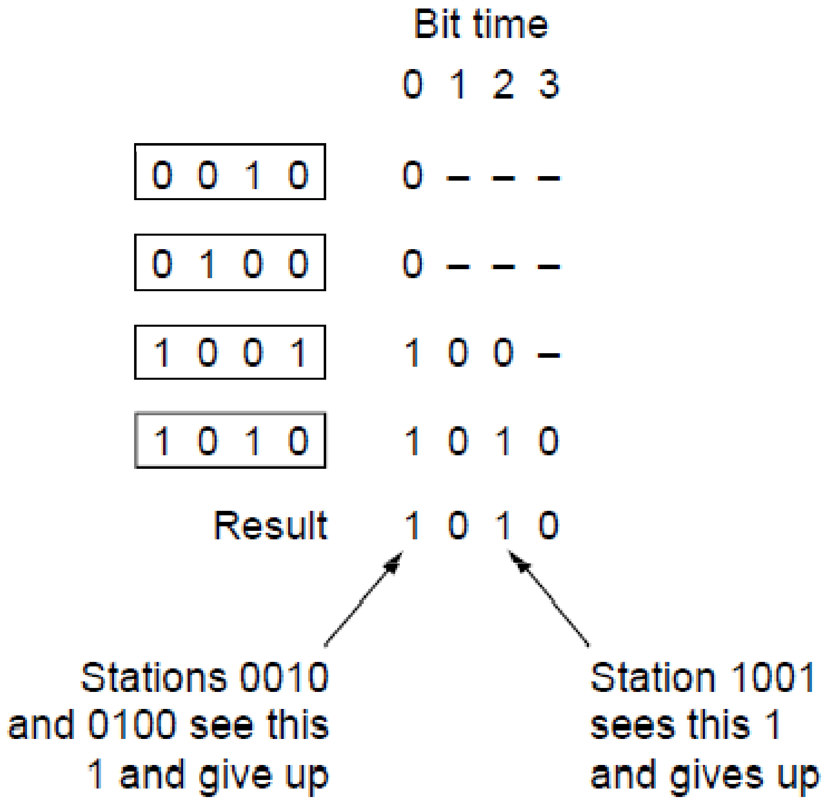


Countdown-Collision Free Protocol

-Bitmap does not scales to thousands of stations

-Binary countdown improves on the bitmap protocol

- Stations send their address in contention slot (log N bits instead of N bits)
- Medium ORs bits; stations give up when they send a “0” but see a “1”
- Station that sees its full address is next to send



	Bit time 0 1 2 3
0 0 1 0	0 – – –
0 1 0 0	0 – – –
1 0 0 1	1 0 0 –
1 0 1 0	1 0 1 0
Result	1 0 1 0

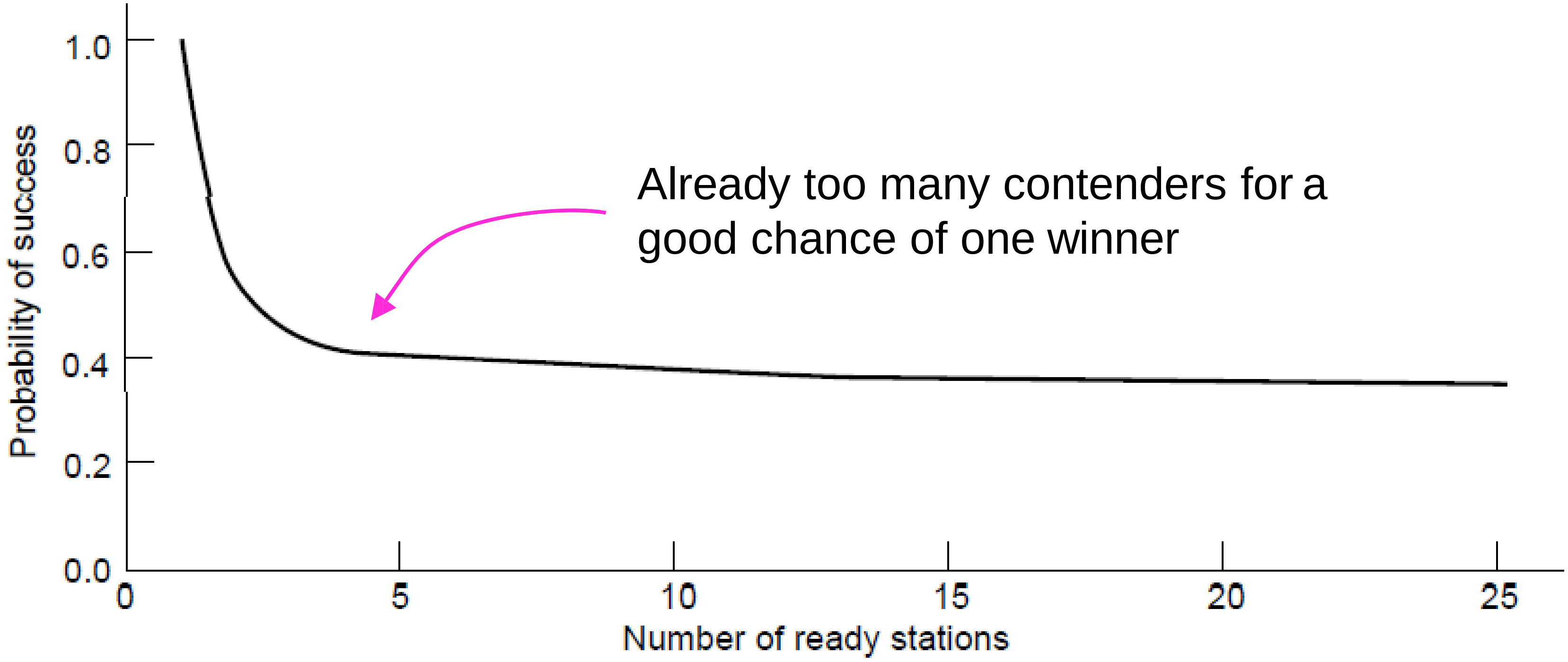
Stations 0010 and 0100 see this 1 and give up

Station 1001 sees this 1 and gives up

Limited-Contention Protocols

Idea is to divide stations into groups within which only a very small number are likely to want to send

- Avoids wastage due to idle periods and collisions

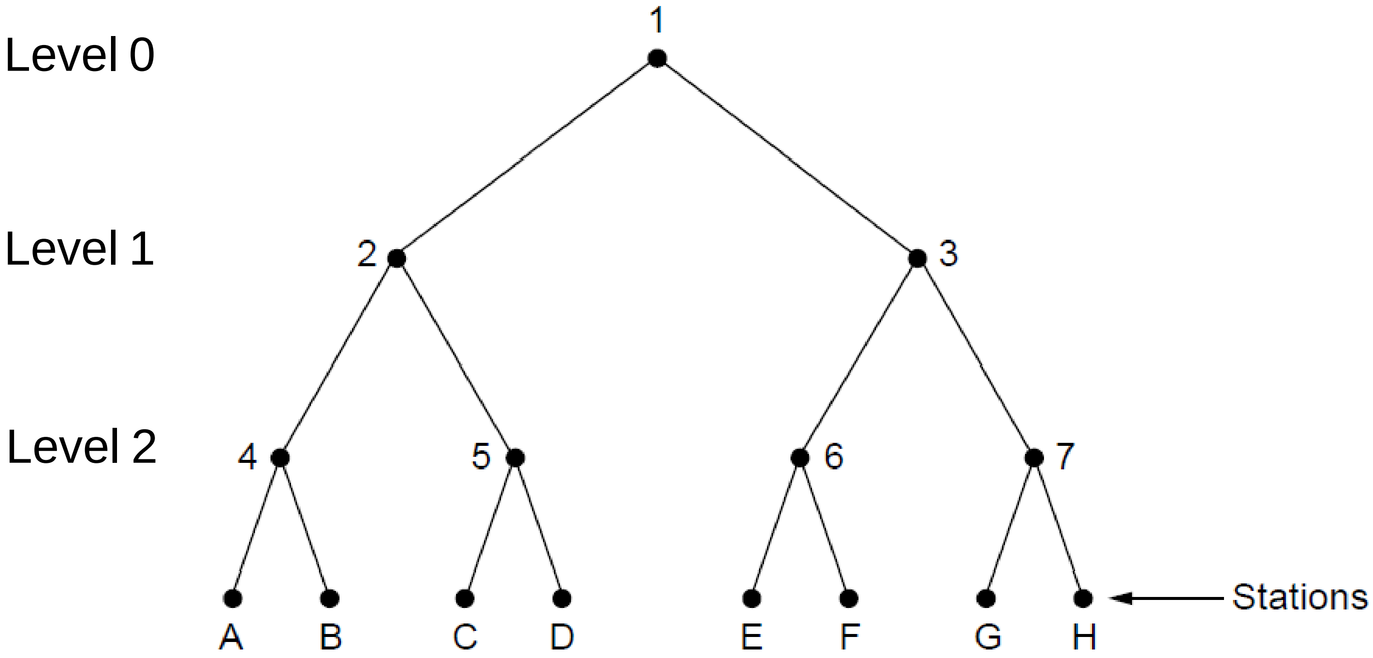


Already too many contenders for a good chance of one winner

Limited Contention (2) –Adaptive Tree Walk

Tree divides stations into groups (nodes) to poll

- Depth first search under nodes with poll collisions
- Start search at lower levels if >1 station expected



Wireless LAN Protocols (1)

Wireless has complications compared to wired.

Nodes may have different coverage regions

- Leads to hidden and exposed terminals

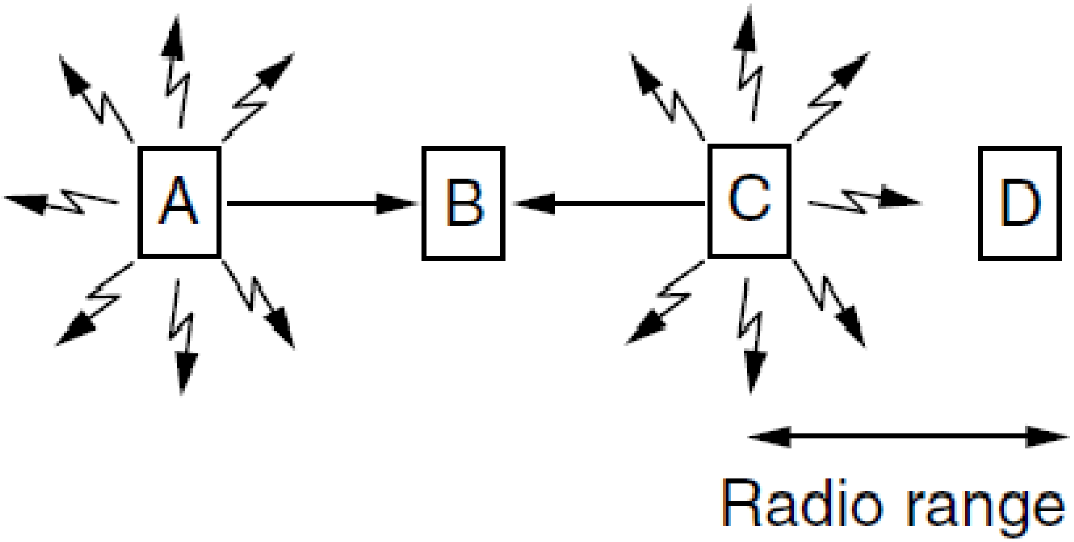
Nodes can’t detect collisions, i.e., sense while sending

- Makes collisions expensive and to be avoided

Wireless LANs (2) – Hidden terminals

Hidden terminals are senders that cannot sense each other but nonetheless collide at intended receiver

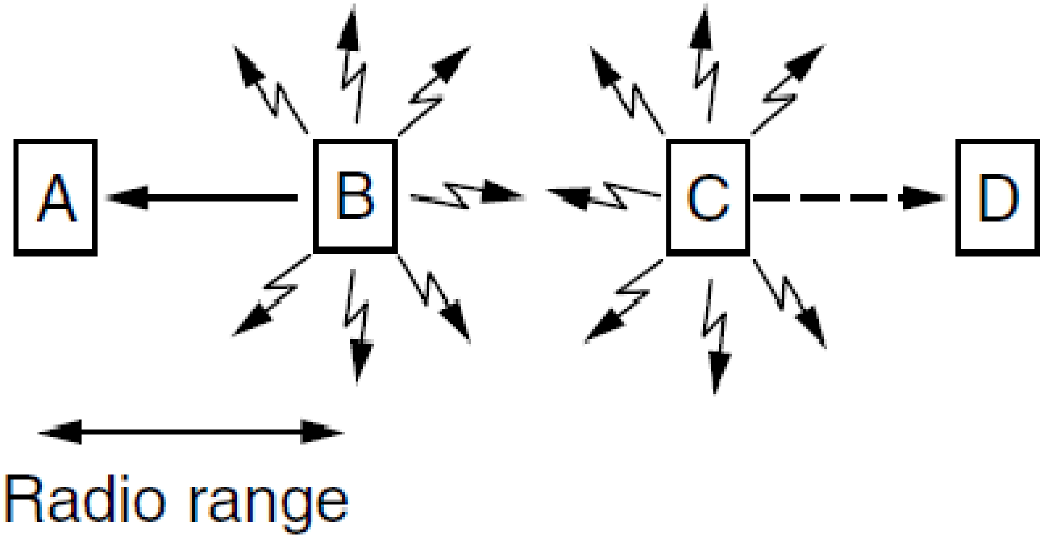
- Want to prevent; loss of efficiency
- A and C are hidden terminals when sending to B



Wireless LANs (3) – Exposed terminals

Exposed terminals are senders who can sense each other but still transmit safely (to different receivers)

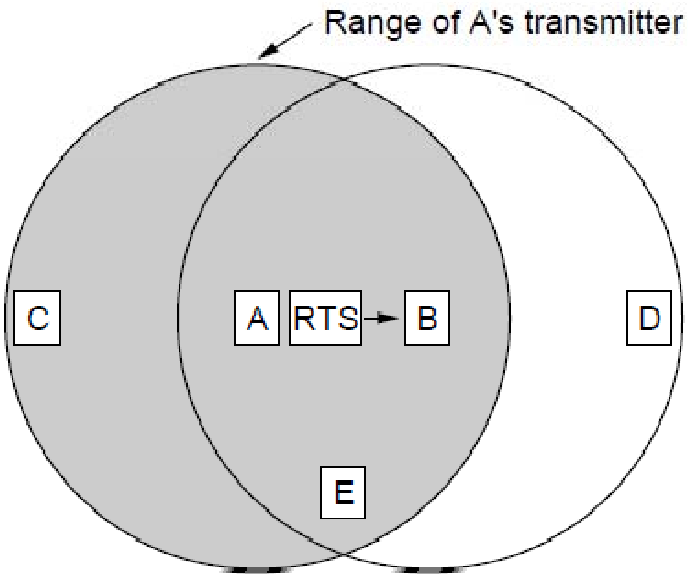
- Desirably concurrency; improves performance
- B → A and C → D are exposed terminals



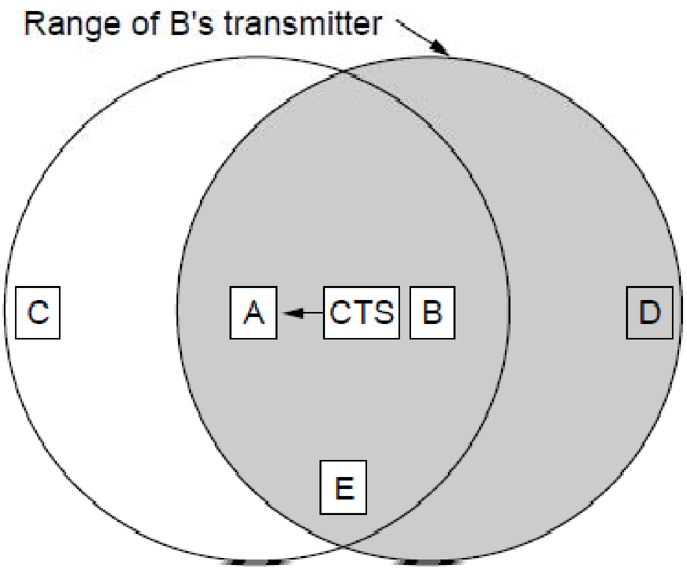
Wireless LANs (4) – MACA

MACA protocol grants access for A to send to B:

- A sends RTS to B [left]; B replies with CTS [right]
- A can send with exposed but no hidden terminals



A sends RTS to B; C and E hear and defer for CTS



B replies with CTS; D and E hear and defer for data

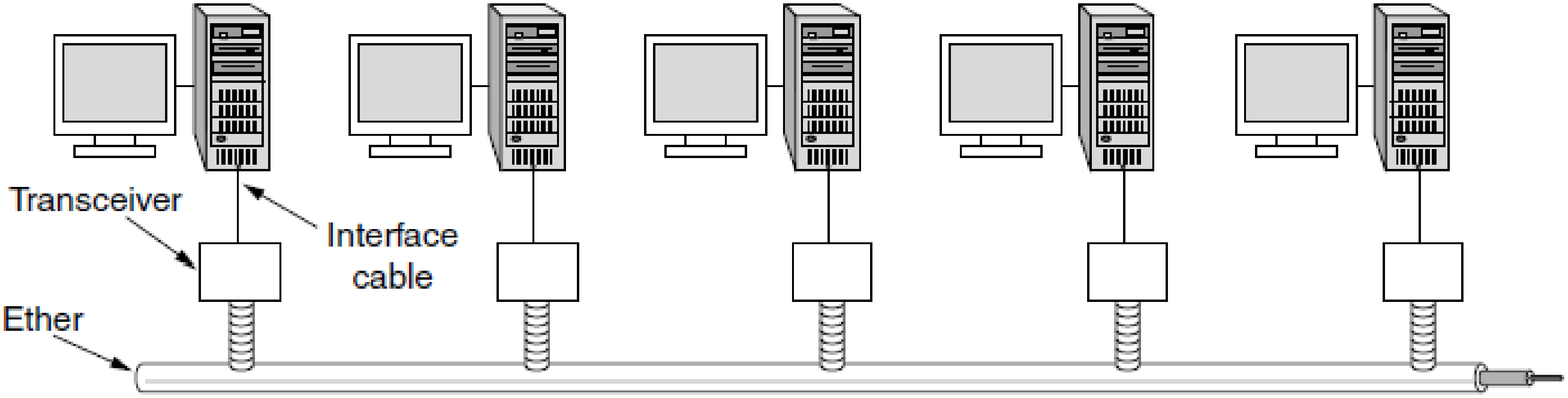
Ethernet

- Classic Ethernet »
- Switched/Fast Ethernet »
- Gigabit/10 Gigabit Ethernet »

Classic Ethernet (1) – Physical Layer

One shared coaxial cable to which all hosts attached

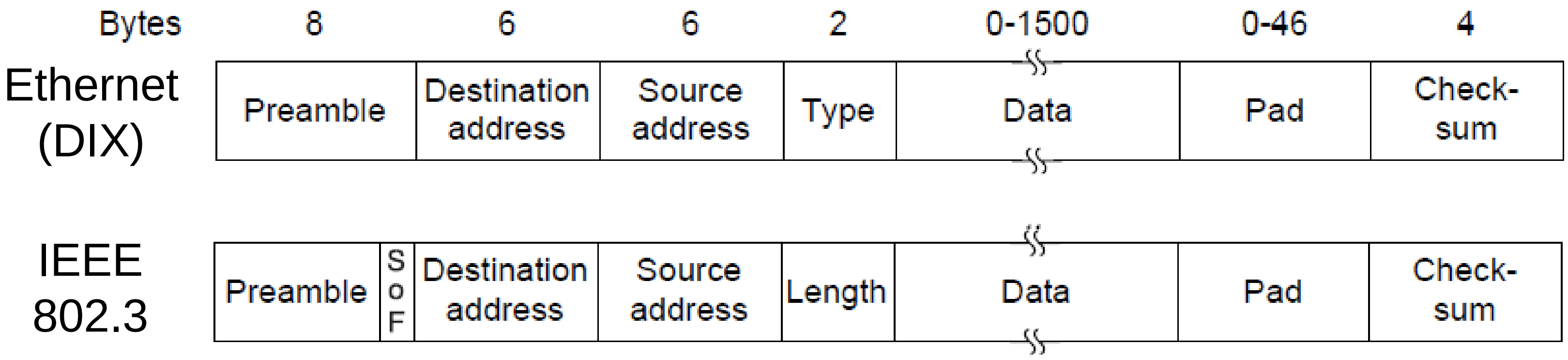
- Up to 10 Mbps, with Manchester encoding
- Hosts ran the classic Ethernet protocol for access



Classic Ethernet (2) – MAC

MAC protocol is 1-persistent CSMA/CD (earlier)

- Random delay (backoff) after collision is computed with BEB (Binary Exponential Backoff)
- Frame format is still used with modern Ethernet.

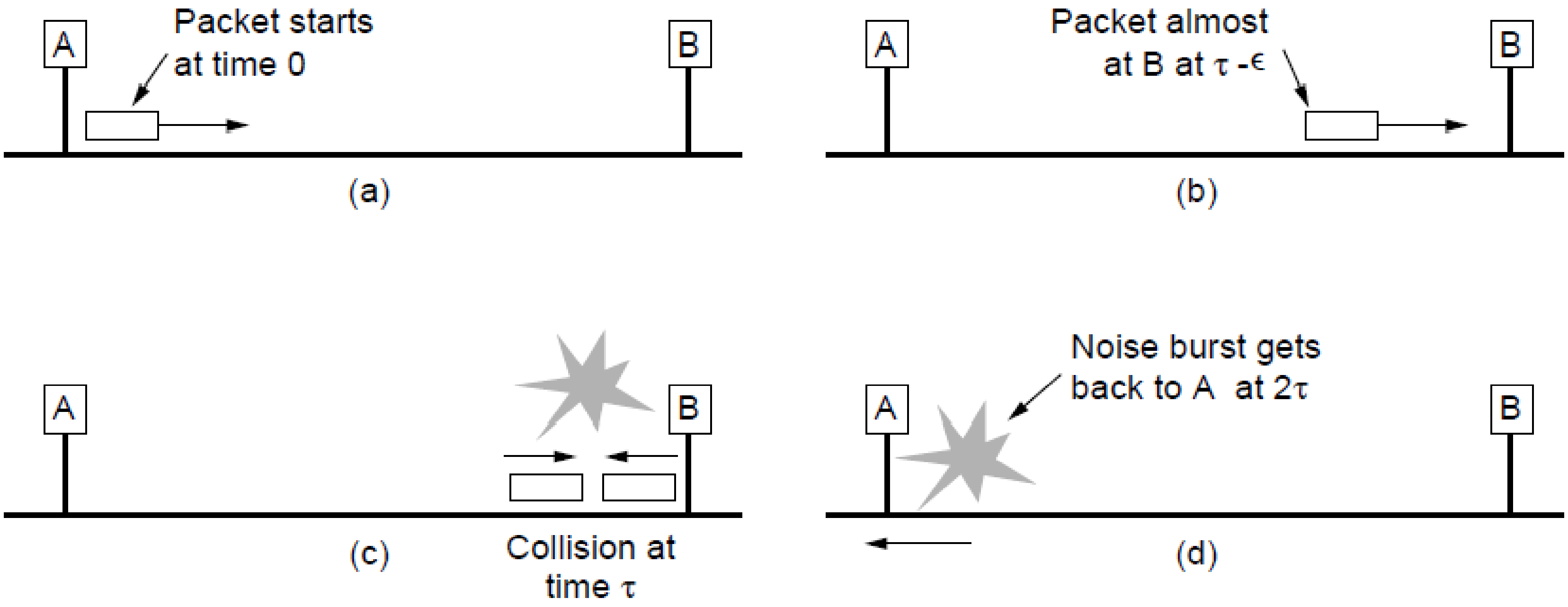


Bytes	8	6	6	2	0-1500	0-46	4
Ethernet (DIX)	Preamble	Destination address	Source address	Type	Data	Pad	Check-sum
IEEE 802.3	Preamble SOF	Destination address	Source address	Length	Data	Pad	Check-sum

Classic Ethernet (3) – MAC

Collisions can occur and take as long as 2τ to detect

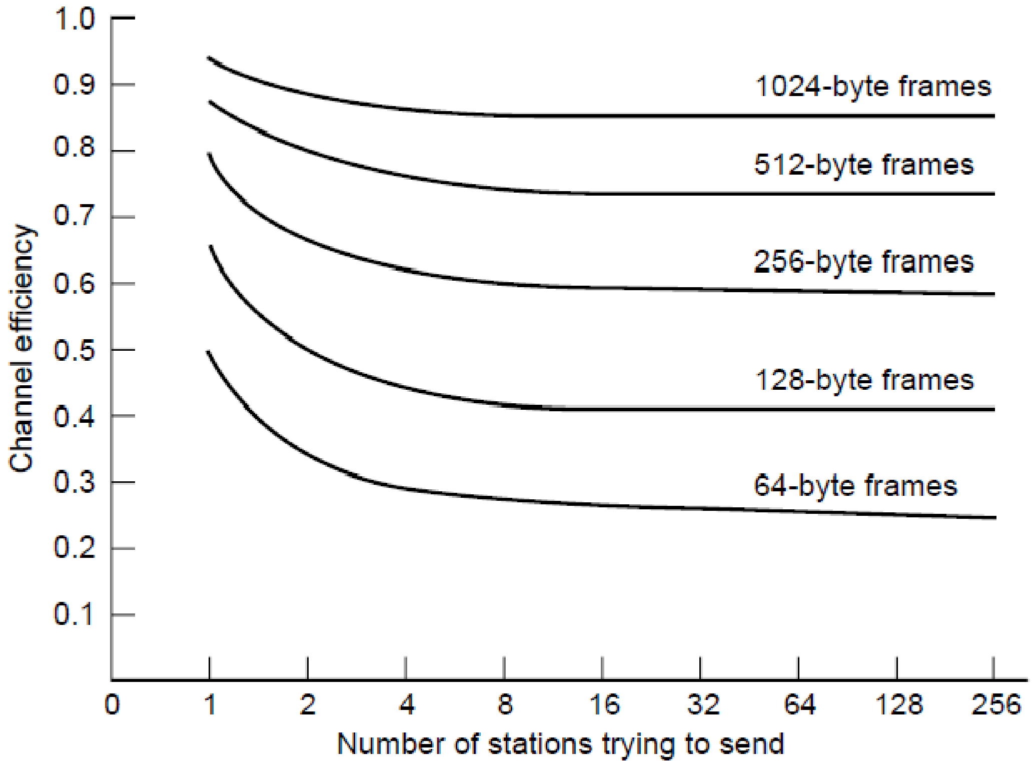
- τ is the time it takes to propagate over the Ethernet
- Leads to minimum packet size for reliable detection



Classic Ethernet (4) – Performance

Efficient for large frames, even with many senders

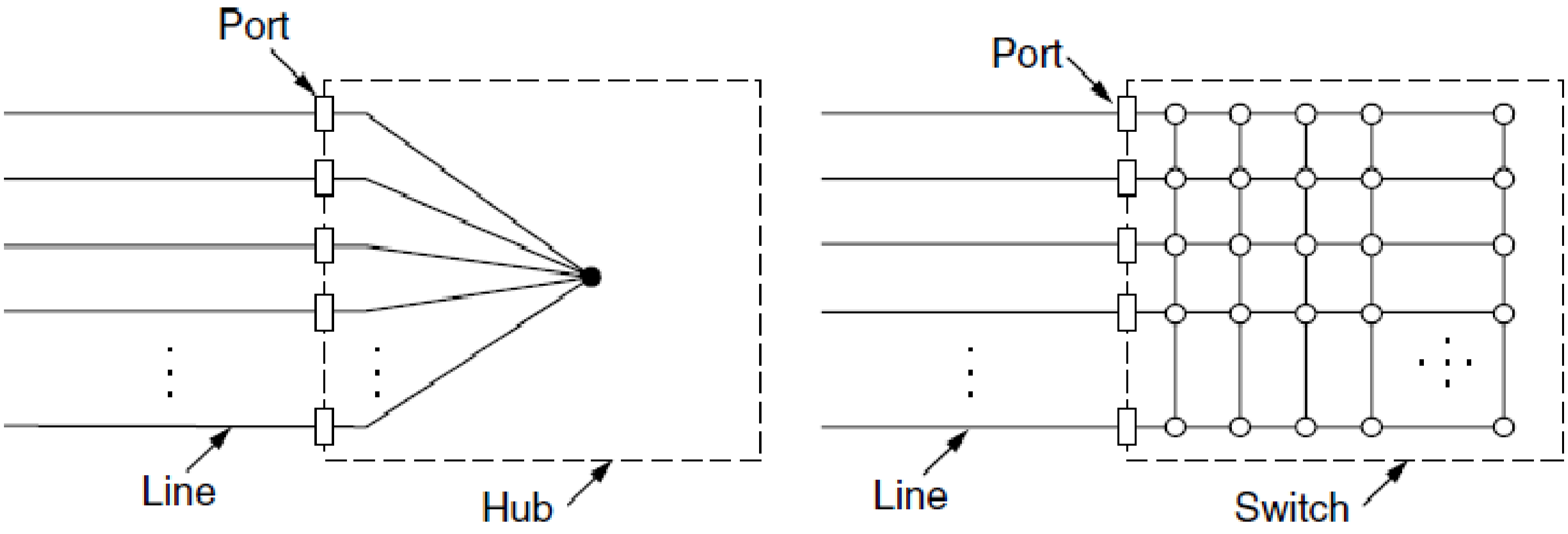
- Degrades for small frames (and long LANs)



10 Mbps Ethernet,
64 byte min. frame

Switched/Fast Ethernet (1)

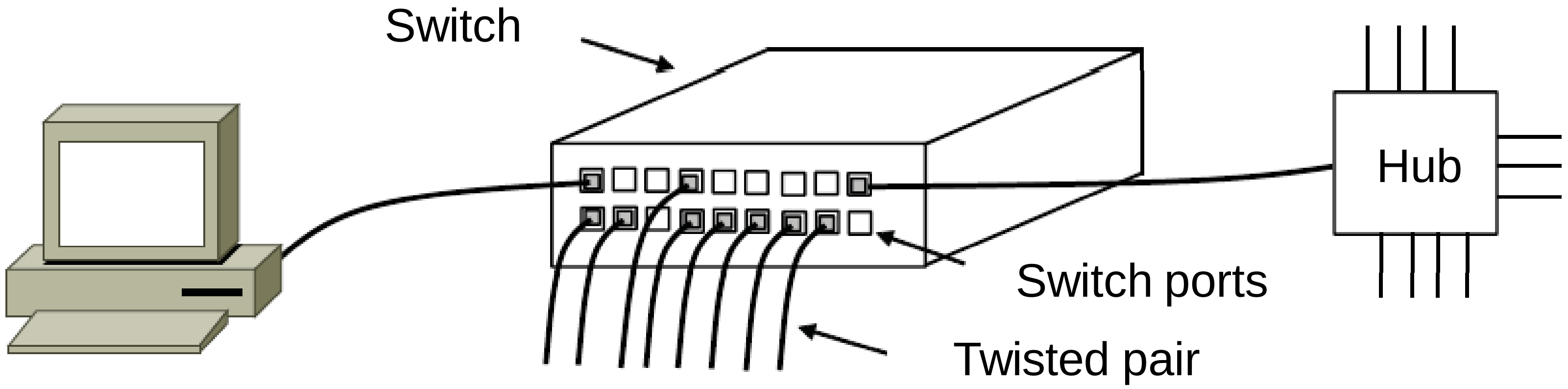
- Hubs wire all lines into a single CSMA/CD domain
- Switches isolate each port to a separate domain
    - Much greater throughput for multiple ports
    - No need for CSMA/CD with full-duplex lines



Switched/Fast Ethernet (2)

Switches can be wired to computers, hubs and switches

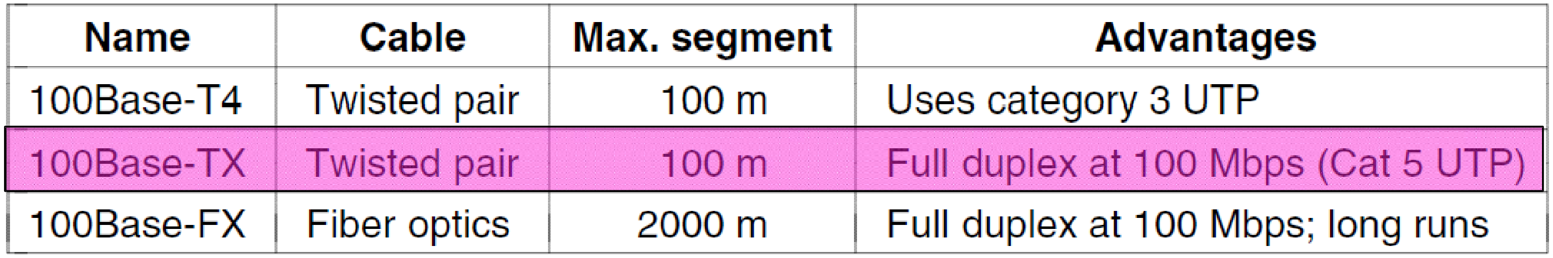
- Hubs concentrate traffic from computers
- More on how to switch frames the in 4.8



Switched/Fast Ethernet (3)

Fast Ethernet extended Ethernet from 10 to 100 Mbps

- Twisted pair (with Cat 5) dominated the market

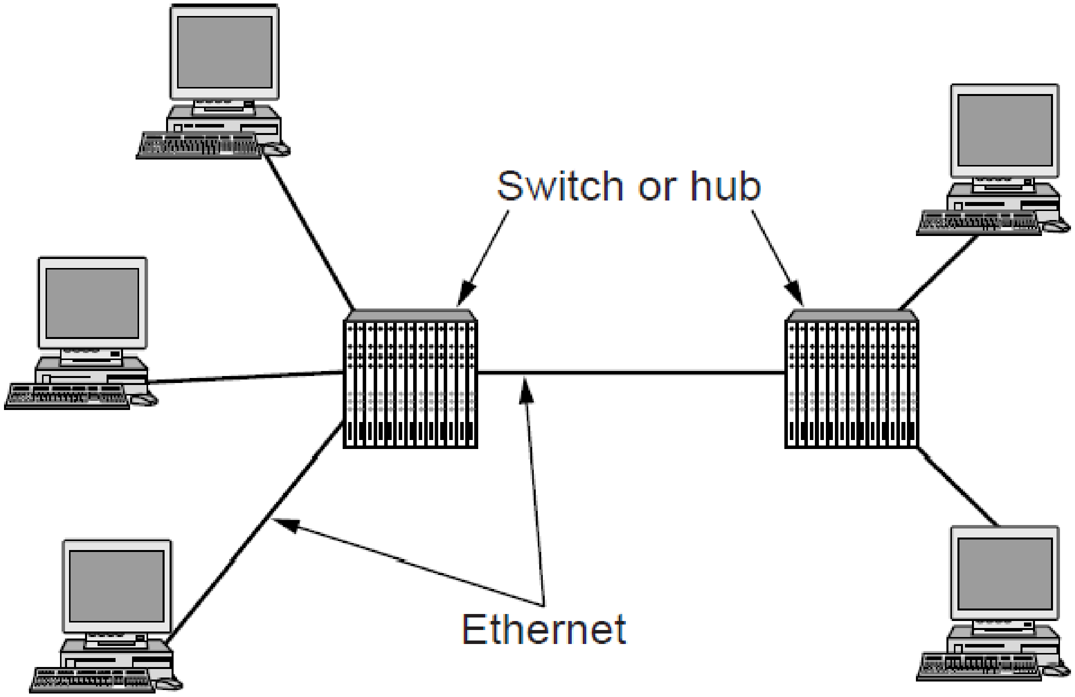


Name	Cable	Max. segment	Advantages
100Base-T4	Twisted pair	100 m	Uses category 3 UTP
100Base-TX	Twisted pair	100 m	Full duplex at 100 Mbps (Cat 5 UTP)
100Base-FX	Fiber optics	2000 m	Full duplex at 100 Mbps; long runs

Gigabit / 10 Gigabit Ethernet (1)

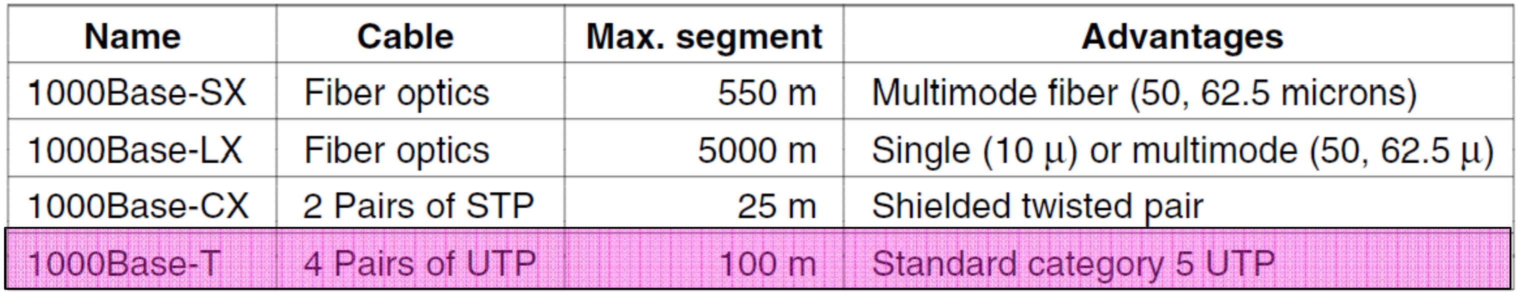
Switched Gigabit Ethernet is now the garden variety

- With full-duplex lines between computers/switches



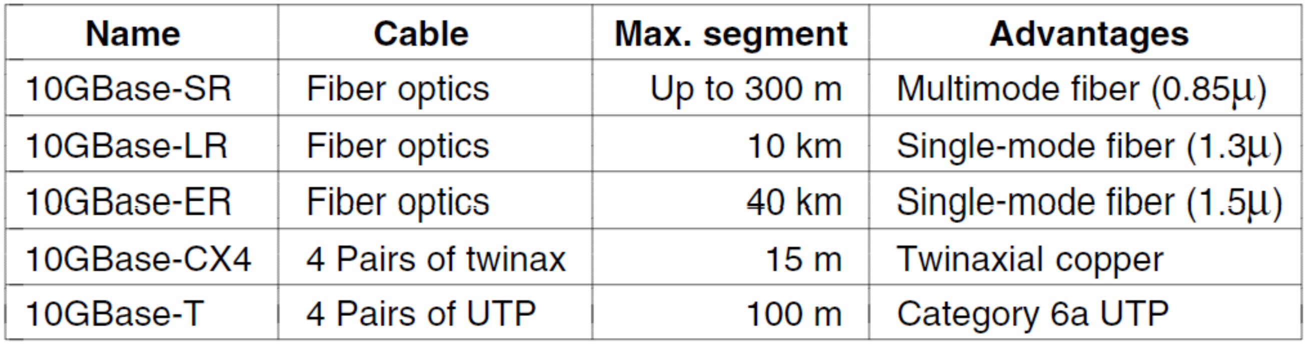
Gigabit / 10 Gigabit Ethernet (1)

- Gigabit Ethernet is commonly run over twisted pair



Name	Cable	Max. segment	Advantages
1000Base-SX	Fiber optics	550 m	Multimode fiber (50, 62.5 microns)
1000Base-LX	Fiber optics	5000 m	Single (10 µ) or multimode (50, 62.5 µ)
1000Base-CX	2 Pairs of STP	25 m	Shielded twisted pair
1000Base-T	4 Pairs of UTP	100 m	Standard category 5 UTP

- 10 Gigabit Ethernet is being deployed where needed



Name	Cable	Max. segment	Advantages
10GBase-SR	Fiber optics	Up to 300 m	Multimode fiber (0.85µ)
10GBase-LR	Fiber optics	10 km	Single-mode fiber (1.3µ)
10GBase-ER	Fiber optics	40 km	Single-mode fiber (1.5µ)
10GBase-CX4	4 Pairs of twinax	15 m	Twinaxial copper
10GBase-T	4 Pairs of UTP	100 m	Category 6a UTP

- 40/100 Gigabit Ethernet is under development

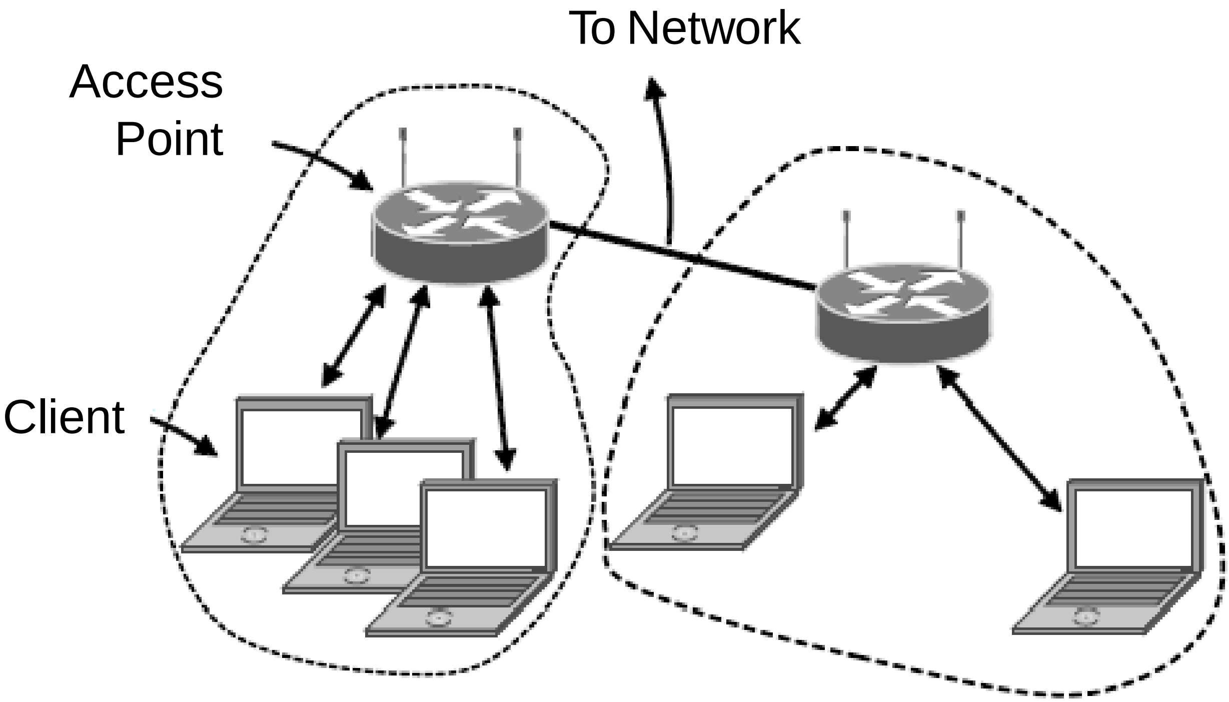
Wireless LANs

- 802.11 architecture/protocol stack »
- 802.11 physical layer »
- 802.11 MAC »
- 802.11 frames »

802.11 Architecture/Protocol Stack (1)

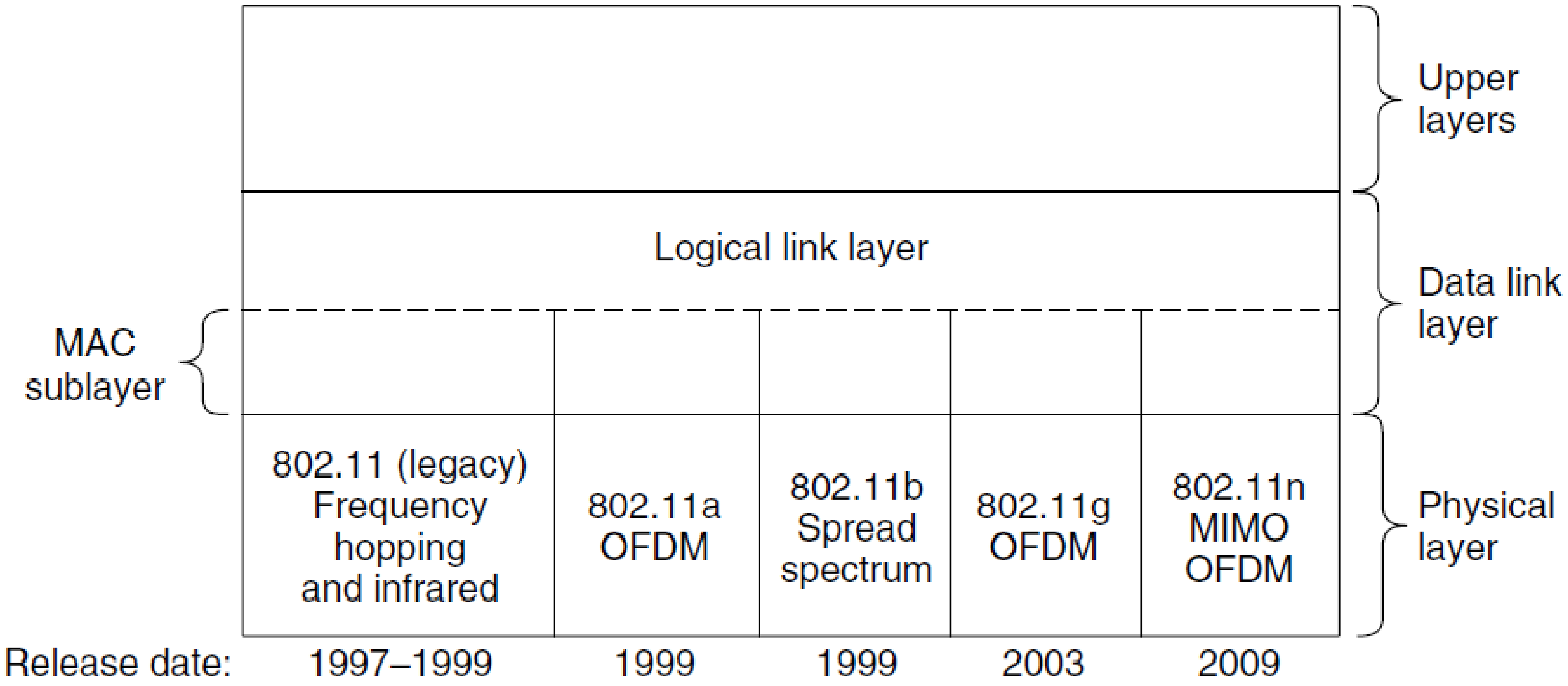
Wireless clients associate to a wired AP (Access Point)

- Called infrastructure mode; there is also ad-hoc mode with no AP, but that is rare.



802.11 Architecture/Protocol Stack (2)

MAC is used across different physical layers



Upper layers

Logical link layer

Data link layer

MAC sublayer

Physical layer

802.11 (legacy) Frequency hopping and infrared

802.11a OFDM

802.11b Spread spectrum

802.11g OFDM

802.11n MIMO OFDM

Release date: 1997–1999 1999 1999 2003 2009

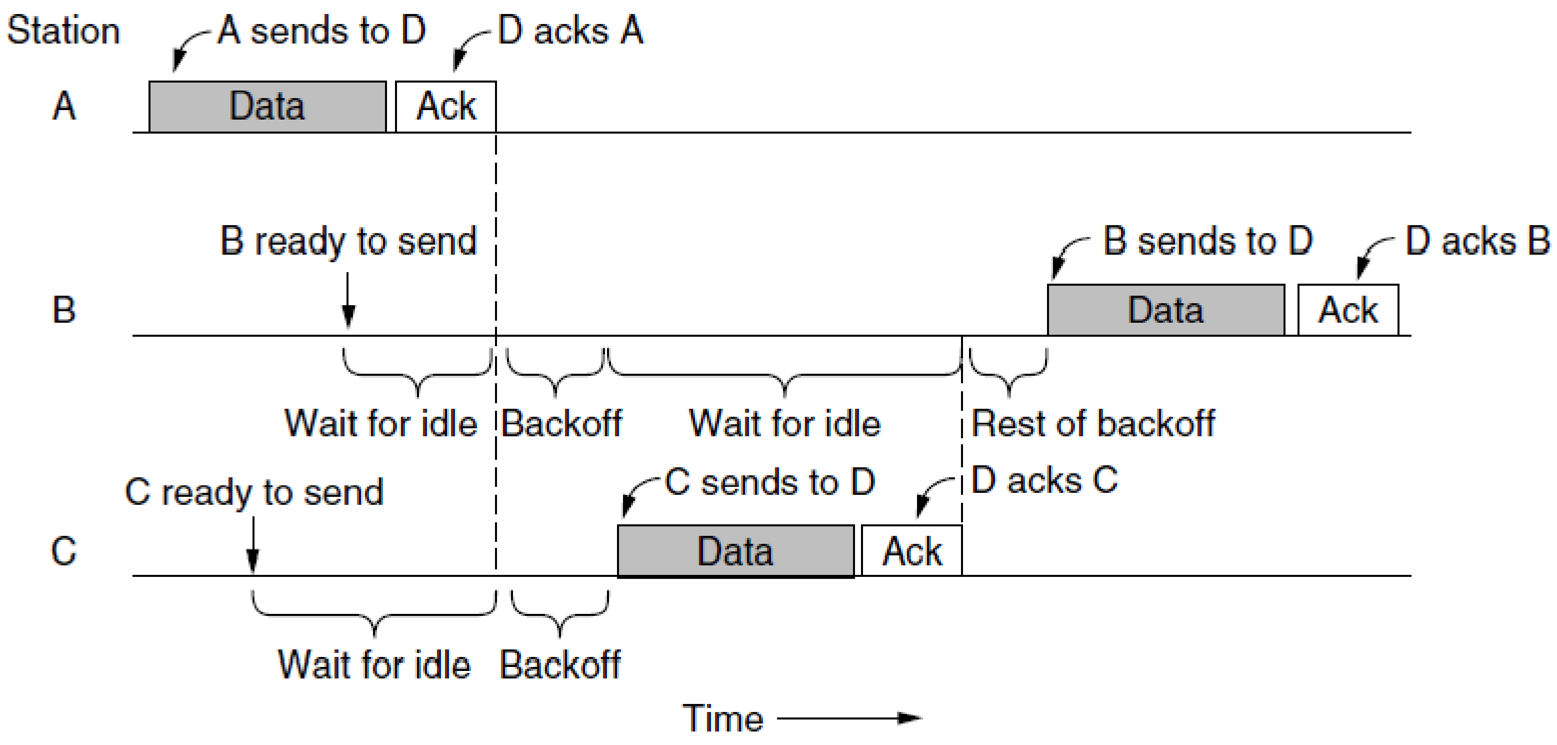
802.11 physical layer

- NICs are compatible with multiple physical layers
  - E.g., 802.11 a/b/g

Name	**Technique**	**Max. Bit Rate**
802.11b	Spread spectrum, 2.4 GHz	11 Mbps
802.11g	OFDM, 2.4 GHz	54 Mbps
802.11a	OFDM, 5 GHz	54 Mbps
802.11n	OFDM with MIMO, 2.4/5 GHz	600 Mbps

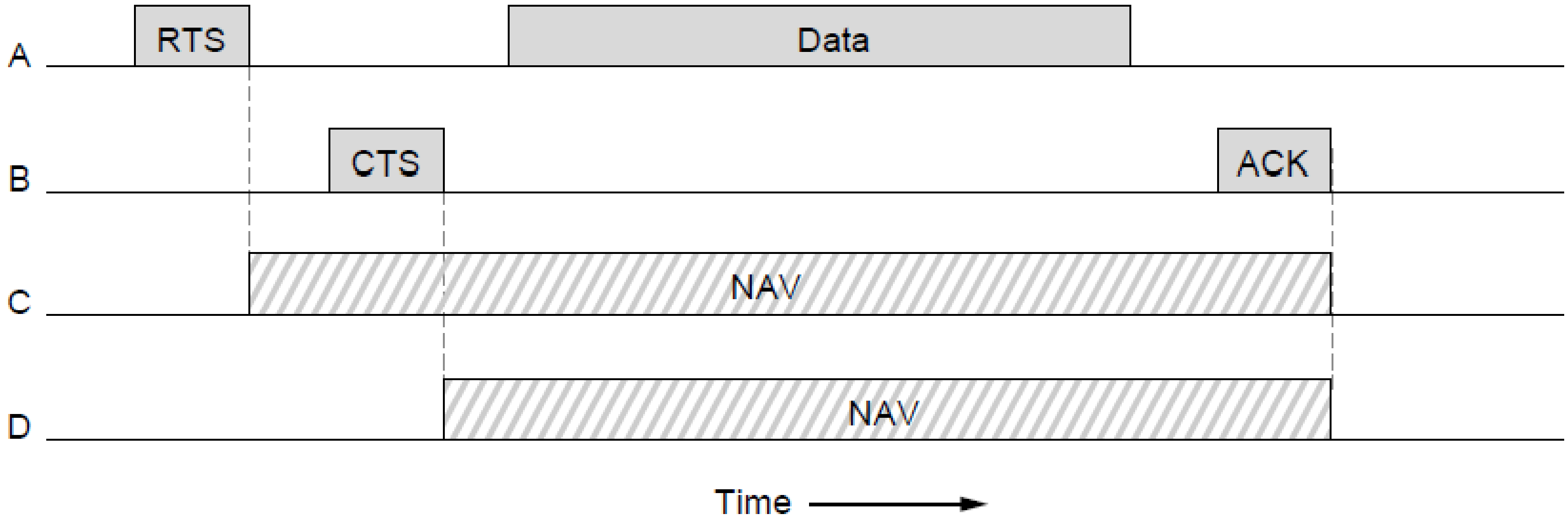
802.11 MAC (1)

- CSMA/CA inserts backoff slots to avoid collisions
- MAC uses ACKs/retransmissions for wireless errors



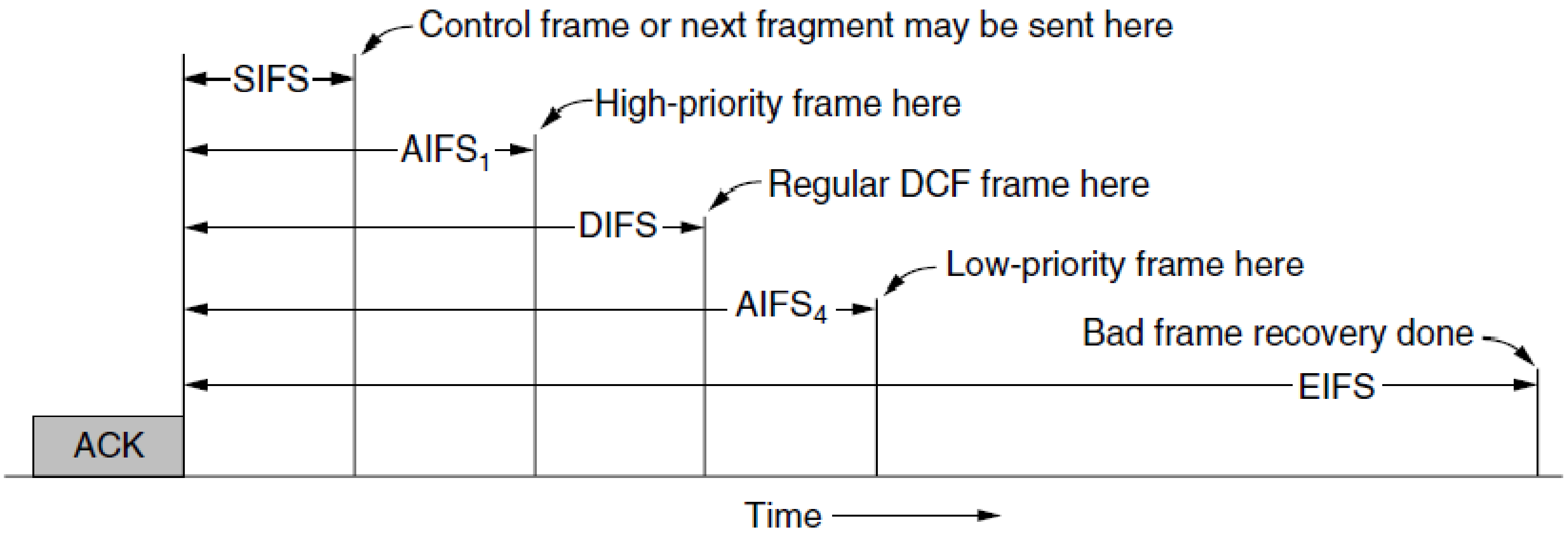
802.11 MAC (2)

Virtual channel sensing with the NAV and optional RTS/CTS (often not used) avoids hidden terminals



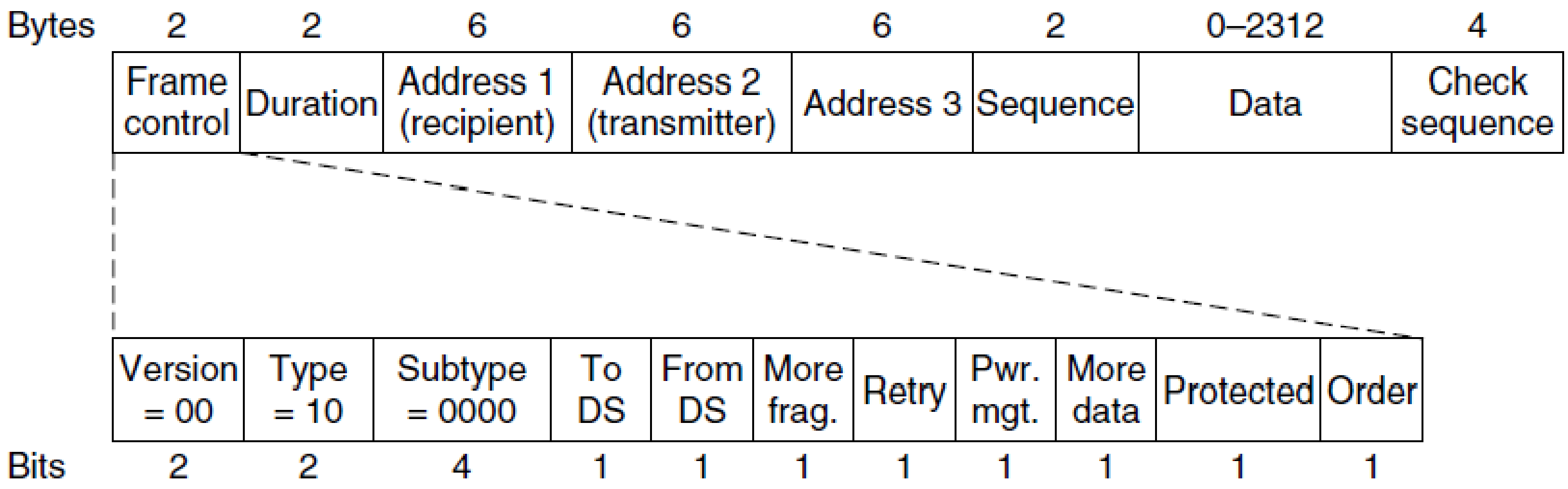
802.11 MAC (3)

- Different backoff slot times add quality of service
  - Short intervals give preferred access, e.g., control, VoIP
- MAC has other mechanisms too, e.g., power save



802.11 Frames

- Frames vary depending on their type (Frame control)
- Data frames have 3 addresses to pass via APs



Bytes	2	2	6	6	6	2	0–2312	4
	Frame control	Duration	Address 1 (recipient)	Address 2 (transmitter)	Address 3	Sequence	Data	Check sequence

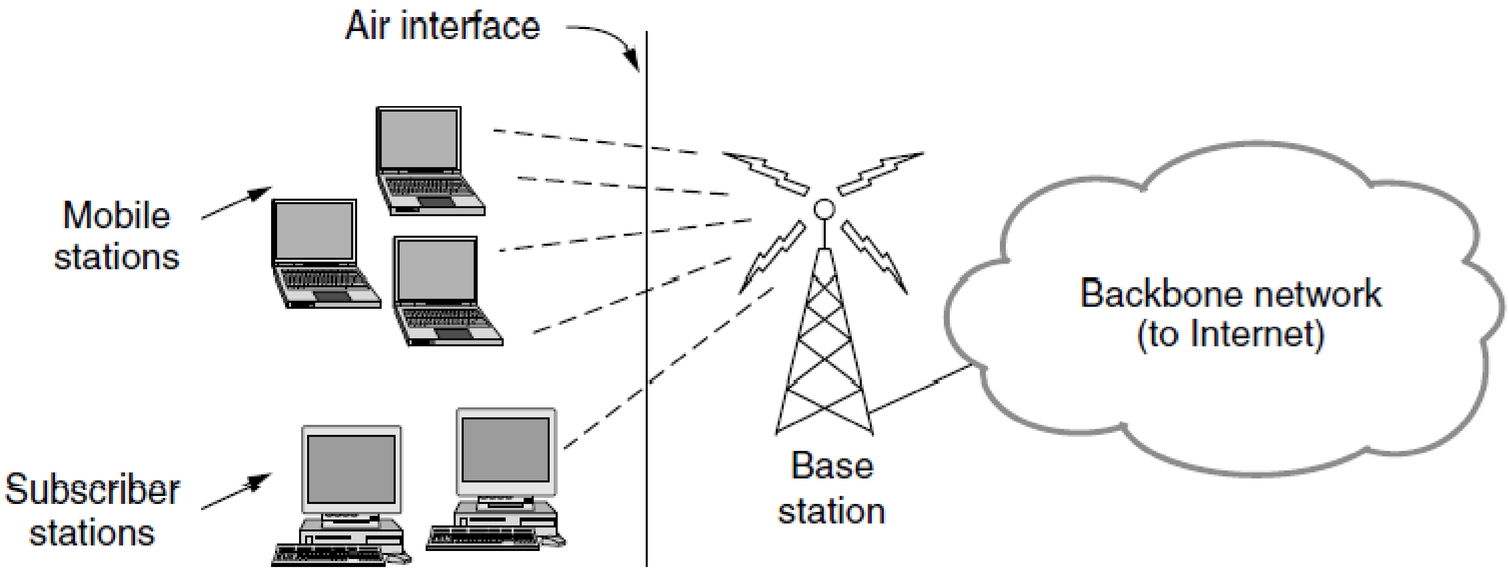
	Version = 00	Type = 10	Subtype = 0000	To DS	From DS	More frag.	Retry	Pwr. mgt.	More data	Protected	Order
Bits	2	2	4	1	1	1	1	1	1	1	1

Broadband Wireless

- 802.16 Architecture / Protocol Stack »
- 802.16 Physical Layer »
- 802.16 MAC »
- 802.16 Frames »

802.16 Architecture/Protocol Stack (1)

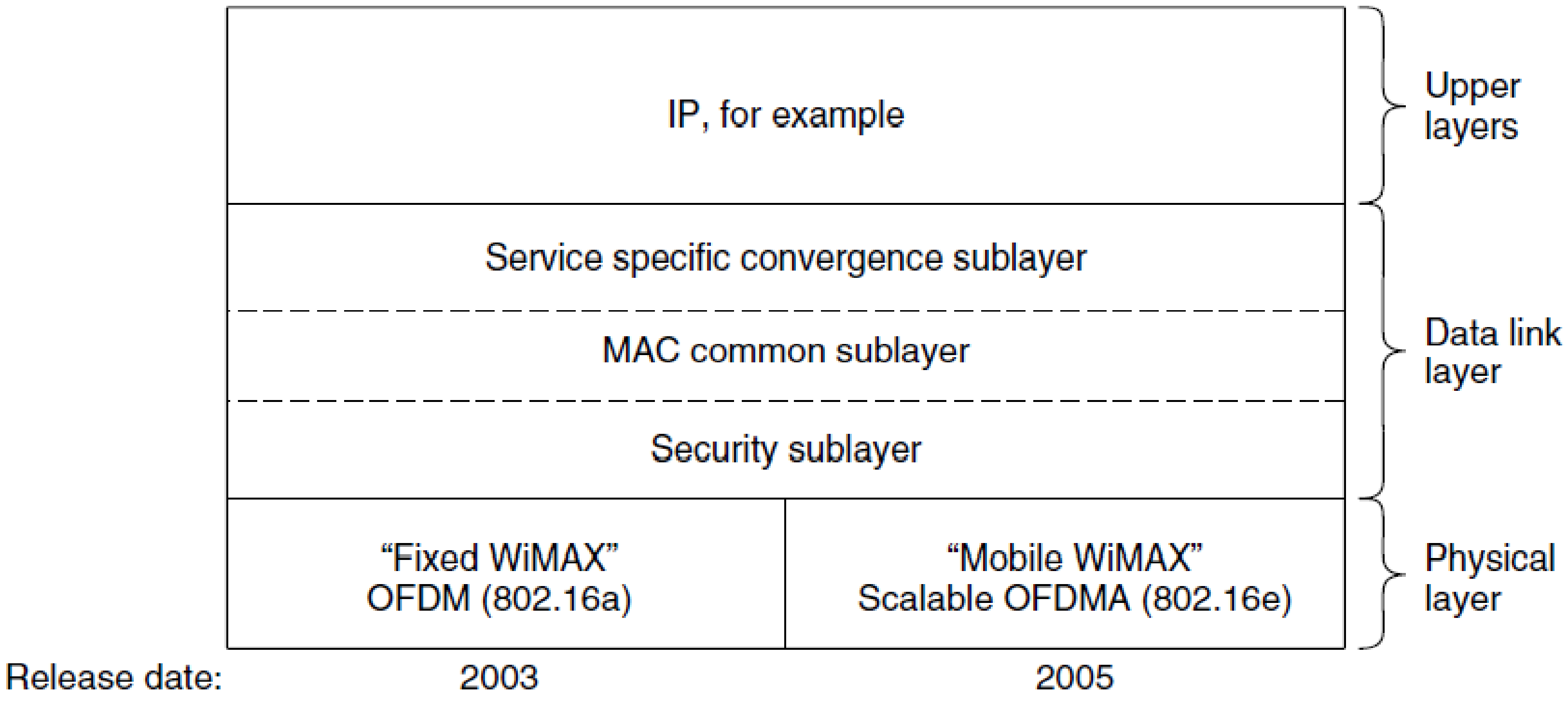
Wireless clients connect to a wired basestation (like 3G)



802.16 Architecture/Protocol Stack (2)

MAC is connection-oriented; IP is connectionless

- Convergence sublayer maps between the two



IP, for example

Upper layers

Service specific convergence sublayer

MAC common sublayer

Security sublayer

Data link layer

"Fixed WiMAX" OFDM (802.16a)

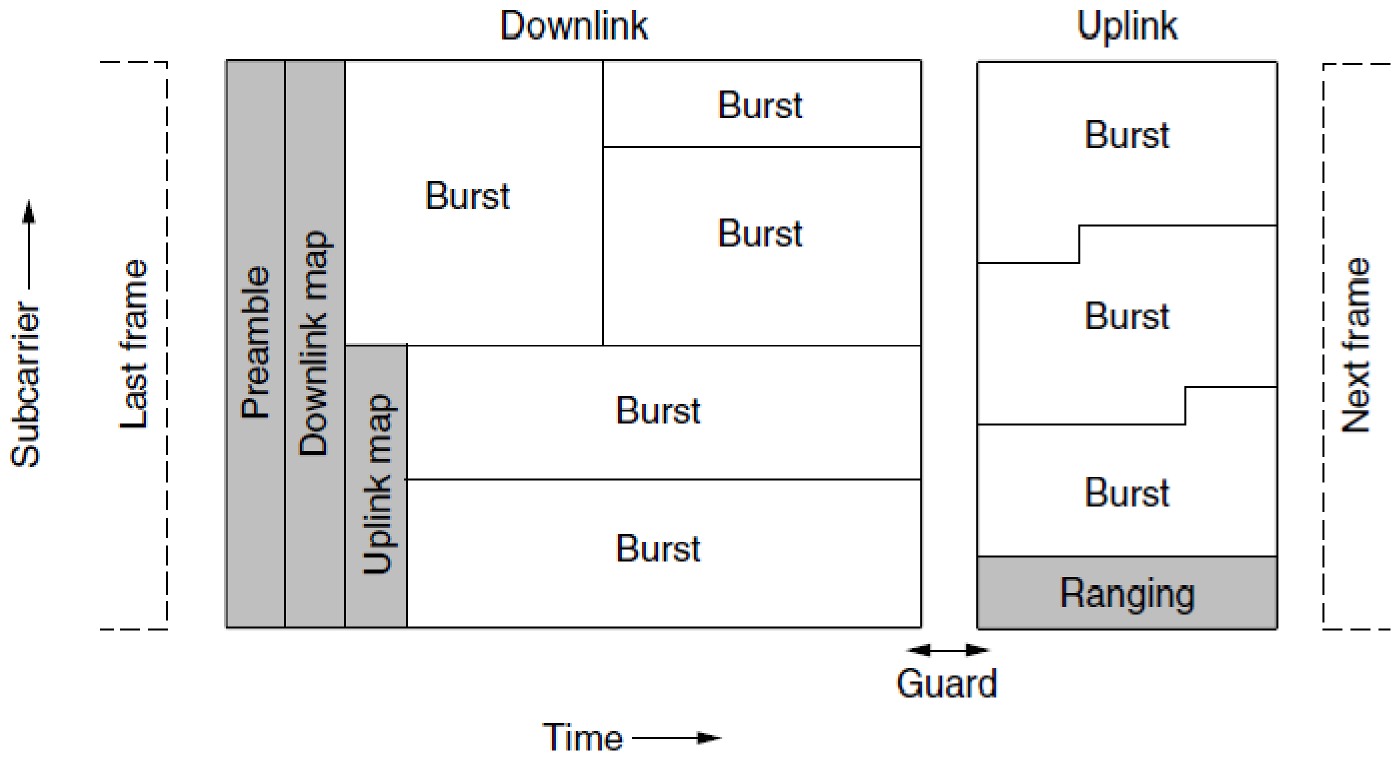
"Mobile WiMAX" Scalable OFDMA (802.16e)

Physical layer

Release date: 2003 2005

802.16 Physical Layer

Based on OFDM; base station gives mobiles bursts (subcarrier/time frame slots) for uplink and downlink



802.16 MAC

Connection-oriented with base station in control

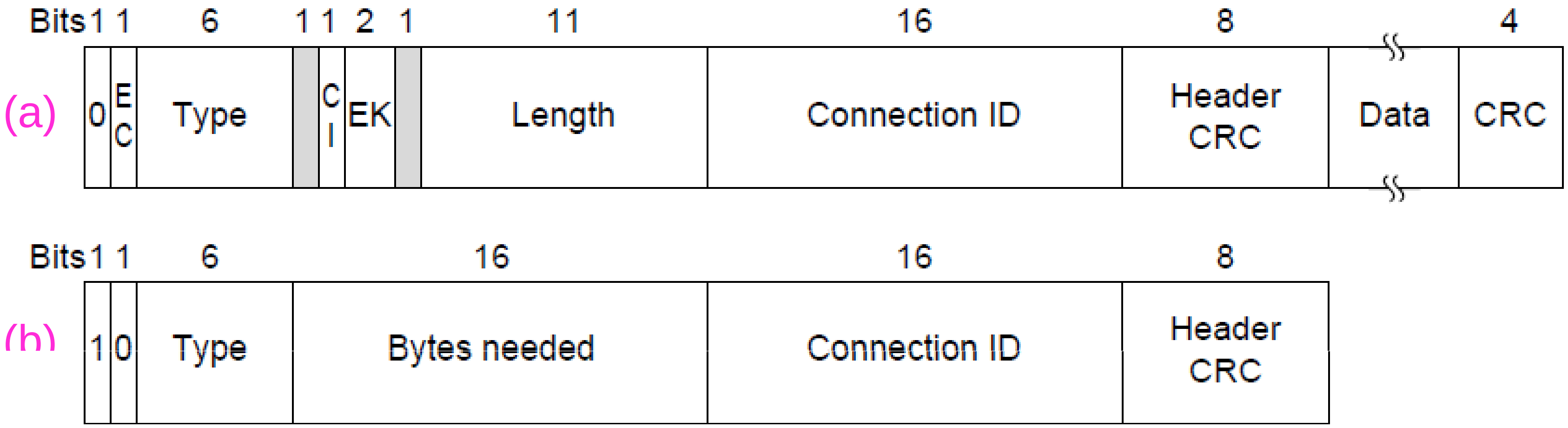
- Clients request the bandwidth they need

Different kinds of service can be requested:

- Constant bit rate, e.g., uncompressed voice
- Real-time variable bit rate, e.g., video, Web
- Non-real-time variable bit rate, e.g., file download
- Best-effort for everything else

802.16 Frames

- Frames vary depending on their type
- Connection ID instead of source/dest addresses



	Bits	1	1	6	1	1	2	1	11	16	8		4
(a)		0	EC	Type	▨	CI	EK	▨	Length	Connection ID	Header CRC	Data	CRC

	Bits	1	1	6	16	16	8
(b)		1	0	Type	Bytes needed	Connection ID	Header CRC

(a) A generic frame. (b) A bandwidth requestframe

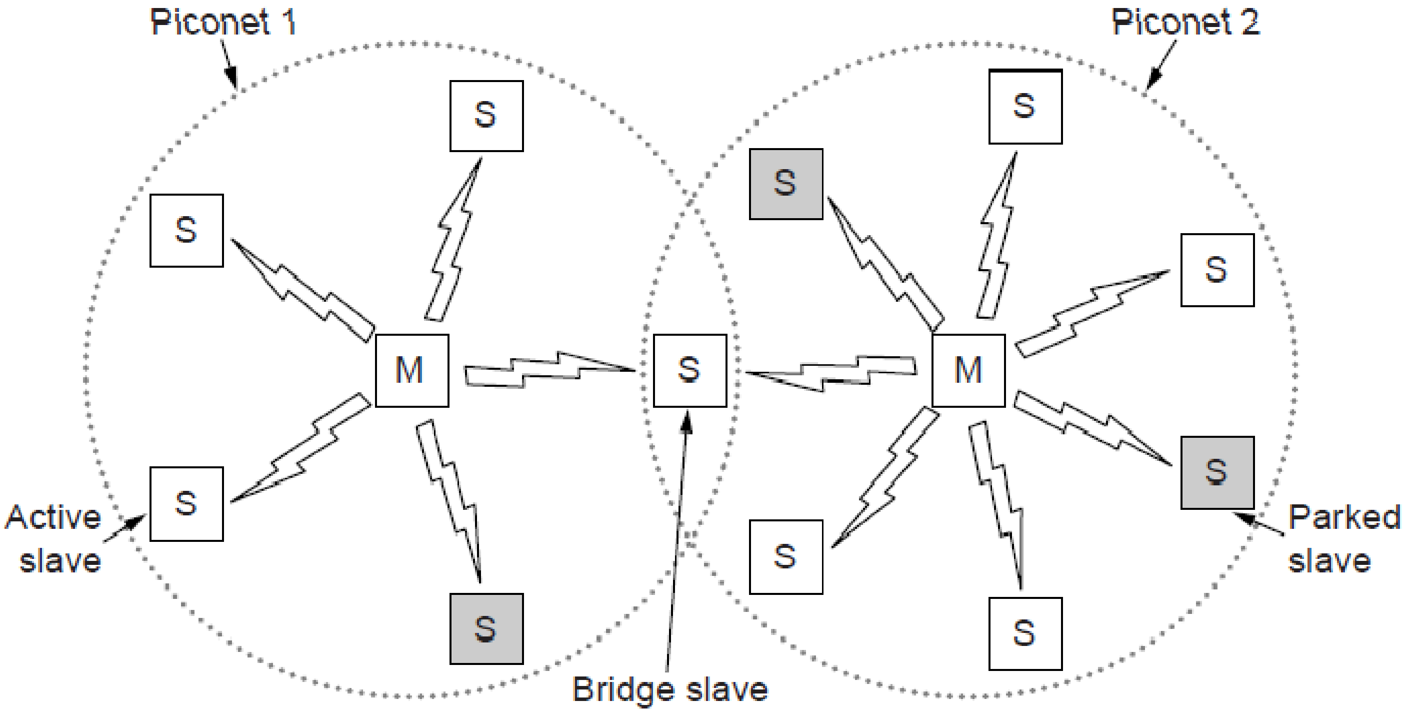
Bluetooth

- Bluetooth Architecture »
- Bluetooth Applications / Protocol »
- Bluetooth Radio / Link Layers »
- Bluetooth Frames »

Bluetooth Architecture

Piconet master is connected to slave wireless devices

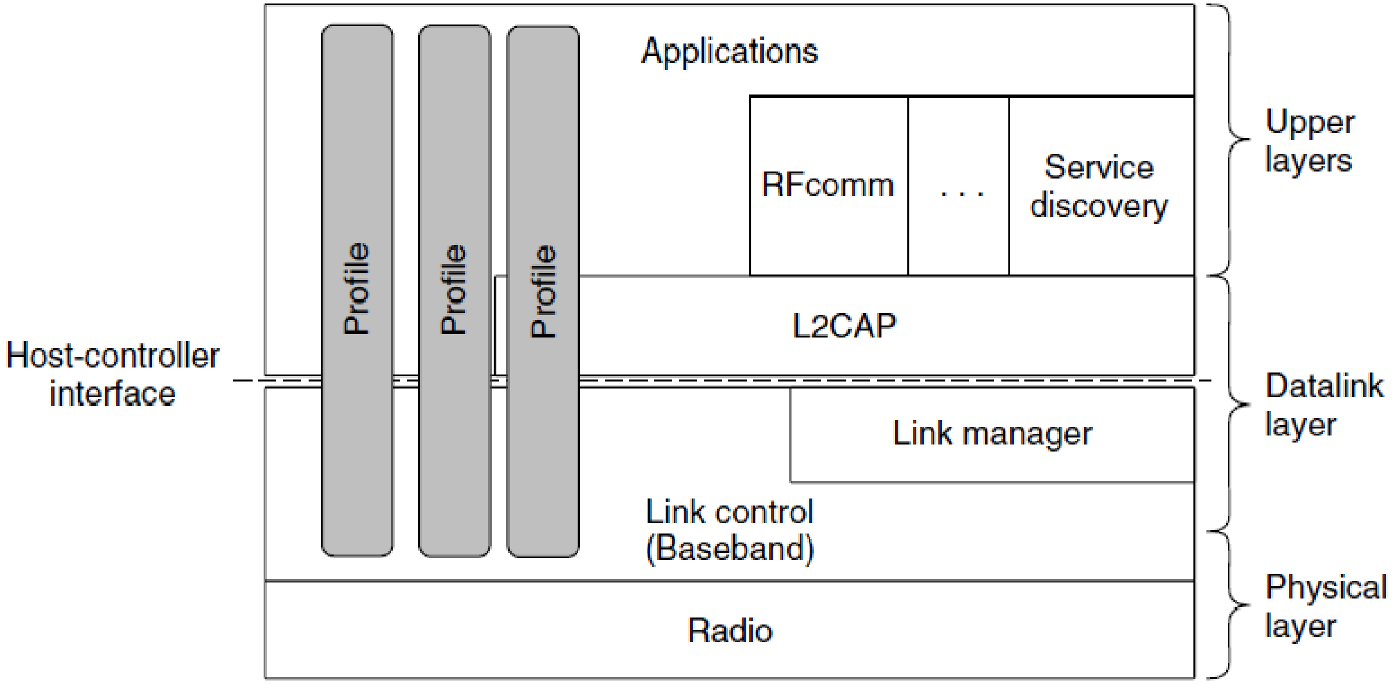
- Slaves may be asleep (parked) to save power
- Two piconets can be bridged into a scatternet



Bluetooth Applications / Protocol Stack

Profiles give the set of protocols for a given application

- 25 profiles, including headset, intercom, streaming audio, remote control, personal area network, …



Bluetooth Radio / Link Layers

Radio layer

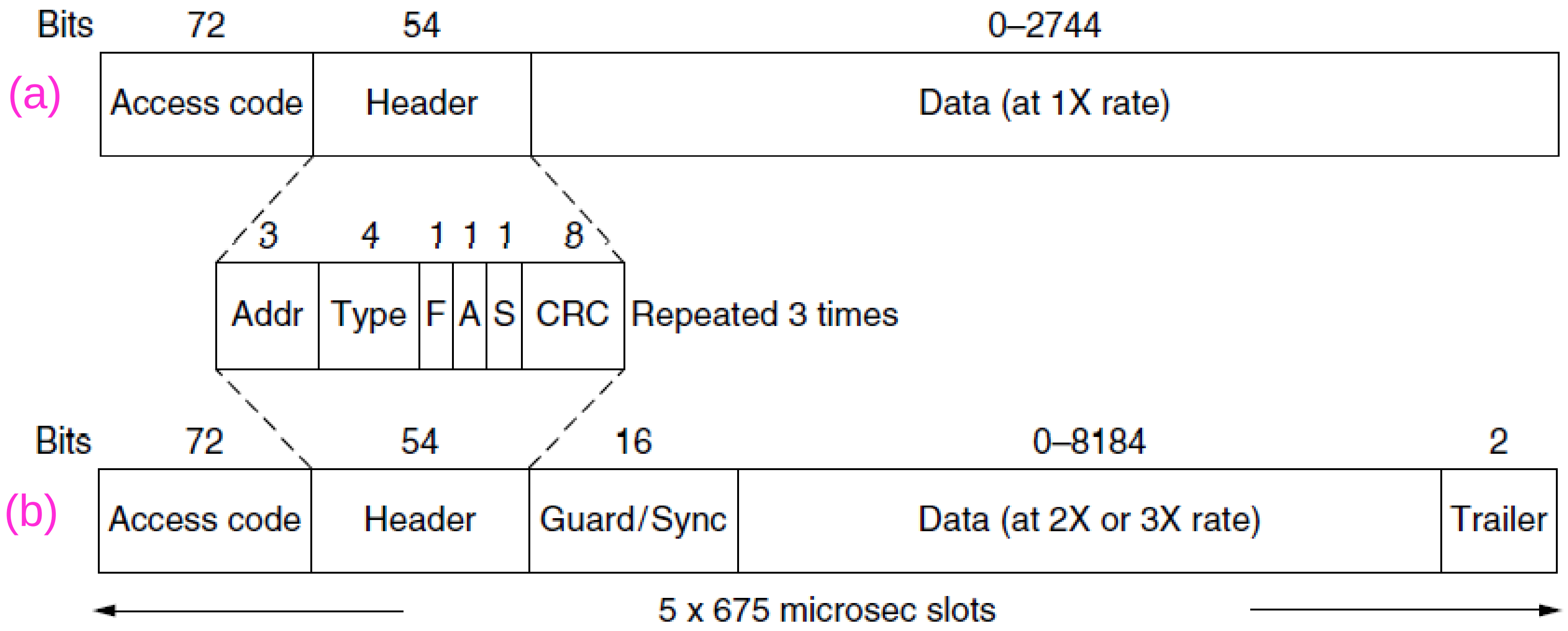
- Uses adaptive frequency hopping in 2.4 GHz band

Link layer

- TDM with timeslots for master and slaves
- Synchronous CO for periodic slots in each direction
- Asynchronous CL for packet-switched data
- Links undergo pairing (user confirms passkey/PIN) to authorize them before use

Bluetooth Frames

Time is slotted; enhanced data rates send faster but for the same time; addresses are only 3 bits for 8 devices



Bits	72	54	0–2744
(a)	Access code	Header	Data (at 1X rate)

3	4	1	1	1	8	
Addr	Type	F	A	S	CRC	Repeated 3 times

Bits	72	54	16	0–8184	2
(b)	Access code	Header	Guard/Sync	Data (at 2X or 3X rate)	Trailer

5 x 675 microsec slots

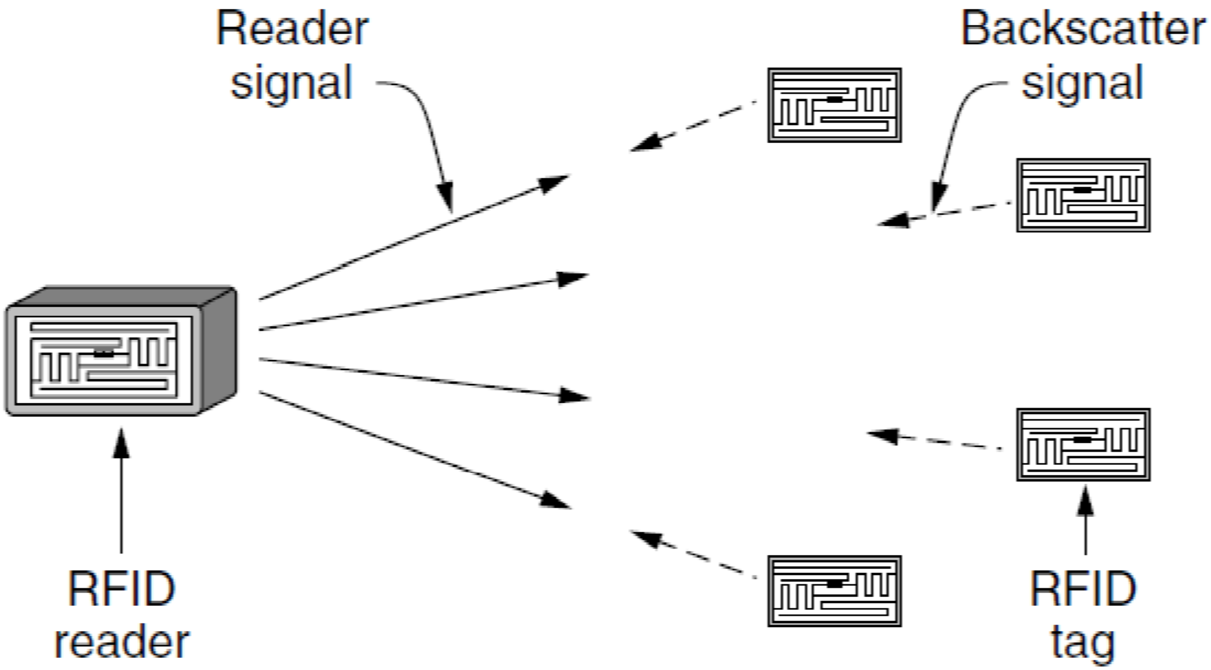
(a) Basic rate data frame (b) Enhanced rate data frame

RFID

- Gen 2 Architecture »
- Gen 2 Physical Layer »
- Gen 2 Tag Identification Layer »
- Gen 2 Frames »

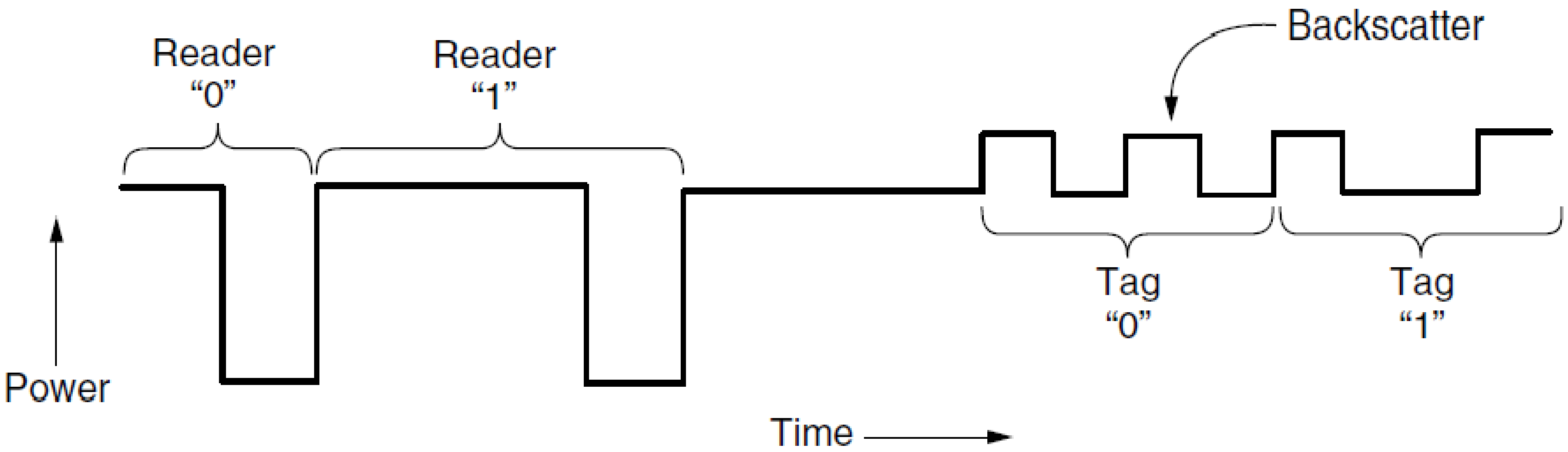
Gen 2 Architecture

Reader signal powers tags; tags reply with backscatter



Gen 2 Physical Layer

- Reader uses duration of on period to send 0/1
- Tag backscatters reader signal in pulses to send 0/1



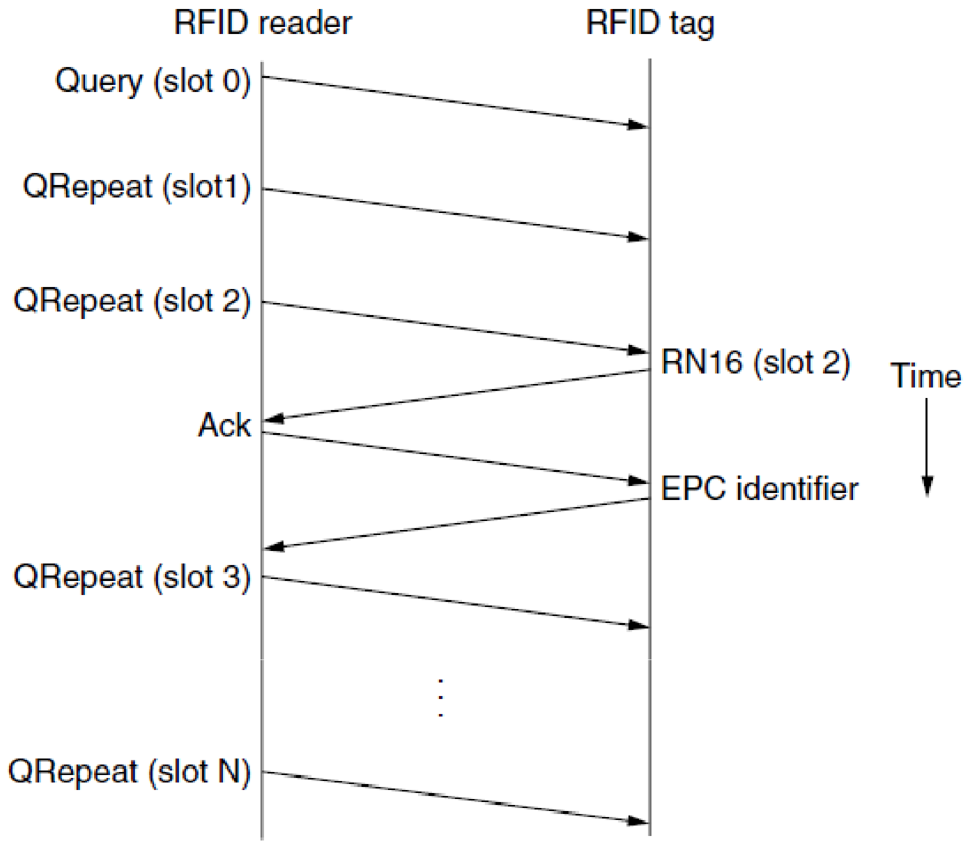
Gen 2 Tag Identification Layer

Reader sends query and sets slot structure

Tags reply (RN16) in a random slot; may collide

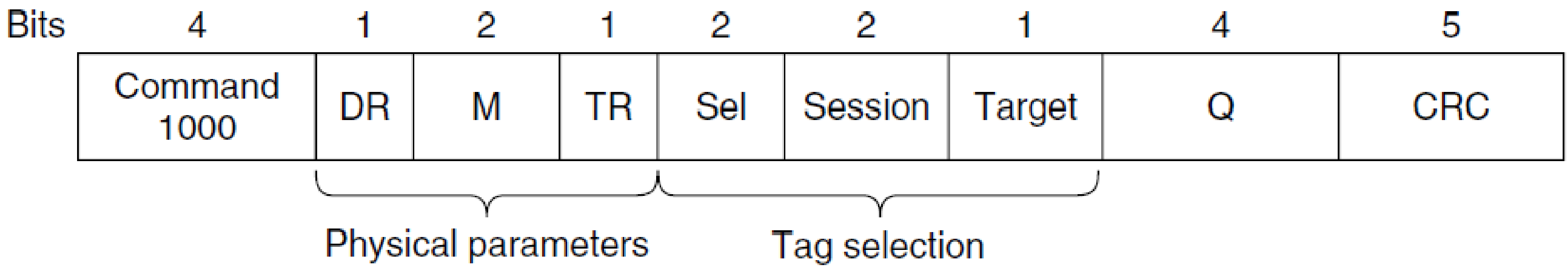
Reader asks one tag for its identifier (ACK)

Process continues until no tags are left



Gen 2 Frames

- Reader frames vary depending on type (Command)
  - Query shown below, has parameters and error detection
- Tag responses are simply data
  - Reader sets timing and knows the expected format



Bits	4	1	2	1	2	2	1	4	5
	Command 1000	DR	M	TR	Sel	Session	Target	Q	CRC

Query message

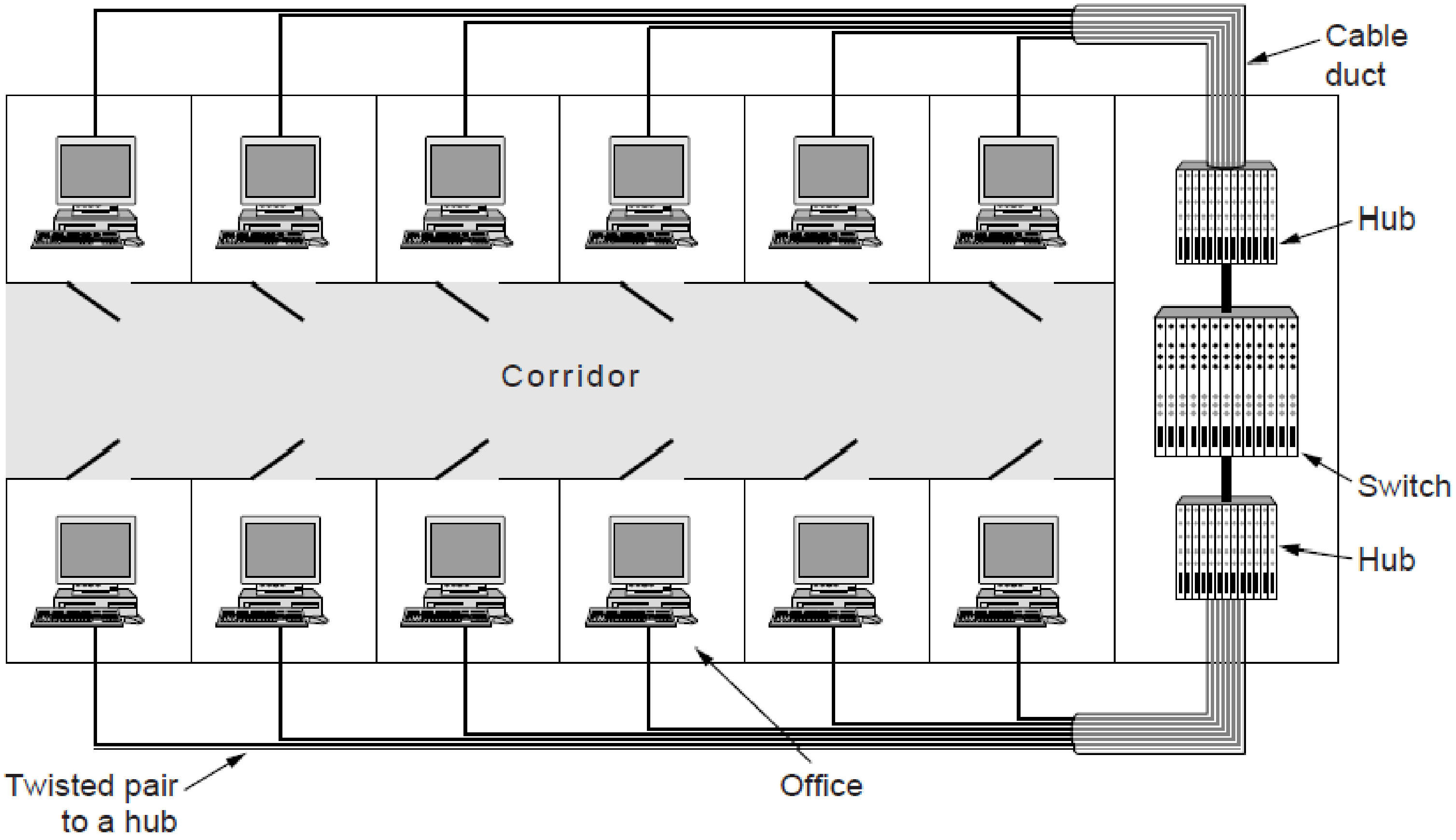
Data Link Layer Switching

- Uses of Bridges »
- Learning Bridges »
- Spanning Tree »
- Repeaters, hubs, bridges, .., routers, gateways »
- Virtual LANs »

Uses of Bridges

Common setup is a building with centralized wiring

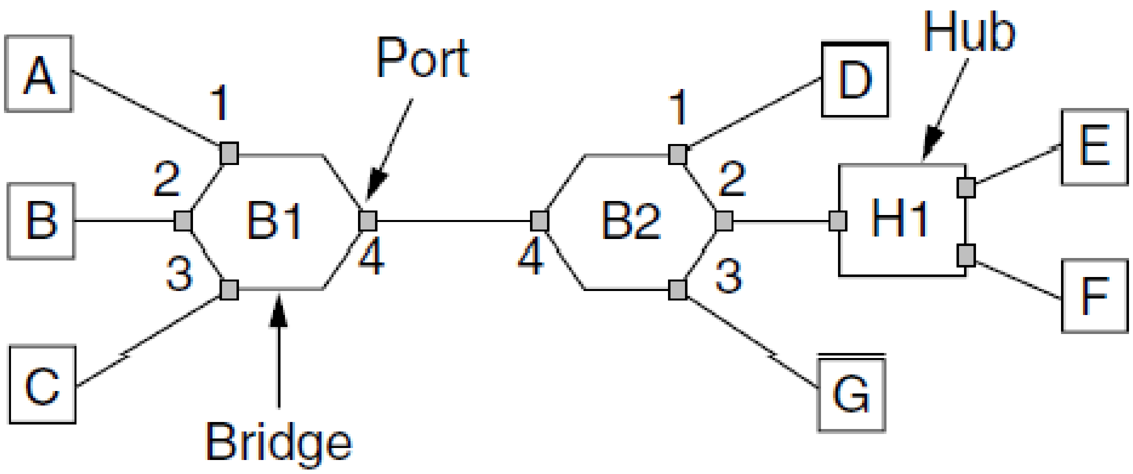
- Bridges (switches) are placed in or near wiring closets



Learning Bridges (1)

A bridge operates as a switched LAN (not a hub)

- Computers, bridges, and hubs connect to its ports



Learning Bridges (2)

Backward learning algorithm picks the output port:

- Associates source address on frame with input port
- Frame with destination address sent to learned port
- Unlearned destinations are sent to all other ports

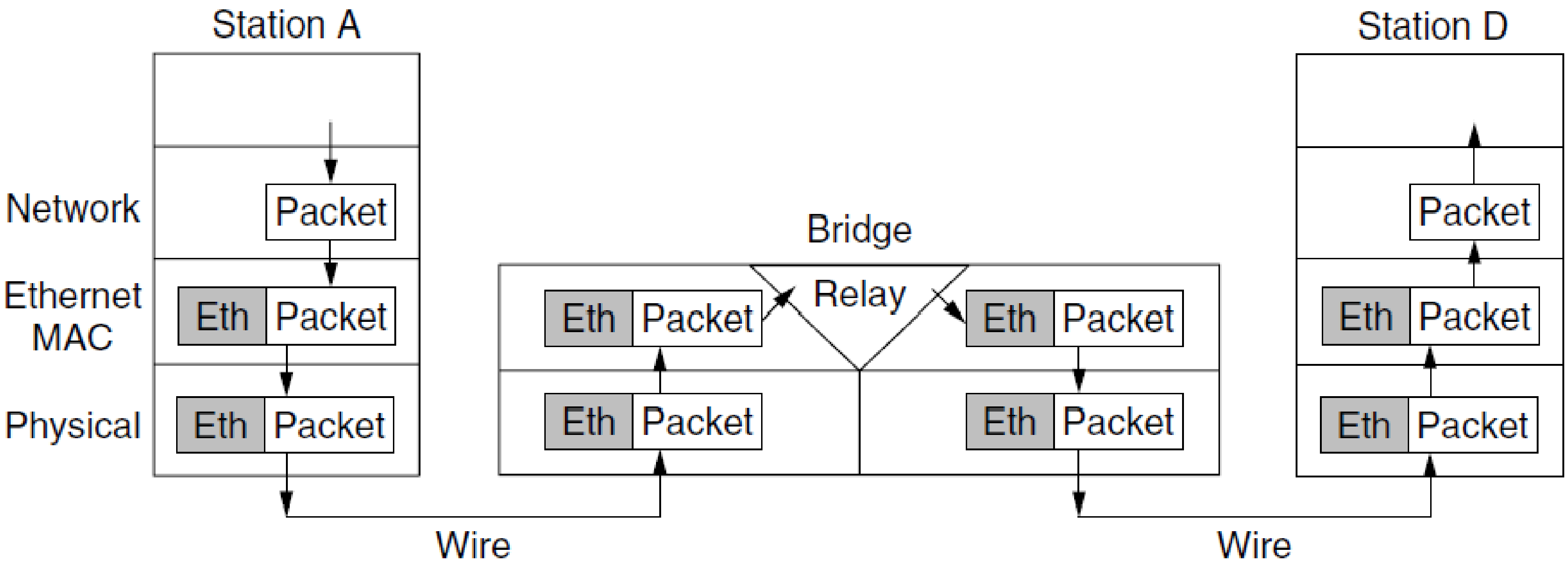
Needs no configuration

- Forget unused addresses to allow changes
- Bandwidth efficient for two-way traffic

Learning Bridges (3)

Bridges extend the Link layer:

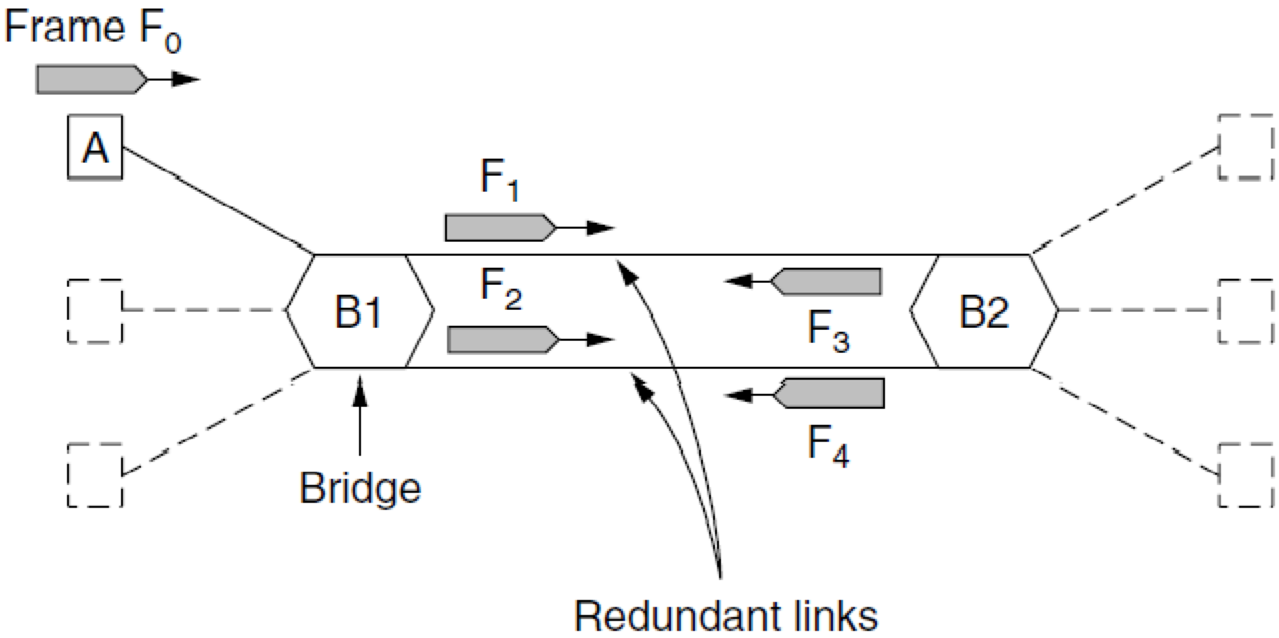
- Use but don’t remove Ethernet header/addresses
- Do not inspect Network header



Spanning Tree (1) – Problem

Bridge topologies with loops and only backward learning will cause frames to circulate for ever

- Need spanning tree support to solve problem



Spanning Tree (2) – Algorithm

- Subset of forwarding ports for data is use to avoid loops
- Selected with the spanning tree distributed algorithm by Perlman

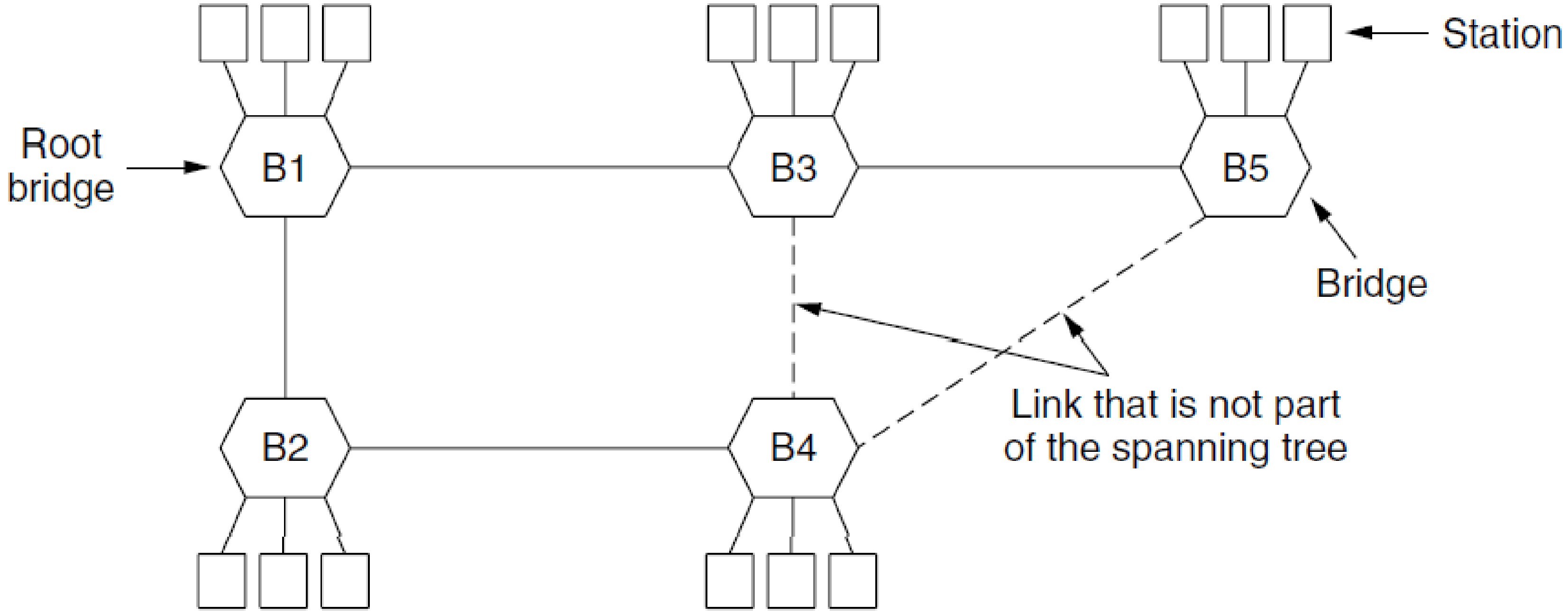
I think that I shall never see
A graph more lovely than a tree.
A tree whose crucial property
Is loop-free connectivity.
A tree which must be sure to span.
So packets can reach every LAN.
First the Root must be selected
By ID it is elected.
Least cost paths from Root are traced
In the tree these paths are placed.
A mesh is made by folks like me
Then bridges find a spanning tree.

– Radia Perlman, 1985.

Spanning Tree (3) – Example

After the algorithm runs:

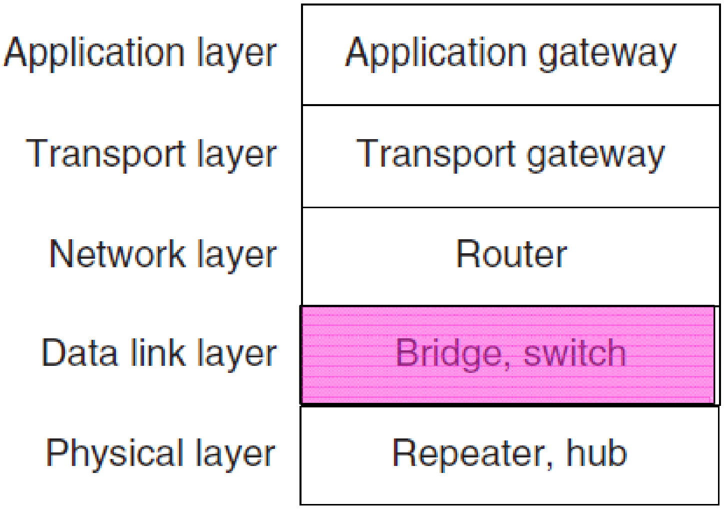
- B1 is the root, two dashed links are turned off
- B4 uses link to B2 (lower than B3 also at distance 1)
- B5 uses B3 (distance 1 versus B4 at distance 2)



Repeaters, Hubs, Bridges, Switches, Routers, & Gateways

Devices are named according to the layer they process

- A bridge or LAN switch operates in the Link layer

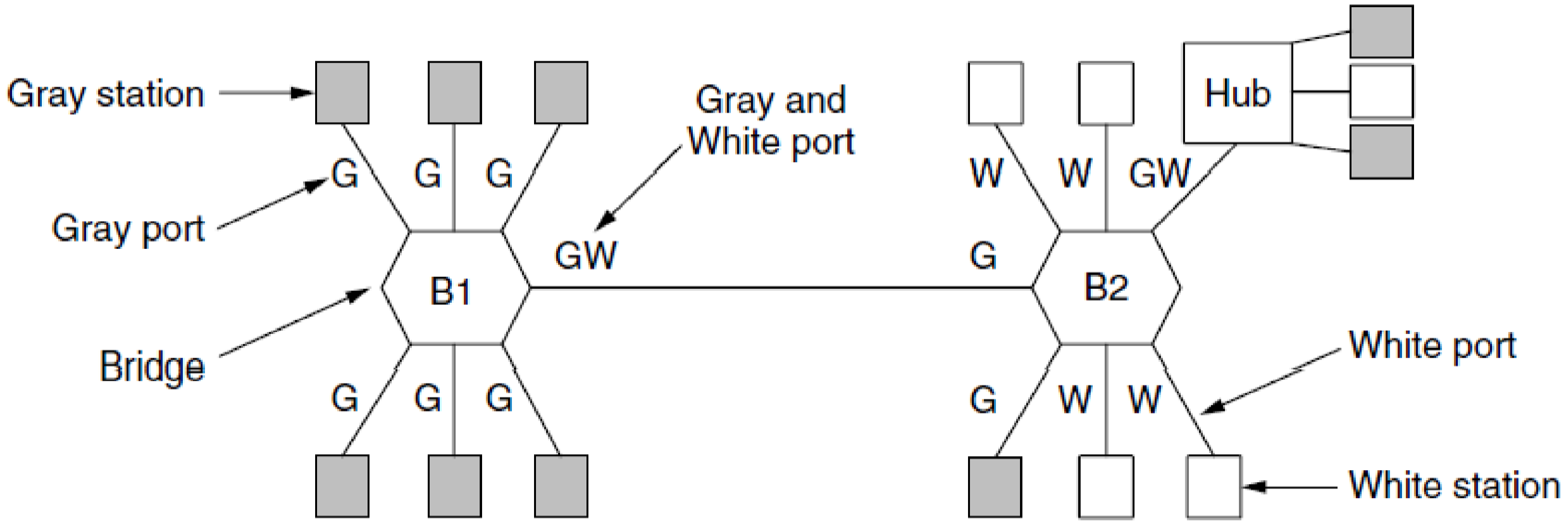


Application layer	Application gateway
Transport layer	Transport gateway
Network layer	Router
Data link layer	Bridge, switch
Physical layer	Repeater, hub

Virtual LANs (1)

VLANs (Virtual LANs) splits one physical LAN into multiple logical LANs to ease management tasks

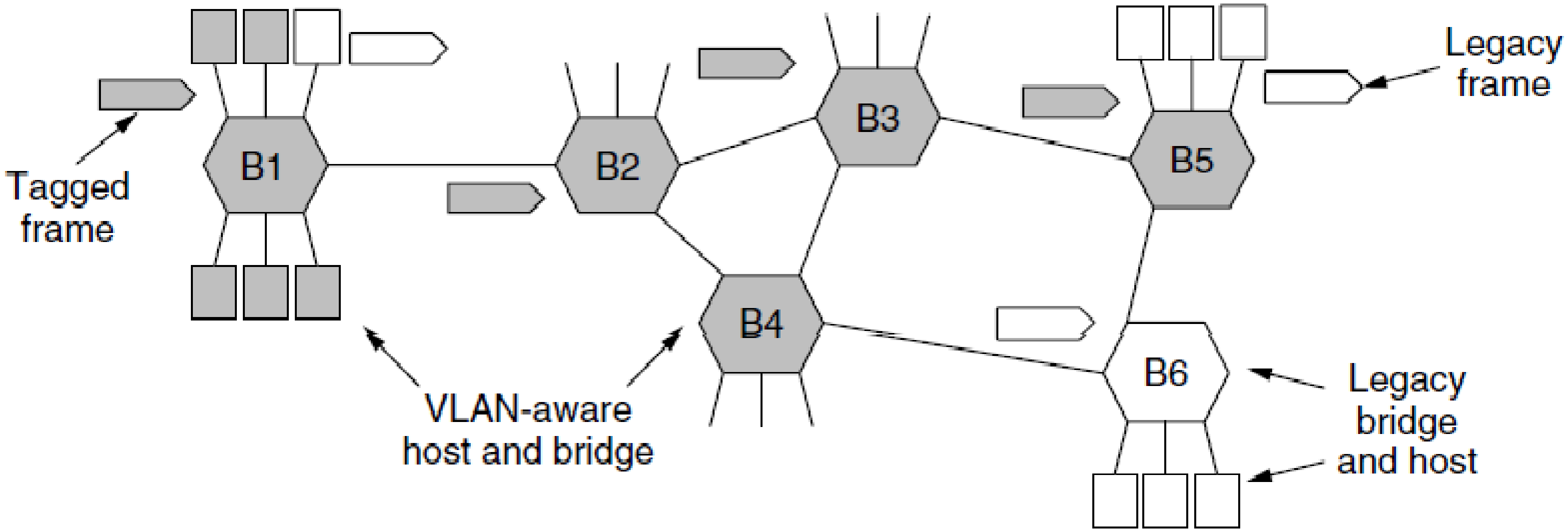
- Ports are “colored” according to their VLAN



Virtual LANs (2) – IEEE 802.1Q

Bridges need to be aware of VLANs to support them

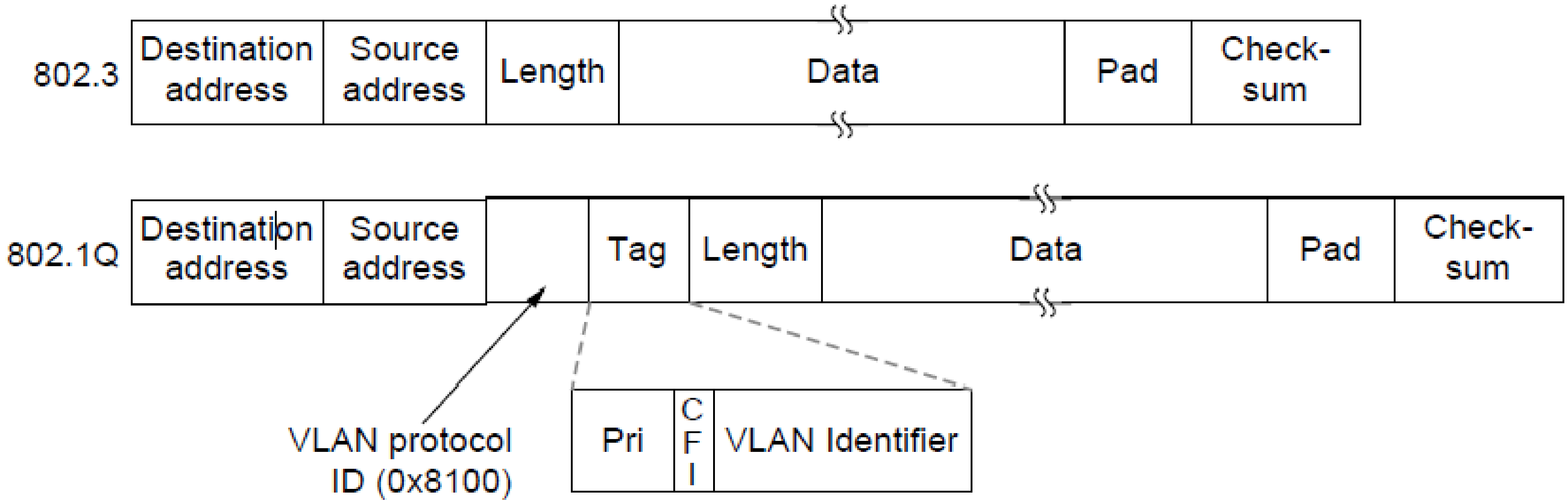
- In 802.1Q, frames are tagged with their “color”
- Legacy switches with no tags are supported



Virtual LANs (3) – IEEE 802.1Q

802.1Q frames carry a color tag (VLAN identifier)

- Length/Type value is 0x8100 for VLAN protocol



End

Chapter 4