NANJING UNIVERSITY

Computer Networks

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Material with thanks to James F. Kurose, Mosharaf Chowdhury, and other colleagues.

Chapter 2. Link Layer

- Link Layer Service
  - Framing
  - Link access
  - Reliable delivery
  - Error detection and correction
- Local Area Network (LAN)
  - Token Ring
  - Ethernet
- Medium access control (Cont.)
- Bridges and Layer-2 switch
- Wireless Networks

Performance of MAC

Performance Metric

- Media Utilization
  - Time used for frame transmission vs. time the shared media is occupied

$$U = \frac{\text{Time for frame transmission}}{\text{total time for a frame}}$$

- Relative Propagation Time

$$a = \frac{\text{propagation time}}{\text{transmission time}} \quad or$$

$$a = \frac{\text{length of the data path (in bits)}}{\text{length of a standard frame (in bits)}}$$

Different Networks

- Contention free
  - Point-to-Point Link
  - Ring LAN

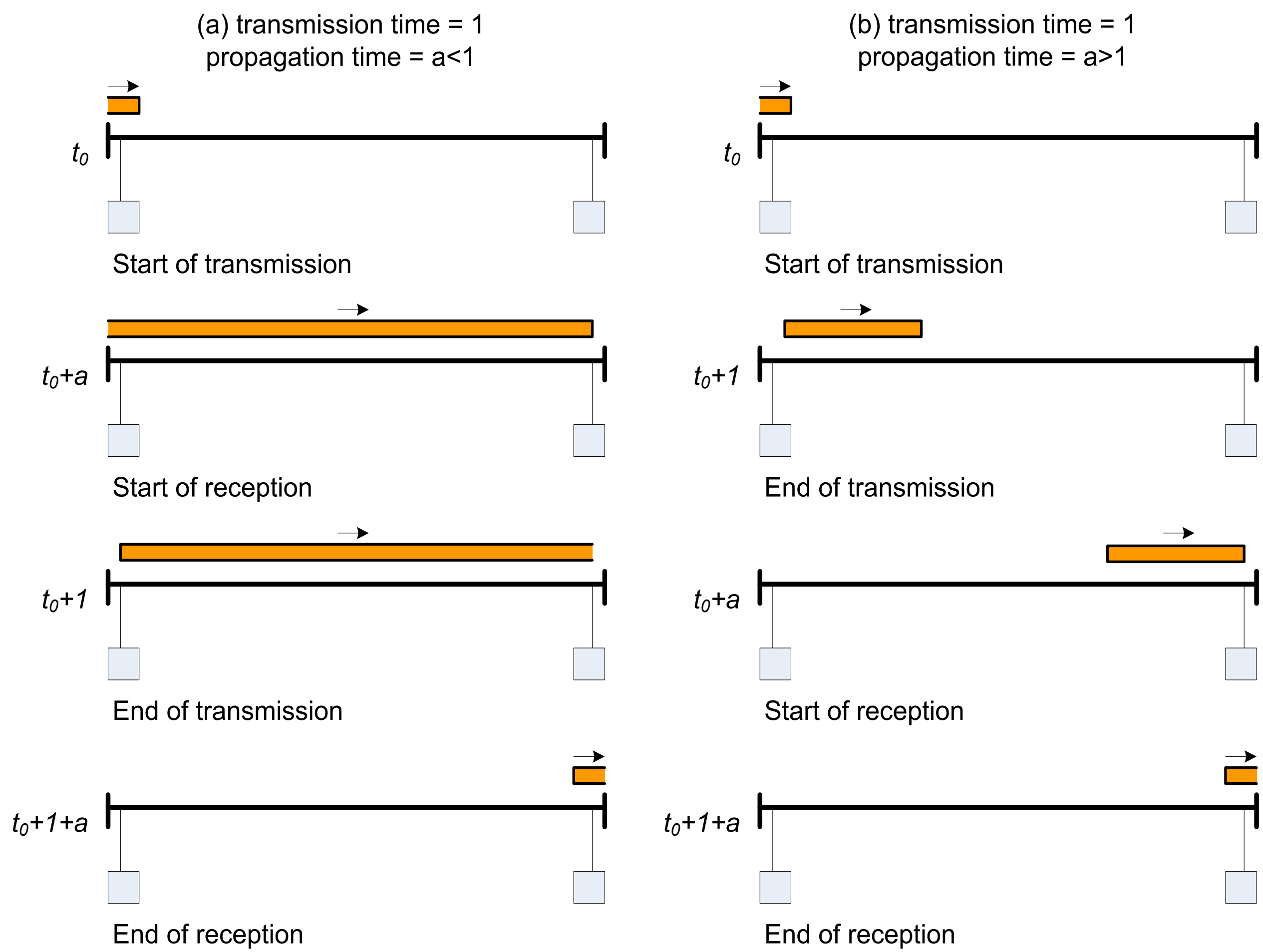
- Random access
  - ALOHA, slotted ALOHA
  - CSMA/CD

Point-to-Point Link with No ACK

$$U = \frac{\text{Time for frame transmission}}{\text{total time for a frame}}$$

Large frame

Small frame



Define

1: normalized frame transmission time

a: end to end propagation delay

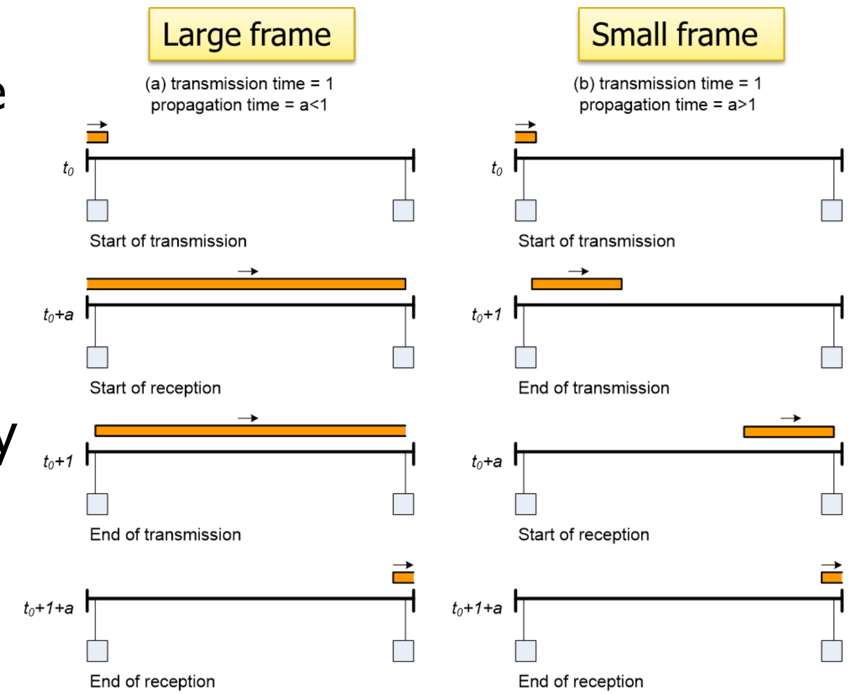
N: number of stations

Q:
Max Utilization U=?

Max Utilization for Point-to-Point Link

- Parameters and assumptions
  - 1: normalized frame transmission time
  - a: end to end propagation delay
  - N: number of stations
- Each station has frames to transmit
- Total frame time=transmission delay + propagation delay: $1+a$
- Max Utilization:

$$U = \frac{1}{1+a}$$

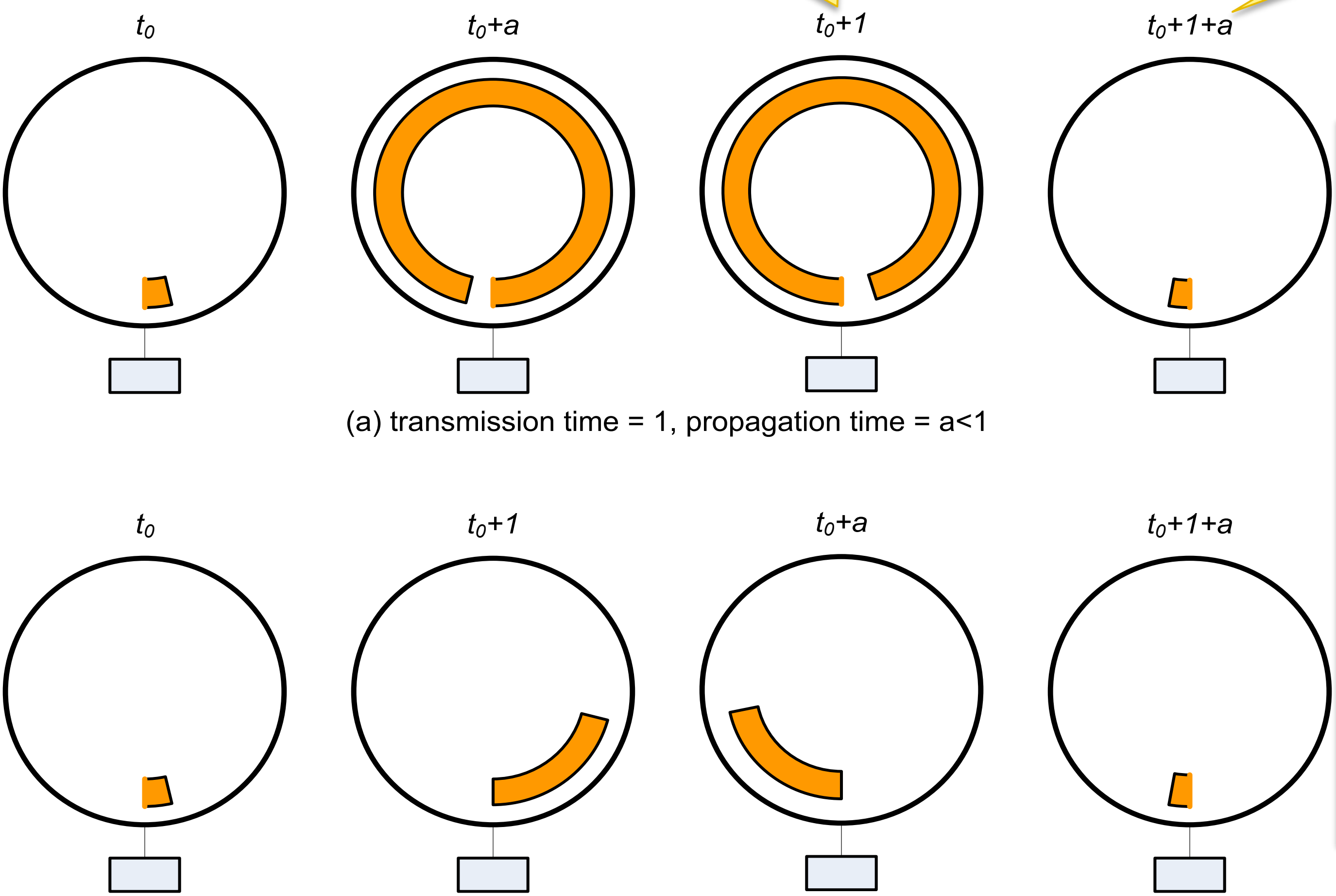


$$U = \frac{\text{Time for frame transmission}}{\text{total time for a frame}}$$

Ring

Token is released at t_0+1, and it will arrive the next station at t_0+1+a/N (next transmission starts).

End of the previous transmission at t_0+1+a.



(a) transmission time = 1, propagation time = a<1

(b) transmission time = 1, propagation time = a>1

Define:

T_1 : Average time to transmit a frame, i.e. $T_1 = 1$

T_2 : Average time to pass the token after frame transmission

N: number of stations

Q:

Max Utilization: $U = ?$

Token is released at t_0+a, and it will arrive the next station at t_0+a+a/N (next transmission starts).

End of the previous transmission at t_0+1+a.

Max Utilization for Ring LAN

- Define
  - T_1 : Average time to transmit a frame, i.e. $T_1 = 1$
  - T_2 : Average time to pass the token after frame transmission
- Max Utilization: $U = T_1/(T_1+T_2)$

2 cases

- Case 1: $a<1$ (frame longer than ring)
  - T_2 = time to pass token to the next station = a/N
- Case 2: $a>1$ (frame shorter than ring)
  - T_2 = sender wait for frame returns after transmission = $a-1+a/N$

$$U = \begin{cases} \dfrac{1}{1+a/N} & a<1 \\ \dfrac{1}{a+a/N} & a>1 \end{cases}$$

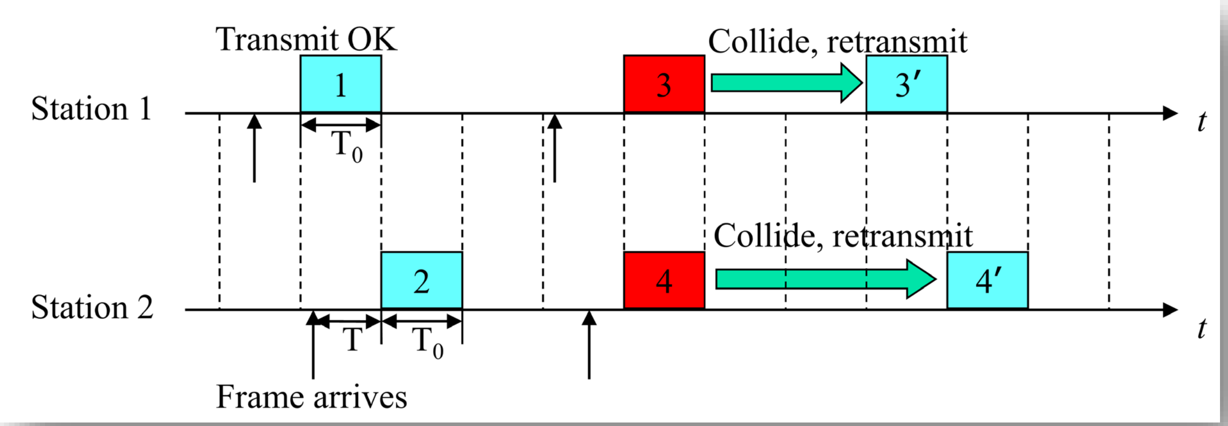
Slotted ALOHA

- All frames have same size
- Time is uniformly slotted
- Nodes are synchronized
- Transmission begins at slot boundary
- Frames either miss or overlap totally

Operation:

- N nodes with many frames to send
- Each transmits in each slot with probability p until success

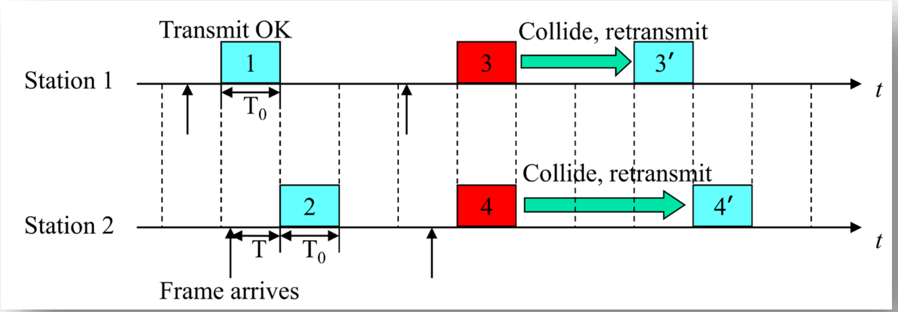
- Q:
- Max Utilization: $U = ?$



Slotted ALOHA

- Suppose:
  - N nodes with many frames to send, each transmits in slot with probability p
- Probability of successful transmission
  - One node has success in a slot $= p(1-p)^{N-1}$
  - Any node has a success $A = Np(1-p)^{N-1}$
- Maximize value of A (let A'(p)=0)

$$p = \frac{1}{N} \Longrightarrow A = \left(1 - \frac{1}{N}\right)^{N-1}$$



Slotted ALOHA Efficiency

- Utilization if a slot is successfully used

$$U_s = \frac{1}{1+2a} \approx 1 \quad (a \ll 1)$$

Before data transmission, it takes a to detect collision;
After transmission, it takes a to make sure the transmission of the last bit

- Since A is the rate of success slot

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

$$U = U_s \times A \approx \left(1 - \frac{1}{N}\right)^{N-1}$$

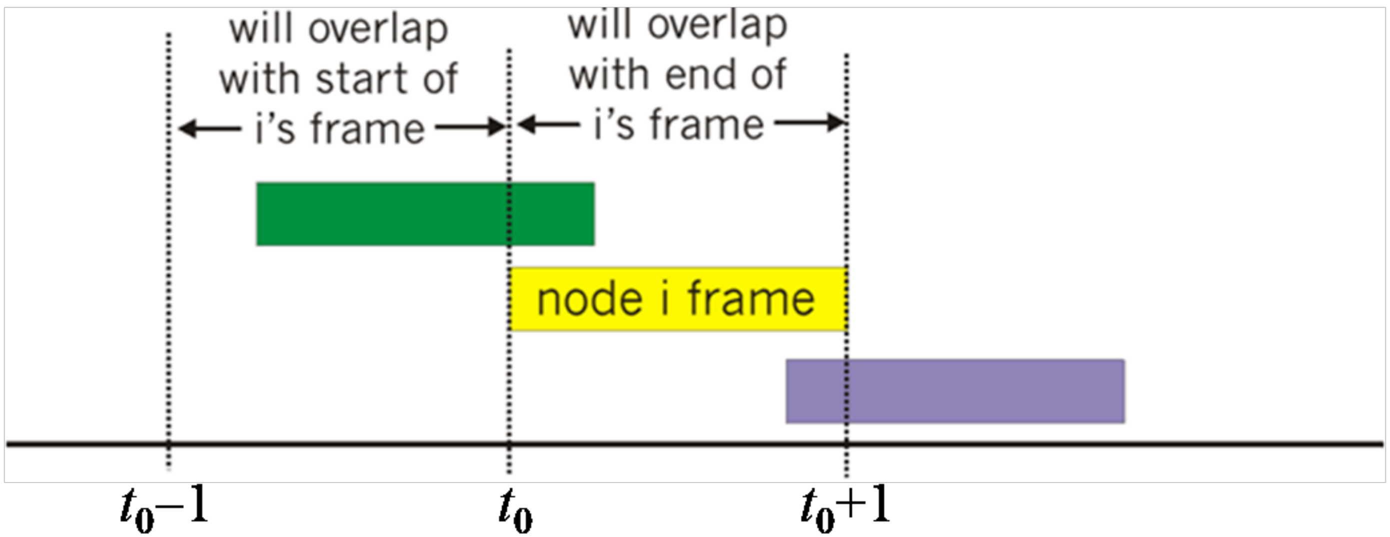
Let $N \to \infty$

$$U \approx e^{-1} = 0.367879$$

$$\lim_{x\to\infty}(1-\frac{1}{x})^x = e^{-1}$$

Pure ALOHA

- Simpler but collision probability increases
  - Frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



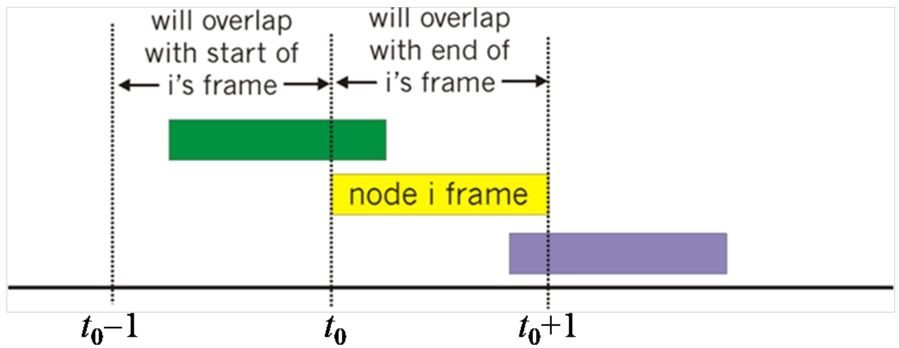
Suppose:

N nodes with many frames to send, each transmits in any time with probability p

Q: Max Utilization: $U=?$

Pure ALOHA Efficiency

- Probability of successful transmission



$$A = N \cdot P(\text{one transmits in the slot}) \cdot$$
$$P(\text{no other node transmits in } [t_{0-1}, t_0] \cdot$$
$$P(\text{no other node transmits in } [t_0, t_{0+1}]$$
$$U \approx A = Np \cdot (1-p)^{2N-1}$$
$$\approx \frac{1}{2}(1 - \frac{1}{2N})^{2N-1} \quad (p = \frac{1}{2N})$$
$$\approx 1/(2e) = 0.183940 \quad (N \to \infty)$$

CSMA/CD

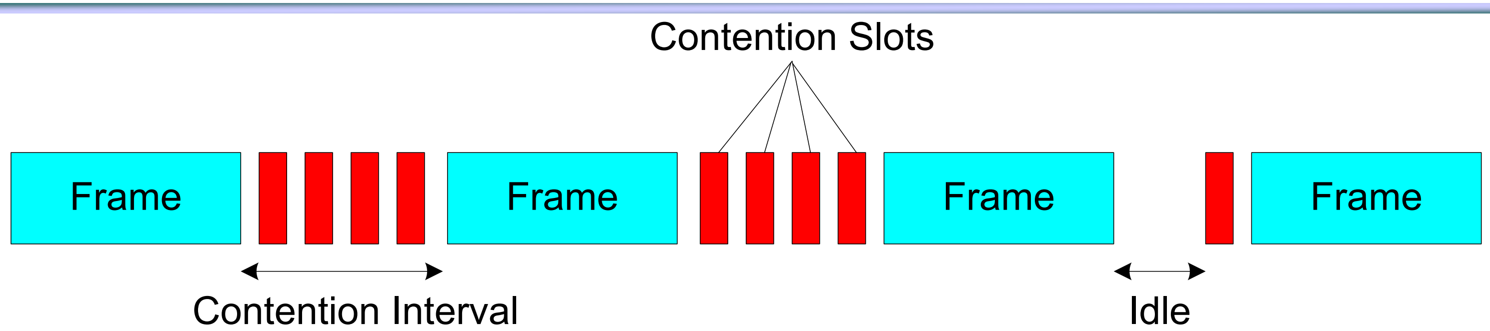
- With CSMA, collision occupies medium for duration of transmission
  - Colliding transmissions aborted once detected

- Stations listen whilst transmitting

1. If medium idle, transmit; otherwise, step 2
2. If busy, listen for idle, then transmit immediately

3. If collision detected, send jam signal then abort
4. After jam, wait random time then start from step 1

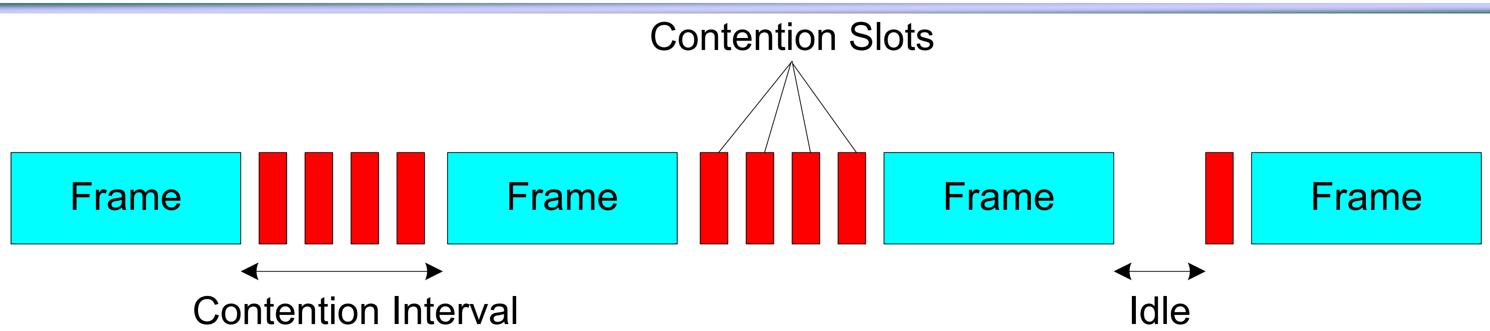
CSMA/CD (p-persistent): Max Utilization



- Contention slots end in a collision
- Contention interval is a sequence of contention slots
  - Length of a slot in contention interval is $2a$

    (in worst case it takes $2a$ time to detect contention)
- Assume p-persistent:
  - The probability that a station attempts to transmit in a slot is p
- Q: Max Utilization: $U = ?$

Max Utilization for CSMA/CD (1)



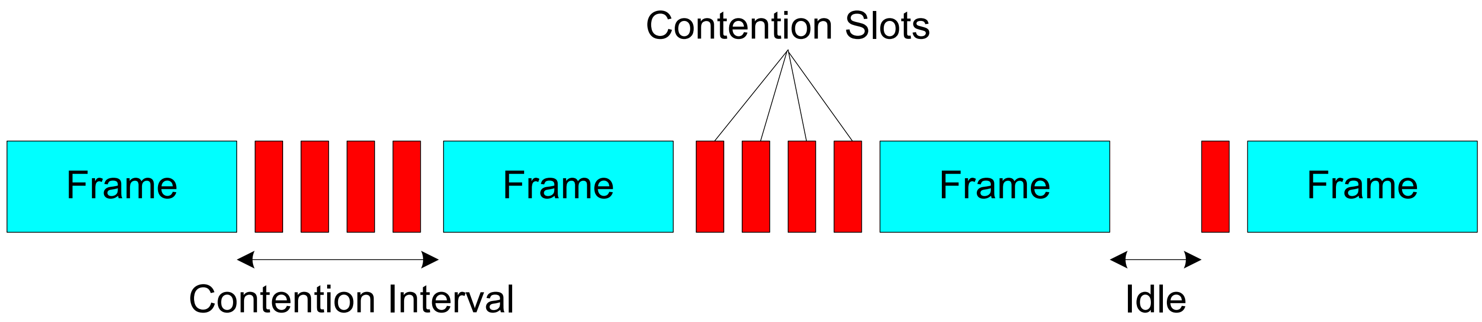
- Let A be the probability that some station can successfully transmit in a slot, then:

$$A = \binom{N}{1} p^1 (1-p)^{N-1} = Np(1-p)^{N-1}$$

- In above formula, A is maximized when $p=1/N$, thus:

$$A = \left(1 - \frac{1}{N}\right)^{N-1}$$

Max Utilization for CSMA/CD (2)



- Probability of a contention interval with j slots

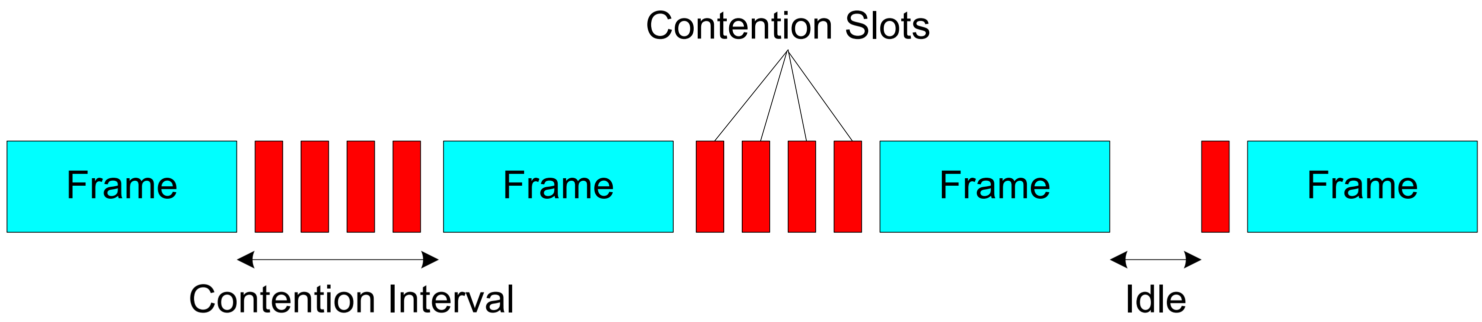
$$Prob[j \text{ unsuccessful attempts}] \times Prob[1 \text{ successful attempt}] =$$

$$A(1-A)^j$$

- The expected number of slots in a contention interval is then calculated as (Geometric distribution, mean=(1-p)/p):

$$\sum_{j=1}^{\infty} jA(1-A)^j = \frac{1-A}{A}$$

Max Utilization for CSMA/CD (3)



- Maximum Utilization

$$U = \frac{\text{Frame time}}{\text{Frame time+Propagation time+Average contention interval}}$$

$$= \frac{1}{1 + a + 2a\dfrac{1-A}{A}} = \frac{1}{1 + \dfrac{2-A}{A}a}$$

- Let $N \rightarrow \infty$, $A = (1-1/N)^{N-1} = 1/e$ $(e=2.718)$

$$U = \frac{1}{1 + \dfrac{2-A}{A}a} = \frac{1}{1 + (2e-1)a} \approx \frac{1}{1 + 4.44a}$$

MAC Address and Discovery

What is MAC Address?

- **Medium Access Control (MAC) Address**
  - Numerical address associated with a network adapter
  - Flat name space of 48 bits (e.g., 00-15-C5-49-04-A9 in HEX)
  - Unique, hard-coded in the adapter when it is built
- Hierarchical Allocation
  - Blocks: assigned to vendors (e.g., Dell) by the IEEE
    - First 24 bits (e.g., 00-15-C5-**-**-**)
  - Adapter: assigned by the vendor from its block
    - Last 24 bits

Address Configuration

C:\WINDOWS\System32\cmd.exe

```
C:\Documents and Settings\X129>ipconfig /all

Windows IP Configuration

        Host Name . . . . . . . . . . . . : X129-T
        Primary Dns Suffix  . . . . . . . : seven.parkland.cc.il.us
        Node Type . . . . . . . . . . . . : Hybrid
        IP Routing Enabled. . . . . . . . : No
        WINS Proxy Enabled. . . . . . . . : No
        DNS Suffix Search List. . . . . . : seven.parkland.cc.il.us
                                            parkland.cc.il.us
                                            cc.il.us
                                            il.us

Ethernet adapter Local Area Connection:

        Connection-specific DNS Suffix  . : parkland.edu
        Description . . . . . . . . . . . : Intel(R) PRO/100 VE Network Connection
        Physical Address. . . . . . . . . : 00-07-E9-6F-37-53
        Dhcp Enabled. . . . . . . . . . . : Yes
        Autoconfiguration Enabled . . . . : Yes
        IP Address. . . . . . . . . . . . : 10.10.2.111
        Subnet Mask . . . . . . . . . . . : 255.255.0.0
        Default Gateway . . . . . . . . . : 10.10.1.1
        DHCP Server . . . . . . . . . . . : 216.125.249.50
        DNS Servers . . . . . . . . . . . : 216.125.249.48
                                            206.166.53.20
                                            206.166.49.21
        Primary WINS Server . . . . . . . : 216.125.249.50
        Secondary WINS Server . . . . . . : 216.125.249.51
        Lease Obtained. . . . . . . . . . : Wednesday, October 22, 2003 10:29:37 PM
        Lease Expires . . . . . . . . . . : Thursday, November 06, 2003 10:29:37 PM

C:\Documents and Settings\X129>_
```

MAC Address:
only can be seen in the same subnet

IP Address

Subnet mask:
define the range of a subnet

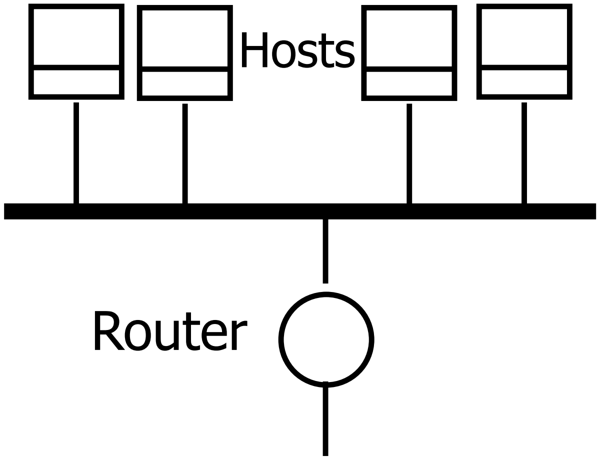
Default Gateway:
all packets to the IPs in the same subnet will be broadcasted;
all packets to the other IPs will be sent to the default gateway (if no other route rule is given)

Discovery

- A host is “born” knowing only its MAC address
- Must discover lots of information before it can communicate with a remote host B
  - What is my IP address?
  - What is B’s IP address? (remote)
  - What is B’s MAC address? (if B is local)
  - What is my first-hop router’s address? (if B is not local)
  - …

ARP and DHCP

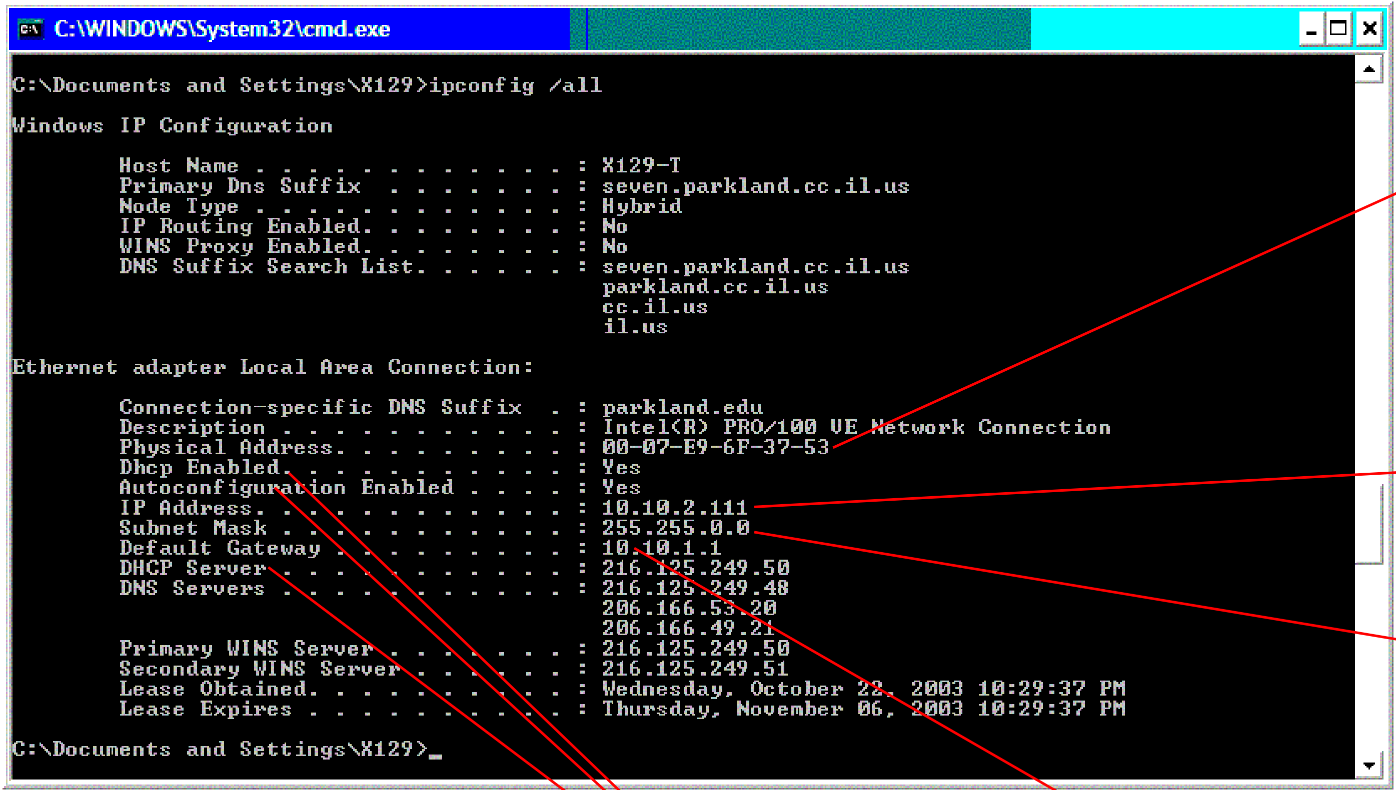
- Link layer discovery protocols
  - ARP → Address Resolution Protocol
  - DHCP → Dynamic Host Configuration Protocol
  - Confined to a single local-area network (LAN)
  - Rely on broadcast capability



ARP and DHCP

- Link layer discovery protocols
- Serve two functions
  - Discovery of local end-hosts
    - For communication between hosts on the same LAN
  - Bootstrap communication with remote hosts
    - What’s my IP address?
    - Who/where is my local DNS server?
    - Who/where is my first hop router?

Address Configuration



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Windows IP Configuration

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        Node Type . . . . . . . . . . . . : Hybrid
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        Physical Address. . . . . . . . . : 00-07-E9-6F-37-53
        Dhcp Enabled. . . . . . . . . . . : Yes
        Autoconfiguration Enabled . . . . : Yes
        IP Address. . . . . . . . . . . . : 10.10.2.111
        Subnet Mask . . . . . . . . . . . : 255.255.0.0
        Default Gateway . . . . . . . . . : 10.10.1.1
        DHCP Server . . . . . . . . . . . : 216.125.249.50
        DNS Servers . . . . . . . . . . . : 216.125.249.48
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C:\Documents and Settings\X129>_
```

MAC Address:
only can be seen in the same subnet

IP Address

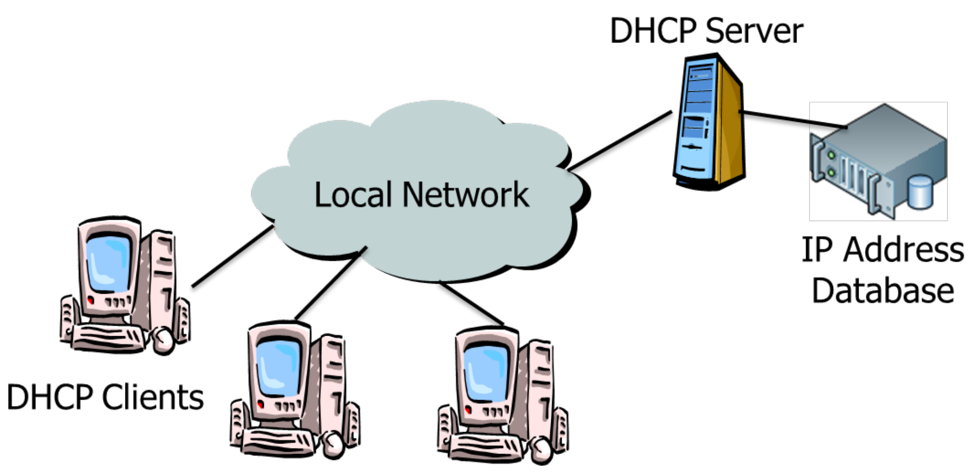
Subnet mask:
define the range of a subnet

Default Gateway

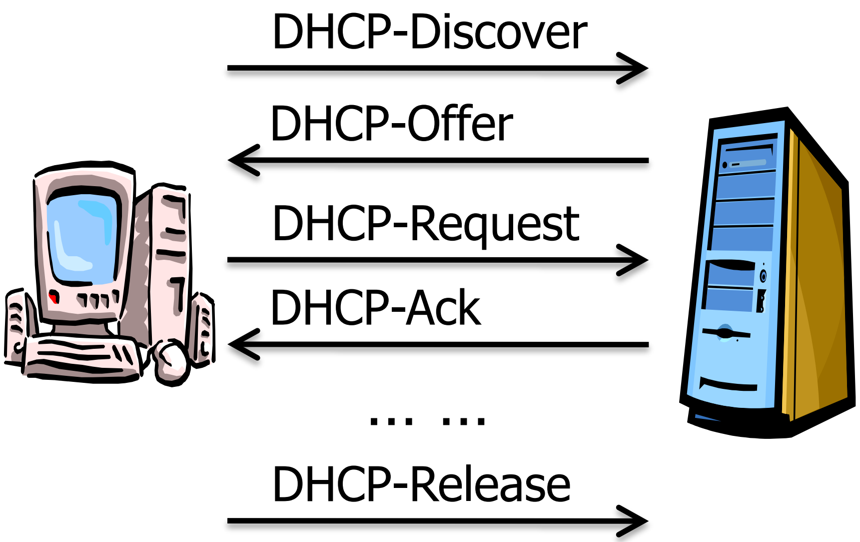
DHCP
Automatic address configuration

DHCP

- Dynamic Host Configuration Protocol
  - Defined in RFC 2131
- A host uses DHCP to discover
  - Its own IP address
  - Its netmask
  - IP address(es) for its local DNS name server(s)
  - IP address(es) for its first-hop “default” router(s)

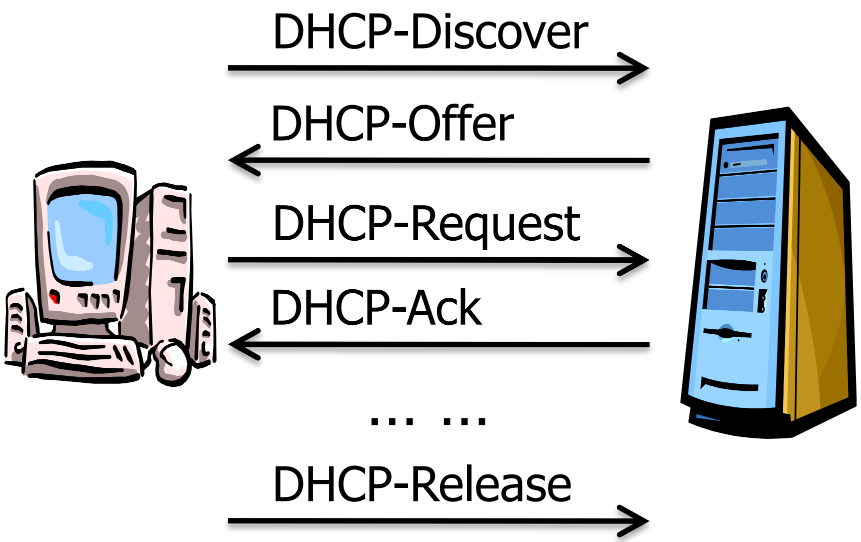


Typical Procedure of DHCP



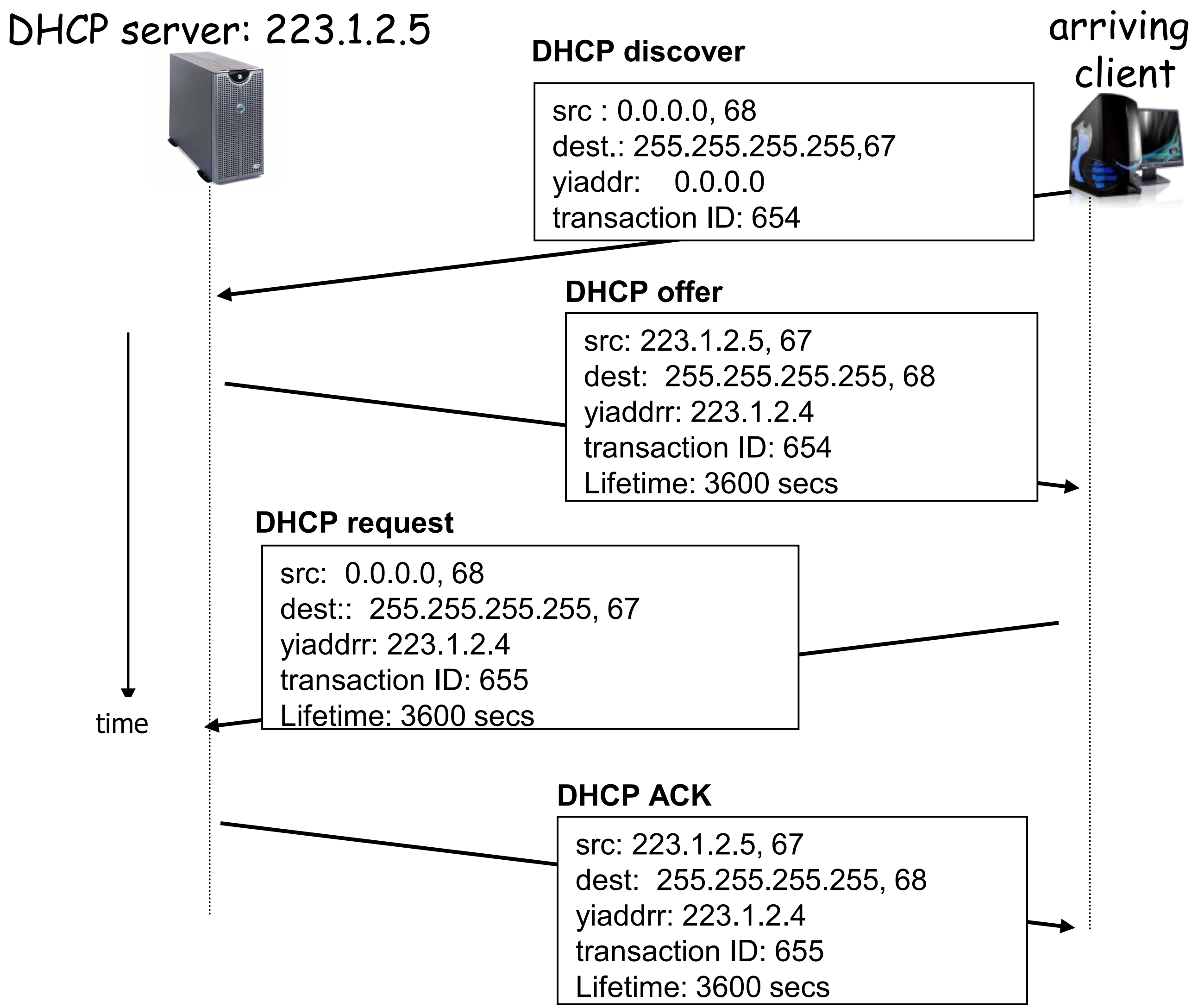
- The client broadcasts a DHCP-DISCOVER message on its subnet
- Each server may respond with a DHCP-OFFER message
- The client chooses one server, broadcasts a DHCP-REQUEST message including server IP
- The selected server commits the binding, responds with a DHCP-ACK message

Typical Procedure of DHCP

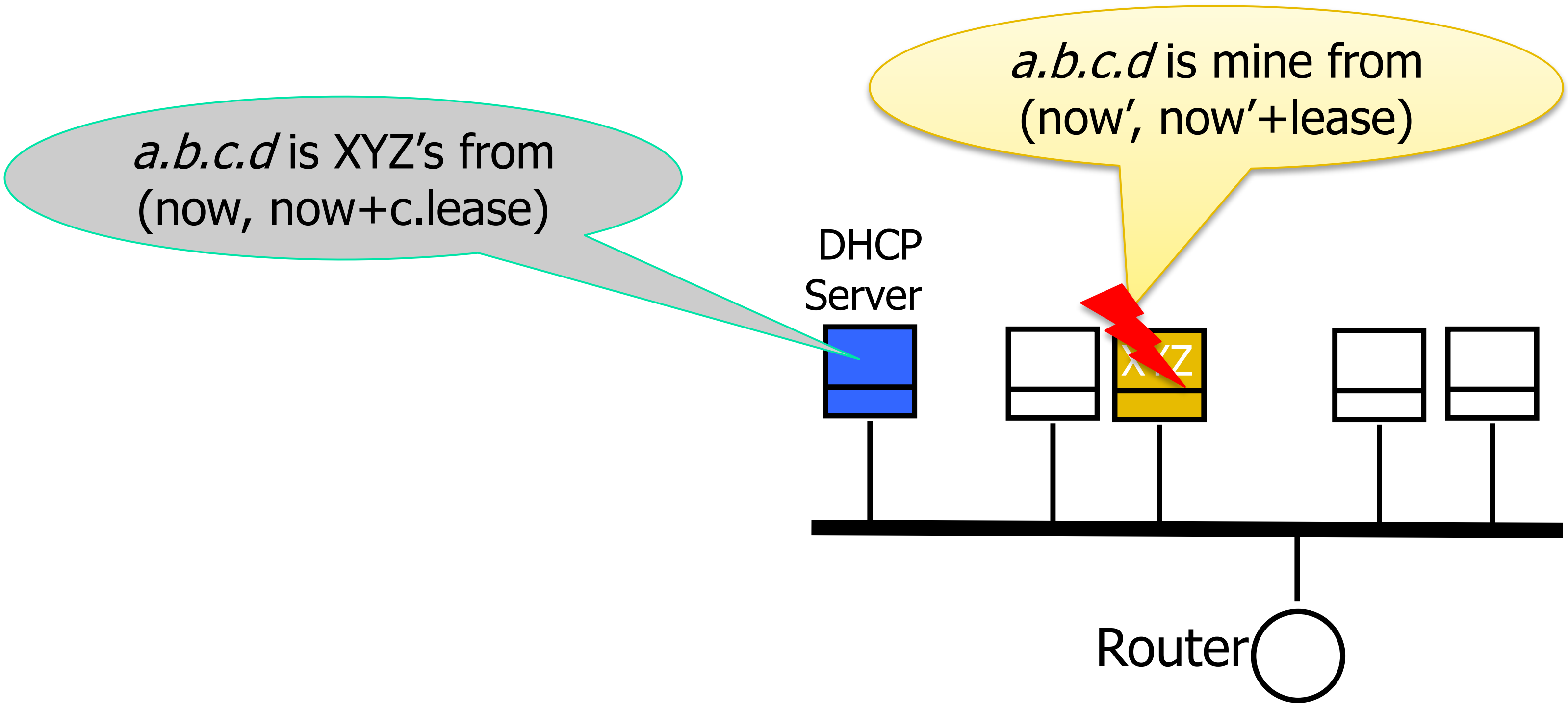


- The client set its configuration parameters within the DHCP-ACK
- The client relinquish the binding by a DHCP-RELEASE message
- The binding will be expired if the client does not renew (rebind) the binding before

DHCP Messages

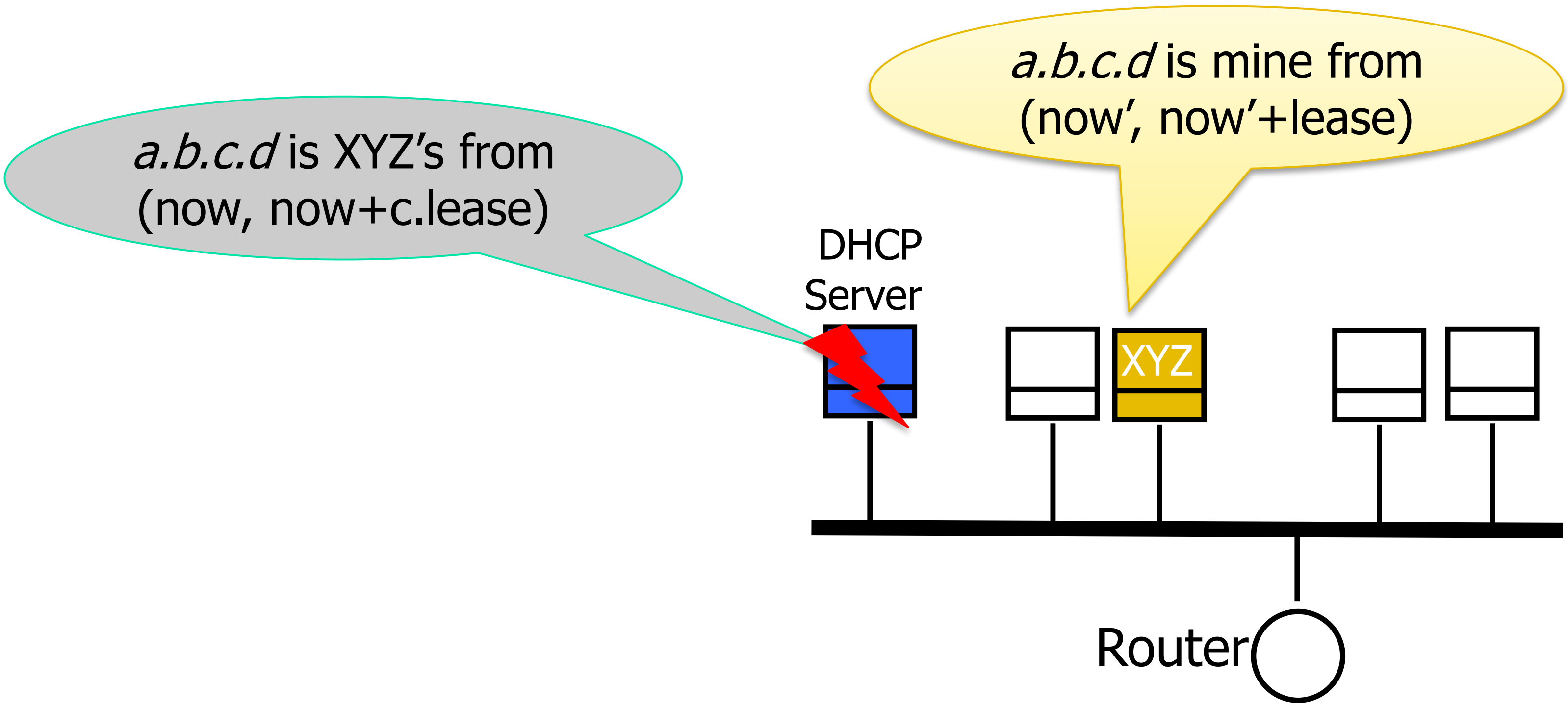


Soft state under failure



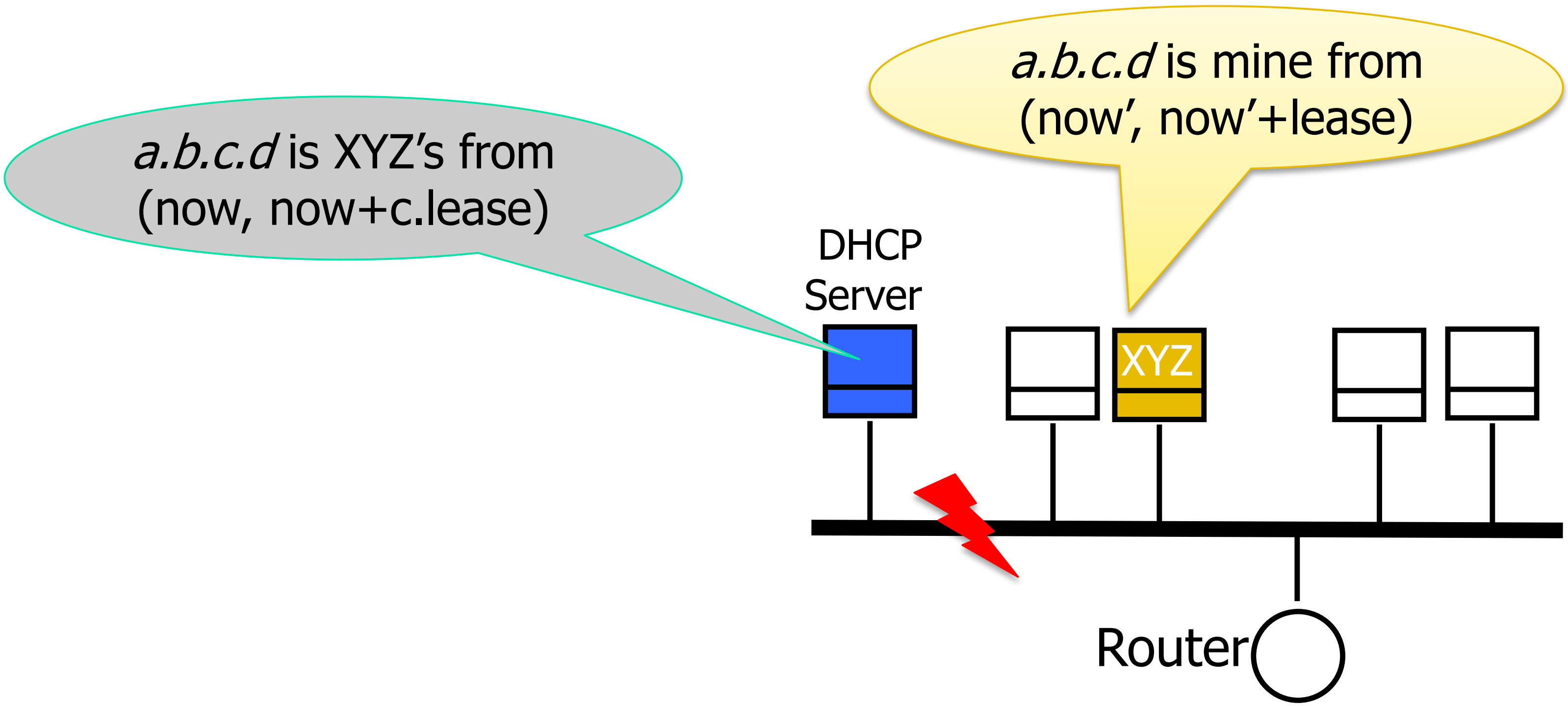
- What happens when host XYZ fails?
  - Refreshes from XYZ stop
  - Server reclaims a.b.c.d after O(lease period)

Soft state under failure



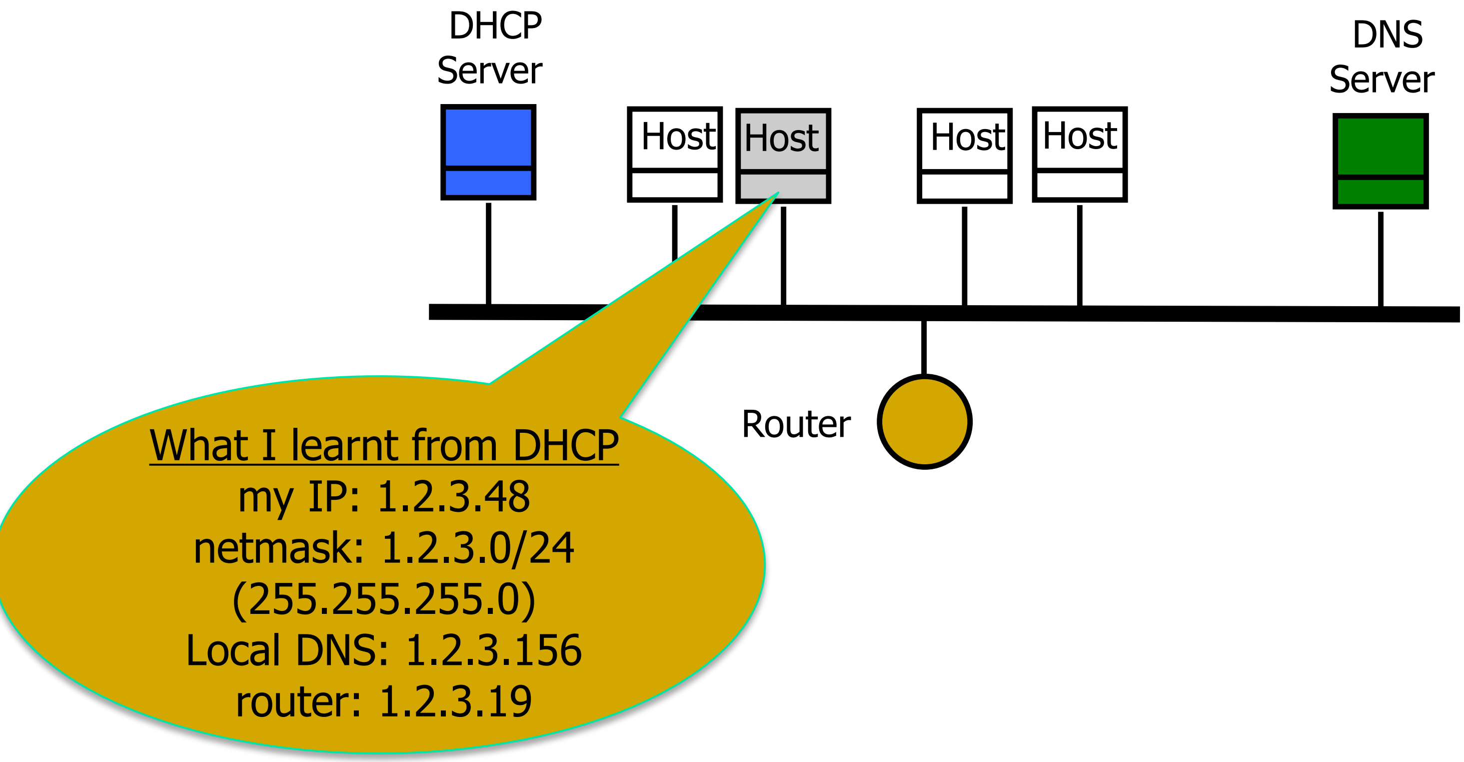
- What happens when server fails?
  - ACKs from server stop
  - XYZ releases address after O(lease period); send new request
  - A new DHCP server can come up from a `cold start' and we are back on track in ~lease time

Soft state under failure



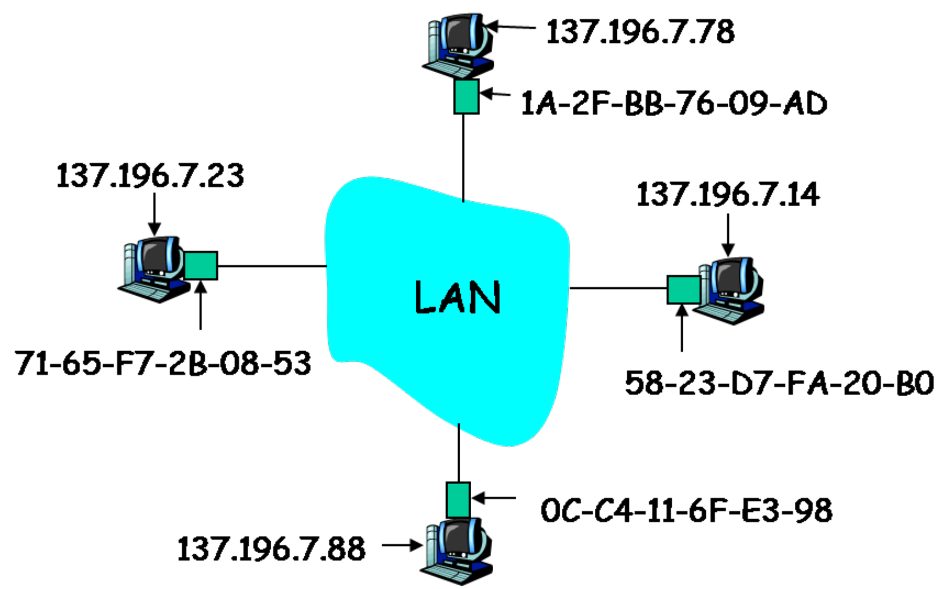
- What happens if the network fails?
  - Refreshes and ACKs don't get through
  - XYZ release address; DHCP server reclaims it

Are we there yet?



MAC Address Resolution Problem

- User 137.196.7.23 want to Ping 137.196.7.88
  - Source IP: 137.196.7.23
  - Destination IP: 137.196.7.88
  - Source MAC: 71-65-F7-2B-08-53
  - Destination Mac: ?
- Its MAC address is needed to deliver the data
- On LAN, ARP is used get a host/router's MAC given its IP address



20 octets

Bit: 0	4	8	16	19	31
Version	IHL	Type of Service	Total Length		
Identification			Flags	Fragment Offset	
Time to Live		Protocol	Header Checksum		
Source Address					
Destination Address					
Options + Padding					

Ethernet MAC frame

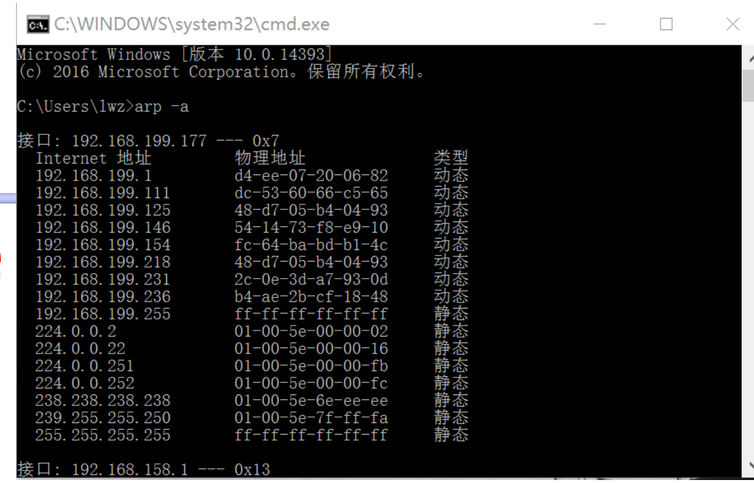
Preamble	DA	SA	Type	Data	FCS
8 octets	6	6	2	46~1500	4

Address Resolution Protocol

- ARP (Address Resolution Protocol)
  - Map IP address to MAC address
  - 192.168.1.2 -> 00-15-C5-49-04-A9
  - Only works in a LAN

- Compare: DNS (domain name system)
  - Map domain name to IP address
  - Baidu.com -> 220.181.38.148

ARP Procedure



```
C:\WINDOWS\system32\cmd.exe
Microsoft Windows [版本 10.0.14393]
(c) 2016 Microsoft Corporation。保留所有权利。

C:\Users\lwz>arp -a

接口: 192.168.199.177 --- 0x7
  Internet 地址         物理地址              类型
  192.168.199.1         d4-ee-07-20-06-82     动态
  192.168.199.111       dc-53-60-66-c5-65     动态
  192.168.199.125       48-d7-05-b4-04-93     动态
  192.168.199.146       54-14-73-f8-e9-10     动态
  192.168.199.154       fc-64-ba-bd-b1-4c     动态
  192.168.199.218       48-d7-05-b4-04-93     动态
  192.168.199.231       2c-0e-3d-a7-93-0d     动态
  192.168.199.236       b4-ae-2b-cf-18-48     动态
  192.168.199.255       ff-ff-ff-ff-ff-ff     静态
  224.0.0.2             01-00-5e-00-00-02     静态
  224.0.0.22            01-00-5e-00-00-16     静态
  224.0.0.251           01-00-5e-00-00-fb     静态
  224.0.0.252           01-00-5e-00-00-fc     静态
  238.238.238.238       01-00-5e-6e-ee-ee     静态
  239.255.255.250       01-00-5e-7f-ff-fa     静态
  255.255.255.255       ff-ff-ff-ff-ff-ff     静态

接口: 192.168.158.1 --- 0x13
```

- Every host maintains an ARP table
  - List of (IP address → MAC address)
- Sender
  - Looks into local cache first, if none
  - Constructs ARP request, insert <*sender IP, sender MAC, destination IP*>
  - Broadcasts using MAC frame
  - Caches destination's <*MAC, IP*> pair with timestamp
- Receiver
  - Checks the destination IP, if OK
  - Constructs ARP reply, insert <*destination IP, destination MAC*>
  - Sends to sender MAC using MAC frame
  - Caches sender's <*MAC, IP*> pair with timestamp

Illustration of ARP


C:\WINDOWS\system32\cmd.exe

```
Microsoft Windows [版本 10.0.14393]
(c) 2016 Microsoft Corporation。保留所有权利。

C:\Users\lwz>arp -a

接口: 192.168.199.177 --- 0x7
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  192.168.199.1         d4-ee-07-20-06-82     动态
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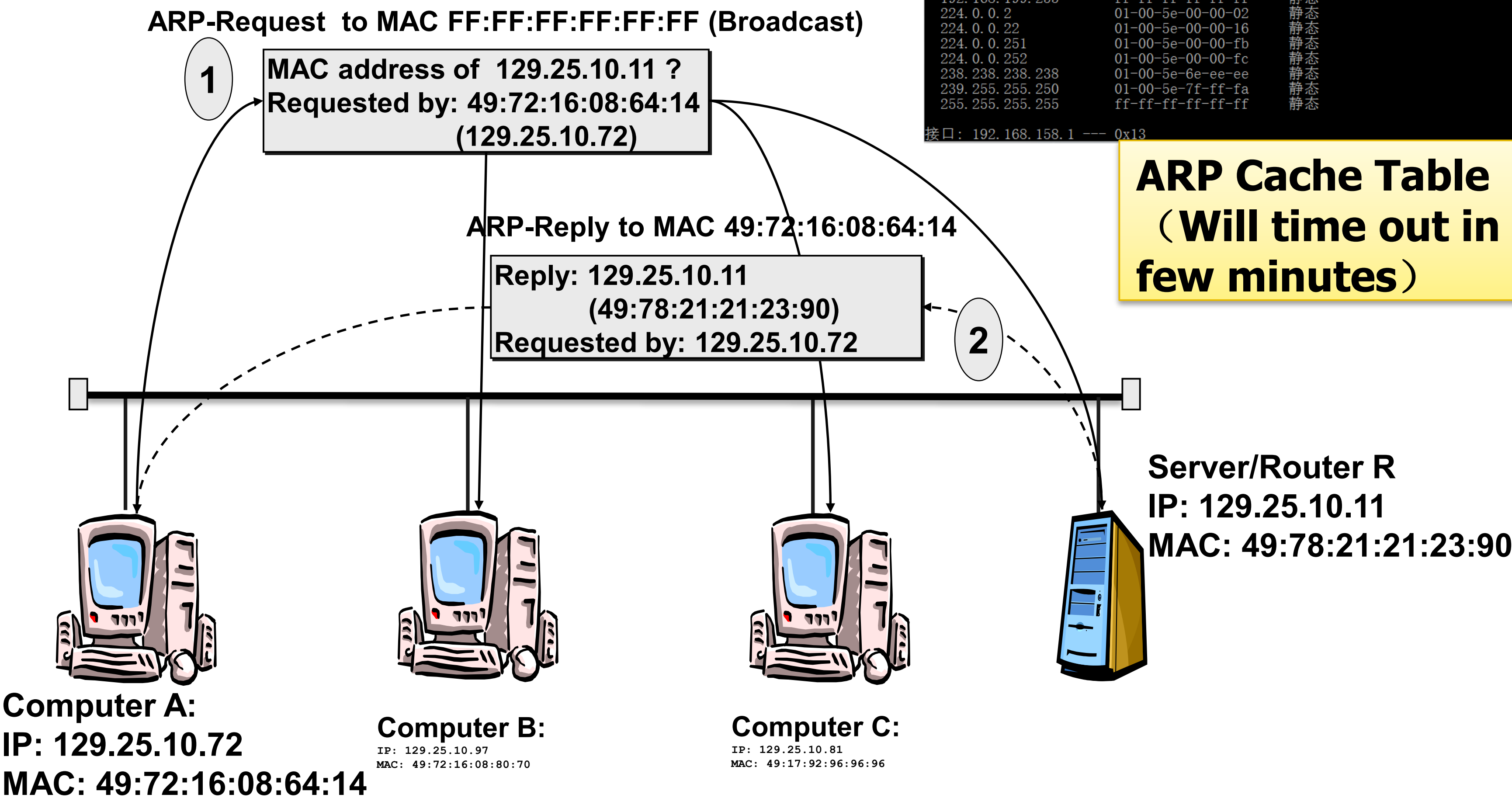
  192.168.199.146       54-14-73-f8-e9-10     动态
  192.168.199.154       fc-64-ba-bd-b1-4c     动态
  192.168.199.218       48-d7-05-b4-04-93     动态
  192.168.199.231       2c-0e-3d-a7-93-0d     动态
  192.168.199.236       b4-ae-2b-cf-18-48     动态
  192.168.199.255       ff-ff-ff-ff-ff-ff     静态
  224.0.0.2             01-00-5e-00-00-02     静态
  224.0.0.22            01-00-5e-00-00-16     静态
  224.0.0.251           01-00-5e-00-00-fb     静态
  224.0.0.252           01-00-5e-00-00-fc     静态
  238.238.238.238       01-00-5e-6e-ee-ee     静态
  239.255.255.250       01-00-5e-7f-ff-fa     静态
  255.255.255.255       ff-ff-ff-ff-ff-ff     静态

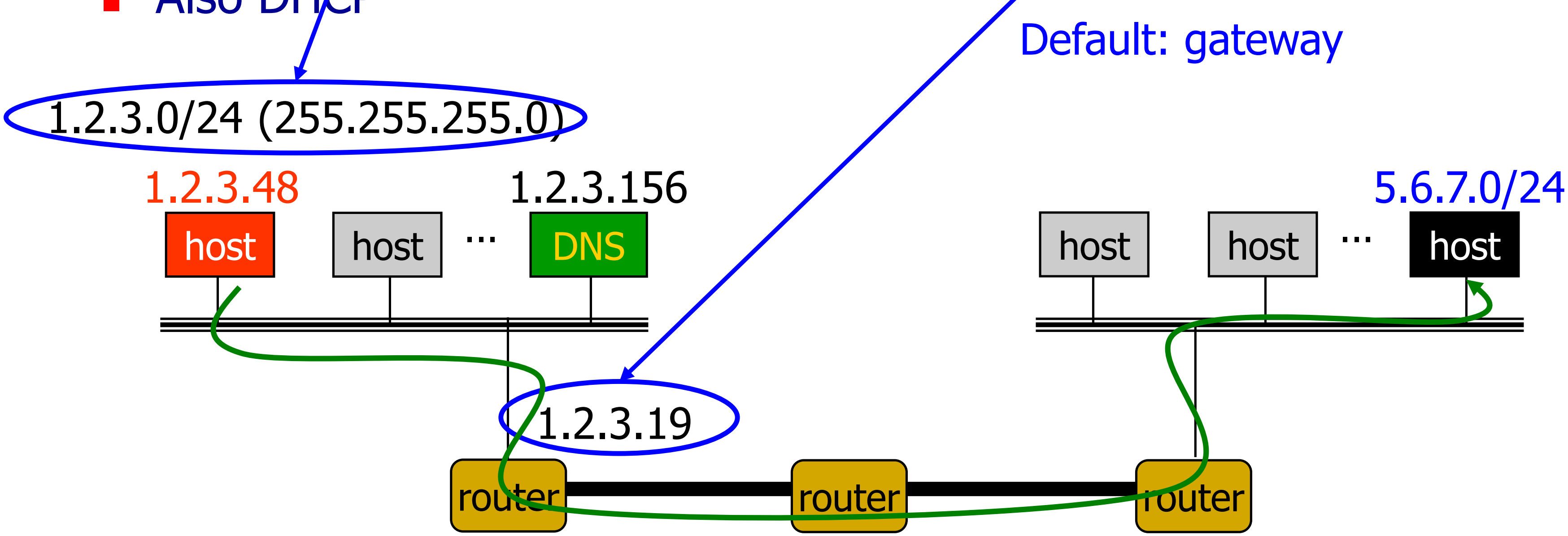
接口: 192.168.158.1 --- 0x13
```

ARP Cache Table （Will time out in a few minutes）



What if the destination is remote?

- Look up the MAC address of the first hop router
  - 1.2.3.48 uses ARP to find MAC address for first-hop router **1.2.3.19** rather than ultimate destination IP address
- How does the red host know the destination is not local?
  - Uses netmask (discovered via DHCP)
- How does the red host know about 1.2.3.19?
  - Also DHCP

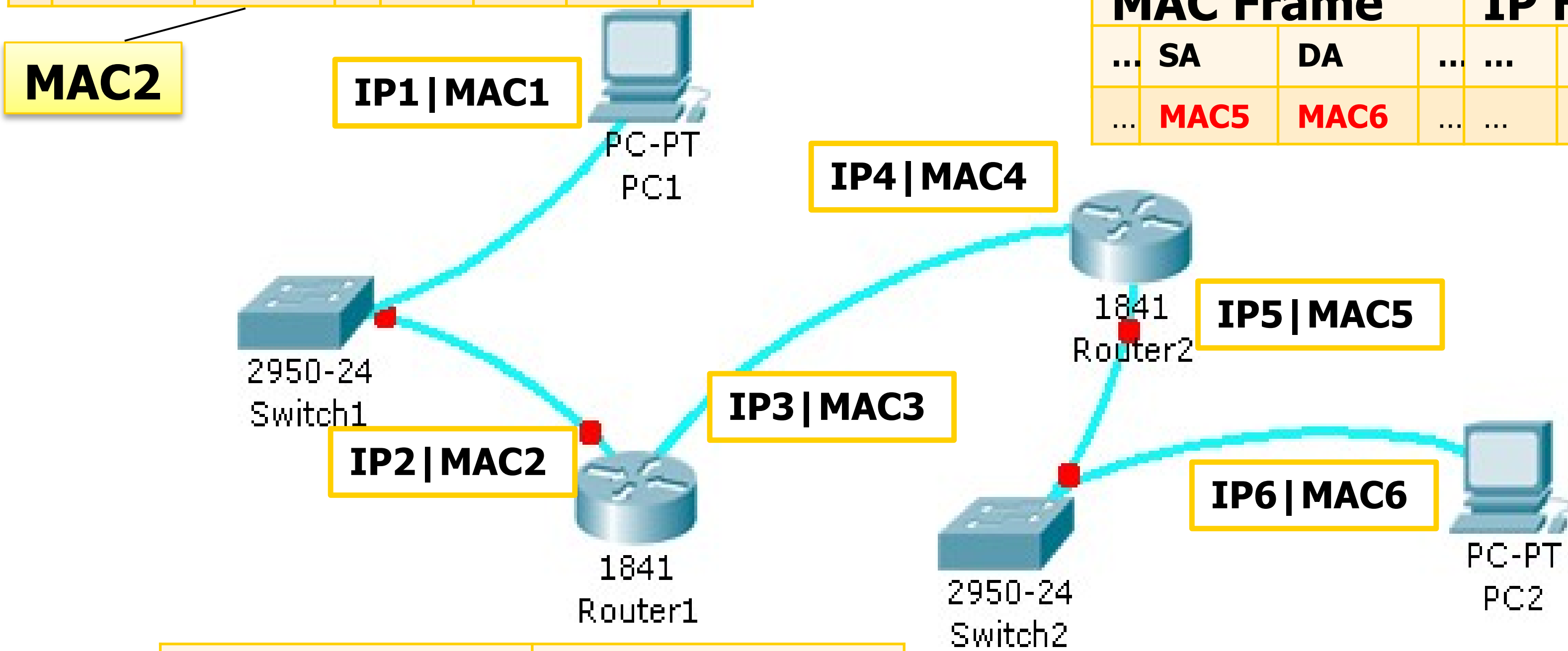


Example: PC1 Ping PC2

MAC Frame				IP Head			
..	**SA**	**DA**	...	...	**SA**	**DA**	...
...	**MAC1**	**?**	...	...	IP1	IP6	...

Use ARP to find the next-hop MAC!

MAC Frame				IP Head			
...	**SA**	**DA**	...	...	**SA**	**DA**	...
...	**MAC5**	**MAC6**	...	...	IP1	IP6	...



MAC Frame				IP Head			
...	**SA**	**DA**	...	...	**SA**	**DA**	...
...	**MAC3**	**MAC4**	...	...	IP1	IP6	...

Key ideas in both ARP and DHCP

- Broadcasting: Can use broadcast to make contact
  - Scalable because of limited size
- Caching: remember the past for a while
  - Store the information you learn to reduce overhead
- Soft state: eventually forget the past
  - Associate a time-to-live field with the information
  - … and either refresh or discard the information
  - Key for robustness in the face of unpredictable change

ID resolution in the networking stack

Layer	Examples	Structure	Configuration	Resolution Service
App. Layer	cse.umich.edu	Organizational hierarchy	~ manual	DNS
Network Layer	123.45.6.78	topological hierarchy	DHCP	ARP
Link layer	45-CC-4E-12-F0-97	vendor (flat)	hard-coded	

Discovery mechanisms

- We have seen two approaches
  - Broadcast (ARP, DHCP)
    - Flooding does not scale
    - No centralized point of failure
    - Zero configuration
  - Directory service (DNS)
    - No flooding / scalable
    - Root of the directory is vulnerable (caching is key)
    - Needs configuration to bootstrap (local, root servers, etc.)

Summary

- MAC机制性能分析
  - Point-to-point link
  - Ring LAN
  - ALOHA, Slotted ALOHA
  - CSMA/CD （ p-persistent ）
- MAC地址发现
  - 自动地址配置：DHCP
  - MAC地址解析：ARP

Homework

- 第6章：P8, P10, P18, P19