

COMPUTER NETWORKING

Study Notes

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Chapter 1

Computer Networks and the Internet

1.1 The Internet

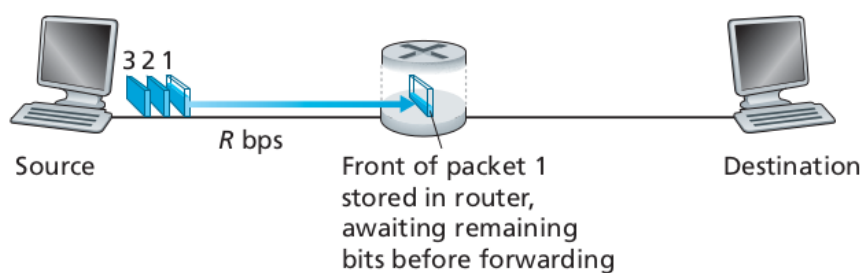
1.1.1 Terminology

1. ISP: Internet Service Provider
2. Host: End System
3. DSL: Digital Subscriber Line
4. FTTH: Fiber To The Home
5. LAN: Local Area Network
6. WAN: Wide Area Network

1.2 Packet Switching

packets :smaller chunks of data known as .

1.2.1 Store and Forward Transmission



1. The packet switch must receive the entire packet before it can transmit it.
2. Store: the switch buffer the packet's bits.
3. Forward: transmit the packet onto the outbound link.

1.2.2 Queuing Delays and Packet Loss

1. Each node has an output buffer/queue.
2. Each packet on the buffer wait for its turn to be transmitted.
3. Queuing Delay: The time that packet waits in the buffer.
4. Packet Loss: when buffer is completely full, the arriving packets will be dropped.

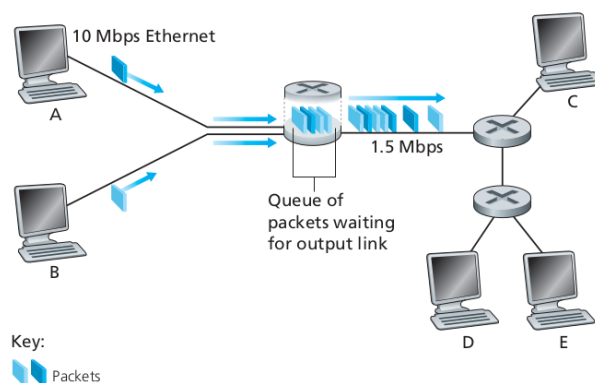


Figure 1.1: Packet Switching

1.2.3 Forwarding Tables and Routing Protocols

1. Each router has an IP address.
2. Each router has a **forwarding table**: Maps the destination addresses to outbound links.
3. End-to-end routing \Leftrightarrow taxi driver who doesn't use map but instead prefers to ask the directions.

1.3 Circuit Switching

Usage: traditional telephone networks.

1. Circuit Switching reverse resources.

1.3.1 Multiplexing in Circuit-Switched networks

1. FDM: frequency-division multiplexing
2. TDM: time-division multiplexing

FDM: frequency-division multiplexing

Frequency spectrum of a link is divided up among the connections established across the link. For example, FM radio stations use FDM to share frequency spectrum between 88MHz and 108MHz.

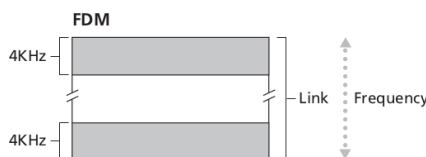


Figure 1.2: FDM

TDM: time-division multiplexing

Time is divided into frames of fixed duration, each frame is divided into fixed number of time slots. Each frame is like a round. At each frame, the user has guaranteed time slots to use.

1.3.2 Packet Switching Versus Circuit Switching

Advantage of Packet Switching

1. It offers better sharing of transmission capacity
2. Simpler, more efficient, and less costly to implement.

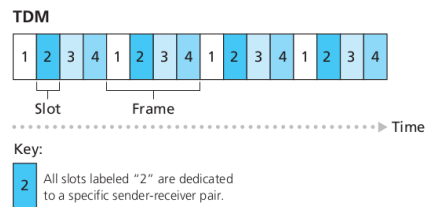


Figure 1.3: TDM

1.3.3 Why Packet Switching is more efficient?

Assumption: 90/10 rule: 90 percent of the time the user is idling.

Suppose users share a 1 Mbps link. Also suppose that each user alternates between periods of activity, when a user generates data at a constant rate of 100 kbps, and periods of inactivity, when a user generates no data. Suppose further that a user is active only 10 percent of the time.

With Circuit Switching, 100 kbps must be reserved even the user is drinking coffee. Therefore only $1\text{Mbps}/100\text{Kps} = 10$ users can share the link at the same time.

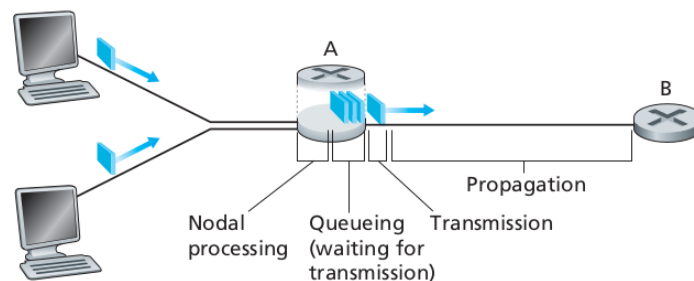
With Packet Switching, if there are 35 users, the probability that there are 11 or more users using the link simultaneously is less than 0.0004. Statistically, the packet switching is more efficient.

1.3.4 Advantage of Circuit Switching

1. Rate is guaranteed, suitable for real time services.

1.3.5 Delay, Loss, and Throughput in Packet-Switched Networks

Nodal delay = Processing Delay + Queuing Delay + Transmission Delay + Propagation Delay



1. Throughput: The amount of data per unit time that can be transferred between end hosts.
2. Processing Delay: The time required to examine the packet's header and determine where to direct packet is part of processing delay.
3. Queuing Delay: The time that the packet waits in the buffer.
4. Transmission Delay: The amount of time to put the complete packet onto the link.
5. Propagation Delay: The time required to propagate from the beginning of the link to the next node.

Processing Delay

Several parts of the processing delay:

1. The time required to examine the packet's header
2. The time required to check bit-level errors

Queuing Delay

The length of queuing delay is depended on the number of packets waiting in the buffer/queue. If the queue is empty and no other packet is currently being transmitted, the queuing delay will be zero. Queuing can vary in a large scope. Queuing delays can be on the order of microseconds to milliseconds in practice.

Transmission Delay

Transmission delay depends on the physical medium of the link.

Transmission delay = the time the first bit is put on the link - the time the last bit is put on the link.

Denote the packet size L , and the transmission rate R .

The transmission delay will be $\frac{L}{R}$.

Propagation Delay

Propagation Delay depends on the physical medium of the link.

Denote the distant between nodes d , and the speed of propagation (the speed of the link, usually a little less than the speed of light).

The propagation delay is d/s .

The propagation delay can be negligible using fiber, but can be dominant if using satellite link.

1.3.6 Queuing Delay and Packet Loss

Unlike other delays, queuing delay can vary from packet to packet. For example 10 packets arrive at the same empty queue at the same time, the first packet will have zero queuing delay and the last packet will have relatively large queuing delay.

When is the queuing delay large and when is it insignificant? \Rightarrow Depends on the rate of the arriving traffic (packets), the transmission rate of the link, and whether the traffic arrives periodically or arrives in bursts.

Let a denote the average rate at which packets arrive at the queue (a is in units of packets/sec). Recall that R is the transmission rate; that is, it is the rate (in bits/sec) at which bits are pushed out of the queue. Also suppose, for simplicity, that all packets consist of L bits.

Traffic intensity: $\frac{La}{R}$

If $\frac{La}{R} > 1$, the link is very busy and the queuing delay will continuously increase and into infinite. If $\frac{La}{R} < 1$, it is necessary for reduce the queuing delay.

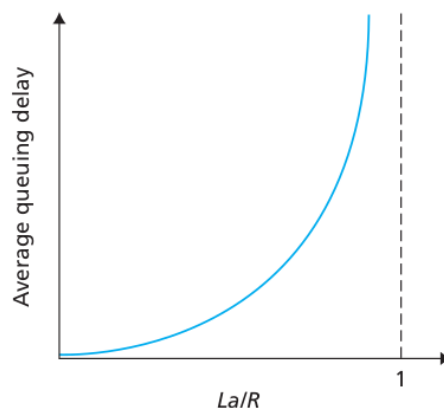


Figure 1.4: Dependence of average queuing delay on traffic intensity

1.3.7 End-to-End Delay

Suppose there are $N - 1$ routers between the source host and the destination host. The transmission rate is fixed R , and the distance between each router is L . The end-to-end delay is:

$$d_{end} - end = \sum_{i=1}^N d_{proc} + d_{trans} + d_{prop} + d_{queu_i}$$

1.4 Protocol layering

Five-layer Internet Protocol Stack: Each layer provides services to the layer above it by 1) performing certain actions within that layer and by 2) using the services of the layer directly below it.

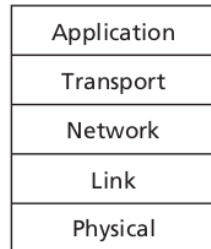


Figure 1.5: Five-layer Protocol Stack

1.4.1 Packet at different layers

1. Message : Application Layer
2. Segment : Transport Layer
3. Datagram : Network Layer
4. Frame : Link Layer

1.4.2 Application Layer

The Internet's application layer includes many protocols:

1. HTTP
2. SMTP
3. FTP
4. DNS
5. ...

1.4.3 Transport Layer

1. TCP
2. UDP

1.4.4 Networking Layer

Only one protocol is available at this layer => **IP** (*Internet Protocol*).

1.4.5 Link Layer

Examples of linklayer protocols include:

1. Ethernet
2. WiFi
3. DOCSIS

1.4.6 Physical Layer

The protocols in this layer are again link dependent and further depend on the actual transmission medium of the link. For example, Ethernet has many physical-layer protocols:

1. twisted-pair copper wire
2. coaxial cable
3. fiber

need to be In each case, a bit is moved across the link in a different way.

1.5 Encapsulation

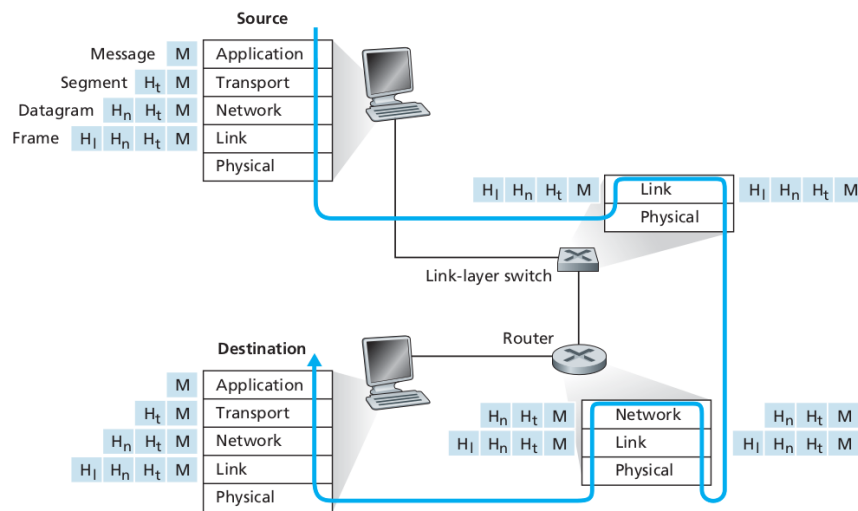


Figure 1.6: Encapsulation

Chapter 2

Application Layer

2.1 Principles of the Network Applications

2.1.1 Network Applicatoin Architectures

Application Architecture is designed by the application developer and *dictates how the application is structured* over various end systems.

Two predominant architectural paradigms:

1. client-server architecture
2. peer-to-peer(P2P) architecture

Client-Server

1. Server: the always-on host which services requests from many other hosts.
2. Client: the end host whic request services from the server.

Note that with the client-server architecture, clients do not directly communicate with each other;for example, in the Web application, two browsers do not directly communi- cate.

Another characteristic of the client-server architecture is that ***the server has a fixed, well-known address, called an IP address***. Because the server has a fixed, well-known address, and because the server is always on, a client can always contact the server by sending a packet to the server's IP address. Some well-known applications within client-server architecture:

1. Web
2. FTP
3. Telnet
4. e-mail

2.1.2 P2P architecture

There is minimal (or no) reliance on dedicated servers in data centers.Instead the application exploits direct communication between pairs of intermittently connected hosts, called peers.

Characteristics that P2P architecture has:

1. ***Self-Scalability***:although each peer generates workload by requesting files, each peer also adds service capacity to the system by distributing files to other peers.
2. Cost effective: normally don't require significant server infrastructure and server bandwidth

The problems that P2P need to face:

1. ISP's asymmetrical bandwidth usage: ISPs are dimensioned for much more downstream than up-stream traffic. But in p2p architecture, every residential ISPs will face a gigantic amount of up-stream traffic.

2. Security: Because of their highly distributed and open nature, P2P applications can be a challenge to secure.
3. Incentives: Need users to volunteer bandwidth, storage, and computation resources to application.

2.1.3 Transport services available to applications

We can broadly classify the possible services along four dimensions:

1. Reliable data transfer
2. Throughput
3. Timing
4. Security

2.2 Socket

Most applications consist of pairs of communicating processes, with the two processes in each pair sending messages to each other.

Socket: the interface that a process sends messages into, and receives messages from.

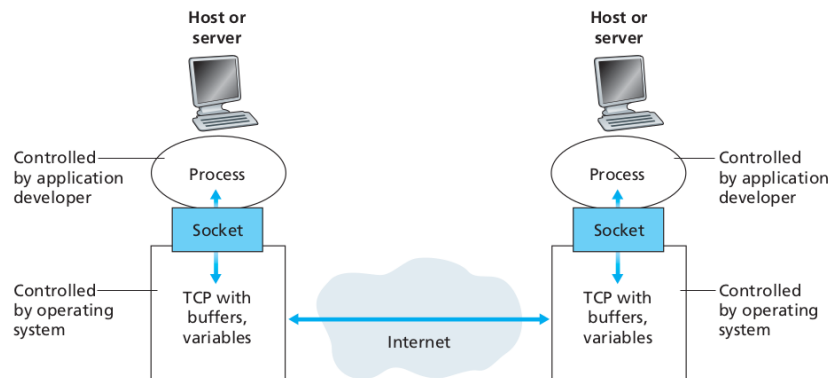


Figure 2.1: Socket

Socket is also referred as the API between the application and the network. The developer has control of everything on the application-layer side but only little control of the transport-layer side of the socket:

1. the choice of transport protocol
2. fix a few transport-layer parameters such as maximum buffer and maximum segment sizes.

2.2.1 Address Processes

Similarly, in order for a process running on one host to send packets to a process running on another host, the receiving process needs to have an address. In particular:

1. The address of the host: **IP address**.
2. an identifier that specifies the receiving process in the destination host: **Port number**.

Some ports are reserved by well-known applications. For example, a Web server has port number 80. A mail server process has port number 25.

2.3 The Web and HTTP

The Web operates on demand.

2.3.1 Overview of HTTP

The Web's application-layer protocol: HTTP(HyperText Transfer Protocol). HTTP is implemented both in client program and server program. HTTP defines the structure of the messages and how the client and server exchange the messages.

Web browsers: Client side of HTTP.

Web servers: Server side of HTTP, addressable by a URL.

HTTP uses TCP

The flow:

1. The HTTP client initiates a TCP connection with the server.
2. The HTTP client sends request messages into its socketnd and waits to receive HTTP response messages from its socket interface.
3. The HTTP server receives request from its socket and sends response into its socket interface.
4. The HTTP client receives the response.

Another important thing is that HTTP is *stateless protocol*.

2.3.2 HTTP with different connections

There are two connection types for HTTP:

1. Non-persistent connection: the application sends response using existing TCP connection.
2. Persistent connection: the appication sends each response with a new TCP connection.

RTT(Round Trip Time)

Non-persistent connection will take around two RTT for a single HTML file,and for each TCP established the TCP variables need to be stored in both client and server side. This can place a significant burden on the Web server.

Persistent connection will only take one RTT once the connection is established, and persistent connection with pipelining is the default mode of the HTTP.

2.3.3 HTTP Request Format

```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
Connection: close
User-agent: Mozilla/5.0
Accept-language: fr
```

The first line is called: the *request line*; The subsequent lines are called: the *header lines*. The request line has three fields:

1. The method field: including *GET,POST,HEAD,PUT* and *DELETE*.
2. The URL field
3. The HTTP version field

The great majority of HTTP request messages use the GET method. The GET method is used when the browser requests an object, with the requested object iden tified in the URL field.

The header line *Host: wwwwww.someschool.edu* specifies the host on which the object resides. The header line *Connection: close* tells the server close the connection after sending the requested object. The *User-agent* and *Accept-Language* are self-explanatory.

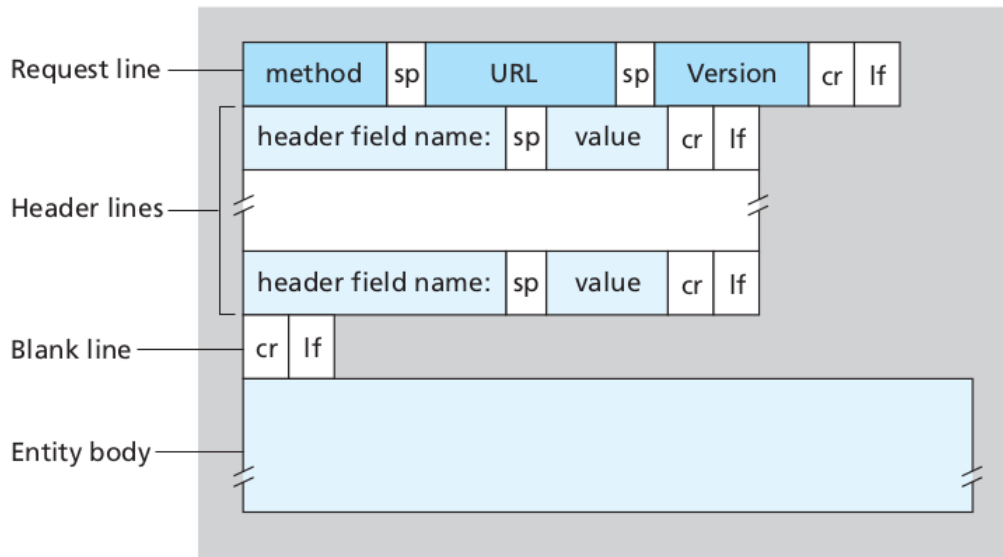


Figure 2.2: General format of an HTTP request message

The *entity body* is empty with **GET** method, but is used in **POST** method: HTTP client often uses the POST method when the user fills out a form. For example, when a user provides search words to a search engine.

However HTML forms often use the **GET** method and include the inputted data in the request URL. For example, inputted data is banana and money, then the URL will look like *www.somesite.com/search?monkeys&bananas*. The **HEAD** method only responds with an HTTP message but it leaves out the requested object (used to debug).

The **PUT** method allows a user to upload an object to specific path on specific Web server. It is also used by applications that need to upload objects to Web servers.

The **DELETE** method allows a user, or an application, to delete an object on a Web server.

2.3.4 HTTP Response Format

```

HTTP/1.1 200 OK
Connection: close
Date: Tue, 09 Aug 2011 15:44:04 GMT
Server: Apache/2.2.3 (CentOS)
Last-Modified: Tue, 09 Aug 2011 15:11:03 GMT
Content-Length: 6821
Content-Type: text/html
(data data data data data ...)

```

The example has three sections: an initial *status line*, six *header line*, and then the *entity body*.

The **status line** has three fields:

1. The protocol version field
2. A status code: 200 in the example
3. A corresponding status message.

The **six header lines**:

1. **Connection:** *close* header line: tell the client that it is going to close the TCP connection.
2. The **Date:** header line indicates the time and date when the HTTP response was created and sent by the server.
3. The **Server:** header line indicates that the message was generated by an Apache Web server.

4. The ***Last-Modified:*** header line indicates the time and date when the object was created or last modified.
5. The ***Content-Length:*** header line indicates the number of bytes in the object being sent.
6. The ***Content-Type:*** header line indicates that the object in the entity body is HTML text.

General format of an HTTP response message

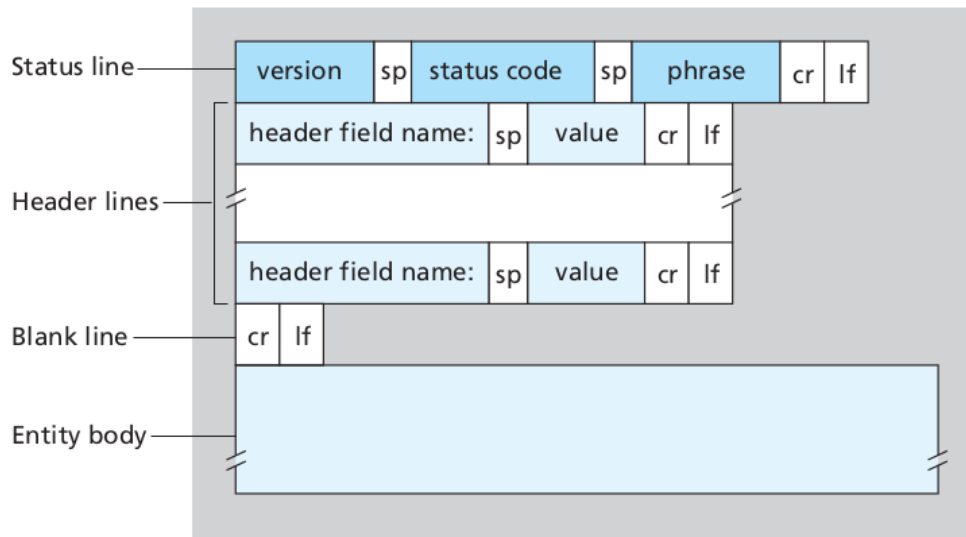


Figure 2.3: General format of an HTTP response message

Some common status codes and associated phrases include:

1. ***200 OK:*** Request succeeded and the information is returned in the response.
2. ***301 Moved Permanently:*** Requested object has been permanently moved; the new URL is specified in Location: header of the response message. The client software will automatically retrieve the new URL.
3. ***400 Bad Request:*** This is a generic error code indicating that the request could not be understood by the server.
4. ***404 Not Found:*** The requested document does not exist on this server.
5. ***505 HTTP Version Not Supported:*** The requested HTTP protocol version is not supported by the server.

2.3.5 Cookies

HTTP use cookies to identify users.

Major cookies components

1. A cookie header line in the HTTP response message.
2. A cookie header line in the HTTP request message.
3. A cookie file kept on the user's end system and managed by the user's browser.
4. A back-end database at the Web site.

Flows of using cookies:

1. Alice send HTTP request message without a cookie header line.

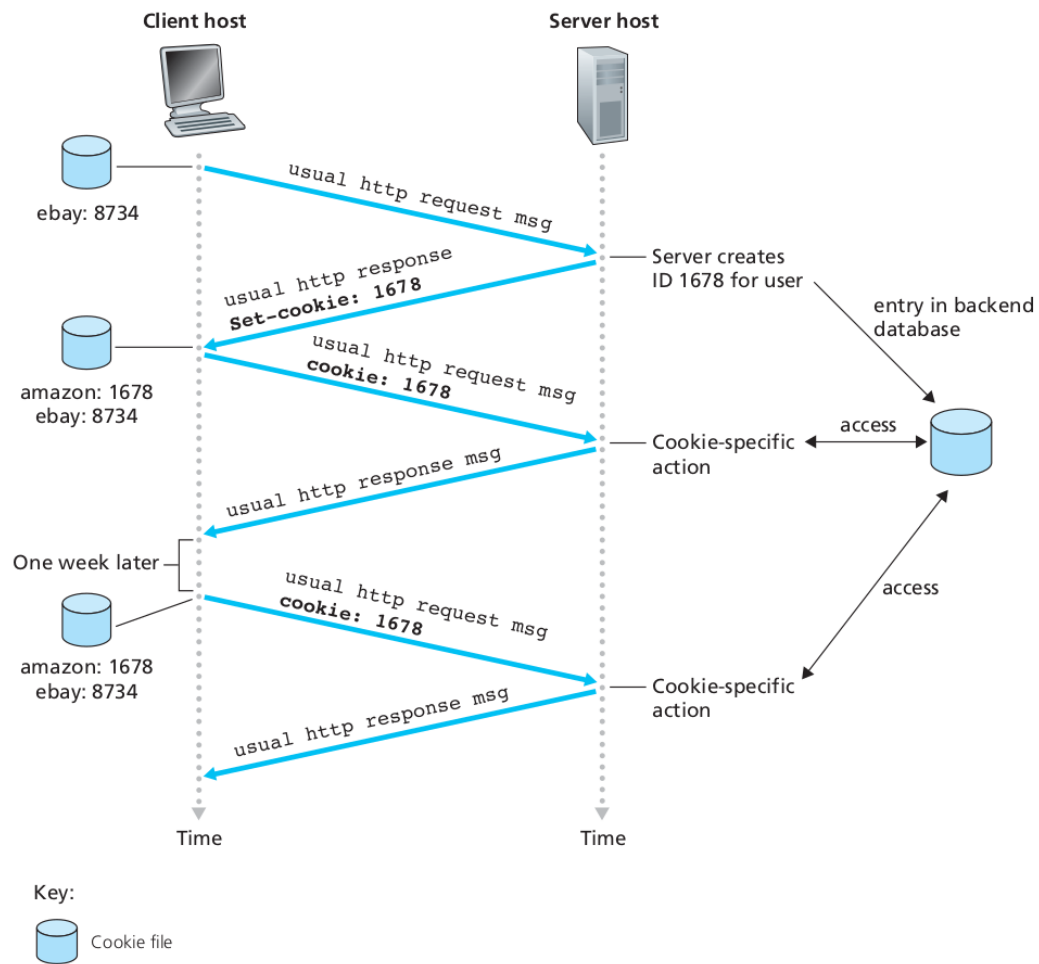


Figure 2.4: Use cookie to identify users

2. The server generates a new cookies number and stores it to the database. Then responds with Set-cookie: header **Set-cookie: 1678**.
3. When Alice receives the response message, her browser appends a line to the special cookie file that it manages.
4. In the following requests, Alice's browser will include the cookie for the server in the header lines. Like **Cookie: 1678**.
5. The server will identify Alice with the cookie it receives in the header lines.

2.3.6 Web Caching

A **Web cache**—also called a **proxy server**—is a network entity that satisfies HTTP requests on the behalf of an origin Web server. *The Web cache is both a client and a server.*

The web caching process:

1. The browser establishes TCP connection to the Web cache and sends HTTP request for the object to the Web cache
2. The Web cache checks to see if it has a copy of the object stored locally. If it does, the Web cache returns the object within an HTTP response message to the client browser.
3. If the Web cache does not have a copy of the object, it sends HTTP request for the object to the origin server.
4. The web cache receives the object from the origin server with HTTP response, it stores a copy of the object and sends back to the browser.

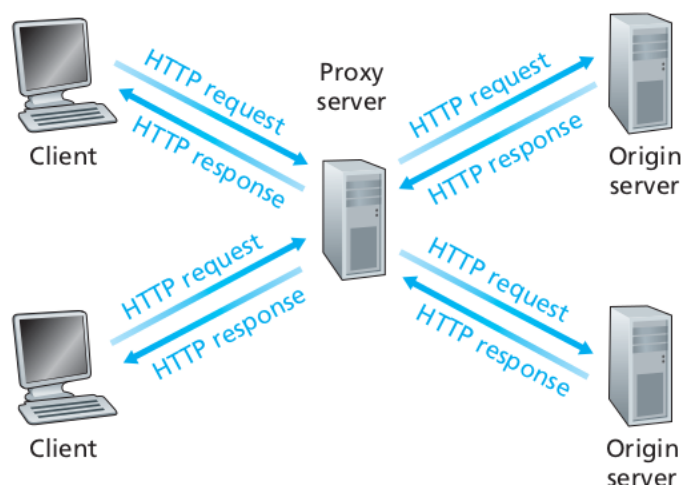


Figure 2.5: Web Caching

Typically a Web cache is purchased and installed by an ISP. For example, a university might install a cache on its campus network and configure all of the campus browsers to point to the cache. Or a major residential ISP (such as AOL) might install one or more caches in its network and preconfigure its shipped browsers to point to the installed caches.

Advantage of using a web cache/proxy server

1. A Web cache can substantially reduce the response time for a client request, particularly if the bottleneck bandwidth between the client and the origin server is much less than the bottleneck bandwidth between the client and the cache.
2. Web caches can substantially reduce traffic on an institution's access link to the Internet. By reducing traffic, the institution does not have to upgrade bandwidth as quickly, thereby reducing costs.
3. Web caches can substantially reduce Web traffic in the Internet as a whole, thereby improving performance for all applications.

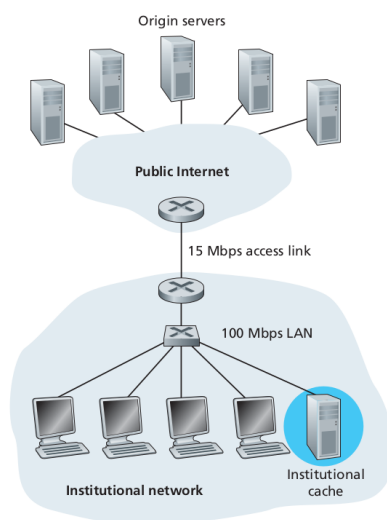


Figure 2.6: Adding a cache to the institutional network

Suppose that the average object size is 1Mbits and that the average request rate from institution's browsers to origin server is 15 requests per second.

The traffic intensity on the LAN is:

$$(15\text{requests/sec}) \cdot (1\text{Mbits/request}) / (100\text{Mps}) = 0.15 \quad (2.1)$$

The traffic intensity on the access link(from the Internet router to institution router) is:

$$(15\text{requests/sec}) \cdot (1\text{Mbits/request}) / (15\text{Mps}) = 1 \quad (2.2)$$

Which is really bad and goes to infinite.

However, when we use the Web cache in the [Figure 2.6](#) when the hit rate is 0.4, we will a traffic intensity on the access link:

$$(15 * 0.6\text{requests/sec}) \cdot (1\text{Mbits/request}) / (15\text{Mps}) = 0.6 \quad (2.3)$$

Which is much better.

The conditional GET

The Web cache uses *conditional GET* to check whether the copy of the object is up to date. A HTTP request message is *conditional GET* if

1. The request message uses the *GET* method.
2. The request message includes an *If-Modified-Since:* header line.

First, on the behalf of a requesting browser, a proxy cache sends a request message to a Web server:

```
GET /fruit/banana HTTP/1.1
HOST: www.walmart.ca
```

Second, the Web server receives the HTTP response from origin server:

```
HTTP/1.1 200 OK
Date: Sat, 8 Oct 2011 15:39:32
Server: Apache/1.3.0 (UNIX)
Last-Modified: Wed, 7 Sep 2011 09:23:24
Content-Type: image/gif
(data data data data data ...)
```

The Web cache would forward the object to the requesting browser and store a copy of it. When the next time someone sends a same request message, the Web cache would send a *conditional GET*:

```
GET /fruit/banana HTTP/1.1
HOST: www.walmart.ca
If-modified-since: Wed, 7 Sep 2011 09:23:24
```

Suppose the object is not updated after the last *GET*, the origin server would response:

```
HTTP/1.1 304 Not Modified
Date: Sat, 15 Oct 2011 15:39:29
Server: Apache/1.3.0 (Unix)
(empty entity body)
```

304 Not Modified indicates that the requested object is not modified since Wed, 7 Sep 2011 09:23:24. Therefore, it doesn't attach the data in the entity. The Web cache would forward the local copy of the object back to the browser.

Note that an HTTP request/response message is negligible. Therefore, a *conditional GET* does not cause delay to forward the copy of the object to the browser if there is no modification made.

2.4 FTP: File Transfer Protocol

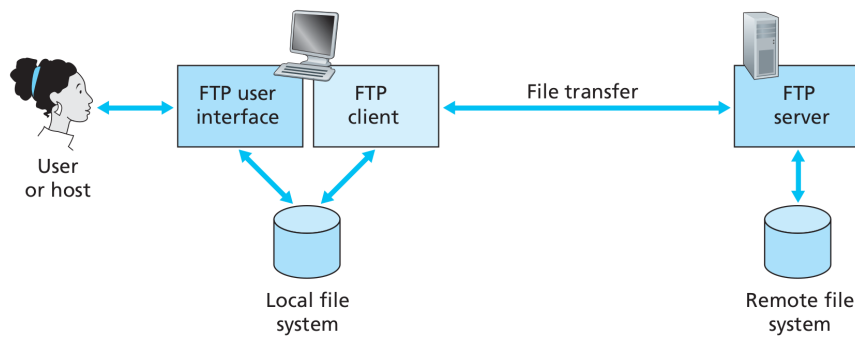


Figure 2.7: FTP

2.4.1 Overview of FTP

In [Figure 2.7](#):

1. User interacts with FTP with an FTP user agent and provides the hostname of the remote host.
2. The process in the local host starts a TCP connection with the FTP server process.
3. The user provides identification and password via the established TCP connection.
4. The server authenticates and authorizes the user.
5. User can copy files from(into) the server(local).

2.4.2 Control connection and data connection

The **FTP** uses *two parallel TCP connections* to transfer a file, a **control connection** and a **data connection**.

The **control connection** is used for sending control information between processes - information such as user identification, password, commands to change remote directory, and commands to "put" and "get" files.

The **data connection** is used to actually send a file. Because TCP uses a separate control connection, FTP authentication is said to send its control information **out-of-band**. HTTP sends request and response header lines into the same TCP connection that carries the transferred file itself. Therefore, HTTP is said to send its control information **in-band**.



Figure 2.8: Control and data connections

1. The client process starts an FTP session with a remote host.
2. The client process initiates a control TCP connection with the server process on **port 21**.
3. The client process sends user identification and password over the control connection.

4. The client process sends a command via control connection.
5. The server process receives a command for a file transfer over the control connection.
6. The server initiates a TCP data connection to client process on *port 20*.

Note that FTP sends exactly one file over the data connection and closes the data connection. If, during the same session, the user wants to transfer another file, FTP opens another data connection. Thus, with FTP, the control connection remains open throughout the duration of the user session. New data connection is created for each file transferred within a session.

1. Data connection is non-persistent.
2. Control connection is persistent.

Also, the FTP server must maintain *state* about the user:

1. Associate the control connection with specific user account
2. Keep track of the user's current directory in the remote directory tree.

Keeping track of this state information for each ongoing user session significantly constrains the total number of sessions that FTP can maintain simultaneously.

2.4.3 FTP commands and replies

The commands, from client to server, and replies, from server to client, are sent across the control connection in 7-bit ASCII format. FTP commands are readable by people. Each command consists of four uppercase ASCII characters, some with optional arguments.

Some common commands:

1. USER username: Used to send the user identification to the server.
2. PASS password: Used to send the user password to the server.
3. LIST: Used to ask the server to send back a list of all the files in the current remote directory. The list of files is sent over a (new and non-persistent) data connection.
4. RETR filename: Used to retrieve (that is, get) a file from the current directory of the remote host. This command causes the remote host to initiate a data connection and to send the requested file over the data connection.
5. STOR filename: Used to store (that is, put) a file into the current directory of the remote host.

Each command is followed by a reply, sent from server to client.

Some common replies:

1. 331 Username OK, password required
2. 125 Data connection already open; transfer starting
3. 425 Can't open data connection
4. Error writing file

2.5 Electronic Mail in the Internet

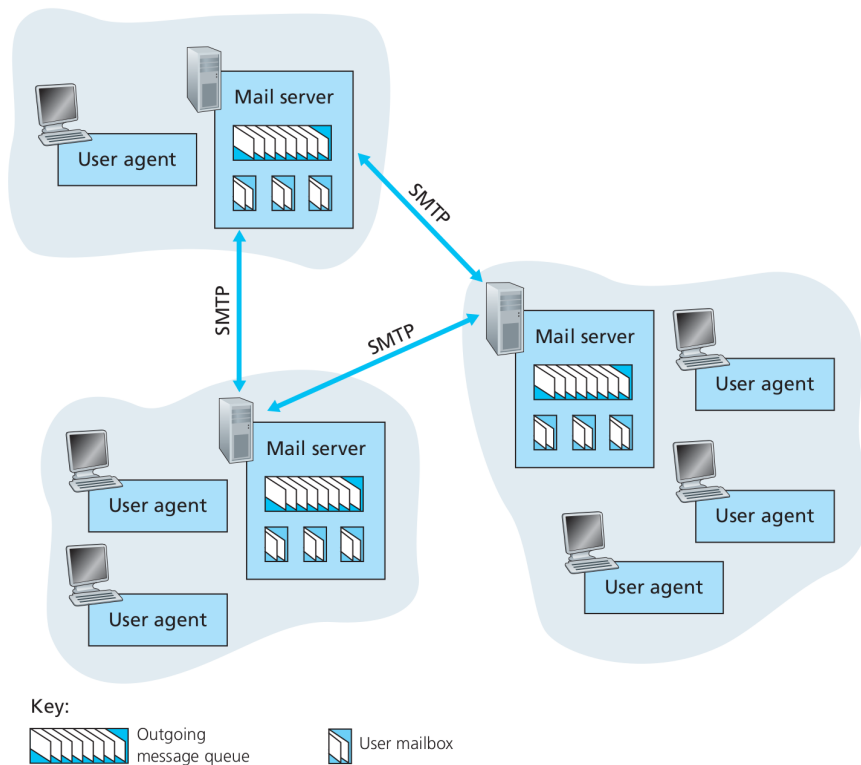


Figure 2.9: High-level view of email system

Three major components of in Figure 2.9:

1. User agents
2. Mail servers
3. SMTP: Simple Mail Transfer Protocol

Sender's view:

1. User agent allows the sender to compose the message.
2. The user agent sends the message to the email server.
3. The message is placed in the mail server's outgoing message queue.
4. The recipient retrieves the message from his/her mailbox in the mail server.

Mail servers form the core of the e-mail infrastructure. Each recipient has a *mailbox* located in one of the mail servers. The mailbox manages and maintains the messages that have been sent to the recipient.

The typical message's journey:

1. Sender's user agent.
2. Sender's mail server.
3. Recipient's mail server.
4. Recipient's mailbox.

The sender mail server must also deal with failures in the recipient mail box: If the sender server can not delivery mail to the recipient server, sender server holds the message in a message queue and attempts to transfer the message later.

2.5.1 SMTP: Simple Mail Transfer Protocol

SMTP uses TCP to transfer mail *from the sender's mail server to the recipient's mail server*.

When a mail server sends mail to other mail servers, it acts as an SMTP client. When a mail server receives mail from other mail servers, it acts as an SMTP server.

SMTP restricts the body of all mail messages to simple 7-bit ASCII.

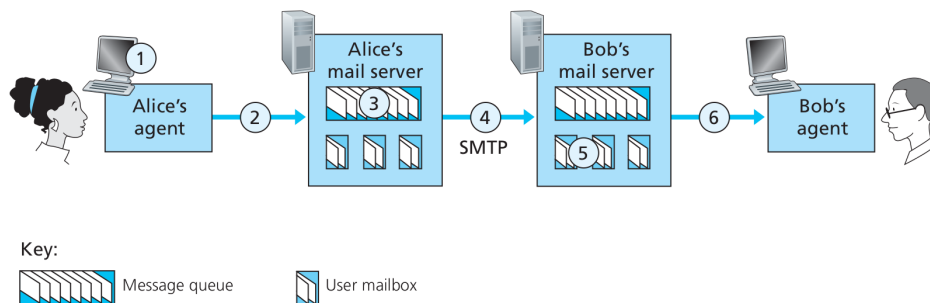


Figure 2.10: Alice sends a message to Bob

When Alice sends Bob an ASCII message:

1. Alice invokes her user agent for e-mail, provides Bob's e-mail address (for example, bob@someschool.edu), composes a message, and instructs the user agent to send the message.
2. Alice's user agent sends the message to her mail server, where it is placed in a message queue.
3. The client side of SMTP, running on Alice's mail server, sees the message in the message queue. It opens a TCP connection to an SMTP server, running on Bob's mail server.
4. After some initial SMTP handshaking, the SMTP client sends Alice's message into the TCP connection.
5. At Bob's mail server, the server side of SMTP receives the message. Bob's mail server then places the message in Bob's mailbox.
6. Bob invokes his user agent to read the message at his convenience.

Detailed SMTP

SMTP does not use intermediate email servers for sending email. SMTP establishes a connection to port 25 at the server SMTP. Once the connection is established, the server and client perform some application layer-handshaking. SMTP client indicates the e-mail address of the sender and the e-mail address of the recipient. Once the handshaking is complete, the client sends the message and repeats if there are more messages to send to the same server.

Example:

1. S: 220 hamburger.edu
2. C: HELO crepes.fr
3. S: 250 Hello crepes.fr, pleased to meet you
4. C: MAIL FROM: <alice@crepes.fr>
5. S: 250 alice@crepes.fr ... Sender ok
6. C: RCPT TO: <bob@hamburger.edu>
7. S: 250 bob@hamburger.edu ... Recipient ok
8. C: DATA

9. S: 354 Enter mail, end with "." on a line by itself
10. C: Do you like ketchup?
11. C: How about pickles?
12. C: .
13. S: 250 Message accepted for delivery
14. C: QUIT
15. S: 221 hamburger.edu closing connection

Comparison with HTTP

Common: Both persistent HTTP and SMTP use persistent connections.

Difference:

1. The HTTP is mainly a *pull protocol*; SMTP is primarily a *push protocol*.
2. The message has to be encoded into 7-bit ASCII while using SMTP; HTTP doesn't impose this restriction.
3. HTTP encapsulates each object in its own HTTP response message; Internet mail places all of the message's objects into one message.

Mail message format

A typical message header looks like this:

From: alice@crepes.fr
To: bob@hamburger.edu
Subject: Searching for the meaning of life.

Mail access protocol

Recall that a mail server manages mailboxes and runs the client and server sides of SMTP. If Bob's mail server were to reside on his local PC, then Bob's PC would have to remain always on, and connected to the Internet. Instead, a typical user runs a user agent on the local PC but accesses its mailbox stored on an always-on shared mail server. This mail server is shared with other users and is typically maintained by the user's ISP.

How can Bob retrieve his email from the mailbox?

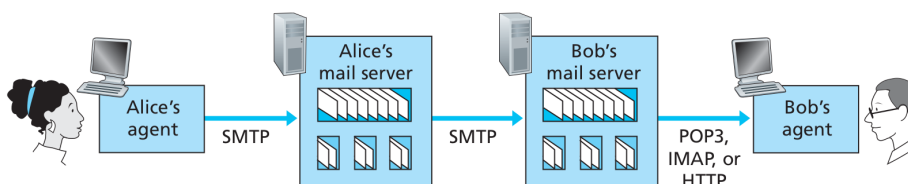


Figure 2.11: Retrieve mail from mailbox

Protocols like **POP3** (Post Office Protocol version 3.0), **IMAP** (Internet Mail Access Protocol), and **HTTP** are used to pull mail from mail server to the recipient's agent.

POP3

POP3 is extremely simple mail access protocol, and it is short and readable. Because the protocol is so simple, its functionality is rather limited.

POP3 begins when the user agent opens a TCP connection to mail server on *port 110*. With the TCP connection established, POP3 progresses through three phases: authorization, transaction, and update.

During the first phase, authorization, the user agent sends a username and a password (in the clear) to authenticate the user.

During the second phase, transaction, the user agent retrieves messages; also during this phase, the user agent can mark messages for deletion, remove deletion marks, and obtain mail statistics.

The third phase, update, occurs after the client has issued the quit command, ending the POP3 session; at this time, the mail server deletes the messages that were marked for deletion.

In a POP3 transaction, the user agent issues commands, and the server responds to each command with a reply. There are two possible responses: *+OK* (sometimes followed by server-to-client data), used by the server to indicate that the previous command was fine; and *-ERR*, used by the server to indicate that something was wrong with the previous command.

The sequence of commands issued by a POP3 user agent depends on which of these two modes the user agent is operating in. In the download-and-delete mode, the user agent will issue the list, retr, and dele commands.

Transaction phrase example:

1. C: list
2. S: 1 498
3. S: 2 912
4. S: .
5. C: retr 1
6. S: (blah blah ...
7. S:)
8. S:blah)
9. S: .
10. C: dele 1
11. C: retr 2
12. S: (blah blah ...
13. S:)
14. S:blah)
15. S: .
16. C: dele 2
17. C: quit
18. S: +OK POP3 server signing off

2.5.2 IMAP: Internet Mail Access Protocol

The POP3 doesn't provide any means of a user to create remote folders and assign messages to folders. => IMAP is introduced to solve this problem, but it is significantly more complex.

An IMAP server will associate each message with a folder; when a message first arrives at the server, it is associated with the recipient's INBOX folder. The recipient can then move the message into a new, user-created folder, read the message, delete the message, and so on.

Another important feature of IMAP is that it has commands that permit a user agent to obtain components of messages. For example, a user agent can obtain just the message header of a message or just one part of a multipart MIME message. This feature is useful when there is a low-bandwidth connection between the user agent and its mail server.

2.5.3 Web-Based E-mail

Hotmail introduced Web-based access in the mid 1990s. With this service, the user agent is an ordinary Web browser, and the user communicates with its remote mailbox via HTTP.