SPECIFICATION OF INTERNET TRANSMISSION CONTROL PROGRAM

TCP (Version 2)

Vinton Cerf

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1. Introduction

This document describes the functions to be performed by the internetwork Transmission Control Program (TCP) and its interface to programs or users that require its services. There have been two previous TCP specifications, the first [CDS74] defined version 1 of TCP. A second, [PGR76a], was written for the Defense Communication Agency in connection with its AUTODIN II project. That version marked improvements (such as a specification of the resynchronization process) and additions (security and priority) which were known requirements of AUTODIN II. The present specification represents version 2 TCP, a direct descendent of the version 1 found in [CDS74]. Elements of version 2 can be found in [PGR76a], but the overlap is incomplete. A simpler resynchronization procedure has been found; an “option” field has been defined for the TCP header to accommodate not only security and priority but other special features connected with, for example, packet speech services, diagnostic timestamping, and so on.

Version 2 eliminates all error messages but for RESET and this simplifies the header format. There are still many local errors which can be reported to the user, but none of these need cross the network(s) between TCP’s.

Connection closing is slightly more elaborate in Version 2 than in version 1 because the FIN signals must be acknowledged. Furthermore, the INT and FIN facilities no longer cause flushing of the data stream. A separate “flush” facility was tested, but eliminated, in the end. Dealing with flow-control windows that have gone to zero is a new feature of version 2, and, finally, the reassembly of fragments into segments has been more carefully specified. In the AUTODIN II version of TCP, modifications were made to support security and priority. These have been left out of this version 2 specification pending their further assessment in connection with ARPA-sponsored end-to-end security projects. A version 3 TCP is anticipated which will address facilities needed for reliable broadcast services, packet speech, an graphics, as well as security, priority, internetwork flow control and routing.

Although the list of participants in the TCP work is very long (see [CEHKKS77]—the final TCP project report), special acknowledgements are due to R. Kahn, R. Tomlinson, Y. Dalal, R. Karp and C. Sunshine for their active participation in the design of TCP.

Several basic assumptions are made about process to process communication and these are listed here without further justification. The interested reader is referred to [CK74, Tomlinson74, Belsnes74, Dalal74, Dalal75, Sunshine76a, CEHKKS77] for further discussion. Processes are viewed as the active elements of all HOST computers in a network. Even terminals and files or

other I/O media are viewed as communicating through the use of processes. Thus, all network communication is viewed as inter-process communication.

Since a process may need to distinguish among several communication streams between itself and another process [or processes], we imagine that each process may have a number of PORTs through which it communicates with the ports of other processes.

Since port names are selected independently by each operating system, TCP, or user, they may not be unique. To provide for unique names at each TCP, we concatenate a NETWORK identifier, and a TCP identifier with a port name to create a SOCKET name which will be unique throughout all networks connected together.

A pair of sockets form a CONNECTION which can be used to carry data in either direction [i.e. full duplex]. The connection is uniquely identified by the <local socket, foreign socket> address pair, and the same local socket name can participate in multiple connections to different foreign sockets [see section 2.2].

Processes exchange finite length LETTERS as a way of communicating; thus, letter boundaries are significant. However, the length of a letter may be such that it must be broken into SEGMENTS before it can be transmitted to its destination. We assume that the segments will normally be reassembled into a letter before being passed to the receiving process. Throughout this document, it is legitimate to assume that a segment contains all or a part of a letter, but that a segment never contains parts of more than one letter.

Furthermore, there is no restriction on the length of a letter. A connection might be formed to send a single long letter (a stream of bytes, in effect). In fact, processes can communicate via TCP without ever marking the end of a letter, but we think this is atypical of most anticipated use.

We specifically assume that segments are transmitted from Host to Host through means of a PACKET SWITCHING NETWORK [PSN] [RW70, Pouzin73]. This assumption is probably unnecessary, since a circuit switched network, or a hybrid combination of the two, could also be used, but for concreteness, we explicitly assume that the hosts are connected to one or more PACKET SWITCHES [PS] of a PSN [HKOCW70, Pouzin74, SW71].

Processes make use of the TCP by handing it letters (or buffers filled with parts of a letter). The TCP breaks these into segments, if necessary, and then embeds each segment in an INTERNETWORK PACKET. Each internetwork packet is in turn embedded in a LOCAL PACKET suitable for transmission from the host to one of its serving PS. The packet switches

may perform further formatting, fragmentation, or other operations to achieve the delivery of the local packet to the destination Host.

The term LOCAL PACKET is used generically here to mean the formatted bit string exchanged between a host and a packet switch. The format of bit strings exchanged between the packet switches in a PSN will generally not be of concern to us. If an internetwork packet is destined for a TCP in a foreign PSN, the packet is routed to a gateway which connects the origin PSN with an intermediate or the destination PSN. Routing of internetwork packets to the gateway may be the responsibility of the source TCP or the local PSN, depending upon the PSN services available.

One model of TCP operation is to imagine that there is a basic gateway associated with each TCP which provides an interface to the local network. This basic gateway performs routing and packet reformatting or embedding, and may also implement congestion and error control between the TCP and gateways at or intermediate to the destination TCP.

At a gateway between networks, the internetwork packet is unwrapped from its local packet format and examined to determine through which network the internetwork packet should travel next. The internetwork packet is then wrapped in a local packet format suitable to the next network and passed on to a new packet switch.

A gateway is permitted to break up a segment carried by an internetwork packet into smaller FRAGMENTS if this is necessary for transmission through the next network. To do this, the gateway produces a set of internetwork packets, each carrying a fragment. Fragments may be broken into smaller ones at intermediate gateways. The packet format is designed so that the destination TCP can reassemble fragments into segments and verify the end-to-end checksum associated with the segment. Segments, of course, can be reassembled into letters.

The TCP is responsible for regulating the flow of internetwork packets to and from the processes it serves, as a way of preventing its host from becoming saturated or overloaded with traffic. The TCP is also responsible for retransmitting unacknowledged packets, and for detecting duplicates. A consequence of this error detection/retransmission scheme is that the order of letters received on a given connection can also be maintained [CK74, Sunshine74]. To perform these functions, the TCP opens and closes connections between ports as described in section 4.2. The TCP performs retransmission, duplicate detection, sequencing, and flow control on all communication among the processes it serves.

2. The TCP Interface to the User

The functional description of user commands to the TCP is, at best, fictional, since every operating system will have different facilities. Consequently, we must warn readers that various TCP implementations may have different user interfaces. These will all be TCP's, as long as control messages are properly interpreted or emitted, as required. In spite of this caveat, it appears useful to have at least one concrete view of a user interface to aid in thinking about TCP-derived services.

2.1 The TCP as a Post Office

The TCP acts in many ways like a postal service since it provides a way for processes to exchange letters with each other. It sometimes happens that a process may offer some service, but not know in advance what its correspondents' addresses are. The analogy can be drawn with a mail order house which opens a post office box which can accept mail from any source. Unlike the post box, however, once a letter from a particular correspondent arrives, a port becomes specific to the correspondent until the owner of the port declares otherwise (thus making the TCP more like a telephone service). Without this particularization, the TCP could not perform its flow control, sequencing, duplicate detection, end-to-end acknowledgement, and error control services.

2.2 Sockets and Addressing

We have borrowed the term SOCKET from the ARPANET terminology [CCC70, DCA76]. In general, a socket is the concatenation of a NETWORK identifier, TCP identifier, and PORT identifier. A CONNECTION is fully specified by the pair of SOCKETS at each end since the same local socket name may participate in many connections to different foreign sockets.

Once the connection is specified in the OPEN command [see section 2.3.2], the TCP supplies a [short] local connection name by which the user refers to the connection in subsequent commands. In particular this facilitates using connections with initially unspecified foreign sockets.

TCP's are free to associate ports with processes however they choose. However, several basic concepts seem necessary in any implementation. There must be well known sockets which the TCP associates only with the "appropriate" processes by some means. We envision that processes may "own" sockets, and that processes can only initiate connections on the sockets they own [means for implementing ownership is a local issue, but we envision a Request Port

user command, or a method of uniquely allocating a group of ports to a given process, e.g. by associating the high order bits of a port name with a given process].

Once initiated, a connection may be passed to another process that does not own the local socket [e.g. from logger to service process]. Strictly speaking this is a reconnection issue which might be more elegantly handled by a general reconnection protocol as discussed in section 3.3. To simplify passing a connection within a single TCP, however, such “invisible” switches may be allowed, as in TENEX systems.

Of course, each connection is associated with exactly one process, and any attempt to reference that connection by another process will be signaled as an error by the TCP. This prevents another process from stealing data from or inserting data into another process’ data stream, and also prevents masquerading, spoofing, or other forms of malicious mischief.

A connection is initiated by the rendezvous of an arriving internetwork packet and awaiting Transmission Control Block [TCB] created by a user OPEN, SEND, INTERRUPT, or RECEIVE command [see section 2.3]. The matching of local and foreign socket identifiers determines when a successful connection has been initiated. The connection becomes established when sequence numbers have been synchronized in both directions as described in section 4.2.2.

It is possible to specify a socket only partially by setting the PORT identifier to zero or setting both the TCP and PORT identifiers to zero. A socket of all zero is called UNSPECIFIED. The purpose behind unspecified sockets is to provide a sort of “general delivery” facility [useful for processes offering services on well known sockets].

There are bounds on the degree of unspecificity of socket identifiers. TCB’s must have fully specified local sockets, although the foreign socket may be fully or partly unspecified. Arriving packets must have fully specified sockets.

We employ the following notation:

x.y.z = fully specified socket with x=net, y=TCP, z=port
x.y.u = as above, but unspecified port
x.u.u = as above, but unspecified TCP and port
u.u.u = completely unspecified
with respect to implementation, u=0 [zero]

We illustrate the principles of matching by giving all cases of incoming packets which match with existing TCB's. Generally, both the local (foreign) socket of the TCB and the foreign (local) socket of the packet must match.

	TCB local	**TCB foreign**	**Packet local**	**Packet foreign**
(a)	a.b.c	e.f.g	e.f.g	a.b.c
(b)	a.b.c	e.f.u	e.f.g	a.b.c
(c)	a.b.c	e.u.u	e.f.g	a.b.c
(d)	a.b.c	u.u.u	e.f.g	a.b.c

There are no other legal combinations of socket identifiers which match. Case (d) is typical of the ARPANET well known socket idea in which the well known socket (a.b.c) LISTENS for a connection from any (u.u.u) socket. Cases (b) and (c) can be used to restrict matching to a particular TCP or net. More elaborate masking facilities could be implemented without adverse effects, so this matching facility could be considered the minimum acceptable for TCP operation.

2.3 TCP User Commands

2.3.1 A Note on Style

The following sections functionally characterize a USER/TCP interface. The notation used is similar to most procedure or function calls in high level languages, but this usage is not meant to rule out trap type service calls [e.g., SVC's, UUO's, EMT's,…].

The user commands described below specify the basic functions the TCP will perform to support interprocess communication. Individual implementations should define their own exact format, and may provide combinations or subsets of the basic functions in single calls. In particular, some implementations may wish to automatically OPEN a connection on the first SEND, RECEIVE, or INTERRUPT issued by the user for a given connection.

In providing interprocess communication facilities, the TCP must not only accept commands, but also return information to the processes it serves. This communication consists of:

1. general information about a connection [e.g., interrupts, remote close, binding of unspecified foreign socket].
2. replies to specific user commands indicating success or various types of failure.

Although the means for signalling user processes and the exact format of replies will vary from one implementation to another, it would promote common understanding and testing if a common set of codes were adopted. Such a set of event codes is described in section 2.4.

2.3.2 Open

Format: OPEN (local port, foreign socket [, timeout])

We assume that the local TCP is aware of the identity of the processes it serves and will check the authority of the process to use the connection specified. Depending upon the implementation of the TCP, the source network and TCP identifiers will either be supplied by the TCP or by the processes that serve it [e.g. the program which interfaces the TCP to its packet switch or the packet switch itself]. These considerations are the result of concern about security, to the extent that no TCP be able to masquerade as another one, and so on. Similarly, no process can masquerade as another without the collusion of the TCP.

If no foreign socket is specified [i.e. the foreign socket parameter is 0 or not present], then this constitutes a LISTENING local socket which can accept communication from any foreign socket. Provision is also made for partial specification of foreign sockets as described in section 2.2.

If the specified connection is already OPEN, an error is returned, otherwise a full-duplex transmission control block [TCB] is created and partially filled in with data from the OPEN command parameters. The TCB format is described in more detail in section 4.3.2.

No network traffic need be generated by the OPEN command. The first SEND or INTERRUPT by the local user or the foreign user will typically cause the TCP to synchronize the connection, although synchronization could be immediately initiated on non-listening opens.

The timeout, if present, permits the caller to set up a timeout for all buffers transmitted on the connection. If a buffer is not successfully delivered to the destination within the timeout period, the TCP will abort the connection. The present global default is 30 seconds. The buffer retransmission rate may vary, and is the responsibility of the TCP and not the user. Most likely, it will be related to the measured time for responses from the remote TCP.

Depending on the TCP implementation, either a local connection name will be returned to the user by the TCP, or the user will specify this local connection name (in which case another parameter is needed in the call). The local connection name can then be used as a short hand term for the connection defined by the <local socket, foreign socket> pair.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

2.3.3 Send

Format: SEND(local connection name, buffer address, byte count, EOL flag [, timeout])

This call causes the data contained in the indicated user buffer to be sent on the indicated connection. If the connection has not been opened, the SEND is considered an error. Some implementations may allow users to SEND first, in which case an automatic OPEN would be done. If the calling process is not authorized to use this connection, an error is returned.

If the EOL flag is set, the data is the End Of a Letter, and the EOL bit will be set in the last internetwork packet created from the buffer (see section 4.3.2—internetwork packet format). If the EOL flag is not set, subsequent SENDs will appear to be part of the same letter.

If no foreign socket was specified in the OPEN, but the connection is established [e.g. because a LISTENing connection has become specific due to a foreign packet arriving for the local socket] then the designated buffer is sent to the implied foreign socket. In general, users who make use of OPEN with an unspecified foreign socket can make use of SEND without ever explicitly knowing the foreign socket address.

However, if a SEND is attempted before the foreign socket becomes specified, an error will be returned. Users can use the STATUS call to determine the status of the connection. In some implementations the TCP may notify the user when an unspecified socket is bound.

If the timeout is specified, then the current timeout for this connection is changed to the new one.

In the simplest implementation, SEND would not return control to the sending process until either the transmission was complete or the timeout had been exceeded. This simple method is both highly subject to deadlocks [for example, both sides of the connection might try to do SENDs before doing any RECEIVEs] and offers poor performance, so it is not recommended. A more sophisticated implementation would return immediately to allow the process to run concurrently with network I/O, and, furthermore, to allow multiple SENDs to be in progress. Multiple SENDs are served in first come, first served order, so the TCP will queue those it cannot service immediately.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

We have implicitly assumed an asynchronous user interface in which a SEND later elicits some kind of SIGNAL or pseudo-interrupt from the serving TCP. An alternative is to return a response immediately. For instance, SENDs might return immediate local acknowledgment, even if the packet sent had not been acknowledged by the distant TCP. We could optimistically assume eventual success. If we are wrong, the connection will close, anyway, due to the timeout. In implementations of this kind (synchronous), there will still be some asynchronous signalling, but these will deal with the connection itself, and not with specific packets or letters.

NOTA BENE: In order for the process to distinguish among error or success indications for different SENDs, the buffer address should be returned along with the coded response to the SEND request. We will offer an example event code format in section 2.4, showing the information which should be returned to the calling process.

2.3.4 Receive

Format: RECEIVE (local connection name, buffer address, byte count)

This command allocates a receiving buffer associated with the specified connection. If no OPEN precedes this command or the calling process is not authorized to use this connection, an error is returned.

In the simplest implementation, control would not return to the calling program until either the buffer was filled, or some error occurred, but this scheme is highly subject to deadlocks [see section 2.3.3]. A more sophisticated implementation would permit several RECEIVE's to be outstanding at once. These would be filled as letters, segments, or fragments arrive. This strategy permits increased throughput, at the cost of a more elaborate scheme [possibly asynchronous] to notify the calling program that a letter has been received or a buffer filled.

If insufficient buffer space is given to reassemble a complete letter, the EOL flag will not be set in the response to the RECEIVE. The buffer will be filled with as much data as it can hold (see section 2.4.2).

The remaining parts of a partly delivered letter will be placed in buffers as they are made available via successive RECEIVES. If a number of RECEIVES are outstanding, they may be filled with parts of a single long letter or with at most one letter each. The event codes associated with each RECEIVE will indicate what is contained in the buffer.

To distinguish among several outstanding RECEIVES, and to take care of the case that a letter is smaller than the buffer supplied, the event code is accompanied by both a buffer pointer and a byte count indicating the actual length of the letter received.

Responses from the TCP which may occur as a result of this command are detailed in sections 2.4 and 4.2.6.

Alternative implementations of RECEIVE might have the TCP allocate buffer storage, or the TCP might share a ring buffer with the user. Variations of this kind will produce obvious variation in user interface to the TCP.

2.3.5 Close

Format: CLOSE(local connection name)

This command causes the connection specified to be closed. If the connection is not open or the calling process is not authorized to use this connection, an error is returned. Closing connections is intended to be a graceful operation in the sense that outstanding SENDs will be transmitted (and retransmitted), as flow control permits, until all have been serviced. Thus, it should be acceptable to make several SEND calls, followed by a CLOSE, and expect all the data to be sent to the destination. It should also be clear that users should continue to RECEIVE on CLOSING connections, since the other side may be trying to transmit the last of its data. Thus, CLOSE means “I have no more to send” but does not mean “I will not receive any more.” It may happen (if the user level protocol is not well thought out) that the closing side is unable to get rid of all its data before timing out. In this event, CLOSE turns into ABORT, and the closing TCP gives up.

The user may CLOSE the connection at any time on his own initiative, or in response to various prompts from the TCP [e.g., remote close executed, transmission timeout exceeded, destination inaccessible].

Because closing a connection requires communication with the foreign TCP, connections may remain in the closing state for a short time. Attempts to reopen the connection before the TCP replies to the CLOSE command will result in errors.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

2.3.6 Interrupt

Format: INTERRUPT(local connection name)

A special control signal is sent to the destination indicating an interrupt condition. This facility can be used to simulate “break” signals from terminals or error or completion codes from I/O devices, for example. The semantics of this signal to the receiving process are unspecified. The receiving TCP will signal the interrupt to the receiving process upon receiving all data preceding the interrupt.

If the connection is not open or the calling process is not authorized to use this connection, an error is returned.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

2.3.7 Status

Format: STATUS (local connection name)

This is an implementation dependent user command and could be excluded without adverse effect. Information returned would typically come from the TCB (see section 4.3.3) associated with the connection.

This command returns a data block containing the following information:

> local socket, foreign socket, local connection name, receive window, send window, connection state, number of buffers awaiting acknowledgement, number of buffers pending receipt [including partial ones], default transmission timeout

Depending on the state of the connection, or the implementation some of this information may not be available or meaningful. If the calling process is not authorized to use this connection, an error is returned. This prevents unauthorized processes from gaining information about a connection.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

2.3.8 Abort

Format: ABORT (local connection name)

This command causes all pending SENDs, INTERRUPTS, and RECEIVES to be aborted, the TCB to be removed, and a special RESET message to be sent to the TCP on the other side of the connection. Depending on the implementation, users may receive abort indications for each outstanding SEND, RECEIVE, or INTERRUPT, or may simply receive an ABORT-acknowledgment. The mechanism of resetting a connection is discussed in sections 4.2.3 and 4.2.6.

Responses from the TCP which may occur as a result of this call are detailed in sections 2.4 and 4.2.6.

2. 4 TCP-to-User Messages

2.4.1 Type Codes

All messages include a type code which identifies the type of user call to which the message applies. Types are:

0 — General message, spontaneously sent to user
1 — Applies to OPEN
2 — Applies to CLOSE
3 — Applies to INTERRUPT
4 — Applies to ABORT
10— Applies to SEND
20— Applies to RECEIVE
30— Applies to STATUS

2.4.2 Message Formats [notional]

All messages include the following three fields:

Type code
Local connection name
Event code

For message types 0–4 [General, Open, Close, Interrupt, Abort] only these three fields are necessary.

For message type 10 [Send] one additional field is necessary:

Buffer address

For message type 20 [Receive] three additional fields are necessary:

Buffer address
Byte count (counts bytes received)
End-of-Letter flag

For message type 30 [Status] additional data might include:

Local socket, foreign socket
Send window [measures buffer space at foreign TCP]
Receive window [measures buffer space at local TCP]
Connection state [see section 4.2.6]
Number of buffers awaiting acknowledgement
Number of buffers awaiting receipt
User timeout

Once more, it is important to note that these formats are notional. Implementations which deal with buffering in different ways may or may not need to include buffer addresses in some responses, for example.

2.4.3 Event Codes

The event code specifies the particular event that the TCP wishes to communicate to the user. Generally speaking, non-zero event codes indicate import state changes or errors.

In addition to the event code, two flags may be useful to classify the event into major categories and facilitate event processing by the user:

E flag: set if event is an error
P flag: set if permanent error (otherwise, retry may succeed).

Events are encoded in 8 bits, the two high order bits being reserved for E and P flags, respectively.

Events specified so far are listed below with their codes and flag settings.

flags	code	meaning
	0	general success
E,P	1	connection illegal for this process
	2	unspecified foreign socket has become bound
E,P	3	connection not OPEN
	4	insufficient resources
E	5	foreign socket not specified
E,P	6	connection already OPEN
	7	unused
	8	unused
E,P	9	user timeout, connection aborted
	10	unused
	11	user interrupt received
P	12	connection closing
E	13	general error
P	14	connection reset

Possible responses to each of the user commands are listed below. Section 4.2.6 offers substantially more detail.

Type 0[general] : 2,9,11,12,14
Type 1[open] : 0,1,4,6,13
Type 2[close] : 0,1,3,9,13,14
Type 3[interrupt] : 0,1,3,4,5,9,12,13,14
Type 4[Abort] : 0,1,3,13
Type 10[send] : 0,1,3,4,5,9,12,13,14
Type 20[receive] : 0,1,3,4,9,12,13,14
Type 30[status] : 0,1,3,13

3. Higher Level Protocols

3.1 Introduction

It is expected that the TCP will be able to support higher level protocols efficiently. It should be easy to interface existing ARPANET protocols like TELNET [DCA76] and FTP [DCA76] to the TCP. Support of Network Voice Protocol, Network Graphics Protocol and broadcast protocols has been left to version 3 TCP, in preparation.

3.2 Well Known Sockets

Well known sockets are a convenient mechanism for a priori associating a socket name with a standard service. For instance, the “logger” process might be permanently assigned to socket 1, and other sockets reserved for File Transfer, Remote Job Entry, text generator, reflector, or sink (the last being for test purposes). A socket name might be reserved for access to a “look-up” service which would return the specific socket at which a newly instantiated service would be provided.

For compatibility with ARPANET socket naming conventions, we have reserved a few socket names as follows:

n.t.1 = Logger port
n.t.3 = File Transfer Port
n.t.5 = Remote Job Entry port
“n” and “t” are network and TCP identifiers, respectively

TCP implementors should note, however, that the gender and directionality of NCP sockets do not apply to TCP sockets, so that even numbered as well as odd ones can serve as well known sockets.

3.3 Reconnection Protocol

Port identifiers fall into two categories: permanent and transient. For example, a Logger process is generally assigned a port identifier that is fixed and well known. Transient processes will in general have port identifiers which are dynamically assigned.

In a distributed processing environment, two processes that don’t have well known port identifiers may often wish to communicate. This can be achieved with the help of a well known process using a reconnection protocol. Such a protocol is briefly outlined using the communication facilities provided by the TCP. It essentially provides a mechanism by which port identifiers are exchanged in order to establish a connection between a pair of sockets.

Such a protocol can be used to achieve the dynamic establishment of new connections in order to have multiple processes solving a problem co-operatively, or to provide a user process access to a server process via a logger, when the logger’s end of the connection can not be invisibly passed to the server process.

A paper on this subject by R. Schantz [Schantz74] discusses some of the issues associated with reconnection, and some of the ideas contained therein went into the design of the protocol outlined below.

In the ARPANET, a protocol (called the Initial Connection Protocol [Postel72]) was implemented which would allow a process to connect to a well known socket, thus making an implicit request for service, and then be switched to another socket so that the well known socket could be freed for use by others. Since sockets in our TCP are permitted to participate in more than one connection name, this facility may not be explicitly needed (i.e. connections <A,B> and <A,C> are distinguishable).

However, the well known socket may be in one network and the actual service socket(s) may be in another network (or at least in another TCP). Thus, the invisible switching of a connection from one port to another within a TCP may not be sufficient as an “Initial Connection Protocol”. We imagine that a process wishes to use socket N1.T1.Q to access well known socket N2.T2.P. However, the process associated with socket N2.T2.P will actually start up a new process somewhere which will use N3.T3.S as its server socket. The N(i) and T(i) may be distinct or the same. The user will send to N2.T2.P the relevant user information such as user name, password, and account. The server will start up the server process and send to N1.T1.Q the actual service socket identifier: N3.T3.S. The connection (N1.T1.Q,N2.T2.P) can then be closed, and the user can do a RECEIVE on (N1.T1.Q,N3.T3.S). The serving process can SEND on (N3.T3.S,N1.T1.Q). There are many variations on this scheme, some involving the user process doing a RECEIVE on a different socket (e.g. (N1.T1.X,U.U.U)) with the server doing SEND on (N3.T3.S,N1.T1.X).

Without showing all the detail of synchronization of sequence numbers and the like, we can illustrate the exchange as shown below.

```
USER                                SERVER
                                 1. RECEIVE(N2.T2.P,U.U.U)
1. SEND(N1.T1.Q,N2.T2.P)    ==>
                            <==  2. SEND(N2.T2.P,N1.T1.Q) with "N3.T3.S" as data
2. RECEIVE(N1.T1.Q,N2,T2.P)
3. CLOSE(N1.T1.Q,N2.T2.P)   ==>
                            <==  3. CLOSE(N2.T2.P,N1.T1.Q)
4. RECEIVE(N1.T1.Q,N3.T3.S)
                            <==  4. SEND(N3.T3.S,N1.T1.Q)
```

Reconnection Protocol Example

Figure 3.3-1

At this point, a connection is open between N1.T1.Q and N3.T3.S. A variation might be to have the user do an extra RECEIVE on (N1.T1.X,U.U.U) and have the data "N1.T1.X" be sent in the first user SEND. Then, the server can start up the real serving process and do a SEND on (N3.T3.S,N1.T1.X) without having to send the "N3.T3.S" data to the user.

Or perhaps both server and receiver exchange this data, to assure security of the ultimate connection (i.e. some wild process might try to connect to N1.T1.X if it is merely RECEIVING on foreign socket U.U.U.).

We do not propose any specific reconnection protocol here, but leave this to further deliberation, since it is really a user level protocol issue.

4. TCP Design

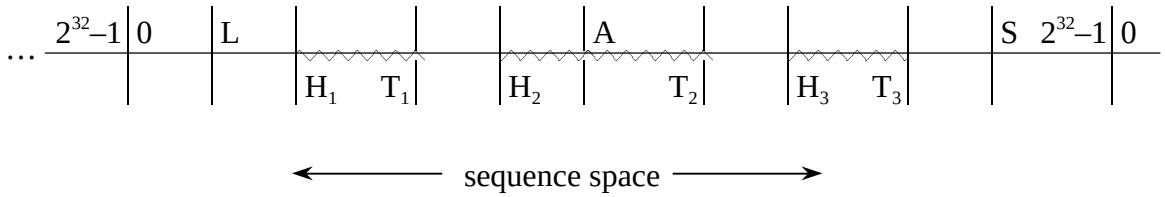
4.1 Introduction

The TCP is designed to offer highly reliable, sequenced, and flow-controlled interprocess communication across network boundaries. A fundamental notion in the design is that every octet (8 bit byte) of data in an internetwork packet has a sequence number. This permits gateways to fragment packets as needed to get them across networks with short packet sizes. Since every octet is sequenced, each of them can be acknowledged individually or collectively. In particular, the acknowledgment mechanism employed is cumulative so that an acknowledgment of sequence number X indicates that all octets up to but not including X have been received. This mechanism allows for straight-forward duplicate detection in the presence of retransmission.

It is essential to remember that the actual sequence number space is finite, though very large. In the current design, this space ranges from 0 to 2**32–1. Since the space is finite, all arithmetic dealing with sequence numbers must be performed modulo 2**32. This unsigned arithmetic preserves the relationship of sequence numbers as they cycle from 2**32–1 to 0 again. The typical kinds of sequence number comparisons which the TCP must perform include:

(1) determining that an acknowledgement refers to some sequence number sent but not yet acknowledged.
(2) determining that all sequence numbers occupied by a packet have been acknowledged (e.g. to remove the packet from a retransmission queue).
(3) determining that an incoming packet contains sequence numbers which are expected (i.e. that the packet "overlaps" the receive window).

The TCP typically maintains status information about each connection, as is illustrated in figure 4.1-1, below.



L = oldest, unacknowledged sequence number
S = next sequence number to be sent
A = acknowledgement (next sequence number expected by the acknowledging TCP)
H(i) = first sequence number of the i-th packet
T(i) = last sequences number of the i-th packet

TCP State Information for Sending Sequence Space
Figure 4.1-1

An acceptable acknowledgement, A, is one for which the inequality below holds:

$$0 < (A - L) <= (S - L) \qquad (4.1\text{-}1)$$

We will often write equation (4.1-1) in the form below:

$$L < A <= S \qquad (4.1\text{-}1')$$

Note that all arithmetic is modulo 2**32 and that comparisons are unsigned. "<=" means "less than or equal."

Similarly, the determination that a particular packet has been fully acknowledged can be made if the equation below holds:

$$0 < (T(i) - L) <= (A - L) \qquad (4.1\text{-}2)$$

In this instance, H(i) and T(i) are related by the equation:

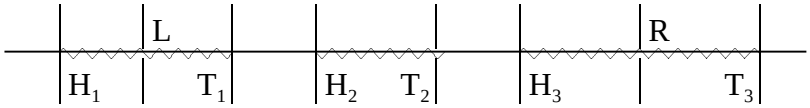
$$T(i) = H(i) + n(i) - 1 \qquad (4.1\text{-}3)$$

where n(i) = the number of octets occupied by the packet (including control). It is important to note that n(i) must be non-zero; packets which do not occupy any sequence space (e.g. empty acknowledgement packets) are never placed on the retransmission queue, so would not go through this particular test.

Finally, a packet is judged to occupy a portion of valid receive sequence space if

$$0 <= (T - L) < (R - L) \qquad (4.1\text{-}4)$$

Where T is the last sequence number occupied by the packet and R is the right edge of the receive window, as shown in figure 4.1-2.



L = next sequence number expected on incoming packets
R = last sequence number expected on incoming packets, plus one
H(i) = first sequence number occupied by the i-th incoming packet
T(i) = last sequence number occupied by the i-th incoming packet

Receive Sequence State Information
Figure 4.1-2

R and L in figure 4.1-2 are related by the equation:

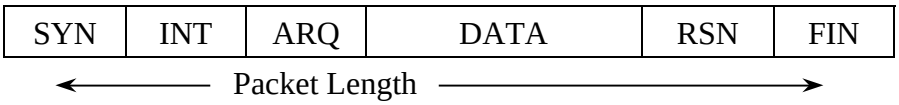
$$R = L + W \qquad (4.1\text{-}5)$$

Where W = the receive window size

Note that the acceptance test for a packet, since it requires the end of a packet to lie in the window, is somewhat more restrictive than is absolutely necessary. If at least the first sequence number of the packet lies in the receive window, or if some part of the packet lies in the receive window, then the packet might be judged acceptable. Thus, in figure 4.1-2, at least packets (H(1)–T(1)) and (H(2)–T(2)) are acceptable by the strict rule and packet (H(3)–T(3)) may or may not be, depending on the rule.

Note that when R = L, the receive window is zero and no packets should be acceptable except ACK packets. Thus, it should be possible for a TCP to maintain a zero receive window while transmitting data and receiving ACKs on a non-zero send window.

We have taken advantage of the numbering scheme to protect certain control information as well. This is achieved by implicitly including some control flags in the sequence space so they can be retransmitted and acknowledged without confusion (i.e. one and only one copy of the control will be acted upon). Control information is not physically carried in the packet data space (see section 4.3.2 for typical internet TCP packet format). Consequently, we must adopt rules for implicitly assigning sequence numbers to control. Figure 4.1-3 shows where, in the sequence space occupied by a packet, the controls (if present) are considered to lie. The packet length includes both data and sequence-space-occupying controls.



Implicit Control Sequence Numbering

Figure 4.1-3

The main jobs of the TCP are:

a. Connection management (establishing and closing full-duplex connections)
b. “Packetizing” of user letters into segments for internet transmission
c. Reassembly of fragments into segments and segments into letters.
d. Flow control, sequencing, duplicate detection, and retransmission for each connection.
e. Reacting to user requests for service

In the sections which follow, we elaborate on the way in which the TCP is designed to carry out each of these tasks.

4.2 Connection Management

4.2.1 Initial Sequence Number Selection

The protocol places no restriction on a particular connection being used over and over again. New instances of a connection will be referred to as incarnations of the connection. The problem that arises owing to this is, “how does the TCP identify duplicate packets from previous incarnations of the connection?”. This problem becomes harmfully apparent if the connection is being opened and closed in quick succession, or if the connection breaks with loss of memory and is then reestablished.

The essence of the solution [Tomlinson74] is that the initial sequence number [ISN] must be chosen so that a particular sequence number can never refer to an “old” octet. Once the connection is established the sequencing mechanism provided by the TCP filters out duplicates.

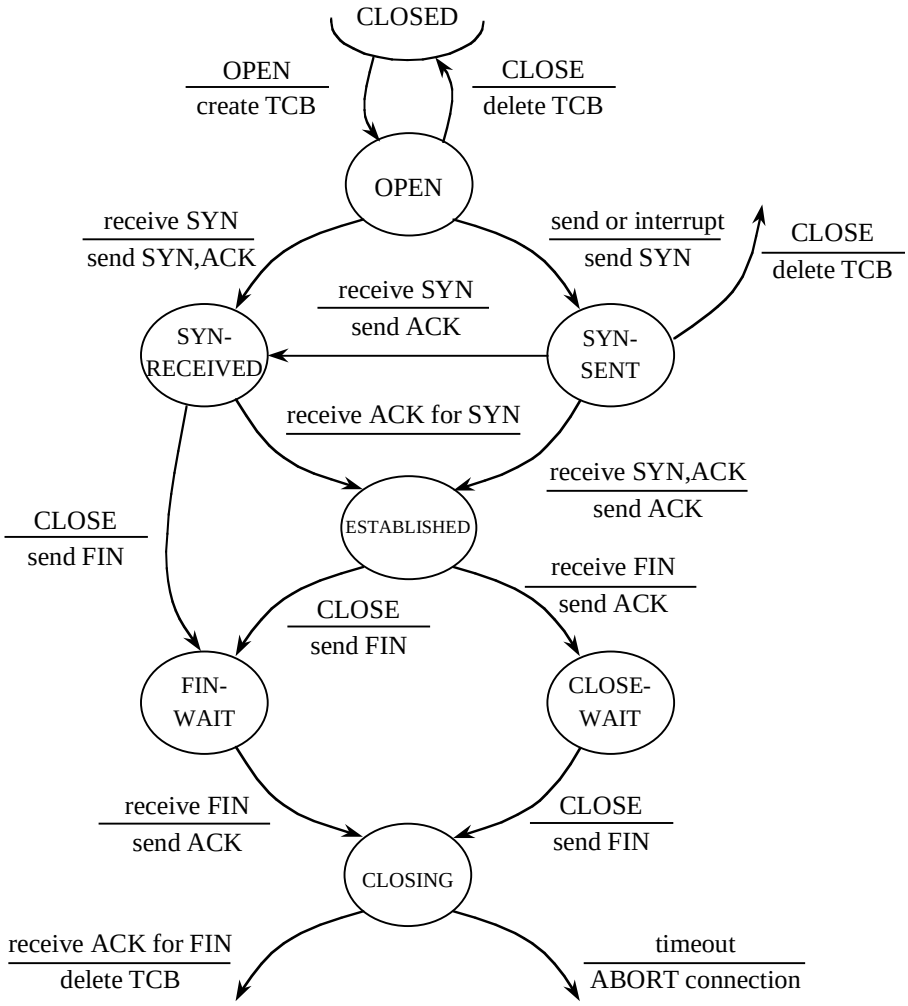
For an association to be established or initialized, the two TCP’s must synchronize on each others initial sequence numbers. Hence the solution requires a suitable mechanism for picking an initial sequence number, and a slightly involved handshake to exchange the ISN’s. A “three way handshake” is necessary because sequence numbers are not tied to a global clock in the network, and TCP’s may have different mechanisms for picking the ISN’s. The receiver of the first SYN has no way of knowing whether the packet was an old delayed one or not, unless it remembers the last sequence number used on the connection (which is not always possible), and so it must ask the sender to verify this SYN.

The “three way handshake” and the advantages of a “clock-driven” scheme are discussed in [Tomlinson74]. More on the subject, and algorithms for implementing the clock-driven scheme can be found in [Dalal74, Dalal75, Cerf76b].

4.2.2 Establishing a connection

The “three-way handshake” is essentially a unidirectional attempt to establish a connection, i.e. there is an initiator and a responder. The TCP can also establish a connection when a simultaneous initiation occurs. A simultaneous attempt occurs when one TCP receives a “SYN” packet which carries no acknowledgement after having sent a “SYN” earlier. Of course, the arrival of an old duplicate “SYN” packet can potentially make it appear, to the recipient, that a

simultaneous connection initiation is in progress. Proper use of “reset” packets can disambiguate these cases. Several examples of connection initiation are offered below, using a notation due to Tomlinson. Although these examples do not show connection synchronization using data-carrying packets, this is perfectly legitimate, so long as the receiving TCP doesn’t deliver the data to the user until it is clear the data is valid (i.e. the data must be buffered at the receiver until the connection reaches the ESTABLISHED state (see figure 4.2-1)).



TCP Connection State Diagram

Figure 4.2-1

The simplest three-way handshake is shown in figure 4.2-2 below. The figures should be interpreted in the following way. Each line is numbered for reference purposes. Right arrows (-->) indicate departure of a TCP packet from TCP A to TCP B, or arrival of a packet at B from A. Left arrows (<--), indicate the reverse. Ellipsis (…) indicates a packet which is still in the network (delayed). An “XXX” indicates a packet which is lost or rejected. Comments appear in

parentheses. TCP states are keyed to those in figure 4.2-1, and represent the state AFTER the departure or arrival of the packet (whose contents are shown in the center of each line). Packet contents are shown in abbreviated form, with sequence number, control flags, and ACK field. Other fields such as window, addresses, lengths, and text have been left out, generally, in the interest of clarity.

	TCP A				TCP B
1.	OPEN				OPEN
2.	SYN-SENT	-->	<SEQ 100><SYN>	-->	SYN-RECEIVED
3.	ESTABLISHED	<--	<SEQ 300><SYN><ACK101>	<--	SYN-RECEIVED
4.	ESTABLISHED	-->	<SEQ 101><ACK 301>	-->	ESTABLISHED
5.	ESTABLISHED	-->	<SEQ 101><ACK 301><DATA>	-->	ESTABLISHED

Basic 3-Way Handshake for Connection Synchronization

Figure 4.2-2

In line 2 of figure 4.2-2, TCP A begins by sending a SYN packet indicating that it will use sequence numbers starting with sequence number 100. In line 3, TCP B sends a SYN and acknowledges the SYN it received from TCP A. Note that (per figure 4.1-3), the acknowledgement field indicates TCP B is now expecting to hear sequence 101, implicitly acknowledging the SYN which occupied sequence 100.

At line 4, TCP A responds with an empty packet containing an ACK for TCP B's SYN, and in line 5, TCP A sends some data. Note that the sequence number of the packet in line 5 is the same as in line 4 because the ACK does not occupy sequence number space (if it did, we would wind up ACKing ACK's!).

Simultaneous initiation is only slightly more complex, as is shown in figure 4.2-3. Each TCP cycles from OPEN to SYN-SENT to SYN-RECEIVED to ESTABLISHED.

The principle reason for the three-way handshake is to prevent old duplicate connection initiations from causing confusion. To deal with this, a special control message, RESET, has been devised. A TCP which receives a RESET message first verifies that the ACK field of the RESET acknowledges something the TCP sent (otherwise, the message is ignored). If the receiving TCP is in a non-synchronized state (i.e. SYN-SENT, SYN-RECEIVED), it returns to OPEN on receiving an acceptable RESET. If the TCP is in one of the synchronized states (ESTABLISHED, FIN-WAIT, CLOSE-WAIT, CLOSING) it aborts the connection and informs its user. We discuss this latter case under "half-open" connection in section 4.2.3.

	TCP A				TCP B
1.	OPEN				OPEN
2.	SYN-SENT	-->	<SEQ 100><SYN>	…	
3.	SYN-RECEIVED	<--	<SEQ 300><SYN>	<--	SYN-SENT
4.		…	<SEQ 100><SYN>	-->	SYN-RECEIVED
5.	SYN-RECEIVED	-->	<SEQ 101><ACK 301>	…	
6.	ESTABLISHED	<--	<SEQ 301><ACK 101>	<--	SYN-RECEIVED
7.		…	<SEQ 101><ACK 301>	-->	ESTABLISHED

Simultaneous Connection Synchronization

Figure 4.2-3

	TCP A				TCP B
1.	OPEN				OPEN
2.	SYN-SENT	-->	<SEQ 100><SYN>	…	
3.	(duplicate)	…	<SEQ 1000><SYN>	-->	SYN-RECEIVED
4.	SYN-SENT	<--	<SEQ 300><SYN><ACK 1001>	<--	SYN-RECEIVED
5.	SYN-SENT	-->	<SEQ 1001><RST><ACK 301>	-->	OPEN (ACK is ok)
6.		…	<SEQ 100><SYN>	-->	SYN-RECEIVED
7.	SYN-SENT	<--	<SEQ 400><SYN><ACK 101>	<--	SYN-RECEIVED
8.	ESTABLISHED	-->	<SEQ 101><ACK 401>	-->	ESTABLISHED

Recovery from Old Duplicate SYN

Figure 4.2-4

As a simple example of recovery from old duplicates, consider figure 4.2-4. At line 3, and old duplicate SYN arrives at TCP B. TCP B cannot tell that this is an old duplicate, so it responds normally (line 4). TCP A detects that the ACK field is incorrect and returns a RST (reset) with its SEQ and ACK fields selected to make the packet believable. TCP B, on receiving the RST, returns to the OPEN state. When the original SYN (pun intended) finally arrives at line 6, the synchronization proceeds normally. If the SYN at line 6 had arrived before the RST, a more complex exchange might have occurred with RST's sent in both directions.

4.2.3 Half-Open Connections and Other Anomalies

An established connection is said to be "half-open" if one of the TCP's has closed or aborted the connection at its end without the knowledge of the other, or if the two ends of the connection have become desynchronized owing to a crash that resulted in loss of memory. Such connections

will automatically become reset if an attempt is made to send data in either direction. However, half-open connections are expected to be unusual, and the recovery procedure is mildly involved.

If one end of the connection no longer exists, then an attempt by the other user to send any data on it will result in the sending TCP receiving a RESET control message. Such a message should indicate to the receiving TCP that something is wrong and it is expected to ABORT the connection.

Assume that two user processes A and B are communicating with one another when a crash occurs causing loss of memory to A's TCP. Depending on the operating system supporting A's TCP, it is likely that some error recovery mechanism exists. When the TCP is up again A is likely to start again from the beginning or from a recovery point. As a result A will probably try to OPEN the connection again or try to SEND on the connection it believes open. In the latter case it receives the error message "connection not open" from the local TCP. In an attempt to establish the connection A's TCP will send a packet containing SYN. This scenario leads to the example shown in figure 4.2-5. After TCP A crashes, the user attempts to re-open the connection. TCP B, in the meantime, thinks the connection is open.

	TCP A				TCP B
1.	(CRASH)				(send 300, receive 100)
2.	OPEN				ESTABLISHED
3.	SYN-SENT	-->	<SEQ 400><SYN>	-->	(??)
4.	(!!)	<--	<SEQ 300><ACK 100>	<--	ESTABLISHED
5.	SYN-SENT	-->	<SEQ 100><RST><ACK 300>	-->	(Abort!!)

Half-Open Connection Discovery

Figure 4.2-5

When the SYN arrives at line 3, TCP B, being in a synchronized state, responds with an acknowledgment indicating what sequence it next expects to hear (ACK 100). TCP A sees that this packet does not acknowledge anything it sent and, being unsynchronized, sends a reset (RST) because it has detected a half-open connection. TCP B aborts at line 5. TCP A will continue to retransmit its SYN and if the user at TCP B re-opens the connection, eventually everything will work out.

An interesting alternative case occurs when TCP A crashes and TCP B tries to send data on what it thinks is synchronized connection. This is illustrated in figure 4. 2-6. In this case, the data arriving at TCP A from TCP B (line 2) is unacceptable because no such connection exists, so TCP A sends a RST. The RST is acceptable so TCP B processes it and aborts the connection.

In figure 4.2-7, we find the two TCP's A and B with passive connections waiting for SYN. An old duplicate arriving at TCP B (line 2) stirs B into action. A SYN-ACK is returned (line 3) and causes TCP A to generate a RST (the ACK in line 3 is not acceptable). TCP B accepts the reset and returns to its passive OPEN state.

	TCP A				TCP B
1.	(CRASH)				(send 300, receive 100)
2.	(??)	<--	<SEQ 300><ACK 100><DATA 10>	<--	ESTABLISHED
3.		-->	<SEQ 100><RST><ACK 310>	-->	(ABORT!!)

Active Side Causes Half-Open Connection Discovery

Figure 4.2-6

	TCP A				TCP B
1.	OPEN				OPEN
2.		…	<SEQ Z><SYN>	-->	SYN-RECEIVED
3.	(??)	<--	<SEQ X><SYN><ACK Z+1>	<--	SYN-RECEIVED
4.		-->	<SEQ Z+1><RST><ACK X+1>	-->	(return to OPEN!)
5.	OPEN				OPEN

Old Duplicate SYN Initiates a Reset on two Passive Sockets

Figure 4.2-7

A variety of other cases are possible, all of which are accounted for by the following rules for RST generation and processing.

Reset Generation

(1) If the connection is in any non-synchronized state (OPEN, SYN-SENT, SYN-RECEIVED) or if the connection does not exist, a reset (RST) should be formed and sent for any packet that does not acknowledge something the receiver sent earlier. The RST should take its SEQ field from the ACK field of the offending packet (if it has one) and its ACK field should acknowledge all data and control in the offending packet.

(2) If the connection is in a synchronized state (ESTABLISHED, FIN-WAIT, CLOSE-WAIT, CLOSING), any unacceptable packet should elicit only an empty acknowledgment packet containing the current send-sequence number and an acknowledgment indicating the next sequence number expected to be received.

Reset Processing

All RST (reset) packets are validated by checking their ACK-fields and SEQ fields (if appropriate). If the RST acknowledges something the receiver sent (but has not yet received acknowledgment for), the RST must be valid. RST packets will have ACK fields which acknowledge any data and control in the offending packet to assure acceptability of the RST.

The receiver of a RST first validates it, then changes state. If the receiver was in a non-synchronized state (OPEN, SYN-SENT, SYN-RECEIVED) it returns to the OPEN state (possibly modifying the foreign socket specification in the process—see section 4.3.3). If the receiver was in a synchronized state (ESTABLISHED, FIN-WAIT, CLOSE-WAIT, CLOSING), it aborts the connection and advises the user (see section 2.4.3—error 14).

4.2.4 Resynchronizing a Connection

A basic goal of the TCP design is to prevent packets from being emitted with sequence numbers which duplicate those which are still in the network. We want to assure this even if a TCP crashes and loses all knowledge of the sequence numbers it has been using. When new connections are created, an initial sequence number (ISN) generator is employed which selects a new 32 bit ISN. The generator is bound to a (possibly fictitious) 32 bit clock whose low order bit is incremented roughly every 500 nanoseconds. The ISN thus cycles every 4.55 hours, approximately. Since we assume that packets will stay in the network no more than tens of seconds or minutes, at worst, we can reasonably assume that ISN's will be unique.

In figure 4.2-8, we show the history of sequence numbers used by a particular connection. The ordinate shows sequence number and the abscissa shows time.

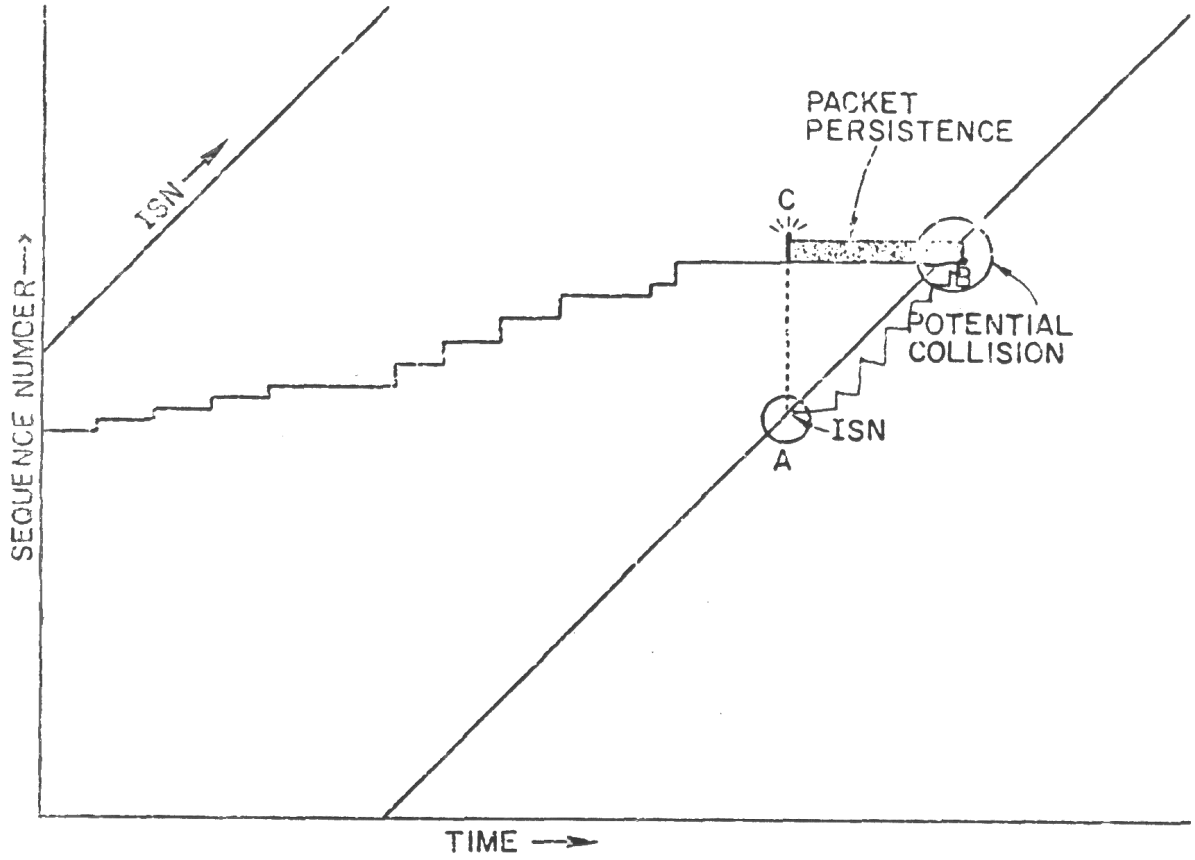
If a TCP were to crash at the point labeled "C" and were to restart, selecting the ISN at "A", there is a chance that packets emitted just before point "C" will still be in the network when new packets bearing these sequence numbers are emitted by the new incarnation of the connection. The shaded area to the right of point "C" represents the packet lifetime in the network. Point "B" represents the point of "collision."

To avoid this, it is necessary to detect that a connection is not using up sequence space fast enough and to jump the sequence numbers ahead to avoid a situation like that shown in the figure. Figure 4.2-9 illustrates the situation in more detail. The ISN curve is a step function, changing by 2**18 every second. The "Forbidden Zone" is one maximum packet lifetime wide and follows the ISN+STEP curve. At point "A" an attempt was made to transmit data which

would include sequence numbers lying above ISN+STEP. In this case, the TCP should send only as much as is allowed and then wait until the clock ticks to send the rest. If we assume the proposed packet occupies sequence numbers [SEQ, SEQ + L–1] , where L is the length in octets, then the test for type “A” collision is:

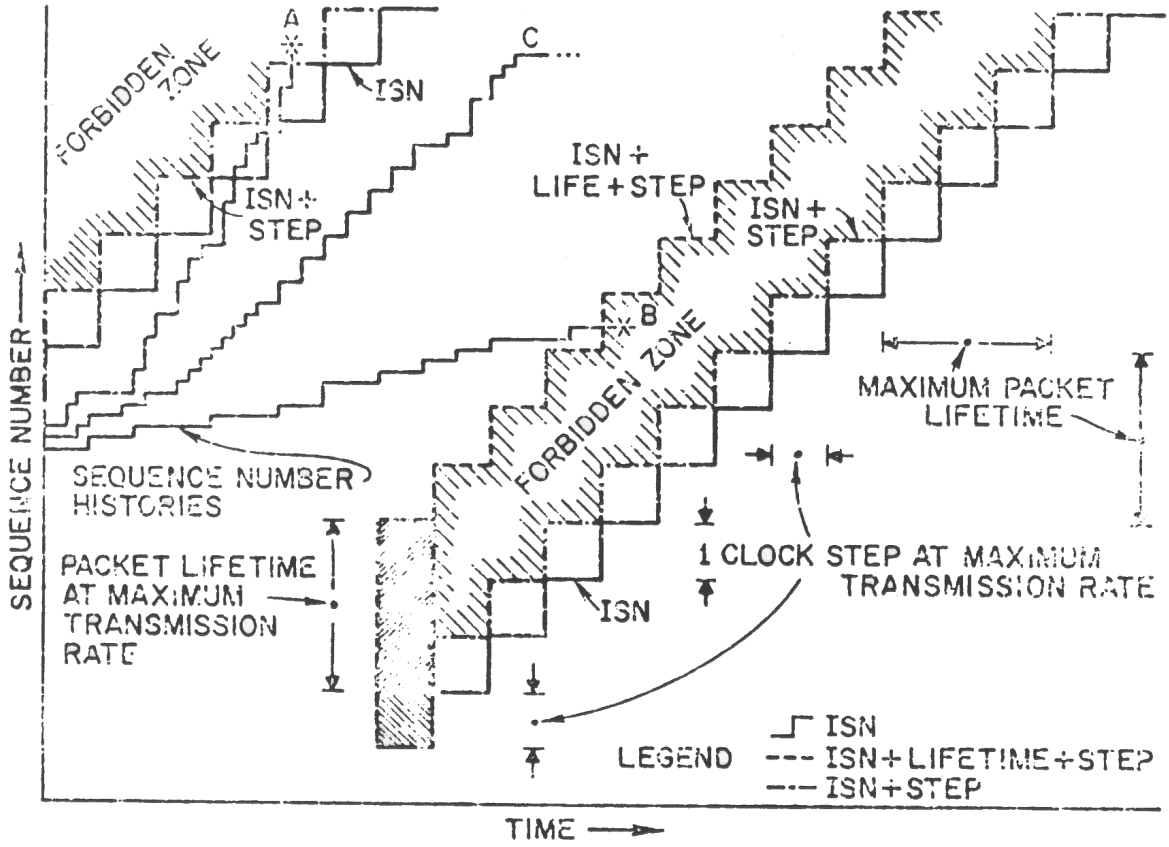
$$0 < (ISN + STEP – SEQ) <= L) \qquad (4.2\text{-}1)$$

Note that tests are modulo 2**32 to account for circularity of the sequence space. If type “A” collision is about to occur, either delay one clock step or only send as much as is “safe”.



The Need for Resynchronization

Figure 4.2-8



Detecting the Forbidden Zone

Figure 4.2-9

The more complex case is that of type “B” collision—the ISN curve catches up with the actual sequence numbers in use. To accommodate for the delays resynchronization might involve, it is essential to choose to resynchronize in time to avoid disaster. Of course, any TCP about to assign a sequence number which is in the forbidden zone must fall silent until the forbidden zone is past. Presumably this will only last a few tens of seconds or minutes (depending on the maximum packet lifetime).

We have chosen to create a “Panic Zone” midway between the ISN cycles. The test for initiating resynchronization is thus whether SEQ lies in the range [ISN, ISN + S/2 + B X (T + STEP)].

where S = 2**32 (sequence number space)
B = maximum bandwidth = 2**18 octets/sec
T = maximum packet lifetime = 30 seconds
STEP = clock tick = 1 second = 2**18 octets

So the test for initializing resynchronization is

$$0 < (SEQ - ISN) <= 2^{**}31 + 33 \text{ X } 2^{**}18 \qquad (4.2\text{-}2)$$

The actual resynchronization is straightforward. A special control packet containing a resynchronize (RSN) flag (see section 4.3.2) is sent which carries the current send sequence number as SEQ but the new ISN in an option field. A receiver of RSN validates it on the basis of the SEQ and ACK fields, processes it in sequence (that is, only after it has processed packets occupying the immediately preceding sequence space), changes its expected receive sequence number to the contents of the RSN packet's ACK field, and acknowledges in the new sequence number. Thus, RSN occupies two sequence numbers, the old (SEQ) and the new (ISN). We illustrate this in figure 4.2-10.

It should be recognized that when TCP A transmits the RSN, it may still have unacknowledged packets in its retransmission queue. In our example (figure 4.2-10), these might occupy sequence numbers 50–99. The receiving TCP won't send the ACK for the RSN until it has received all preceding packets, but ACKS for these may be lost. A key observation is that the ACK of 10001 (line 3, figure 4.2-10) will serve to acknowledge all the packets still on TCP A's retransmission queue. To understand this, we need some terminology. A TCP maintains certain status information about each connection it manages. In particular, it keeps a send sequence number (SENDSEQ) telling it the next number to assign an outgoing packet.

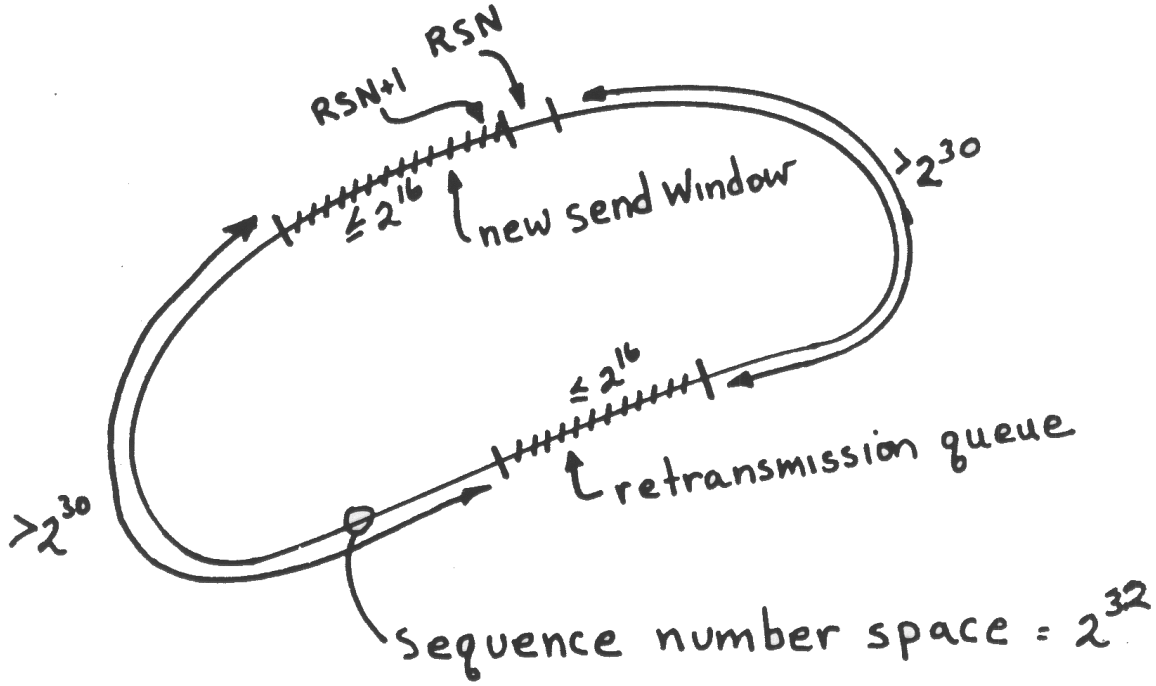
	TCP A			TCP B
1.	ESTABLISHED			ESTABLISHED
2.	ESTABLISHED	--> <SEQ 500><RSN 10000><ACK 100>	-->	ESTABLISHED
3.	ESTABLISHED	<-- <SEQ 100><ACK 10001>	-->	ESTABLISHED
4.	ESTABLISHED	--> <SEQ 10001><ACK 100><DATA>	-->	ESTABLISHED

Resynchronization

Figure 4.2-10

It also keeps a "left-window edge" (LWEDGE) which tells it the last sequence number that has been acknowledged. A send "window" is maintained telling the TCP which sequence numbers the receiving TCP has given permission for the sender to transmit (SENDWINDOW). A packet is deemed acknowledged if, on receipt of a valid acknowledgment packet (i.e. the ACK lies in the range [LWEDGE, LWEDGE + SENDWINDOW – 1]), it is the case that (SEQ + L – 1) lies outside the range [ACK, ACK + SENDWINDOW – 1] , where SEQ and L are the beginning sequence number and length of any packet in the retransmission queue requiring acknowledgment.

The ACK which returns from the RSN in figure 4.2-10 will typically carry a window (for flow control) ranging from 0 to 2**16–1, and LWEDGE will become ISN + 1. As is shown in figure 4.2-11, all packets on the retransmission queue, including RSN must be acknowledged by this. It can easily be shown that the new sendwindow cannot overlap the old retransmission queue, and this guarantees everything will be acknowledged.



RSN Acknowledgement ACKs Retransmission Packets

Figure 4.2-11

4.2.5 Closing a Connection

There are essentially three cases:

(1) The user initiates by telling the TCP to CLOSE the connection
(2) The remote TCP initiates by sending a FIN control signal
(3) Both users CLOSE simultaneously

Case 1: Local user initiates the close

In this case, a FIN packet can be constructed and placed out the outgoing packet queue. No further SENDs from the user will be accepted by the TCP, and it enters the FIN-WAIT state. RECEIVES are allowed in this state. All packets preceding and including FIN will be retransmitted until acknowledged. When the other TCP has both acknowledged the FIN and sent a FIN of its own, the first TCP can ACK this FIN and delete the connection (see figure

4.2-1). It should be noted that a TCP receiving a FIN will ACK but not send its own FIN until the user has CLOSED the connection also.

Case 2: TCP receives a FIN from the network

If an unsolicited FIN arrives from the network, the receiving TCP can ACK it and tell the user that the connection is closing (see Event Codes, section 2.4.3). The user should respond with a CLOSE, upon which the TCP can send a FIN to the other TCP. The TCP then waits until its own FIN is acknowledged whereupon it deletes the connection. If an ACK is not forthcoming, after a timeout the connection is aborted and the user is told (see 2.4.3).

Case 3: both users close simultaneously

A simultaneous CLOSE by users at both ends of a connection causes FIN packets to be exchanged. When all packets preceding the FIN have been processed and acknowledged, each TCP can ACK the FIN it has received. Both will, upon receiving these ACKs, delete the connection.

CLOSE is an operation meaning “I have no more data to send.” The notion of closing a full-duplex connection is subject to ambiguous interpretation, of course, since it may not be obvious how to treat the receiving side of the connection. We have chosen to treat CLOSE in a simplex fashion. The user who CLOSES may continue to RECEIVE until he is told that the other side has CLOSED also. Thus, a program could initiate several SENDs followed by a CLOSE, and then continue to RECEIVE until signalled that a RECEIVE failed because the other side has CLOSED. We assume that the TCP will unilaterally inform a user, even if no RECEIVEs are outstanding, that the other side has closed, so the user can terminate his side gracefully. A TCP will reliably deliver all buffers SENT before the connection was CLOSED so a user that expects no data in return need only wait to hear the connection was CLOSED successfully to know that all his data was received at the destination TCP.

4.2.6 TCP Connection State Transitions

The foregoing sections on connection management were succinctly represented with a simple state diagram, shown in figure 4.2-1. The figure only illustrates state changes (and actions which occur as a result), but neither addresses error conditions nor actions which are not connected with state changes. In this section, more detail is offered with respect to the reaction of the TCP to various events (user command, packet arrivals). The characterization of TCP processing of control packets and reaction to user commands is relatively terse. Certain implementation choices can make the realization of the specified processing fairly compact, but these implementation issues are dealt with in sections 4.3–4.5. For the sake of succinctness, this section deliberately avoids much explanatory material which can be found in the implementation

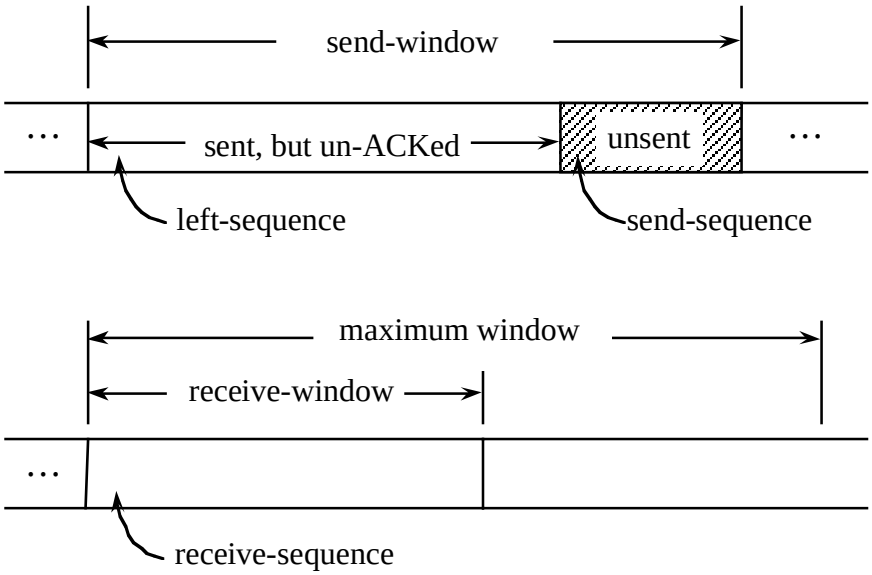
sections. Thus, this section is intended more as a reference than as a tutorial, and really requires exposure to sections 4.3–4.5 to be fully useful.

Furthermore, it should be kept in mind that some control information occupies sequence number space along with data (see figure 4.1-3). This latter point means that there is a natural order in which to process the data and control portions of an incoming packet and that certain controls will change the connection state BEFORE later control or data (i.e., those assigned higher sequence numbers) is processed. An implementation could take advantage of this sequencing to keep track of which portions of a packet (data and control) had already been processed. Note that by assigning sequence numbers to some control bits, it is possible to use the normal acknowledgement mechanisms to acknowledge receipt of control information and to filter out duplicates.

A natural way to think about incoming packet processing is to imagine that they are first tested for proper sequence number (i.e., that their contents lie in the range of the expected “receive window” in the sequence number space) and then that they are queued and processed in sequence number order. We are, in this view, ignoring for the moment the problem of reassembling segments that were fragmented at gateways, or which overlap other, already received, packets.

We have chosen to organize the description according to the connection state, to key the description to figure 4.2-1. When a packet causes a state change, but carries more data or control which should be processed, it may be appropriate to continue processing in the new state, but processing of the packet’s acknowledgement field or sequence number field should not be repeated (lest a packet which looked valid before appear to be an old duplicate or have a bad acknowledgement field as an artifact of the state change).

A TCP must typically maintain certain state information about each connection in order to sequence packets and to determine when resynchronization is required. For reference, we present a list of terms below (see section 4.3 for more detail) which are used in the action summaries for each state (also see figure 4.2-12).



Sequence Number Management

Figure 4.2-12

Glossary of terms

ACK — A control bit (acknowledge) occupying no sequence space, which indicates that the acknowledgment field of the incoming packet indicates the next sequence number the sender of the packet is expecting to receive.

ARQ — A control bit (acknowledge requested) occupying one sequence number, indicating that the packet must be acknowledged. No other semantics are associated with this control.

EOL — A control bit (End of Letter) occupying no sequence space, indicating that this packet ends a logical letter with the last data octet in the packet.

FIN — A control bit (finis) occupying one sequence number, which indicates that the sender will send no more data or control occupying sequence space.

INT — A control bit (interrupt) occupying one sequence number, used to indicate that the receiving user should be signalled or interrupted (out of band signal).

LEFT-SEQUENCE — This is the next sequence number to be acknowledged by the remote TCP and is sometimes referred to as the left edge of the transmit “window.”

PKT-ACKNOWLEDGMENT — The acknowledgment sequence number in the arriving packet.

PKT-LENGTH — The amount of sequence number space occupied by a packet, including any controls which occupy sequence space.

RECEIVE-SEQUENCE — This is the next sequence number the TCP is expecting to receive.

RECEIVE-WINDOW — This represents the sequence numbers the local TCP is willing to receive. Thus, the local TCP considers that packets overlapping the range RECEIVE-SEQUENCE to RECEIVE-SEQUENCE + RECEIVE-WINDOW – 1 carry acceptable data or control. Packets containing sequence numbers entirely outside of this range are considered duplicates and discarded. This topic is discussed in detail in section 4.5 on window allocation policies.

RSN — A control bit (resynchronize) occupying one sequence number, indicating that the packet contains a new sequence number in an option field. This control bit is unique in that it has two sequence numbers, the last of the old sequence numbers and the first of the new ones. This choice was made so that the acknowledgment using the new sequence numbers would serve to remove the packet containing the RSN from the retransmission queue.

RST — A control bit (reset) occupying no sequence space, indicating that the receiver should delete the connection without further interaction. The receiver can determine, based on the sequence number and acknowledgment fields of the incoming packet, whether it should honor the reset command or ignore it. In no case does a packet containing RST give rise to a RST packet.

SEND-SEQUENCE — This is the next sequence number the TCP will use on the connection. It is initially selected from an initial sequence number curve (ISN, see section 4.2.1) and is incremented for each octet of data or control transmitted. It may be “jumped forward” through resynchronization (section 4.2.4).

SEND-WINDOW — This represents the sequence numbers which the remote TCP is willing to receive. The range of sequence numbers which may be emitted by a TCP lies between SEND-SEQUENCE and LEFT-SEQUENCE + SEND-WINDOW – 1.

SYN — A control bit in the incoming packet, occupying one sequence number, used to indicate at the initiation of a connection, where the sequence numbering will start.

Certain error responses shown below are generic. User commands referencing connections do not exist receive “connection not open” (EP3) and references to connections not accessible to the caller receive “connection illegal for this process” (EP1). We have not repeated these generic responses in each description of action performed for each connection state. Overt attempts to SEND or INTERRUPT on a connection with unspecified foreign socket results in a “foreign socket unspecified” (E5) response.

CLOSED state (i.e. connection does not exist)

User Commands

1. OPEN
   Create a new transmission control block TCB to hold connection state information. Fill in local socket identifier, foreign socket (if present). The connection is passively “listening” if the foreign socket is unspecified, user timeout information. Some implementations may issue SYN packets if the foreign socket is fully specified. In this case, an initial sequence number (ISN) is selected and a SYN packet formed and sent. The LEFT-SEQUENCE is set to ISN, the SEND-SEQUENCE to ISN + 1, and SYN-SENT state is entered.

   If the caller does not have access to the local socket specified, return “connection illegal for this process” (EP1). If there is no room to create a new connection, return “insufficient resources” (4)

2. SEND, INTERRUPT, CLOSE, ABORT, RECEIVE, STATUS
   Error return “Connection not open” (EP3).

   If the user should not have access to such a connection, “connection, illegal for this process” (EP1) may be returned.

Incoming Packets

All incoming packets are discarded and, except for incoming RST packets which should be ignored, an RST is created with a sequence number (PKT-SEQUENCE) equal to the acknowledgment field (PKT-ACKNOWLEDGMENT) of the incoming packet (if it has one; otherwise PKT-SEQUENCE may be zero or, perhaps, ISN). The acknowledgment field of the RST should be set to the sum of the incoming PKT-SEQUENCE and PKT-LENGTH. The RST and ACK control bits for the bound packet should be set (see figure 4.2-6).

OPEN state

User Commands

1. OPEN
   Return “already OPEN” (EP6)

2. SEND or INTERRUPT
   Select an ISN, send a SYN packet, set LEFT-SEQUENCE to ISN and SEND-SEQUENCE to ISN + 1. Enter SYN-SEND state. Data associated with SEND may be sent with SYN packet or queued for transmission after entering ESTABLISHED state. INTERRUPT can be sent as a combination SYN, INT packet (see figure 4.1-3 and section 4.3.2). If there is no room, respond with “insufficient resources” (4).

3. RECEIVE
   Queue request, if there is space or respond with “insufficient resources” (4)

4. CLOSE
   Delete TCB, return “ok” (0). Any outstanding RECEIVES should be returned with “closing” responses P12.

5. ABORT
   Delete TCB, return “ok” (0); any outstanding RECEIVES should be returned with “connection reset” (P14) responses.

6. STATUS
   Return state = OPEN.

Incoming Packets

1. ACK —
   Any acknowledgement is bad if it arrives on a connection still in the OPEN state. A reset (RST) packet should be formed for any arriving ACK-bearing Packet, except another RST. The RST should be formatted as follows:

   <SEQ PKT-ACKNOWLEDGEMENT><RST><ACK PKT-SEQUENCE + PKT – LENGTH>

   Thus the RST will acknowledge any text or control in the offending packet.

2. SYN
   RECEIVE-SEQUENCE should be set to PKT-SEQUENCE + 1 and any other control or text should be queued for processing later. ISN should be selected and a SYN packet sent of the form:

   <SEQ ISN><SYN><ACK RECEIVE-SEQUENCE>

   SEND-SEQUENCE should be set to ISN + 1 and LEFT-SEQUENCE to ISN. The connection state should be changed to SYN-RECEIVED. Note that any other incoming control (combined with SYN) will be processed in the SYN-RECEIVED state. Processing of SYN and ACK should not be duplicated.

3. Other text or control
   Any other control or text-bearing packet (not containing SYN) will have an ACK and thus will be discarded by the ACK processing. An incoming RST packet could not be valid, since it could not have been sent in response to anything sent by this incarnation of the connection.

SYN-SENT state

User Commands

1. OPEN
   Return “already OPEN” (EP6)

2. SEND or INTERRUPT
   Queue for processing after the connection is ESTABLISHED or packetize, starting with the current SEND-SEQUENCE number. Typically, nothing can be sent yet, anyway, because the send window has not yet been set by the other side. If no space, return “insufficient resources” (4).

3. RECEIVE
   Queue for later processing unless there is no room, in which case return “insufficient resources” (4).

4. CLOSE
   Delete the TCB and return “closing” (P12) responses to any queued SENDs, RECEIVES, or INTERRUPTS.

5. ABORT
   Delete the TCB and return “reset” (P14) responses to any queued SENDS, RECEIVES, or INTERRUPTS.

6. STATUS
   Return state = SYN-SENT; SENT-SEQUENCE, RECEIVE-WINDOW

Incoming packets

1. ACK
   If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE then the ACK is acceptable. LEFT-SEQUENCE should be advanced to equal PKT-ACKNOWLEDGMENT, and any packet(s) on the retransmission queue which are thereby acknowledged should be removed.

   If the packet acknowledgment is not acceptable, a RST packet should be formed (except when the offending packet is also a RST) which carries the PKT-ACKNOWLEDGMENT as a sequence number, and acknowledges all text and control of the offending packet.

2. SYN
   RECEIVE-SEQUENCE should be set to PKT-SEQUENCE + 1 and any packet text or control queued for later processing. If the packet has an ACK, change the connection state to ESTABLISHED, otherwise enter SYN-RECEIVED. In any case, form an ACK packet:

   <SEQ SEND-SEQUENCE><ACK RECEIVE-SEQUENCE> and send it.

3. Other text or control.
   Incoming packets with other control or text combined with SYN will be processed in SYN-RECEIVED or ESTABLISHED state. Arriving packets which do not contain SYN are either old duplicates or out-of-order arrivals. Since these must contain ACK fields, they will have been discarded by earlier ACK processing. Note that a valid RST could not be received in SYN-SENT state since it could not have been sent in response to a SYN.

4. User Timeout.
   If the user timeout expires on a packet in the retransmission queue, abort the connection, notifying the user “retransmission timeout, connection aborted” (EP9), and flushing all

queues, returning RECEIVES, SENDS or INTERRUPTS with the same error (EP9). Delete the TCB.

SYN-RECEIVED STATE

User Commands

1. OPEN
   Return “already OPEN” (EP6)

2. SEND or INTERRUPT
   Queue for later processing after entering ESTABLISHED state, or packetize and queue for output. If no space to queue, respond with “insufficient resources” (4)

3. RECEIVE
   Queue for processing after entering ESTABLISHED state. If there is no room to queue this request, respond with “insufficient resources” (4).

4. CLOSE
   Queue for processing after entering ESTABLISHED state or packetize and send FIN packet. If the latter, enter FIN-WAIT state.

5. ABORT
   Delete TCB, send a RST of the form;

   <SEQ SEND-SEQUENCE><RST><ACK RECEIVE-SEQUENCE>

   and return any unprocessed SENDs, INTERRUPTs, or RECEIVEs with “reset” code (P14).

6. STATUS
   Return state = SYN-RECEIVED, LEFT-SEQUENCE, SEND-SEQUENCE, SEND-WINDOW, RECEIVE-SEQUENCE, RECEIVE-WINDOW, and other desired statistics number of (SEND, RECEIVE buffers queued), packets queued for reassembly, for retransmission, etc.

Incoming Packets

1. Check PKT-SEQUENCE
   If RECEIVE-SEQUENCE < OUT-SEQUENCE + max (0, PKT-LENGTH – 1) < RECEIVE-SEQUENCE + RECEIVE-WINDOW then the packet sequence is acceptable. If not, form a reset (RST) packet:

   <SEQ PKT-ACKNOWLEDGMENT><RST><ACK PKT-SEQUENCE + TEXT-LENGTH>

   If the incoming packet is RST or has no ACK, discard it, and do not send RST formed above. Note that the test above guarantees that the last sequence number used by the packet lies in the receive-window. Insisting that PKT-SEQUENCE (i.e., the first sequence number occupied by the packet) lie in the RECEIVE-WINDOW could lead to deadlock in the case of alternate gateway routing and different fragmentation. The special "MAX" operation makes certain that empty ACK packets whose length is 0, will be accepted. If the RECEIVE-WINDOW is zero, no packets will be acceptable, but special allowance should be made to accept valid ACKS.

2. ACK
   If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE then set LEFT-SEQUENCE = PKT-ACKNOWLEDGMENT, remove any acknowledged packets from the retransmission queue, and enter ESTABLISHED state.

   If the packet acknowledgment is not acceptable, form a reset packet, as for the bad sequence case above and send it, unless the incoming packet is an RST, in which case, it should be discarded.

3. RST
   If the packet has passed sequence and acknowledgment tests, it is valid. Return this connection to OPEN state. The user need not be informed. All packets on the retransmission queue should be removed. All packetized buffers must be assigned new sequence numbers, so they should be requeued for re-packetizing.

4. Other text or control
   If there is other control or text in the packet, it can be processed when the connection enters the ESTABLISHED state.

5. User Timeout
   If the user timeout expires on any packet in the retransmission queue, flush all queues,

return outstanding SENDs, INTERRUPTs or RECEIVEs with “user timeout, connection aborted” (EP9), and delete the TCB.

ESTABLISHED state

User Commands

1. OPEN
   Respond with “already OPEN” (EP6)

2. SEND or INTERRUPT
   Packetize the buffer, send or queue it for output. If there is insufficient space to remember this buffer, simply respond with “insufficient resources” (4).

3. RECEIVE
   Reassemble queued incoming segments into receive buffer, and return to user. Mark “end of letter” (EOL) if this is the case. If insufficient incoming segments are queued to satisfy the request, queue the request. If there is no queue space to remember the RECEIVE, respond with “insufficient resources” (4)

4. CLOSE
   Queue this until all preceding SENDs or INTERRUPTs have been packetized, then form a FIN packet and send it. In any case, enter FIN-WAIT state.

5. ABORT
   Delete TCB and send a reset packet:

   <SEQ SEND-SEQUENCE><RST><ACK RECEIVE-SEQUENCE>

   All queued SENDs, INTERRUPTs, and RECEIVEs should be given “reset” responses (P14); all packets queued for transmission (except for the RST formed above) or retransmission should be flushed.

6. STATUS
   Return state = ESTABLISHED; SEND SEQUENCE, LEFT-SEQUENCE, SEND-WINDOW, RECEIVE-SEQUENCE, RECEIVE-WINDOW, and other statistics, as desired.

Incoming Packets

1. Check PKT-SEQUENCE
   All packets are generally processed in sequence. Initial tests on arrival are used to discard old duplicates, but further processing is done in PKT-SEQUENCE order. If a packet's contents straddle the boundary between old and new, only the new parts should be processed.

   If RECEIVE-SEQUENCE <= PKT-SEQUENCE + max (PKT-LENGTH – 1, 0) < RECEIVE-SEQUENCE + RECEIVE-WINDOW then packet is acceptable. Otherwise if PKT-LENGTH is non-zero, an empty acknowledgment packet should be sent:

   <SEQ SEND-SEQUENCE><ACK RECEIVE-SEQUENCE>

   In any case, unacceptable packets should be discarded.

2. ACK
   If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE then set LEFT-SEQUENCE = PKT-ACKNOWLEDGMENT. Any packets on the retransmission queue which are thereby entirely acknowledged are removed. Users should receive positive acknowledgments for buffers which have been SENT and fully acknowledged (i.e. SEND buffer should be returned with "OK" (0) response). If the ACK is a duplicate, it can be ignored.

3. RST
   All RECEIVEs, SENDs, and INTERRUPTs receive "reset" (P14) responses. All packet queues are flushed. The TCB is deleted. User also receives an unsolicited general "reset" signal (P14).

4. SYN
   Ignore the SYN. A packet carrying a SYN could not have passed through the sequence check unless it had control or text lying beyond the SYN which was acceptable. To prevent duplicate processing, such packets could be "marked" so that all duplicate control or text is removed before they exit sequence-number check. Other marking strategies could be employed to achieve the same effect.

5. INT
   Signal user that remote side has "interrupted" (P11) and advance RECEIVE-SEQUENCE

to account for INT. Format and send an acknowledgement for the INT, or piggy back the ACK on return traffic.

6. ARQ
   Format and send an ACK packet after advancing RECEIVE-SEQUENCE to account for ARQ. Alternatively, simply set a flag to send an ACK (possibly by piggy-backing on return packets) at the earliest opportunity.

7. RSN
   Since packet contents are being processed in sequence, the sequence number of the RSN should now equal RECEIVE-SEQUENCE. RECEIVE-SEQUENCE can be replaced by the RSN option-field containing the new sequence number. An ACK packet should be returned or a flag set to send an ACK at the earliest opportunity.

8. Packet text
   Once in the ESTABLISHED state, it is possible to deliver packet text to user RECEIVE buffers. Some preliminary packet reassembly may be required to form valid segments from fragments created at a gateway. Text from segments can be moved into buffers until either the buffer is full or the segment is empty. If the segment empties and carries an EOL flag, then the user is informed, when the buffer is returned, that an EOL has been received.

9. FIN
   An ACK packet should be sent, acknowledging the FIN. The user should be signalled “connection closing” (P12) and similar responses should be returned for any outstanding RECEIVEs which cannot be satisfied. Connection state should be changed to CLOSE-WAIT.

10. User Timeout
    If the user timeout expires on a packet in the retransmission queue, flush all queues, return “user timeout, connection aborted” (EP9) for all outstanding SENDs, INTERRUPTs, and RECEIVEs, and delete the TCB. The user should receive an unsolicited message of the same form (EP9).

FIN-WAIT

User-Commands

1. OPEN
   Return “already OPEN” (EP6)

2. SEND or INTERRUPT
   Return “connection closing” (EP12) and do not service request.

3. RECEIVE
   Reassemble and return a letter, or as much as will fit, in the user buffer. Queue the request if it cannot be serviced immediately.

4. CLOSE
   Strictly speaking, this is an error and should receive a “connection closing” (EP12) response. An “ok” (0) response would be acceptable, too, as long as a second FIN is not emitted.

5. ABORT
   A reset packet (RST) should be formed and sent:

   <SEQ SEND-SEQUENCE><RST><ACK RECEIVE-SEQUENCE>

   Outstanding SENDs, INTERRUPTS, RECEIVEs, CLOSEs, and/or packets queued for retransmission, or packetizing, should be flushed, with appropriate “connection reset” (P12).

6. STATUS
   Respond with state = FIN-WAIT, SEND-SEQUENCE, LEFT-SEQUENCE, SEND WINDOW, RECEIVE-SEQUENCE, RECEIVE WINDOW, and other statistical information, as desired.

Incoming packets

(1) Check PKT-SEQUENCE
   If RECEIVE-SEQUENCE <= PKT-SEQUENCE + MAX (PKT-LENGTH – 1,0) < RECEIVE-SEQUENCE + RECEIVE-WINDOW then packet sequence is acceptable. Otherwise, if PKT-LENGTH is non-zero, an ACK packet should be sent:

<SEQ SEND-SEQUENCE><ACK RECEIVE-SEQUENCE>

In any case, an unacceptable packet should be discarded.

(2) ACK

If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE, then LEFT-SEQUENCE should be advanced appropriately and any acknowledged packets deleted from the retransmission queue. SENDs or INTERRUPTs which are thereby completed can also be acknowledged to the user. ACK's outside of the SEND-WINDOW can be ignored. If the retransmission queue is empty, the user's CLOSE can be acknowledged ("OK" (0)) and the TCB deleted.

(3) RST

All RECEIVEs, SENDs, and INTERRUPTs still outstanding should receive "reset" (P14) responses. All packet queues should be flushed and the connection TCB deleted. User should also receive an unsolicited general "connection reset" (P14) signal.

(4) SYN

This case should not occur, since a duplicate of the SYN which started the current incarnation will have been filtered in the PKT-SEQUENCE processing. Other SYN's could not have passed the PKT-SEQUENCE check at all (see SYN processing for ESTABLISHED state).

(5) INT

Advance RECEIVE-SEQUENCE by one and signal the user that the remote side has "interrupted" (P11). An ACK packet should be sent in return, or a flag set to send an ACK at the earliest possible time.

(6) ARQ

RECEIVE-SEQUENCE should be advanced by one and an ACK packet sent in return, or a flag set to accomplish this as soon as possible.

(7) Packet Text

If there are outstanding RECEIVEs, they should be satisfied, if possible, with the text of this packet, remaining text should be queued for further processing. If a RECEIVE is satisfied, the user should be notified, with "end-of-letter" (EOL) signal, if appropriate.

(8) RSN

RECEIVE-SEQUENCE should be updated to 1 + NEW-SEQUENCE (carried in the RSN option field of this packet). An ACK packet should be prepared, acknowledging the new sequence number

<SEQ SEND-SEQUENCE><ACK RECEIVE-SEQUENCE>

(9) FIN

The FIN should be acknowledged. Return any remaining RECEIVEs with “connection closing” (P12) and advise user that connection is closing with a general signal (P12). If the retransmission queue is not empty, then enter CLOSING state, otherwise, delete the TCB.

(10) User Timeout

If the user timeout expires on a packet in the retransmission queue, flush all queues, return “user timeout, connection aborted” messages for all outstanding SENDs, RECEIVEs, CLOSES or INTERRUPTS, send an unsolicited general message of the same form to the user, and delete the TCB.

CLOSE-WAIT

User Commands

1. OPEN
   Return “already OPEN” error (EP6)

2. SEND or INTERRUPT
   Packetize any text to be sent and queue for output. If there is insufficient space to remember the SEND or INTERRUPT, return “insufficient resources” (4)

3. RECEIVE
   Since the remote side has already sent FIN, RECEIVEs must be satisfied by text already reassembled, but not delivered to the user. If no reassembled packet text is awaiting delivery, the RECEIVE should get a “connection closing” (P12) response. Otherwise, any remaining text can be used to satisfy the RECEIVE. In implementations which do not acknowledge packets until they have been delivered into user buffers, the FIN packet which led to the CLOSE-WAIT state will not be processed until all preceding packet text has been delivered into user buffers. Consequently, for such an implementation, all RECEIVEs in CLOSE-WAIT state will receive the “connection closing” (P12) response.

4. CLOSE
   Queue this request until all preceding SENDs or INTERRUPTs have been packetized, then send a FIN packet, enter CLOSING state.

5. ABORT
   Flush any pending SENDs, RECEIVEs and INTERRUPTs, returning “connection reset” (P14) responses for them. Form and send a RST packet:

   <SEQ SEND-SEQUENCE><RST><ACK RECEIVE-SEQUENCE>

   Flush all packet queues and delete the TCB.

6. STATUS
   Return state = CLOSE-WAIT, all other TCB values as for ESTABLISHED case.

Incoming Packets

1. Check PKT-SEQUENCE
   If RECEIVE-SEQUENCE <= PKT-SEQUENCE + MAX (PKT-LENGTH – 1, 0) < RECEIVE-SEQUENCE + RECEIVE-WINDOW then the packet sequence is acceptable. Otherwise, if PKT-LENGTH is non-zero, an ACK should be sent:

   <SEQ SEND-SEQUENCE ><ACK RECEIVE-SEQUENCE>

   Unacceptable packets should be discarded. Others should be processed in sequence number order.

2. ACK
   If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE, then LEFT-SEQUENCE should be advanced appropriately and any acknowledged packets removed from the retransmission queue. Completed SENDs or INTERRUPTs should be acknowledged to the user (“OK” (0) returns). ACK’s which are outside the receive window can be ignored.

3. RST
   All RECEIVEs, SENDs, and INTERRUPTs still outstanding should receive “reset” (P14) responses. Packet queues should be flushed and the TCB deleted. The user should also receive an unsolicited general “connection reset” signal (P14).

4. SYN
   This case should not occur, since a duplicate of the SYN which started the current connection incarnation will have been filtered in the PKT-SEQUENCE processing. Other SYN's will have been rejected by this test as well (see SYN processing for ESTABLISHED state).

5. INT
   This should not occur, since a FIN has been received from the remote side. Ignore the INT.

6. ARQ
   This should not occur, since a FIN has been received from the remote side. Ignore the ARQ.

7. Packet text
   This should not occur, since a FIN has been received from the remote side. Ignore the packet text.

8. RSN
   This should not occur, since a FIN has been received from the remote side. Ignore the RSN.

9. FIN
   This should not occur, since a FIN has already been received from the remote side. Ignore the FIN.

10. User Timeout
    If the user timeout expires on a packet in the retransmission queue, flush all queues, return "user timeout, connection aborted" (EP9) for any outstanding SENDs, RECEIVEs or INTERRUPTs, send an unsolicited general message of the same form to the user and delete the TCB.

CLOSING

User Commands

1. OPEN
   Respond with "already OPEN" (EP6)

2. SEND, INTERRUPT
   Respond with “connection closing” (EP12)

3. RECEIVE
   Respond with “connection closing” (EP12)

4. CLOSE
   Respond with “connection closing” (EP12)

5. ABORT
   Respond with “OK” (0) and delete the TCB, flush any remaining packet queues. If a CLOSE command is still pending, respond “connection reset” (P14).

6. STATUS
   Return State = CLOSING along with other TCP parameters.

Incoming packets

1. Check PKT-SEQUENCE
   If RECEIVE-SEQUENCE <= PKT-SEQUENCE + MAX(PKT-LENGTH – 1,0) < RECEIVE-SEQUENCE + RECEIVE-WINDOW then packet sequence is acceptable. Otherwise, if PKT-LENGTH is non-zero, an ACK packet should be formed and sent:

   <SEQ SEND-SEQUENCE><ACK RECEIVE-SEQUENCE>

   In any case, an unacceptable packet should be discarded.

2. ACK
   If LEFT-SEQUENCE < PKT-ACKNOWLEDGMENT <= SEND-SEQUENCE, then LEFT-SEQUENCE should be advanced and any acknowledged packets deleted from the retransmission queue. SENDs or INTERRUPTs which are thereby completed can also be acknowledged to the user. ACK’s outside of the SEND-WINDOW can be ignored.

3. RST
   Any outstanding RECEIVEs, SEND, and INTERRUPTs should receive “reset” responses (P14). All packet queues should be flushed and the TCB deleted. Users should also receive an unsolicited general “connection reset” (P14) signal.

4. Packet text or control
   No other control or text should be sent by the remote side, so packets containing non-zero PKT-LENGTH should be ignored.

5. User Timeout
   If the user timeout expires on a packet in the retransmission queue, flush all queues, return “user timeout, connection aborted” (EP9) responses for all outstanding SENDs, INTERRUPTs, RECEIVEs, or CLOSEs, send an unsolicited message of the same form (EP9) to the user and delete the TCB.

4.3 TCP Data Structures

4.3.1 Introduction

Our basic view of internetworking is that all internetwork packets (TCP and otherwise) have a basic internet header consisting of source/destination address, data and header length fields, and format indicator. The TCP header follows the internet header, supplying information specific to the TCP protocol. This division allows for the existence of internet protocols other than TCP, and for experimentation with TCP variations.

4.3.2 Internetwork Packet Format

In this section, we offer a terse descriptive summary of the contents of the internetwork and TCP header (see also figure 4.3-1).

Destination Network Identifier: 8 bits

Decimal	Octal	Network
0	0	Reserved
1	1	BBN Packet Radio Network
2	2	SF Bay Area Packet Radio Network
3	3	BBN RCC Network
4	4	Atlantic-Satellite Network
5	5	Washington, D.C. Packet Radio Network
6–9	6–9	Not assigned
10	12	ARPANET
11	13	University College London Network
12	14	CYCLADES
13	15	National Physical Laboratory
14	16	TELENET
15	17	British Post Office EPSS
16	20	DATAPAC
17	21	TRANSPAC
18	22	LCS Network
19	23	TYMNET
20–254	24–376	Unassigned
255	377	Reserved

Destination Host Identifier: 24 bits

Usually synonymous with a TCP, but more than one TCP may reside at a host.

Source Network Identifier: 8 bits

Source Host Identifier: 24 bits

Packet length: 16 bits

Measured in 8 bit octets, this length accounts for all octets in the packet including control bits, but not including header-bits.

Header length: 8 bits

Measured in 8 bit octets, this length accounts for all octets in the header including source/destination addresses, packet length and format fields, etc. Options are included in the header length, but follow the fixed fields of the header. The format field can be used to identify the header type and implicit fixed field length. For TCP, the standard header (without options) is 34 (decimal) octets long.

Format: 4 bits

Types:

0: Raw internet packet
1: TCP
2: Secure TCP
3–14: Not assigned
15: Internet debugger (XNET)
Note: all type codes above are decimal.

The fields below are TCP specific.

TCP version number: 4 bits

Sequence number: 32 bits

Window: 16 bits

Control Flags: 16 bits (from left to right):

bit 0:	SYN:	Request to synchronize sending sequence numbers.
bit 1:	ACK:	the acknowledgment field contains an ACK
bit 2:	FIN:	Sender will not send any more data
bit 3:	RSN:	Sender is resynchronizing
bit 4:	EOS:	End of Segment; end-end checksum present
bit 5:	EOL:	End of Letter
bit 6:	INT:	Sender is interrupting
bit 7:		unused
bit 8:	BOS:	Beginning of segment
bit 9:		unused
bit 10:	ARQ:	Acknowledgment requested
bit 11:	RST:	Reset the connection packet.
bits 12–15:		unused

Reserved: 8 bits

Destination Port Identifier: 24 bits

Reserved: 8 bits

Source Port Identifier: 24 bits

Acknowledgment: 32 bits

If the ACK control bit is set this field contains the value of the next sequence number the sender of the packet is expecting to receive. If the RSN control bit is set, this field contains the value of the new next sequence number the sender will use.

checksum: 16 bits

The checksum field is the 16 bit one's complement of the one's complement sum of all words in the header and text, excluding those words which represent unchecksummed options (see below). If a packet contains an odd number of header and text bytes to be checksummed, the last byte is padded with zero to form a 16 bit word for checksum purposes. The pad is not transmitted as part of the packet.

Options (a multiple of 8 bits in length): 8n bits

Following the checksum, but preceding the data, there may be options in the header. Options occupy the space between the end of the standard TCP header (34 octets) and the end of the header as accounted for in the header length field. All options have the same basic format:

8 bits: Option length in octets (including two octets of length and kind information)

8 bits: Option kind

C: 1 bit

If set, this option is not included in the checksum calculation.

P: 1 bit

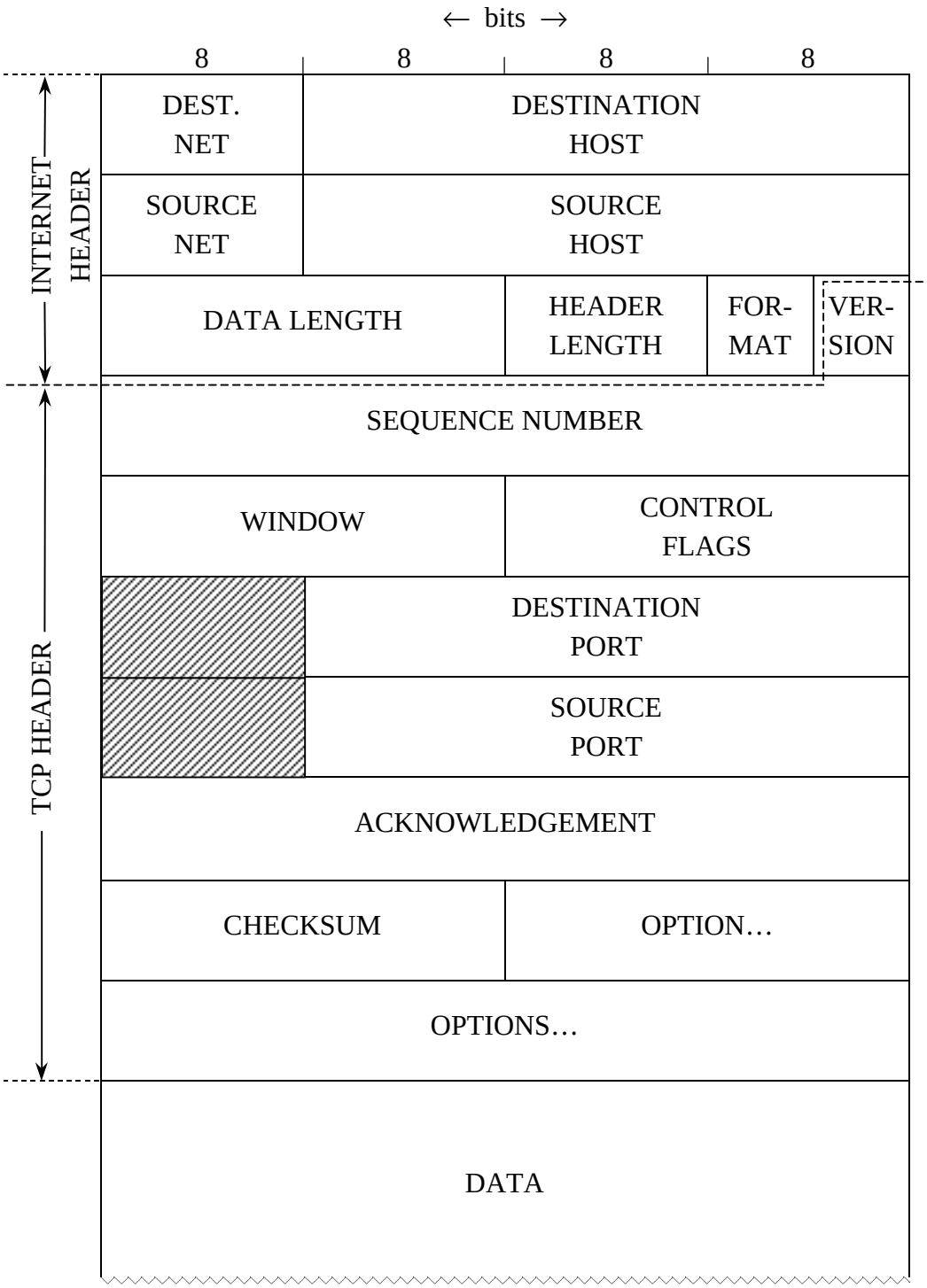
If set, this option is protocol specific, i.e. option is interpreted based on format and protocol version specified in those internet packet header fields.

Option identifier: 6 bits

There are two special cases for options. The first is an option whose length field is zero. This marks the end of the option list. Only one octet is associated with this option, the length octet itself. The second is an option whose length field is one. This option serves as padding and is also one octet long. This option does not terminate the option list. Note that the list of options may be shorter than the header length field might imply. No guarantees concerning the content of the header beyond the end-of-option mark are made.

Currently defined options (octal numbering) include:

Code	Length	Meaning
0XX	---	checksummed and protocol independent
000	---	reserved
1XX	---	checksummed, protocol dependent (TCP)
100	---	reserved
101	4	Packet label-sequence number for debugging purposes.
102	4	Secure Open—used by TCP's communicating with BCR security system
103	2	Secure Close—used by TCP's communicating with BCR security system
2XX	---	Not checksummed and Protocol independent
200	---	reserved
204	variable	Internetwork timestamp field used to accumulate timestamping information during internet transit.
205	variable	satellite timestamp—(as above)
3XX	---	Not checksummed and Protocol Dependent
304	6	Internal TCP timestamp for diagnostics.



TCP Header Format

Figure 4.3-1

4.3.3 Transmission Control Block

It is highly likely that any implementation will include shared data structures among parts of the TCP and some asynchronous means of signalling users when letters have been delivered.

One typical data structure is the Transmission Control Block (TCB) which is created and maintained during the lifetime of a given connection. The TCB contains the following information (field sizes and content are notional only and may vary from one implementation to another):

Local connection name: 16 bits

Local socket: 64 bits

Foreign socket: 64 bits

Receive window size in octets: 16 bits

Receive left window edge (next sequence number expected): 32 bits

Send window size in octets: 16 bits

Send left window edge (earliest unacknowledged octet): 32 bits

Next packet sequence number to send: 32 bits

Last sequence number used to update send window (make sure that only the most recent window information is used): 32 bits

Connection state: 4 bits

See figure 4.2-1 for basic state diagram.

CLOSED (0), OPEN (1), SYN-SENT (2), SYN-RECEIVED (3), ESTABLISHED (4), CLOSE-WAIT (5), FIN-WAIT (6), CLOSING (7).

Foreign connection specification (U,U.N,U.T,U.P): 4 bits

U.N is set if the foreign network was not specified in the OPEN command. U.T is set if the foreign TCP was not specified in the OPEN command. U.P is set if the foreign Port was not specified in the OPEN command. U is set if any of U.N, U.T, or U.P are set. U.T implies U.P and U.N implies both U.T and U.P (see section 2.20). U.N, U.T, and U.P are used to remember the state of unspecificity of the foreign socket at the initial OPEN so that a RST (reset) will return the foreign socket to its proper state. U is reset (i.e. made false) when a SYN is received, but may be set again on receipt of RST, depending upon U.N, U.T. or U.P. Once in the ESTABLISHED state, U.N, U.T, and U.P can be reset, since the connection will not return to OPEN on receiving RST after it has become ESTABLISHED.

Retransmission timeout: 16 bits

Head of Send buffer queue [buffers SENT from user to TCP, but not packetized]: 16 bits

Tail of Send buffer queue: 16 bits

Pointer to last octet packetized in partially packetized buffer (refers to the buffer at the head of the queue): 16 bits

Head of Send packet queue: 16 bits

Tail of Send packet queue: 16 bits

Head of Packetized buffer queue: 16 bits

Tail of Packetized buffer queue: 16 bits

Head of Retransmit packet queue: 16 bits

Tail of Retransmit packet queue: 16 bits

Head of Receive buffer queue [queue of buffers given by user to RECEIVE letters, but unfilled]: 16 bits

Tail of Receive buffer queue: 16 bits

Head of Receive packet queue: 16 bits

Tail of receive packet queue: 16 bits

Pointer to last octet filled in receive buffer: 16 bits

Pointer to next octet to read from partly emptied packet: 16 bits

[Note: The above two pointers refer to the head of the receive buffer and receive packet queues respectively]

Forward TCB pointer: 16 bits

Backward TCB pointer: 16 bits

4.4 Structure of the TCP

4.4.1 Introduction

Any particular TCP could be viewed in a number of ways. It could be implemented as an independent process, servicing many user processes. It could be viewed as a set of re-entrant library routines which share a common interface to the local PSN, and common buffer storage. It could even be viewed as a set of processes, some handling the user, some the input of packets from the net, and some the output of packets to the net.

We offer one conceptual framework in which to view the various algorithms that make up the TCP design. In our concept, the TCP is written in two parts, an interrupt or signal driven part (consisting of five processes), and a reentrant library of subroutines or system calls which interface the user process to the TCP. The subroutines communicate with the interrupt part through shared data structures (TCB's, shared buffer queues etc.). The five processes are the Output Packet Handler which sends packets to the packet Switch; the Packetizer which formats letters into internet packets; the Input Packet Handler which processes incoming packets; the Reassembler which builds letters for users; and the Retransmitter which retransmits unacknowledged packets.

As an example, we can consider what happens when a user executes a SEND call to the TCP service routines. The buffer to be sent is placed on a SEND buffer queue associated with the user's TCB. A 'packetizer' process is awakened to create one or more output packets from the

buffer. The packetizer attempts to maintain a non-empty queue of output packets so that the output handler will not fall idle waiting for the packetizing operation.

A major implementation issue is whether to use TCP resources or user resources for incoming and outgoing packets. If the former, there is a fairness issue, both among competing connections and between the sending and receiving sides of the TCP.

When a packet is created, it is placed on a FIFO send-packet queue associated with its origin TCB. The packetizer wakes the output handler and then continues to packetize a few more buffers, perhaps, before going to sleep. The output handler is awakened either by a ‘hungry’ packet switch or by the packetizer. The send packet queue can be used as a ‘work queue’ for the output handler. After a packet has been sent, but usually before an ACK is returned, the output handler moves the packet to a retransmission queue associated with each TCB.

Retransmission timeouts can refer to specific packets or the retransmission queue can be periodically searched for the timed-out packets. If an ACK is received, the retransmission entry can be removed from the retransmit queue. The send packet queue contains only packets waiting to be sent for the first time.

As usual, simultaneous reading and writing of the TCB queue pointers must be inhibited through some sort of semaphore or lockout mechanism. When the packetizer wants to serve the next send buffer queue, it must lock out all other access to the queue, remove the head of the queue (assuming of course that there are enough buffers for packetization), advance the head of the queue, and then unlock access to the queue.

Incoming packets are examined by the input packet handler. Here they are checked for valid connection sockets and acknowledgements are processed, causing packets to be removed, possibly, from the RETRANSMIT packet queue, as needed.

Packets which should be reassembled into buffers and sent to users are queued by the input packet handler, on the receive packet queue, for processing by the reassembly process. The reassembler looks at its FIFO work queue and tries to move packets into user buffers which are queued up in an input buffer queue on each TCB. If a packet has arrived out of order, it can be queued for processing in the correct sequence. Each time a packet is moved into a user buffer, the left window edge of the receiving TCB is moved to the right so that outgoing packets can carry the correct ACK information. If the SEND buffer queue is empty, then the reassembler creates a packet to carry the ACK.

As packets are moved into buffers and the buffers filled, the buffers are dequeued from the RECEIVE buffer queue and passed to the user. The reassembler can also be awakened by the RECEIVE user call should it have a non-empty receive packet queue with an empty RECEIVE buffer queue.

4.4.2 Input Packet Handler

The Input Packet Handler is awakened when a packet arrives from the network. It first verifies that the packet is for an existing TCB (i.e. the local and foreign socket numbers are matched with those of existing TCB's). If this fails, a "reset" message is constructed and sent to the point of origin.

The input packet handler looks out for control or error information and acts appropriately. As an example, if the incoming packet is a RESET request, and is believable, then the input packet handler clears out the related TCB, empties the associated send and receive packet queues, and prepares error returns for outstanding user SEND(s) and RECEIVE(s) on the reset TCB. The TCB is marked unused and returned to storage. If the RESET refers to an unknown connection, it is ignored.

Any ACK's contained in incoming packets are used to update the send left window edge, and to remove the ACK'ed packets from the TCB retransmit packet queue. If the packet being removed was the end of a user buffer, then the buffer must be dequeued from the packetized buffer queue, and the User informed.

The packet sequence number, the current receive window size, and the receive left window edge determine whether the packet lies within the window or outside of it.

Let W = window size
S = size of sequence number space
L = left window edge
R = L + W = right window edge
x = sequence number to be tested

For any sequence number, x, if

$$0 <= (x - L) \bmod S < (R - L) \bmod S = W \qquad (4.4\text{-}1)$$

then x is within the window.

A packet should be rejected only if all of it lies outside the window. This is easily tested by letting x be, first the packet sequence number, and then the sum of packet sequence number and packet length, less one in equation 4.4-1 above.

The other case to be checked occurs when the packet has both head and tail outside of the receive window, but includes the window.

Let PL = packet length
L,R are as before
H = packet sequence number
T = H + PL – 1 = last packet sequence number

For any packet ranging over sequence numbers [H, T], if

$$0 <= L – H < PL$$

and

$$0 <= R – H < PL \qquad (4.4\text{-}2)$$

then the packet includes the receive window.

If the packet length is zero (e.g. an ACK packet), tests should be performed as if the packet length were one to accommodate the case that the receive window is zero.

If the packet lies outside the window, and there are no packets waiting to be sent, then the input packet handler should construct an ACK of the current receive left window edge and queue it for output on the send packet queue, and signal the output packet handler. Successfully received packets are placed on the receive packet queue in the appropriate sequence order, and the reassembler signalled.

The packet window check can not be made if the associated TCB has not received a SYN, so care must be taken to check for control and TCB state before doing the window check.

4.4.3 Reassembler

The Reassembler process is activated by both the Input Packet Handler and the RECEIVE user command. When the reassembler is awakened it looks at the receive packet queue for the associated TCB. If there are some packets there then it sees whether the RECEIVE buffer queue

is empty. If it is then the reassembler gives up on this TCB and goes back to sleep, otherwise if the first packet matches the left window edge, then the packet can be moved into the user's buffer. The reassembler keeps transferring packets into the user's buffer until the packet is empty or the buffer is full. Note that a buffer may be partly filled and then a sequence 'hole' is encountered in the receive packet queue. The reassembler must mark progress so that the buffer can be filled up starting at the right place when the 'hole' is filled. Similarly a packet might be only partially emptied when a buffer is filled, so progress in the packet must be marked.

If a letter was successfully transferred to a user buffer then the reassembler signals the user that a letter has arrived and dequeues the buffer associated with it from the TCB RECEIVE buffer queue. If the buffer is filled then the user is signaled and the buffer dequeued as before. The event code indicates whether the buffer contains all or part of a letter, as described in section 2.4.

In every case, when a packet is delivered to a buffer, the receive left window edge is updated, and the packetizer is signaled. This updating must take account of the extra octets included in the sequencing for certain control functions [SYN, RSN, ARQ, INT, FIN]. If the send packet queue is empty then the reassembler must create a packet to carry the ACK, and place it on the send packet queue.

Reassembly of incoming packets containing both the beginning and end-of-segment (BOS, EOS; see figure 4.3-1) marks is straightforward. The packet checksum is intact in the packet header and can be used to validate the end-to-end correctness of the data.

Arriving packets with only one or neither bit set are fragments created at a gateway. The intent behind the TCP design is to preserve the end-to-end nature of the checksum and acknowledgement procedure, even in the presence of fragmentation. To achieve this goal, fragments must be reassembled into segments and checksummed. This means, in particular, that the original segment header must be reconstructed.

The rules of gateway fragmentation are straightforward. A packet consisting of sequence numbers 100–599 can be fragmented, for instance, into two packets of 250 octets each (including control). The gateway uses figure 4.1-3 to determine which sequence-bearing control flags to set in each fragment header. In the worst case, suppose all sequence-bearing control bits are set (i.e., SYN, INT, ARQ, RSN, FIN), leaving 495 octets of data. A gateway could produce two fragments, the first beginning with sequence number 100 and including SYN, INT, ARQ and up to and including data sequence 349. BOS would be set, along with ACK and the window field. The checksum field would be zero.

The second packet would contain data sequences 350–597 and controls RSN and FIN, as well as EOS, a checksum (for the original segment—it is not recomputed), and the next sequence number associated with RSN in an option field. The ACK and window fields are duplicates of those in the first fragment.

If EOL is present in the original packet, it is carried only in the last fragment produced. Note that a segment can be divided into more than two fragments, and that a fragment can also be divided. The BOS bit stays with the first fragment, even if that fragment is subdivided later. The EOS and EOL bits stay with the last fragment. Intermediate fragments may not carry any of BOS, EOS, or EOL.

During reassembly of a segment, it may happen that fragments arrive with sequence number extents which overlap (due to alternate gateway routing and different fragmentation). This makes the job of reassembling fragments more difficult, but not impossible. Although it is not part of the current specification, it may be useful for gateways to produce a fragment checksum in addition to passing the segment checksum intact. In this way, a bad fragment is less likely to mess up reassembly of a segment.

Gateway fragmentation rules may require modification or augmentation to deal with option fields in packet headers. While it is generally true that options tend to stay with the fragment marked “BOS” we have already seen that an RSN-bearing packet keeps the option with the packet containing the RSN.

The rules of packet retransmission require that retransmitted packets contain the latest ACK and window information available. This means that a duplicate of a segment, if fragmented, may have a different checksum than earlier copies. To assure that segment reassembly is not frustrated by this effect, the ACK and window information used to validate the reassembled checksum should be taken from the packet containing the checksum (i.e. the fragment marked “EOS”).

4.4.4 Packetizer

The Packetizer process gets work from both the Input Packet Handler and the SEND user call. The signal from the SEND user call indicates that there is something new to send, while the one from the input packet handler indicates that more TCP buffers may be available from delivered packets.

When the packetizer is awakened it looks at the SEND buffer queue for the associated TCB. If there is a new or partial letter awaiting packetization, it tries to packetize the letter, TCP buffers

and window permitting. For every packet produced it signals the output packet handler (to prevent deadlock in a time sliced scheduling scheme). If a ‘run to completion’ scheme is used then one signal only need be produced, the first time a packet is produced since awakening. If packetization is not possible the packetizer goes to sleep.

If a partial buffer was transferred then the packetizer must mark progress in the SEND buffer queue. Completely packetized buffers are dequeued from the SEND buffer queue, and placed on a packetized buffer queue, so that the buffer can be returned to the user when an ACK for the last bit is received.

When the packetizer packetizes a letter it must see whether it is the first piece of data being sent on the connection, in which case it must include the SYN bit. Some implementations may not permit data to be sent with SYN and others may discard any data received with SYN.

4.4.5 Output Packet Handler

When activated by the packetizer, or the input packet handler, or some of the user call routines, the Output Packet Handler attempts to transmit packets to the net (may involve going through some other network interface program). Transmitted packets are dequeued from the send packet queue and put on the retransmit queue along with the time when they should be retransmitted.

All data packets that are (re)transmitted have the latest receive left window edge in the ACK field. Some error messages may set the ACK field to refer to a received packet’s sequence number.

4.4.6 Retransmitter

This process can either be viewed as a separate process, or as part of the output packet handler. Its implementation can vary; it could either perform its function, by being awakened at regular intervals, or when the retransmission time occurs for every packet put on the retransmit queue. In the first case the retransmit queue for each TCB is examined to see if there is anything to retransmit. If there is, a packet is placed on the send packet queue of the corresponding TCB. The output packet handler is also signaled.

Another “demon” process monitors all user Send buffers and retransmittable control messages sent on each connection, but not yet acknowledged. If the global retransmission timeout is exceeded for any of these, the user is notified and the connection aborted.

4.5 Buffer and Window Allocation

4.5.1 Introduction

The TCP manages buffer and window allocation on connections for two main purposes: equitably sharing limited TCP buffer space among all connections (multiplexing function), and limiting attempts to send packets, so that the receiver is not swamped (flow control function). For further details on the operation and advantages of the window mechanism see [CK74].

Good allocation schemes are one of the hardest problems of TCP design, and much experimentation must be done to develop efficient and effective algorithms. Hence the following suggestions are merely initial thoughts. Different implementations are encouraged with the hope that results can be compared and better schemes developed.

4.5.2 The SEND Side

The window is determined by the receiver. Currently the sender has no control over the SEND window size, and never transmits beyond the right window edge (except during resynchronization).

Buffers must be allocated for outgoing packets from a TCP buffer pool. The TCP may not be willing to allocate a full window's worth of buffers, so buffer space for a connection may be less than what the window would permit. No deadlocks are possible even if there is insufficient buffer or window space for one letter, since the receiver will ACK parts of letters as they are put into the user's buffer, thus advancing the window and freeing buffers for the remainder of the letter.

It is not mandatory that the TCP buffer outgoing packets until acknowledgements for them are received, since it is possible to reconstruct them from the actual buffers sent by the user. However, for purposes of retransmission and processing efficiency it is very convenient to do.

4.5.3 The RECEIVE Side

At the receiving side there are two requirements for buffering:

(1) Rate Discrepancy:
If the sender produces data much faster or much slower than the receiver consumes it, little buffering is needed to maintain the receiver at near maximum rate of operation.

Simple queueing analysis indicates that when the production and consumption (arrival and service) rates are similar in magnitude, more buffering is needed to reduce the effect of stochastic or bursty arrivals and to keep the receiver busy.

(2) Disorderly Arrivals:
When packets arrive out of order, they must be buffered until the missing packets arrive so that packets (or letters) are delivered in sequence. We do not advocate the philosophy that they be discarded, unless they have to be, otherwise a poor effective bandwidth may be observed. Path length, packet size, traffic level, routing, timeouts, window size, and other factors affect the amount by which packets come out of order.

The considerations for choosing an appropriate window are as follows:

Suppose that the receiver knows the sender's retransmission timeout, 'K'. This is usually close to the round trip transmission time. Suppose also, that the receiver's acceptance rate is 'U' bits/sec, and the window size is 'W' bits. Ignoring line errors and other traffic, the sender transmits at a rate between W/K and the maximum line rate (the sender can send a window's worth of data each timeout period).

If W/K is greater than U, the difference must be retransmissions which is undesirable, so the window should be reduced to W', such that W'/K is approximately equal to U. This may mean that the entire bandwidth of the transmission channel is not being used, but it is the fastest rate at which the receiver is accepting data, and the line capacity is free for other users. This is exactly the same case where the rates of the sender and receiver were almost equal, and so more buffering is needed. Thus we see that line utilization and retransmissions can be traded off against buffering.

If the receiver does not accept data fast enough (by not performing sufficient RECEIVES) the sender may continue retransmitting since unaccepted data will not be ACK'ed. In this case the receiver should reduce the window size to "throttle" the sender and inhibit useless retransmissions.

Limited experimentation, simulation, and analysis with buffering and window allocation suggests that the receiver should set aside buffer space to accommodate any window sent to the remote transmitter. Any attempts at optimistically setting a large window with inadequate buffer appears to lead to poor bandwidth owing to occasional (or frequent) discard of arriving packets for which no buffers are available. Theoretically selection of the ratio of window size granted to buffer store reserved should be equivalent to the selection of a buffer size for a statistical multiplexer.

If the user at the receiving side is not accepting data, the window should be reduced to zero. In particular, if all TCP incoming packet buffers for a connection are filled with received packets, the window must go to zero to prevent retransmissions until the user accepts some packets.

Setting the receive window to zero can have some interesting side effects. In particular, it is not enough to merely send an empty ACK packet with the new, non-zero window, when the window is re-opened. If the ACK is lost, the other TCP may never transmit again. ACK's cannot be retransmitted since they cannot, themselves, be ACKed (we would not know when to stop retransmitting). The solution is to send an ARQ packet whenever the receive window is to change from zero to non-zero. The ARQ can be retransmitted until acknowledged, since ARQ takes up one sequence number. A TCP which receives a zero send window should stop transmission, but can continue to acknowledge incoming traffic.

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A. Appendix A—Pathological Examples and Other Notes

Other solutions to the resynchronization problem were examined than those in the specification and we illustrate them here in the hope that these examples will save others the trouble of exploring dry wells.

Our original resynchronization scheme involved exchanging DSN, ACK, SYN, ACK on one or both sides of the connection. J. Mathis constructed a pathological example showing that the unprotected acceptance of SYN after a DSN leads to potential trouble, and it was this example which led us to conclude, initially, that resynchronization must be assumed to occur long after any old SYNs from previous connection initiation or resynchronizations had died away.

	TCP A				TCP B
1.	SYN-SENT	-->	<SEQ 0><SYN>	…	(delayed)
2.	SYN-SENT	-->	<SEQ 0><SYN>	-->	SYN-RECEIVED
3.	SYN-SENT	<--	<SEQ 50><SYN><ACK>	<--	SYN-RECEIVED
4.	ESTABLISHED	-->	<SEQ 1><ACK 51><9 data bytes>	-->	ESTABLISHED
5.	DSN-SENT	-->	<SEQ 10><DSN><ACK 51>	-->	DSN-RECEIVED
6.	DESYNCHED	<--	<SEQ 51><ACK 11>	<--	DESYNCHED
7.	RESYNCH	-->	<SEQ 1000><SYN>	…	(delayed)
8.	(delayed duplicate)	…	<SEQ 0><SYN>	-->	RESYNCH
9.	Bad ACK!	<--	<SEQ 51><ACK 1>	<--	ESTABLISHED
10.	(delayed)	…	<SEQ 1000><SYN>	-->	Bad SEQ!
11.	HUH?	<--	<SEQ 51><ERR 6><1000>	<--	Unexpected SYN!
12.	(reset!)	-->	<SEQ 1000><ERR 7><51>	-->	aborted

Resynchronization Failure under Delayed Duplicate SYN Conditions

Figure A-1

In this example, an old duplicate original SYN (line 1, figure A-1) completely confuses TCP B, after which an exchange of errors 6 and 7 (“unexpected SYN” and “RESET”) result when TCP A’s resynchronizing SYN (lines 7, 10, figure A-l) finally appears. Thus, a perfectly ordinary resynchronization procedure initiated by TCP A results in TCP B discarding its end of the connection, thinking it was only half-open. Part of the problem was that the error message affected both sides of the connection (perils of full duplex connections!).

In an early attempt to bind sequence numbers across the resynchronization gap, we considered another strategy in which both sides would desynchronize and then resynchronize (the earlier example failed because there was no 3-way handshake on the resychronizing SYN).

	TCP A		TCP B		
1.	DSN SENT	-->	<SEQ 10><DSN><ACK 20>	-->	DSN RECEIVED
2.	DSN SENT	<--	<SEQ 20><DSN><ACK11>	<--	DSN RECEIVED
3.	DESYNC	-->	<SEQ 11><ACK 21>	-->	DESYNC
4.		<--	<SEQ 2000><SYN><ACK 11>	<--	SYN SENT
5.	SYN SENT	-->	<SEQ 1000><SYN><ACK 21>	-->	
6.		-->	<SEQ 1001><ACK 2001>	-->	ESTABLISHED
7.	ESTABLISHED	<--	<SEQ 2001><ACK 1001>	<--	

Dual DSN with SYN,ACK

Figure A-2

In this example (figure A-2), both sides desynchronize and then go through a handshake which is protected (lines 4,5) by the presence of an old ACK field referencing the old sequence numbers of the other side. It was noted that this mechanism does not easily reduce to one-sided resynchronization since, if TCP B has sent no data or control (other than the original SYN) on the connection, the ACK fields of the resynchronizing SYN and the original SYN from TCP A would be identical. We then had to postulate the use of a NOP control to acknowledge the DSN and thus guarantee uniqueness of the ACK field in TCP A's resynchronizing SYN packet. This solution was not pursued further, but contains the seeds of the RSN described in section 2.1.3. But in that case, old and new sequence numbers of the same sides of the connection, rather than opposite sides, are bound together.