APRIL 1992

WRL
Research Report 92/2

Observing TCP Dynamics in Real Networks

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Observing TCP Dynamics in Real Networks

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April, 1992

Abstract

The behavior of the TCP protocol in simple situations is well-understood, but when multiple connections share a set of network resources the protocol can exhibit surprising phenomena. Earlier studies have identified several such phenomena, and have analyzed them using simulation or observation of contrived situations. This paper shows how, by analyzing traces of a busy segment of the Internet, it is possible to observe these phenomena in ‘‘real life’’ and measure both their frequency and their effects on performance. A TCP implementation might use similar techniques to support rate-based congestion control.

This Research Report is a slightly expanded version of a paper to appear in the *Proceedings of the SIGCOMM ’92 Conference on Communications Architectures and Protocols*.

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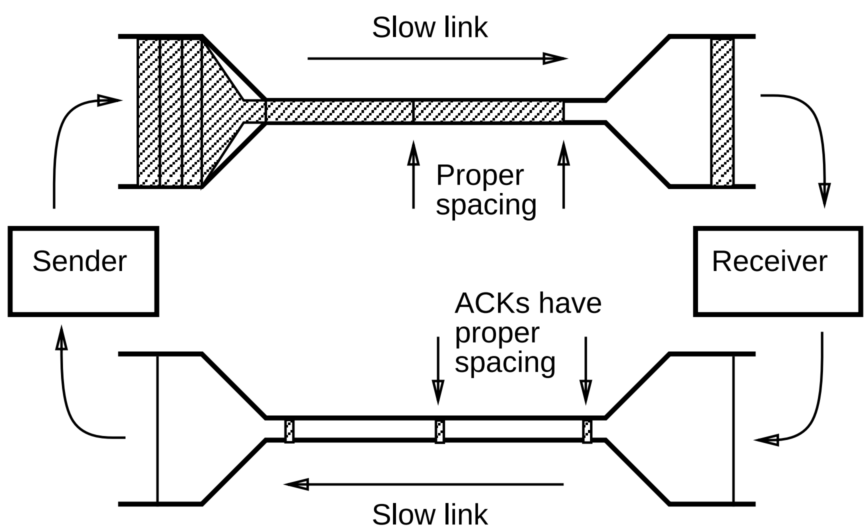
1. Introduction

Although the TCP protocol has a relatively brief specification [14], and a functionally correct implementation can be as short as ten pages of source code, the dynamics of TCP in real networks are not well understood. Real networks in particular suffer from congestion; that is, contention for insufficient resources. While modern TCP implementations attempt to avoid or recover from congestion, they do this using delayed feedback mechanisms that exhibit complex behavior.

Most TCP implementations now in use include the congestion avoidance and control algorithms described by Van Jacobson [8]. Jacobson developed his algorithms by observing the behavior of TCP implementations attempting to send data across a congested network. In these observations, the congestion was mostly due to a small number of connections, all sending data in the same direction via a single shared bottleneck link.

The essence of the congestion avoidance algorithms is the observation that data packets arrive at the receiving host at the rate that the bottleneck link will support. If the receiver's acknowledgements (ACKs) arrive at the sender with the same spacing, then by sending new data packets at the same rate the sender can avoid overrunning the bottleneck link. It is by correctly exploiting this self-clocking property of TCP that congestion may be avoided (figure 1).



The horizontal dimension represents time, and the shaded area is proportional to packet size (after [8]).

Figure 1: TCP self-clocking

Zhang, Shenker, and Clark [18] studied the slightly more complex case of a single link with TCP data flowing in both directions at once. Their simulations showed that several surprising phenomena could arise in such a situation, even when Jacobson's algorithms were employed.

One such phenomenon they called ''ACK-compression.'' A TCP sender's self-clocking depends on the arrival of ACKs at the same spacing with which the receiver generated them. If these ACKs spend any time sitting in queues during their transit through the network, however, their spacing may be altered (figure 2). When ACKs arrive closer together than they were sent, the sender[1] might be misled into sending more data than the network can accept, which could lead to congestion and loss of efficiency. (This analysis assumes that acknowledgement packets are small enough that queueing is the major cause of their delay.)

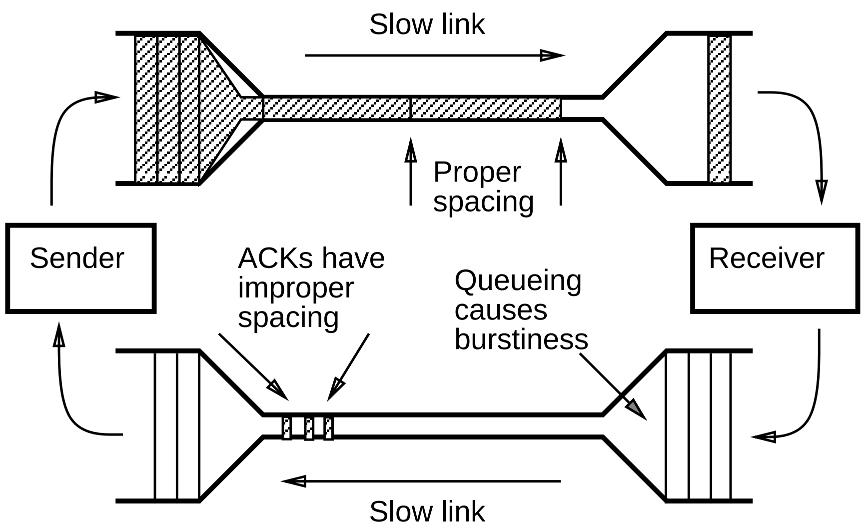


Figure 2: Self-clocking disrupted by ACK-compression

The insights of Zhang *et al.* were based on simulations. Two other studies have detected ACK-compression in actual implementations. Heybey [7] made traces of connections through the actual Internet, but these connections were set up specifically for the traces and might not have been representative. Wilder *et al.* [17] made traces of OSI TP4 connections, also in a testbed network. In all three cases, the results were analyzed by hand to detect interesting patterns, a technique that, while enlightening, cannot be applied to more complex situations.

This paper describes the results of a trace-based studies of large numbers of uncontrived connections through the Internet. These were obtained by monitoring the packets flowing in and out of a busy ‘‘gateway’’ system, widely used by sites all over the Internet for electronic mail and similar protocols. Tools were developed to automatically analyze the traces to detect ACK-compression and other interesting phenomena, and in some cases to show the correlation between various phenomena in order to detect causal relationships.

1.1. Motivation

The primary motivation for these experiments was to determine if ACK-compression could actually be detected automatically, and to discover if it causes any problems. The experiments show that ACK-compression can indeed be detected automatically from packet traces, and that it does happen in real networks. They do not show any serious consequences of ACK-compression in today’s Internet, although this may be a result of our temporary inability to exploit the full bandwidth of the network.

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[1] The terms *sender* and *receiver* will always be used with respect to the data packets, unless further qualified. That is, ACKs are sent from the *receiver* to the *sender*.

Other phenomena besides ACK-compression, such as synchronization of losses between several connections, out-of-order packet delivery, and some forms of improper TCP behavior, can also be automatically detected from traces, as will be described in this paper.

A secondary question is whether, if ACK-compression does happen, there is anything that one could do about it. A TCP implementation could use techniques, similar to the trace-analysis tools described here, to infer when acknowledgements are being compressed. It could then limit the rate of outgoing packets to avoid overloading the bottleneck link.

The emphasis of the discussion in this paper will be on the methods and tools used to detect ACK-compression and related phenomena, rather than a broad study of the frequency of ACK-compression.

1.2. Related work

Timothy Shepard's work on the problem of TCP packet trace analysis [16] extended the repertoire of graphical methods for visualizing TCP traces, and described a way to quantify the burstiness of a connection. Automated detection of ACK-compression relies on a similar method (see section 2.3). Trevor Mendez [12] worked on the problem of identifying ‘‘pathological’’ TCP connections among the many connections captured in a long trace, concentrating on the retransmission behavior of TCP hosts.

Several studies have used traces to study the behavior of many simultaneous TCP connections in wide-area networks. Caceres *et al.* [1] analyzed traces to discover summary information about TCP connections, such as the number of packets transferred or the packet interarrival time. Vern Paxon [13] did similar analyses of a set of traces, and calculated the distribution of per-connection average bandwidths.

Much ongoing work on TCP behavior continues to use simulation, since trace analysis cannot capture all the aspects of a network (such as instantaneous window sizes and queue lengths). Recent studies include an analysis of traffic phase effects by Sally Floyd and Van Jacobson [6], Floyd's analysis of connections through multiple congested routers [4], and the paper that describes ACK-compression [18].

Several simulation studies have identified other phenomena that might be visible to a trace-based analysis. For example, Shenker *et al.* [15] found in their simulations that when multiple connections use the same path, the packets from a given connection tend to be clustered together, rather than interleaved with those of other connections.

2. Methodology

Automatic detection of ACK-compression depends on successful approaches to several problems:

1. **Choosing the monitoring point:** The traces must be made of connections that have a reasonable likelihood of exhibiting ACK-compression.
2. **Obtaining traces:** The traces should be long, must have high-resolution timestamp information, and should contain essentially all of the packets (i.e., there should be few dropped packets).

3. **Defining the phenomena:** Unlike a simulation or a contrived experiment, in these trace it is impossible to observe the actual spacing of ACKs at both ends of the network path. Therefore, compression must be defined indirectly, based on observable aspects of the trace.

The rest of this section discusses the approach taken to each of these issues, and similar issues in the detection of related phenomena.

Section 3 will discuss the tools that have been created to analyze the traces. These tools must solve two problems:

1. **Detecting the phenomena in the traces:** Algorithms must be created to analyze the traces to detect when the defined phenomena are present.
2. **Visualizing the results:** Because there may be thousands of connections and events represented in a trace, the results of the analysis should be presented in a form that allows easy and rapid understanding.

2.1. Choosing the monitoring point

The ideal site for obtaining these traces would be one through which passes many TCP connections, between a wide variety of TCP hosts throughout the Internet, and which transfer more than just a few packets' worth of data at a time. (If the connections are too short, they will not generate enough ACKs to allow compression.) Also, the traces should be made as close as possible to the end-point of these connections, since it is only there that the final spacing of ACKs may be observed.

These criteria suggest monitoring at a major ‘‘gateway’’ complex, one which makes long TCP connections with sites all over the Internet. Fortunately, the author has easy access to the DECWRL gateway, operated by the Network Systems Laboratory of Digital Equipment Corporation. This site exchanges over 16,000 electronic mail messages every day, as well as thousands of USENET ‘‘news’’ articles. The gateway also includes a popular ‘‘anonymous FTP’’ site, from which several thousand files are retrieved each day.

Although most mail messages are too short to give rise to interesting TCP behavior, the gateway also provides an ‘‘FTP-by-mail’’ facility that produces about 150 relatively lengthy messages every day. News articles are also short, but they are sent in batches via the NNTP [9] protocol, and so give rise to long connections. Many FTP transfers involve large files.

Since the traces are being made at one endpoint of the TCP connections, ACK-compression can only be observed on those connections that carry bulk data away from the gateway complex. This halves the number of potentially interesting ACK-compression events in the trace.

Additional traces were made on a subnet of Digital's internal IP network, adjacent to a host that serves as the primary USENET distribution center for the company, as well as several heavily-used electronic mail hosts. While fewer long-distance connections are visible to these traces than at the DECWRL gateway site, many of the internal paths traverse low-bandwidth, congested links, and so the frequency of ACK-compression might be much higher than on the Internet.

During the initial phases of this study, a question arose as to whether the TCP window sizes in common use would be large enough to stimulate ACK-compression. Many hosts use window sizes of just 4k bytes, which might be too small to elicit the phenomenon, but quite a few hosts now use 16k-byte windows. (In our traces, at least half of the connections used windows of 16k bytes or more.) In any case, although the NSFNet can transport 1500-byte datagrams to many sites, most TCP hosts use a segment size of 512 bytes in order to avoid possible fragmentation; this means that even with a relatively small window size of 4k bytes, up to eight packets may be in transit at once. Our results show that for whatever reason, the issue of window size has not been an impediment to the detection of ACK-compression.

One advantage of making the traces at an endpoint site, rather than at a backbone, is that by definition that site is a party to all of the connections traced. This simplifies the issue of obtaining permission, but it would be unethical (and perhaps illegal) to monitor the content of the connections without the permission of both parties [2]. The traces therefore contain only packet header data, and not anything that could be used to compromise the privacy of the messages traced.

2.2. Obtaining traces

The traces were obtained by ‘‘promiscuous-mode’’ monitoring of 10 Mbit/sec Ethernet networks. This passive monitoring technique eliminates any effect that the trace-gathering process might have on the connections being traced. It also means that no changes need be made to the hosts whose connections are traced.

2.2.1. Tracing environment

The trace-gathering program runs on any ULTRIX™ version 4.2 system, and for these experiments was run on DECstation™ 3100 workstations. During the traces, little additional activity was present on the trace-gathering system. Trace files were written to disk for later analysis, rather than being transferred over the network in real-time (which might have affected the network being traced).

Some simple arithmetic will demonstrate that to detect ACK-compression, the traces must contain high-resolution timestamps. For example, suppose that a TCP connection is using 1500-byte packets over a path with an effective bandwidth of 10 Mbit/sec. This means that properly-spaced ACKs will be sent approximately 1.2 msec apart. A timestamp resolution coarser than about half of that will make some properly-spaced ACKs appear to be compressed together, since they will arrive during the same ‘‘tick.’’

ULTRIX normally updates its timebase just 256 times per second, yielding a resolution of about 4 msec. To obtain better timestamps, the ULTRIX kernel used on the tracing systems was modified to use a 4096 hz timebase, yielding a resolution of about 244 usec. Additionally, the traces record the length of each packet; this allows some subsequent ‘‘decompression’’ of timestamps because the minimum spacing between two packets, as they were transmitted on the monitored Ethernet, can be calculated from their lengths (see section 3).

For the traces made on Digital’s internal IP network, the DECstation 3100 used was equipped with specially-constructed clock hardware. This provides a basic timestamp resolution of 100 nsec, although the usable resolution is not quite this good because the timestamps are applied by the kernel and so are smeared by the latency of the interrupt-handling code.

2.2.2. Creation of a trace file

The tracing program is conceptually quite simple. The IP header of each TCP packet received is parsed to obtain source and destination addresses, and the TCP header is parsed to obtain the source and destination ports, the sequence and acknowledgement numbers, the flags, and the window size.

Since the addressing information is repetitive, the program maintains a map from TCP address tuples (the two IP addresses and the two TCP port numbers) to a compact connection identifier. (At any one time, this is enough information to uniquely identify a connection, but during the life of a trace there may be several connections that reuse the same address tuple. In a post-processing phase, it is easy to split the trace up into distinct connections, because the TCP protocol has rules to prevent any confusion.) Whenever a new connection is seen, the tracing program emits a record containing the new connection ID and the associated addressing information. For each packet received, the program emits a record containing the timestamp, connection ID, and the non-address fields from the TCP header.

Note that the connection ID identifies one direction of packet flow; TCP connections are always full-duplex, and the relationship between the two half-connections can be recreated in a post-processing phase.

The connection ID mapping is done using a hash table, with 1024 hash slots each pointing to a chain of entries. A simple hash function on the address information distributes the entries remarkably evenly, with no chain more than three times longer than the average. A ‘‘one-behind’’ cache bypasses the hash table lookup whenever two or more successive packets belong to the same connection.

In spite of the compression of address information, the trace files are still quite bulky. A file representing a trace of 1 million packets requires just under 32 Mbytes of disk space. In order to avoid cluttering the trace with irrelevant information, the trace program can be made to ignore packets between pairs of ‘‘local’’ hosts, where ‘‘local’’ refers to a host whose address is the same as the tracing host, when compared under a given bit mask. For traces made at the DECWRL gateway site, this mask covered the IP network number; for traces made internal to Digital’s IP network, the mask covered the network and subnet numbers.

2.2.3. Potential problems with passive monitoring

Passive monitoring techniques can miss packets if the throughput of the monitoring system is insufficient, or if there is not enough buffering in the monitor to handle the occasional burst of packets. When looking for ACK-compression, it is especially important to capture all the packets in a burst, since the compressed ACKs will by definition be received in a burst. The ULTRIX kernel provides a moderate amount of queueing to absorb bursts, and keeps an accurate count of the number of packets dropped from the queue. The tracing program emits an error record, containing the count of dropped packets, whenever this occurs, and so the analysis tools can reconstruct exactly how many packets were dropped and approximately when this happened.

In the traces made for this paper, the trace-gathering system was able to keep up with the traffic. In no case were even 0.2% of the packets dropped. While it is impossible to tell if the dropped packets conceal an unusually high number of ACK-compression events, it is unlikely that this is the case.

Another problem with passive monitoring is that it occasionally accepts packets with checksum errors. While it is theoretically possible to have the tracing program check the header checksums on each packet, in practice this would so slow the program that it would certainly lose far too many packets. (Checksumming is now considered to be the most expensive part of processing a TCP packet [3].) Statistics kept by the gateway machines show that packets with bad checksums, while present, are quite rare. The danger for this experiment is that a damaged packet might give rise to a trace record that confuses the analysis tools. The tools take some care to ignore connections that contain bizarre packets, but it is possible that corruption of a few bits could cause false conclusions to be drawn on rare occasions.

2.3. Defining the phenomena

When ACKs are observed arriving at the end of their transit through the Internet, it is impossible to know precisely how they were spaced when they were sent. (When ACKs are observed near the receiver, we can tell their spacing, but we then do not see them arriving at the other end and so can say nothing at all about their possible compression.) This means that the trace analysis tools must infer ACK-compression from indirect evidence. Choosing a satisfactory definition is thus key to the utility of the analysis, and proved to be somewhat difficult.

What we can observe, by looking at the number of bytes acknowledged by a set of ACKs and the time spacing between them, is the apparent network bandwidth that these ACKs promise to the sender. (This is precisely the information that the sender uses to meter out its data traffic.) This is called the ‘‘instantaneous ACK bandwidth’’ of the observed ACKs. We want to know if this value is much higher than the actual bandwidth of the path, which would indicate that ACK-compression has occurred.

Another thing we can observe is the actual progress of the connection over intervals long compared to the TCP window size. Clearly, the bandwidth obtained during such an interval cannot be higher than the actual available bandwidth. If we can measure this ‘‘true’’ bandwidth, then we can define ACK-compression as occurring when the instantaneous ACK bandwidth is significantly greater than the true bandwidth.

The simplest way of calculating the bandwidth of a connection, given a trace of all its ACKs, is to divide the total number of bytes acknowledged by the total time required. Unfortunately, most connections do not proceed at a steady rate, and so this average rate is almost always far too small.

Plots of ACK-value versus time for actual TCP connections show phases of relatively steady progress (diagonal lines) interspersed with dead periods (horizontal lines). Clearly, what we want is to ignore the dead periods when computing the true bandwidth.

Previous work by Shepard [16] suggests a solution. In order to visualize the burstiness of TCP connections, he plotted the distribution of the instantaneous bandwidths for a connection. The x-axis of these plots shows the number of bytes carried in a packet divided by the time since the previous packet; the y-axis shows the total number of bytes transferred at a given instantaneous bandwidth. Since the dead periods transfer few or no bytes, they contribute little to the distribution, and the peaks of the distribution show the approximate true bandwidths attained during various phases of the connection.

If there is one main peak to this distribution, we can find its approximate position on the x-axis by taking the median of the distribution. This provides a simple, automatic mechanism for estimating the true bandwidth of a connection that transfers a lot of data over a stable path.

It is possible that if the connection's rate is actually limited by something external to the network, such as a disk drive on one of the end systems, this mechanism will underestimate the true bandwidth. There is not much one can do about this, if the information in the traces is all that is available. One could in principle set up ''probe connections'' along the paths followed by interesting connection, and attempt to measure the available bandwidth; this is not always possible, and was not done for this study. Anyway, the results suggest that the alleged ACK-compression events are often real, since they are often associated either with subsequent segment loss or with periods of reduced throughput. If they were a consequence of an underestimate of the available bandwidth, one would expect to see them associated with periods of increased throughput.

Some additional filtering reduces falsely-detected ACK-compression. First, we can insist that a compression event last for at least a certain number of packets (i.e., the ACK-bandwidth is measured over a window of A packets, where A might be greater than the minimum of two.) Second, we can insist that the ACK-bandwidth exceed the estimated true bandwidth by a ratio R (such as 5 or 10) in order to correct for serious underestimates of this value. Third, we can insist that a compression event show a certain minimum ACK-bandwidth B, in order to omit connections that don't actually transmit much data. This threshold should be set slightly above an estimate of the lowest link-bandwidth in the network, since setting it much higher could hide ACK-compression on low-bandwidth links.

2.3.1. Segment loss and out-of-order delivery

We would like to be able to detect TCP segment losses since these are the main consequence of improper segment spacing. Since we cannot directly know when a segment has been lost, we have to infer segment loss from the observed retransmission of a segment. Note also that if a segment flowing into the monitored site is lost, we will never know this because even if we receive a retransmitted copy, without having seen the original we will not recognize the retransmission as such. In other words, we can only detect retransmissions on connections that transfer data out of the monitored site. Fortunately, since we can detect ACK-compression on only these same full-connections, it should be possible to detect correlations between ACK-compression and segment loss, if the correlations exist.

We define retransmission to have occurred if we see a segment whose sequence number lies within the ranges of bytes transmitted by another segment.

We can also detect out-of-order delivery of a segment (presumably because of multiple paths through the Internet). This is deemed to have happened when we see a sequence number arrive that precedes a previously-received sequence number, and does not overlap with another segment.

3. Analysis Tools

Once the traces are made, they must be analyzed to detect the phenomena of interest. Analysis is done offline, because a connection cannot be analyzed until it is complete, and because on-line analysis would interfere with packet-gathering and cause packet loss. Many kinds of off-line analysis can be applied to a single trace file.

Several different primary analyses can be applied to the connections[2] in a trace:

- **Aggregate statistics:** For each connection, we compute the total duration, number of bytes sent (i.e., the net change in sequence number), number of bytes acknowledge (the net change in acknowledgement number), and the median ACK-bandwidth.
- **ACK-compression:** Given parameter values for the ACK-compression detection window, minimum ACK-bandwidth, and minimum ratio to the median, we find those ACK packets that appear to have been compressed.
- **Segment retransmission, out-of-order delivery:** By examining sequence numbers, packet lengths, and timestamps we discover those segments that have been retransmitted or have arrived out of order.

These primary analyses can then be combined in several ways (for example, to find correlations between ACK-compression and segment loss) and the results then plotted.

3.1. Data structures to support analysis

Each analysis tool starts by reading a saved trace file. An in-memory database is built up from the connection and packet-header records in the file. For each new connection, a connection record is created and inserted into a hash table (for rapid location based on the compact connection ID.) Each packet-header record is stored in a header record, and added to the end of a linked-list of headers attached to the appropriate connection record. Since the trace file is ordered by packet arrival time, the lists of headers are also time-ordered.

During this process, the timestamps being read in are checked to make sure that they are no closer together than the minimal possible spacing on an Ethernet. (If traces were made on a different LAN, such as FDDI, this calculation would have to be modified.) If one header record follows the previous one with a timestamp difference shorter than would be possible based on the length of the previous packet, the timestamp of the new record is increased accordingly.

Another problem with the raw trace data is that while at any given time the TCP address tuple uniquely identifies a connection, once a connection is terminated the same address tuple may be reused shortly thereafter. Since the sequence numbers from the two connections bear no relation to each other, in order to make sense of the sequence numbers the connections must be separated. This is done by searching for tell-tale signs of the end or beginning of a connection: packets bearing the FIN or SYN flags, or large jumps in the sequence or acknowledgement num-

[2] Remember that the term ‘‘connection’’ refers in this case to a half-duplex, one-way packet flow. An actual TCP connection is represented by two of these half-connections.

bers. The largest legal jump in a TCP sequence number is the maximum window size of 64k bytes. Any jump larger than this suggests that a new connection has been made, although it is also possible that the trace-gathering program has either dropped a bunch of packets, or has accepted a corrupted packet. In either case, since we are lacking sufficient information to analyze the entire connection, splitting into two connections avoids the problem of data integrity.

Once in a while, a trace contains data that just doesn't make sense. For example, the final sequence or acknowledgement number is much lower than the initial value. While this could occur because of sequence-number wraparound, it can also be due to corrupted data, so the tools simply discard the entire connection in this case.

The in-memory database of connection and header records can be quite large. Each header record in its in-memory form contains 36 bytes; this could be reduced somewhat with compression techniques, but that would make the whole process run slower. As a result, a trace of 1 million packets requires somewhat more than 36 Mbytes of virtual address space, and since the locality of reference to this database is poor, the analysis must be carried out on a machine with at least that much real memory. The largest machine available for these experiments, a DECstation 5000/200, has 480 Mbytes of RAM, so traces of up to about 10 million packets could have been analyzed, but such traces would have required a lot of disk storage.

The running time of the analysis programs depends heavily on the cost of reading the trace file and constructing the internal database. On the systems with 480 Mbytes of RAM, the file system's buffer cache can hold an entire trace file of 1 million packets, so the cost of an analysis depends entirely on CPU speed. On the DECstation 5000/200, the simplest analysis (not requiring the computation of median ACK-bandwidths) takes about 30 seconds, 20% of which is spent in the *read()* system call and 30% of which is spent correcting the timestamps and inserting header records into the database. (The more complex analyses take several minutes, because the algorithm used for finding medians is quite crude.)

3.2. Detecting the phenomena in the traces

Once all of the connection and header records have been created, passes can be made over the entire database, or over the header record list for a specific connection.

3.2.1. Detecting ACK-compression

If the analysis requires detection of ACK-compression in a connection, the first pass computes the median of the instantaneous ACK-bandwidths. First, the program calculates the instantaneous ACK-bandwidth for each packet with the ACK flag set; this is computed by dividing the difference in acknowledgment numbers between successive ACK packets by the time elapsed between their reception. The program then records the instantaneous bandwidth samples in an array, and sorts the array. Finally, it locates the median value, weighted by the number of bytes acknowledged at each rate. (A more sophisticated median-finding algorithm might reduce the time required for an analysis, but since it takes less than 90 seconds to analyze a 1-million packet trace, this has not been a problem.)

The next pass again traverses the list of header records and calculates the ACK-bandwidth, but this time instead of using the instantaneous difference between two successive packets, the bandwidth is calculated over the ‘‘ACK window size’’ A, specified as a parameter to the analysis. For example, if $A = 3$, then the ACK-bandwidth is calculated between an ACK-packet and the third following ACK-packet. If the instantaneous bandwidth exceeds the connection’s median by a specified ratio R, and also exceeds a specified minimum value B, the header records in the window are flagged as being ‘‘compressed.’’

3.2.2. Detecting segment retransmission and out-of-order delivery

A separate pass over the header record list is made to find retransmitted TCP segments. During this pass, an array is created containing an entry containing the sequence number and length of each packet, a serial number indicating the order of reception, and a back-pointer to the associated header record.

This array is then sorted, using the sequence number as the primary key, the length as the secondary key, and the reception order as the tertiary key. One more pass over the sorted array suffices to detect retransmissions and out-of-order delivery:

- If an array entry’s sequence number falls within the range of bytes carried by a previous packet, then the entry is a retransmission. (We ignore packets with SYN set, since typically a lot of these are sent during an attempt to make a connection with a dead host.) The earlier packet is flagged as having been lost, and the later packet is flagged as a retransmission.
- During the pass over the sorted array, we can also detect and flag packets delivered out of order, since these are ones whose reception order is earlier than their predecessor in the array (which is sorted by sequence number), if the predecessor is not a retransmission.

4. Visualizing the results

Once the automated analysis has found connections with anomalous behavior, one needs some way to visualize the results. Visualization methods for these experiments can be divided into those showing just one connection, and those that show all (or a subset) of the connections. Also, the methods can be divided into graphical presentations, which abstract a lot of the details of individual packets, and textual presentations, which provide detailed insights but do not easily reveal interesting patterns. All four combinations of scope and presentation are useful.

4.1. Graphical presentation of single connections

Van Jacobson [8] seems to have pioneered the use of plotting sequence numbers versus time to visualize a single TCP connection. Since the automated analysis described above marks packet header records that are part of ACK-compression, segment-loss, or out-of-order delivery events, the Jacobson plots are easily extended to show when these events occur. Note that since ACK-compression happens to packets carrying acknowledgements, which flow on the other half-connection from the packets that suffer from segment loss and out-of-order delivery, it is profitable to plot on one graph both the sequence numbers from one half-connection, and the acknowledgement numbers from the ‘‘partner’’ half-connection.

An example of one such plot is shown in figure 3. The sequence-number plot is a solid line, and the acknowledgement-number plot is a broken line. (This connection starts with a period of about 25 seconds during which few bytes are transferred.) Regions of ACK-compression are bounded by ‘‘+’’ symbols, segment losses are marked with ‘‘X’’ symbols. In color media, these symbols can be made much easier to distinguish, and color may also be used to highlight regions of the curve suffering from ACK-compression.

Examination of such plots quickly provides insight into such issues as the actual underlying bandwidth of the connection (from the slope of the diagonal segments of the curve), and the relationship between ACK-compression and overall performance. For example, if ACK-compression were deleterious, one would expect to see decreases in the slope, or segment loss events, shortly after an instance of ACK-compression. In figure 3, this seems to be the case; shortly after the first ACK-compression event, an entire window-full of packets is sent in a brief interval, and all of these packets are lost.

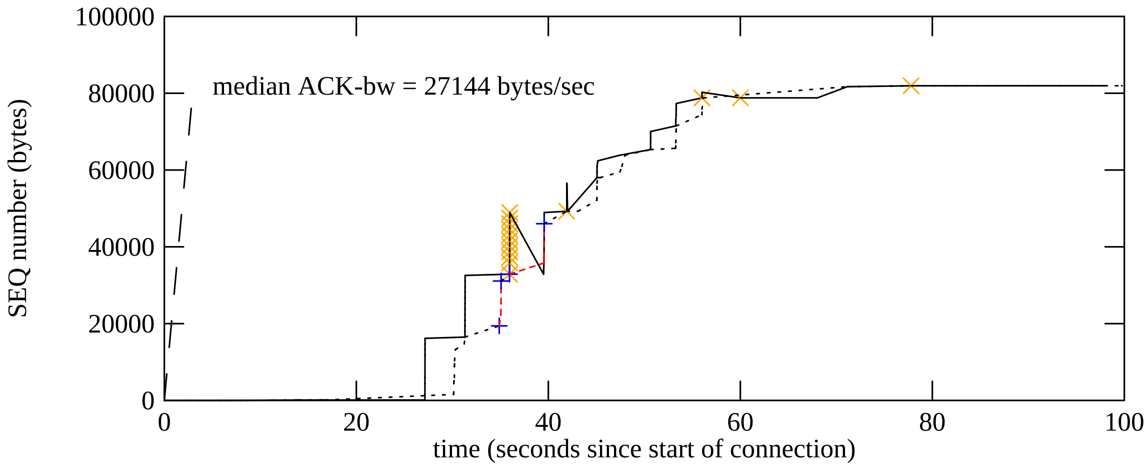

Figure 3: Sequence numbers vs. time for single connection

Following Shepards’s approach [16], we can also plot the distribution of instantaneous ACK bandwidths, as in figure 4. This more directly reveals the underlying network bandwidth, if one assumes that the spikes near 1 Mbyte/sec are the result of ACK compression rather than an indication of the true bandwidth.

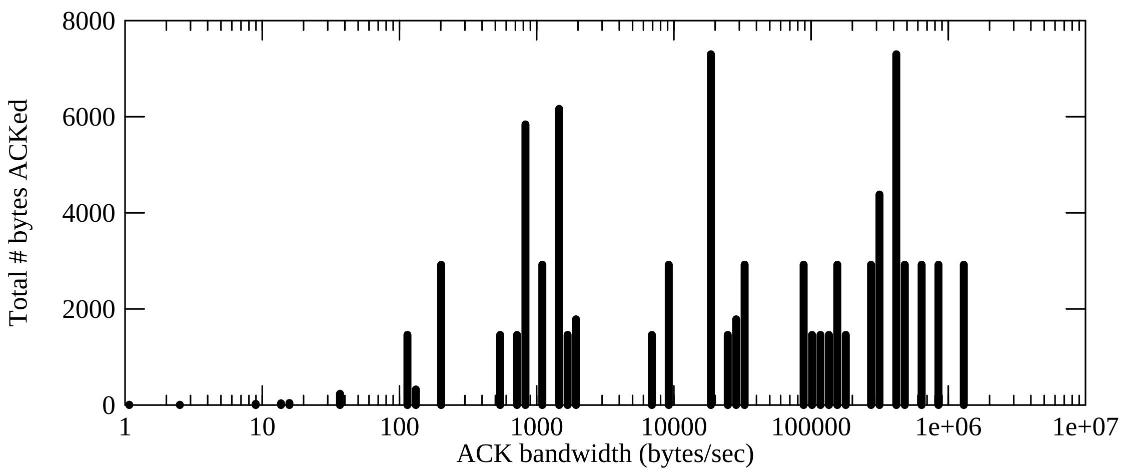

Figure 4: Instantaneous bandwidth distribution (same connection as fig. 3)

4.2. Textual presentation of single connections

Sometimes the Jacobson plots do not show enough detail to understand the precise dynamics of a connection. In this case, it helps to look at a trace of the individual packets of a connection, showing the exchange of packets in both directions in the correct time sequence.

(Because TCP is not a lock-step protocol and the hosts involved may be separated by a long-delay path, the actual ordering of packets may depend on where one observes it. For example, if host A and host B are 100 milliseconds apart, and host A sends an acknowledgment packet to host B 10 milliseconds after host B sends a data packet to host A, an observer near host A will see the packets in the opposite order from an observer near host B. This ‘‘relativistic effect’’ rarely appears.)

Packet traces can be difficult to analyze, even for an expert, but some help can be provided. For example, although TCP's 32-bit sequence numbers are hard to deal with directly, the *tcpdump* program [11] reports not the absolute sequence numbers but the relative value since the first observed packet of a connection. It seems even more useful to report the difference in sequence numbers between two successive packets, because that can be directly related to the amount of data transferred. Also, by showing the two halves of a connection in side-by-side columns, following Shepard's example [16], one gets a picture of the time-ordering of the packets. By displaying relative instead of absolute timestamps, the short-term dynamics are made apparent. Figure 5 shows part of the same connection as figure 3, packet-by-packet.

In figure 5, the sender's packets are shown on the left, and the receiver's on the right. The first column numbers the packets, for convenience in explanation. The second column shows the timestamp, in seconds since the preceding packet. The next four columns show the data length (exclusive of headers), the increment in sequence and acknowledgment numbers, the offered window size, and the TCP flag bits. The final column on the sender's side marks lost or retransmitted packets (with ‘‘L’’ or ‘‘R’’, respectively). On the receiver's side, the sixth column shows the instantaneous ACK-bandwidth, and the final column marks compressed packets (with ‘‘C’’).

On lines 1 through 12, we see the series of data packets being sent, then a burst of ACKs (lines 13 through 18). The last column shows that some of these ACKs (lines 14 through 17) appear to have been compressed[3], and indeed most of the packets in the next burst (lines 19 through 30) are lost (marked with ‘‘L’’). After a 3.5 second timeout, the sender realizes this and enters a slow-start phase (starting with line 31), which revives the transfer of data.

4.3. Graphical presentation of multiple connections

Although the sequence-number curve in figure 3 is useful for displaying one connection, an entire trace might contain thousands of connections, and it would be impossible to study all those curves. There is a variety of more useful ways to display the aggregate behavior of many connections.

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[3]All the ACKs in a compression event are marked with ‘‘C,’’ including those which arrive first and thus whose instantaneous ACK bandwidth is small (because they have been delayed the longest).

	Timestamp	Sender						Receiver						
		len	seq	ack	win	flags	loss?	len	seq	ack	win	flags	ACKbw	comp?
1	0.005883	1460	324	0	16384	A								
2	0.001890	1460	1460	0	16384	A								
3	0.001230	1460	1460	0	16384	A								
4	0.001850	1460	1460	0	16384	A								
5	0.001230	1460	1460	0	16384	A								
6	0.002279	1460	1460	0	16384	A								
7	0.001230	1460	1460	0	16384	A								
8	0.001957	1460	1460	0	16384	A								
9	0.001594	1460	1460	0	16384	A								
10	0.001230	1460	1460	0	16384	A								
11	0.002090	1460	1460	0	16384	A								
12	0.000321	324	1460	0	16384	PA								
13	3.554472							0	0	2920	16384	A	816	
14	0.166976							0	0	2920	16384	A	17488	C
15	0.019490							0	0	2920	16384	A	149820	C
16	0.003268							0	0	2920	16384	A	893513	C
17	0.002416							0	0	2920	16384	A	1.21e+06	C
18	0.878066							0	0	1784	16384	A	2032	
19	0.005965	1460	324	0	16384	A	L							
20	0.002010	1460	1460	0	16384	A								
21	0.001230	1460	1460	0	16384	A	L							
22	0.001923	1460	1460	0	16384	A	L							
23	0.001230	1460	1460	0	16384	A	L							
24	0.001230	1460	1460	0	16384	A	L							
25	0.001230	1460	1460	0	16384	A	L							
26	0.001672	1460	1460	0	16384	A	L							
27	0.001663	1460	1460	0	16384	A	L							
28	0.001230	1460	1460	0	16384	A	L							
29	0.001230	1460	1460	0	16384	A	L							
30	0.000321	324	1460	0	16384	PA	L							
31	3.527212	1460	-16060	0	16384	A	R							
32	0.034586							0	0	2920	16384	A	815	C
33	0.003511	1460	2920	0	16384	A	R							
34	0.001868	1460	1460	0	16384	A	R							
35	0.007660							0	0	1460	16384	A	111972	C
36	0.003226	1460	1460	0	16384	A	R							
37	0.001876	1460	1460	0	16384	A	R							
38	0.002012							0	0	2920	16384	A	410458	C
39	0.003221	1460	1460	0	16384	A	R							
40	0.002171	1460	1460	0	16384	A	R							
41	0.001230	1460	1460	0	16384	A	R							
42	0.000067							0	0	2920	16384	A	436538	C
43	0.002441	1460	1460	0	16384	A	R							
44	0.001696	1460	1460	0	16384	A	R							
45	0.000430	324	1460	0	16384	PA	R							
46	0.004250							0	0	2920	16384	A	331178	C
47	2.339836							0	0	3244	16384	A	1386	
48	0.006527	1460	324	0	16384	A	L							
49	0.002122	1460	1460	0	16384	A								
50	0.001230	1460	1460	0	16384	A								
51	0.001740	1460	1460	0	16384	A								
52	0.001286	1460	1460	0	16384	A								
53	0.001230	1460	1460	0	16384	A								

Figure 5: Partial packet trace (same connection as fig. 3)

Since we have an algorithm to detect connections that display ACK-compression, if there are only a few such connections it is feasible to overlap their acknowledgement-number curves. Figure 6 shows those curves for one trace; figure 7 shows the same curves, normalized for both the duration and byte-count of each connection.

One interesting question is how sensitive the ACK-compression detection algorithm is to the three input parameters: the ACK-window size A, the minimum ACK-bandwidth B, and the minimum ratio R of instantaneous to median bandwidths. Figures 8, 9, and 10 show how the total number of compression events detected varies with changes in two of these parameters (while the third is held constant). Observe that varying A or R can change the number of alleged events by several orders of magnitude, while varying B has much less of an effect (until it becomes close to Ethernet rates).

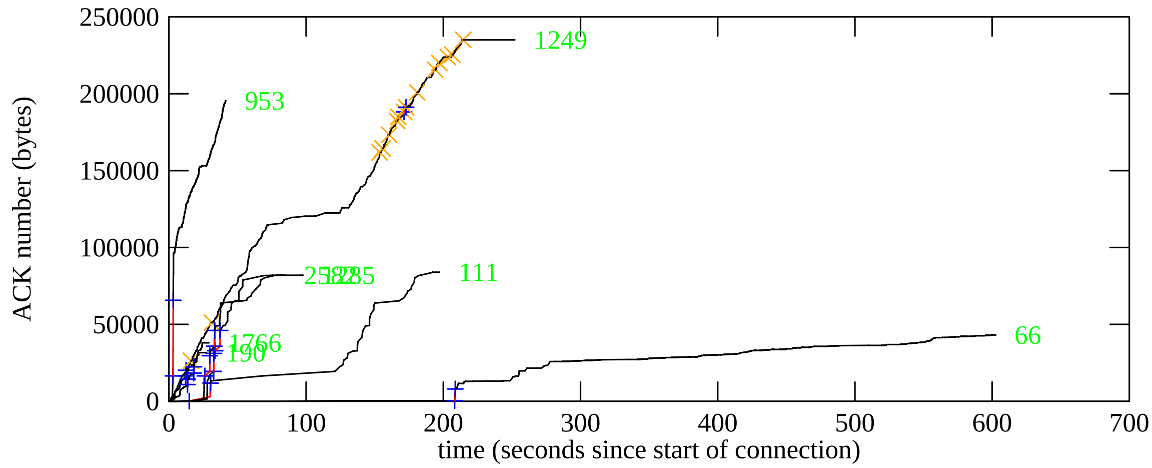

Figure 6: Acknowledgement-number curves for ACK-compressed connections

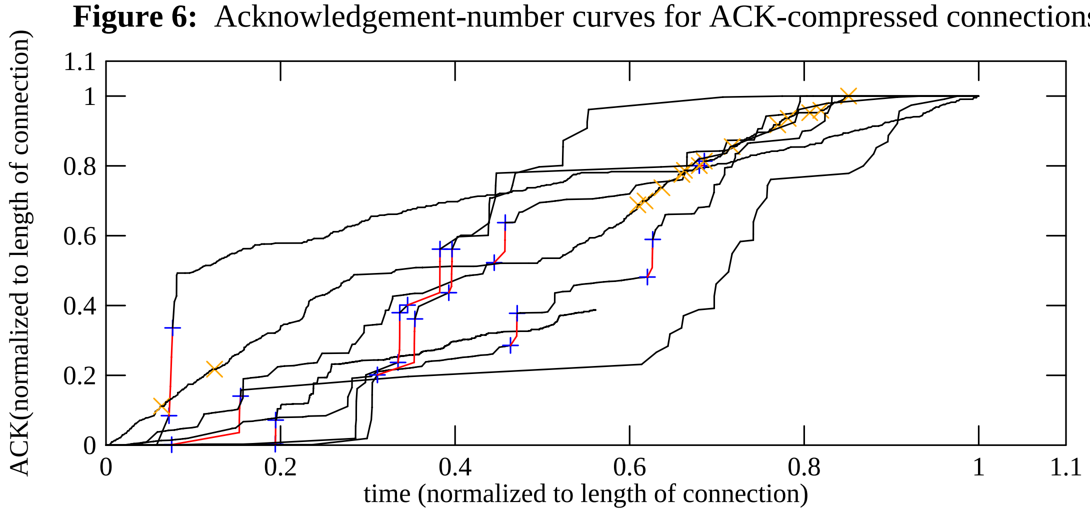

Figure 7: Normalized curves (same traces as fig. 6)

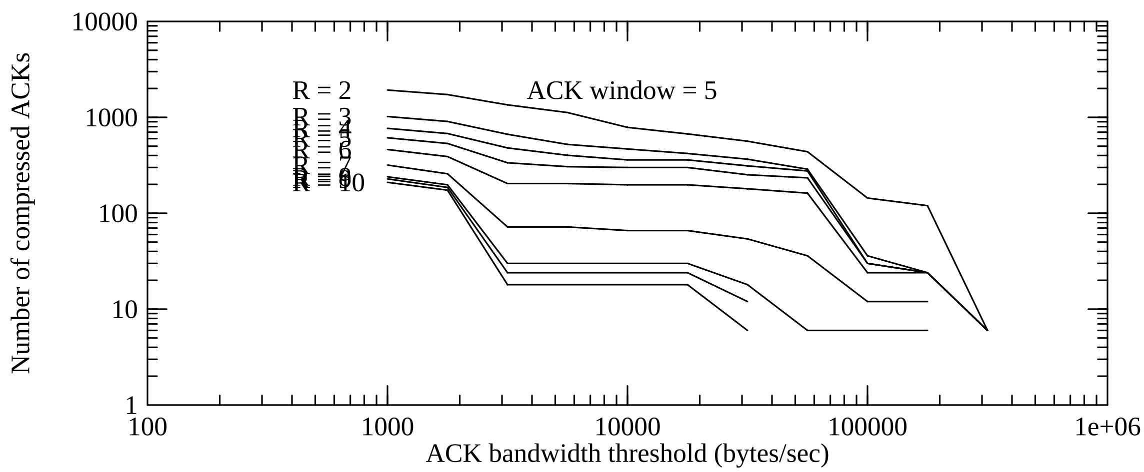

Figure 8: Sensitivity of ACK-compression analysis (ACK-window size held constant)

One can also plot distributions of various statistics for the connections in a trace (figures 11

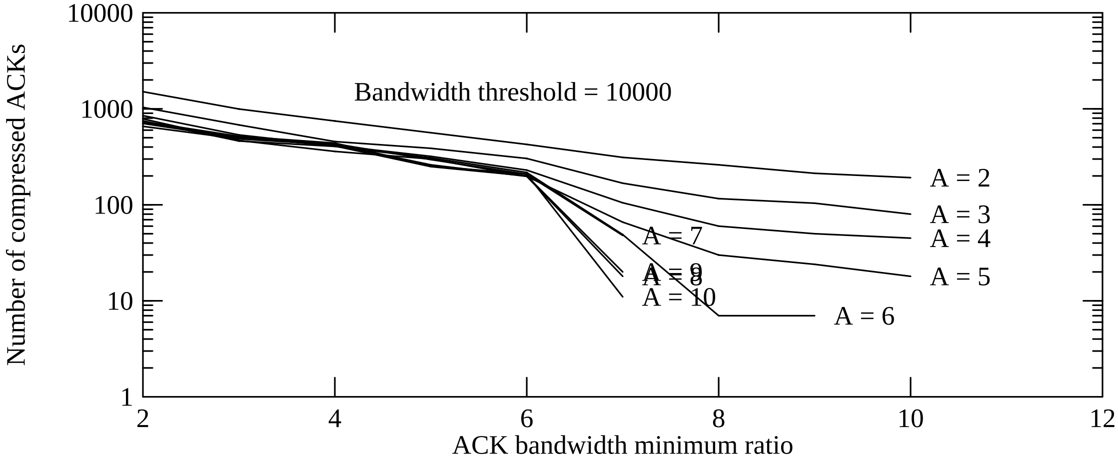

Figure 9: Sensitivity of ACK-compression analysis (minimum bandwidth held constant)

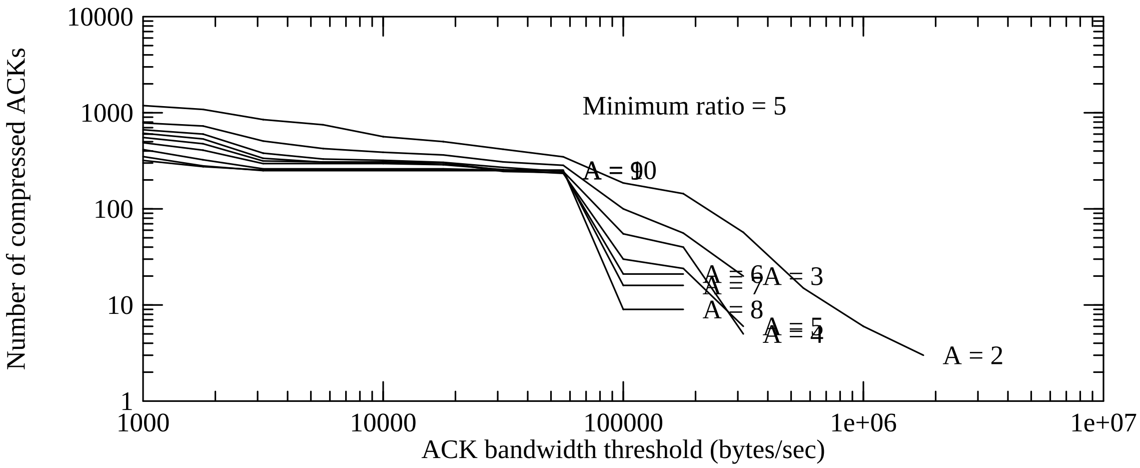

Figure 10: Sensitivity of ACK-compression analysis (minimum ratio held constant)

through 18)[4]. Some of these are useful for providing a context for understanding the important of ACK-compression. The data plotted in figure 13 show that most connections transfer only a few thousand bytes (about 75% of the connections transfer less than 10k bytes), and so are unlikely to suffer from ACK-compression. Figures 17 and 18, respectively, show that very few connections suffer from segment retransmission or out-of-order delivery.

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[4]To avoid expanding the vertical scale, figures 13 through 18 do not include samples for which the *x*-axis value is zero (e.g., figure 13 only includes those connections that transferred at least one byte). The figures include parenthetical notes giving the number of omitted samples. Also, note that the statistics are shown for half-connections, not duplex connections.

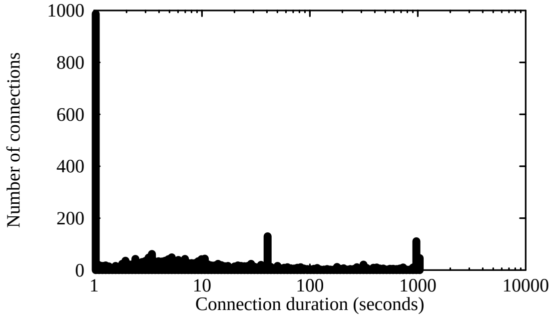

Figure 11: Distribution of connection durations

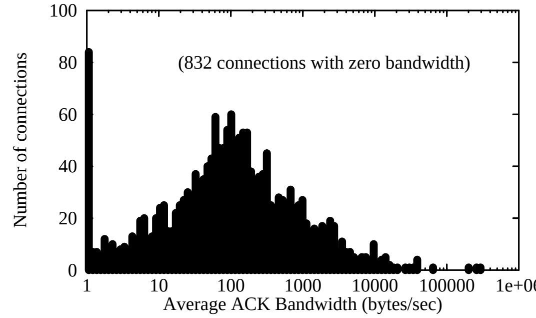

Figure 15: Distribution of average connection bandwidths

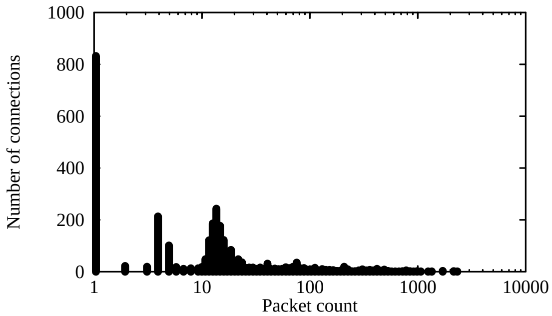

Figure 12: Distribution of packet counts

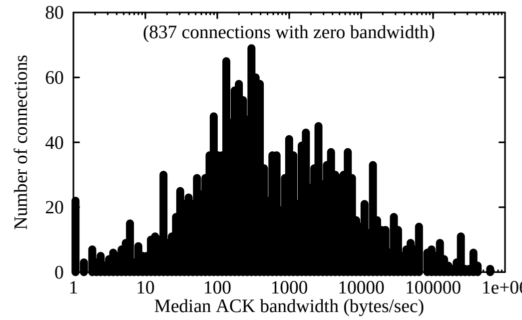

Figure 16: Distribution of median bandwidths

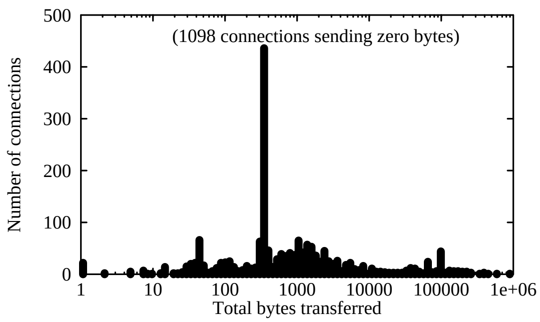

Figure 13: Distribution of connection lengths in bytes

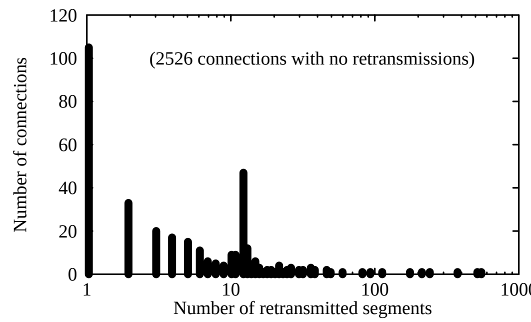

Figure 17: Distribution of lost segment counts

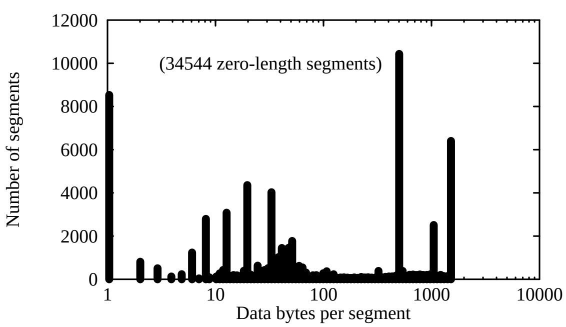

Figure 14: Distribution of segment lengths

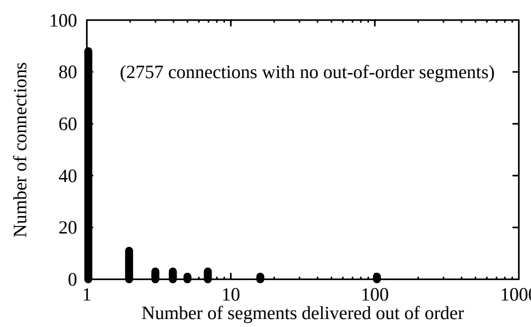

Figure 18: Distribution of out-of-order delivery counts

4.4. Statistical analyses of multiple connections

It is interesting to ask whether there are frequent correlations between ACK-compression and segment losses. One could obtain timestamps for all the compression events and all the loss events in a trace, and try to establish if a statistically significant correlation exists. A more direct approach is to look at each full connection that experiences both compression and segment loss, and analyze the timestamps to see if there is a causal relationship between compression and loss.

Inference of a causal relationship can be done in a number of ways. One would be to assume that any packets lost in the next TCP window after a compression event are caused by that event, but it is not always possible to be sure that those packets were not sent before the compressed ACKs arrived at the sender. Another approach is to measure the time between an ACK-compression event and the next segment loss event. One could then compare this interval to an estimate of the round-trip time. Even simpler is to see if the interval is small compared to the median interval between loss events; this last method shows that in many cases there does seem to be a causal relationship.

For example, in one trace made on Digital's internal network, 63 connections experienced at least one loss event subsequent to a compression event, and in 42 of those cases the time between a compression event and a subsequent loss event was less than the median time between losses. (These intervals between reception of compressed ACKs and transmission of a lost segment are typically on the order of several milliseconds or tens of milliseconds.)

Simulations by Shenker *et al.* [15] suggested that when multiple TCP connections are sharing a congested resource, their congestion-recovery behavior could become synchronized, with each connection loosing a packet at each congestion epoch. The timestamped segment-loss events obtained from traces could, in principle shed some light on this effect. Synchronized segment loss can be detected by making an array of all the loss events in a trace, sorting this array by timestamp, and then looking for losses from different connections that occur within no more than a specified interval. (The choice of this interval is an arbitrary parameter, because of course no two packets can be lost at precisely the same instant.)

In the trace mentioned above, out of 5142 losses, in 287 cases losses from two or more connections occurred less than 10 msec apart. It is not clear, however, if this reflects a statistically significant correlation between losses from multiple connections. Figures 19, 20, and 21 show for this trace the distribution of interarrival times (respectively) for packet losses among all connections, for two losses encountered by a single connection, and for two losses where second occurs to a different connection than the first. The spikes at 460 usec and 1200 usec reflect the back-to-back transmissions of 576-byte and 1500-byte packets, respectively: when TCP sends a burst of packets, the entire burst is likely to be lost as a group. Aside from these spikes, the data might reflect a Poisson distribution, but it may be too noisy to demonstrate a clear correlation between losses from differing connections.

5. Summary of Experiments

Traces were made on several days at both the external and internal locations. The traces are summarized in table 1. Note that the count of packets refers to the number saved for later analysis, not the number that went by on the network. Times are Pacific Standard Time; dura-

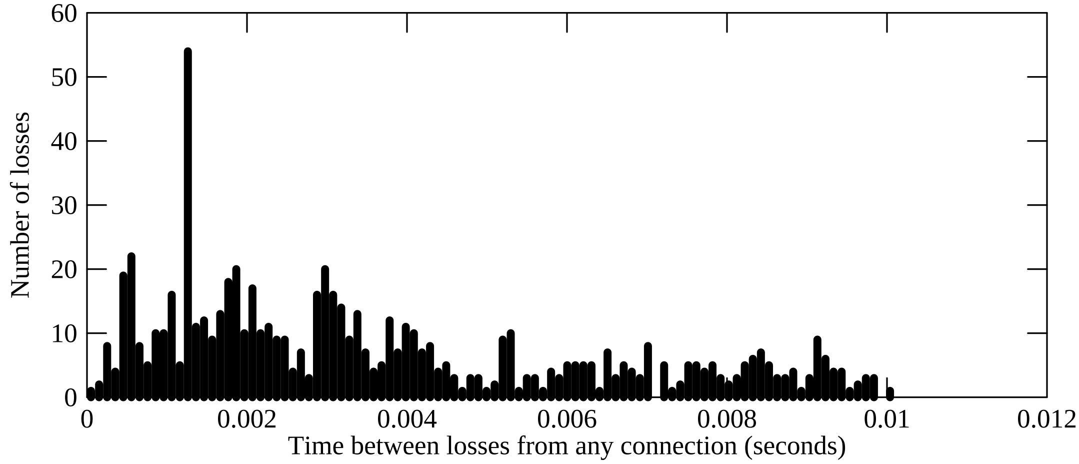

Figure 19: Loss interarrival times, all connections

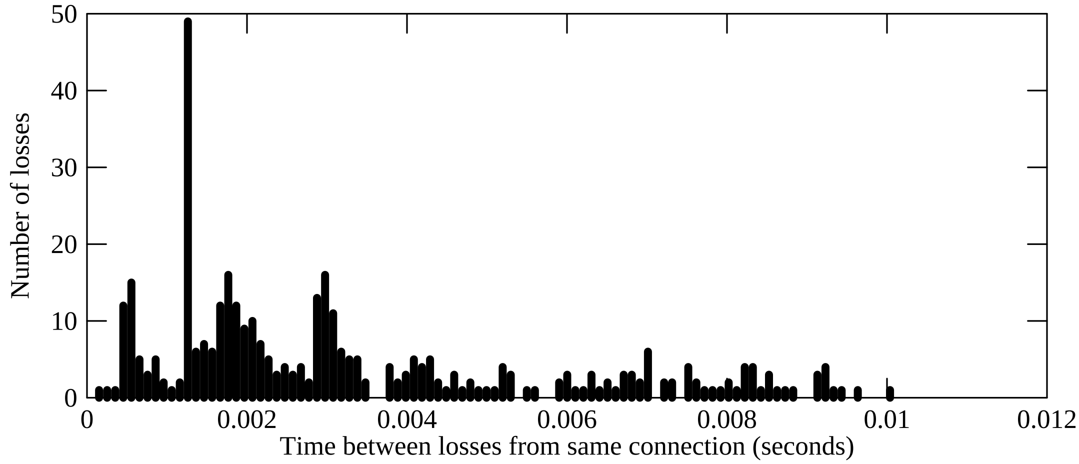

Figure 20: Loss interarrival times, single connection

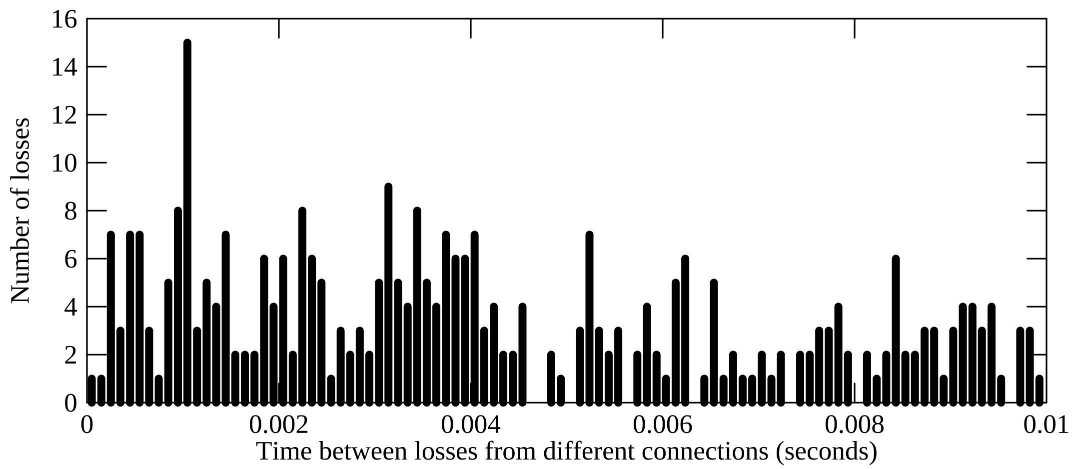

Figure 21: Loss interarrival times, differing connections

tions are in seconds. ‘‘Dropped packets’’ are those discarded because the monitoring system could not keep up; there is no way to know precisely what kinds of packets were dropped.

The figures in section 3 are all drawn from Trace **I1**, since the longer traces produce more confusing graphs.

ID	Site	Date/Time	Duration	Packets	Connections	Dropped pkts
I1	Internal	2 Jan 92, 13:21	1079	100K	2868	0
I2	Internal	2 Jan 92, 10:21	7099	1M	17595	158
I3	Internal	3 Jan 92, 10:14	5518	1M	14635	88
E1	External	2 Jan 92, 10:19	8227	1M	25907	880
E2	External	3 Jan 92, 10:17	7029	1M	24498	1149

Table 1: Summary of traces

Tables 2 and 3 summarize the number of lost segments detected. They also show the number of ACK-compression events and causally-correlated segment-loss events for two different combinations of ACK-compression detection parameters.

ID	Losses	Compressions	Correlations
I1	5142	388	10
I2	19321	2076	42
I3	10443	2832	33
E1	19778	2732	95
E2	18491	5124	144

ACK-window $A = 3$
Bandwidth threshold $B = 10$Kbytes/sec
Minimum ratio to median $R = 5.0$

Table 2: Summary of detected events

ID	Losses	Compressions	Correlations
I1	5142	0	0
I2	19321	156	1
I3	10443	168	1
E1	19778	240	6
E2	18491	264	12

ACK-window $A = 5$
Bandwidth threshold $B = 100$Kbytes/sec
Minimum ratio to median $R = 10.0$

Table 3: Summary of detected events

As a check on the reliability of the method that looks for cause-effect relationships between ACK-compression and segment loss, plots were made of the 12 connections in Trace **E2** identified as having such correlations even with the stricter parameters used in table 3. Inspection of these plots suggests that in about half of the cases, a causal relationship is likely, and could not be ruled out in several other cases.

The possibility exists that some of the detected instances of ACK-compression are actually periods during which the available bandwidth is much higher than normal. This is probably true in some cases, but there are definitely connections for which the reverse is true. Figure 22 shows a connection for which there is a period with many ACK-compression events. During this period, the average bandwidth is far lower than it is during other phases of the connection, which do not exhibit ACK-compression.

Intuition suggests that ACK-compression should indeed be associated with periods of reduced available bandwidth, since the compressed ACKs result from non-empty queues on the return path. Increased queue length should increase the round-trip time, thus decreasing the available bandwidth [5].

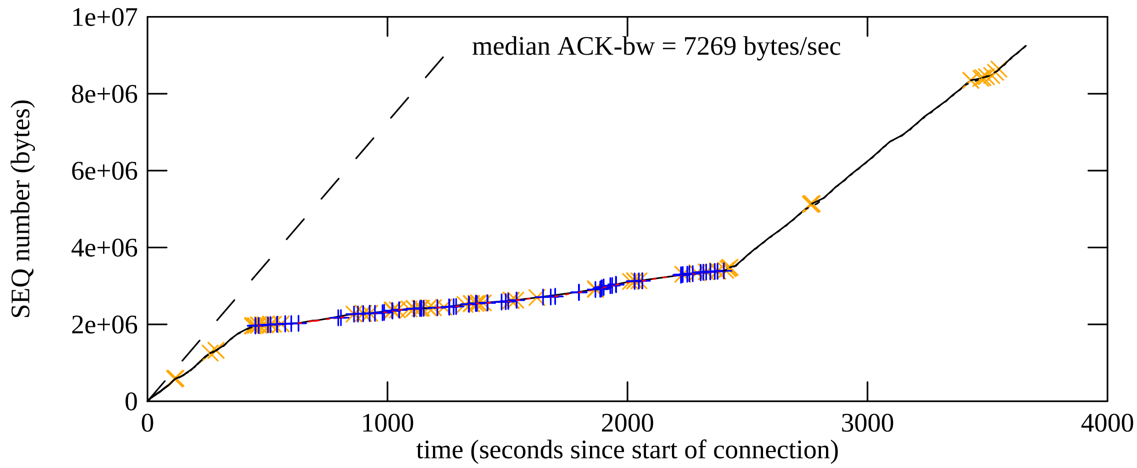

Figure 22: Connection with reduced average bandwidth associated with frequent ACK-compression

6. Future work

6.1. Application to congestion avoidance

Since ACK-compression and subsequent packet loss occurs even on networks that are believed to be uncongested over the long term, this implies that portions of the Internet experience temporary congestion over short periods. These periods may in fact be shorter than the response time of feedback-based congestion-avoidance schemes, which means that some form of rate-based congestion avoidance may be required. While most proposals for rate-based schemes have the network provide explicit rate-limit information to the end-hosts, it may be possible for an end-host to infer the true available bandwidth and thus set its own rate limit. In effect, the end-host could use the ACK-compression detection methods described in this paper to avoid being misled by compressed acknowledgments.

This may prove difficult, for several reasons. The sending host needs:

- A high-resolution clock in order to measure the arrival times of acknowledgements and thus compute ACK-bandwidths.
- An efficient way of computing the median ACK-bandwidth as the connection evolves.
- An efficient, accurate mechanism to throttle the rate of transmitted packets, slow enough to avoid overrunning the bottleneck link but fast enough to keep the pipe full.

The trick will be to provide mechanims that are sufficiently accurate to avoid ACK-compression, yet sufficiently cheap to avoid reducing the transfer rate when ACK-compression is not a threat.

If one were designing a new transport protocol to replace TCP, it might pay to include timestamps on acknowledgement packets. The receiver would timestamp each ACK to reflect the arrival time of the acknowledged segment. The sender would use the ACK timestamps, rather than the times at which they arrive at the sender, to control the rate at which data segments are sent. This would, in effect, convert the ‘‘real-life’’ situation depicted in figure 2 into the idealized situation depicted in figure 1, since queueing delays on the return path would not affect the self-clocking mechanism. A 32-bit timestamp, scaled for a resolution of 100 nsec, would not wrap around during the maximum lifetime of an IP packet.

6.2. Other interesting analyses

The information in the trace files can be analyzed to discover other interesting information about TCP dynamics. For example, the instantaneous round-trip time (RTT) for a connection can be estimated by measuring the time from the transmission of a segment to the receipt of an acknowledgement for the corresponding sequence number. (When segments are lost, there are a number of complications that arise, for which good heuristics are known [10].) It would be interesting to know if there are correlations between the variations in RTT among several concurrent connections; this would be expected if multiple connections through the same newly-congested router suffer queueing delay simultaneously. There might also be correlations between jumps in the RTT and segment loss or ACK-compression.

Another open question is whether ACK-compression events occur nearly simultaneously on multiple connections. One might expect this to be the case, and the consequences might worse than for isolated compression events (since the resulting burst of data packets would be multiplied by the number of connections involved).

One might ask what fraction of segment losses are caused by ACK-compression, either directly (i.e., the connection suffering losses is the one that transmits too many packets) or indirectly (an innocent bystander loses packets when another connection overflows a queue). Answering this could be difficult, since it would require coordinated observations at many points in the network.

6.3. Performance of analysis tools

The existing analysis tools all build an in-memory database describing every event in a trace. While this makes analysis modules relatively easy to write, it limits the size of trace that can be analyzed. Analyzing a trace of one million packets requires about 40 Mbytes of main memory; if the process starts to page, its running time increases by several orders of magnitude because the database is not organized for high locality.

There are several ways to solve the problem of analyzing longer traces. One could pre-process the trace file, to select only ‘‘interesting’’ connections for later analysis. This might be done with a relatively small amount of memory and a two-pass algorithm.

In the absence of memory-system thrashing, the most expensive part of the algorithm for detecting ACK-compression is the method used to find the median ACK-bandwidth. This is done by sorting an array of weighted values and then finding the weighted center; this takes $O(n*log(n))$ time where n is the number of packets per connection. Since the sorting routine used is not ideal, the running time might be reduced either by using a better sort routine, or by using a more sophisticated algorithm that takes $O(n)$ time.

7. Conclusions

The results of this study show that it is indeed possible to detect ACK-compression in traces made on real networks. Moreover, it is possible to correlate ACK-compression events with subsequent packet losses, even on networks that are not particularly congested. Both detection of ACK-compression and correlation with packet loss can be done automatically, which means that it is possible to apply these techniques to traces of busy networks over lengthy periods.

If, in the future, the Internet is operated much closer to its long-term capacity, the connection between ACK-compression and congestion may become acute, and automatic detection of ACK-compression could be a key to efficient utilization of the network.

Acknowledgements

I would like to thank Lixia Zhang, Sally Floyd, and K. K. Ramakrishnan for their numerous helpful comments on early drafts of this paper. Comments from anonymous SIGCOMM reviewers also helped to guide the presentation. Andrei Broder and Susan Owicki provided valuable consultation on how to interpret the data I obtained.

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