4. APPLICATION EXPERIMENT ON LAN BRIDGE

These experiments evaluated the performance of TCP/IP-based applications where an ISDN LAN bridge was included in the communications link to transform two remote LAN's into a single logical LAN. TCP/IP applications involved both real-time interactive and noninteractive uses. Additionally, the communications service was based on virtual circuit or datagram service. In this experiment, each of these components was evaluated for usability and stability. A terrestrial baseline was established for evaluating changes in application performance when a satellite link was introduced.

4.1 Experiment Objectives

The experiments were intended to identify the performance issues that should be considered when a satellite link is included in the communications system. The objectives of these experiments were not intended to evaluate the COTS implementations.

4.2 Experiment Methods

A 66-MHz/486 personal computer and a Sun® workstation were used as the end systems for the LAN bridge experiments. These systems were selected because they represent commonly available workstations that were capable of sustained TCP/IP transfer rates significantly greater than could be supported by the LAN-bridge.

The experiments were conducted using the two equipment configurations illustrated in Figure 4.1. For terrestrial experiments, two workstations were connected to a local Ethernet segment in Boulder and Gaithersburg. The Ethernet segments were bridged via Combinet Interchange® LAN bridges communicating with each other via proprietary protocols over an ISDN BRI connection from a local ISDN PBX (Teleos Network Hub). The PBX's were interconnected via PRI ISDN service from FTS2000 (Network A). A bit-error simulator (Adtech SX-12) was connected between the FTS2000 PRI and the PBX at the Boulder end of the circuit to inject errors into the datastream in both directions independently.

For ACTS-based experiments, the same two workstations were connected to the same LAN bridges and PBX's in Boulder and Gaithersburg. The Gaithersburg PBX was connected via dedicated ISDN PRI service to a PBX in Clarksburg (COMSAT). The Boulder and Clarksburg PBX's were interconnected via PRI ISDN service from the ACTS T1-VSAT's in Boulder and Clarksburg. A bit-error simulator was connected between the T1-VSAT PRI and the PBX at the Boulder end of the circuit to inject errors into the datastream in both directions independently.

The bit-error simulator was used to simulate error scenarios that might be observed over a link in actual operations. Two scenarios were investigated. The first was based on a "steady-state" environment. For this scenario, the statistics of the random bit errors were uncorrelated and Gaussian distributed for the duration of the experiment. This simulates the errors caused by noise from a variety of background sources. Thresholds for usability and application failure were determined. The second scenario was based on a transient error environment that causes severe error bursts for some period. These tests were intended to determine the stability/recoverability of the applications to transient error rates. A moderate error background was used with a periodic severe burst of random errors of a fixed duration. Thresholds for recovery/failure were determined by varying the burst length and intensity.

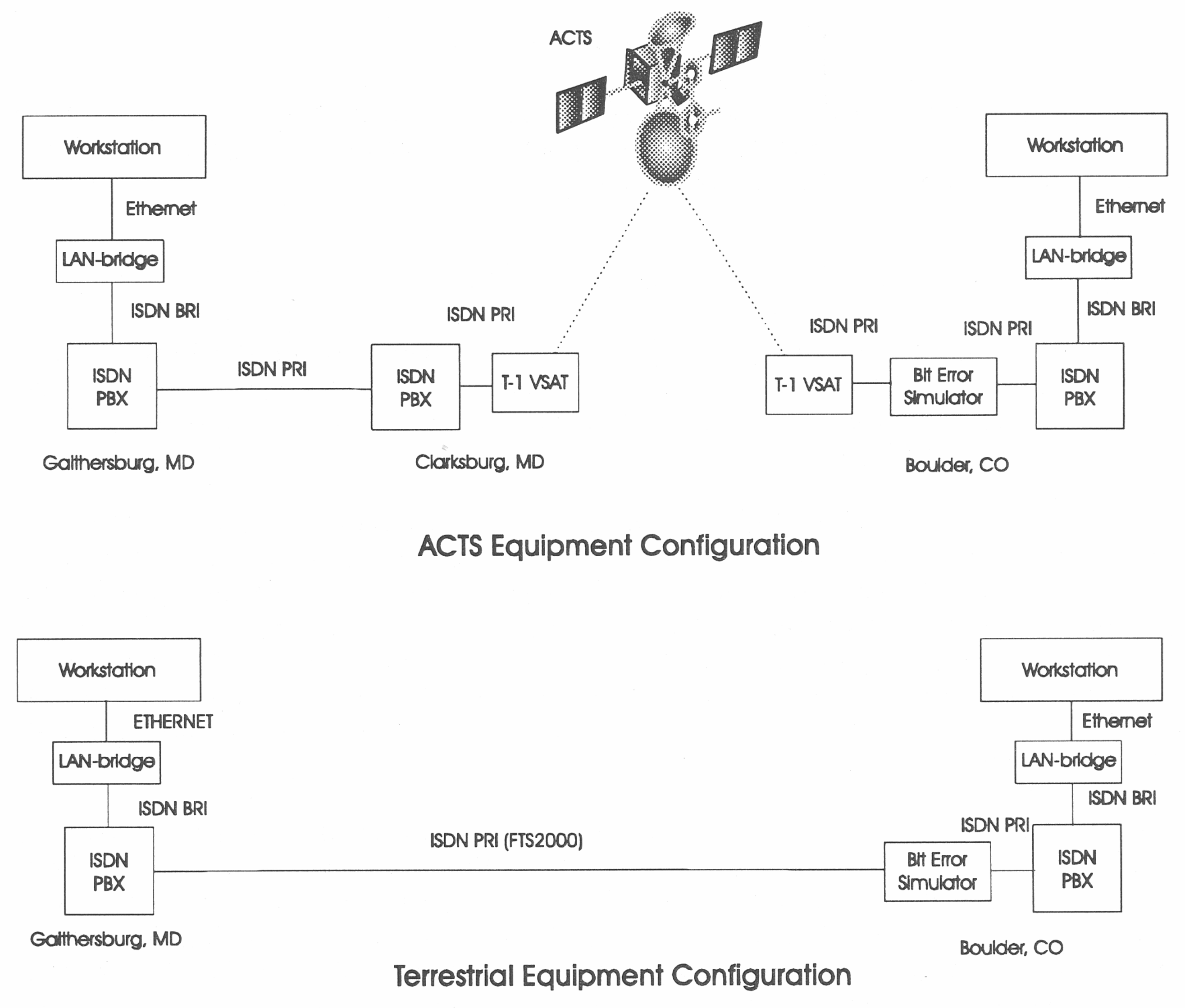

Figure 4.1. Experiment equipment configuration.

4.2.1 File Transfer Protocol

The file transfer protocol (FTP) experiments are designed to evaluate performance of bulk data transfers. These transfers are typically not time-critical, as in a real-time interactive application. However, correctness and completeness of the data are typically important.

A 278,507-byte image was used as the bulk data. To give some indication of the information that may be contained in such a transfer, the image is shown in Figure 4.2.

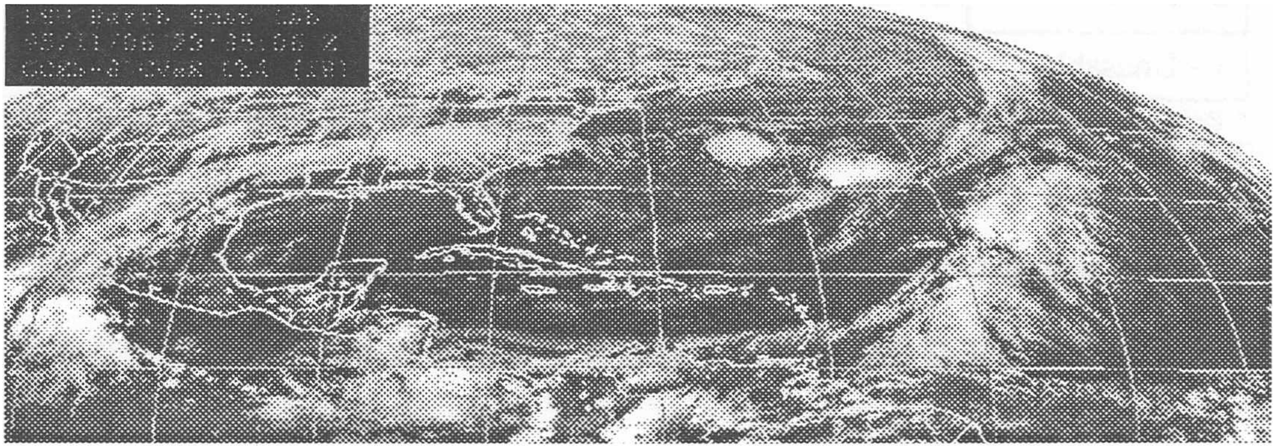

Figure 4.2. File used in FTP experiments (actual file is a color image).

4.2.2 Telnet

Telnet experiments are designed to evaluate performance of interactive keystroke-oriented applications. Such applications become “annoying” if the response time is excessively long. Correctness is important, but often not critical since rekeying can resolve the error.

4.2.3 Ping

The ping experiments are designed to evaluate the performance of datagram-oriented applications. A datagram is the underlying transport mechanism for most TCP/IP communication. These experiments determined the reliability of the datagram service by measuring the packet loss rate.

4.3 Metrics

Opinion Score (OS): An OS was used to evaluate the subjective usability for the FTP and Telnet applications. The rating scale was defined as found in Table 4.1 (fractional scores were not excluded from use).

Table 4.1. Definition of Opinion Score Values

Opinion Score	Description
5 - Excellent	Incapable of discriminating between LAN* and bridged LAN.
4 - Good	Subtle differences between LAN and bridged LAN performance.
3 - Fair	Obviously a bridged LAN, but not disturbing to the user in most cases.
2 - Poor	Somewhat disturbing differences in performance, but still usable.
1 - Unusable	Use of system is not practical or useful.

* References to "LAN" performance assume a system where expected throughput typically exceeds 1 Mb/s and ping round-trip delays of about 2 IDS.

Packet Loss Percentage: The fraction of packets that were transmitted, but not received.

Throughput: The number of bits per second (b/s) successfully transmitted to the destination.

4.4 Experimental Procedure

The following sections describe the procedures used in the FTP, ping and TELNET experiments.

4.4.1 FTP

1. Observe link signal quality via E_b/N_0 at Earth stations to verify low link BER. (A terrestrial link is assumed to have a BER less than 10^{-9}.)

2. Set BER for the experiment via the bit-error simulator (Tables 4.2 and 4.3).

3. Issue commands to initiate file transfer.

4. Record transmission statistics: elapsed time and transfer rate.

5. Check file transmitted for any errors in the data. Record number of bytes in error.

6. Assess FTP usability via subjective OS including any other observations. Record OS and observations.

Table 4.2. Steady State BER Configurations

Measurement Number	BER
1	0
2	10^{-9}
3	10^{-6}
5	10^{-5}
5	10^{-4}
6	10^{-3}
7	10^{-2}

Table 4.3. Burst BER Configurations

Measurement	Background BER	Burst BER	Burst Duration (s)	Burst Gap (s)
1	10^{-6}	10^{-2}	0.5	10
2	10^{-6}	10^{-2}	1.0	10
3	10^{-6}	10^{-2}	1.0	10
4	10^{-6}	10^{-2}	2.0	10
5	10^{-6}	10^{-2}	3.0	10
6	10^{-6}	10^{-2}	5.0	10
7	10^{-6}	10^{-2}	10.0	10
8	10^{-5}	10^{-2}	0.5	10
9	10^{-5}	10^{-2}	1.0	10
10	10^{-5}	10^{-2}	5.0	10
11	10^{-5}	10^{-2}	10.0	10

4.4.2 Telnet

1. Observe link signal quality via E_b/N_0 at Earth stations to verify low link BER. (A terrestrial link is assumed to have a BER less than 10^{-9}.)

2. Set BER for the experiment via the bit-error simulator (Tables 4.2 and 4.3).

3. Issue command to establish Telnet session.

4. Type terminal commands, check data transmitted for any errors, and record number of bytes m error.

5. Assess Telnet usability via subjective OS including any other observations. Record OS and observations.

4.4.3 Ping

1. Observe link signal quality via E_b/N_0 at Earth stations to verify low link BER. (A terrestrial link is assumed to have a BER less than 10^{-9}.)

2. Set BER for the experiment via the bit-error simulator (see Tables 4.2 and 4.3).

3. Issue commands to generate 100 pings, 64 bytes long.

4. Record transmission statistics: round-trip delay and percent packet loss.

Table 4.3 defines the set of BER configurations used in step 2 of the above procedures for burst BER configurations. These experiments characterize the transient behavior (e.g., failure/recovery) of the application in response to changes in the BER. The burst duration and the burst gap were periodic delays (i.e., not random). This permits viewing the experiment as a collection of burst events that could be observed independently to note transient behavior to a single burst event.

The background BER is the bit error rate between bursts. The burst BER is defined as the bit error rate during an error burst event. The burst gap is defined as the interval between the end of one error burst and the beginning of the next. The burst interarrival time is the sum of the burst duration and the burst gap.

4.5 Expected Results

The following summarizes the expected results for the experiments.

- Telnet and FTP usability will degrade and become unusable with increased bit error rate.

- Additional delay introduced by the satellite path may cause protocol timers to expire causing application failure.

- Undetected errors may be introduced into data transmitted.

- Satellite propagation delays may cause some difficulty in real-time Telnet response because character echos will be delayed.

- The experiments involving error bursts will characterize the transient behavior of the application to errors. Longer duration bursts are likely to cause application and/or link failure due to expiration of timers; short bursts will probably make the application unusable during the burst, but identify the recovery behavior of the system.

4.6 Results

Figure 4.3 illustrates the throughput observations for FTP over both terrestrial and ACTS configurations. These scores were based on experiments with a BER defined as the mean of Gaussian bit error arrival times, which simulates errors from many independent noise sources. The statistics for these errors are time-invariant for the duration of the experiment. These experiments describe the steady-state application performance for a given environment.

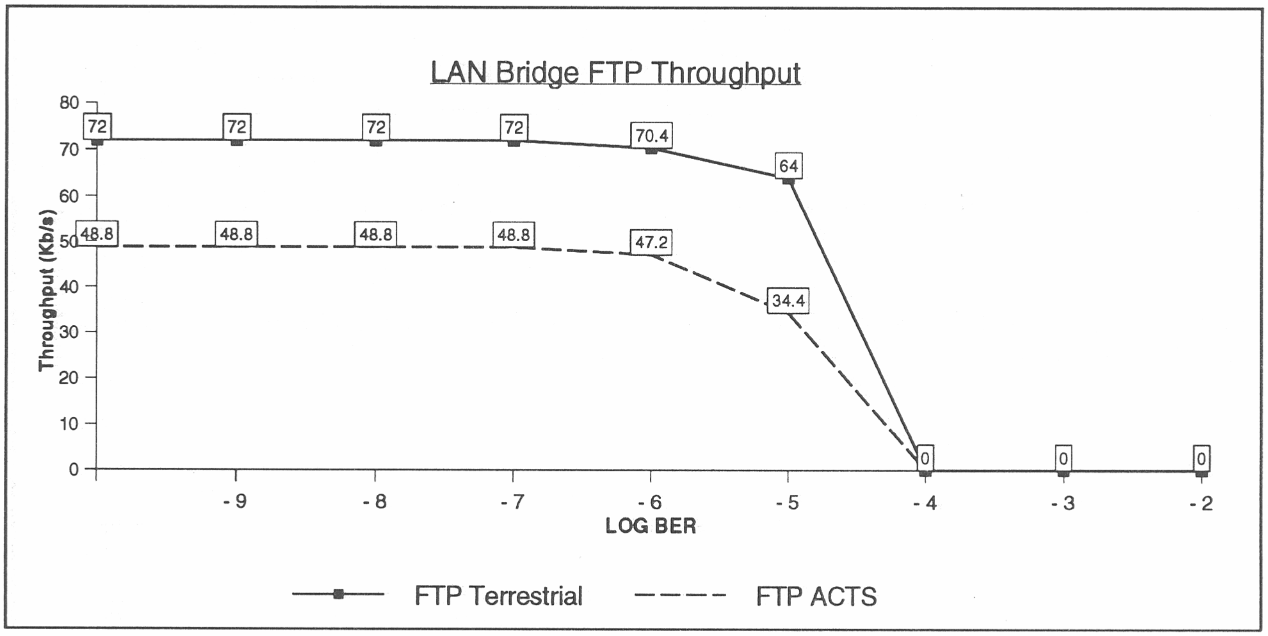

Figure 4.3. LAN bridge FTP throughput results.

Table 4.4 summarizes the recovery behavior of FTP over a LAN bridge in the presence of error bursts over a terrestrial line.

Table 4.4. Burst BER Results Over the Terrestrial Line

Background BER	Burst BER	Burst Duration (s)	Burst Gap (s)	Behavior
10^{-6}	10^{-2}	0.5	10	Recovery
10^{-6}	10^{-2}	1.0	10	Recovery
10^{-6}	10^{-2}	2.0	10	Recovery
10^{-6}	10^{-2}	3.0	10	Failure
10^{-6}	10^{-2}	5.0	10	Failure
10^{-6}	10^{-2}	10.0	10	Failure
10^{-5}	10^{-2}	0.5	10	Recovery
10^{-5}	10^{-2}	1.0	10	Recovery
10^{-5}	10^{-2}	2.0	10	Recovery
10^{-5}	10^{-2}	3.0	10	Failure
10^{-5}	10^{-2}	5.0	10	Failure
10^{-5}	10^{-2}	10.0	10	Failure

Table 4.5 summarizes the recovery behavior of FTP over a LAN bridge in the presence of error bursts over ACTS.

Figure 4.4 illustrates the usability opinion scores for the FTP, Telnet, and Ping experiments in the ACTS configuration.

Table 4.5. Burst BER Results Over ACTS

Background BER	Burst BER	Burst Duration (s)	Burst Gap (s)	Behavior
10^{-6}	10^{-2}	0.5	10	Recovery
10^{-6}	10^{-2}	1.0	10	Recovery
10^{-6}	10^{-2}	2.0	10	Recovery
10^{-6}	10^{-2}	3.0	10	Recovery
10^{-6}	10^{-2}	5.0	10	Failure
10^{-6}	10^{-2}	10.0	10	Failure
10^{-5}	10^{-2}	0.5	10	Recovery
10^{-5}	10^{-2}	1.0	10	Recovery
10^{-5}	10^{-2}	5.0	10	Failure
10^{-5}	10^{-2}	10.0	10	Failure

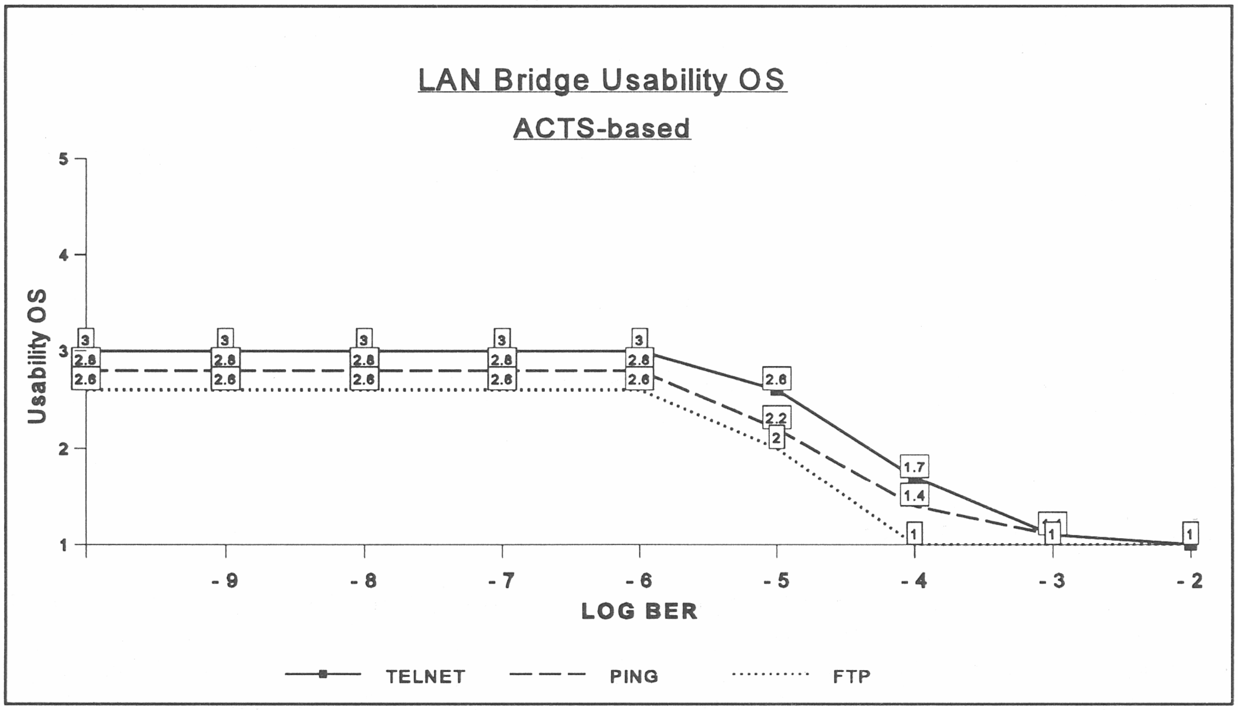

Figure 4.4. LAN bridge usability over ACTS.

Figure 4.5 illustrates the usability opinion scores for the FTP, Telnet, and Ping experiments in the terrestrial configuration.

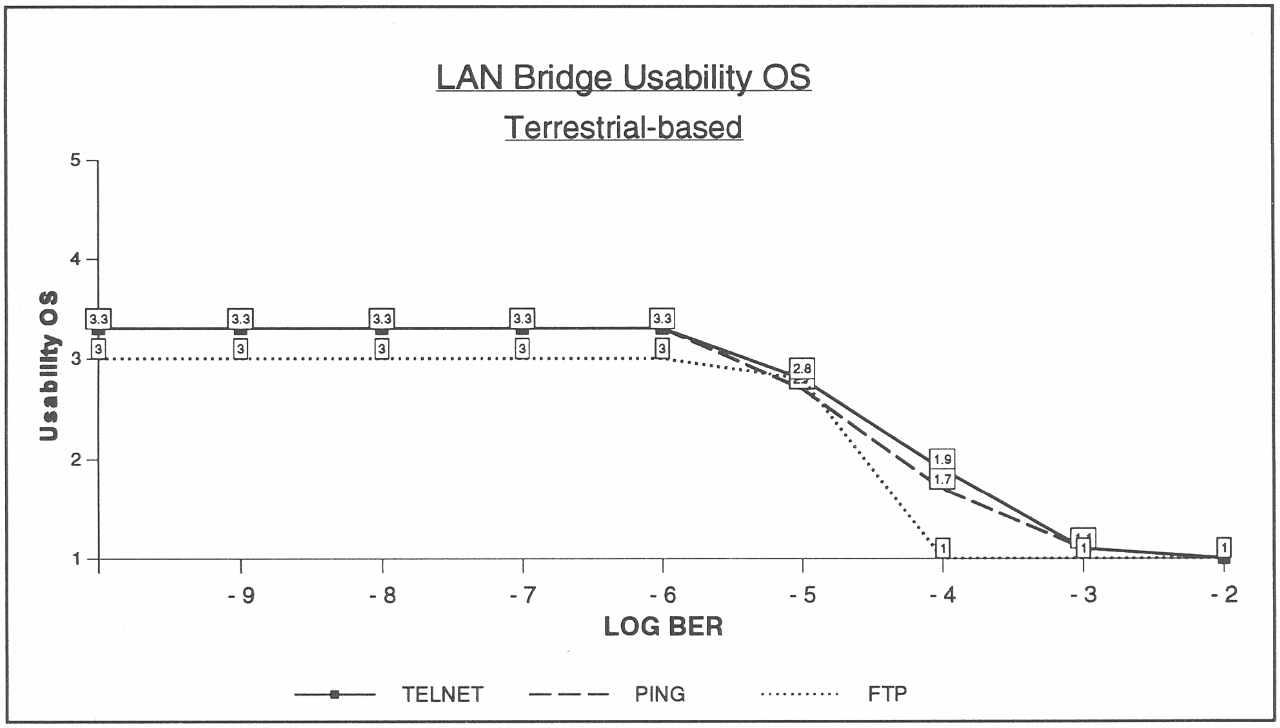

Figure 4.5. LAN bridge usability opinion scores for the terrestrial line.

Figure 4.6 illustrates the percent packet loss for repeated pings as a function of BER for both terrestrial and ACTS configurations.

4.7 Analysis

All applications tested began to degrade with error rates greater than 10^{-6} and were not useful for error rates greater than 10^{-3}.

4.7.1 File Transfer Protocol

The curves for FTP throughput as a function of BER over both terrestrial and ACTS configurations exhibited parallel behavior. The throughput over ACTS was consistently less than that over a terrestrial line. This difference was due to the additional propagation delay causing throttling of the end-to-end protocols of the LAN bridge and FTP. This was confirmed through additional experiments conducted with a delay simulator and no additional bit errors. No degradation of throughput was observed for one-way delays less than about 100 ms.

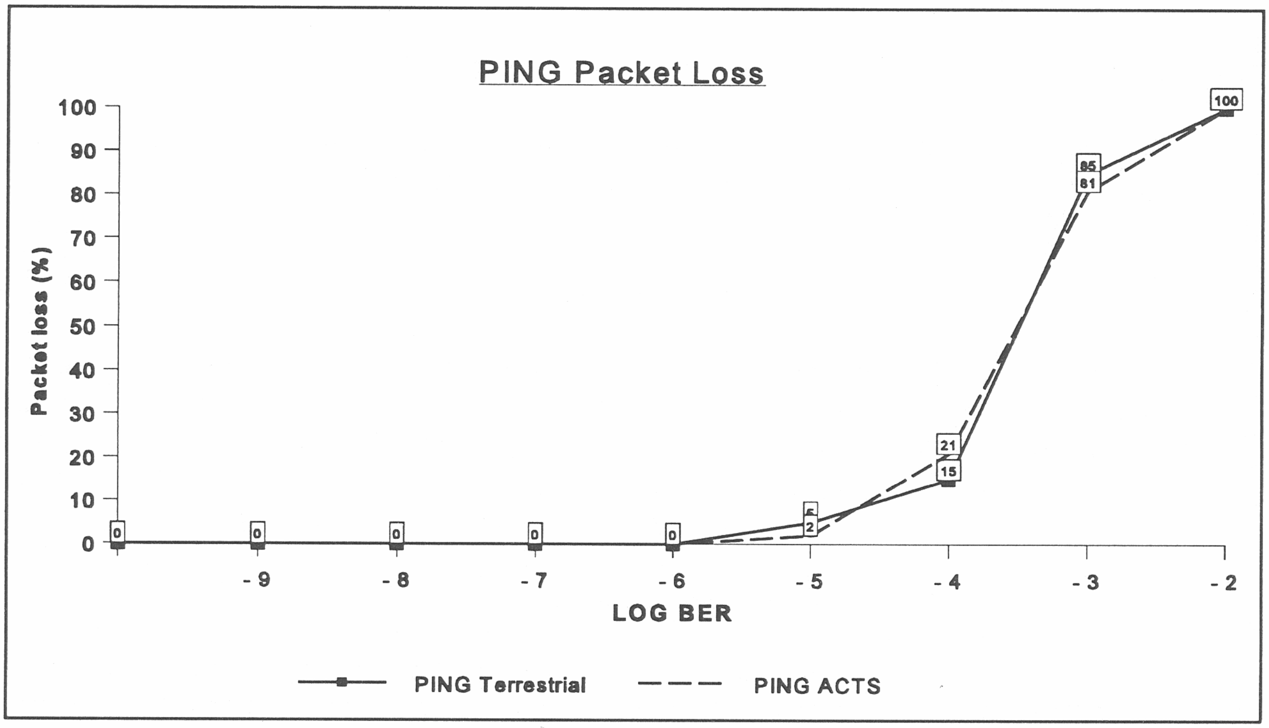

Figure 4.6. Ping packet loss results.

Other supplemental tests revealed that FTP becomes unstable with a BER of about 10^{-4} or greater. The burst test revealed that FTP would recover if the BER improved to 10^{-5} or less within 5 s. If the burst lasted longer, the transfer failed independent of the error density before, during or after the burst.

There were no errors in the transmitted data for any configuration in which the transmission completed normally. Abnormal termination resulted in a partial transfer of correct data.

The differences in the opinion scores for terrestrial and ACTS configurations were insignificant. Lower opinions resulted from bit errors causing extremely long transfer times, many times larger than that on an error-free connection. The main factor in usability was successful transmission, not differences in transmission speed.

4.7.2 Telnet

Propagation delay in ACTS experiments caused some reduction in the opinion scores for Telnet, which resulted from increased delay for character echo. However, the character echo became significantly larger for a BER in excess of 10^{-4}. BER was the major factor that caused unusability. No transmission errors were observed in the echoed characters for any keystrokes, at any BER.

4.7.3 Ping

The ping experiments indicated insignificant packet loss differences between terrestrial and ACTS configurations. The packet loss statistics were only a function of BER.

4.8 Interpretations

1. BER, not delay, is the principal factor in LAN bridge usability. The data indicate that all applications used with a LAN bridge began to degrade with a BER in excess of 10^{-6} and became essentially unusable with a BER of 10^{-3}. The usability scores for satellite versus terrestrial communications services were essentially identical, indicating that satellite delay was not a significant factor for usability.

However, FTP throughput was impaired by the additional satellite delay at all error rates. This appears to be due to acknowledgment window sizes in the TCP/IP protocol and/or the LAN bridge protocol. This could be addressed through modifications in the protocols, as described in Section 5, to improve performance in the presence of delay. Experiments indicated that one-way delays less than 100 ms did not have any impact on throughput using the current protocols.

A maximum BER of 10^{-6} is recommended for reliable LAN bridge service.

2. Additional delay due to the satellite is an important factor in highly interactive activities. While the additional delay of a satellite link is a minimal problem for file transfer and datagram delivery (ping), highly interactive uses (Telnet) become increasingly difficult with increasing frequency of interaction. If keystrokes are echoed from the remote system, the delay can become disturbing to a reasonably fast typist. This also could be a problem for other interactive applications such as remote graphic-based applications.

3. While additional delay due to satellite reduces FTP throughput, a high BER makes FTP unusable. While FTP throughput was reduced as a result of the additional satellite delay, FTP usability was impacted only minimally because of the noninteractive nature of bulk file transfers. The decreased performance was not significant to the user due to the already relatively long transfer time via terrestrial service. However, FTP was rendered unusable with a BER of 10^{-4} or greater, independent of the presence of a satellite.

4. Terrestrial communications links may fail when sustained, severe bit errors are present. Data transmitted through the public terrestrial network with a BER in excess of 10^{-3} that persists for several seconds resulted in lost connections. However, the applications themselves, except FTP, were able to remain stable with higher error rates when the errors did not propagate through the network, but were generated locally. This behavior may be attributed to an administrative decision in the terrestrial network to terminate connections that have persistent errors.

FTP appeared to fail with severe, sustained error bursts due to expiration of FTP protocol timers during these bursts.

5. Optimization of end-to-end protocols for channels with high propagation delay is needed for efficient use with satellites. The FTP experiments indicated that propagation delays were causing degraded performance over a satellite channel. However, the degradation did not occur for delays less than 100 ms. This indicates that protocol parameters, such as window sizes, might be adjusted to improve performance over channels with longer delays. The protocol-oriented experiments, reported in Section 5, address this issue.

5. PROTOCOL EXPERIMENT ON TCP-LFN OVER FRAME RELAY

With the growth of the Internet, the TCP/IP protocol has become the most widely used protocol in use today. TCP/IP implementations are commonly found on almost every hardware platform/ operating system with a wide variety of applications running over it. Originally designed in the 1960's, the protocol has evolved through the years to meet requirements of LAN's, WAN's, and other systems and networks.

When TCP is used over a satellite link, however, the large bandwidth-delay product can cause problems with throughput. TCP-LFN, an enhanced version of TCP for "long-fat" networks, attempts to rectify these problems [5]. The large bandwidth-delay product of a satellite channel requires larger window sizes to "keep the pipe full" in order to make full use of the channel capacity. Assuming the round-trip time over a satellite link is 0.6 s, the window size required to completely utilize a T1 link would be 1,536,000 b/s (0.6 s /8 b/B) = 116 kB. Most current TCP implementations have 64 kB for their maximum window size. TCP-LFN increases this limit to 2^{31}-1 B.

TCP retransmits packets when a retransmission timer expires. If this timer expires too soon, packets are unnecessarily retransmitted; if it expires too late, the pipe becomes empty during the intermediate period. Either way, this leads to wasted bandwidth. Current TCP implementations measure one round-trip time (RTT) per window in order to set the retransmission timer. As the window grows, the accuracy of this measurement degrades. TCP-LFN attempts to correct this by measuring an RTT per packet by time-stamping the packet. Another problem that arises for long delays is that the packet sequence numbers can wrap around (be reused). This means that a packet that arrives late has a higher probability of being mistaken for one that was transmitted later with the same sequence number, confusing TCP and delivering incorrect data to the application. TCP-LFN use of time-stamps eliminates the need for sequence numbers, providing protection against wrapped sequence (PAWS) numbers.

5.1 Introduction

The use of frame relay as a WAN protocol has grown significantly over the last few years. Frame relay can support several logical connections over the same physical connection. Although X.25 does this, it uses link-by-link recovery. This type of recovery is wasteful because it leads to lower throughput and requires more complex hardware and software at each network node. Also, with X.25, when the delay is large such as on a satellite link, packets are more likely to be lost and then retransmitted. Frame relay, on the other hand, performs end-to-end recovery leading to a simpler protocol, higher throughput and less complexity in each network node.

Older networks used static bandwidth management to allocate bandwidth to users. More recently, however, there has been a significant growth in the use of bandwidth-on-demand capability since that provides more efficient sharing of network resources, given the bursty nature of data. Also, users observe less delay since the pipe expands as data flow increases. Users can be charged based on usage as opposed to paying a fixed charge decided at subscription time.

TCP-LFN running over frame relay with bandwidth-on-demand capability is a good solution for networks required for emergency operations that use satellite links. Satellite ground stations are easy to deploy during an emergency and the ability to adjust bandwidth to meet requirements at the emergency site is essential. Satellite networks themselves are less prone to failure since there are fewer physical links and it is possible to enhance link quality dynamically (by coding, etc.). Prioritization of messages is fairly simple to implement within a frame relay network, and is supported by most user devices (such as routers). Most of the user equipment is inexpensive and is commonly available from several vendors; this makes redundant sites more feasible to implement.

This experiment evaluated the performance of TCP-LFN over frame relay using the COMSAT - ACTS frame relay access switch (FRACS) over the ACTS network. The frame relay switches are capable of implementing bandwidth-on-demand over ACTS using the ISDN signaling interface on the ACTS Earth station.

5.2 Experiment Methods and Procedures

TCP packets generated by the application running on the Sun® workstation were encapsulated in IP packets and sent over the Ethernet to the WAN router, then they were encapsulated in frame relay packets and sent to the FRACS. The FRACS monitored data flow to each destination periodically and allocated bandwidth by obtaining usage information from the ACTS terminal. The packets were then sent to the ACTS terminal through the T1. The reverse process took place at the destination until the packets reached the application. Figure 5.1 shows the setup for the TCP-LFN over frame relay experiment.

Performance evaluation software tools like TTCP (public domain software) and TCPTGEN (COMSAT proprietary software) were run on the Sun® workstations. TTCP opens a TCP socket, sends a specified number of packets of specified size through it, and reports the average throughput measured at the end of the exchange. TCPTGEN is similar except that it measures throughput periodically and also reports the long-term average, therefore it is useful for observing TCP slow start and congestion control mechanisms in action.

The Solaris® (Sun® operating system) “netstat” command was used to obtain various TCP/IP statistics such as number of data packets sent, maximum segment size, number of retransmissions, retransmission timeout, and fast retransmissions. Another analysis program, SNOOP, was used to observe the following information about packet traces: the times at which each was sent, the outstanding transmit packets, and TCP/IP retransmission behavior.

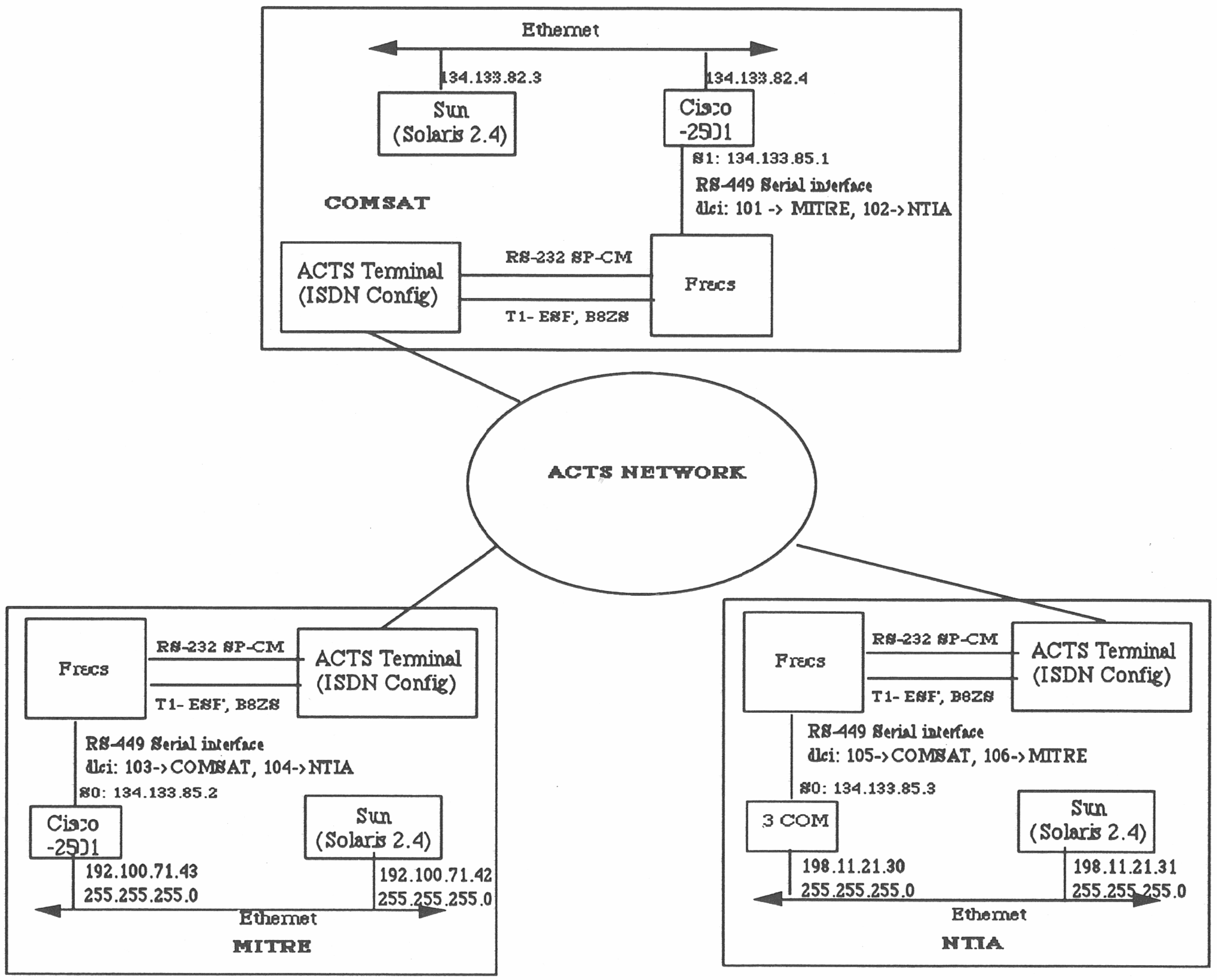

Figure 5.1. Experiment setup.

The FRACS itself also provided a number of valuable statistics, including traffic rate measurements, packet statistics at the data link and trunk levels, link quality measurements, bandwidth and call management statistics, and availability of buffers.

The WAN routers (CISCO and 3-COM) also provided some packet statistics at each of its interfaces, including transmitted and received packets, rate measurements, and buffer information.

5.3 Performance Analysis of TCP-LFN

The performance capabilities of TCP and TCP-LFN were examined using both static and dynamic bandwidth management.

5.3.1 Static Bandwidth Management

Figure 5.2 shows the performance of TCP-LFN when static bandwidth management was used. Both the expected and the measured throughput are as seen by the application. The expected throughput was computed as follows for an application packet size of 1400 B: TCP adds 32 B of overhead, IP adds 20 B, the router adds 4 B, and the FRACS adds 48 B. Hence, the overhead is 104 B or 7%, and the expected throughput is 93% of the allocated bandwidth.

As can be seen in Figure 5.2, the measured throughput is fairly close to the expected throughput. The difference could be made even smaller by using TCP header compression and upgrading the FRACS to use a packet size of 1600 B.

5.3.2 TCP-LFN vs. TCP

Figure 5.3 shows the relative performance of TCP and TCP-LFN with static bandwidth management. The TCP default parameters curve shows the performance of TCP with the standard window size of 8 kB and a maximum (congestion) window size of 32 kB. The throughput is limited to 90 kb/s. Some TCP implementations (e.g., Solaris) allow the user to change some of the TCP driver parameters from their default values. When the transmit and receive window sizes were changed to 64 kB, and the maximum (congestion) window size was changed to 64 kB, the peak: throughput increased to 577 kb/s. With TCP-LFN, however, the throughput increased in proportion to the allocated bandwidth.

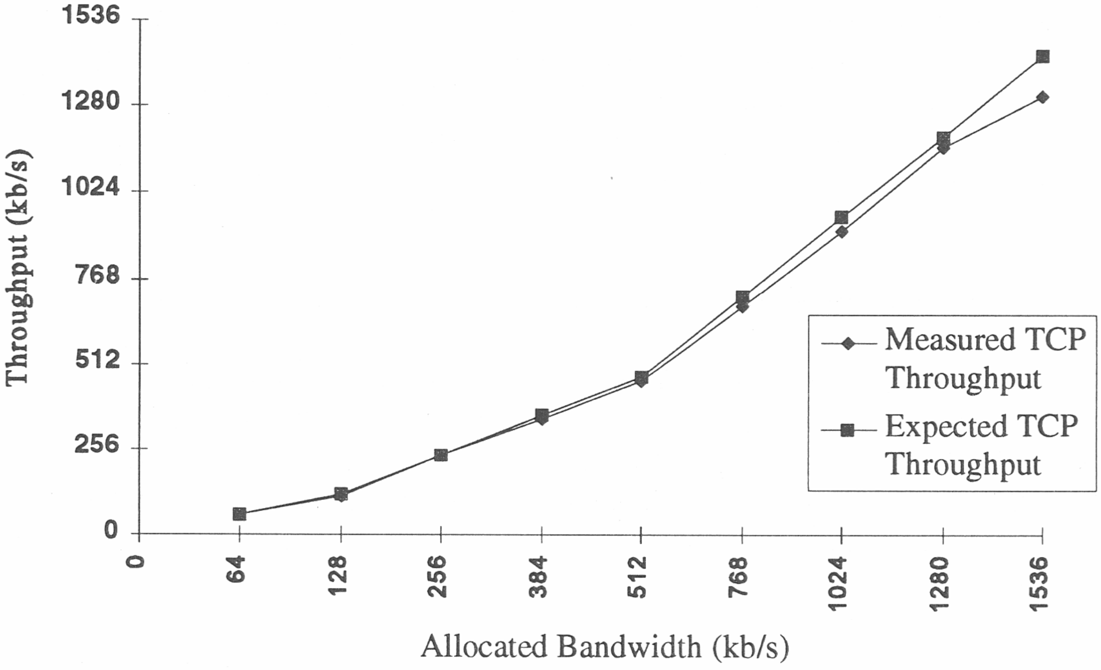

Figure 5.2. TCP-LFN throughput for the static bandwidth management case.

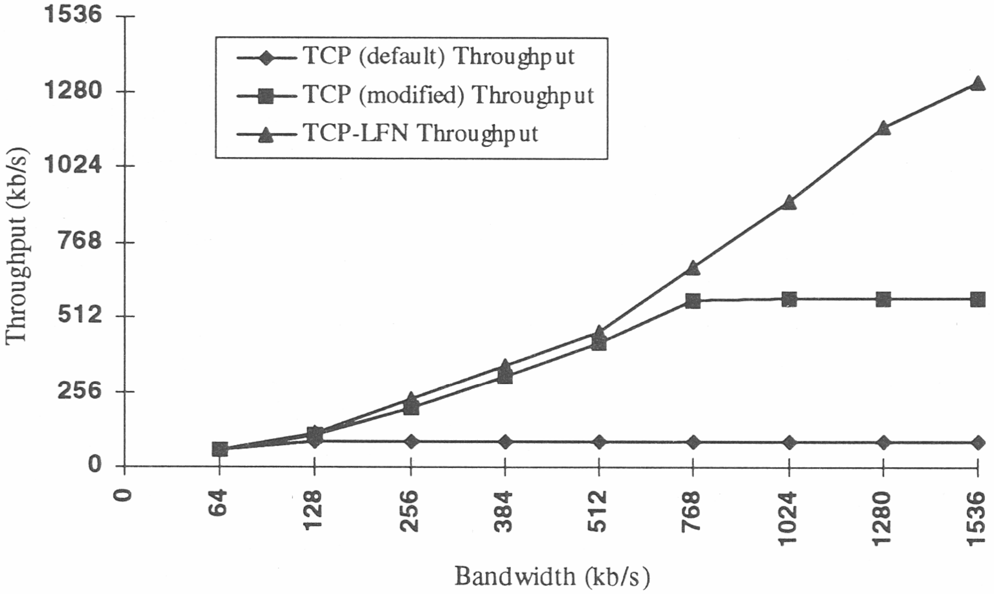

Figure 5.3. Regular TCP vs. TCP-LFN throughput.

Note that several operating systems do not allow the user to change driver parameters from their default values and those that do often have limits lower than 64 kB (e.g., 50 kB in Solaris®) due to implementation/buffer constraints. Also, the application may have to be changed (e.g., "set socket" option in Solaris® when opening a TCP socket) or the operating system may have to be rebuilt to do this. Even if this were possible, the larger window sizes would be applied to every connection, not only to those being routed over the satellite. This would result in wasted memory at the hosts; it would also use a large number of buffers at the router, which would lead to longer delays for other connections through the router and less tolerance to short periods of congestion.

5.3.3 Dynamic Bandwidth Management – Preallocated Mode

Figure 5.4 shows the performance of TCP-LFN with dynamic bandwidth management. On the abscissa is the maximum allocated bandwidth. As can be seen in this figure, the measured and the expected TCP-LFN throughput (computed in the same way as in Section 5.3.1) are fairly close. This shows that TCP-LFN works well over a link where bandwidth is allocated on demand. During this measurement, there were no lost packets.

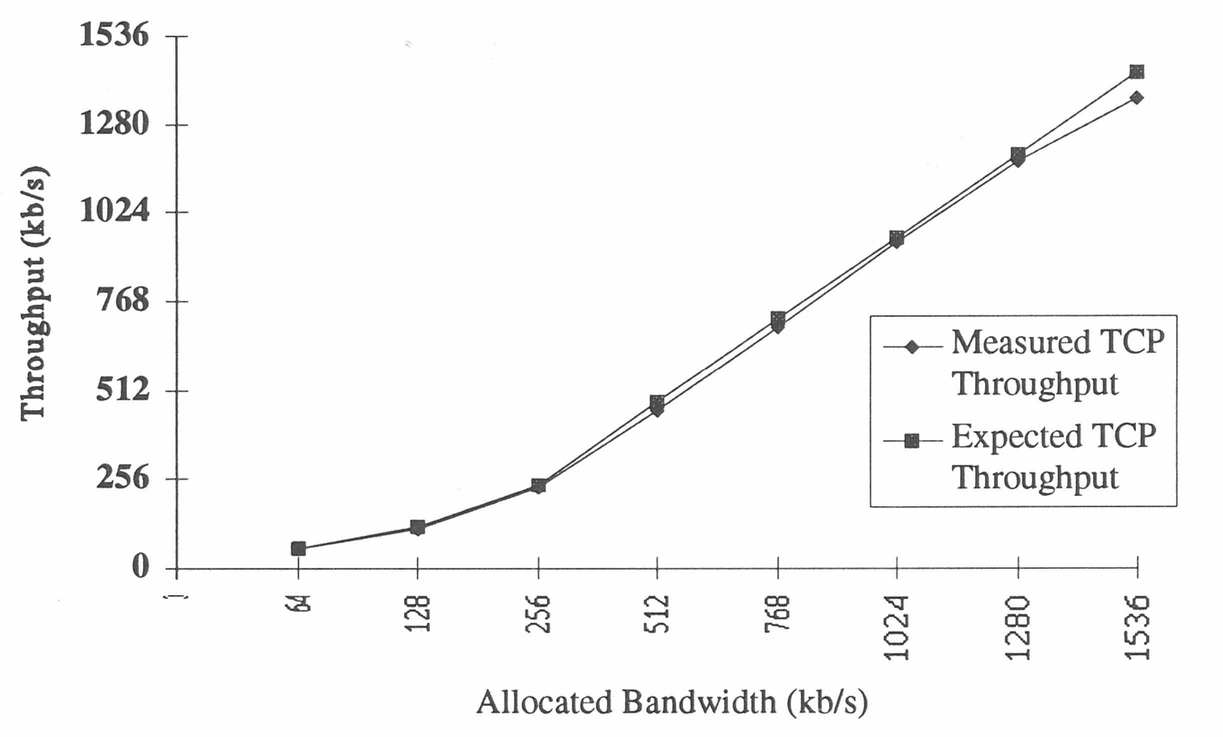

Figure 5.4. TCP-LFN preallocated mode throughput.

In the preallocated mode, a fixed number of channels were reserved from the source to the destination terminal by the FRACS, and these channels were made available to the TCP-LFN traffic as determined by the bandwidth management algorithm. There were several reasons for doing this as opposed to an actual bandwidth-on-demand operation. First, when the ACTS terminal informs the FRACS that a new call has been connected, this may not be true due to latency. Therefore, the first packet(s) sent through this channel may be lost. When this happens, TCP-LFN retransmits the lost packets and reduces the size of its congestion window. As a result the FRACS releases some of the allocated bandwidth. The cycle continues with the throughput rising to about 600 kb/s, and then dropping and rising again. Second, the time taken by the ACTS system to connect a new 64-kb/s call was fairly high (about 5 s). And finally, if there was more than one outstanding call request made to the system it would automatically stop. All of these effects taken together would result in a long delay before the TCP-LFN throughput would rise to its peak value. The preallocated mode alleviates these problems; the results obtained using this mode are the results expected if the above problems did not exist.

5.3.4 Effect of Slow Start

Slow start is a process in TCP-LFN that increases the window size each RTT if no retransmissions are required for the packets sent from the present window. Figure 5.5 shows the time taken by TCP to reach the peak throughput due to slow start (assuming no errors are observed during this period). The peak throughput information was obtained by reviewing the packet traces, finding the congestion window size, and cross-checking it with the periodic measurements done by TCPTGEN.

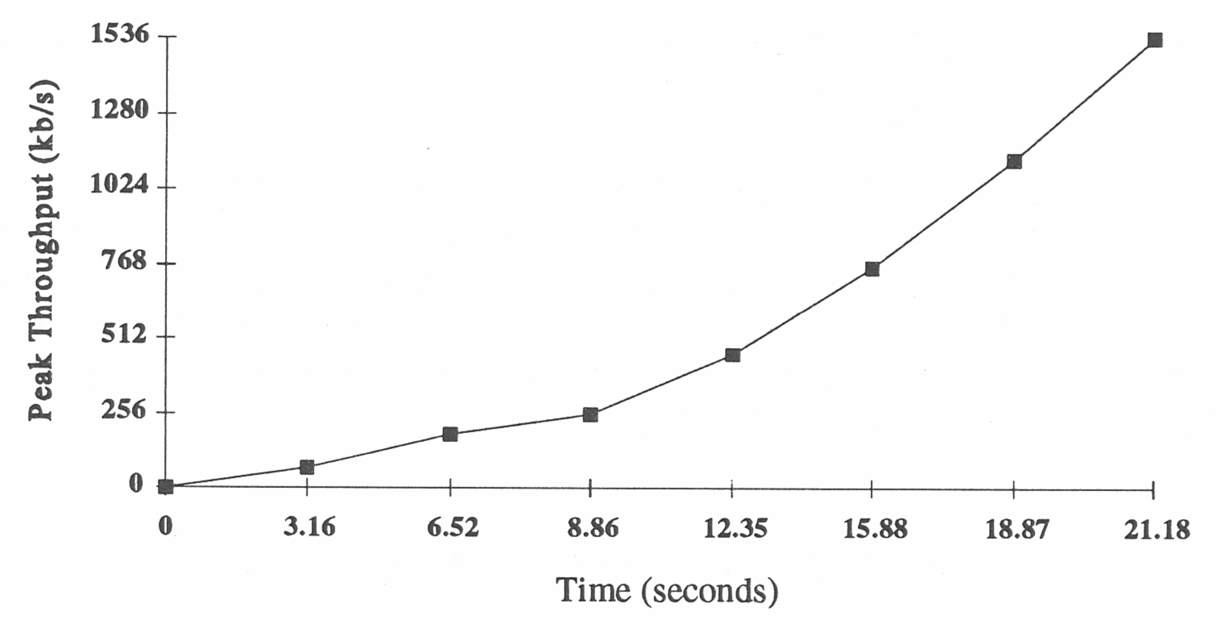

Figure 5.5. Effect of slow start on throughput.

In this case, several interesting observations were made. First, the round-trip time was 0.8 s, significantly more than the expected value of roughly 0.6 s. The FRACS uses 24 64-kb/s channels (since it may be splitting the T1 amongst several destinations). If a packet is segmented (the mean transmission unit (MTU) on the T1 is 256 B), all segments for the same packet are sent through the same channel. Given a packet size of 1504 B (1400 B of application data + 104 B of headers), the transmission delay is 0.18 s. The rest of the delay (a few milliseconds) is in the transmission delay for the acknowledgment, and the queuing delays in the router, Sun, and FRACS. In order to accommodate this delay, the window size was set to 154,000 B [1,536 kb/s (0.8s / 8 b/B)].

Assuming an initial congestion window and segment size of 1,500 B, a round-trip time of 0.8 s and assuming the congestion window doubles every round-trip time, the peak throughput of 1,536 kb/s (congestion window = 154,000 B) was expected to occur at about 5.6 s (7 round-trip times). As shown in the figure, it actually took 21.18 s for peak throughput to be reached. This is due to the way in which slow start is implemented. Every time the transmitter receives an acknowledgment, the congestion window is incremented by one segment size. This means that if the receiver sent one acknowledgment per data packet, the congestion window would double every round-trip time. However, the receiver sends one acknowledgment for every two (sometimes more) received packets when there is no data flowing in the reverse direction. As a result, the congestion window takes a lot longer to increase to its maximum value. If the transmitter accounted for the number of acknowledged bytes, the congestion window would reach its maximum much earlier. Given that the RTT of a satellite link is significantly larger, slow start severely limits the throughput for transfers that involve a small amount of information.

5.3.5 Effect of Link Errors

Figure 5.6 shows the performance of TCP-LFN with an elevated BER. The errors were injected by putting a bit-error generator on the T1 link between the FRACS and the ACTS terminal.

When the BER was 10^{-6} or worse, the throughput was degraded significantly. When a packet is lost, TCP's fast retransmit algorithm retransmits the packet immediately when a third duplicate acknowledgment is received. TCP then performs congestion avoidance, reducing its congestion window size and slow start threshold (and, hence, the throughput) to half the current value. It then slowly increases its throughput until it reaches the peak value or another error occurs. Using TCPTGEN, this fall and rise of throughput can be observed for each error.

5.4 Results of TCP-LFN over Frame Relay

In this section, the performance of several applications running over TCP-LFN over frame relay, including web browsers, FTP, Telnet, and remote login (Rlogin) is presented.

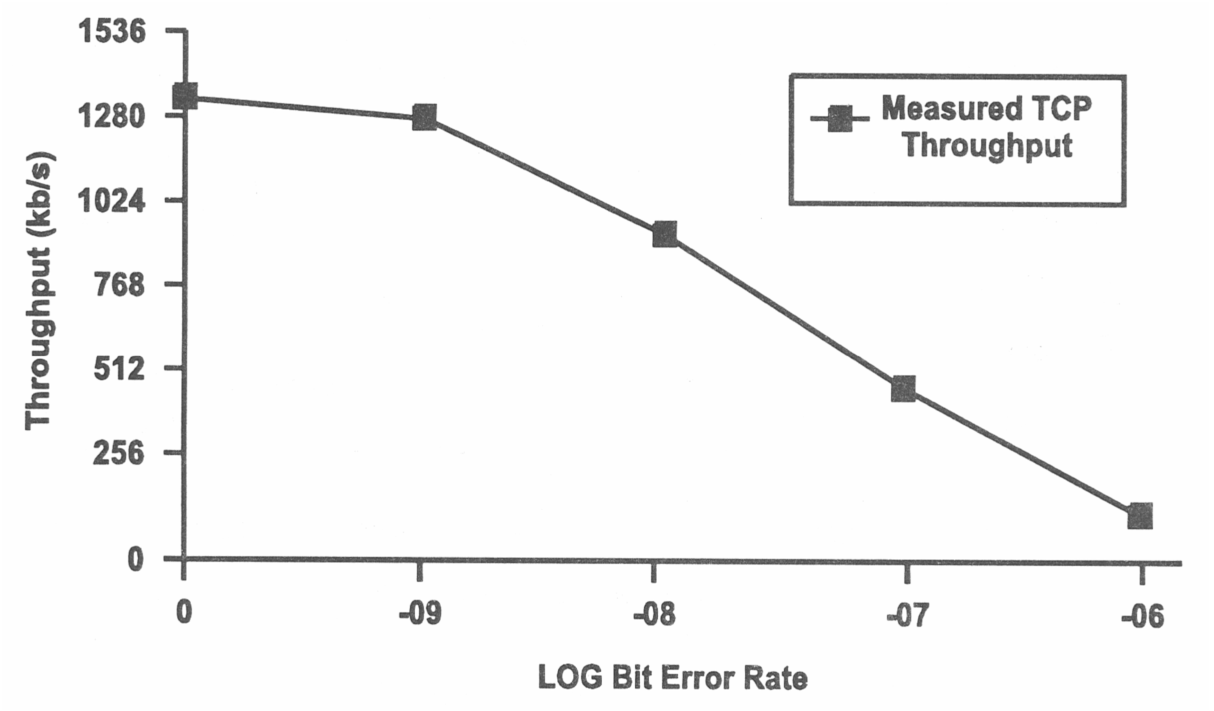

Figure 5.6. TCP-LFN throughput vs. BER.

5.4.1 Web Browsers

Slow start severely limits the throughput seen by the user for small transfers. Since most browsers (like Netscape® and Mosaic®) typically open a connection, transfer data from the highlighted link, and then close the connection, the throughput seen by the user is much lower than the link speed. Better performance is seen while transferring large images that are at least several megabytes long.

5.4.2 FTP Performance

Figure 5.7 shows the performance of FTP over TCP-LFN. As can been seen from the figure, the actual throughput at higher bandwidths was lower than that measured using TTCP and TCPTGEN. While the reasons for this were not completely understood, there are several possible reasons. Unlike TCPTGEN, the throughput could not be measured periodically, so the measured throughput was affected by slow start. The size of the file used for the measurements was 9 MB. If larger files had been used, higher throughput may have been observed. The accesses to the hard drive on the computer could also potentially have been a bottleneck at higher throughput.

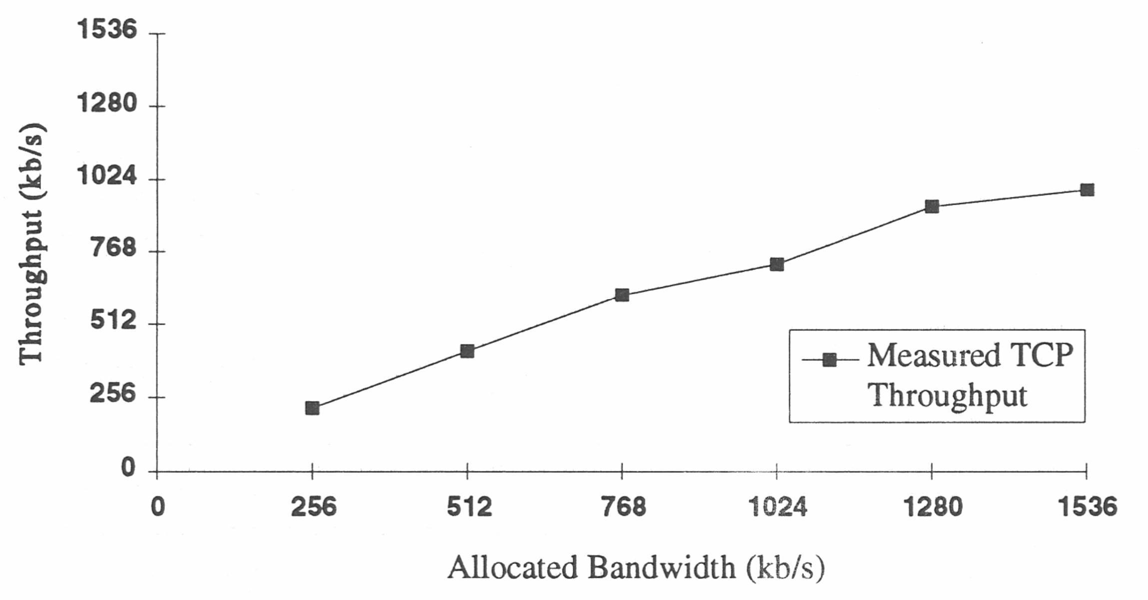

Figure 5.7. FTP performance over TCP-LFN.

In comparison, when regular TCP was used with the window size set to 50 kB with an allocated bandwidth of 1.536 Mb/s, the measured throughput was 437 kb/s. When multiple FTP sessions were established, the following throughput values were measured.

Table 5.1. Throughput vs. Number of FTP Sessions

Number of FTP Sessions	Throughput (kb/s)
2	776
3	880
4	926

When the number of FTP sessions was increased to five, retransmissions occurred; at six FTP sessions, some packet loss occurred (due to lack of buffers). In both cases, the throughput was about 1 Mb/s.

5.4.3 Telnet and Rlogin

With both Telnet and Rlogin, the longer delay of the satellite link plays a significant role. Operation in the in-line mode can reduce the effects of delay; because this mode produces a local echo of the characters typed at the terminal. This mode cannot be used for applications such as “vi” hence its usefulness is limited.

5.5 Conclusions

The following conclusions were drawn from the experiment:

The peak throughput that could be attained by TCP over a satellite link was limited to a few hundred kb/s. However, this occurred only when the TCP window sizes were changed to 64 kB. Using the default window size of 8 kB, the peak throughput was less than 100 kb/s. With TCP-LFN, the throughput scaled well with the allocated bandwidth up to 1.544 Mb/s (the limit for this experiment) and can be expected to do so into the gb/s range.

Slow start and the manner in which it is implemented introduces a significant delay in reaching the peak throughput. Most transfers from browsers such as Netscape® and Mosaic® will not reach peak throughput since they are usually of very short duration and involve setting up and tearing down a connection for each transaction.

TCP and TCP-LFN worked well with bandwidth-on-demand networks with no penalty in the delay or throughput as long as the bandwidth management algorithms were well tuned.

With the introduction of link errors (and no coding on the satellite link), TCP throughput was unaffected at error rates of 10^{-8} or better but degrades significantly at error rates of 10^{-6} or worse.

Interactive applications such as Telnet, which transfer very small amounts of data, suffer mainly from the longer delay. Some limited solutions (line mode) may help alleviate this problem.

6. ACKNOWLEDGMENTS

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Many government telecommunications needs, especially those that support National Security and Emergency Preparedness (NS/EP) missions, are becoming increasingly dependent on commercially available equipment and services. This is consistent with the goals and concepts of the National Information Infrastructure. This report examines the use of an advanced satellite--in this case, NASA's Advanced Communications Technology Satellite (ACTS)--with ISDN and frame relay protocols to support NS/EP communications requirements. A network using three ACTS earth stations was established as a research facility. With this small network, several experiments were performed. Using new objective methods, voice quality was measured over the satellite and compared to other connections such as commercial, terrestrial lines. The performance of applications--desktop conferencing, file transfer, and LAN bridging--that are likely to be useful in NS/EP situations, was determined. The performance of TCP/IP running over frame relay was examined. The results indicate that advanced satellites can be very useful for emergency communications due to the rapidity that earth stations can be deployed, the ease of reconfiguring the satellite, and the practicality of using commonly available applications running over commonly used protocols. However, there are some limitations to the performance of some applications or parts of applications due to the propagation delay of a satellite channel. Telecommunications protocols such as TCP/IP must be significantly modified to perform well over a satellite channel and to take full advantage of bandwidth-on-demand capabilities of an advanced satellite.

Key words: Advanced Communications Technology Satellite (ACTS); Integrated Services Digital Network (ISDN); Frame relay; National Security and Emergency Preparedness (NS/EP).

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