Improving File Transfers Using SCTP Multistreaming*

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Abstract

We identify overheads associated with FTP, attributed to separate TCP connections for data and control, non-persistence of the data connections, and the sequential nature of command exchanges. We argue that solutions to avoid these overheads using TCP place an undue burden on the application. Instead we propose modifying FTP to use SCTP and its multistreaming service. FTP over SCTP avoids the identified overheads in the current FTP protocol without introducing complexity at the application, while still remaining "TCP-friendly". We implemented FTP over SCTP in three ways: (1) simply replacing TCP calls with SCTP calls, thus using one SCTP association for control and one SCTP association for each data transfer, (2) using a single multistreamed SCTP association for control and all data transfers, and (3) enhancing (2) with the addition of command pipelining. Our experiments compared these 3 variations with the classic FTP over TCP. Results indicate significant improvements in throughput for multiple file transfers with all three of our variations. The largest benefit occurs for (3) FTP over a single, pipelined, multistreamed SCTP association. More generally, this paper encourages the use of SCTP's innovative services to benefit existing and future application performance and presents the case for multistreaming.

1. Introduction

The past decade has witnessed an exponential growth of traffic in the Internet, with a proportionate increase in Hyper Text Transfer Protocol (HTTP) [BFF96] and decline in File Transfer Protocol (FTP) [PR85], both in terms of use and the amount of traffic. The decline in FTP traffic is chiefly attributed to the inflexible nature of its interface. Over the years several FTP extensions have been proposed (e.g., [AOM98], [EH02], [HL97]), but few aim at reducing file transfer latency [Kin00, AO97]. FTP uses TCP to provide end-to-end reliability. In this paper, we identify reasons why modifying FTP to reduce latency overheads has been difficult, mainly due to TCP's semantics which constrain the FTP application. One result of these constraints has been that several FTP implementations aiming to enhance performance use parallel TCP connections to achieve better throughput.

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However, opening parallel TCP connections (whether for FTP or HTTP) is regarded as "TCP-unfriendly" [FF99] as this allows an application to gain an unfair share of bandwidth at the expense of other network flows, potentially sacrificing network stability. Moreover multiple parallel TCP connections consume more system resources than are necessary. This paper focuses on improving end-to-end FTP latency and throughput in a TCP-friendly manner.

Although FTP traffic has proportionately declined in the past decade, FTP still remains one of the most popular protocols for bulk data transfer on the Internet [MC00]. For example, Wuarchive [WUARCHIVE] serves as a file archive for a variety of files including mirrors of open source projects. Wuarchive statistics for the period of April 2002 to March 2003 indicate FTP accounting for 5207 Gigabytes of traffic, and HTTP accounting for 7285 Gigabytes of traffic. FTP is exclusively used in many of the mirroring software on the Internet, for various source repositories, for system backups and for file sharing. All these applications require transferring multiple files from one host to another.

In this paper we identify the overheads associated with the current FTP design. We present modifications to FTP to run over Stream Control Transmission Protocol (SCTP) [SXY+03] instead of TCP. SCTP is an IETF standards track transport layer protocol. Like TCP, SCTP provides an application with a full duplex, reliable transmission service. Unlike TCP, SCTP provides additional transport services. This paper focuses on the use of one such service: multistreaming. SCTP multistreaming logically divides an association into streams with each stream having its own delivery mechanism. All streams within a single association share the same congestion and flow control parameters. Multistreaming decouples data delivery and transmission, and in doing so prevents Head-of-Line (HOL) blocking.

This paper shows how SCTP multistreaming benefits FTP in reducing overhead, especially for multiple file transfers. We recommend two modifications to FTP that make more efficient use of the available bandwidth and system resources. We implemented these modifications in a FreeBSD environment, and carried out experiments to compare the current FTP over TCP design vs. our FTP over SCTP designs. Our results indicate dramatic improvements in transfer time and throughput for multiple file transfers under certain network conditions. Moreover, our modifications to FTP solve concerns current FTP protocol faces with NATs and firewalls in transferring IP addresses and port numbers in the payload data ([AOM98], [Tou02], [Bel94]).

The remainder of this paper is organized as follows. Section 2 details and quantifies the overheads in the current FTP over TCP design. This section also discusses possible solutions to eliminate these overheads while still using TCP as the transport. Section 3 introduces SCTP multistreaming. Section 4 presents our protocol changes in FTP to exploit using SCTP multistreaming, and a description of how these designs reduce the overheads. Section 5 presents the experimental results. Section 6 concludes the paper.

2. Inefficiencies and possible solutions

2.1 Inefficiencies in the current FTP design

FTP's current design includes a number of inefficiencies due to (1) separate control and data connection and (2) non-persistent data connection. Each is discussed in turn.

2.1.1 Distinct control and data connection

A. FTP's out-of-band control signaling approach has consequences in terms of end-to-end latency. Traffic on the control connection is periodic in nature, and hence this connection typically remains in the slow start phase of TCP congestion control [APS99]. The control connection is vulnerable to timeouts because of the send-and-wait nature of control commands. (Also, insufficient packets are flowing to cause a TCP fast retransmit.) An operation (involving a single control command) will be subject to a timeout in the event of loss of either a command or its reply. Attempts are needed to reduce the command exchange over the control connection.

B. Since control and data flow on separate connections, an extra overhead of at least 1.5 Round Trip Time (RTT) is incurred for connection setup-teardown (1RTT for setup and 0.5 RTT for teardown). Moreover the end hosts create and maintain on average two Transport Control Blocks (TCBs) for each FTP session. This factor is negligible for clients, but may significantly degrade performance of busy servers that are subject to reduced throughput due to memory block lookups [FTY99]. However, TCB overheads may be reduced by using ensemble sharing [BS01, Tou97].

C. Over the past years there have been considerable discussions on FTP's lack of security, some of them attributed to data connection information (IP address, port number) being transmitted in plain text in the PORT command on the control connection to assist the peer in establishing a data connection. Moreover, transferring IP addresses and port numbers in the protocol payload creates problem for NATs and firewalls that must monitor and translate addressing information [AOM98, Tou02].

2.1.2 Non-persistence of the data connection

A. The non-persistence of the data connection causes connection setup overhead at least on the order of 1 RTT each time a file transfer or directory listing request is serviced. Queuing delays can significantly increase the RTT. To improve end-to-end delays, every attempt should be made to minimize the number of round trips.

B. Every new data connection causes a new probing of the congestion window (cwnd) during the connection's slow start phase. Each connection begins by probing for the available bandwidth before it reaches its steady state cwnd. Moreover, a loss early in the slow start phase, before the cwnd is large enough to allow for fast retransmit, will result in a timeout at the server. Figure 1 graphically shows the nature of this re-probing overhead in the event of three consecutive file transfers. The interval between the transfers indicates the time involved in terminating the previous connection, setting up a new connection, and transferring control commands. (The reader should be able to understand that this is a generic example and not an exact indication of cwnd evolution.)

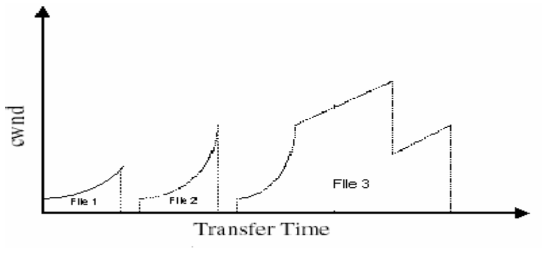


Figure 1: Expected cwnd evolution during a multiple file transfer in FTP over TCP

C. For each file transfer, a one RTT overhead is incurred for each exchange of the PORT command and its 200 reply.

D. In the event of multiple small file transfers, the server ends up having many connections in the TCP TIME-WAIT state and hence maintain on average more than two TCBs per session. This per-connection memory load can adversely affect a server's connection rate and throughput [FTY99].

2.2. Possible solutions and drawbacks

We describe some of the possible solutions that try to avoid the above stated overheads while still using TCP as the underlying transport service. The drawbacks associated with each solution are presented.

A. Use one persistent TCP connection for control and data

Improvements: This approach avoids most overheads associated with FTP's current design listed in the previous section. The commands over the control connection can be pipelined (in the event of a multiple file transfer) to improve latency, and maintain the probed congestion window for subsequent transfers.

Drawbacks: TCP provides a byte-stream service and does not differentiate between the different types of data it transmits over the same connection. Using a single TCP connection requires the application to use markers to differentiate between control and data. This marking burden increases application layer complexity. Control and file data in an FTP session are logically different types of data, and conceptually, are best kept logically if not physically, separate. Additionally, using a single connection risks Head-of-Line (HOL) blocking (HOL blocking is discussed in Section 3).

B. Use two persistent TCP connections: one for control, one for data

Improvements: A persistent data connection eliminates the connection setup-teardown and command exchange overheads for every file transfer, thus reducing number of round trips.

Drawbacks: Due to the sequential nature of commands over the control connection, the data connection will remain idle in between transfers of a multiple files transfer. When data is send after this idle time, the data connection congestion window may reduce to as much as the initial default size, and later require TCP to re-probe for the available bandwidth [HPF00]. Moreover this approach suffers from the overhead listed in Section 2.1.1 B.

C. Use two persistent TCP connections: one for control, one for data. Also use command pipelining on control connection.

Improvements: A persistent data connection with command pipelining will maintain a steadier flow of data (i.e., higher throughput) over the data connection by letting subsequent transfers utilize the already probed bandwidth.

Drawbacks: This approach suffers from the overhead listed in Section 2.1.1 B.

D. Use one TCP connection for control, and 'n' parallel data connections

Improvements: Some FTP implementations achieve better throughput using parallel TCP connections for a multiple file transfer.

Drawbacks: This approach is not TCP-friendly [FF99] as it may allow an application to gain an unfair share of bandwidth and adversely affect the network's equilibrium [FF99, BFF96]. Moreover past research has shown that parallel TCP connections may suffer from aggressive congestion control resulting in a reduced throughput [FF99]. As such, this solution should not be considered. This approach also suffers all the overheads listed in Section 2.1.1.

Related Work: Apart from the above solutions, researchers in the past have suggested ways to overcome TCP's limitations in order to boost application performance (e.g. [Bra94], [BS01], [Tou97]). For example, T/TCP [Bra94] reduced the connection setup/teardown overhead by allowing data to be transferred in the TCP connection setup phase. But due to a fundamental security flaw, T/TCP was removed from operating systems. Objectives (of aggregating transfers) have also been discussed for HTTP over the past years [PM94]. But while HTTP semantics allowed for persistent data connections and command pipelining, FTP semantics do not allow similar solutions without introducing changes to the application (see *A.* above).

Having summarized ways for improving FTP performance while still using TCP, we now consider improving FTP performance by using SCTP, an emerging IETF general-purpose transport protocol [SXM$^+$00]. We would like to note that the TCP alternatives that incorporate temporal and ensemble sharing (e.g. [Bra94], [BS01], [Tou97]) have not been discussed further in this paper. Future work should include and evaluate such alternatives.

3. SCTP multistreaming

One of the innovative transport layer services that promises to improve application layer performance is SCTP multistreaming. A stream in an SCTP association is "A uni-directional logical channel established from one to another associated SCTP endpoint, within which all user messages are delivered in sequence except for those submitted to the unordered delivery service" [SXM$^+$00].

Multistreaming within an SCTP association separates flows of logically different data into independent streams. This separation enhances application flexibility by allowing it to identify semantically different flows of data, and having the transport layer "manage" these flows (as the authors argue should be the responsibility of the transport layer, not the application layer). No longer must an application open multiple end-to-end connections to the same host simply to signify different semantic flows.

In Figure 2, Hosts A and B have a multistreamed association. Three streams go from A to B, and one stream goes from B to A. The number of streams in each direction is negotiated during SCTP's association establishment phase.

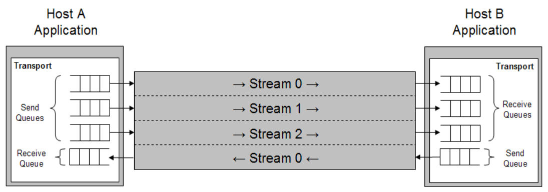


Figure 2: Use of streams within an SCTP association

Each stream has an independent delivery mechanism, thus allowing SCTP to differentiate between data delivery and reliable data transmission and avoid HOL blocking. Similar to TCP, SCTP uses a sequence number to order information. However, TCP sequences bytes, and SCTP sequences PDU's or "chunks". SCTP uses Transmission Sequence Numbers

(TSN) for reliable transmission. The TSN is global over all streams. Each stream is uniquely identified by a Stream ID (SID) and has its own Stream Sequence Numbers (SSN). In TCP, when a sender transmits multiple TCP segments, and the first segment is lost, the later segments must wait in the receiver's queue until the first segment is retransmitted and arrives correctly. This HOL blocking delays the delivery of data to the application, which in signaling and some multimedia applications is unacceptable. In SCTP, however, if data on *stream 1* is lost, only *stream 1* may be blocked at the receiver while awaiting retransmissions. With streams being logically independent flows, data on remaining streams is deliverable to the application. SCTP's socket API extensions [SXY$^+$03] provide data structures and socket calls through which an application can indicate or determine the stream number on which it intends to send or receive data.

4. FTP over SCTP variants

4.1 FTP over SCTP

FTP over SCTP keeps the same semantics as the classic FTP over TCP. Thus, this FTP model uses one separate SCTP association for control, and a new SCTP association for each file transfer, directory listing, or file namelist. The changes to the classic implementation involved only changing the socket call parameters from IPPROTO_TCP to IPPROTO_SCTP in both the client and the server sources.

4.2 FTP over SCTP with multistreaming

In this second model, we use multistreaming to combine the FTP control and data connections in a single SCTP association. Only one SCTP association exists for the entire FTP session. First, an FTP client establishes an SCTP association with the server. During initialization, two streams are opened in each direction. The client and the server send control information (commands and replies) on their respective *stream 0*. Their respective data stream or *stream 1* is used to transfer data (files, directory listings, and file namelists). This approach maintains semantics for streams analogous to control and data connections in FTP over TCP.

Recall that the data connection in FTP over TCP is non-persistent and the end of data transfer (EOF) is detected by the data connection's close. To detect EOF in our approach, we utilize the SIZE command [EH02]. The SIZE command is already widely used in FTP for the purpose of detecting restart markers. For directory listings, the end of data transfer is detected by using the info (# of bytes read by *resvmsg* call) provided by the SCTP socket API [SXY$^+$03].

In the event of a multiple file retrieval issued, the client sends out the request on outgoing *stream 0* and receives the data on incoming *steam 1* for each file in a sequential manner. Figure 3 shows the retrieval of multiple files using FTP over multistreamed SCTP. The outgoing stream for all messages and data has been identified. Data on *stream 1* is represented by dashed lines, and control messages on *stream 0* have been represented by solid lines. The dashed box on the timeline in Figure 3 indicates the operations that are repeated sequentially for each file to be transferred.

This approach has various advantages, and avoids most of the overheads described in Section 2.1. The number of round trips is reduced as: (1) a single connection (association in SCTP terminology) exists throughout the FTP session, hence repeated setup-teardown of each data connection is avoided, and (2) exchanging PORT commands for data connection information is not needed. The server load is reduced as the server maintains TCBs for at most half of the connections as required with FTP over TCP.

The drawback that this approach faces is similar to the drawbacks described in Section 2.1.2 (B). In the event of a multiple file transfer, each subsequent file transfer will not be able to utilize the prior probed available bandwidth. Before transmitting new data chunks, the sender calculates the cwnd based on the SCTP protocol parameter Max.Burst [SOA$^+$03] as follows:

$$\begin{aligned} & \textit{if ((flightsize + Max.Burst*MTU) < cwnd)} \\ & \quad \textit{cwnd = flightsize + Max.Burst*MTU} \end{aligned} \qquad (1)$$

Since the next file transfer of *file i+1* cannot take place immediately (due to the exchange of control commands before each transfer (see Figure 3)), all data sent by the server for *file i* gets acked, and reduces the flightsize at the server to zero. Thus in multiple file transfers, the server's cwnd may be reduced to *Max.Burst*MTU* ([SOA$^+$03] recommends the value of the protocol parameter Max.Burst to be set to 4) before starting each subsequent file transfer.

4.3 FTP over SCTP with multistreaming and command pipelining

Finally in this third model we introduce command pipelining in our design from Section 4.2 to avoid unnecessary cwnd reduction for a multiple file transfer. The command pipelining is similar to that defined in [PM94]. In Section 4.2's model, the cwnd reduction between file transfers occurs because the SIZE and RETR commands for each subsequent file are sent only after the previous file has been received completely by the client.

In Figure 4, we present a solution that allows each subsequent transfer to utilize the probed value of congestion window from the prior transfer. Command pipelining ensures a continuous flow of data from the server to client throughout the execution of a multiple file transfer. As seen in Figure 4, after parsing the name list of the files, the client sends SIZE commands for all files at once. As soon as a reply for each SIZE command is received, the client sends out the RETR command for that file. Since the control stream is ordered, the replies for the SIZE and RETR commands will arrive in the same sequence as the commands.

By using SCTP multistreaming and pipelining, FTP views multiple file transfers as a single data cycle. Command pipelining aggregates all of the file transfers resulting in better management of the cwnd. This solution overcomes all of the drawbacks listed in Section 2.1, resulting in a more efficient utilization of the bandwidth.

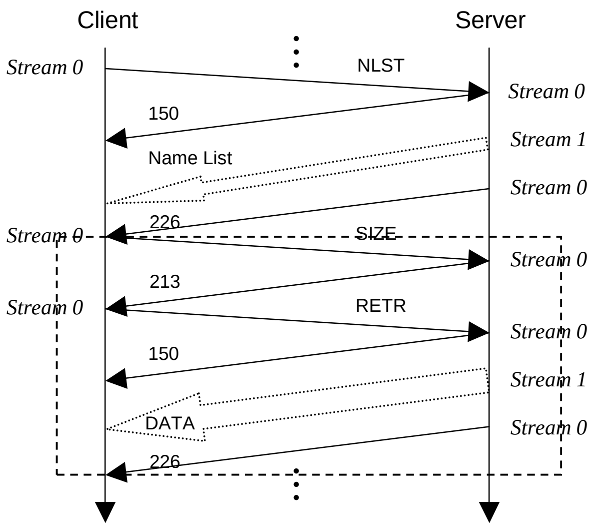


Figure 3: FTP over multistreamed SCTP timeline showing a multiple file transfer.

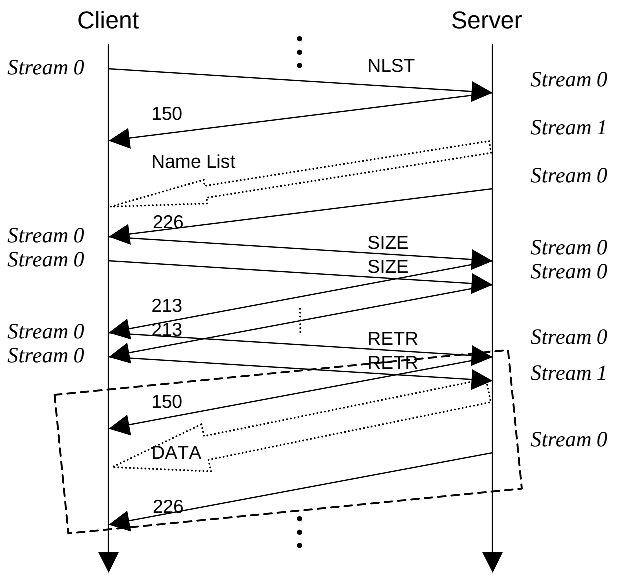


Figure 4: FTP over multistreamed SCTP with command pipelining timeline showing a multiple file transfer.

5. Experimental results

We now report on our experimental study of FTP over TCP vs. FTP over SCTP. We measured the total transfer time observed for a multiple file transfer for a varied set of parameters.

- *Bandwidth-Propagation Delay (B-D) configuration*: Three path configurations were evaluated: (1Mbps, 35ms), (256Kbps, 125ms), (3Mbps, 1ms). Both the client to server and server to client paths share the same characteristics. In this section, we focus on the results of (1Mbps, 35ms) configuration. Results of the other two configurations have been described in Appendix A.
- *Packet Loss Ratio (PLR)*: The PLRs studied were (0, .01, .03, .06, and .1). Each value represents the loss ratio for both the client to server and the server to client paths experience the same loss rate. We used a uniform probability distribution to emulate packet loss. Certainly 10% loss represents an extreme case but we were interested in general trends as the loss rate increases. Moreover, higher loss rates may be of interest to wireless and military networks.
- *File sizes:* Although FTP is widely used for bulk data transfer, some applications (e.g., source updates) use FTP to transfer small files. To evaluate potential reduced overheads in a variety of these applications, we chose file sizes as (10K, 50K, 200K, 500K, and 1M).

Two sets of experiments were performed with different number of files transferred (10 and 100 files) to observe the effect of total transfer time on the number of files being transferred.

5.1 Experimental setup

We used *Netbed* [WLS$^+$02] (an outgrowth of Emulab) which provides integrated access to experimental networks. Three nodes were used for each experiment, one for the FTP client and one for the FTP server. The third node acted as a router for shaping traffic between the client and server. The client and server nodes are 850MHz Intel Pentium III processors, and based on the Intel ISP1100 1U server platform. All three nodes run FreeBSD-4.6. The FreeBSD kernel implementation of SCTP available with the KAME Stack [KAME] was used on the client and server nodes. KAME is an evolving and experimental stack mainly targeted for IPv6/IPsec in BSD based operating systems. An updated snapshot of the stack (KAME snap kit) is released every week. We used the snap kit of 14th October, 2002. The router node runs *Dummynet* [Riz97] which simulates a drop tail router with a queue size of 50 packets, and specified bandwidth, propagation delay and packet loss ratio.

We implemented protocol changes by modifying the FTP client and server source code available with the FreeBSD 4.6 distribution. In our experiments, total transfer was measured using packet level traces as follows. The starting time was taken as the time the client sends out the first packet to the server following the user's *"mget"* command. The end time was the time the "226 control reply" from the server reached the client after the last file transfer. Each combination of parameters (3 B-D configurations x 5 PLR x 5 file sizes) was run multiple times to achieve a 90% confidence level for the total transfer time. *Tcpdump* [TCPDUMP] (version 3.7.1) was used to perform packet level traces. SCTP decoding functionality in *tcpdump* was developed in collaboration of UD's Protocol Engineering Lab and Temple University's Netlab. Our results compare four FTP variants:

(1) *FTP over TCP:* The current FTP protocol which uses a separate TCP connection for control, and a new TCP data connection for every file transfer, directory listing and name list. The TCP variant used was New-Reno.

(2) *FTP over SCTP:* The original FTP protocol design but using SCTP at the transport. See Section 4.1.

(3) *FTP over multistreamed SCTP:* This design, described in Section 4.2, uses a single SCTP association for both control and data. It uses multistreaming to assign one stream to control, and one stream to data. The SCTP association between the client and the server persists throughout the FTP session.

(4) *FTP over multistreamed SCTP with command pipelining:* (see Section 4.3) This design adds command pipelining over multistreamed SCTP to ensure the congestion window is not needlessly probed for each file transfer.

We have performed experiments involving single as well as multiple file transfer. Although the improvement of file transfers using SCTP multistreaming is also witnessed in single file transfers, we emphasize the results of experiments involving multiple file transfer for two reasons. First, the positive impact of multistreaming is more predominant in the event of multiple file transfers. Second, comparing variant (1) vs. variant (2) provides insight on single file transfer.

5.2 Results

Figure 5 shows the results obtained for (1Mbps, 35ms) bandwidth-delay configuration. The results represent the loss probabilities vs. total transfer time to retrieve 10 files (each the same size) using four different FTP variants. Figure 6 shows the same comparisons but with retrieval of 100 files.

5.2.1 Comparing (1) vs. (2). Since (2) is simply a straightforward substitution of TCP calls with SCTP calls, any difference in performance must be attributed to SCTP's handling of data (i.e., congestion control, loss recovery) and not to multistreaming. Figure 5 shows that for small file transfers, (1) and (2) overall perform similarly. (2) performs worse than (1) at low loss rates (~ 0-3%) since SCTP's per packet payload (1408 bytes) is less than TCP's (1448 bytes). SCTP's overhead is slightly more than TCP's. (When experiments were performed, the SCTP fragmentation threshold for the FreeBSD implementation was 1408. This threshold was increased recently thus reducing its effect on per packet overhead.) As the packet loss rate increases, (2) outperforms (1). We believe this reversal is due to SCTP's more robust loss recovery and congestion control mechanisms that outbalance the effects of per packet overheads. Details on the differences of congestion control mechanisms between SCTP and TCP can be found in [AAI02].

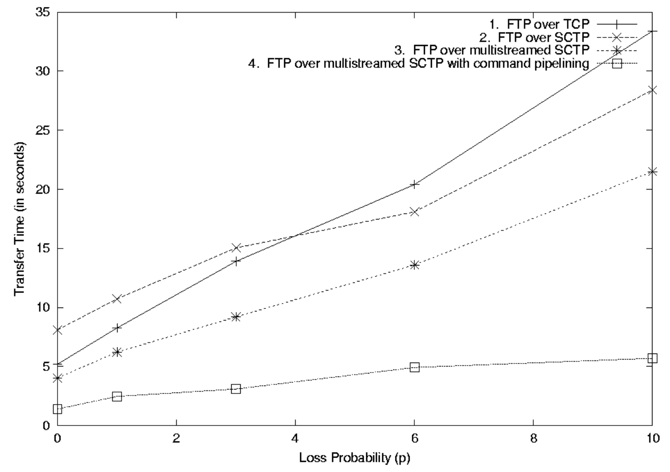
For small file transfers, the data connection in both (1) and (2) is dominated by slow start phase of the congestion control. As the file size increases, the data connection's life time in both (1) and (2) is dominated by the congestion avoidance phase. Hence as the file size increases, both the scale and ratio of performance benefit seen by (2) as compared to (1) at loss rates (1-10%) increases. For example, at 3% loss rate the ratio of total transfer time taken by (1) to (2) is 0.92, 1.14, 1.29, 1.31, 1.56 for ten 10K, 50K, 200K, 500K and 1M multiple file transfers, respectively. This steady increase results because as the number of loss events generated increases proportionally with the size of file transfers, SCTP takes advantage over TCP on a per loss event basis eventually reducing latency by nearly or more than 50%. This improvement can be seen in Figure 6 at a 3% loss, (1) requires 2210 seconds to transfer 100 1M-files whereas (2) requires 1409 seconds.

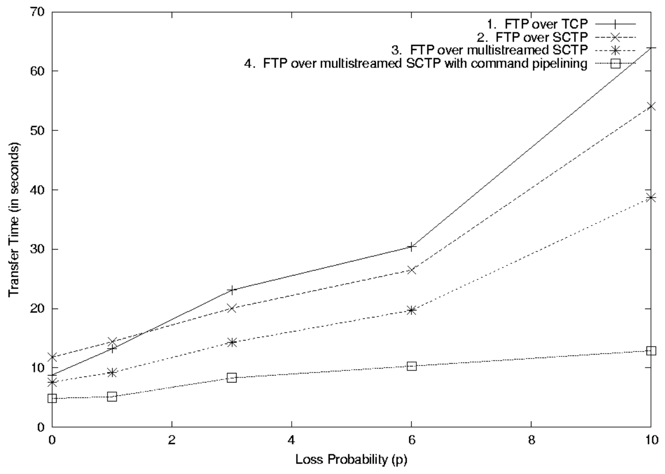
From Figures 5 and 6, as the number of files transferred increase from 10 to 100, the scale of performance of (2) as compared to (1) also increases. As the loss rate increases, more significant performance improvements can be seen. SCTP's significant out performance of TCP at medium to high loss rate came as a surprise as it was widely understood that the congestion control mechanisms in TCP and SCTP are approximately the same. We have validated our results using simulations, and are currently investigating the effect of the subtle differences between the congestion control mechanisms in TCP and SCTP, which result in such significant difference observed in overall steady state performance (e.g., SCTP's congestion control semantics incorporate Limited Transmit [ABF01], Appropriate Byte Counting [All03], while the TCP implementation that is currently prevalent (and the TCP implementation used in our experiments) does not use such features.). The congestion control mechanisms in TCP are in the process of being fine tuned, a research task underway in the IETF [e.g., ABF01, All03]. Once the TCP extensions are included in TCP implementations, we expect (1) and (2) to perform similarly at different loss rates.

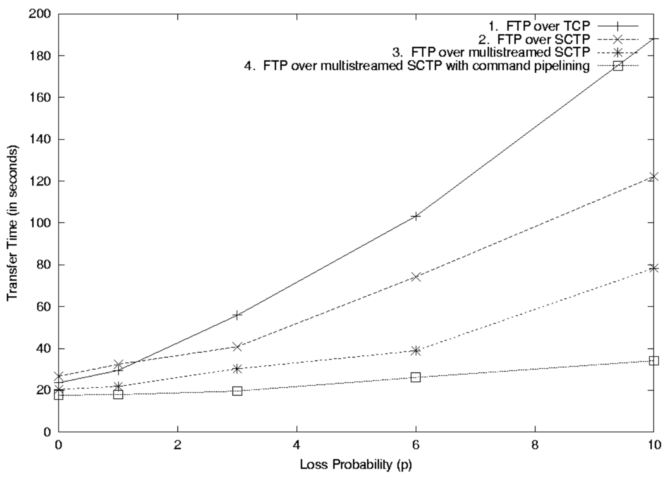
5.2.2 Comparing (3) and (4) vs. (2). We now turn our discussion to the multistreamed FTP variants (3) and (4). We compare (3) and (4) with (2) and not with (1) because our main focus is to evaluate the effect of SCTP multistreaming and command pipelining on multiple file transfers.

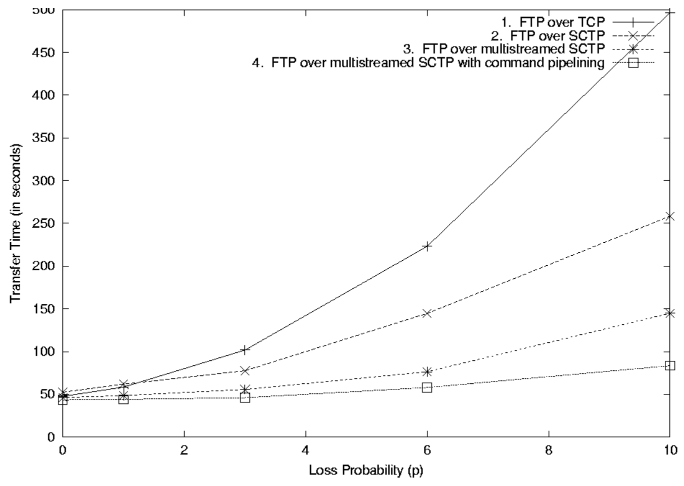
As noted in Sections 2 and 4, using multistreaming and command pipelining (a) reduces round trips in command exchanges and connection setup-teardown, and (b) maintains the probed value of the congestion window for subsequent transfers in a multiple file transfer. We hypothesized the effect of (a) would remain fairly constant irrespective of file sizes being transferred, and the effect of (b) would be more evident in transfer of small files than for large files. For small files, non-persistent data connections tend to remain longer in slow start probing for available bandwidth, whereas the time spent in probing in large file transfers would be smaller compared to time spent in steady state congestion avoidance. We expected the effects of both (a) and (b) would be directly proportional to the number of files being transferred.

In (3) we reduce the number of round trips but do not maintain the probed congestion window for subsequent transfers (see Section 4.2). As noted above this effect should have a constant scale as compared to (2). We can see from Figure 5 that the ratio of transfer time taken by (2) vs. (3) remains fairly constant ranging between 1.5 and 1.7. The small variance can be attributed to the losses (which result in timeouts) incurred by the extra round trips involved in (2).









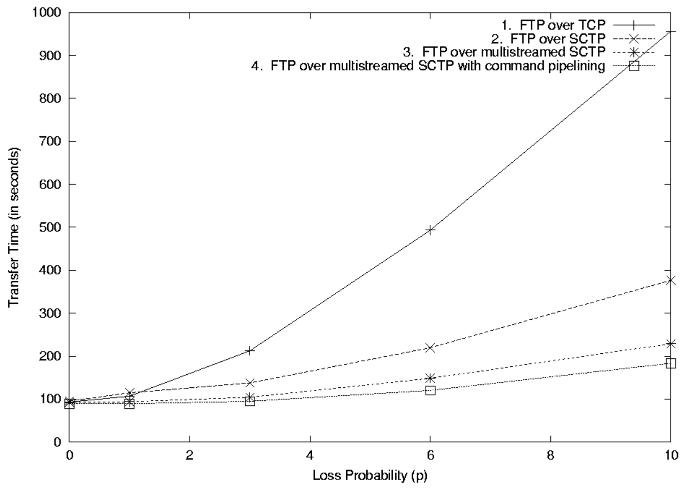


Figure 5: Transfer Time vs. Loss Probability for a multiple transfer of *10 files* (Bandwidth = 1Mbps Propagation Delay = 35ms)

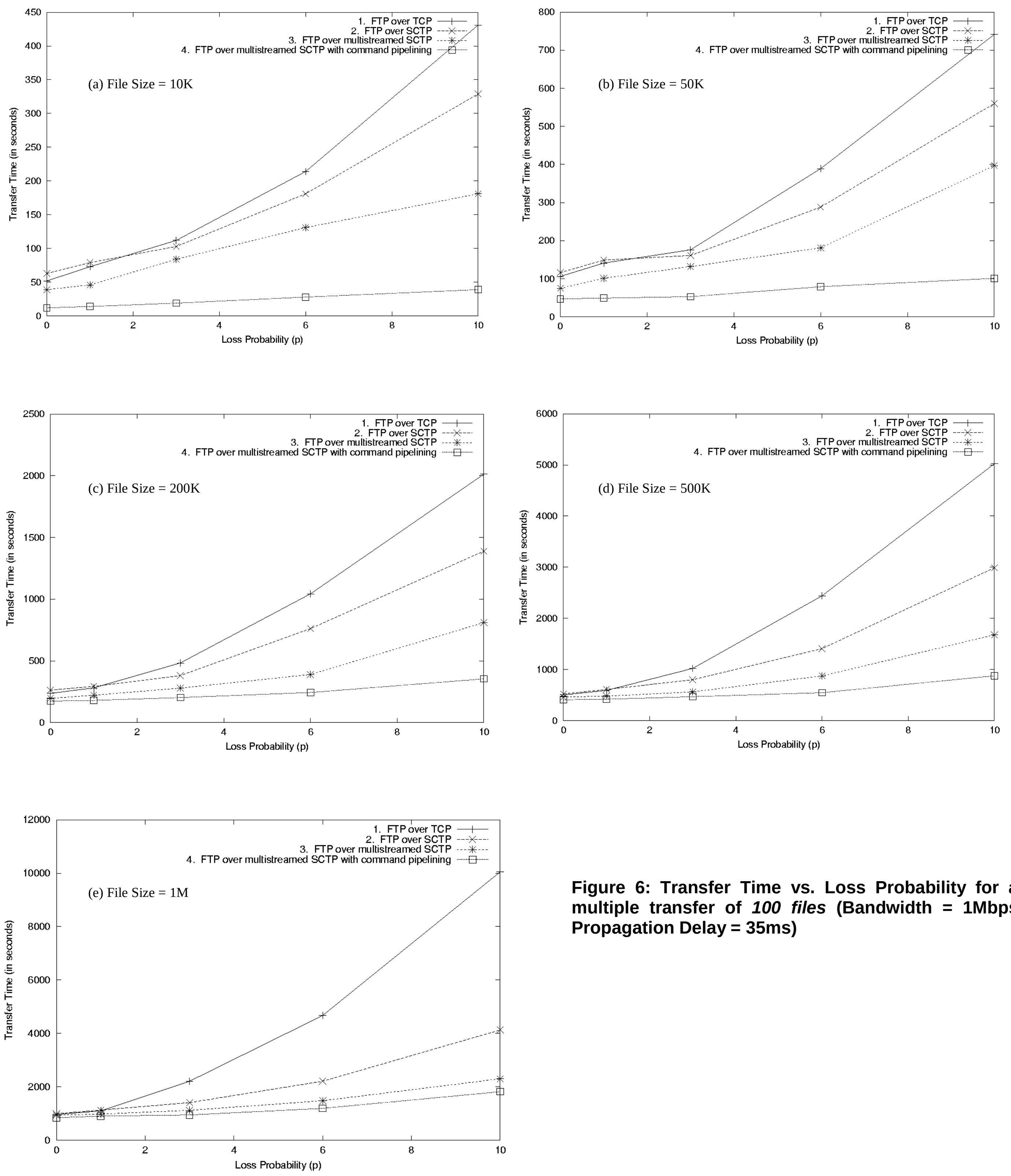


Figure 6: Transfer Time vs. Loss Probability for a multiple transfer of *100 files* (Bandwidth = 1Mbps Propagation Delay = 35ms)

As noted above, the most significant impact of (4) as compared to (2) comes for short transfers. For example in Figure 6(a), at a 3% loss scenario, (2) requires 103 seconds to transfer 100 files of size 10K each, as compared to (4) which takes only 19 seconds. From Figure 5, at 3% loss rate the ratio of total transfer time taken by (2) to (4) is 4.9, 4.1, 3.5, 3.1, and 2.1 for ten 10K, 50K, 200K, 500K and 1M file transfers, respectively. Thus this effect, which is also seen by comparing the ratio of (3) vs. (4), demarcates the benefits that multistreaming and command pipelining provide.

Moreover, it can be seen from Figures 5 and 6 that as the number of files to be transferred increase from 10 to 100, the performance gain by (4) as compared to (2) increases. This increase implies significant benefits to mirroring applications that use FTP (e.g., *fmirror*) which often have to mirror a large number of files from one server to the other.

We note that comparing (1) which is FTP over TCP-New Reno (the Internet's prevalent variant) to (4) shows the tremendous impact that SCTP, multistreaming and command pipelining can have in FTP transfer time. From Figure 6(e), (1) takes 2210 seconds as compared to (4) which takes 948 seconds to transfer 100 1M-files at 3% loss. Also note that (3) and (4) perform consistently better as compared to either (1) or (2) irrespective of the loss rates.

5.2.3 Summary: We observe that (2) performs close to (1) at lower loss rates, and as the loss rate increases, (2) outperforms (1) significantly. For smaller loss rates, per packet overhead in (2) results in marginally lower performance as compared to (1). (This factor does not play into the latest SCTP implementation) Past research shows the congestion control semantics and loss recovery mechanisms in SCTP are robust as compared to TCP, which result in better steady state throughput at higher loss rates [AAI02].

- Exploiting SCTP multistreaming in (3) performs better by a steady scale factor of approx. 1.5 (in relation to file sizes) as compared to FTP over SCTP without multistreaming in (2). This gain is attributed to multistreaming helping reduce a constant number of round trips directly proportional to the number of files being transferred. The slight variance witnessed is due to the loss (and eventually timeouts) that these extra round trips can incur.
- Adding command pipelining to multistreaming in (4) further reduces total transfer time for a multiple file transfer. The effect of command pipelining is more predominant in small transfers due to the fact that short flows spend most of the time probing for the available bandwidth.
- The absolute scale of transfer time improvement in FTP over multistreamed SCTP with/without command pipelining is directly proportional to the number of files being transferred in a multiple file transfer request: more files transferred results in more relative savings in transfer time.

6. Conclusions and future work

Our experimental results confirm that modifying FTP to use SCTP multistreaming and command pipelining dramatically reduces latency of multiple file transfers. These features:

- reduce the number of connections by aggregating the control and data connections,
- reduce the number of round trips required for connection setup/teardown, and command exchange, and
- use the bandwidth more efficiently by preserving the congestion window between file transfers.

Apart from transfer time improvements, other advantages of FTP over SCTP (with multistreaming and/or command pipelining) instead of over TCP are:

- The number of connections a server must maintain is reduced. Quantifying server load and its effects on throughput is beyond the scope of this paper. The interested reader is pointed to [FTY99]. We however expect that by using either modification (3) or (4), servers could serve at least twice the number of clients compared to the current FTP over TCP design (assuming the bottleneck for the number of simultaneous clients served is the TCBs reserved for the connections). This result may be of interest to busy servers who are constrained by the number of simultaneous clients.
- The number of packets exchanged between the client and the server is reduced (ex., by reducing the command exchanges) thus reducing the overall network load.
- Aggregating control and data connections into one SCTP multistreamed association solves concerns that current FTP protocol faces with Network Address Translators (NAT) and firewalls in transferring IP addresses and port numbers through the control connection [AOM98, Tou02].

The authors further argue that the benefits of SCTP's multistreaming can be exploited by other applications. SCTP's multistreaming provides a TCP-friendly mechanism for parallel transfers. Ongoing research at UD's PEL is investigating whether web transfers using HTTP can benefit from aggregation of multiple transfers in a single SCTP association.

Three limitations of this work which we plan to address in the future:

- We have used a uniform loss distribution model for emulating losses on the path. We are investigating a variation that can models burst losses.
- Recent additions to the TCP congestion control [ABF01, All03] fine-tune TCP's behavior for faster recovery from loss, and fewer timeouts. An extension to our work could be to take such TCP fine tunings into consideration.
- TCP alternatives incorporating temporal and ensemble sharing ([Bra94], [BS01], [Tou97]) can be considered in further evaluation of FTP over SCTP.

Disclaimer

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