SSthreshless Start: A Sender-Side TCP Intelligence for Long Fat Network

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Abstract

Measurement shows that 85% of TCP flows in the internet are short-lived flows that stay most of their operation in the TCP startup phase. However, many previous studies indicate that the traditional TCP Slow Start algorithm does not perform well, especially in long fat networks. Two obvious problems are known to impact the Slow Start performance, which are the blind initial setting of the Slow Start threshold and the aggressive increase of the probing rate during the startup phase regardless of the buffer sizes along the path. Current efforts focusing on tuning the Slow Start threshold and/or probing rate during the startup phase have not been considered very effective, which has prompted an investigation with a different approach.

In this paper, we present a novel TCP startup method, called threshold-less slow start or SSthreshless Start, which does not need the Slow Start threshold to operate. Instead, SSthreshless Start uses the backlog status at bottleneck buffer to adaptively adjust probing rate which allows better seizing of the available bandwidth. Comparing to the traditional and other major modified startup methods, our simulation results show that SSthreshless Start achieves significant performance improvement during the startup phase. Moreover, SSthreshless Start scales well with a wide range of buffer size, propagation delay and network bandwidth. Besides, it shows excellent friendliness when operating simultaneously with the currently popular TCP NewReno connections.

I. INTRODUCTION

TCP is a connection-oriented, reliable and in-order transport protocol which carries applications ranging from bulk data transmission to web browsing. Over the years, TCP has evolved from original TCP Tahoe [2] to the currently most widely used TCP NewReno [3]. TCP uses Slow Start during startup phase to probe the capacity of a network path with unknown characteristics. The TCP probing rate is controlled by its congestion window, $cwnd$, where a TCP connection can transmit up to $cwnd$ amount of unacknowledged packets.
TCP carries 95% of today’s Internet traffic and constitutes 80% of the total number of flows in the Internet [5]. Among those TCP traffic, short-lived TCP flows spend most of their operational lifetime within the Slow Start process when \( cwnd \) ramps up in an exponential manner. Measurement in [49] shows that 85% of the TCP traffic are short flows. This implies that the majority of data transmission in the Internet is dominated by the TCP startup behavior.

In the Slow Start process, \( cwnd \) is set between one and four TCP packets initially [16], and its value is incremented by one packet upon each reception of an ACK in order to probe and test the available bandwidth. With this increment, \( cwnd \) is doubled for each round trip time (RTT) when all ACKs are returned. As a result, the value of \( cwnd \) is increased monotonically with an exponential rate for every RTT until when the network cannot cope with the amount of transmission from the TCP connection. The network congestion is signaled by triple duplicated ACKs or more seriously a Timeout detected by the TCP sender. When this congestion signal is detected, the TCP connection ends the Slow Start process and the Congestion Avoidance process takes over the adjustment of \( cwnd \). Unlike Slow Start, Congestion Avoidance maintains a linear increment of \( cwnd \) every RTT to avoid congestion.

The exponential increment of \( cwnd \) in Slow Start may significantly overshoot the available bandwidth when probing and testing the bandwidth availability. This overshooting of \( cwnd \) may cause serious congestion and packet loss which require a long time to recover. To prevent this overshooting, Slow Start introduces a parameter called Slow Start threshold, \( ssthresh \), where when \( cwnd \) reaches \( ssthresh \) where an overshooting is likely, the TCP connection ends the Slow Start process and lets the Congestion Avoidance process to take over turning the growth of \( cwnd \) to a conservative linear rate.

In general, the current Slow Start process combines an estimation of the bandwidth availability described by \( ssthresh \) and a rate probing algorithm in order to achieve high bandwidth utilization. Depending on the accuracy of the bandwidth availability estimation, a corresponding rate probing algorithm can be designed to achieve a certain high level of bandwidth utilization during the Slow Start process. For example, in an extreme case where the bandwidth availability estimation is highly accurate, the rate probing is unnecessary as a TCP sender can immediately operate at the optimal rate based on the estimation. In contrast, an inaccurate bandwidth availability estimation should accompany with a prudent rate probing algorithm to compensate the inaccuracy of the estimation.

However, Slow Start is known to be extremely inefficient. Two obvious problems in the current Slow Start algorithm design leads to this inefficiency, and these problems are particularly severe in long fat networks (LFNs) [41], [42]. The first obvious problem is the blind initial setting of \( ssthresh \) due to lack
of bandwidth availability estimation. With the blind initial setting of $ssthresh$, a prudent rate probing algorithm should be sought. However, the current Slow Start process uses exponential rate increment probing which is an aggressive rate probing algorithm. This combination amplifies the performance penalty of the problem. Precisely, when $ssthresh$ is set too high compared to the bandwidth-delay product (BDP), which represents the capacity of a network pipe, a TCP connection may inject more packets into a network causing congestion. This problem is serious in LFNs, because $cwnd$ is doubled every RTT, and this aggressive increase may easily cause burst losses and consequent Timeout \cite{2} by overshooting the network capacity. Conversely, when $ssthresh$ is set too low, a TCP connection will exit Slow Start and enter Congestion Avoidance prematurely. Thus, $cwnd$ may take a long time to reach an optimal operating point that matches the capacity of the LFN. Both cases cause low link utilization. Here, we call this drawback the blind $ssthresh$ setting problem.

Another problem in the current Slow Start is related to the temporal queue buildup occurs during Slow Start. Packets buildup in a buffer occurs when a TCP connection increases $cwnd$ and transmits more packets within a RTT round. An adequate buffer size is critical to hold this buildup of packets, otherwise packet loss will occur. Since Slow Start disregards of the backlog status in the bottleneck buffer, packet losses may occur even before $cwnd$ has reached the available bandwidth, which significantly degrades the performance. This problem is significant when the buffer size of the bottleneck router is much smaller than the BDP. Here, we call this drawback the temporal queue buildup problem. This problem has been observed and discussed in \cite{21}.

The current efforts in improving the performance of TCP Slow Start largely focus on improving bandwidth estimations \cite{6,8,9,22,7} for optimal $sshtresh$ setting and/or designing an appropriate rate probing algorithm based on the reliability of bandwidth availability estimation. However, due to the limited ability of a TCP sender in observing the network resource, together with the fast changing network bandwidth availability, the accuracy of bandwidth availability estimation is largely uncertain giving no basis for the design of an adequate rate probing algorithm for optimizing the Slow Start performance.

Recognizing the challenges in finding optimal settings for the $sshtresh$ and the probing algorithm, in this paper, we take a different approach that bypasses the need for $ssthresh$ setting which influences greatly to the performance. Our solution, called threshold-less slow start or SSthreshless Start (pronounced as s-thresh-less start), is a sender-side enhancement that offers immediate benefits upon deployment. The key idea of our method is that it makes use of backlog status at the bottleneck buffer, monitored by RTT to refine the $cwnd$ ramping up behavior and adaptively adjust probing rate to meet the available
network capacity. SSthreshless Start proposes alternating between an exponential and a linear growth of $cwnd$ based on backlog status during the TCP startup phase. Our preliminary results reported in [1] have shown encouraging performance gain in TCP startup. In this paper, extensive simulation and in depth investigations are conducted to evaluate the benefit of rate alternation on TCP startup performance.

Briefly, The alternating of two rates achieves benefits in three aspects. Firstly, it eliminates the need of $ssthresh$ to decide when Congestion Avoidance should take over to end the exponential growth of $cwnd$. Without $ssthresh$, the blind $ssthresh$ setting problem does not exist in SSthreshless Start. In other words, the network status detection does not translate to $ssthresh$, instead, the status is used directly to control the rate probing algorithm between aggressive and prudent modes, where $cwnd$ is increased continuously alternating between an exponential and a linear rates until a congestion signal is detected. Secondly, SSthreshless Start monitors the backlog status and switches the growth rate of $cwnd$ to linear when queue buildup is observed. This prevents continuous queue buildup in the buffer and hence avoids the temporal queue buildup problem from materialized into a packet lost event before the available bandwidth is reached. Finally, since $cwnd$ increases monotonically during SSthreshless Start, packet loss is inevitable due to the finite availability of the bandwidth. However, as network congestion approaches, the number of backlogged packets at the bottleneck buffer will have increases. This will signal SSthreshless Start turning to linear growth rate for $cwnd$. The preemptive switch to a linear growth rate for $cwnd$ as network congestion approaches allows a fast recovery when a packet loss event eventually occurs.

We implement our TCP startup solution and combine it with NewReno. NewReno is chosen because several existing startup modifications, for example Hoe’s Change [18] and Limited Slow Start [10], are also refined based on NewReno. This also allows a direct comparison to existing modifications. Comparing with traditional Slow Start and existing modifications, our enhancement shows significant improvement in link utilization during the startup process with various BDP and buffer configurations. Besides, our enhancement also shows good convergence behavior without adversely affecting coexisting TCP connections. Therefore, the throughput gain during startup is achieved by using the spared bandwidth effectively rather than aggressively depriving bandwidth from other co-existing TCP connections.

The remainder of the paper is organized as follows. We start by demonstrating the problems with Slow Start by simulations in the next section. After summarizing some related works in Section III, we describe the SSthreshless Start in Section IV, validate it through intensive simulation experiments in Section V, and we finally conclude this paper in Section VI.
II. PROBLEMS WITH TRADITIONAL SLOW START

To illustrate the inefficiency of Slow Start in a LFN, we conduct simulation experiments using ns-2.34 [55]. Fig. 1 shows our considered network topology used commonly for this purpose of study. In Fig. 1, TCP Src represents the TCP sender and TCP Dst represents the TCP receiver. Routers A and B are two droptail bottleneck routers. Side links are all with bandwidth of 500 Mbps, and one-way delay of 0.1 ms. Between the two routers there is a bottleneck link with 40 Mbps bandwidth and 50 ms one-way delay. For convenience, congestion window size is measured in number of packets, and the packet size is 1000 bytes while ACK is set to 40 bytes long. This gives the BDP value to be 500 packets. The bottleneck router is with 250 packets buffer size (BDP/2). TCP sources run NewReno with traditional Slow Start. All the other simulation experiments conducted in this paper also use this dumbbell topology with varying buffer size, one-way delay and bandwidth.

In traditional Slow Start [2], before a TCP connection starts, initial ssthresh is set to an arbitrary value, ranging from 4 KB to extremely high. This blind ssthresh setting problem severely degrade TCP startup performance, especially in LFN. We conduct an simulation to illustrate the impact of ssthresh setting on the performance of Slow Start for short transfers.

In our setup, we consider a single TCP connection with three cases of different ssthresh values where one is higher than, one is equal to and one is low than the BDP value. Precisely, we set the ssthresh values to 5000, 500 and 32 packets in each simulation and label them as “NR with SS (L)”, “NR with SS (A)”, “NR with SS (S)”, respectively. We plot the cwnd and sequence number evolution of the three studied cases in Fig. 2.

As can be seen from the results in Fig. 2(a), “NR with SS (L)” that overestimates the BDP quickly overshoots the BDP and produces burst losses at the router. These burst losses cause a series of Timeout events in TCP that forces its cwnd to exit exponential grow phase prematurely after Timeout restart. When ssthresh is set much lower than the BDP in the case of “NR with SS (S)”, we see that the TCP
We further record the link utilization and the highest sequence number of the packet being sent for each case in Table I. By comparing the throughput, it is clear that an inadequate setting of \textit{ssthresh} affects greatly the transmission capability of short connections.

However, even the \textit{ssthresh} is set to match the BDP at the start, we found that \textit{cwnd} may still fail to reach the BDP as also reported by others in the literature \cite{50}. To illustrate the effect, we test a TCP connection whose initial \textit{ssthresh} matches the BDP and the buffer size is set to only 0.2 times of the BDP. The \textit{cwnd} and buffer utilization evolutions during the startup are plotted in Fig. 3.

As can be seen, as \textit{cwnd} reaches over 250 packets, the bottleneck buffer hits its maximum utilization and a small amount of packet drops is recorded. Since the TCP sender takes an RTT period to realize the packet loss, it continues to ramp up its \textit{cwnd} by doubling the value to over 400 packets resulting in significant packet drops.

Upon detection of the first triple duplicate ACKs, the TCP connection switches to Fast Recovery and cuts \textit{ssthresh} to just below 250. The increment of \textit{cwnd} stalls as only duplicate ACKs are returned. During this period, since \textit{cwnd} remains constant, the queue barely builds up in the buffer. Being unable to recover all lost packets, a Timeout event finally occurs at around 1.3s where \textit{cwnd} is set to 1 and \textit{ssthresh} is adjusted to just above 100, and the connection returns to Slow Start at a much lower \textit{ssthresh} value. At this point, the TCP connect has seriously underestimated the available bandwidth which results in significant underperformance. The cause of this problem is attributed to the failure of probing rate control when temporal queue buildup occurs in the bottleneck buffer.

**TABLE I**

| Protocol          | Link Utilization | Highest Sequence No. Sent |
|-------------------|------------------|---------------------------|
| NR with SS (L)    | 11.13%           | 5636                      |
| NR with SS (A)    | 87.50%           | 44249                     |
| NR with SS (S)    | 6.08%            | 3010                      |
III. RELATED WORKS

One critical problem of traditional Slow Start performance inefficiency is that TCP sender lacks the ability to estimate the network condition properly. To improve TCP startup performance, many approaches have been attempted in the past to achieve better estimation of network bandwidth availability and/or design a rate probing mechanism that is less susceptible to the accuracy of the bandwidth availability estimation. Generally, these efforts to enhance startup performance can be categorized into four different strategies...
A. The Rate Probing Refinement Approach

The rate probing refinement approach seeks modification of the cwnd ramping up behavior such that the increment of the probing rate is less susceptible to the accuracy of the initial guess of the bandwidth availability estimation. A typical example of this approach is the Limited Slow Start (LSS) [10] which uses an additional threshold to prevent the Slow Start algorithm from increasing too fast. It introduces a new Slow Start threshold, max_ssthresh, that prevents the probing rate from growing excessively high. Precisely, when cwnd ≤ max_ssthresh, cwnd doubles for each RTT as in the traditional Slow Start. When max_ssthresh < cwnd ≤ ssthresh, cwnd is increased by a fixed amount of max_ssthresh/2 packets for every RTT. This condition reduces the growth rate of cwnd which in turns reduces the number of drops described below.

- The rate probing refinement approach: In this approach, a TCP connection uses a different rate probing mechanism than the traditional one to achieve better utilization of available network bandwidth. Some proposed mechanisms also use dynamic rate probing mechanisms, where returned ACKs are used to indicate the network status and adjust the rate probing mechanisms.
- The bandwidth estimation approach: In this approach, a TCP connection performs an estimation of the network to assist rate probing. The estimation may perform continuously.
- The history-based approach: In this approach, a TCP connection uses historical data about the network resource availability cached by previous or concurrent connections to estimate the current network status and derive optimal parameters for the TCP connection to start.
- The router-assisted approach: In this approach, a TCP connection uses direct feedbacks from routers to indicate network resources and adjusts its sending rate accordingly.

Fig. 3. Ramping up behavior of NewReno with Slow Start (ssthresh=500pkts, Buffer Size=1/5BDP).
during the startup. However, the blind *ssthresh* setting problem remains unsolved with this approach. Other schemes based on a similar strategy such as CapStart [15] and Smooth-Start [12], [13] suffers the same shortcoming.

In [11], TCP Vegas has demonstrated that the packet delay at the bottleneck router can be estimated by observing the RTT of each packet transmission. This provides a better guidance for a TCP sender to either refine its rate probing strategy or adjust Slow Start parameters such as *ssthresh* to enhance its Slow Start performance. Based on the observed packet delay, TCP Vegas uses a different rate probing strategy, namely, it doubles *cwnd* every other RTT, and exits the Slow Start phase when the estimation of packet delay exceeds a certain threshold. This method, however, often leads to low bandwidth utilization due to premature exiting of Slow Start as a result of temporary queue buildup in the buffer caused by bursty TCP transmission [21]. Enhancing the usage of RTT information, Delay-base Slow Start (DBSS) [14] uses RTT information to adjust *max_ssthresh* which indirectly prevents *cwnd* from overshooting and avoid premature exiting of the Slow Start phase. However, it requires a threshold on RTT to function and setting of an appropriate threshold remains a challenge.

**B. The Bandwidth Estimation Approach**

The bandwidth estimation approach aims to solve arbitrary *ssthresh* setting problem by setting it to some estimated BDP value to mitigate the effect of overshooting while maintaining the original rate probing strategy. Bandwidth estimation is first introduced in [17] by using packet pair bandwidth measurement technique. Packet pair measurement uses the inter-arrival time between the ACK pair received at the source to infer the bottleneck bandwidth along the path. Based on this technique, Hoe [18] proposed to set initial *ssthresh* to the product of the measured delay and the estimated bandwidth. However, attribute to the aggressive *cwnd* increase manner, Hoe’s Change may suffer temporary queue overflow and multiple losses when the bottleneck buffer is not large enough compared to the BDP, or many flows are coexisting [21]. Several improvements based packet pair bandwidth measurement have been proposed to enhance Hoe’s method [19], [24], [25], [26], [39]. Nevertheless, evidenced in [27], [28], the packet pairs technique gives a reliable estimation of the bottleneck link capacity rather than an available bandwidth on a network path. Hence, only limited performance gain can be achieved.

Beside the packet pairs technique, the packet trains estimation measurement appears to be more reliable for the estimation of the instantaneous available bandwidth of a path. Early Slow Start Exit (ESSE) proposed in [23] uses observation from a series of ACK returning times to estimate the instantaneous available bandwidth and set the initial *ssthresh* value. Paced Start proposed in [40] further uses the
difference between data packet train dispersion and ACK train dispersion to interactively for bandwidth estimation and ssthresh setting. TCP Westwood uses Eligible Rate Estimation (ERE) [22] that relies on ACK train from receiver for bandwidth estimation. Adaptive Start [20] proposes using ERE to assist the Slow Start.

However, researches carried in [29], [30] have shown that the dispersion of long packet trains does not measure the available bandwidth in a path, rather, it tells another bandwidth metric known as Average Dispersion Rate (ADR), the value which is in between an available bandwidth and a capacity of the path. The direct use of the dispersion of long packet trains for available bandwidth measure may cause misleading estimation leading to undesirable performance. Inspired by these findings, Hybrid Slow Start [31] combines ACK train estimation and increase in packet delays in the the Slow Start algorithm for performance enhancement.

In summary, while these estimation techniques achieve a certain performance gain compared to Slow Start that uses arbitrary default ssthresh value, the performance gain is limited due to their accuracy in the estimation caused by various factors. One obvious factor is due to the additional manipulation of ACK replies in modern TCP operations, such as ACK clustering and compression [33], [52], Delayed ACK [51] are affecting the accuracy of bandwidth estimation. Other factors such as TCP coarse-grained clocks [34], rerouting [35] and route asymmetry between forward and reverse path also pose challenges to the accuracy of bandwidth estimation. Besides, even an accurate bandwidth estimation technique is achieved, this approach of using bandwidth estimation do not deal with and hence cannot resolve the temporal queue buildup problem.

C. The History-Based Approach

The history-based approach makes use of history information cached by previous or concurrent connections to improve Slow Start performance. It is based on the assumption that any hosts in the sub-domain would experience similar performance to distant hosts. Usually schemes fall into this catalog is intended for a restart transmission on connections that have been idle for a long time to benefit some certain applications (i.e., web browsing).

Transaction TCP [43], [44] caches previous connection count history in order to save the three-way handshake in certain situations to speed up future connection establishment. Expanding on the available historical information, TCP Control Block Sharing [48] and Congestion Manager [32] propose sharing of Slow Start related information among recent or concurrent TCP connections with the same end nodes.
Other incremental enhancements falling within this approach include TCP with Shared Passive Network Discovery (SPAND) or TCP/SPAND [47] [46] and Adaptive TCP Slow Start [45].

In summary, the historical-based approach makes use of historical information to help a new TCP connection tune to a more appropriate sending rate. However, the usefulness of the historical information may vanish quickly due to the fast changing load conditions in the network. Besides, this approach is unable to benefit TCP startup performance when historical information does not exist. For example, when a connection is established to a new destination, traditional Slow Start is adopted instead.

D. The Router-Assisted Approach

It is illustrated that assistance from routers for TCP rate control is effective to achieve high utilization of network bandwidth [38]. Measured directly at the routers, it offers accurate bandwidth availability utilization, and the role of rate probing algorithm can be significantly reduced. Quick-Start [36] and XCP [37] are some typical examples for this approach. In Quick-Start, a TCP sender advertises a desired sending rate during the three-way handshake to let the network (each hop along the path) approve, reject or reduce the requested sending rate. This way, a sender can quickly tune to an appropriate rate without the time consuming probing procedure. Comparatively, XCP proposes a more fine-grained feedback to TCP senders for them to decide their sending rates.

In summary, while the router-assisted approach gives potential to significantly improve the utilization of networks especially during the startup phase of a TCP connection, they require special operations in routers which prevents them from immediate deployment and thus their attractiveness is not high.

IV. THE ENHANCEMENT

We shall introduce a novel startup scheme, called SSthreshless Start, with the goal to address the two aforementioned problems in the traditional Slow Start. As discussed in Section III, with the accuracy limitation in the bandwidth estimation and the history-based approaches, and the deployment drawback in the router-assisted approach, we argue that the rate probing refinement approach remains a potential approach that can offer significant performance gain in Slow Start with immediate deployment. However, the main challenge of the rate probing refinement approach is the ability to quickly probe available bandwidth for the setting of the sending rate to ensure high utilization based on a certain bandwidth availability estimation translated into ssthresh setting. Recognizing the challenges in finding an optimal setting for ssthresh based on a certain bandwidth availability estimation and an adequate rate probing algorithm, we take a difference that bypasses the need for ssthresh. With this novel attempt, we design a
new startup scheme that not only achieves efficient sending rate, but also copes well with the temporal queue buildup problem. Owing to needless of ssthresh, we call our startup scheme threshold-less slow start or SSsthresholdless Start. We detail SSsthresholdless Start in the following subsections.

A. Backlogged Packet Detecting

TCP Vegas is known as a delay-based congestion control mechanism since it uses RTT for each packet transmission to estimate the backlog status of the buffer to adjust its congestion control strategy. Past research \cite{4,11} has shown that this estimation, in terms of the delayed packets due to buffering at the bottleneck router, leads to a more accurate estimation of network traffic load condition. Capitalizing on this effective estimation, we reuse this estimation mechanism in our proposed SSsthresholdless Start.

In TCP Vegas, the throughput difference is calculated by

$$\text{Diff} = (\text{Expected} - \text{Actual}) = \left( \frac{\text{cwnd}_{\text{BaseRTT}} - \text{cwnd}_{\text{RTT}}}{\text{BaseRTT}} \right)$$

where BaseRTT is the minimum of all measured RTT, and RTT is the actual round trip time of a tagged packet. Denote the delayed packets at bottleneck buffer by $N$, we have,

$$\text{RTT} = \text{BaseRTT} + \frac{N}{\text{Actual}}.$$

Rearranging the above equation, we obtain

$$N = \left( \frac{\text{cwnd}_{\text{BaseRTT}} - \text{cwnd}_{\text{RTT}}}{\text{BaseRTT}} \right) \times \text{BaseRTT}. \quad (1)$$

During startup phase we can use (1) to calculate the delayed packets at bottleneck buffer. This provides the information of backlog status for our SSsthresholdless Start.

B. SSsthresholdless Start

The key idea of SSsthresholdless Start is that it makes use of backlog status at the bottleneck buffer, monitored by RTT to refine the cwnd ramping up behavior and adaptively adjust probing rate to meet the available network capacity. Rather than translating the network status into ssthresh, the network status is directly used to control the rate probing algorithm.

We propose a two-mode operation in the rate probing procedure, namely, Linear Increase Mode and Adjustive Increase Mode, each mode is intended to operate in the situation when the queue buildup is detected or not detected, respectively. Recall that the estimated delayed packets number is $N$, a certain number of estimated delayed packets, $N \geq \beta$, can be used to signal a packet building up event at the
bottleneck router. The quantity $\beta$ is a design time protocol parameter for SSthreshless Start to switch between Linear Increase and Adjustive Increase modes. While $\beta$ is arbitrary set, we shall show that the Slow Start performance is insensitive to this threshold.

Based on (1), SSthreshless Start measures $N$, the estimation of backlog at the bottleneck router, and compares with the threshold $\beta$. If the estimated number of backlog packets exceeds $\beta$, we assume that the bottleneck router is experiencing packet building up. Once the backlog is clear below $\beta$, the TCP sender is said to have experienced one congestive event. In our scheme, the TCP sender monitors the congestive status and records the total number of congestive event experienced for rate probing purpose.

Each TCP connection begins with the binary exponential increase of $cwnd$ as in the traditional Slow Start. Different from the traditional Slow Start, each TCP continuously monitors the backlog packets. When the monitored number of the backlog packets exceeds $\beta$ indicating the occurring of packet building up, SSthreshless Start takes over the control of $cwnd$.

SSthreshless Start operates in either Linear Increase Mode or Adjustive Increase Mode, and it always starts in Linear Increase Mode. In Linear Increase Mode, the TCP connection increases its $cwnd$ by one for every RTT which confines the $cwnd$ increment to a linear rate. SSthreshless Start is activated when the estimated backlog packets exceeds $\beta$ for the first time, thus starting SSthreshless Start in this conservative increase manner helps clear temporary buildup by slowing down the transmission from the source to the buffer to avoid buffer overflow and multiple losses. SSthreshless Start remains in this mode as long as the monitored number of backlog packets exceeds $\beta$.

Once the monitored number of backlog packets falls below $\beta$, SSthreshless Start switches to Adjustive Increase Mode where $cwnd$ increment rate turns aggressive again. The aggressiveness of the increment also depends on the number of encounters of congestive events. In our design, the more congestive events a TCP connection encounters, the milder is the increment of its $cwnd$. This is because as $cwnd$ increases monotonically in either Linear Increase Mode or Adjustive Increase Mode, the likelihood of $cwnd$ reaching the available bandwidth also increases, and a milder increment in $cwnd$ should be used to prevent it from overshooting the available bandwidth causing serious losses.

Note that, different from Delay-based TCP startup schemes (i.e., TCP Vegas and DBSS), where delay-based information is used the find the threshold of exiting startup phase, SSthreshless Start uses backlog status to dynamically switch $cwnd$ ramping up behavior in an exponential-linear cycles, adaptively seizing the available bandwidth. SSthreshless Start exits when packet losses occur. The pseudo code of SSthreshless Start is given in the following.
Algorithm 1 SSthreshless Start

if (three DUPACKs are received)/*startup phase exits*/ then

  ssthresh=cwnd/2;

  Congestion_Event_No=0;

  Congestive_Status=0 // congestive status of last RTT;

  /*switch to Congestion Avoidance Mode*/

else

  if (N ≥ β) then

    Congestive_Status=1;

    cwnd+=cwnd; on each ACK

    /*Linear Increase Mode*/

  else

    if (Congestive_Status=1) then

      Congestion_Event_No++;

      Congestive_Status=0;

    end if

    cwnd+=max(1/cwnd, 1/2*Congestion_Event_No);

    for every ACK

    /*Adjustive Increase Mode*/

  end if

end if

In the above pseudo code, Congestion_Event_No indicates the times of congestive events occurred with its initial value set to 0. According to our design shown in Algorithm 1, the increment of cwnd in Adjustive Increase Mode is set between 1/cwnd and 1 for every ACK. In other words, for every RTT, cwnd is increased by a value between 1 and cwnd.

V. PERFORMANCE EVALUATION

In this section, we present numerical results of SSthreshless Start, compared with the tradition Slow Start and other variants, given different network environments with dissimilar parameter settings. We first evaluate the parameter setting of SSthreshless Start, then demonstrate the ramping up behavior and throughput advantages over other variants. Finally, we also show the fairness and friendliness of our
SSthreshless Start.

A. Parameter Setting

In Fig. 4 we vary the value of switch, $\beta$, to assess its sensitivity to the performance of SSthreshless Start. Surprisingly, varying $\beta$ does not cause much difference in the performance. We present in Table II the numerical details for the link utilization and highest sequence number of packets being sent for three different $\beta$ values from small to large. As can be seen from Table II, the performance difference is very small. This indicates that the value of $\beta$ is not a mainly decisive factor in the performance, which makes SSthreshless Start tolerable to the inaccuracy of TCP timers [53] [54], which affects the backlog estimation, and the setting of $\beta$.

As shown in Fig. 4, as $\beta$ goes large, the ramping up behavior is slightly more aggressive. To an extreme when $\beta$ is set to infinity, SSthreshless Start will behave like the traditional Slow Start since the congestive event can never occur. In contrast, when $\beta$ is set to a small value, the occurrence of the congestive event increases and $cwnd$ grows in a more conservative rate. Based on the past experiences [10], [12], conservative growth in $cwnd$ may significantly reduce burst losses, we thus suggest a smaller $\beta$ setting.

Fig. 4. SSthreshless Start $cwnd$ evolution under different values of $\beta$.

| $\beta$ | Link Utilization | Highest Sequence No. Sent |
|---------|-----------------|---------------------------|
| $\beta = 3$ | 82.15% | 41075 |
| $\beta = 10$ | 83.95% | 41973 |
| $\beta = 20$ | 85.39% | 42699 |
We recommend the setting of $\beta = 3$ as this setting gives conservative growth in $cwnd$ yet maintain a high link utilization as reported in Table II.

**B. SSthreshless Start Ramping up behavior**

Fig. 5 compares the single flow ramping up behaviors of SSthreshless Start, Slow Start and Vegas, along with the monitored backlog at bottleneck router. The buffer size is set to a small value of 200 packets, or $\frac{2}{5}$ of the BDP, and $stthresh$ of Slow Start is set to accurate value of BDP in this case.

Depending on the instantaneous backlog status, SSthreshless Start switches between exponential and linear rate to increase $cwnd$. It allows $cwnd$ to adaptively ramp up to the BDP in a timely manner. The $cwnd$ value reaches an eligible window size in around 2s, and maintains high link utilization ever since. By monitoring the backlog status, SSthreshless Start would have switched to a linear rate just before the occurrence of a packet loss that ends the SSthreshless Start operation, and this helps the Congestion Avoidance operation which takes over SSthreshless Start to cope with the loss.

In comparison, the aggressive Slow Start increases its $cwnd$ to the BDP size in around 1s. However, the temporary queue buildup occurs with packet drops and following Fast Recovery [3] fails to recover the multiple losses since Slow Start remains in exponential growth when losses occurred, and this causes a Timeout. Consequently, the $sshtresh$ is repeatedly adjusted downward to eventually a small value which forces the TCP connection to enter Congestion Avoidance phase prematurely. For Vegas, it also enters Congestion Avoidance prematurely right after backlog exceeds its threshold. Being too conservative, it manages to avoid multiple losses but operates in a very low throughput. Over the evaluation time shown in Fig. 5, neither Slow Start nor Vegas is capable of seizing the eligible BDP where majority of available bandwidth is left unused. As listed in Table III, SSthreshless Start captures as high as 80% of the link utilization, where Slow Start and Vegas utilize below 30%.

| Scheme       | Link Utilization | Highest Sequence No. Sent |
|--------------|------------------|----------------------------|
| NR with SLS  | 80.30%           | 40025                      |
| NR with SS (A)| 28.20%           | 14100                      |
| Vegas        | 22.35%           | 11173                      |

TABLE III

**Performance comparison of TCP startup schemes (Buffer=2/5BDP, first 10s).**
C. Throughput Comparison

In this subsection, we compare NewReno with SSthreshless Start (SLS), Hoe’s Change (HC), Limited Slow Start (LSS), Slow Start with small $ssthresh$, 32 packets (SS (S)), Slow Start with large $ssthresh$, 5000 packets, (SS (L)), and TCP Vegas. It shows that the SSthreshless Start significantly improves startup performance with regards to various buffer size, one-way delay, and bandwidth. To focus on the startup performance, we only evaluate the performance in the first 20 seconds. In addition, we use Throughput Ratio, calculated as the throughput of SSthreshless Start over other variants, as a measure to evaluate the performance enhancement of our proposal.

In Fig. 6, we fix the bandwidth to 40 Mbps, delay to 50 ms, and vary the buffer size from 100 packets to 300 packets to study impact of buffer sizes on the performance. In this case, we also evaluate the Slow Start with $ssthresh$ setting to the accurate BDP size, 500 (SS (A)), to show the buffer robustness of our proposal. It is evident that high throughput is achieved by our SSthreshless Start in all the test cases. Also as can be seen, when the buffer size is small, Hoe’s Change, Limited Slow Start and even Slow Start with $ssthresh$ set to accurate BDP suffer severe performance degradation. These startup algorithms fail to obtain a high throughput even with the help of ample buffer size. The case with a small buffer size, 1/5 BDP, is shown in Table IV. The performance benefit of SSthreshless Start is significant, which gains up to 3 to 14 times over other variants.

As aforementioned, one of characteristic of LFN is long link delay. Thus, to assess performance with long RTT, we vary the bottleneck one-way delay from 10 ms to 100 ms. The bandwidth and buffer size are fixed to 40 Mbps and BDP/2, respectively. Fig. 7 shows the throughput comparison under this scenario. The subtle changes in the throughput of NewReno with SSthreshless Start and Hoe’s Change shows their
Fig. 6. NewReno (NR) throughput versus buffer size (first 20s).

TABLE IV
PERFORMANCE COMPARISON OF TCP STARTUP SCHEMES (40Mbps BOTTLENECK BANDWIDTH, 50MS ONE-WAY BOTTLENECK DELAY, BUFFER SIZE=1/5BDP).

| Scheme       | Link Utilization | Throughput Ratio |
|--------------|------------------|------------------|
| NR with SLS  | 74.08 %          | 100.00%          |
| NR with HC   | 9.05%            | 820.77%          |
| NR with LSS  | 5.33%            | 1391.08%         |
| NR with SS (S) | 24.25%        | 305.46%          |
| NR with SS (A) | 19.02%        | 305.46%          |
| NR with SS (L) | 4.55%          | 849.00%          |
| Vegas        | 10.11%           | 271.34%          |

ability to scale well with long delay, while other startup algorithms suffer from performance degradation as delay increases. The case with largest tested one-way delay, 100 ms, is listed in Table V-C. Note that the throughput of SSthreshless Start achieves over 18 times that of the traditional Slow Start.

TABLE V
PERFORMANCE COMPARISON OF TCP STARTUP SCHEMES (40Mbps BOTTLENECK BANDWIDTH, 100MS ONE-WAY BOTTLENECK DELAY, BUFFER SIZE=1/2BDP).

| Scheme       | Link Utilization | Throughput Ratio |
|--------------|------------------|------------------|
| NR with SLS  | 83.35%           | 100.00%          |
| NR with HC   | 86.40%           | 96.70%           |
| NR with LSS  | 29.80%           | 280.40%          |
| NR with SS (S) | 6.55%          | 459.07%          |
| NR with SS (L) | 4.55%          | 1836.26%         |
| Vegas        | 10.11%           | 623.95%          |
To evaluate the performance of SSthreshless Start with respect to another characteristic of LFN, high bandwidth, we vary the bottleneck bandwidth from 10 Mbps to 150 Mbps. Besides, we fix the bottleneck one-way delay to 50 ms and buffer size to BDP/2. Fig. 8 reports on NewReno throughput achievements with different startup schemes under this scenario. It is shown that, NewReno with SSthreshless Start and Hoe’s Change scale well with a wide range of bandwidth. Other schemes lack the ability to adapt to network bandwidth effectively, leading to poor throughput achievements. The case with largest tested bandwidth, 150Mbps, is listed in Table V-D. Notably, SSthreshless Start outperforms the traditional Slow Start just over 35 times in terms of throughput.

D. Dynamic Bandwidth

Considering that available bandwidth may change several times during the startup phase of a TCP session under a dynamic environment (i.e., other connections may join or leave the link), a well-performed startup scheme should be aware of the instantaneous available bandwidth to adjust the cwnd ramping up strategy. To assess the capability of SSthreshless Start in the network with dynamic network load, we add a burst UDP cross-traffic set to 10 Mbps, starting at the first second and stopping at the fifth second. Fig. 9 shows the comparison of SSthreshless Start and Slow Start under this scenario.

During the first second, cwnd of SSthreshless Start ramps up just as usual. After initiating the burst of UDP traffic, SSthreshless Start detects the decrease of available bandwidth quickly through the backlogged queue, and accordingly, halves cwnd growth rate each time when congestive event happens. After reaching the available bandwidth, cwnd turns linear increment. Then, right after the termination of UDP traffic flow, SSthreshless Start detects the clearing up of bottleneck backlog and alternates cwnd growth rate back to exponential again. This simulation shows that the alternation between exponential and linear growth rate
of cwnd can cope well with dynamic changing bandwidth availability.

TABLE VI
PERFORMANCE COMPARISON OF TCP STARTUP SCHEMES (50MS ONE-WAY DELAY, 150Mbps BOTTLENECK BANDWIDTH, BUFFER SIZE=1/2BDP).

| Scheme       | Link Utilization | Throughput Ratio |
|--------------|------------------|------------------|
| NR with SLS  | 82.84%           | 100.00%          |
| NR with HC   | 90.58%           | 91.45%           |
| NR with LSS  | 51.54%           | 160.71%          |
| NR with SS (S) | 6.55%        | 1265.38%         |
| NR with SS (L) | 2.37%        | 3500.28%         |
| Vegas        | 10.11%           | 819.66%          |

On the other hand, due to the aggressive and blind increase strategy, Slow Start incurs losses upon the presence of UDP flow. Following Fast Recovery fails to recover the multiple losses which leads to a consequent Timeout.

In addition, to compare the transmission capability, the Link Utilization and the highest sequence number of packets being sent are recorded in Table VI-E. The amount of data SSthresholdless Start manages to send is almost two times larger than that of Slow Start. This makes SSthresholdless Start greatly benefit short flows, that lasts only for several seconds under a dynamic environment.

E. Friendliness to Slow Start

Fig. 10 shows the coexistence of multiple SSthresholdless Start and Slow Start connections. We consider five NewReno connections, in which connections 1 and 2 are NewReno with Slow Start (ssthresh = 32 packets) and connections 3, 4, 5 are NewReno with SSthresholdless Start. Connections 1, 2, 3, 4 start at 0
second to investigate the effect of SSthreshless Start and Slow Start startup at the same time. Connection 5 starts at 30th second to estimate the effect of SSthreshless Start on existing TCP connections. It is shown that SSthreshless Start utilizes network bandwidth left unused by Slow Start connections at the very beginning. After several rounds of synchronized packet losses, a window for each connection converges to a same value. When connection 5 joins the network, it does not adversely affect existing TCP connections. It is able to probing rate quickly to reach the state of other concurrent TCP connections. Finally, all five connections converge to the same window size, which is around 10 packet sizes or one-fifth of the BDP. Each connection utilizes its own share fairly, demonstrating the friendliness of NewReno with SSthreshless Start in bandwidth sharing with the traditional Slow Start.

TABLE VII

| Scheme        | Throughput (Mbps) | Highest Sequence No. Sent |
|---------------|-------------------|----------------------------|
| NR with SLS   | 27.73             | 34663                      |
| NR with SS (S)| 10.50             | 13126                      |
| Vegas         | 8.86              | 11080                      |

VI. CONCLUSIONS

In this paper, we present a novel sender-side enhancement, SSthreshless Start, to improve TCP startup performance in long fat networks. The key idea is to make use of backlog status at the bottleneck buffer, monitored by RTT to refine the cwnd ramping up behavior, dynamically and adaptively adjusting probing rate to reach the available bandwidth. By alternating between exponential and linear growth rates of
"cwnd" based on the backlog status, SSthreshless Start eliminates the need for the Slow Start threshold, \textit{ssthresh}, and the blind \textit{ssthresh} setting problem vanishes. The use of backlog status at the bottleneck buffer also allows SSthreshless Start to cope with various buffer sizes especially small buffer sizes that cause performance degradation in many TCP startup variants.

Simulation results demonstrated that, compared with traditional Slow Start and many other variants, SSthreshless Start significantly improves link utilization during startup phase, meanwhile shows good performances to a wide range of buffer size, propagation delay and bandwidth of bottleneck. Moreover, SSthreshless Start shows good convergence behavior without adversely affecting coexisting TCP connections. Therefore, being aware of backlog status, the enhanced throughput during startup phase is achieved by using the bandwidth effectively and fairly rather than aggressively depriving bandwidth from other co-existing TCP connections.

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