Performance simulation analysis of transport layer protocol for satellite network

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Abstract. This paper studies the performance of transport layer protocol in the design of satellite network. The main transport layer protocols proposed in recent years are analyzed, and the performance of different satellite application scenarios is compared and simulated. The results show that the corresponding transport layer protocol should be selected according to the process of building satellite network and the characteristics of transmission link can effectively improve the network transmission performance.

Keywords: satellite network, Performance simulation, transport layer protocol.

1. Introduction

Based on web browsing and file transmission are the main services of the current Internet. The traffic of such services is asymmetric, especially for Internet users. The amount of downlink data is much higher than that of uplink data, which is similar to the transmission link between satellite and ground, and these all belong to asymmetric transmission. Web browsing and file transmission are implemented based on TCP protocol in TCP / IP (Transmission Control Protocol / Internet Protocol) protocol suite. Although the service mode is asymmetric transmission, due to the high bit error rate and extended propagation time of satellite link, the direct application of ground TCP transmission protocol to satellite network will bring problems such as insufficient utilization of network bandwidth and poor real-time performance. Therefore, this paper first analyzes the inherent characteristics of satellite network transmission link, and then analyzes and simulates five kinds of transmission layer protocols mainly used in satellite network, including the improved TCP protocol versions TCP_Vegas, TCP_Hybla, TCP_Cubic, and SCPS-TP (Space Communication Protocols Specification-Transmission Protocol) proposed by CCSDS (Consultative Committee for Space Data Systems), and LTP (Licklider Transmission Protocol) proposed by DTNRG (Delay/Disruption-Tolerant Networking Research Group), to provide technical support for the engineering application of satellite Internet.

2. Satellite network features

Whether it is a near-Earth satellite network or a deep space satellite network, the satellite network has the following characteristics.

Large transmission delay: The disconnection of the network causes a long transmission delay, which can last for minutes, hours or even days. At the same time, the accumulation of node queues caused by network disconnection will also increase the transmission delay. As a result, various existing network protocols that rely on receiving reply messages in a short time cannot work normally.

(2) High bit error rate: The high bit error rate caused by unstable network environment and obstacles or weather conditions, the cost of point-to-point error correction in the network is much lower than that of end-to-end error correction. The number of retransmissions increases linearly from point to point rather than exponentially from end to end.

(3) Bandwidth asymmetry: the forward and reverse link bandwidth of satellite network are asymmetric, and the bandwidth of forward link is much larger than the reverse link bandwidth.

(4) Intermittent transmission: The network is often disconnected due to node movement or obstacles. Therefore, there is no traditional end-to-end connection between the source node and the
destination node. As a result, the TCP/IP protocol used in the traditional network cannot work. A new algorithm must be proposed to meet the requirements of satellite networks.

3. Introduction to existing transport layer protocol

3.1 SCPS-TP

The SCPS protocol was raised by CCSDS in 1999, including transport layer protocol SCPS-TP, which provides end-to-end data transmission services for space communication networks. SCPS-TP can provide the completely reliable service, best-effort reliable service and service without reliability assurance. The completely reliable service is provided by TCP. The best-effort reliable service is achieved through partial modification and expansion of TCP to adapt to variable space link with round-trip delay, asymmetric bandwidth, intermittent connection and other characteristics, so as to provide end-to-end data transmission for space communication network. The service without reliability assurance is provided by UDP(User Datagram Protocol). In order to overcome the problems of large transmission delay, easy link interruption, asymmetric uplink and downlink, and extremely low signal-to-noise ratio in deep space communication, SCPS-TP modifies and extends TCP in the following aspects:

1. The handshake signal in TCP Start phase is reduced to accelerate the start of data transmission;
2. The size of TCP window is expanded to meet the requirements of large space communication round-tip delay;
3. Round-trip delay can be measured;
4. The process of serial number for retransmission is protected;
5. With selective passive confirmation function (SNACK);
6. Packet headers are compressed to save overhead;
7. The protocol contains a rate-based mechanism which can directly control the transmission rate of the connection to prevent traffic congestion.

3.2 LTP

The LTP is a transmission protocol proposed by DTNRG, which provides reliable transmission based on retransmission for long RTT (Round-Trip Time) and frequently interrupted link environments. The following are important design concepts:

1. LTP introduces the concept of session. One LTP data block is sent per session, and the LTP suggests that as many sessions as possible can be opened according to link conditions, which means that more data blocks can be transmitted in parallel on the link.
2. LTP retransmits unconfirmed data.
3. LTP does not need to establish a connection.
4. LTP connection is unidirectional. Therefore, both parties communicating using the LTP will have to open two unidirectional connections.
5. LTP provides aggregation layer services for BP (bundle protocol) on the high-latency space communication links.

3.3 TCP_Vegas

In a large BDP (Bandwidth Delay Product) network, the time taken by TCP from connection establishment to reaching the optimal transmission rate has an important impact on the overall performance. If the window cannot approach BDP during slow start phase, it will take a long time to make full use of the network bandwidth during congestion avoidance phase, which will seriously reduce the working efficiency of TCP. And Vegas flexibly decides when to switch to the congestion avoidance phase according to the change of RTT, and quickly reaches a suitable transmission rate. Therefore, it can make full use of the available bandwidth and have better adaptability to network conditions. RTT is composed of various delays of data packets and acknowledgment packets, including transmission delay, propagation delay, queuing delay and other overheads. Generally, the
difference between RTTC and RTTBase is mainly reflected in the queuing delay determined by the network load condition, which is also the basis for Vegas to estimate the network bandwidth.

Slow start phase:

(1) Increase W by a factor of two every two RTTs, and then calculate δ. If δ is greater than γ, end the slow start phase, reduce W by 1/8, and transfer to the congestion avoidance phase.

(2) The previous RTT is exponential growth, that is, every time a confirmation packet is received, 1 will be added, and two data packets will be sent at the same time, which can be called growth period. The last RTT remains unchanged to observe the change of RTT, which is called the observation period.

(3) The Vegas slow start phase consists of a growth period and an observation period. At the end of each observation period, new RTTC and δ are calculated to decide whether to continue the next cycle or end the slow start phase.

(4) Ideally, the slow start should end when W is close to BDP when the throughput reaches the maximum; If affected by some factors, δ is greater than γ when w is smaller, the exponential growth of W will end prematurely, and the transmission efficiency will be seriously reduced. The slow start ended early because RTTC exceeded RTTBase when w was still small:

\[ \frac{W \cdot RTT_c - RTT_{\text{Base}}}{RTT_c} > \gamma \]

During the growth period of slow start, the data packets are sent intensively in a short time, resulting in a temporary increase of RTT and an early end of slow start.

Congestion avoidance phase:

(1) Two thresholds are used α and β (α<β), W is adjusted once after each RTT:

\[ W_{\text{new}} = \begin{cases} W_{\text{old}} + \delta & \text{if } \alpha < \delta < \beta \\ \text{unchanged} & \text{else} \end{cases} \]

If α<δ<β, W remains unchanged.

(2) Vegas does not end the slow start phase according to the packet loss situation or the preset window upper limit, but determines when to end the exponential growth of the crowded window according to the actual network conditions. Such a mechanism can make the sending rate close to the available network bandwidth in the slow-start state as much as possible under the premise of avoiding congestion, and quickly achieve high throughput.

(3) In congestion avoidance phase, Vegas adjusts the congestion window in a timely and gentle manner to keep it stable near the optimal value without severe oscillation.

3.4 TCP_Hybla

The protocol aims to solve the problem of TCP performance degradation in long delay network (satellite network) introducing a number of measures such as enhanced control of slow start and congestion avoidance phases, the use of alternative validation mechanisms and use new parameter:

\[ \rho = \frac{\text{RTT}}{\text{RTT}_0} \]

Where ρ is normalization delay, RTT is real round-trip delay, and RTT0 is round-trip delay of reference TCP connection.

The Congestion control strategy rules when hybla receives the acknowledgement packet are as follows:

\[ cwnd_{i+1} = \begin{cases} cwnd_i + 2^\rho - 1 & \text{slow start phase} \\ cwnd_i + \frac{\rho^2}{cwnd_i} & \text{congestion avoidance phase} \end{cases} \]

3.5 TCP_Cubic

Cubic uses a cubic function, and a concave and convex growth curve will appear during the window adjustment process, depending on the time interval of two consecutive congestion events.
making the window growth completely independent of the network delay RTT. So Cubic can maintain good RTT fairness between multiple TCP connections sharing a bottleneck link.

Algorithm description:

When a congestion event occurs, Wmax is set to the window value when congestion occurs at this time, and then the window will be multiplicative decreased by factor $\beta$. When it exits from the fast recovery phase and enters congestion avoidance phase, the window growth of Cubic will grow according to the "concave" growth curve until the window grows to Wmax again. Then, the function turns to the "convex" growth stage. The growth of this method can keep the window near Wmax all the time, so that the high utilization rate of the network bandwidth and the stability of the protocol itself can be achieved.

(2) The growth function of the window is as follows:

$$ W(t) = C \ast (t - K)^\beta + W_{\text{max}} $$

Where C and $\beta$ are constants, T indicates the time difference between the current time and the reduction of the previous window, K is the time period during which the function increases from $w$ to Wmax. Cubic calculates the window growth rate in the next RTT, that is, $W(t+\text{RTT})$ using this algorithm, after receiving the confirmation message. This value will be used as the target value of cwnd. According to the size of cwnd, Cubic will enter three different modes. If cwnd is less than the window size that should be reached after the last congestion (this value is calculated through the window growth function of standard TCP), cubic is in the standard TCP mode. If it is less than Wmax, it is in the concave stage. If it is greater than Wmax, it is in the convex stage.

4. Simulation platform

4.1 Introduction to the experimental scene

In order to compare the protocol performance of LTP, SCPS-TP, TCP_Vegas, TCP_Hybla, and TCP_Cubic in the space link with long delay, high bit error and channel asymmetry, the following network experiment platform is established. Figure 1 shows the topology of the network experiment platform. From the physical point of view, the network experiment platform directly connects three computers together using network cables. Among them, both computers are equipped with two 10M/100M/1000M adaptive Ethernet cards. In the network experimental platform, the ground station serves as the data transmitting source node, the satellite is used as the data receiving node, and the network analyzer is used to simulate different delay and link packet loss environments.

![Figure 1. Network experiment platform topology](image)

4.2 Experimental parameter setting

Table 1 shows the main protocols and parameter configurations in the experiment. The downlink bandwidth is set to 10Mbps, and the uplink bandwidth is set to range from 20 Kbps to 10 Mbps, that is, the bandwidth ratio changes from 500:1 to 1:1. The bit error rate varies from 10-5, 10-6 to 0. The link delay varies from 0 to 135 milliseconds. The spacecraft transmits a 10 MB file to the ground station, and the ground station counts the transmission rate under different protocol configurations and different channel conditions.
Table 1. Parameter configuration

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol configuration</td>
<td>LTP, scpstp, tcp-cubic, tcp-hybla and tcp-vegas</td>
</tr>
<tr>
<td>Uplink rate</td>
<td>20kbps, 50kbps, 100kbps, 1mbps</td>
</tr>
<tr>
<td>Downlink rate</td>
<td>10mbps</td>
</tr>
<tr>
<td>Bit error rate</td>
<td>0, 10⁻⁵, 10⁻⁶</td>
</tr>
<tr>
<td>Transmission delay</td>
<td>0ms, 3ms, 10ms, 30ms, 50ms, 80ms, 135ms</td>
</tr>
<tr>
<td>file size</td>
<td>10MB</td>
</tr>
</tbody>
</table>

5. Simulation results and analysis

The protocol performance of LTP, SCPS-TP, TCP_Vegas, TCP_Hybla and TCP_Cubic in space link with long delay, high error code and channel asymmetry is compared from uplink rate, downlink rate, bit error rate and link delay.

5.1 Effect of link delay on protocol performance

Under the same link symmetry ratio and no bit error link condition, the change of link delay has different degrees of impact on LTP, SCPS-TP, TCP_Vegas, TCP_Hybla and TCP_Cubic protocols. As the link symmetry ratio is different, the effect of link delay on protocol performance is also different. Therefore, we will analyze the effect of link delay on protocol performance through the two cases of symmetric link and asymmetric link.

For the symmetric link case, the impact of link delay on protocol performance will be discussed. Figure 2 shows the performance of each protocol, when the uplink rate is 10Mbps, the downlink rate is 10Mbps, and the bit error rate is 0. Overall, although with the increase of link delay, the black line representing LTP is always below the line of SCPS-TP and other types of TCP, indicating that the downlink rate of LTP is lower than that of other protocols. The reason is that LTP has no congestion control and flow control mechanisms, so the packet transmission rate of the LTP based on UDP needs to be controlled manually. In this experiment, the maximum packet transmission rate of LTP is about 6Mbps. When the packet transmission rate is too fast, a large number of packets will be lost, which makes LTP retransmit frequently and seriously affects its performance. Finally, the transmission rate is lower than that of TCP class protocols.

LTP transmission rate is consistently maintained at around 6Mbps performance throughout the delay process, while the transmission rate of SCPS-TP and TCP class protocols decreases greatly, indicating that LTP transmission performance is easily affected by link delay. The reason is that both SCPS-TP and TCP class protocols have congestion control and flow control mechanisms. When the link delay increases, the transmission of data and acknowledgment packets will be affected. Especially when the acknowledgment packet is affected, the buffer occupied by the sent data in the sending window will not be released, and new data cannot be filled into the sending window, even causing the sending to timeout. The sender will think that the data packet is lost and the network has been congested. In this case, SCPS-TP and TCP class protocols will enter the fast retransmission and fast recovery phase, reducing the transmission window and retransmitting lost packets to reduce the transmission rate. The LTP based on UDP has no congestion control and flow control mechanisms and maintains a constant packet sending rate. Even if the delay increases, it will not affect the LTP sending window, but will only retransmit the unacknowledged data packets, and the transmission rate will decrease slightly with small impact.

It can be concluded that for the interstellar link with long delay, the performance of LTP protocol will be better than that of SCPS-TP and TCP class protocols. With the increase of link delay, the impact on the performance of SCPS-TP and TCP class protocols will continue to increase, while the impact on LTP is small, and finally the performance of LTP protocol will be better than SCPS-TP and TCP class protocols.
5.2 Effect of delay on protocol performance in asymmetric link

When the uplink rate is 20kbps, the downlink rate is 10Mbps, the bit error rate is 0, and the link symmetry ratio is 500:1, the performance of each protocol is shown in Figure 3.

In asymmetric links, especially when the link ratio reaches 500:1, the uplink rate is seriously limited because transmission window is seriously limited according to the congestion control mechanism of SCPS-TP and TCP class protocols. At this time, the increase of link delay has become a secondary factor affecting the transmission performance of the protocol. It can be seen from the figure that the transmission rate of SCPS-TP and TCP class protocols is stable in this situation maintained low level at about 1Mbps. The LTP protocol based on UDP without congestion control and flow control mechanism can maintain a constant and relatively high transmission rate. LTP can establish and hold multiple sessions in different data transmission phase at the same time to ensure the transmission rate.

It can be concluded that in the condition of asymmetric link and variable link delay, the performance of LTP protocol is better than SCPS-TP and TCP class protocol.

5.3 Effect of link symmetry ratio on protocol performance

In the case of the same link delay with no error code, the change of link symmetry ratio has different degrees of influence on LTP, SCPS-TP, TCP_Vegas, TCP_Hybla and TCP_Cubic. With the difference of link bit error rate, the impact of link symmetry ratio on protocol performance will also change. Therefore, we will analyze the impact of link symmetry ratio on protocol performance under the two link conditions with no bit error and with bit error.

(1) Under the link with no bit error, the impact of link symmetry ratio on protocol performance is shown in Fig.4. The link bit error rate of Fig. a, Fig. b and Fig. c is 0; The link symmetry ratios in
figure a, b, c are 1:1, 100:1 and 500:1. In order to study the impact of link symmetry ratio on protocol performance, we will compare the transmission rates in the three figures in the same link delay under different link symmetry ratios to judge the protocol performance.

In the case of symmetric link, the transmission performance of SCPS-TP and TCP class protocols is better than that of LTP. As the increase of link delay, the performances of SCPS-TP and TCP class protocol both tend to decrease, while LTP remains almost constant. With the increase of link symmetry ratio, the performance of SCPS-TP and TCP class protocols decreases sharply. Therefore, in the interstellar link with drastic changes in link symmetry ratio, the transmission performance of LTP protocol is relatively stable and changes smoothly. The reason is that LTP adopts the session mechanism without establishing a connection. Each transmission data unit is a short session occupied a block. In order to make full use of the uplink bandwidth, multiple sessions can be established for parallel in one transmission task, That is, LTP increases the cache capacity occupied by the session in exchange for link utilization.

Therefore, in the case of symmetric links, due to the large uplink bandwidth, the number of sessions that LTP needs to establish when completing a transmission task will be relatively small. However, in the case of asymmetric links, due to the reduction of uplink bandwidth, LTP protocol needs to establish more sessions when completing a transmission task to maintain a certain transmission rate. With the increase of link symmetry ratio, the number of sessions established by LTP increases. LTP can maintain a certain transmission rate and make full use of link bandwidth by above mechanisms, so its transmission performance relatively is stable and changing smoothly.

However, SCPS-TP and TCP class protocol must establish a connection to complete a transmission task. Each pair of communication ports maintains a connection for a long time, and the buffer for transmitting data during the connection process is a window. In the case of link symmetry, the uplink bandwidth is relatively large, and the sending window of SCPS-TP and TCP class protocols will be relatively large. While with the increase of the link symmetry ratio and the uplink bandwidth decrease, SCPS-TP and TCP class protocols will reduce the size of the send window leading to the sending rate reduced, thereby affecting the transmission performance.

![Figure 4. Effects of different link symmetry ratios on performance under no error link conditions](image-url)
(2) Effect of link symmetry ratio on protocol performance with bit error

As shown in Fig.5, the link bit error rate of Fig. a, b, c is $10^{-6}$. The link symmetry ratios of Fig. a, b, c are 1:1, 100:1 and 500:1. In order to study the effect of link symmetry ratio on protocol performance, the link delay of the same interval in the three graphs is taken to compare the transmission rate in the three graphs and judge the protocol performance under different link symmetry ratios. As can be seen from the figure, in the case of high bit error rate, the performance of LTP protocol in figure a, b, c is generally better than that of SCPS-TP and TCP class protocol. In the case of high BER, frequent loss and packet loss have a great impact on the performance of TCP protocol. In comparison, the impact of asymmetric link environment on its performance is almost negligible. With the increase of link symmetry ratio, the protocol transmission performance of SCPS-TP and TCP class protocols decreases significantly, while the performance of LTP is stable and changes smoothly. The impact of link symmetry ratio on the protocol is the same in the case of no error code.

(a) The link symmetry ratio is 1:1    (b) The link symmetry ratio is 100:1

(c) The link symmetry ratio is 500:1 respectively

Figure 5. Effect of link symmetry ratio on performance with bit error link

(3) Effect of link bit error rate on protocol performance

Under the condition of the same link delay and symmetry ratio, the change of link bit error rate affects the performance of LTP, SCPS-TP and TCP_Vegas, TCP_Hybla, TCP_Cubic to varying degrees. Fig.6 shows the link symmetry ratio of Fig. a, b, c is 1:1 and the link bit error rates of Fig. a, b, c are 0 and $10^{-6}$ and $10^{-7}$. In order to study the effect of link bit error rate on protocol performance, the link delay in the same interval in the three figures are chosen to compare its transmission rate to determine the pros and cons of protocols under different link bit error rates.

It can be seen from the figure that under the condition of no bit error, the transmission rate of SCPS-TP and TCP class protocols exceeds 6Mbps, while the transmission rate of LTP protocol remains about 6Mbps. In the case of bit error rate is $10^{-6}$, when the delay time is less than 10ms, the transmission rate of SCPS-TP and TCP class protocols is still larger than LTP, while the delay time exceeds 10ms, the performance of TCP class protocols decreases sharply, and SCPS-TP is lower than that of LTP after 110ms. When the bit error rate reaches $10^{-5}$, SCPS-TP can compete with LTP in
performance when the delay time is less than 15ms, and then performance of LTP is far ahead of other protocols.

It can be concluded that the transmission performance of LTP protocol changes gently and stably with the increase of link bit error rate; The transmission performance of SCPS-TP and TCP like protocols decreases sharply. The reasons are:

Each block of LTP consists of red or green. Green requires no confirmation, that is, transmission Green uses a transmission mode similar to UDP and the link bit error rate has little impact on the transmission rate. But for SCPS-TP and types of TCP protocol, high bit error rate will lead to large amount of data packets to pass, will affect the rate performance of protocol;

LTP is parallel transmission based on session. Even if the BLOCK of LTP contains RED which needs to be confirmed, the LTP protocol will not affect the transmission of subsequent packets because it does not confirm the part of packets discarded due to error codes. However, SCPS-TP and TCP class protocols occupy a large number of packets in send-window cache due to a high bit error rate. If the subsequent packets cannot enter the sending window cache, the transmission rate of the protocol will be affected.

LTP has no congestion control mechanism and can maintain a constant packet sending rate. However, TCP class protocol will enter the fast-recovery phase because link congestion due to a large number of error-code packet loss. The transmission window will be rapidly reduced, which ultimately affects the transmission rate of TCP class protocols.

![Figure 6. Effect of link bit error rate performance under link symmetry](image)

In the long delay, high bit error and asymmetric interstellar link network, compared with SCPS-TP protocol and TCP like protocol, LTP protocol has stable transmission performance and is the preferred transport layer protocol of spatial integrated information network protocol stack in the future. For short delay, low bit error and symmetrical ground networks, TCP like protocol has obvious performance advantages.
6. Conclusion

This paper compares the transmission performance of LTP, SCPS-TP and three kinds of TCP protocols in space network. The TCPs protocol family has obvious performance advantages for short delay, low error and symmetrical link environment; SCPS-TP reflects better transmission performance, for the near-Earth space link environment; LTP transmission protocol reflects better Transmission performance, for the interstellar link environment with high bit error, long delay, and link asymmetry.

References


