

Transport Protocols in Deep Space Communication

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ABSTRACT

Reliable data transmission is key to deep space communication for high propagation delays, high link error rates, asymmetrical channel bandwidth and intermittent connectivity. After a brief introduction to the research background of deep space communication, the challenges and solutions to deep space transport protocols are discussed while presenting different solutions in detail. The theory and the performance are analyzed, and the future work of deep space transport protocol is presented.

Key words: deep space communication; transport protocol; asymmetrical bandwidth; intermittent connectivity

I. INTRODUCTION

Over the past 20 years the Consultative Committee for Space Data System (CCSDS)^[1] has brought forward a series of deep space communication standards. The Jet Propulsion Laboratory (JPL)^[2] has been researching the InterPlaNetary Internet^[3-10] by integrating many space stations into the deep space networks. All deep space missions need to transfer the science data. However, current transport protocols have very poor performance in deep space communication. Therefore, there is a need for devel-

oping reliable transfer protocols for deep space network which is characterized by extremely high propagation delays, link errors, asymmetrical channel bandwidth and intermittent connectivity.

The remainder of the paper is organized as follows: in section 2 we present the most relevant aspects of transport protocol and network architecture for deep space communication. The existing transport protocols have been shown to improve performance for deep space communication network. Section 3 discusses the theory and performance analyses of the existing classic transport protocols in deep space communication. Section 4 outlines possible future research directions.

II. ARCHITECTURE AND CHALLENGES

A typical architecture of deep space network^[12,13] is shown in Fig.1. It includes two parts: interplanetary backbone network and planetary network. The backbone network includes the links or multi-hop paths among the outer-space planets, relay station and the Earth. The Planetary network is composed of a planetary satellite network and planetary surface network.

The reliable data transport can be completed by using traditional TCP in the planetary surface network. However, the major challenges for deep space network are listed as follows:

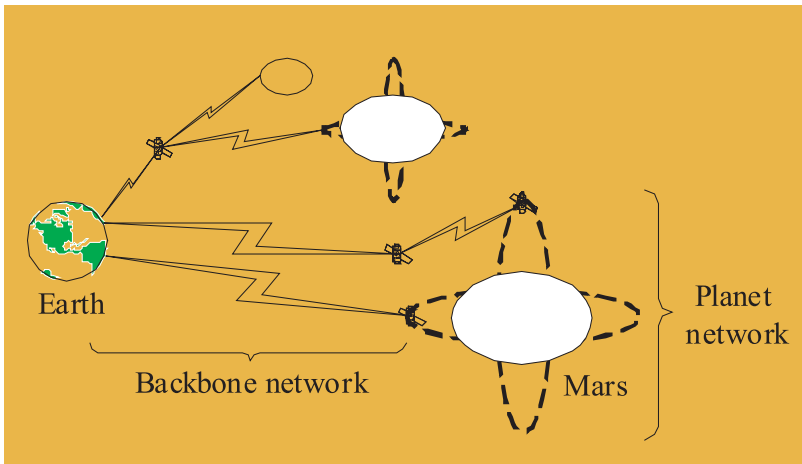


Fig.1 Deep space network architecture

assumptions. For example, continuously available bi-directional connection exists between source and destination to support end-to-end interaction. The max RTT is on the order of ms. The links have relatively little loss or data corruption. Considering the performance of TCP on the deep space network, we can see that conventional TCP is not suitable for deep space.

[14-16]

1. Long Propagation delays: The end-to-end round trip time(RTT) for the LEO network varies from 40 ms to 50 ms. The RTT of Geo-stationary Earth Orbit (GEO) is about 550ms, However, both of them are still very low compared to deep space communication links. For example, the distance from the Earth to the Mars is more than 60 million kilometers with the RTT from 8 to 40 minutes approximately. And the RTT from the Earth to the Jupiter is between 81.6 and 133.3 minutes while to the Pluto is between 593.3 and 1044.4 minutes
2. Transmission Errors: The current satellite bit error rates (BER) are high on the order of 10^{-6} on average and 10^{-4} at worst case. The BER on the backbone links are usually much higher than 10^{-2} .
3. Asymmetry Channels: Many satellite systems offer users with a download capability at tens of Mb/s^[9] but the upload capability is only hundreds of kbps. The ratio of forward and reverse channels on the backbone channel bandwidth capacity is typically on the order of 10^{-3} . In some conditions, the reverse channel bandwidth capacity is even zero.
4. Blackouts: Because of the movement of planetary bodies and spacecraft, the periodic link outage may occur.

The conventional TCP protocol which is window-based additive-increase multiplicative-decrease congestion control depends on some important

Because the currently existing TCP/IP protocols have been designed to operate efficiently over the Earth surface network, its system framework is inherited by deep space network naturally and logically in people's mind.^[9] Based on the deep space communication environment characteristics, some improved protocols have been brought forward as follows:

2.1 Long delay

Increasing the initial window^[17]: The initial size of the congestion window is changed between one and four. The slow start time can be decreased by $3 \cdot RTT$.^[9] However, the utilization of links resource is inefficiency for the satellite network and backbone network.

TCP for Transactions (T/TCP)^[18]: T/TCP cuts out much of the unnecessary handshaking and error detection of the TCP protocol and as a result increases the speed of connection and reduces the necessary bandwidth. This improves the performance of small data transaction.

Path MTU Discovery (PMTU-D)^[19]: It is to send packets that are as large as possible while still avoiding fragmentation. This improves the efficiency of packets transmission and the increase speed of the congestion window control size.

Scaled windows and timestamps options^[20]: Scaled windows option alters window size from 16 bits to 32 bits. It enhances the throughput of satellite links, but brings the PAWS phenomenon. In^[21], the throughput

of TCP over satellite links achieves 100 Mbps. Timestamps option avoids the PAWS phenomenon.

Vegas^[22]: Different from the other TCP protocols, Vegas deploys a proactive approach. It tries to predict when congestion is about to happen and adapts its window to compensate. It attempts to reduce its sending rate before packets start being discarded by the network. Vegas can achieve more than 37% better throughput than the Reno.

TCP spoofing^[23]: The objective of spoofing involves an isolating long latency link by introducing a middle agent which splits the TCP connection. Spoofing is a transparent splitting of a TCP connection between the sender and receiver by some entity within the network path. The responsibility of the middle agent is to inter-accept, cache, and acknowledge data received by the sender and then forward these data to the receiver. Spoofing is beneficial to large file transfers over long delay link.

Fast Start^[14]: The Idea of fast start is to directly use the corresponding transmission speed based on the recent experience of the transmission on the network. The basic idea is that the sender caches network parameters to avoid paying the slow start penalty for each page download. However, there is a risk of performance degradation if the cached information is stale. First, to shield the ill-affection producing by stale information in the whole network, packets sent during the fast start phase are assigned a higher drop priority than other packets. Second, to prevent the connection attempting fast start from experiencing degraded performance under such adverse conditions,^[10] the loss recovery procedure of standard TCP is improved by new algorithms.

Sudden start^[25, 26]: Sudden start is based on the use of dummy packets, which are low-priority packets that do not carry any new data to the receiver. It requires the routers along the connection to implement some priority mechanism at the IP layer. The sudden start algorithm in detail is listed as follows: during the first RTT, the sender transmits a data packet the first and (rwnd-1) dummy packets. In the second RTT, the ACKs related to the data and

dummy packets transmitted in the time interval $0 < t < \text{RTT}$ arrive at the sender. For any received ACK related to a dummy packet, the sender increases its cwnd by 1 and transmits a new data packet.

2.2 Coping with high BER

Explicit Congestion Notification (ECN)^[27]: The TCP Explicit Congestion Notification (ECN) feature provides a method for an intermediate router to notify the end hosts of impending network congestion. It also provides enhanced support for TCP sessions associated with applications that are sensitive to delay or packet loss. The benefit of this feature is the reduction of delay and packet loss in data transmissions. Its disadvantage is that the routers must support the ECN option.

Link corruption notification^[28]: The receiver maintains a weighted moving average of the number of corruption packets received and transmits a link corruption state when the average exceeds a threshold. According to the link corruption notification, the sender adjusts the send rate. The sender invokes congestion control in response to packet loss and uses an open-loop, token bucket rate control mechanism for bit-errors packet loss.

2.3 Coping with asymmetric bandwidth

Periodic acknowledgment^[28]: The receiver relaxes the requirement that TCP immediately acknowledge every packet received. Instead, the receiver delays acknowledgments for a configurable period of time that is related to its estimate of the RTT. The difficulty is how many RTT delays are determined to send ACKs.

ACK Congestion Control and ACK Filter (ACC and AF)^[29]: ACKs occupy slots in the reverse channel buffer. The solution is to use the RED algorithm at the gateway of the reverse link to aid congestion control. The gateway detects incipient congestion by tracking the average queue size over a time window in the recent past. If the average exceeds a threshold, the gateway selects a packet at random and marks it. This notification is reflected to the sender of the

packet by the receiver. Upon receiving a packet with ECN set, the sender reduces its sending rate. ACK filter is a gateway-based technique that decreases the number of TCP ACKs sent over the constrained channel by taking advantage of the fact that TCP ACKs are cumulative.

SACK Options^[30]: SACK is a strategy which corrects its behavior in the face of multiple dropped packets. With selective acknowledgments, the receiver can inform the sender about all packets that have arrived successfully, so the sender need retransmit only the segments that have actually been lost. SACK options fit to deep space network communication.

2.4 Coping with link outage

Zero NIX ACK Option^[32]: During blackout, the receiver keeps sending NIX ACKs with low and high priority. The objective of NIX ACKs is to help the sender to capture accurate information on the blackout situation and take corresponding actions. The performance can be improved in the blackout conditions

III. ANALYSIS EXISTING TRANSFER PROTOCOLS

The theory and performance of transfer protocols in deep space networks are listed as follows:

3.1 Planet satellite network

Satellite Transport Protocol (STP)^[40,41]: STP extends TCP for satellite networks. Overcoming long delay, STP deploys the SACK option and the newreno congestion control scheme. In^[41] shows the average performance of network throughput reducing 10% when RTT is changed between 20 and 600ms. Dealing with the high BER, STP employs the AAL type 5 CRC. To support better mobility in the network layer, the STP checksum does not cover the IP header. Periodically, the sender sends a POLL packet to the receiver. The receiver detects the packet loss and notes the sender's retransfer.

The utilization of reverse channel bandwidth is chosen by the POLL periods. STP shows good performance in a rate controlled environment, even when the BER is severely degraded.

TCP-Peach^[26]: TCP-Peach is composed of two new algorithms, namely Sudden Start and Rapid Recovery. The new algorithms are based on the novel concept of using dummy packets to probe the availability of network resources without carrying any new information to the sender. Dummy packets which are marked low-priority do not effect the delivery of actual data traffic. TCP-Peach+^[25] combines the SACK option and TCP-Peach which uses NIL packets together. The performance of TCP-Peach+ is better than TCP-Peach and achieves fairness as well in satellite IP networks.

3.2 Planet backbone network

Space Communications Protocol Standards-Transport Protocol (SCPS-TP)^[46]: SCPS-TP is SCPS's underlying retransmission control protocol, optimized to provide reliable end-to-end delivery of spacecraft command. The SCPS-TP is based on the well-known Internet Transmission Control Protocol (TCP). To achieve the good transfer performance, SCPS-TP adopts some existing options in TCP, such as window scaling, to improve bandwidth utilization in the presence of long propagation delays. However, it also incorporates other new features, such as selective negative acknowledgement to increase throughput by accelerating the retransmission of packets received in error, header compression to reduce bandwidth overhead, and "best effort" service to deal with loss or impairment of acknowledgement traffic. Another significant improvement related to SCPS-TP is the way it handles channel noise. SCPS-TP is designed to differentiate between the two situations and allow for optimum packet transmission rates under all conditions of channel noise and network congestion.

Transport Protocol for InterPlaNetary Internet (TP-Planet)^[32]: TP-Planet is introduced by Ozgur

B. Akan in 2004. The Algorithm adopts the rate-based AIMD congestion control mechanism. It runs on top of IP layer and does not require any specific modification to the lower layers in the current TCP/IP suite. It deploys two novel algorithms: Initial State and Steady State. Initial State replaces the inefficient slow start algorithm and is composed of two main procedures, i.e., Immediate Start and Follow-Up. In 1st RTT, TP-Planet source sends low priority NIL segments to probe the availability of network resources. In 2nd RTT, source sends both low and high priority NIX segments to gain the steady state to send rate. Four states, hold rate, decrease rate, increase rate and blackout constitute the Steady State Algorithm. By receiving the NIX segments ACK, source adjusts the sending rate. The steady state throughput of the rate-based generic AIMD congestion control mechanism can be expressed as follows

$$T(\alpha, \xi, \sigma, p) = \frac{\alpha \cdot \left[1 + \xi + \sqrt{(3 - \xi)^2 + \frac{8 \cdot (1 - \xi^2)}{\alpha \cdot \sigma \cdot p}} \right]}{4 \cdot (1 - \xi)}$$

Where α is the additive-increase parameter and ξ is the multiplicative-decrease factor and P is the packet loss probability and σ is the round-trip time.

Using the rate-based AIMD congestion control scheme, TP-Planet can avoid the network throughput decreasing. It imports a blackout state part to improve 14 percent of transfer performance and adopts delayed SACK options to solve bandwidth asymmetry. At the Backbone Network, TP-Planet can achieve performance improvement over the traditional TCP. TP-Planet requires that the routers must support QoS services. It lacks the blackout of very long delay transfer and the cooperation of planet satellite network.

IV. CONCLUSIONS

There are two main issues in the current research of the deep space communication protocols, the

complicated characteristics of deep space environment and the lack of systematic research method. The deep space environment results in several problems: 1) How to obtain a precise measurement of RTT. The rotation and movement of the planets and the secondary satellites, and the long-distance timing synchronization all bring non-negligible effects to the measurement of RTT, which degrades the performance of the transmission protocols. 2) In intermittent connectivity, TP-Planet and SCPS-TP can improve the throughput of the deep space communication, however, in a very long distance case e.g. the Jupiter, the negative impact of intermittent connectivity on the throughput will decrease the performance of the current existing protocols. Therefore it is necessary to improve the existing backbone protocols such as TP-Planet.

Recently, it has been found that the deep space transmission performance not only relates to the transmission layer, but also relates to the bottom layer. For examples, the routing information in the link layer has effect on the utilization ratio of the deep space channel and because of the limited power and the processing ability of the deep space node, the cross-layer cooperation can improve the performance. In the case of end-to-end transmission, the mechanism of the current protocols of space backbone and that of the planet network are different, either of which is optimized for its own network. Consequently, there exist problems in the cooperation of sub networks. Hence in order to improve the performance it is required to consider the whole deep space network jointly, which is a hotspot in current research.

In the paper we first introduce several problems in deep space communication protocols and also discuss the advantages and disadvantages of each improved protocol. The performance and theory of existing transfer protocols in deep space networks are analyzed by referring the aspects of the extended TCP and a brand-new protocol.

Finally, we point out several research fields of the optimization for protocols of deep space

communications. There are many issues requiring investigation including the model of the deep space communication network, and the high-efficiency cross-layer framework with extendible support.

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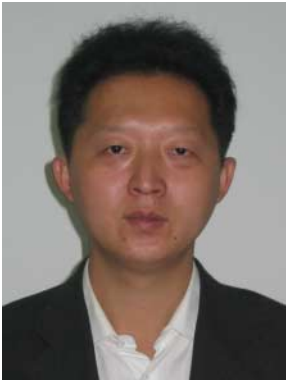
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