An Experimental Study of Checkpoint (CP) Timer of Licklider Transmission Protocol for Energy-Efficient Deep-Space Communications

Zhiyang Shi[1], Ruhai Wang[2*], Kanglian Zhao[3], Siwei Peng[1], Han Hu[2], Yu Zhou[1], and Lei Yang[1]

[1]School of Electronics and Information Engineering, Soochow University, Jiangsu, P. R. China
[2]Phillip M. Drayer Department of Electrical Engineering, Lamar University, Beaumont, TX, USA
[3]School of Electronic Science and Engineering, Nanjing University, Jiangsu, P. R. China

[*]Corresponding Author: Ruhai Wang
Phone: 1-409-880-1829
Fax: 1-409-880-8121
Email: rwang@lamar.edu

Abstract

As the main data transport protocol of delay-/disruption-tolerant networking (DTN), Licklider transmission protocol (LTP) is developed to provide reliable and highly efficient data delivery over unreliable deep-space communication channels. A checkpoint (CP) segment of LTP is sent, with a timer set (simply, CP timer), to check the arrival status of the entire data block at the receiver, and it is retransmitted upon the expiration of the CP timer prior to reception of an acknowledgment. Little work has been seen in analysis of the CP timer for optimal performance of LTP in energy-efficient, reliable data delivery. In this paper, a packet-level analysis of the CP timer setting is presented for reliable data delivery of LTP over unreliable deep-space communication channels based on realistic file transfer experiments conducted using a PC-based testbed. It is our intent to find an optimal CP timer setting so that the reliable file delivery in deep space is ensured with the minimum number of retransmission attempts taken. By this, the energy-efficient, reliable data delivery of LTP can be achieved in deep-space communications.

Index Terms—Satellite Communications, Space Communications, Deep-Space Communications, Space Networks, DTN, Licklider Transmission Protocol (LTP)

I. INTRODUCTION

Extensive work has been done in the past decade in developing space networking architectures and protocols for their application in satellite/space communication networks (including deep-space communications) and similar scenarios, [1-6]. A good number of literature surveys and tutorials [7-10] are also available on them. Developed as one of the main data transport protocols of delay/disruption tolerant networking (DTN) architecture [11-13], the Licklider transmission protocol (LTP) [14, 15] is intended to provide reliable data delivery service in interplanetary solar system Internet (SSI) [16]. In comparison, LTP is a more widely-adopted protocol for reliable and highly efficient data delivery over unreliable space communication channels that are characterized by frequent and random link interruptions and/or very long delay.

For reliable file delivery using LTP, the last segment of each LTP data block is flagged as a checkpoint (CP) intended to check the arrival status of the entire block at the receiver which is either successfully delivered or lost/corrupted. The CP segment serves as both a data segment and a control segment. Therefore, it is transmitted with a timer set and its acknowledgment (ACK) expected. The ACK for a CP segment (actually for an entire block) is termed as a report segment (RS). The CP segment is necessarily retransmitted after the CP Timer [15] expires prior to reception of the RS.

Because the CP timer length determines when the lost segments and CP segment of a block should be retransmitted, its setting is very important for reliable data delivery of LTP for space communications. It is more challenging with the presence of the channel-rate asymmetry which characterizes space communications [17]. This is because the slow ACK channel rate of the asymmetric channel configuration introduces delay to the transmission of ACKs (i.e., RSs for LTP), leading to the increase of the end-to-end round-trip time (RTT) and the total data/file delivery time. If the CP timer length is too short, it might expire too early with respect to the estimated length of RTT, particularly with the additional delivery latency (introduced by channel-rate asymmetry) taken into effect. This will result in unnecessary and frequent retransmissions of data blocks from the LTP sender.

Power energy available on a spacecraft is widely recognized as scarce resource, especially for a deep-space spacecraft. Energy consumption is always an important issue to be considered in deep-space flight. With respect to the energy consumption for data/file delivery in deep-space communications, each retransmission attempt for one or more data blocks of a file surely consumes more energy for presenting an individual data byte onto the channel. Therefore, it is reasonable to estimate an extra number of LTP transmission efforts (or simply, retransmission attempts) taken for successful file delivery as it reflects the amount of additional energy resource consumption of LTP for file delivery.

The extra number of transmission efforts of LTP are basically determined by the retransmission of LTP data blocks (or segments) which is actually controlled by the setting of its CP timer. A longer CP timer can lead to longer waiting time prior to retransmission. The setting of a longer CP timer can avoid unnecessary retransmissions of the blocks and reduce the number of retransmission efforts needed. This is especially significant for those blocks that are actually received successfully but the corresponding RSs are delayed due to the slower ACK channel rate. As a result, the setting of a longer CP timer length may lead to the reduction of the energy consumption of LTP for successful delivery of an entire file.

In this paper, we present an analysis of the CP timer setting for reliable file delivery of LTP over unreliable deep-space communications channels. Based on realistic file transfer experiments conducted using a PC-based testbed, packet-level analysis of the CP timer setting is presented for LTP in deep-space communications. It is intended to set the CP timer in such a way that the reliable file delivery is ensured with the minimum number of retransmission attempts taken. By this, the energy consumption of LTP for successful file delivery is reduced, leading to energy-efficient deep-space communications service.

A series of studies have been done jointly by the NASA's Jet Propulsion Laboratory (JPL), California Institute of Technology and other research teams for DTN in space. While some of them are done for BP [18-23], extensive studies are done for LTP [24-30]. However, among all these previous studies done for LTP, no work has been done in analyzing its CP timer setting for energy-efficient file delivery in deep-space communications characterized by asymmetric channel rates.

The remainder of this paper is organized as follows. In Section II, we provide an overview of the CP timer setting in a scenario characterized by highly asymmetric channels rates. In Section III, the experimental infrastructure and protocol/transmission configurations are discussed. The numerical results of the file transfer experiments over the testbed and packet-level analysis are presented in Section IV. Summary and conclusions are presented in Section V.

II. LTP Data Transmission with CP Timer Setting over Highly Asymmetric Channels

For reliable file delivery of LTP and data encapsulation using the communication service of BP/LTP architecture, a file conveyed by data bundle(s) is first fragmented into multiple data blocks for transmission. See [30, Fig. 1] for an illustration of the data encapsulation and fragmentation process of BP/LTP protocol stack. The transmission of a single block is organized as an independent "session" operating as a sequence of data segment exchanges between the sender and the receiver [15, 31].

As discussed earlier, the last segment of a block is transmitted with a CP flag. A CP segment is intended to trigger the receiver for checking all the segments of the block for data loss or transmission error. If none of the segments are lost or with error, the received segments are reassembled into the original block. Then, the receiver acknowledges to the sender by returning a positive acknowledgment, i.e., an RS, to confirm the successful, cumulative reception for the block.

To ensure reliable delivery of CP and RS, both segments are transmitted with a timer set, leading to two important timers, *CP timer* and *RS timer*. These two countdown timers are set to detect a possible loss of the CP segment and RS segment and to retransmit them as necessary, respectively. The CP timer is actually the timeout timer for retransmission of a CP segment.

It is broadly recognized that highly asymmetric channel rates generally characterize space communications. Specifically, it means that the uplink channel rate deployed for ACK transmission (generally from the Earth to the spacecraft or another planet) is much lower than the downlink channel rate deployed for data transmission in the opposite direction [17]. Because of the much lower ACK channel rate, the time taken by the receiver to transmit an RS (i.e., the transmission time of RS) is even longer than the transmission time of a block at the sender. In this case, before the RS for the *current* block is completely transmitted, all the segments of the *next* block already arrive at the receiver, with its CP checking the status of the entire block. Hence, even assuming that all the segments of *next* block are successfully delivered, its corresponding RS can't be sent until the RS for the *current* block is completely transmitted. This leads to the waiting time for transmission of the current RS. If there are many blocks to be transmitted at the sender, the waiting time resulted for the many blocks (especially those sent at the end of the file transmission) will be dramatically long. This will lead to significant increase of the file delivery time and thus performance degradation of the file transmission.

In view of the highly channel-rate asymmetry which leads to the delay of the RS transmissions and thus monotonical increase of the RTT, the CP timer setting is important for transmission efficiency of LTP over the deep-space communication channel.

III. Overview of Experimental Infrastructure and Configurations

The analysis of the CP timer presented in this paper is done based on realistic file transfer experiments conducted using a PC-based testbed. The testbed infrastructure adopted for the proposed file transfer is the PC-based space communication and networking testbed (SCNT) [24]. The protocol implementation, LTP, used for the experiments was adopted from the Interplanetary Overlay Network (ION) distribution v3.6.2. ION is a software implementation of the DTN protocol suite for space networks and deep-space communications, developed by the NASA's JPL, California Institute of Technology [32].

A one-way delay of 1.35 s, which is common over a cislunar channel, was introduced to each of the data and ACK channels, to emulate the signal propagation delay in deep space. For the sake of comparison, the experiments with both the symmetric channel an asymmetric channel are studied. In the case of symmetric channel, both the downlink channel rate and uplink channel rate are configured to be 2 Mbps.

In the case of asymmetric channel, the downlink channel rate is kept as 2 Mbps while the uplink channel rate is reduced to 4 Kbps, leading to a high channel ratio (CR) of 500/1. In other words, for the transmission with asymmetric channels, the transmission rate of LTP data blocks is 2 Mbps and the transmission rate of RS segments in the opposite direction is 4 Kbps.

A text file of 1 Mbyte is transmitted by running LTP over the testbed to measure the performance of the protocol. With the bundle aggregation capability available with the ION distribution, the file transmission is configured to have five bundles aggregated within each LTP block. The length of each bundle is 1000 bytes. Given that the Ethernet is adopted to provide link layer framing service in our experiments, the aggregated block is fragmented as data segments with each segment of 1400 bytes. By this, the segment even after encapsulation process at the LTP and IP layer, with a length of 1460 bytes, is still able to fit in a frame MTU of 1500 bytes at the data link. The data of each segment is set as 100% red for transmission reliability.

IV. NUMERICAL EVALUATION RESULTS OF LTP TRANSMISSIONS

In this section, the numerical performance results of the file transfer experiments over the testbed are presented. The discussion focuses on the effect analysis of the CP timer using the time sequence graph (TSG) and goodput graph [33]. The impacts of both symmetric channel and asymmetric channel configurations are also considered. A comparison of the goodput performance among multiple CP timers is also presented.

A. *Analysis of CP Timers for LTP Transmissions over Symmetric Channel*

In Fig. 1, a TSG is presented to illustrate the LTP transmission at packets (or segments) level for delivery of a file of 1 Mbyte over an emulated symmetric cislunar channel with a BER of 0 experienced. The TSG is generated using the traffic dumped at the sending node for the file delivery. Provided that the one-way link delay of 1.35 s is configured, the CP timer is set to be 4 s which is greater than the estimated RTT.

It is observed from Fig. 1 that the entire file of 1 Mbyte is transmitted in a linearly increasing time sequence of data segments with continuous LTP block transmission. The corresponding RSs from the data receiver are also transmitted in the same linearly-increased pace as the blocks. This leads to nearly consistent length of RTT for each of the blocks. This observation indicates that the RS transmission is not delayed because of the symmetric channel rate.

The operation of the LTP's bundle aggregation and one RS (i.e., ACK) per block mechanism can be viewed from the TSG at packet level. Fig. 2 shows an enlarged view of the TSG for transmission of two blocks in the middle of the file. As mentioned, the file transmission is operated with five bundles aggregated within each LTP block, with the configured bundle size of 1000 bytes and the size of each aggregated block of 5000 bytes. For the block fragmentation, with each encapsulated segment of 1460 bytes, each block should be divided into four segments according to $\left\lceil \frac{5000}{1460} \right\rceil$. The last one out of all four segments is expected to carry slightly fewer number of data bytes than other three. This is exactly what the data transmission line of the TSG shows in Fig. 2. Following the one RS per block policy, the entire block of four segments is acknowledged by a single RS segment as illustrated. For a detailed discussion of the LTP's bundle aggregation and one RS per block mechanism, refer to [31].

The time gap (over the x-axis) between each block and its corresponding RS segment in Fig. 2 is around 2.8 s. This is consistently the measured RTT interval for this two blocks and all other blocks of the file. This is reasonable given that the one-way propagation link delay is set as 1.35 s with other time components such as processing time and possible queue time considered. Because the CP timer length (of 4 s) is longer than the estimated RTT of 2.8 s for each block, the RS is received by the block sender and thus no need to retransmit the CP segment. Therefore, there is no retransmission of any segment observed between the TSG data line and RS line in Fig. 1 and Fig. 2.

Goodput of a data transport protocol is commonly adopted as a good measure of its application data transmission efficiency. Fig. 3 illustrates the corresponding goodput variation trend measured for the TSG presented in Fig. 1. Corresponding to the linear-type of increase of the data block line in Fig. 1, a smooth and consistent increase in goodput is achieved. It is observed that the goodput keeps increasing until the channel capacity is reached around 2 s. After that, the data segments are transmitted in a more controlled manner so that the channel capacity is fully utilized but not overflowed, leading to consistently high goodput. This attributes to the rate-based transmission mechanism of LTP. The transmission continues until the end of the entire file. It turns out that the averaged goodput performance for the transmission approaches to 220 Kbytes/s.

In summary, for the LTP transmission over symmetric channel, because of no delay in RS transmission, the configured short CP timer length of 4 s is longer than the estimated RTT of 2.8 s for each block. As a result, the RS is received by the block sender prior to the expiration of the CP timeout timer and thus no need to retransmit the CP segment. In other words, only the original transmission of the blocks is able to ensure the successful delivery of the entire file.

B. Analysis of CP Timers for LTP Transmissions over Asymmetric Channel

For LTP transmission over asymmetric channel, as mentioned in Section I, the delayed RS transmission and increase in the RTT are expected because of the slower ACK channel rate. In this case, the setting of the CP timer is important for high transmission efficiency of LTP. If the CP timer is set to be too short, it might expire too early with respect to the estimated length of RTT, resulting in transmission performance degradation. Therefore, for the proposed file transmission experiments over asymmetric channel, a wide range of the CP timers are adopted to measure their performance variation trend.

Fig. 4 presents a comparison of the numerical goodput performance of LTP in transmitting a file of 1 Mbyte with various lengths of the CP timer with highly asymmetric channel rates (with the CR of 500/1) and BER of 0 experienced. The goodput performance of LTP with five CP timer lengths in a broad range is compared, including 4 s, 12 s, 20 s, 28 s, and 36 s. The selection of the timer starts from 4 s because it is already experimented over symmetric channel and works well in the case of no RS delay experienced. With the effect of the asymmetric channel taken into consideration, the estimated RTT length is expected to increase. For this reason, much longer CP timers (12-36 s) are adopted.

It is observed in Fig. 4 that the goodput increases along with the increase of the CP timer length until reaching to 28 s. While the performance improvement is significant in the region of short and medium CP timer lengths (< 28 s), there is no obvious performance change observed for the transmissions with a longer timer between 28 s and 36 s. This indicates that an optimal setting of the CP timer in the given transmission condition should be around 28 s or higher. It further means that a CP timer length of 28 s is able to avoid the retransmissions of the CP segments for each block which experiences the excessive delay for the RS due to the channel-rate asymmetry.

Fig. 5 illustrate the TSG for the LTP transmission done with the CP timer length of 4 s presented in Fig. 4. Similar to the TSG for the transmission with the symmetric channel rates in Fig. 1, both the data blocks and RSs are transmitted in a continuous manner. However, unlike the transmissions with the symmetric channel rates, the slope rate of the RS transmission line is obviously much lower. This is because the transmission of the RS segments for all the LTP blocks (except the first one) experiences delay. The delay is due to the longer transmission time of an RS for each block caused by the significantly reduced ACK channel rate. This delay is accumulated along with the transmission of the blocks. For this reason, the delay experienced by the RS segments grows linearly. Therefore, how long the delay is resulted for an individual block depends on the total number of blocks generated to convey the entire file. In other words, for a very large file which is carried out by a large number of LTP blocks, the blocks that are transmitted later experience longer delay for the transmission of their RS segments than those sent earlier. This leads to varying lengths of RTT for the blocks—the measured RTT is around 2.8 s for the first block while it is close to 23 s for the last block.

The retransmission events of the CP segments increase along with blocks transmission and the increase of the RTT. They are shown as vertical line segments in parallel between the block transmission line and the initially transmitted RS line in Fig. 5. As observed, the CP segments are only retransmitted one time for the sets of blocks at the beginning but they are retransmitted for four times for the last sets of blocks of the file.

Fig. 6 illustrates the corresponding goodput variation trend measured for the TSG presented in Fig. 5. As in Fig. 3, a drastic increase in goodput is observed at the beginning which corresponds to the process of filling out the channel capacity. After that, a consistently high goodput is achieved until the entire file is transmitted. These two phases of the goodput variation are in response to the line-type of increase of the original block transmission in the TSG in Fig. 5 until around 5 s. After that, because of frequent retransmission events of the CP segment for the aforementioned reason, the goodput drops exponentially until the fourth retransmission of the CP segment for the last block of the entire file. The fourth retransmission of the CP segment for the last block is done around 25 s.

As discussed, according to the numerical performance comparison in Fig. 4, the CP timer length around 28 s is very likely long enough to serve as optimal CP timer. As a verification, its TSG is illustrated in Fig. 7. In comparison, both the data block and RS transmission lines and their trends are similar to those for the original RS transmissions in Fig. 5. However, because of the much longer length of CP timer, there is no retransmission of CP segments (and RS segments) observed during the entire course of file transmission of 1 Mbyte. This occurs even though the transmission of the RS segments experiences delay and the delay increases along with the transmission of the blocks. This is because their RS segments arrive at the sender prior to the expiration of the CP timer. In other words, even though with the RS delay involved, the CP timer is longer than the resulted length of RTT for those blocks. Therefore, the corresponding RS segments are received by the sender before their CP timers expire. As the RS segment is received prior to the expiration of the CP timer, there is no need to resend the CP segment for the respective block. This is credited to the configured CP timer length of 28 s, which is longer than the estimated length of RTT for all the blocks, even for the last block which has an estimated RTT length of 23 s.

The observation in Fig. 7 serves as an evidence for that the configured CP timer length of 28 s is able to avoid the retransmissions of the CP segments for each block which experiences the excessive delay for the RS.

The removal of all the retransmitted CP and RS segments from the entire file transmission by setting the CP timer to the optimal length is significant to reduce the unnecessary traffic over both data and ACK channels. This is especially important for an efficient usage of the reduced channel-bandwidth resource in a scenario characterized by highly asymmetric channel rates.

Another important observation is the change of the total time taken for successful file delivery among all three transmission cases. The total file delivery time for the transmission with CP timer length of 28 s in Fig. 7 is only around 28 s. It is much shorter than the time of around 50 s in Fig. 1. This is another indication that the CP timer length of 28 s is considered optimal with respect to the transmission performance of file delivery time, in addition to the significant reduction of the number of retransmitted CP and RS segments.

V. SUMMARY AND CONCLUSIONS

In this paper, an experimental packet-level analysis of the CP timer setting is presented for reliable data delivery of LTP over an experimental infrastructure. The experimented communication environment is configured as a deep-space scenario characterized by a link delay equivalent to cislunar links. For the LTP transmission over symmetric channel, because of no delay in RS transmission involved, the configured short CP timer length (of 4 s) is longer than the estimated RTT for each block. As a result, the RS is received by the block sender prior to the expiration of the CP timeout timer and thus no need to retransmit the CP segment.

For the transmission with a highly asymmetric channel, if file transmission is configured with a short CP timer length (4-24 s), the transmission of the acknowledging RS segments for the LTP blocks experiences delay caused by the significantly reduced ACK channel rate. As a result, the RS segments for the blocks are not received by the sender within the estimated interval of RTT which leads to retransmission of their CP segments upon the expiration of the CP timer. The number of the retransmission events of the CP segments increase along with the transmission of the blocks. The optimal CP timer length which can avoid the transmission delay of RS and lead to the best goodput performance is around 28 s. Any increase of the CP timer length beyond this optimal one does not further reduce the retransmission events of the CP segments and therefore, does not bring additional advantages with respect to the goopdut for the file delivery.

With an optimal CP timer of 28 s configured for a transmission, even in presence of the long delay of RS transmission, the RS segments for all the blocks of the file are received by the sender before their CP timer expires. Therefore, all those CP and RS segments that are resent for transmissions with a shorter timer are removed which reduces the energy consumption of LTP transmission.

REFERENCES

[1] J. Jiao, Q. Guo, and Q. Zhang, "Packets Interleaving CCSDS File Delivery Protocol in Deep Space Communication," *IEEE Aerospace and Electronic Systems Magazine*, vol. 26, No. 2, February 2011, pp. 5-11.

[2] M. De Sanctis, T. Rossi, M. Lucente, M. Ruggieri, and D. Mortari, "Space system architectures for Interplanetary Internet", *IEEE Aerospace Conference* 2010, Big Sky (MT, USA), 6-13 March 2010.

[3] T. Rossi, M. De Sanctis, E. Cianca, C. Fragale, M. Ruggieri, and H. Fenech, "Future space-based communications infrastructures based on High Throughput Satellites and Software Defined

Networking”, 1st *IEEE International Symposium on Systems Engineering* (ISSE) Conference, Rome, Italy, Sept. 29-30, 2015.

[4] M. De Sanctis, T. Rossi, M. Lucente, M. Ruggieri, D. Mortari, and D. Izzo, "Flower Constellation of Orbiters for Martian Communication", *IEEE Aerospace Conference* 2007, Big Sky (MT, USA), March 3-10, 2007.

[5] I. Bisio, G. Araniti, M. De Sanctis, “State of the Art and Innovative Communications and Networking Solutions for a Reliable and Efficient Interplanetary Internet,” *International Journal on Advances in Internet Technology*, vol. 3, No. 1, Feb. 2010, pp. 118-127.

[6] I. Bisio, C. Garibotto, F. Lavagetto, A. Sciarrone and S. Zappatore, “Blind Detection: Advanced Techniques for WiFi-Based Drone Surveillance,” *IEEE Transactions on Vehicular Technology*, vol. 68, No. 1, pp. 938-946, Jan. 2019.

[7] R. Wang, T. Taleb, A. Jamalipour, and B. Sun, “Protocols for reliable data transport in space Internet,” *IEEE Communications Surveys and Tutorials*, vol. 11, No. 2, Second Quarter 2009, pp. 21-32.

[8] G. Araniti, I. Bisio, and M. De Sanctis, “Towards the Reliable and Efficient Interplanetary Internet: a Survey of Possible Advanced Networking and Communications Solutions”, In *Proc. of the First International Conference on Advances in Satellite and Space Communications* (*SPACOMM* 2009), Colmar (France), 2009, pp. 30-34.

[9] I. Bisio, G. Araniti, and M. De Sanctis, “Interplanetary Networks: Architectural Analysis, Technical Challenges and Solutions Overview”, In *Proc. of the IEEE International Conference on Communications* (*ICC*) 2010 (Cape Town, South Africa), pp. 1-5.

[10] M. De Sanctis, T. Rossi, M. Lucente, M. Ruggieri, and D. Mortari, "Space system architectures for Interplanetary Internet", *IEEE Aerospace Conference* 2010, Big Sky (MT, USA), 6-13 March 2010.

[11] S. Burleigh, A. Hooke, L. Torgerson, K. Fall, V. Cerf, R. Durst, K. Scott, and H. Weiss, “Delay-tolerant networking: An approach to inter-planetary Internet,” *IEEE Communications Magazine*, vol. 41, No. 6, pp. 128–136, Jun. 2003.

[12] The Space Internetworking Strategy Group (SISG), “Recommendations on a strategy for space internetworking,” IOAG.T.RC.002.V1, Report of the Interagency Operations Advisory Group, NASA Headquarters, Washington, DC 20546-0001, USA, August 1, 2010.

[13] Consultative Committee for Space Data Systems, “Rationale, scenarios, and requirements for DTN in space,” CCSDS 734.0-G-1. Green Book. Issue 1. Washington, DC, USA: CCSDS, August 2010.

[14] S. Burleigh, M. Ramadas, and S. Farrell, “Licklider Transmission Protocol-Motivation,” IRTF Internet Draft, Oct. 2007.

[15] M. Ramadas, S. Burleigh, and S. Farrell, “Licklider Transmission Protocol Specification,” Internet RFC 5326, Sept. 2008.

[16] Consultative Committee for Space Data Systems, “Solar system internetwork (SSI) architecture,” CCSDS 730.1-G-1. Green Book. Issue 1. Washington, DC, USA: CCSDS, July 2014.

[17] A. Sabbagh, R. Wang, K. Zhao, and D. Bian, "Bundle Protocol Over Highly Asymmetric Deep-Space Channels," *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, April 2017, pp. 2478-2489.

[18] K. Zhao, R. Wang, Scott C. Burleigh, Alaa Sabbagh, Wenwei Wu, and Mauro De Sanctis, "Performance of Bundle Protocol for Deep-Space Communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 52, No. 5, October 2016, pp. 2347-2361.

[19] R. Wang, M. Qiu, K. Zhao, and Y. Qian, "Optimal RTO Timer for Best Transmission Efficiency of DTN Protocol in Deep-Space Vehicle Communications," *IEEE Transactions on Vehicular Technology*, vol. 66, No. 3, March 2017, pp. 2536-2550.

[20] A. Sabbagh, R. Wang, S. Burleigh, and K. Zhao, "Analytical Framework for Effect of Link Disruption on Bundle Protocol in Deep-Space Communications," *IEEE Journal on Selected Areas in Communications special issue on Advances in Satellite Communications*, vol. 36, No. 5, May 2018, pp. 1086-1096.

[21] R. Wang, A. Sabbagh, S. Burleigh, M. Javed, S. Gu, J. Jiao, and Q. Zhang, "Modeling Disruption Tolerance Mechanisms for a Heterogeneous 5G Network," *IEEE Access special section on New Waveform Design and Air-Interface for Future Heterogeneous Networks toward 5G*, vol. 6, May 2018, pp. 25836-25848.

[22] G. Yang, R. Wang, A. Sabbagh, K. Zhao, and X. Zhang, "Modeling Optimal Retransmission Timeout Interval for Bundle Protocol," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, No. 5, October 2018, pp. 2493-2508.

[23] R. Wang, A. Sabbagh, S. Burleigh, K. Zhao, and Y. Qian, "Proactive Retransmission in Delay-/Disruption-tolerant Networking for Reliable Deep-Space Vehicle Communications," *IEEE Transactions on Vehicular Technology,* vol. 67, No. 10, October 2018, pp. 9983-9994.

[24] R. Wang, S. Burleigh, P. Parik, C-J Lin, and B. Sun, "Licklider Transmission Protocol (LTP)-based DTN for cislunar communications," *IEEE/ACM Transactions on Networking*, vol. 19, No. 2, April 2011, pp. 359-368.

[25] Q. Yu, R. Wang, Z. Wei, X. Sun, and J. Hou, "DTN Licklider Transmission Protocol (LTP) over Asymmetric Space Channels," *IEEE Aerospace and Electronic Systems Magazine*, vol. 28, No. 5, May 2013, pp. 14-22.

[26] K. Zhao, R. Wang, S. Burleigh, M. Qiu, A. Sabbagh, and J. Hu, "Modeling Memory Variation Dynamics for the Licklider Transmission Protocol in Deep-Space Communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, No. 4, October 2015, pp. 2510-2524.

[27] Q. Yu, R. Wang, K. Zhao, W. Li, X. Sun, J. Hu, and X. Ji, "Modeling RTT for DTN Protocols over Asymmetric Cislunar Space Channels," *IEEE Systems Journal*, vol. 10, No. 2, June 2016, pp. 556-567.

[28] Z. Yang, R. Wang, Q. Yu, X. Sun, M. Sanctis, Q. Zhang, J. Hu, and K. Zhao, "Analytical characterization of Licklider Transmission protocol (LTP) in cislunar communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, No. 3, July 2014, pp. 2019-2031.

[29] G. Yang, R. Wang, S. Burleigh, and K. Zhao, "Analysis of Licklider Transmission Protocol (LTP) for Reliable File Delivery in Space Vehicle Communications with Random Link Interruptions," *IEEE Transactions on Vehicular Technology*, vol. 68, No. 4, April 2019, pp. 3919-3932.

[30] G. Yang, R. Wang, K. Zhao, X. Zhang, W. Li, and X. He, "Queueing Analysis of DTN Protocol in Deep-Space Communications," *IEEE Aerospace and Electronic Systems Magazine*, vol. 33, No. 12, December 2018, pp. 40-48.

[31] R. Wang, Z. Wei, Q. Zhang, and J. Hou, "LTP Aggregation of DTN Bundles in Space Communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 49, No. 3, July 2013, pp.1677-1691.

[32] S. Burleigh, "Interplanetary overlay network design and operation v3.6.2," JPL D-48259, Jet Propulsion Laboratory, California Institute of Technology, CA, March 2019, [Online]. Available: http://sourceforge.net/projects/ion-dtn/files/latest/download.

[33] TCP Connection Analysis Tool: TCPTRACE, [Online] https://linux.die.net/man/1/tcptrace.

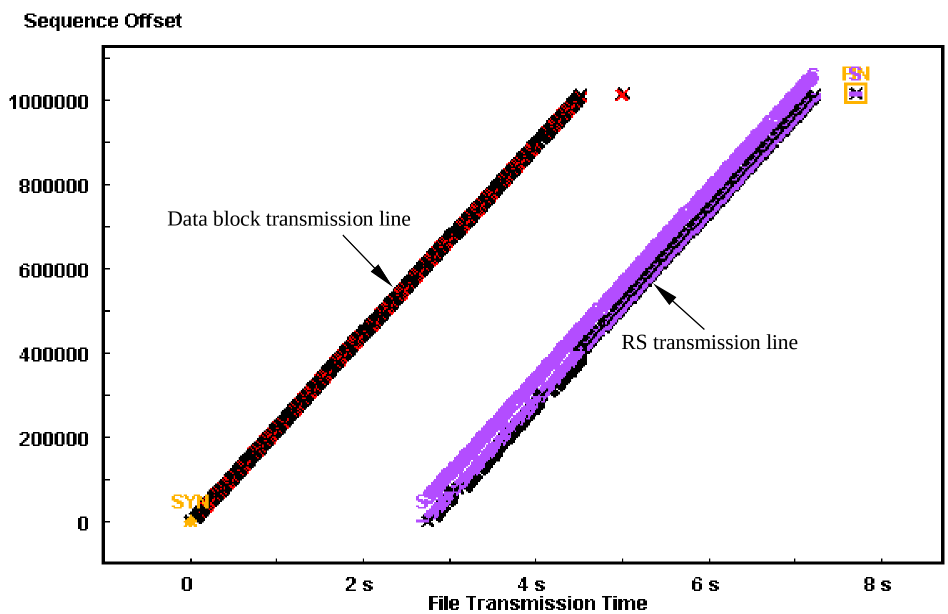

Fig. 1. A TSG illustrating the LTP transmission at packets level at the sending node for delivery of a file of 1 Mbyte over an emulated symmetric cislunar communication channel with a CP timer of 4 s.

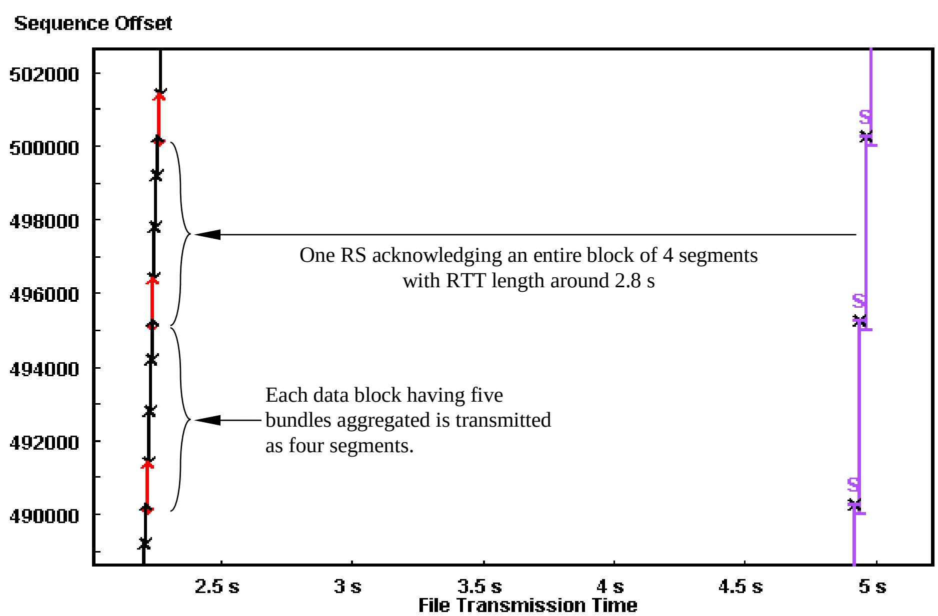

Fig. 2. An enlarged view of the TSG in Fig. 1 for an interactive transmission of two LTP blocks that are sent in the middle of the file that illustrates the bundle aggregation of LTP and the acknowledging mechanism of one RS per block with the receipt of RS prior to the expiration of CP timer.

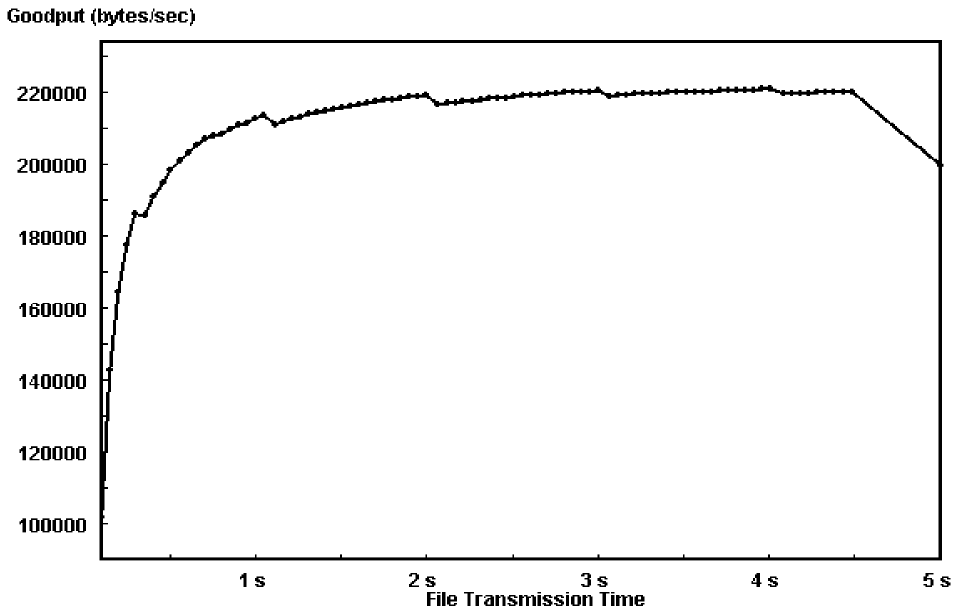

Fig. 3. A goodput graph illustrating the transmission performance at the sending node for delivery of a file of 1 Mbyte over an emulated symmetric cislunar communication channel with a CP timer of 4 s.

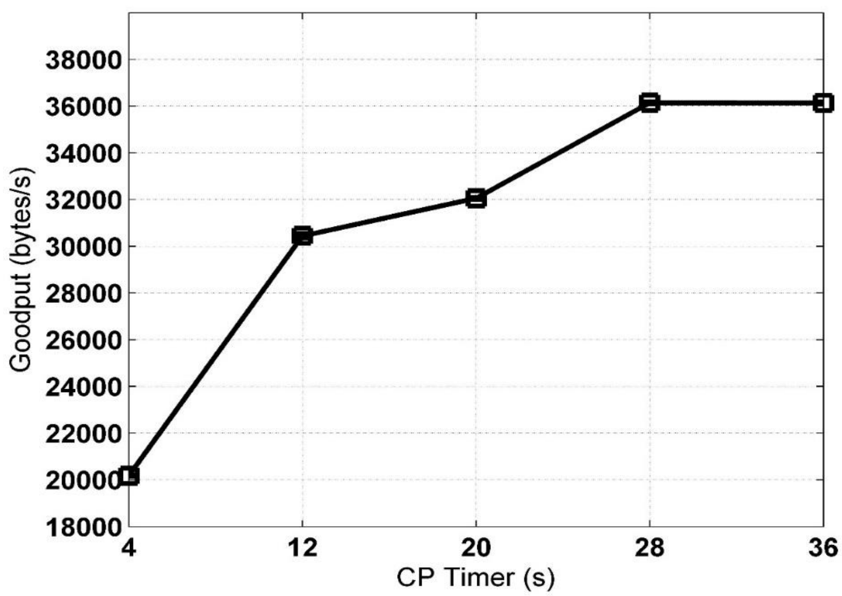

Fig. 4. A comparison of the experimented goodput performance of LTP in transmitting a file of 1 Mbyte over a cislunar communication channel with highly asymmetric channel rates (with the CR of 500/1) and various lengths of the CP timer starting from 4 s.

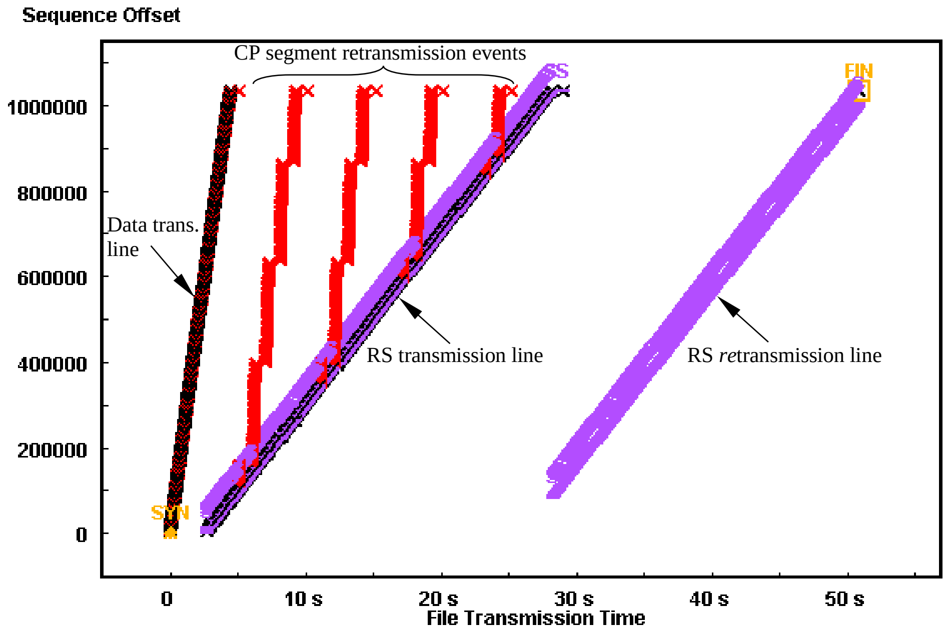

Fig. 5. A TSG illustrating the LTP transmission at packets level at the sending node for delivery of a file of 1 Mbyte over a cislunar communication channel with highly asymmetric channel rates (with the CR of 500/1) and a short CP timer of 4 s.

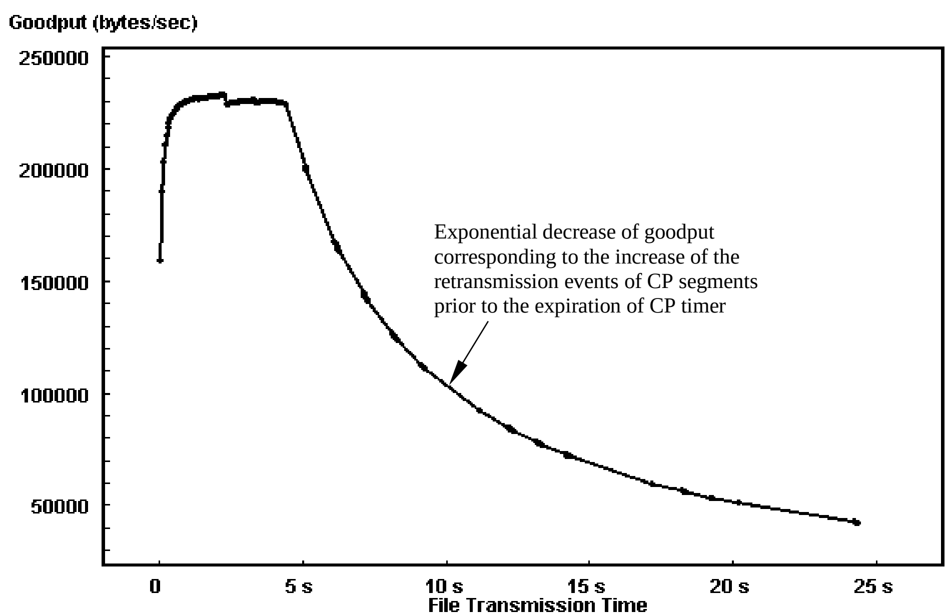

Fig. 6. A goodput graph illustrating the transmission performance at the sending node for delivery of a file of 1 Mbyte over a cislunar communication channel with highly asymmetric channel rates (with the CR of 500/1) and a short CP timer of 4 s.

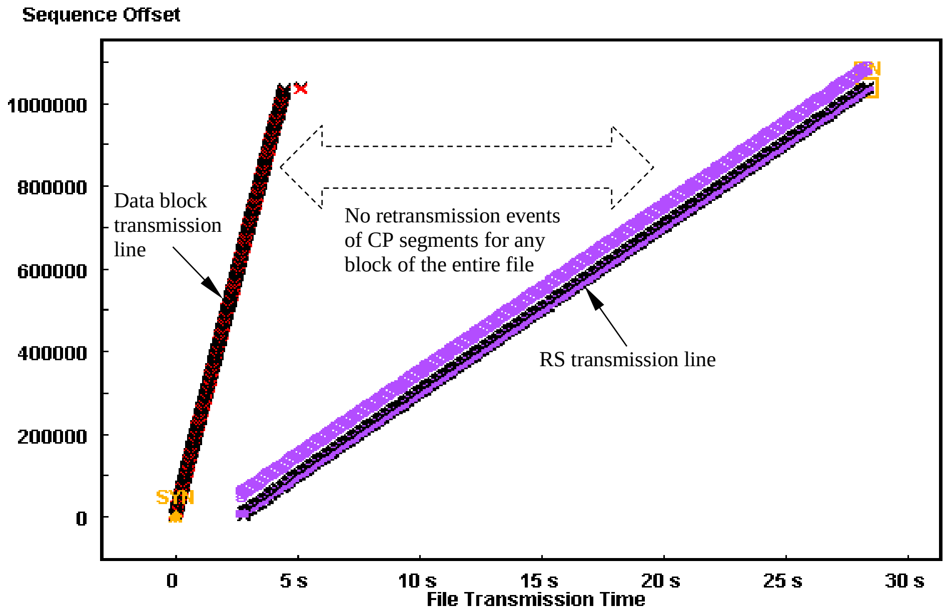

Fig. 7. A TSG illustrating the LTP transmission at packets level at the sending node for delivery of a file of 1 Mbyte over a cislunar communication channel with highly asymmetric channel rates (with the CR of 500/1) and a CP timer of 28 s.