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Ruhai Wang

LAMAR UNIVERSITY

Member The Texas State University System

Reliable Data Transmission in Moon-Earth Communications

June 23 , 2026

Watch on the IEEE Learning Network

Biography

Dr. Ruhai Wang

- Professor in Phillip M. Drayer Department of Electrical and Computer Engineering at Lamar University, Texas.
- Research interests include space networks, deep-space communications, computer networks, and cyber security
- Published around 120 papers in international journals and conferences proceedings
- Received the Ph.D. degree in electrical engineering from New Mexico State University in 2001

Biography

Dr. Wang has been extensively involved with the IEEE AESS.

- Currently an IEEE Distinguished Lecturer of AESS
- Served an Associate Editor of the IEEE Aerospace & Electronics Systems Magazine (AES-M) for ten years
- Served as an Associate Editor for the IEEE Transactions on Aerospace & Electronics Systems (TAES) from July 2018 to August 2020.

Dr. Wang also frequently served as a TPC chair/Co-Chair for international conferences/workshops

- 2007 IEEE International Conference on Communications
- 2008 International Workshop on Satellite and Space Communications (IWSSC 2008)

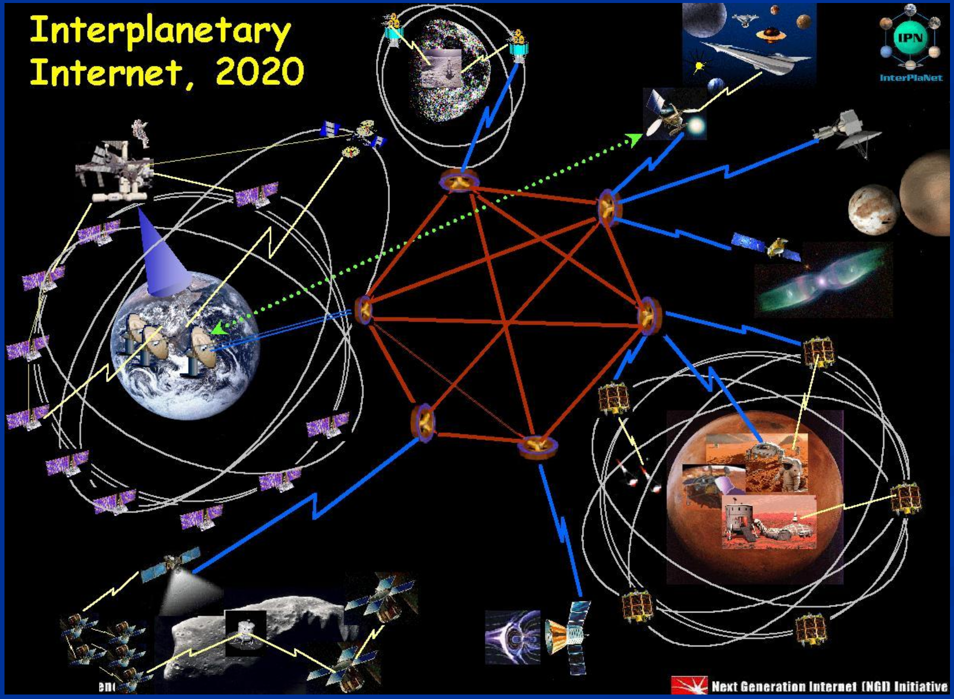
Reliable Data Transmission in Moon-Earth Communications

Abstract

As the NASA returns to the Moon and several other space agencies start the Moon explorations, potential networking technologies for reliable data/file transmission are being studied in cislunar communications. This tutorial presents a comparative overview of the data transmission mechanisms that are suitable for reliable data/file delivery from the Moon to the Earth. The talk features the TCP-based, UDP-based and disruption-tolerant transmission mechanisms in cislunar communications with extensive performance evaluations done in experimental, statistical, and analytical manners.

Background

- NASA has been working towards space Internet to automate mission communications using networking protocols such as TCP/IP
  - Near Earth (e.g., Starlink of SpaceX)
  - Lunar (Moon-Earth)
  - Deep Space Network (Solar System Internet)



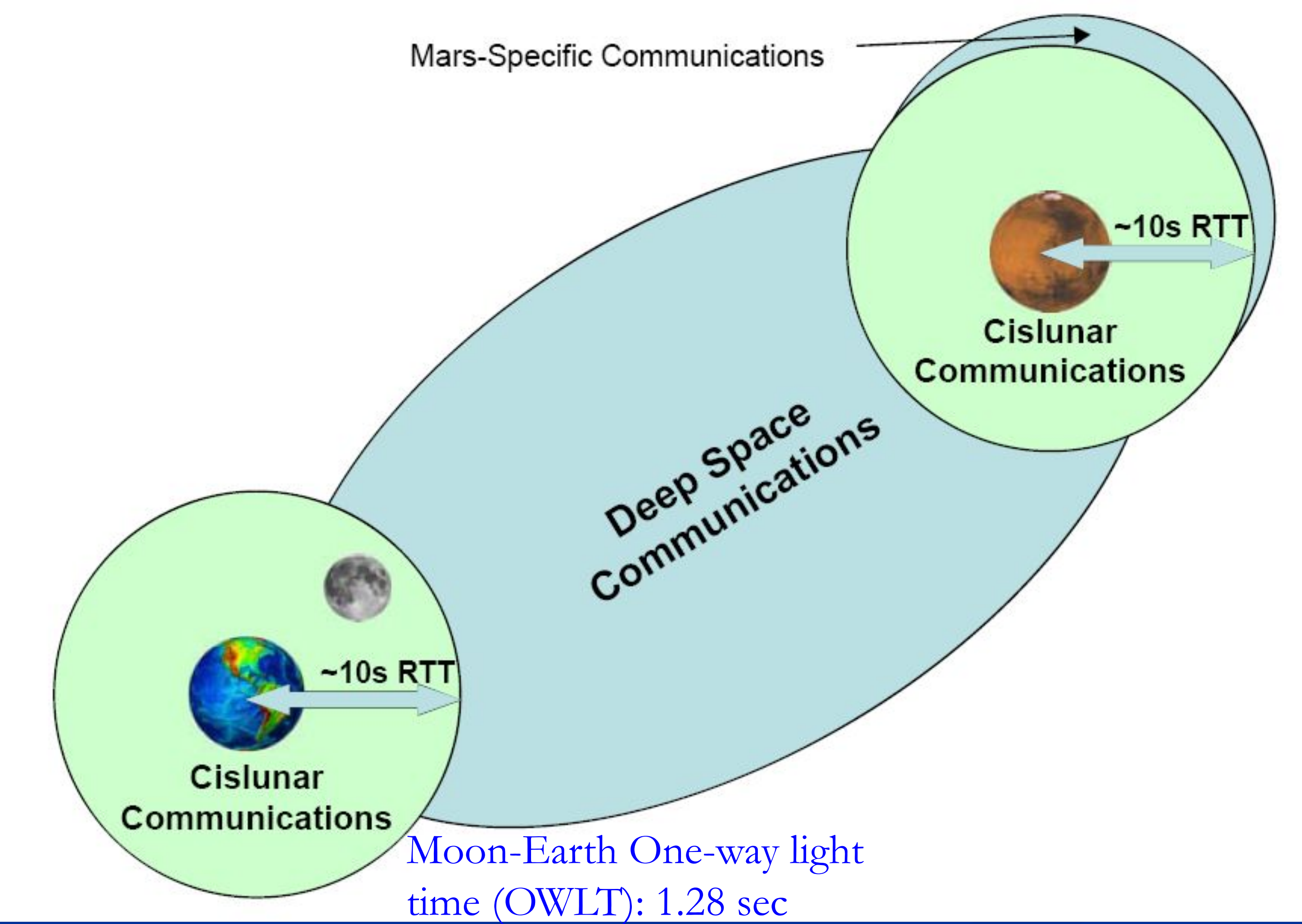
TCP Problems in Space

- TCP/IP are the key technologies of the success of the terrestrial Internet.
- Due to significant differences in communication environments, operation over space channels (especially deep-space channels) poses a number of problems to TCP/IP in providing a reliable end-to-end data communication service.

TCP Problems in Space

- TCP's major problems in deep space environment
  - Long link-delays
  - Frequent/lengthy link outage
  - High channel/transmission errors
  - Asymmetric channel-rates between spacecraft and ground

Lunar and Mars Missions



Moon-Earth One-way light time (OWLT): 1.28 sec

Source: Cislunar Communications Architecture, CCSDS

Concept of DTN

- Delay Tolerant Networking (DTN) is a class of network techniques that are designed to combat long link delays, frequent link disruptions, and asymmetric channel ratios.
- Unlike TCP/IP, DTN employs a **store-and-forward** mechanism; DTN does not discard the data packets, even if the destination node is not found, but rather it stores them until a safe link to the next station is established

DTN for Space

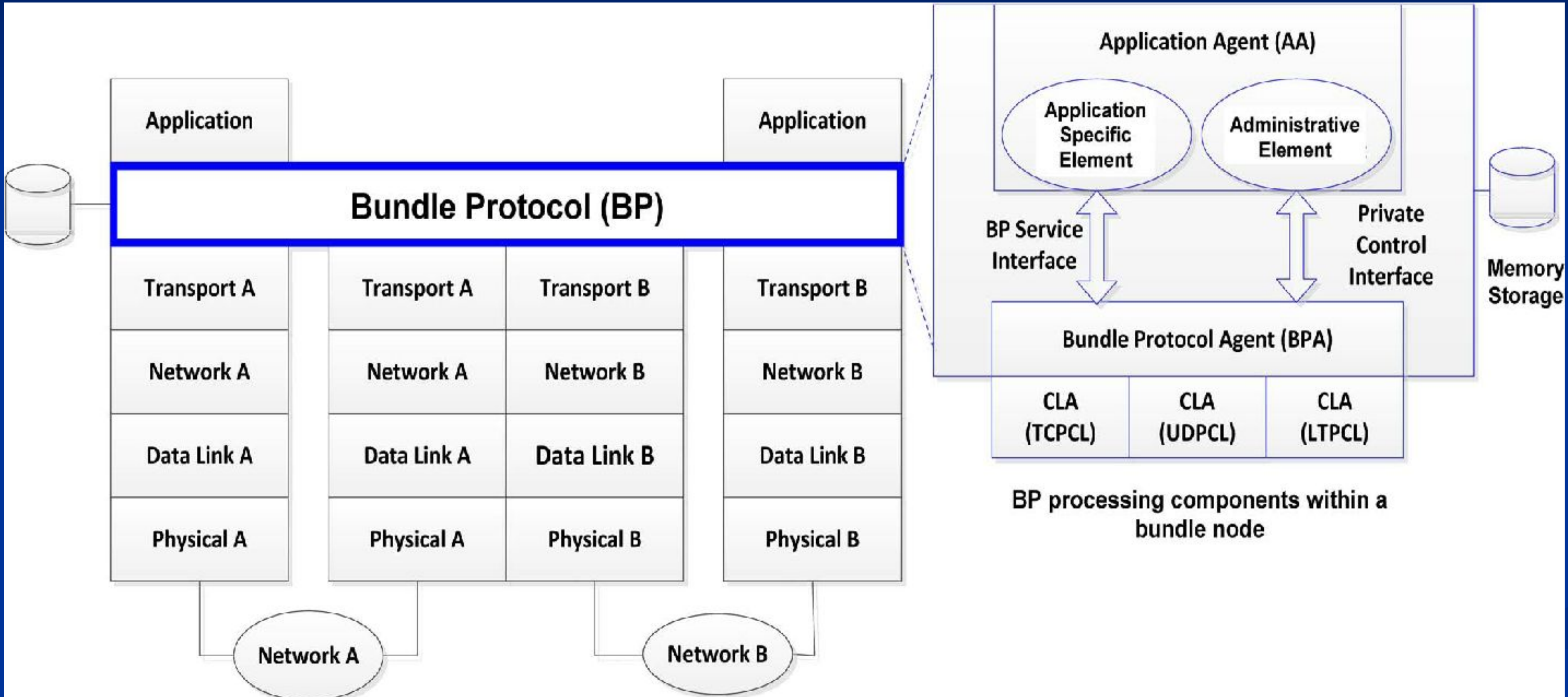
- DTN offers a new solution in space communications involving long link delay and frequent link disruptions, especially in deep space
- NASA considers DTN as the only candidate protocol suite that approaches the level of maturity required to handle the link break and delays inherent in deep space communications.

Concept of DTN

- To provide the store-and-forward message transmission service, a bundle protocol (BP) is designed to operate as an overlay protocol on top of heterogeneous underlying convergence layer protocols (CLPs) stacks, among which may be the Internet protocol stack itself, leading to
  - TCPCL
  - UDPCL
  - Licklider Transmission Protocol CL (LTPCL), a new one particularly designed for deep space communications

DTN Protocol Stack

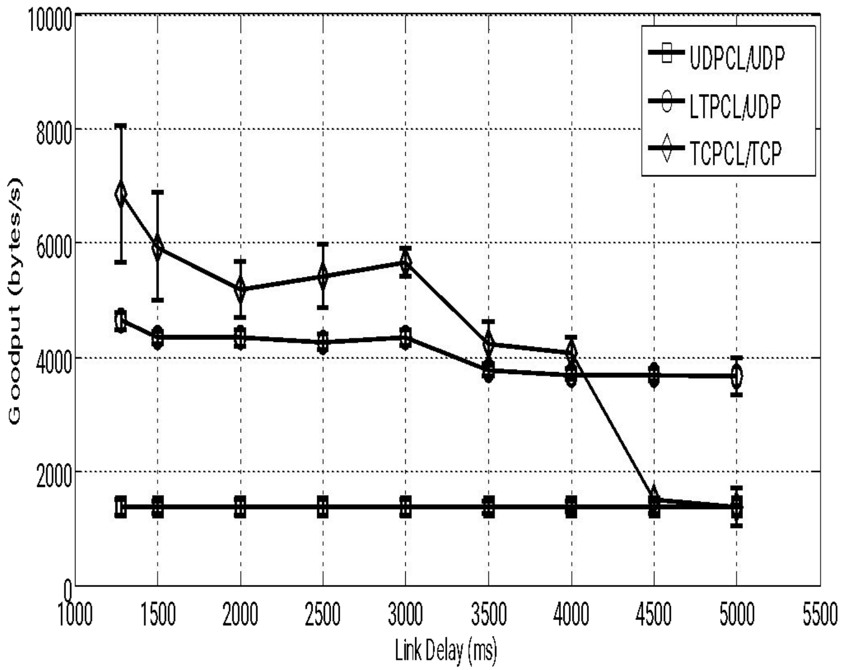
- BP working with various data transport protocols.



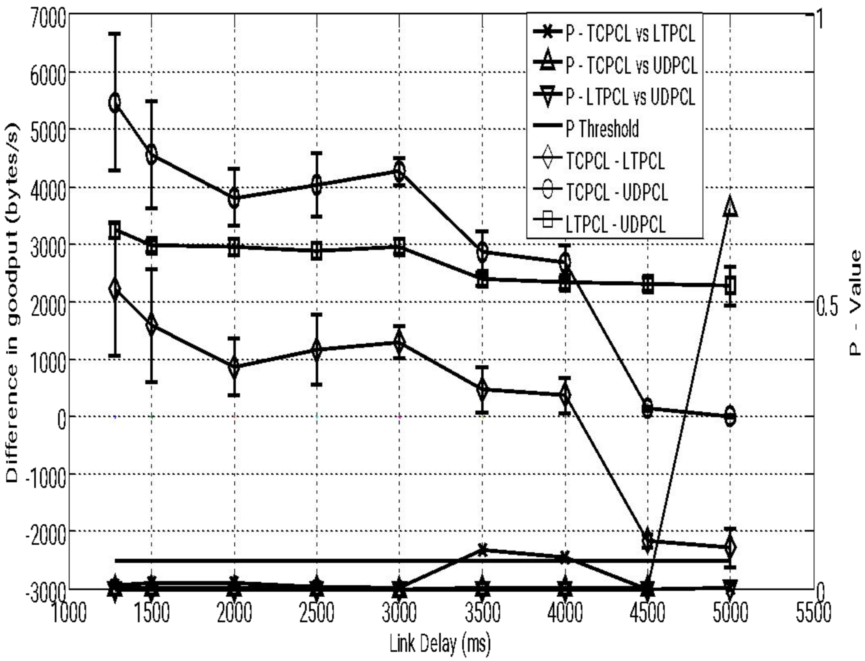
BP functioning as an "overlay" network protocol that interconnects heterogeneous networks for end-to-end reliable transmission

BP processing components within a bundle node

Experimental Performance Results
(Over a PC-based Experimental Infrastructure)

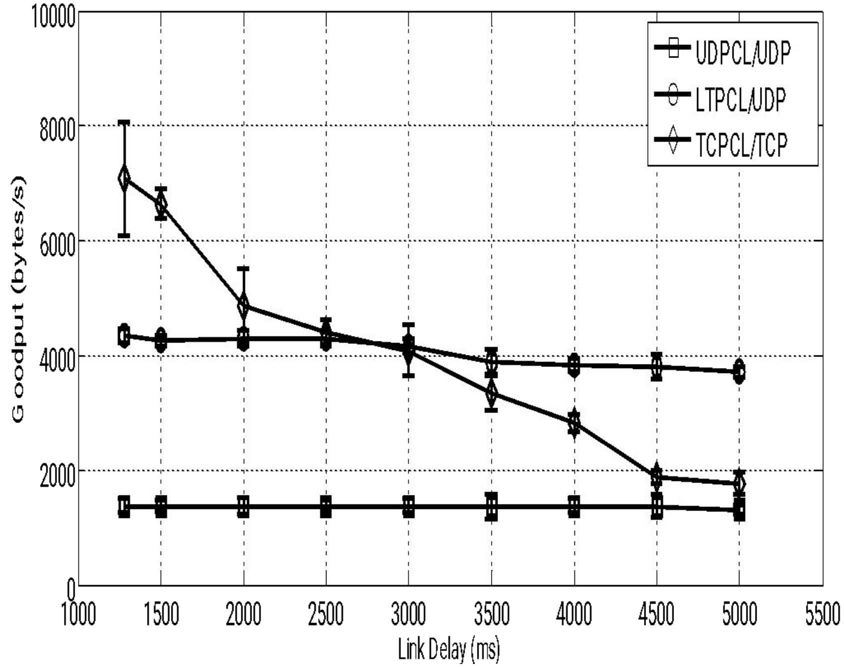


BER=0

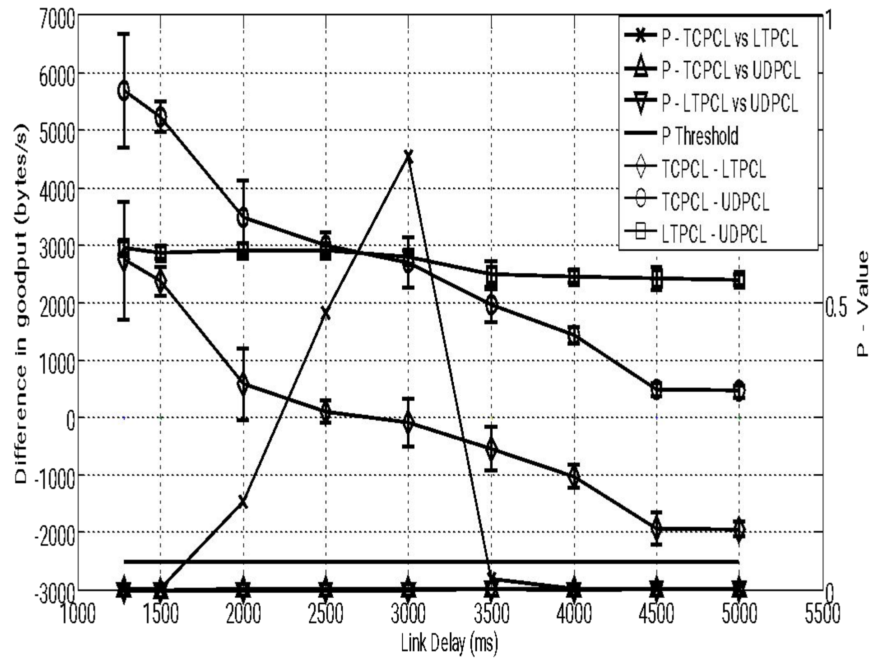


Corresponding Analysis Results at BER=0 using Statistical t-test

Experimental Performance Results

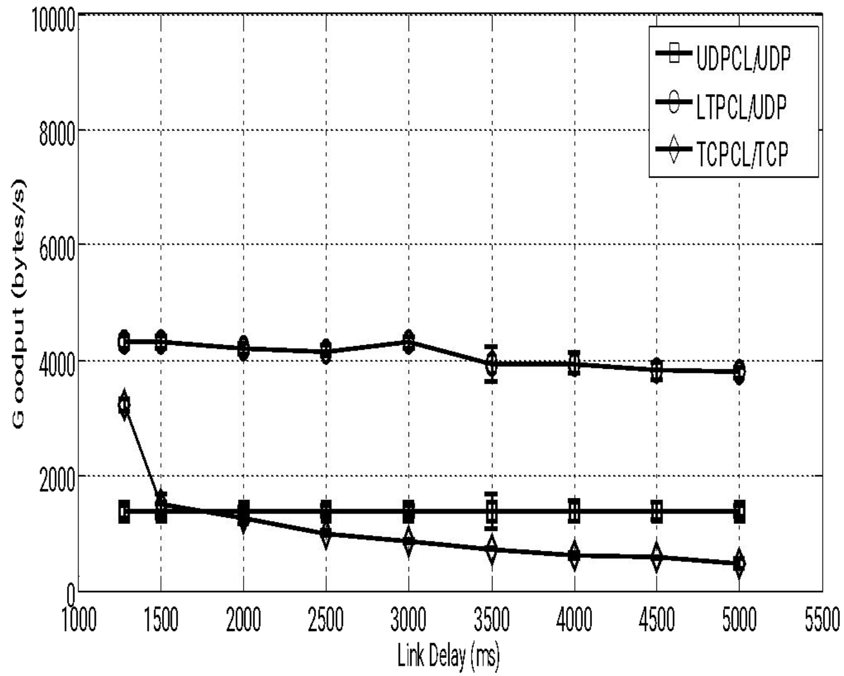


BER=10E-6

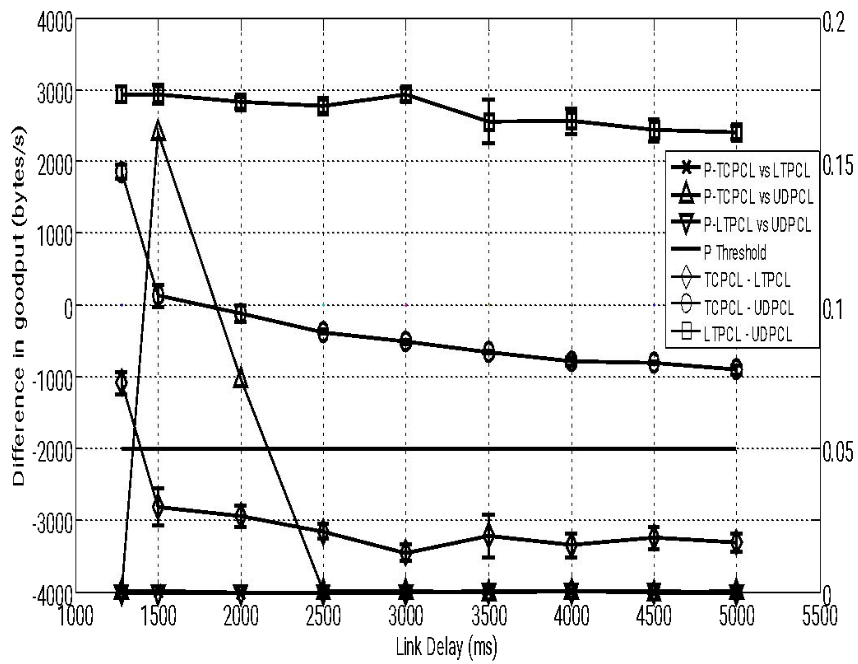


Corresponding Analysis Results at BER=10E-6 using Statistical t-test

Experimental Performance Results



BER=10E-5

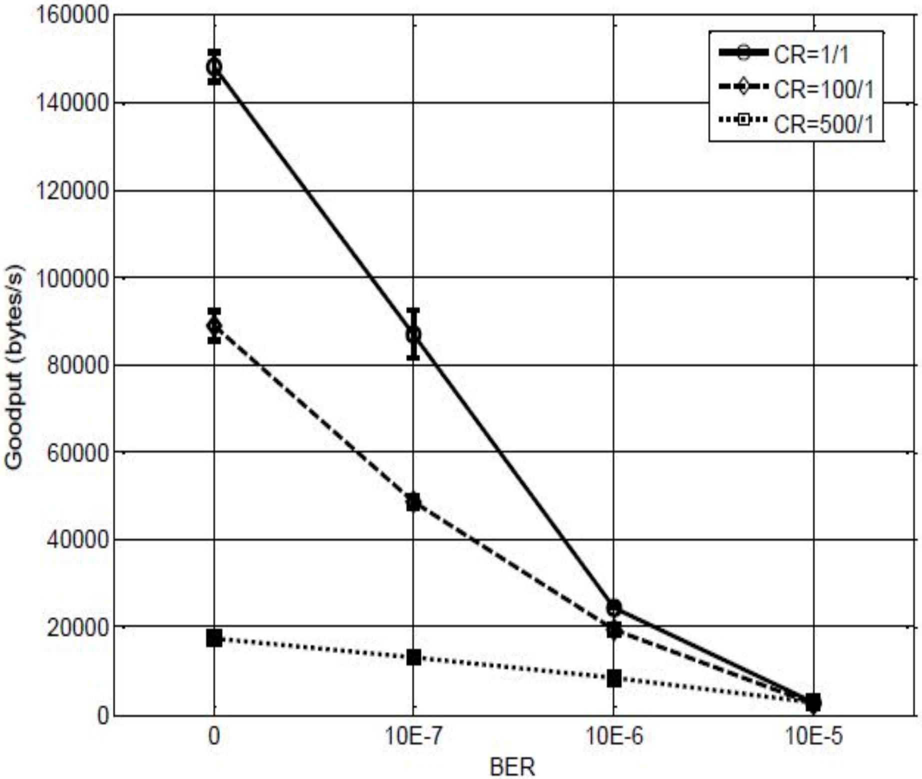


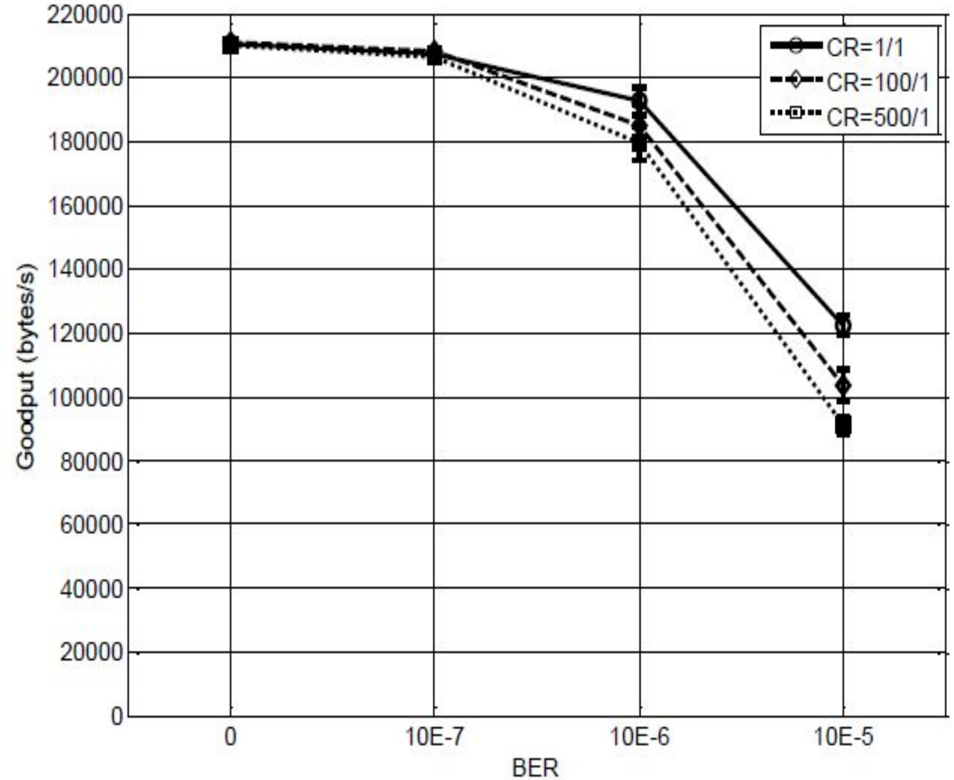
Corresponding Analysis Results at BER=10E-5 using Statistical t-test

Performance Comparison-Findings

- LTPCL has a significant performance advantage over TCPCL for link delays longer than 4000 ms when bit error rate is 10^{-6} or higher.
- For a very lossy channel with a BER of around 10^{-5}, LTPCL has a significant goodput advantage over TCPCL at all the link delay levels studied.
- LTPCL has a consistently significant goodput advantage over UDPCL, around 2500~3000 bytes/s, at all levels of link delays and BERs.
- Unlike TCPCL, for which the goodput rate is severely affected by an increase in link delay and/or channel noise, link delay and BER have only minor impact on the performance of LTPCL.

Experimental Results

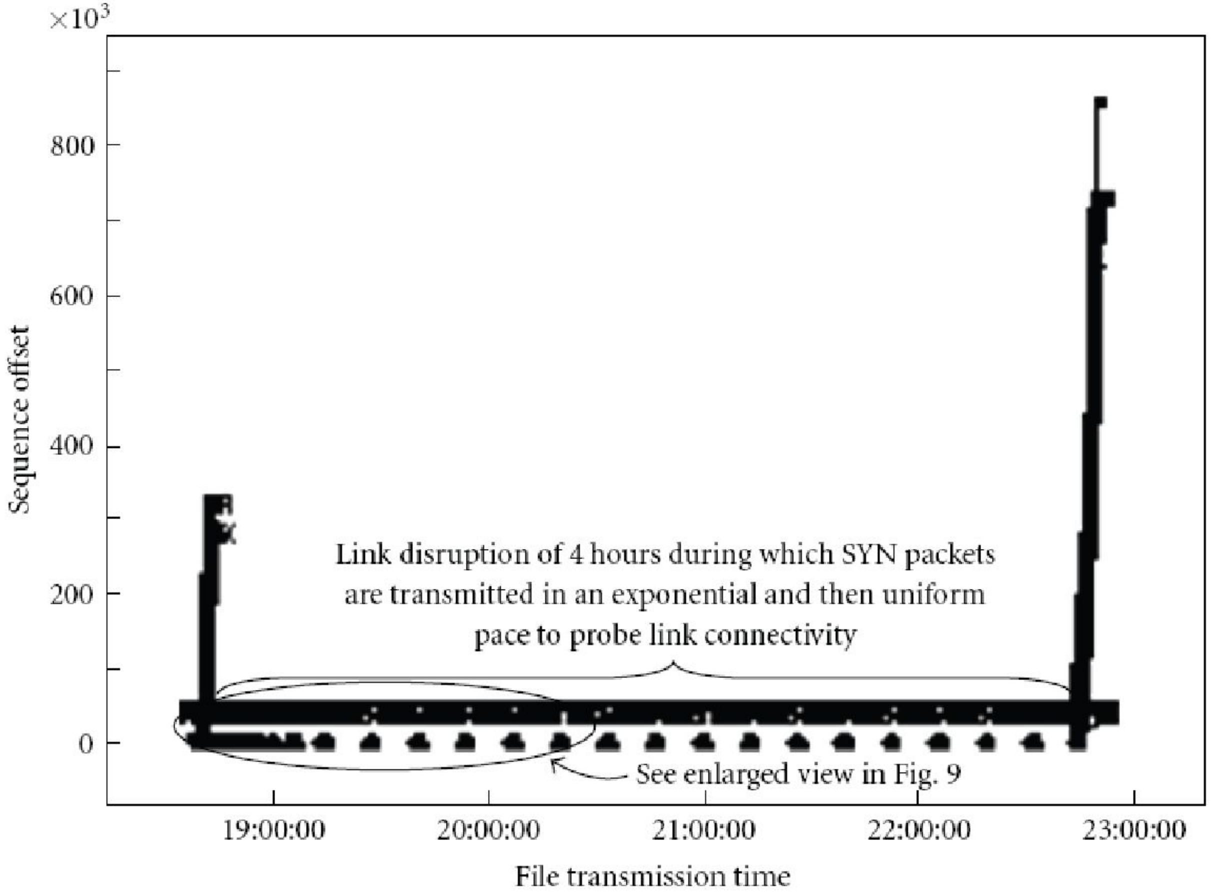




TCPCL LTPCL

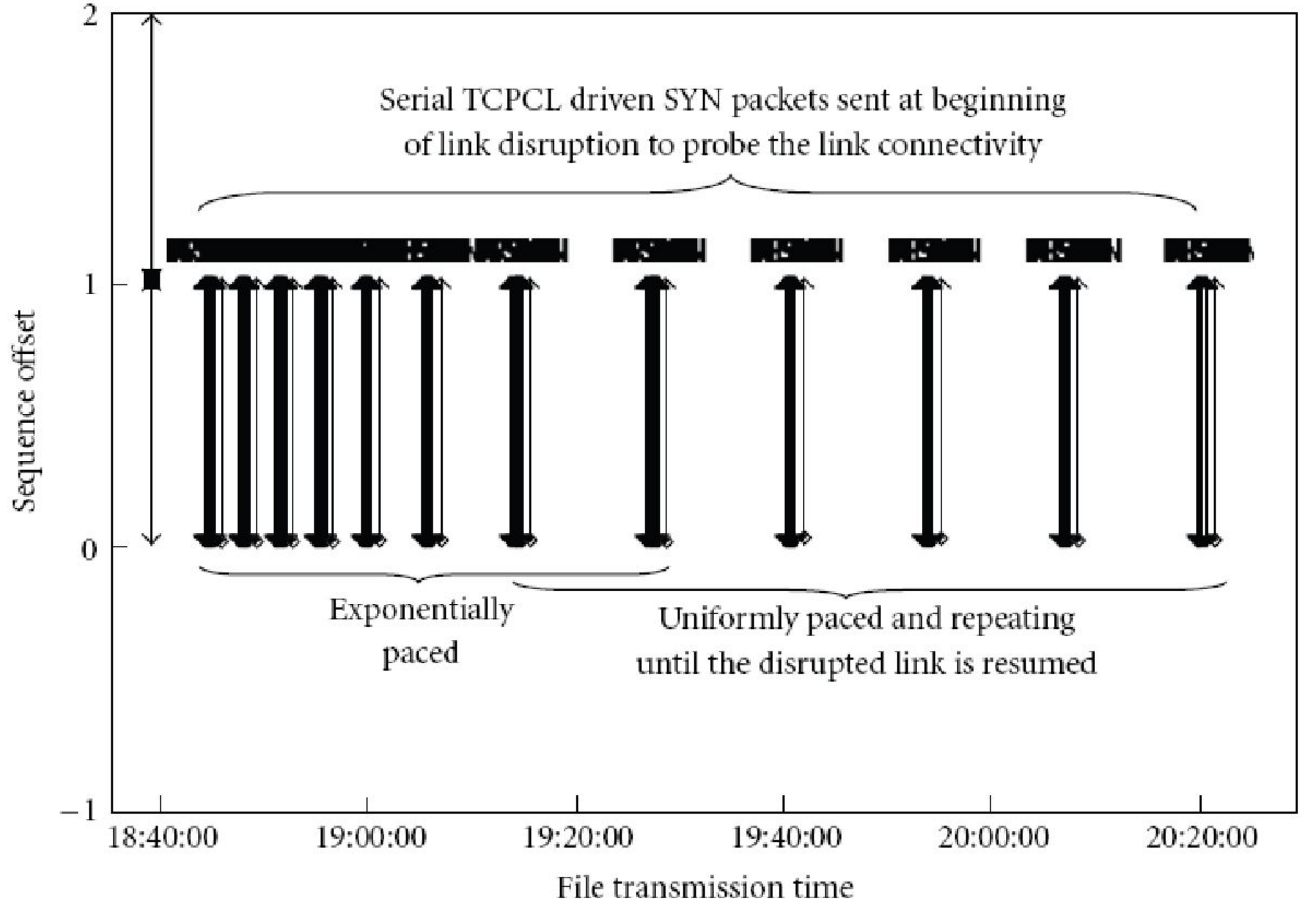
Goodput performance comparison between TCPCL and LTPCL in Cislunar Communications in presence of channel-rate highly asymmetry and high data loss

Experimental Results-TCP



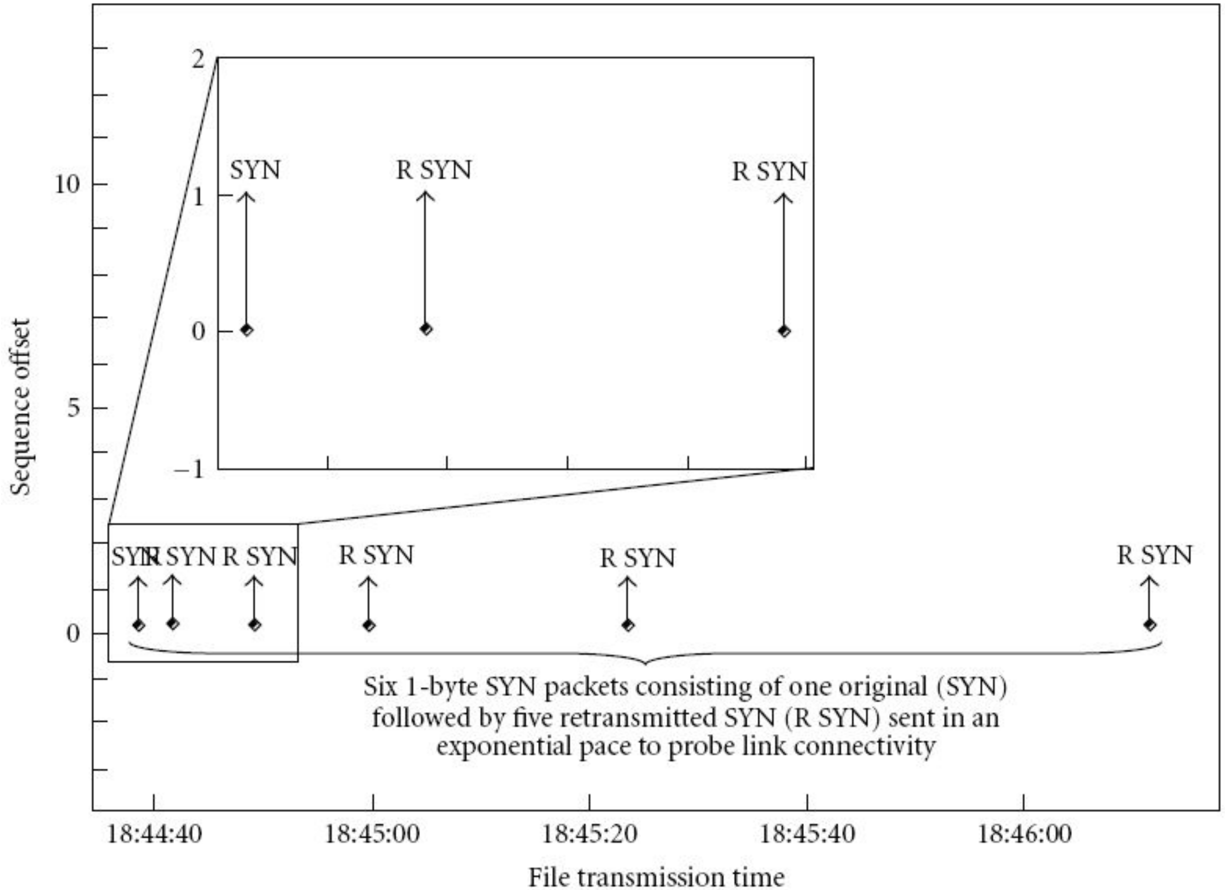
Time Sequence Graph (TSG) with link delay of 3 sec and link disruption of 4 hours at BER of 10^{-6}

Experimental Results-TCP



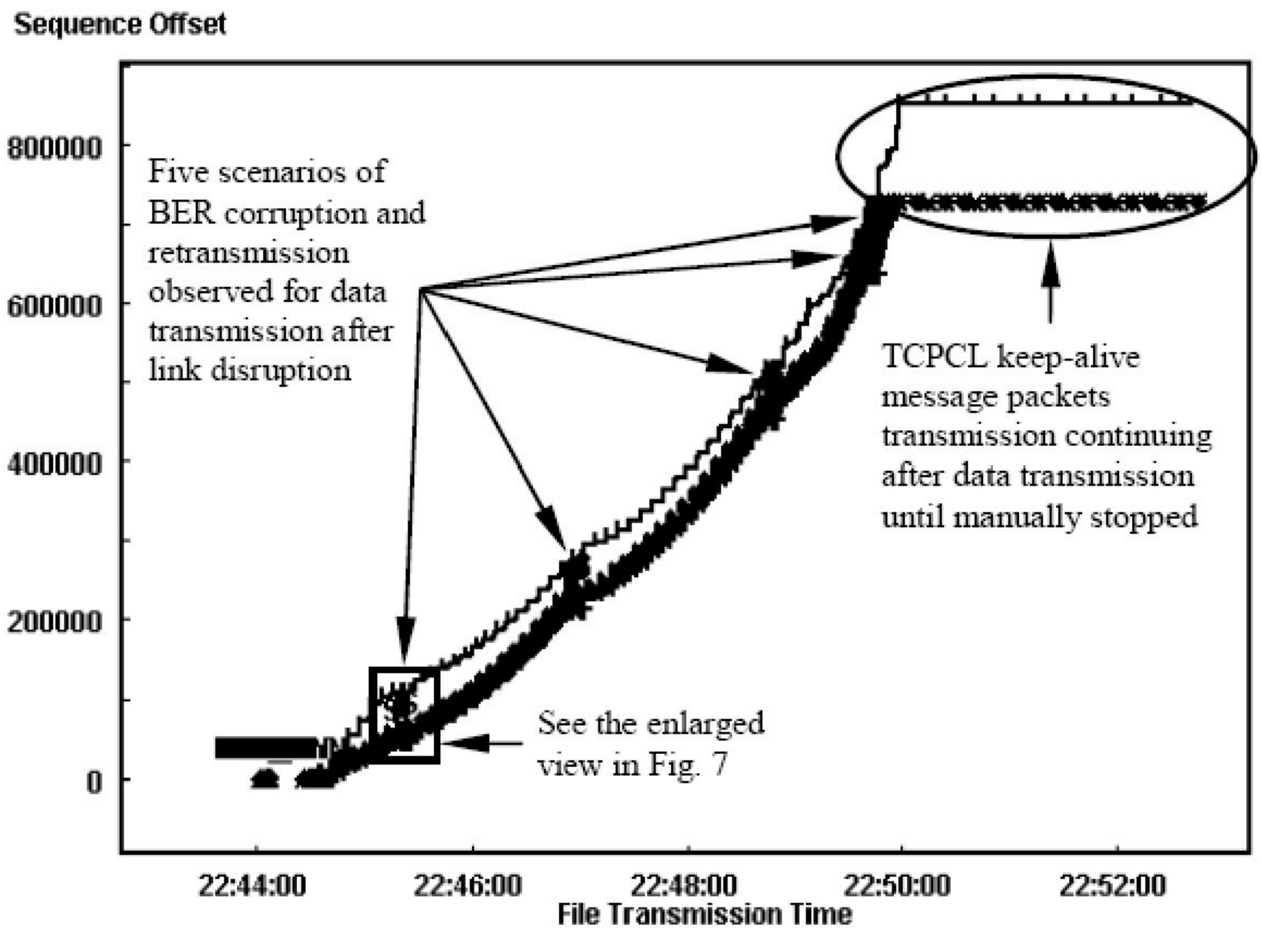
Enlarged view of serial SYN/R SYN packets sent from MX to RX during link disruption

Experimental Results-TCP



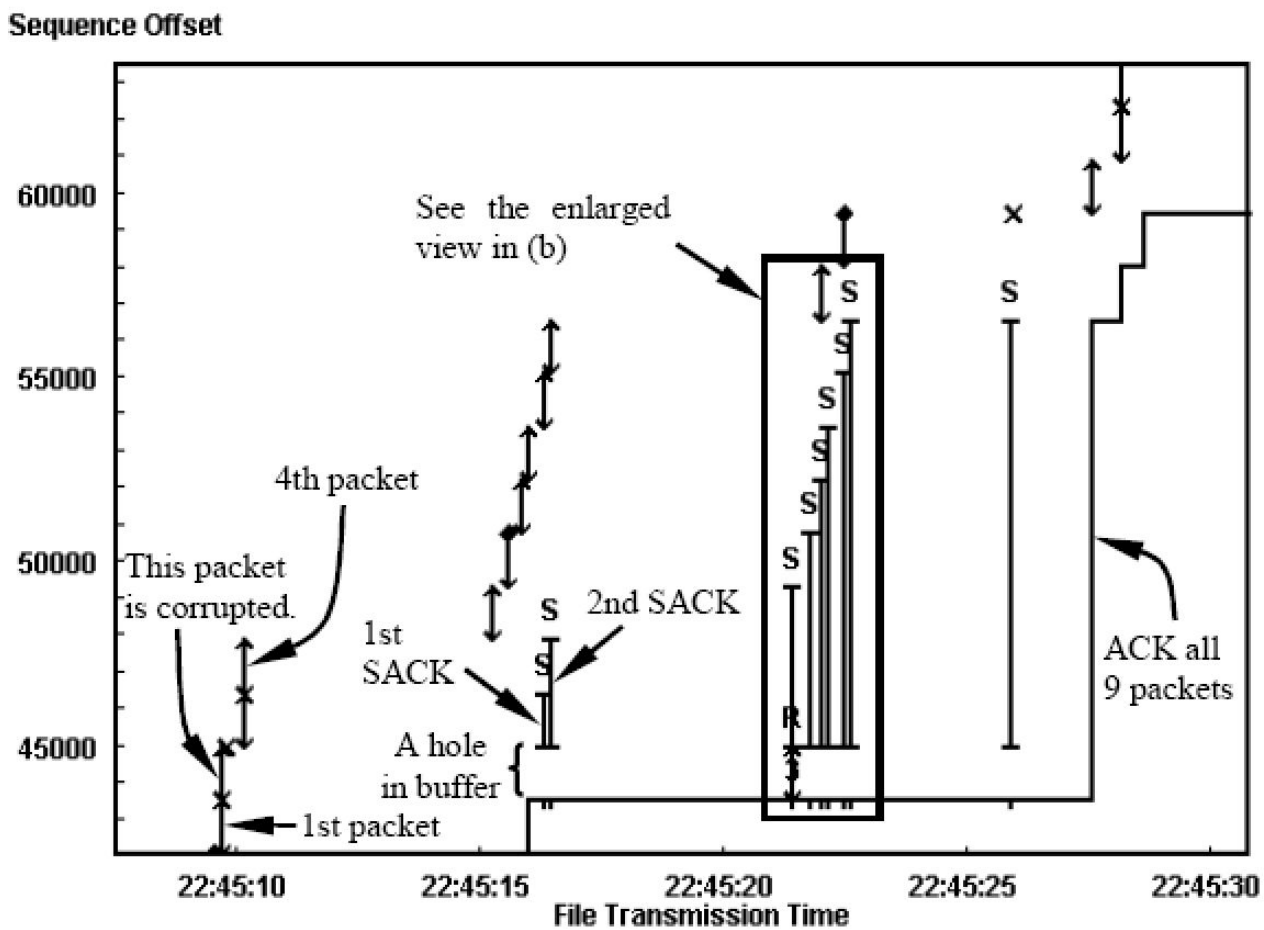
enlarged view of first series of six 1-byte SYN packets sent by MX to RX during link disruption.

Experimental Results-TCP



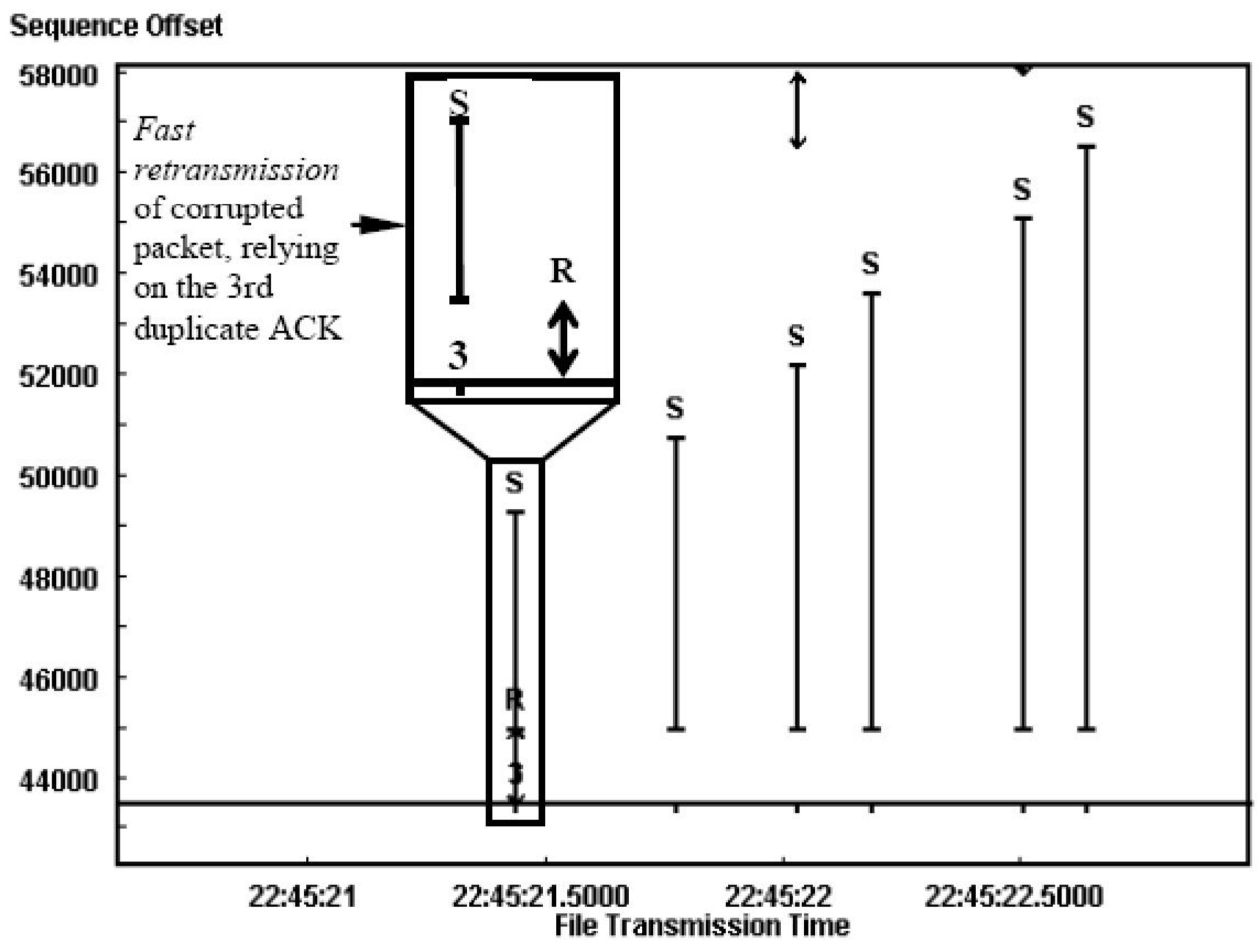
Time Sequence Graph (TSG) with link delay of 3 sec and link disruption of 4 hours at BER of 10^{-6}

Experimental Results-TCP



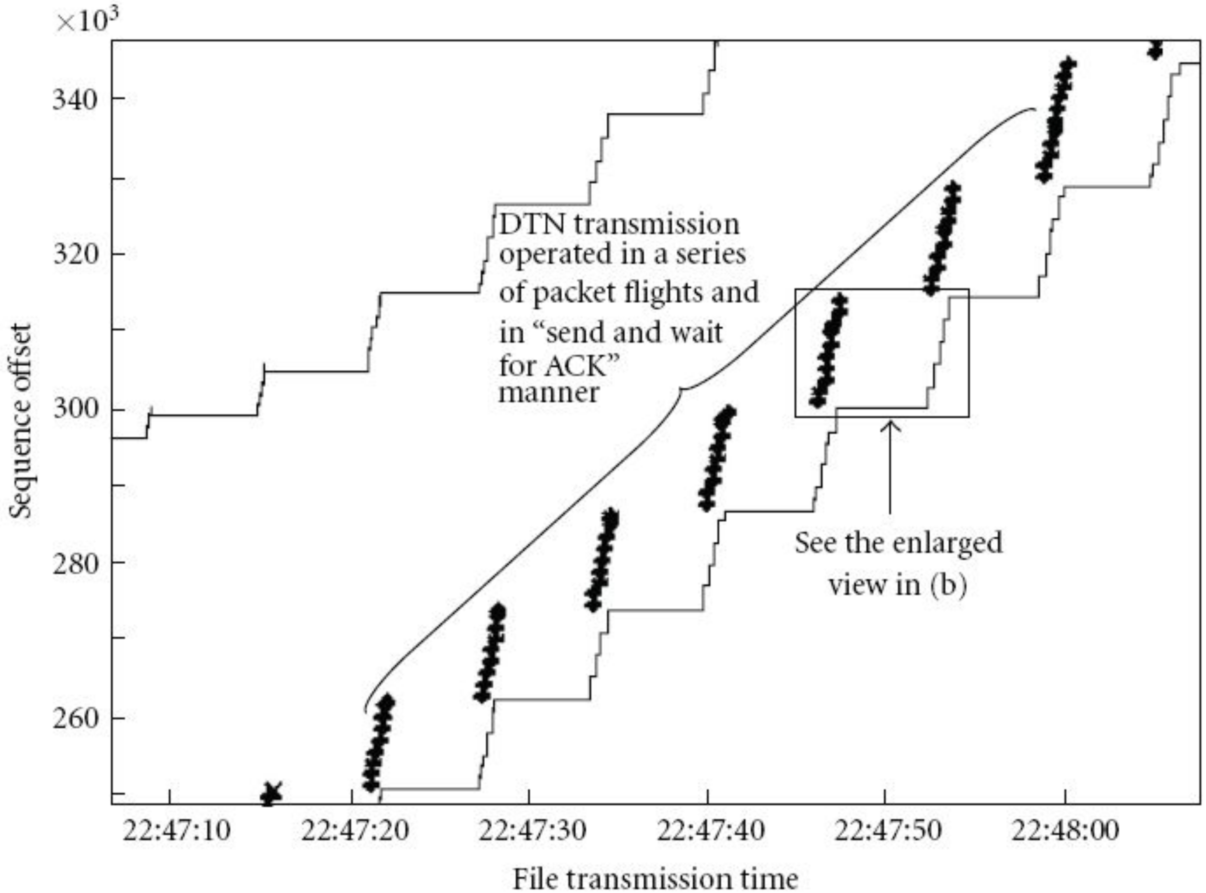
Time Sequence Graph (TSG) for data transmission error scenario with link delay of 3 sec and link disruption of 4 hours at BER of 10^{-6}

Experimental Results-TCP



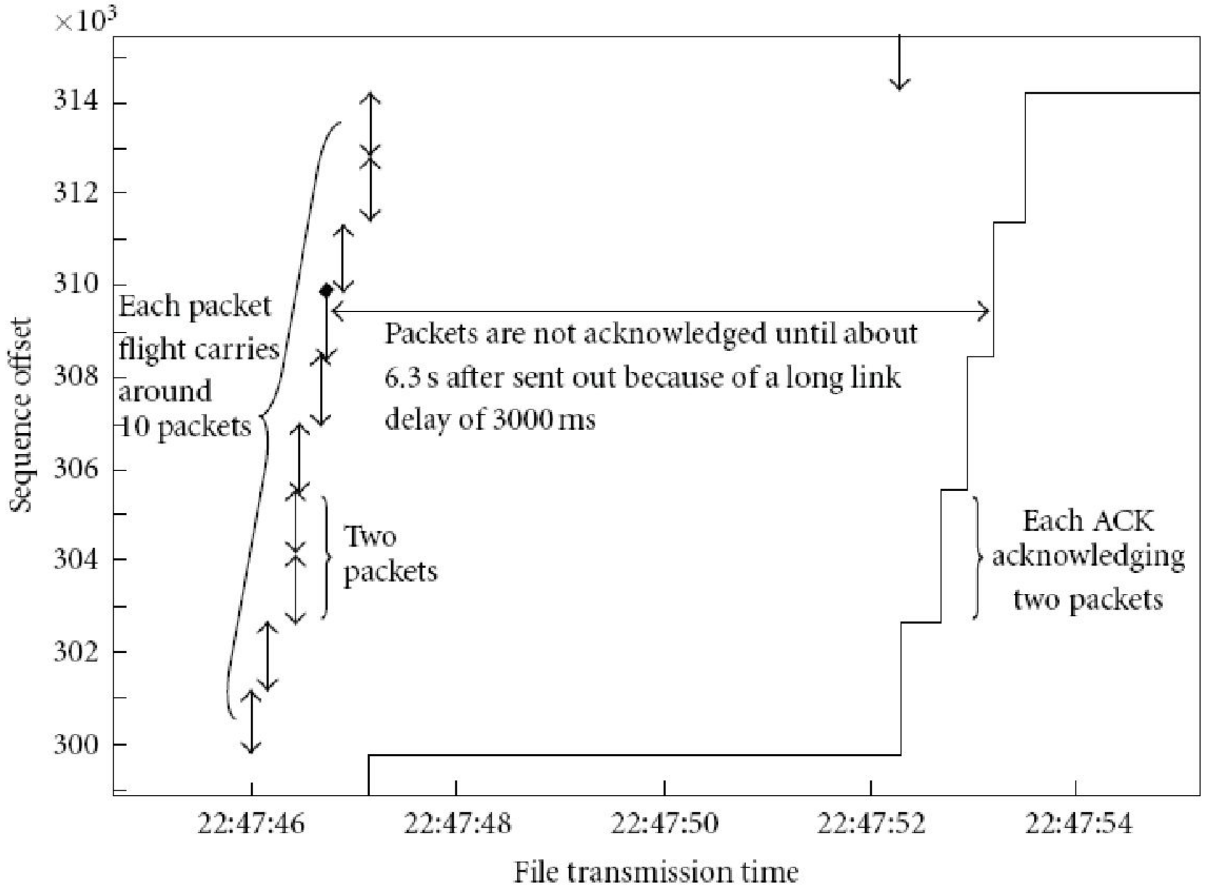
Time Sequence Graph (TSG) for data transmission error scenario with link delay of 3 sec and link disruption of 4 hours at BER of 10^{-6}

Experimental Results-TCP



Traffic pattern of DTN transmission from MX to RX over cislunar channels with link delay of 3000 ms and link disruption of 4hours without error.DTN transmission in a series of packet flights.

Experimental Results-TCP



Traffic pattern of DTN transmission from MX to RX over cislunar channels with link delay of 3000 ms and link disruption of 4hours without error.DTN transmission in a series of packet flights.

Experimental Results-Findings

- When the protocol stack runs over a long-delay cislunar channel without any link disruption, the ACK-clocked transmission mechanism in TCPCL-based DTN suffers severely from the long, idle time spent waiting for the ACKs and very slow error recovery with error-prone cislunar channels, similar to the operation of standard TCP over any other long-delay, lossy channel.

Experimental Results-Findings

- The TCPCL-based DTN protocol is effective in handling a long link disruption (30 minutes ~ 8 hours) experienced in data transmission over a cislunar channel, even with an existence of a very long link delay of 1280 ms~5000 ms and a high channel BER up to 10^{-5}.
- The goodput performance of the DTN transmissions is most adversely affected by link disruption time in comparison to the effect of link delay and BER. There is roughly exponential decrease in goodput along with exponential increase in link disruption time.

Experimental Results-Findings

- For a given BER, the number of retransmissions increases exponentially along with the increase in long link disruption.
- Given link disruption time and BER for a transmission, the change in link delay in cislunar domain has a nominal effect on the number of retransmissions.

DTN - Bundle Aggregation of LTP

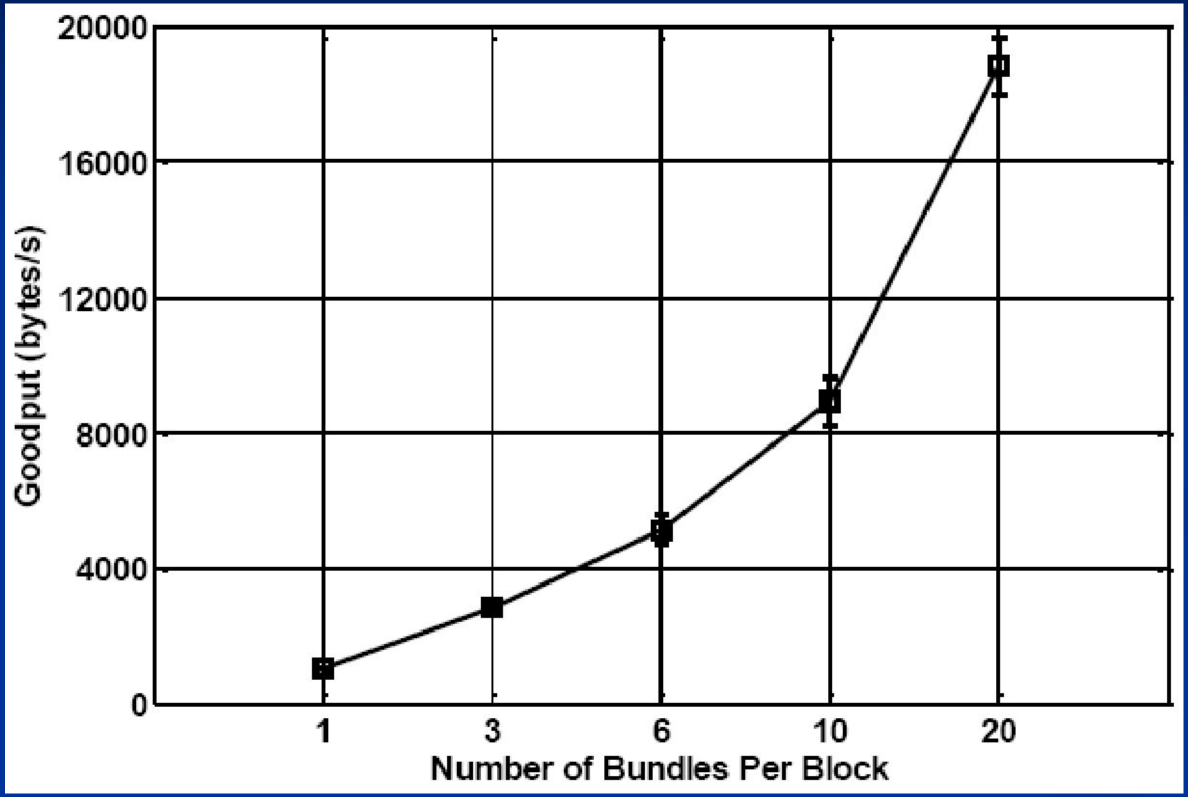
- Minimum number of data bundles that should be aggregated within a block to avoid delay of an ACK transmission for LTPCL

$$N_{\text{Bundle-Min}} = \left\lceil \frac{L_{\text{ACK}} \times R_{\text{Data}}}{R_{\text{ACK}}} \times \frac{L_{\text{LTP-Seg}}}{(L_{\text{Bundle}} + L_{\text{Bundle-Head}}) \times (L_{\text{LTP-Seg}} + L_{\text{Frame-Head}})} \right\rceil$$

- Optimal number of bundles to be aggregated within a block for the best transmission efficiency

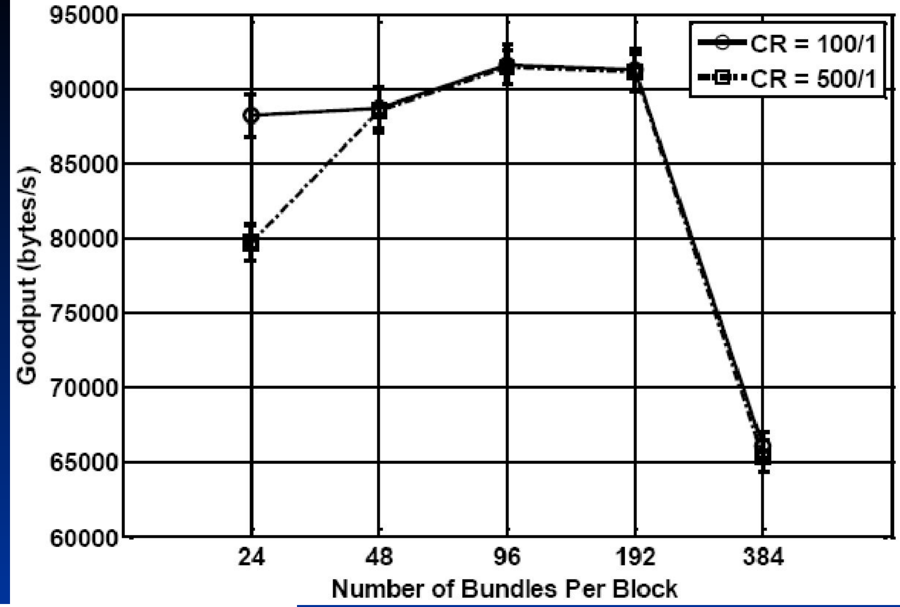
$$N_{\text{Bundle-Optimal}} = \left\lfloor \frac{R_{\text{Data}}}{L_{\text{Bundle}} + L_{\text{Bundle-Head}}} \times \frac{L_{\text{LTP-Seg}}}{L_{\text{LTP-Seg}} + L_{\text{Frame-Head}}} \right\rfloor$$

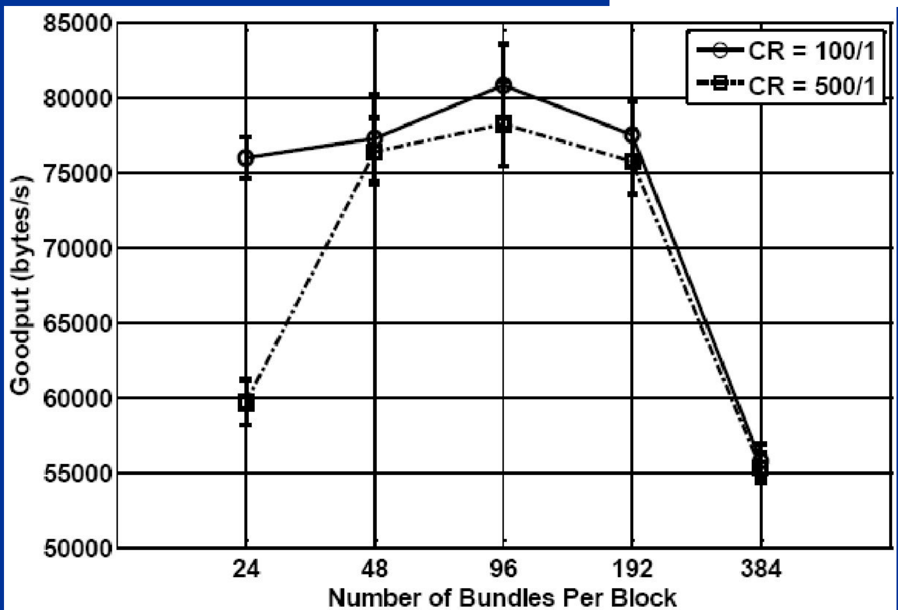
Experimental Results for "One Bundle per Block" vs Aggregation Mechanism

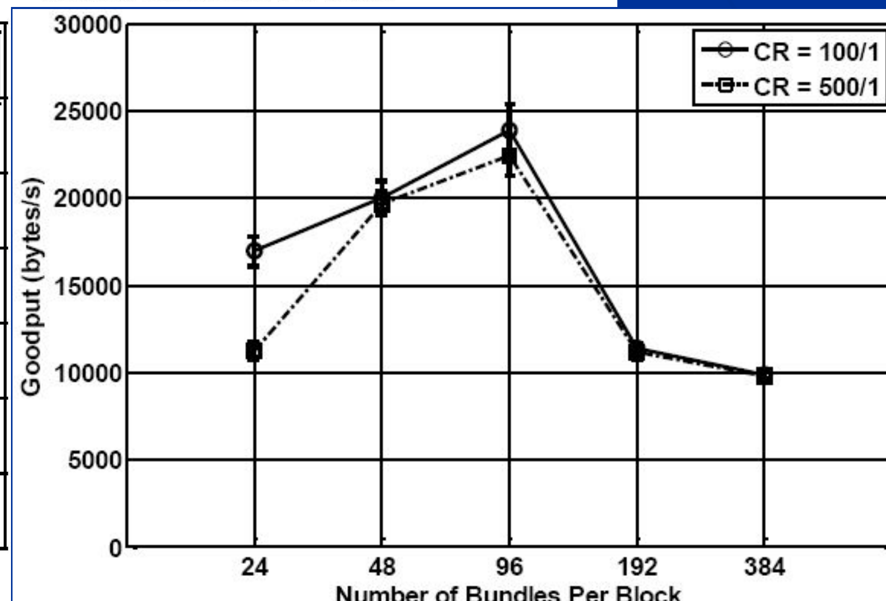


Comparison of goodput performance of DTN LTP between the general approach of "one bundle per block" and the aggregation approach at a BER of 10E-6 and a channel ratio of 100/1.

Results for a Small Window Size of 1 Mbytes

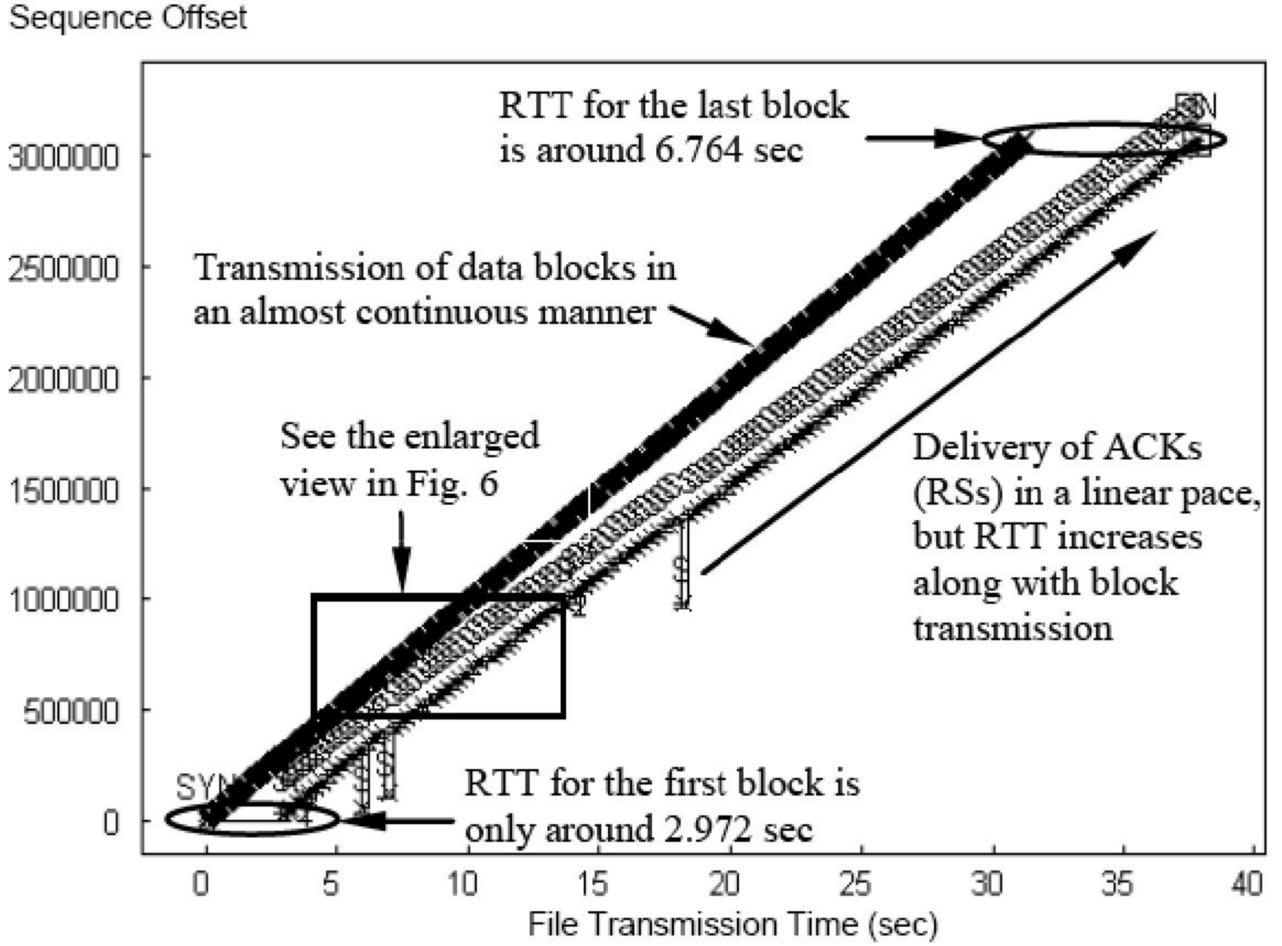






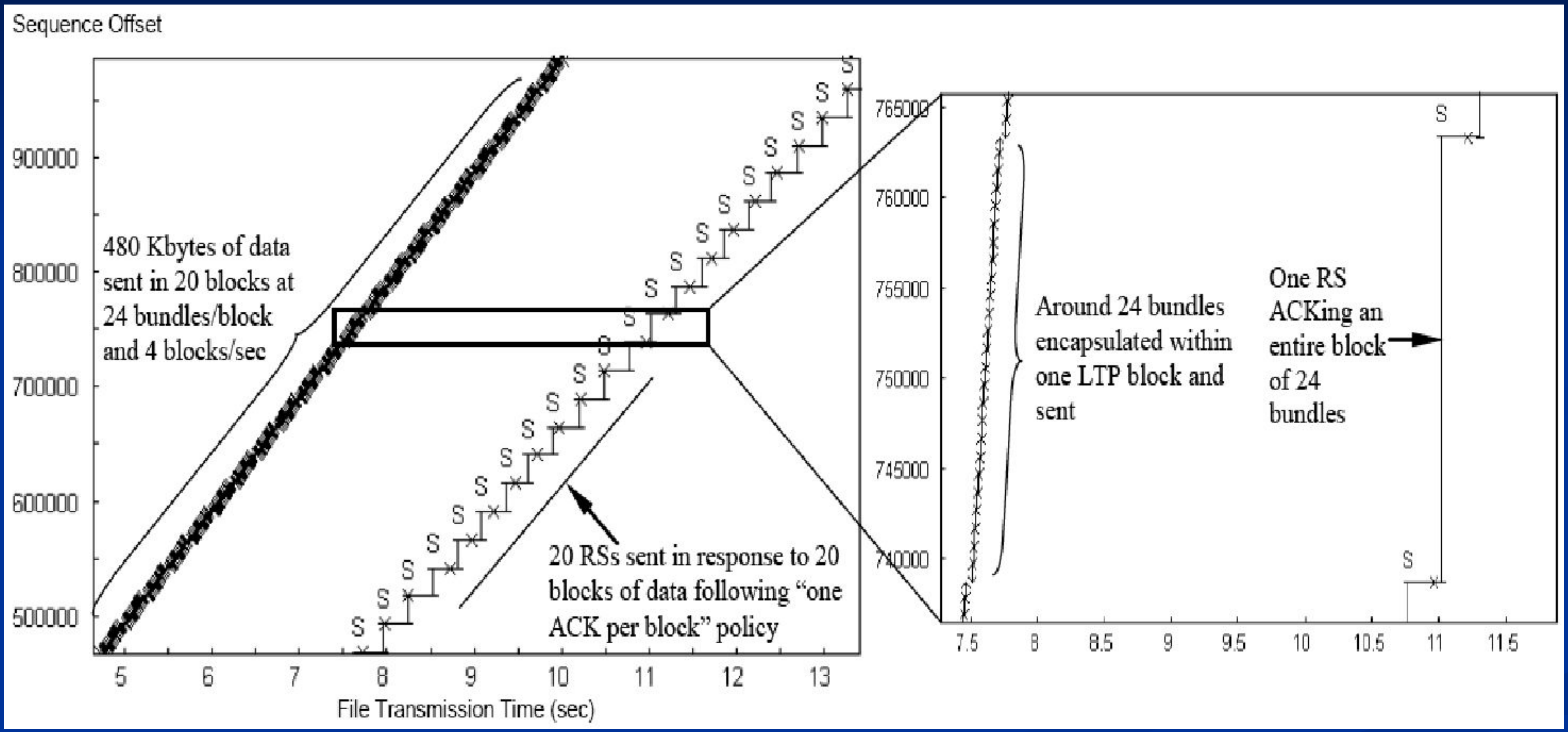
Performance of LTP over a simulated cislunar channel with a window size of 1 Mbytes and two channel ratios of 100/1 and 500/1 for five aggregated block sizes—24 bundles/block, 48 bundles/block, 96 bundles/block, 192 bundles/block and 384 bundles/block. (a) BER = 10E-7. (b) BER = 10E-6. (c) BER = 10E-5.

Traffic Pattern with a Small Window Size of 1 Mbytes and a Small Block Size



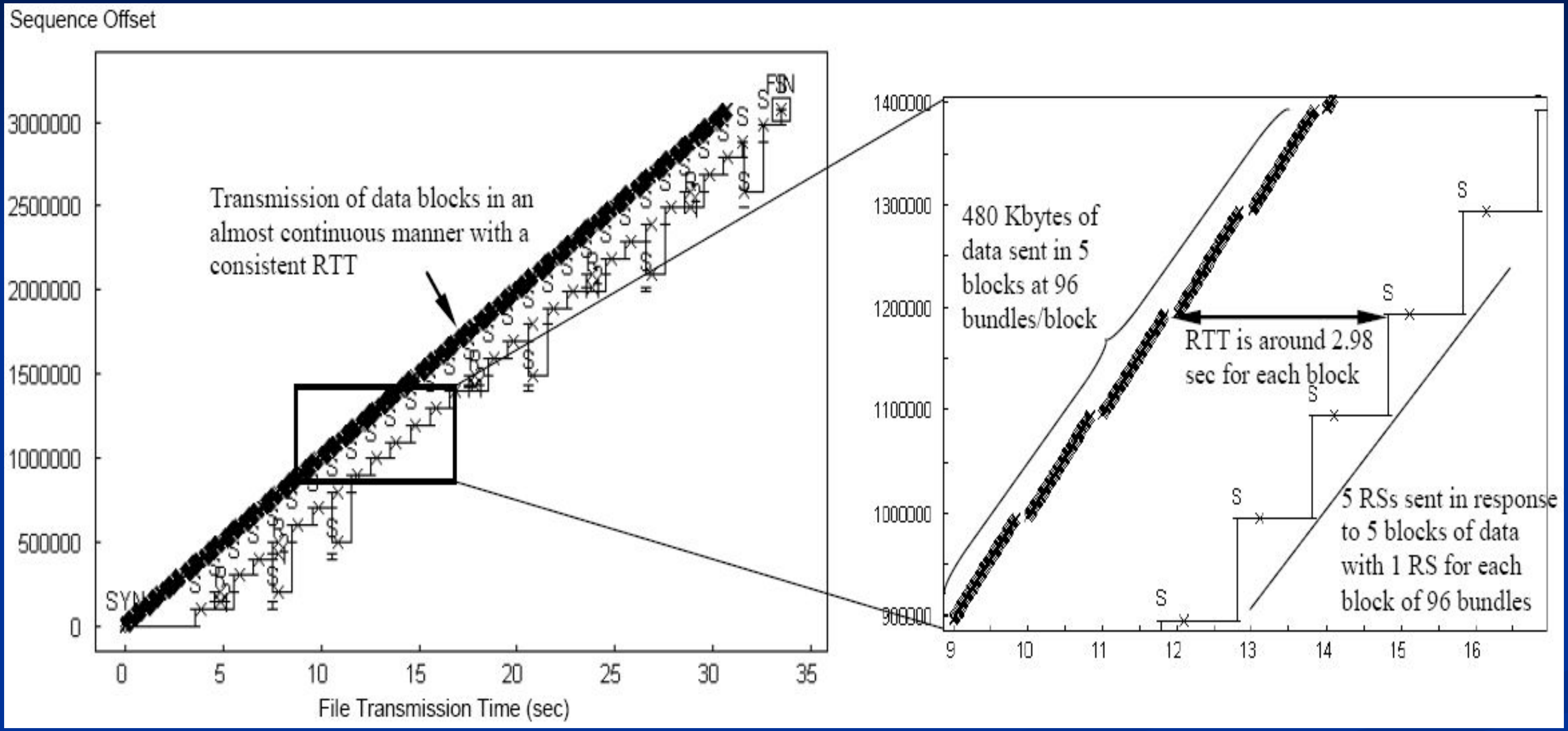
A Time Sequence Graph (TSG) for LTP transmission of a 3 Mbytes file at 24 bundles/block with a cislunar channel ratio of 500/1, a BER of 10E-7, and a window size of 1 Mbytes.

Pattern with a Small Window Size of 1 Mbytes and a Small Block Size



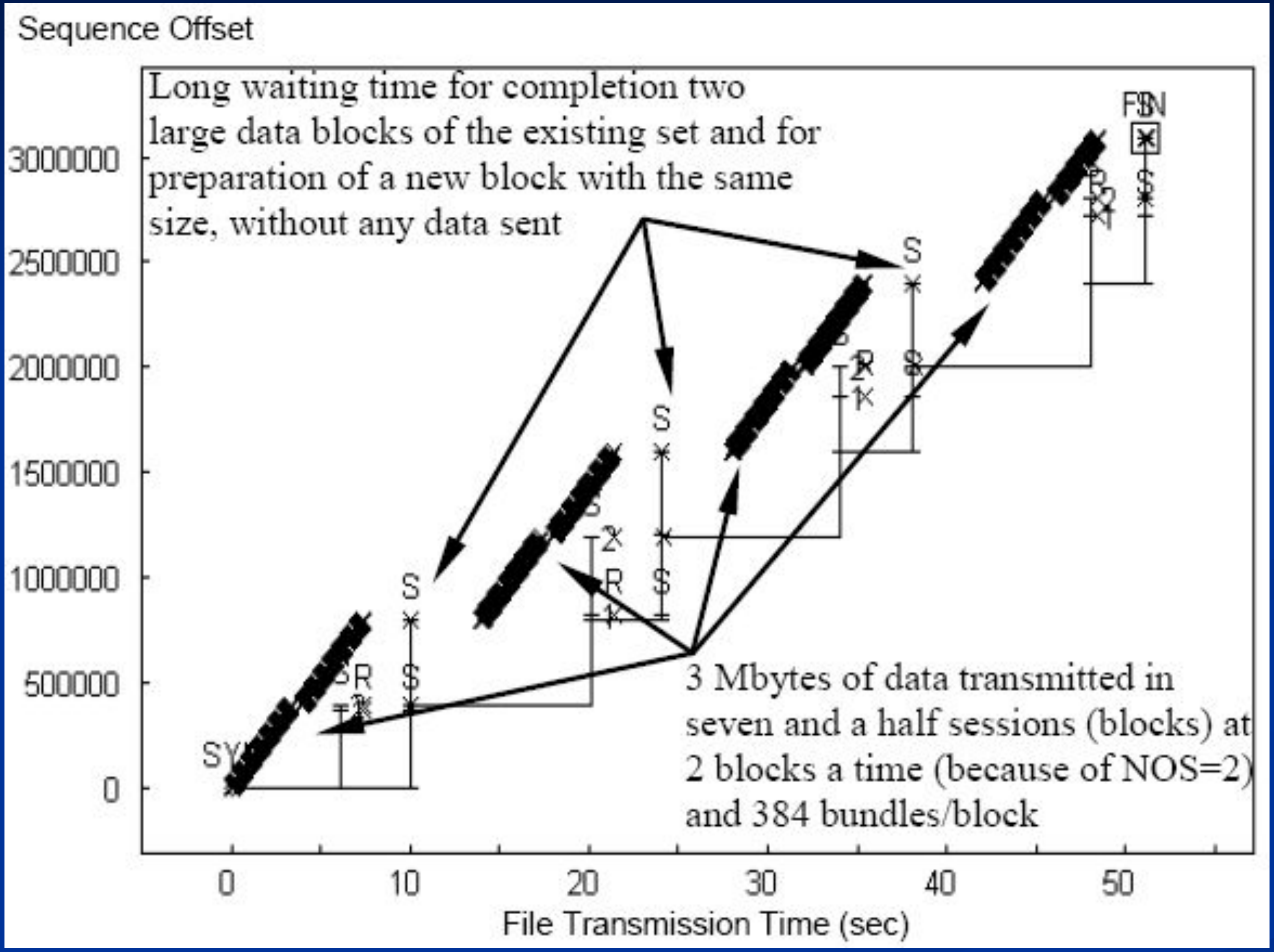
A typical LTP transmission pattern at 24 bundles/block with a cislunar channel ratio of 500/1, a BER of 10E-7, and a window size of 1 Mbytes.

Pattern with a Small Window Size of 1 Mbytes and a Moderate Block Size



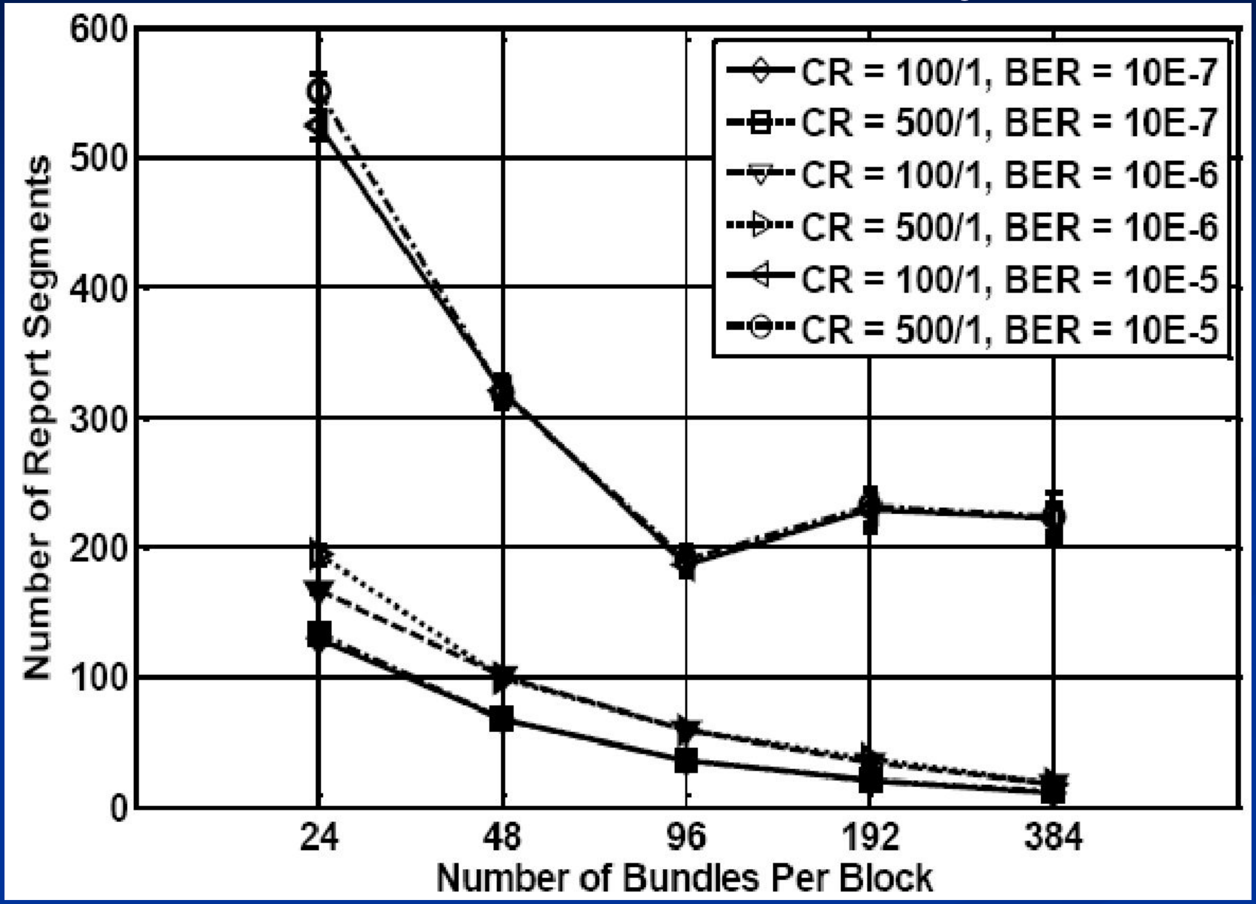
A typical LTP transmission pattern at 96 bundles/block with a cislunar channel ratio of 500/1, a BER of 10E-7, and a window size of 1 Mbytes.

Pattern with a Small Window Size of 1 Mbytes and a Large Block Size



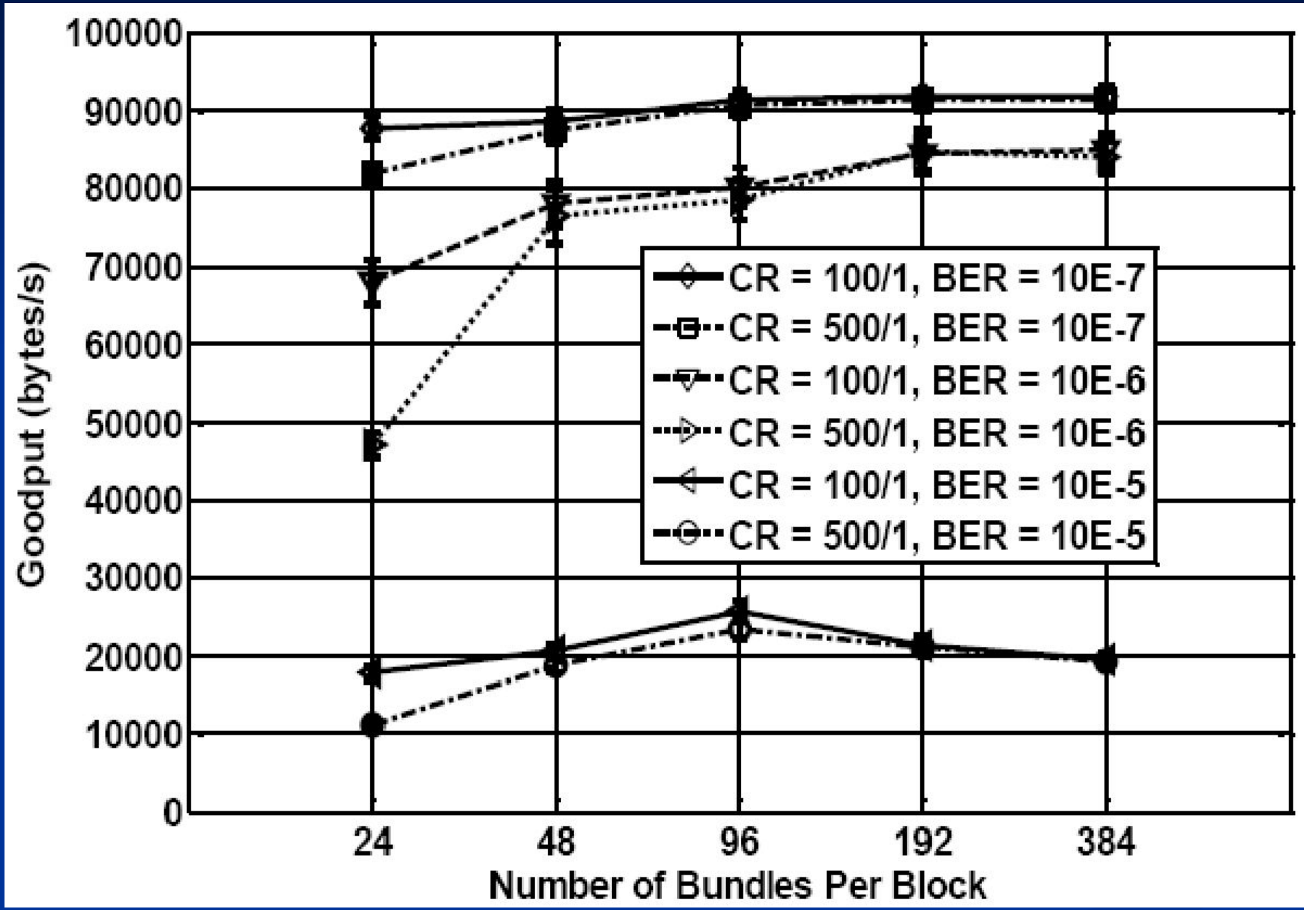
LTP transmission pattern at 384 bundles/block with a cislunar channel ratio of 500/1, a BER of 10E-7, and a window size of 1 Mbytes.

Number of Report Segments (RSs) with a Small Window Size of 1 Mbytes



Number of RSs of LTP in transmission of a 3 Mbytes file versus variable number of bundles per block with two asymmetric channel ratios, three BERs and a window size of 1 Mbytes

Pattern with a Large Window Size of 3 Mbytes



Goodput performance of LTP over a simulated cislunar channel with a window size of 3 Mbytes and two channel ratios of 100/1 and 500/1 for five aggregated block sizes—24 bundles/block, 48 bundles/block, 96 bundles/block, 192 bundles/block and 384 bundles/block.

Findings and Conclusions

- Aggregation of multiple BP bundles within a single LTP block has significant goodput advantage over the general "one bundle per block" approach for cislunar communications in the presence of channel-rate asymmetry and a moderately lossy channel (with a BER around 10E-6 or lower).
- Aggregation of a large number of bundles within a single block significantly reduces the rate of ACKs on the highly constrained ACK channel, resulting in significant performance improvement over a small aggregated block.
  - The advantage is more obvious for a higher asymmetric channel ratio (500/1).

Findings and Conclusions

- It is also found that the aggregated block size must be larger than a threshold in order to avoid an increase in round-trip-time for high performance of DTN
  - The threshold is 35 Kbytes in our experimented work
- When the data amount of the aggregated block reaches the data channel capacity, LTP achieves the best goodput performance.
- However, LTP transmission shows quite different performance depending on the window size, when a block size exceeds the data channel capacity.

Summary

- Space Networks and TCP/IP Problems in Space
- Overview of DTN for Space
- Main Protocols of DTN
- Performance Comparisons between TCP, UDP and LTP in Moon-Earth Communications
- Performance Discussion of BP/LTP

Questions?

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