Performance of Licklider Transmission Protocol (LTP) in LEO-Satellite Communications with Link Disruptions

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Abstract—**Near Earth missions ranging from low-Earth orbit (LEO) to Earth-Sun Lagrangian points will continue to be a majority of future space missions. A few works have been done with delay/disruption tolerant networking (DTN) technology for LEO-satellite communications and provided feasibility for its adoption in LEO space missions. However, no much work has been done to fully evaluate the performance of DTN in such an environment, especially in the presence of long link disruption, data corruption and loss, and link asymmetry. In this paper, we present an experimental performance evaluation of DTN architecture and protocol stack, with Licklider transmission protocol (LTP) serving as a convergence layer adapter (CLA) underneath bundle protocol (BP), in a typical LEO-satellite communication infrastructure accompanied by a very long link outage, various packet corruption and loss rates, and channel rate symmetry and asymmetry. The experiment was conducted by performing realistic file transfers over a PC-based test-bed.**

Index Terms—**Cognitive Computation, LEO-satellite, Space Internet, DTN, bundle protocol (BP), LTP**

I. Introduction

From early low-Earth orbit (LEO) scientific satellites, through the advanced geo-stationary orbit (GEO) tracking and data relay satellite system (TDRSS) and the deep space networks (DSN), to the current space Internet and interplanetary Internet (IPN), space communications have been changing significantly with respect to both communication architecture and operating model. This movement from the traditional model of managed, mission-specific pairwise links to an automated network involving multiple nodes using relay and the Internet technologies is of historical significance.

A large number of network transmission protocols have been developed for satellite and space communication environments [1-4]. A new communication architecture called delay tolerant networking (DTN) [5], has been developed to combat the long link delay and frequent link disruptions that generally characterize space channel. The DTN architecture adopts a store-and-forward custody transmission mechanism to deal with challenging environments: each DTN node keeps a copy of every data packet sent until receiving an acknowledgment (ACK) confirming the packet has been received successfully from the next node in the end-to-end path. This ensures that no data packets are lost even if a router is temporarily out of sight due to occultation or rotation in space. DTN is considered the only candidate protocol that is approaching the level of maturity required to handle the delays and disconnection inherent in space operations.

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In fact, DTN can operate across various communication environments involving both a short-propagation-delay such as in near-planetary or terrestrial environments and a long-propagation-delay such as in deep space [6]. Because of its original development for the IPN, most of the current works on DTN for space communications focus on deep-space environment.

Near Earth missions ranging from LEO to Earth-Sun Lagrangian points will continue to be a majority of future space missions [7]. A few works have been done with Delay/disruption tolerant networking (DTN) technology for LEO-satellite communications and shown feasibility for its adoption in LEO space missions [6]. However, no much work has been done to fully evaluate the performance of DTN in such an environment, especially in the presence of long link disruption, data corruption and loss, and link asymmetry.

In this paper, we present an experimental investigation of DTN architecture and protocol stack, with Licklider transmission protocol (LTP) [8] serving as a convergence layer adapter (CLA) [9] underneath bundle protocol (BP) [9], in a typical LEO-satellite communication infrastructure accompanied by a very long link outage, various packet corruption and loss rates, and channel rate symmetry and asymmetry. The experiment was conducted by performing realistic file transfers over a PC-based test-bed. The intent of the work was to provide a performance evaluation of the LTP-based DTN in LEO-satellite communications in an experimental manner.

The remainder of the paper is organized as follows: In Section II, we discuss the related work on DTN for space; we provide an overview of DTN BP and CLAs in Section III; we briefly describe the experimental setup and configurations in Section IV; in Section V, we present the experimental results; the conclusions are drawn in Section VI.

II. Related Work on DTN for Space Communications

Some transmission control mechanisms [10-13] have been proposed for DTN for space communications. Typically, in [10], a congestion control mechanism is developed for space DTN

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based on both storage-routing schemes and next-hop selection policy. An advanced Random Early Detection (RED) and Explicit Congestion Notification (ECN) are also implemented within the DTN architecture for IPN. In [11], some congestion aware routing strategies are proposed for DTN-based IPN. A DTN congestion control mechanism is also proposed based on an economic pricing model [12]. In [13], a hop-by-hop local flow control mechanism is introduced to DTN architecture to control buffer overflow, link saturation, and unnecessary retransmissions in IPN.

Some experimental work has recently been done to verify the effectiveness of the DTN architecture and protocols in space and interplanetary communications. The Deep Impact Network Experiment (DINET) of DTN [14] was conducted by JPL in 2008 using the EPOXI spacecraft located about 15 million miles from Earth as the first DTN router in space. The DINET project validated the use of DTN protocols in deep-space Internet. NASA also began operating DTN on the International Space Station (ISS) in July 2009, in a deployment led by the University of Colorado, Boulder (CU-Boulder) [15]. A few experiments have been done with a LEO-satellite such as the one with a United Kingdom disaster monitoring constellation (UK-DMC) satellite [16]. These works only demonstrated a possibility to use DTN for data transfer over a LEO-satellite. However, there is no detailed, numerical performance evaluation result provided yet.

Different from the above works, in this work, we intend to evaluate the performance of LTP CLA of DTN in a controlled experimental manner in a LEO-satellite environment in the presence of long link disruption, data corruption and loss, and channel rate asymmetry.

III. Overview of DTN BP and Convergence Layer Protocol Adapters

Operating at the application layer of the Internet architecture, BP [9] forms a store-and-forward overlay network to provide custody-based, message-oriented transmission in DTN. BP is designed to cope with connectivity interruption and to take advantage of scheduled, predicted, and opportunistic connectivity. It conducts message transmission and reception using the services of an underlying CLA [9] stack. Currently, the TCP-based CLA (i.e., TCPCL) [16], user datagram protocol (UDP)-based CLA, and LTP-based CLA [8] are supported under BP.

The TCPCL works jointly with underneath TCP to provide reliable communication services between DTN nodes. A UDP-based CLA is intended for use over dedicated private links where congestion control is not required, and it assumed that a bundle will always fit into a single UDP datagram of around 64 Kbytes. This means that a UDP CLA is not able to support segmentation of large DTN bundles across multiple UDP packets. Different from the basic UDP-based CLA implementation, LTP-based CLA [8] supports segmentation of large DTN bundles across multiple UDP packets. It provides selectable reliable and unreliable services according to mission requirements and transmission capability. Therefore, it is considered that LTP provides both TCP-like and UDP-like transmission service. Due to paper length limitation, the design and operation of LTP are not discussed in details here. Readers can refer to [17] for its details and for a summarized side-by-side comparison between TCP and LTP for their design differences.

Table I.
Experimental Factors and Configuration.

Experimental Factors	Settings/Values
DTN Protocol implementations	Interplanetary Overlay Network (ION) v2.2.1 from JPL, California Institute of Technology, CA
DTN protocol layering	BP/LTPCL/UDP/IP/Ethernet
BP custody transfer option	Enabled
LTP red/green settings	Bundles are set 100% red data
MTU size	1500 bytes
Operating system	Fedora Linux 8 (kernel 2.4.18-3)
Packet corruption rate	0%, 10%, and 20%
Packet loss rate	0% and 5%
Channel ratio (Data rate : ACK rate)	1/1 (6.4 Mbit/s : 6.4 Mbit/s, Symmetric channel) 800/1 (6.4 Mbit/s : 8 Kbit/s, Asymmetric channel)
One-way link delay	5 ms (A typical LEO-satellite link delay)
Experimental file size	5,000,000 bytes
Sample size	16 repetitive runs for each configuration

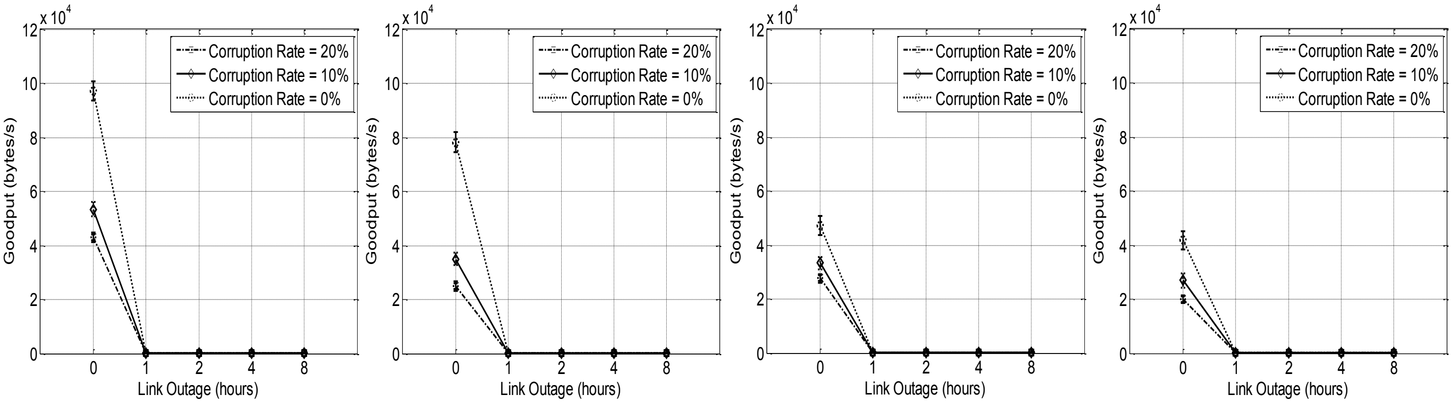
IV. Experimental Setup and Configuration

This work focuses on performance evaluation of DTN in a LEO-satellite environment. LEO-satellite communication architectures have been well described in literature. For a simple point-to-point LEO-satellite communication architecture, refer to [18]. A PC-based Space Communication and Networking Testbed (SCNT) was built at Lamar University to emulate a relay-type of LEO-satellite communications infrastructure for the proposed experimental evaluation of DTN. See [17] for a block diagram of the SCNT and a detailed discussion of its operation. Previous research [17, 18] shows that the evaluation results obtained from the SCNT have generality and the test-bed can effectively evaluate the realistic performance of a protocol. A network emulation package of Linux OS, netem [19], was adopted to simulate the satellite channel conditions such as link outage, propagation delay, packet corruption, and packet loss.

Table I lists the major protocol configuration parameters of our experiment. The experiment was conducted by transferring a text file of 5 Mbyte from the simulated LEO-node in space to the ground station node on the Earth, with the experimental parameters configured over the channel. Each file transfer was performed sixteen (16) times in each configuration. This sample size was chosen according to Fisher’s Least Significant Difference comparison procedure [20].

V. Experimental Results and Discussions

In this section, we present and discuss the performance evaluation results of the LTP-based DTN protocol stack. We



(a) (b) (c) (d)

Fig. 1. Goodput comparison for the LTP-based DTN protocol to transmit a 5 Mbyte file over LEO-satellite channels with respect to no link outage and long link outages involved. (a) SYM with Loss Rate=0%. (b) SYM with Loss Rate=5%. (c) ASYM with Loss Rate=0%. (d) ASYM with Loss Rate=5%.

start with a rough comparison of the goodput performance with and without a link outage involved. Following this, we discuss the performance of the protocol without a link outage. We then discuss the performance when a long link outage is involved.

A. *Comparison of Performance with and without Link Outage Involved*

In Fig. 1, a comparison of goodput performance for the LTP-based DTN protocol to transmit a 5 Mbyte file over LEO-satellite channels is presented among three link corruption rates with respect to no link outage and long link outages of 1 hour, 2 hours, 4 hours and 8 hours involved. A direct observation is that for all the experimented channel-rate configurations (i.e., symmetric and asymmetric) and packet loss rates (0% and 5%), the transmissions without a link outage involved show significantly higher goodput than those with a link outage involved. While the goodput without a link outage involved ranges from 20,000 bytes/s to 100,000 bytes/s, the goodput with a link outage involved merges and approaches zero. This is reasonable because a long link outage dominates the short file transmission time, resulting in very poor goodput performance, provided that a high-speed data channel rate of 6.4 Mbps was configured for transmission of a 5 Mbyte file during the experiment.

It is also observed that the performance is significantly different among three packet corruption rates of 0%, 10% and 20% for all the configurations when no link outage is involved. In comparison, their performance merges and shows no statistically significant differences for all link outage durations varying from 1 hour to 8 hours.

As another observation, for all three corruption rates, the goodput performance without a link outage decreases when either a packet loss rate of 5% and/or asymmetric channel are introduced. This can also be easily explained. Data loss causes retransmission of data packets (although in a deferred mode), creating additional file transmission time thus degradation of goodput. When channel-rate asymmetry is involved, the forward channel rate (from the Earth to a LEO-satellite) may be too low to handle the transmission of returning ACKs effectively, resulting in late arrival or frequent losses of ACKs and consequentially performance degradation of the protocol. The impact of data loss, data corruption, and channel-rate

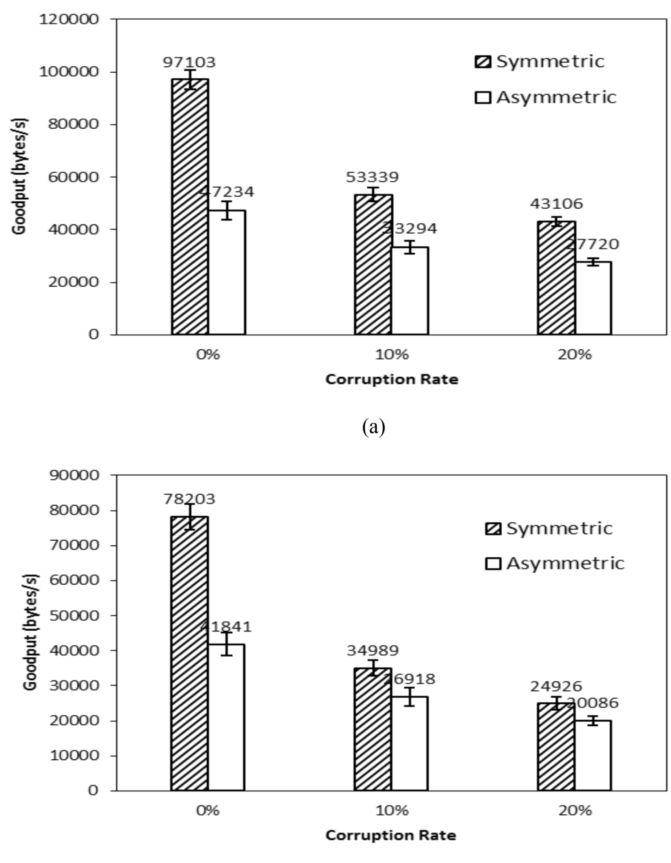


Fig. 2. Goodput comparison for the LTP-based DTN protocol to transmit a 5 Mbyte file over LEO-satellite symmetric and asymmetric channels with respect to packet corruption rates, at two packet loss rates. (a) Loss Rate=0%. (b) Loss Rate=5%.

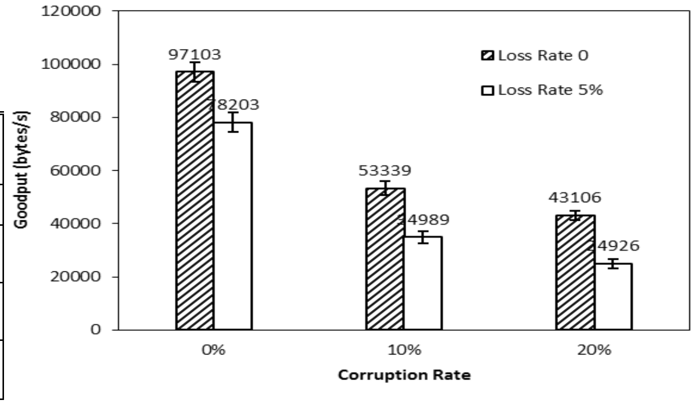
asymmetry on the performance of LTP will be discussed in details in Sections B and C.

B. *Performance without Link Outage Involved*

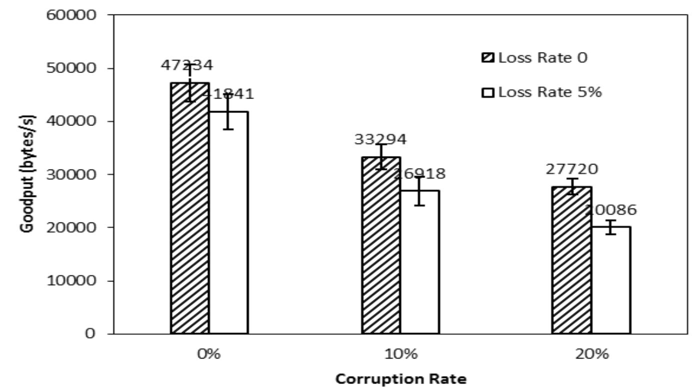
Fig. 2 illustrates a comparison of goodput performance for the transmissions over symmetric and asymmetric channels at three different packet corruption rates of 0%, 10% and 20%,

TABLE II.
NUMERICAL COMPARISON OF THE AVERAGED GOODPUT PERFORMANCE BETWEEN SYMMETRIC AND ASYMMETRIC CHANNELS.

Corruption Rate	Goodput at Loss Rate=0% (bytes/s)			Goodput at Loss Rate=5% (bytes/s)		
	SYM	ASYM	SYM-ASYM	SYM	ASYM	SYM-ASYM
0%	97103	47234	**49869**	78203	41841	**36362**
10%	53339	33294	**20045**	34989	26918	**8071**
20%	43106	27720	**15386**	24926	20086	**4840**



(a)



(b)

Fig. 3. Goodput comparison for the LTP-based DTN protocol to transmit a 5 Mbyte file over LEO-satellite channels between two packet loss rates with respect to packet corruption rates, for two channel configurations. (a) SYM. (b) ASYM.

TABLE III.
NUMERICAL COMPARISON OF THE AVERAGED GOODPUT PERFORMANCE BETWEEN TWO PACKET LOSS RATES.

Corruption Rate	Goodput over SYM Channel (bytes/s)			Goodput over ASYM Channel (bytes/s)		
	Loss Rate 0%	Loss Rate 5%	Difference (0%-5%)	Loss Rate 0%	Loss Rate 5%	Difference (0%-5%)
0	97103	78203	**18900**	47234	41841	**5393**
10%	53339	34989	**18350**	33294	26918	**6376**
20%	43106	24926	**18180**	27720	20086	**7634**

with packet loss rates of 0% and 5%. We observe that for both packet loss rates, the transmissions with channel-rate symmetry show significantly higher goodput than those with channel-rate asymmetry, and the performance advantage is more significant when a loss rate of 0 is involved. The biggest performance advantage is observed at a packet corruption rate of 0%, and it gradually decreases with the increase in the corruption rate. The advantage drops significantly when a 10% corruption rate is introduced but not significantly when the corruption rate is further increased to 20%.

Table II provides a numerical comparison of the averaged goodput performance between channel-rate symmetry and channel-rate asymmetry with both packet loss rates, for the transmissions at all three corruption rates. As we see, the goodput difference between symmetric channel and asymmetric channel at a loss rate of 0% decreases from 49869 bytes/s to 20045 bytes/s and then to 15386 bytes/s when the packet corruption rate is increased from 0% to 10% and then to 20%. In comparison, the goodput difference at a loss rate of 5% decreases more significantly, from 36362 bytes/s to 8071 bytes/s and then to only 4840 bytes/s.

The comparison results indicate that the impact of LEO-satellite channel-rate asymmetry (with a channel ratio of around 800/1) on the goodput performance of LTP-based DTN decreases along with the increase in packet corruption rate. The impact decreases more significantly when data loss (around 5%) is occurred over the channel in comparison to a no loss transmission. In other words, the impact of packet corruption (with a rate around 10%~20%) on the goodput performance of LTP increases when the channel rate becomes asymmetric. The impact increases more significantly over a lossy LEO-satellite channel.

Fig. 3 illustrates a comparison of goodput performance for the transmissions with packet loss rates of 0% and 5% at three packet corruption rates for both symmetric and asymmetric channels. For both channel-rate configurations, the transmissions with a packet loss rate of 0% show significantly higher goodput than those with a packet loss rate of 5%, and the performance advantage is more significant for symmetric channel. This tells us that the impact of the experimented packet loss rate (around 5%) on the goodput performance of LTP is more significant for symmetric channel than that for asymmetric channel.

In contrast to the comparison in Fig. 2 where the performance advantage decreases with respect to the increase in corruption rate, the advantage is about consistent in Fig. 3 for both symmetric and asymmetric channel configurations. Table III provides a numerical comparison of the averaged goodput performance between the packet loss rates of 0% and 5% for both symmetric and asymmetric channels at all three corruption rates. As we see, the goodput differences between two loss rates for symmetric channel is around 18500 bytes/s

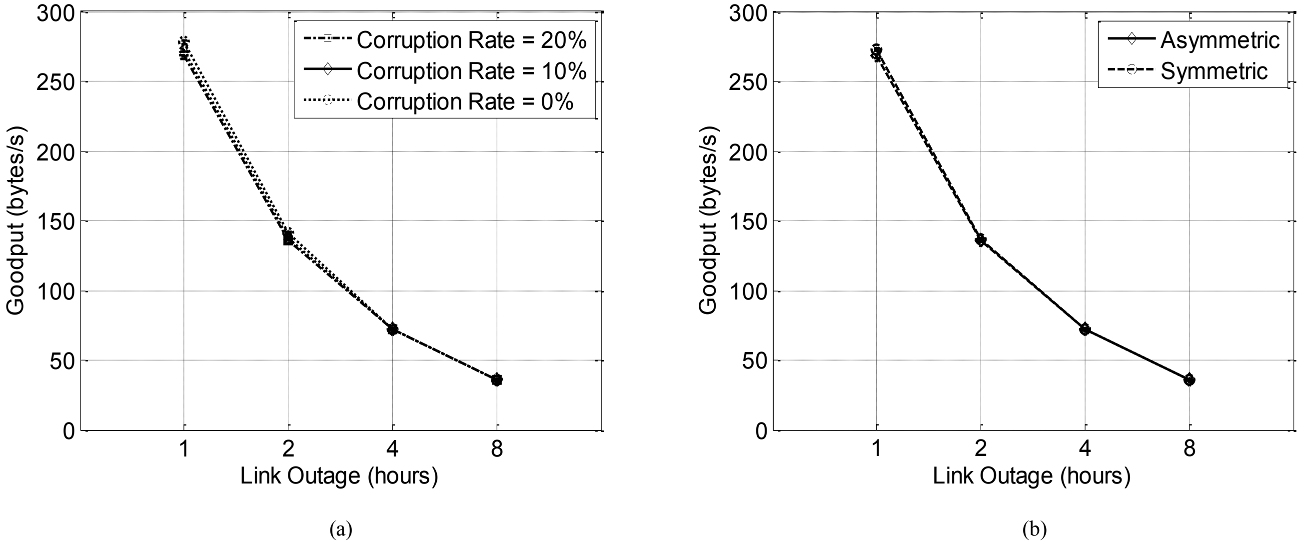


Fig. 4. Goodput comparison for the LTP-based DTN protocol to transmit a 5 Mbyte file over LEO-satellite channels with respect to four link outages (i.e., 1 hour, 2 hours, 4 hours, and 8 hours) involved during transmission. (a) Comparison among three corruption rates with asymmetric channel and a loss rate of 5%. (b) Comparison between symmetric channel and asymmetric channel with a corruption rate of 20% and a loss rate of 5%.

at all three corruption rates while it varies in the range of 5400 bytes/s~7600 bytes/s for asymmetric channel. The comparison results indicate that for each of the symmetric and asymmetric channel configurations, the impact of data loss rate is about the same regardless of the variations of packet corruption rate (0%~20%) for both symmetric and asymmetric channels, but the impact is more significant for symmetric channel than for asymmetric channel.

C. *Performance with Link Outage Involved*

In Fig. 4, we compare the averaged goodput performance for the LTP-based DTN protocol to transmit the 5 Mbyte file over LEO-satellite channels experiencing long link disruptions of 1 hour, 2 hours, 4 hours and 8 hours. In Fig. 4(a), the goodput performance is compared among three corruption rates with asymmetric channel and a loss rate of 5%. The comparisons with symmetric channel and/or other loss rates show very similar results, and therefore, they are not presented in Fig. 4. An obvious observation is that for an exponential increase in the link disruption duration, there is an almost exponential decrease in goodput. In fact, each time when the link outage duration is doubled, the goodput drops to about half. The goodput performance varies in the range of 280 bytes/s~40 bytes/s. We also observe that the goodput is actually about the same when the link outage duration is the same, regardless of the changes of packet loss rate, packet corruption rate, and channel-rate configuration (i.e., symmetric channel or asymmetric channel). This happens because a long link disruption contributes significantly to the total file transfer time even though there is no data transferred during the disruption. Therefore, the goodput of the LTP-based DTN transmissions is most adversely affected by link disruption time in comparison to the effect of packet corruption rate (0%~20%) and packet loss rate (0%~5%). In other words, for a transmission over LEO-satellite channels with long link disruptions, a long link disruption of one hour or longer absolutely dominates the file transfer time and thus goodput performance.

In addition, three packet corruption rates have little noticeable goodput differences for short disruption duration, especially at 1 hour, but they absolutely merge when the outage is around 4 hours~8 hours long. This indicates that the experimented packet corruption rate from 0% to 20% has little impact on the performance of the protocol when the link outage is short but it has no impact at all when the outage duration is around 4 hours or longer because a long outage has much more effect on the goodput than the experimented corruption rates.

To see the impact of channel-rate asymmetry on the performance of the protocol, we compare the goodput performance in Fig. 4(b) between symmetric channel and asymmetric channel with a corruption rate of 20% and a loss rate of 5%. The comparisons at other corruption rates and loss rates show very similar results, and therefore, they are not presented. Similar to the comparison in Fig. 4 (a), we see a roughly exponential decrease in goodput along with the exponential increase in link outage duration. We observe that the performance of two channel-rate configurations well merges. This indicates that the channel-rate configuration has no impact at all on the performance of the protocol because of the very long link outage which dominates the file transmission time.

VI. Conclusions

For transmissions over LEO-satellite channels without a link outage experienced, the impact of channel-rate asymmetry (with a channel ratio around 800/1) on the goodput performance of LTP-based DTN decreases along with the increase in packet corruption rate (from 0% to 20%). The impact decreases more significantly when packet losses (around 5%) are occurred over the channel. The impact of packet corruption (around 10%~20%) on the goodput performance of the protocol increases when the channel rate becomes asymmetric, and it increases more significantly over a lossy channel. In contrast, for each of the symmetric and asymmetric channel configurations, the impact of data loss rate (around 5%) on the goodput performance of LTP-based DTN is about consistent regardless of the variations of corruption rate (0%~20%), and the impact is more significant for symmetric channel than asymmetric channel. For transmissions with a long link outage (1 hour~8 hours) experienced, the goodput decreases exponentially along with an exponential increase in link outage duration. Such an extremely long link outage dominantly degrades the goodput of LTP-based DTN which varies only in the range of 280 bytes/s~40 bytes/s, and the impact of a packet corruption rate around 20% (or less) and the impact of a packet loss rate around 5% (or less) are negligible. Under this condition, the channel-rate asymmetry with a channel ratio around 800/1 also has no impact at all on the performance of the protocol.

VII. FUTURE WORK

DTN has been used successfully for experimental file transfer in space communications. However, DTN has yet to be used operationally in long-running space flight missions. While evaluation of BP and supporting routing protocols is recognized as critical for DTN development, extensive evaluation and optimization of LTP is likewise critical before DTN is deployed in space flight.

In addition, the impact of the LTP flow control "window size" on the performance of DTN should also be investigated in order to achieve the maximum throughput of LTP.

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