Experimental Evaluation of Delay Tolerant Networking (DTN) Protocols for Long-Delay Cislunar Communications

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***Abstract*—TCP experiences severe performance degradation in cislunar communications because of some assumptions built into its design. Delay/disruption tolerant networking (DTN) is a class of network techniques that is developed to work over internet protocols to accommodate long link delay and frequent link disruptions in space communication environment. Most of the work concerning DTN protocols and techniques focused on its application in terrestrial wireless network and sensor-based networks. In this paper, we present an experimental evaluation of the DTN protocols with BP/TCPCL running on top of TCP/IP over a long-delay cislunar communication channel with and without link disruption. We hope the experiment results and analysis in this paper will apply equally well in any deep space mission with a round-trip time (RTT) that is comparable to that of the Earth-Moon system.**

Index Terms—Cislunar communications, Interplanetary Internet, DTN, BP, TCP, and TCPCL

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is moving toward network centric communications based on appropriate architecture and network protocols. The NASA has an interest in operating cislunar communications using the Internet-type protocols such as the Transmission Control Protocol/Internet Protocol (TCP/IP) [1, 2]. TCP [3] experiences severe performance degradation in cislunar communications due to some assumptions built into its design. Delay/disruption tolerant networking (DTN) [4, 5] technology offers a solution to highly stressed communications in space flight environments, including those in near-Earth, cislunar and deep space missions.

DTN is a class of network techniques that used store-and-forward message switching mechanism to combat long link delay and frequent link disruptions that generally characterize space communications. With the message switching, DTN moves the whole message or fragments of such messages from storage on sender node to storage on next node. The store-and-forward message switching ensures that no data packet gets lost, even if a router is out of sight because of rotation in space. DTN communications use an application-layer protocol, the Bundling Protocol (BP) [6], to construct a store-and-forward overlay network. The operation of BP requires the services of a convergence layer protocol (CLP) below it to send and receive bundles using the underlying internet protocols [7]. Main CLPs include TCP, UDP, and Saratoga [8], and Licklider Transmission Protocol (LTP) [9]. The TCP-based convergence layer protocol (TCPCL) for DTN uses the well-known TCP to provide reliable communication services between DTN nodes. The NASA is interested in deploying "DTN for space" and hopes to fly with it on space missions soon.

Extensive work has been done in studying the DTN protocols and techniques [10-17]. However, most of these works focus on its application in terrestrial wireless networks and sensor-based networks. As yet, there is no solid work done in evaluating its effectiveness and performance when applied for an interplanetary Internet such as cislunar environment, even though DTN was originally conceived for deep-space communications. Apart from previous research, we have been investigating the operation of the DTN protocol in interplanetary communication environments, mainly in cislunar domains. In this paper, we present an experimental evaluation of the DTN protocols with BP/TCPCL running on top of TCP/IP over a long-delay cislunar communication link with and without link disruptions.

The remainder of this paper is organized as follows. In Section II, we describe the experimental setup and configuration. We present and discuss the experimental results in Section III. Concluding remarks along with some future work are drawn in Section IV.

II. EXPERIMENTAL SETUP AND CONFIGURATION

A PC-based Space Communication and Networking Testbed (SCNT) was built as an experimental platform for performance evaluation of networking protocols developed for space Internet. SCNT was built by inheriting core design ideas from space link simulator (SLS) [18] but was extended to perform relay operation. The SCNT can be used to conduct real-time file transfer experiments by running the network protocol stacks. The testbed emulated major space communication characteristics including different link delays, BER, intermittent connectivity (link outage), store-and-forward capability, and various channel bit-rates that generally exist in a realistic space environment.

Fig. 1 illustrates a block diagram of SCNT. The test-bed consists of Linux-based file source personal computers (PCs) TX (*tx.lamar.edu*), file relay MX (*relay.lamar.edu*), file destination RX (*rx.lamar.edu*), and the SLS which connects three file PCs. The TX and relay MX function as a cislunar lander and orbiter, respectively, while RX functions as a ground station on the Earth. The relay orbiter is designed for

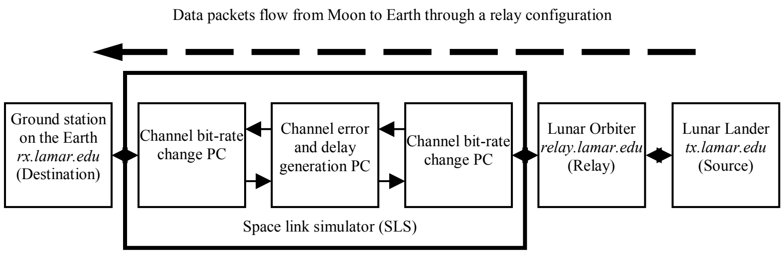


Fig. 1. Block diagram of the SCNT test-bed.

TABLE I.
EXPERIMENTAL FACTORS AND CONFIGURATIONS

Experimental Factors	Settings/Values
DTN implementation	DTN-2 Reference Implementation V2.5.0
DTN protocol layering	BP/TCPCL/TCP/IP
Operating system	Red-Hat Linux 7.3 (kernel 2.4.18-3)
One-way link delay	1280 ms, 1500 ms, 2000 ms, 2500 ms, 3000 ms, 3500 ms, 4000 ms, 4500 ms, and 5000 ms
Channel rate	115,200 bit/s : 115,200 bit/s
Link outage	no breaks, 1 break (30s, 60s, 90s, and 120s)
BER	0, 10^{-6}, and 10^{-5}
Experimental file size	1,000,000 bytes

the purpose of store-and-forward relay operation when the link between the Earth and Moon/Mars is unavailable due to occultation or some other reasons. The SLS is a PC-based Virtual Instrument (VI) designed to provide the simulation of space communication characteristics [18].

Table I lists the major protocol configurations and parameters of our experiment. The file transfer is operated by running BP/TCPCL over TCP/IP. The BP/TCPCL protocols are from DTN-2 Reference Implementation V2.5.0. The TCP and IP protocols are all protocol implementations that come with the Red-Hat Linux 7.3 (kernel 2.4.18-3) operating system running on TX, MX, and RX.

We experiment with the DTN protocol suites over the cislunar link without disruption and with link disruption which is designed to evaluate its store-and-forward capability. The duration of link disruption is 30s, 60s, 90s and 120s. The data rates for the return and forward channels are 115,200 bit/s and 115,200 bit/s, respectively. We chose three BERs, 0, 10^{-6}, and 10^{-5}, to simulate an error free, a moderate error rate, and a maximum acceptable error rate on the channel. The minimal one-way link delay between the Earth and Moon is around 1.25 sec, while the maximal link delay can be as high as 5 sec [2]. With this range, we choose nine different link delays in our experiment, i.e., 1280 ms, 1500 ms, 2000 ms, 2500 ms, 3000 ms, 3500 ms, 4000 ms, 4500 ms and 5000 ms, to evaluate the performance of DTN in cislunar communication.

The experiment was conducted by transferring a text file of 1,000,000 bytes (1Mbyte) from the simulated source node on the Moon, TX, through the orbiter, MX, to the destination node on the Earth, RX, of the SCNT test-bed. The performance was evaluated by conducting the comparisons of the averaged file transfer time of 16 runs.

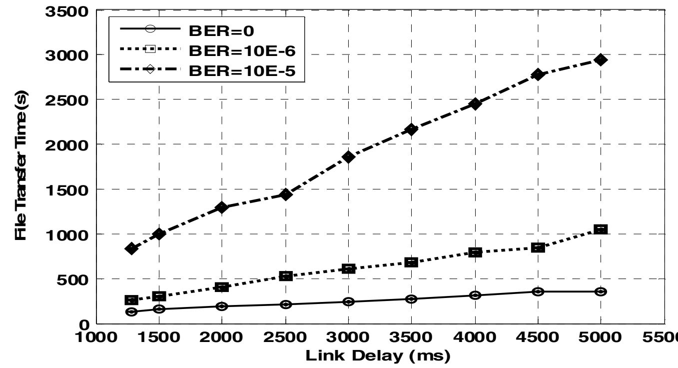


Fig. 2. Comparison of file transfer time for DTN transmissions over a cislunar channel without link disruptions at BERs of 0, 10^{-6} and 10^{-5}.

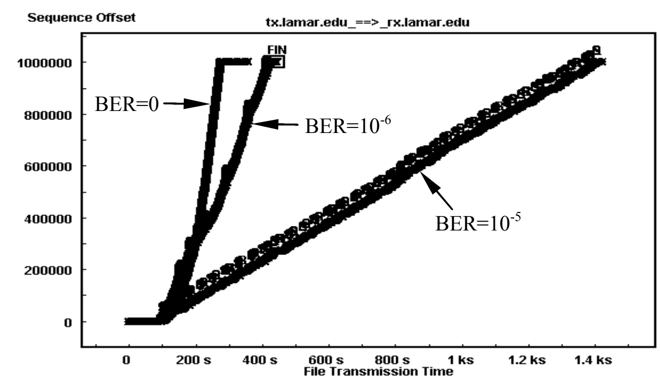


Fig. 3. Comparison of TSG graphs for DTN transmissions over a cislunar channel with a link delay of 2000 ms without link disruptions at BERs of 0, 10^{-6} and 10^{-5}.

III. EXPERIMENT RESULTS AND DISCUSSION

A. *Performance over Cislunar Channels without Link Disruptions*

Fig. 2 presents the file transfer time for the DTN protocol to transmit the 1 Mbyte file over cislunar channels with respect to different link delays and BERs. We see that at a BER of 0, variation of the file transfer time with respect to variation of link delay in the link is nominal, at a rate of only around 8%. At a BER of 10^{-6}, there is noticeable increase in file transfer time at a rate of around 20% with increase in link delay. At a BER of 10^{-5}, there is drastic, almost linear increase in file transfer time at a rate of around 60% with increase in link delay. In comparison, the difference in file transfer time among the transmissions at BERs of 0, 10^{-6} and 10^{-5} is getting large along with the increase in link delay.

To understand how the DTN protocol performs over a long-delayed cislunar channel accompanied by different BERs, Fig. 3 compares the time sequence graphs (TSGs) [19] of the DTN transmissions from MX to RX over cislunar channel with a link delay of 2000 ms at BERs of 0, 10^{-6} and 10^{-5}. A TSG shows transmission activity of packets and events that happen during the lifetime of a connection by plotting the packet sequence numbers versus the file transfer time. In the comparison of three TSGs in Fig. 3, the transmission with BER = 0 has the shortest file transfer time while the transmission with BER = 10^{-5} has the longest file transfer time. The increase in file transfer time is not significant when the

BER is increased from 0 to 10^{-6}. In comparison, a drastic increase occurs when the BER is increased to 10^{-5}. This is reasonable considering the different BERs configured over the channel. For the three transmissions, there are no retransmissions observed for the one with BER = 0 because of the error-free channel. In comparison, about 8 retransmission scenarios are observed in the transmission with BER = 10^{-6}, which is correct according to the calculation: $1000000\times8\times10^{-6} \approx 8$ errors. Similarly, around 80 retransmission scenarios are occurring in the transmission with BER = 10^{-5} in Fig. 3, which is supported by calculation: $1000000\times8\times10^{-5} \approx 80$ errors. A high BER over a noisy channel results in a large number of packets corruptions for the data transmission. This calls for the retransmissions of corrupted or dropped packets, thereby resulting in an increase in file transfer time and a decrease in goodput performance.

Corresponding to the comparison of the TSGs in Fig. 3, a comparison of goodput traces is provided in Fig. 4 for the DTN transmission over cislunar channel with link delay of 2000 ms at BERs of 0, 10^{-6} and 10^{-5}. When the channel is error free (i.e. BER=0), a goodput of around 3000 bytes/s is obtained. When a higher BER is introduced, a significant goodput decrease can be seen. The goodput decreases to around 2260 bytes/s at a BER of 10^{-6}, and to around 700 bytes/s at a BER 10^{-5}. The goodput decrease results from frequent retransmissions because of packet corruptions caused by channel BER. Note that the goodput reflects the performance of the transmissions when the one-byte keep-alive probing traffic, prior to and after data transmission, is taken into account. When the keep-alive message transmission is excluded, their goodput is much higher. They are around 5400 bytes/sec, 2550 byte/sec and 776 bytes/sec, respectively, according to the experimental results.

B. Performance over Cislunar Channels Link Disruptions

According to our experimental results, the DTN protocol is effective in handling a link disruption (30 sec~120 sec) experienced in data transmission over a cislunar channel, even with an existence of a very long link delay and a high channel BER. Fig. 5 presents the file transfer time for the DTN protocol to transmit the 1 Mbyte file over cislunar channels with link disruptions of 0 seconds, 30 seconds, 60 seconds, 90 seconds, and 120 seconds. At all three BERs, for the transmission with a particular link disruption time, we see roughly linear increase in total file transfer time along with a linear increase in link propagation delay. Similarly, for the transmission with a particular link propagation delay, we see total file transfer time increase along with a linear increase in link disruption time.

Fig. 6 illustrates the TSGs for the transmission of 1 Mbyte file over a cislunar link with link delay of 2000 ms, link disruption of 120 seconds at BERs of 0, 10^{-6} and 10^{-5}. Similar to the transmissions without link outage in Fig. 3, the TSGs in Fig. 6 (a), (b) and (c) have about zero error scenarios, eight error scenarios, and eighty error scenarios, corresponding to BERs of 0, 10^{-6} and 10^{-5}, respectively. For the transmissions at BERs of 0, 10^{-6} and 10^{-5}, each of their error scenarios involves packet corruption and retransmission using fast retransmission mechanism, similar to the typical error recovery scenario for the transmission without link disruption. In comparison with

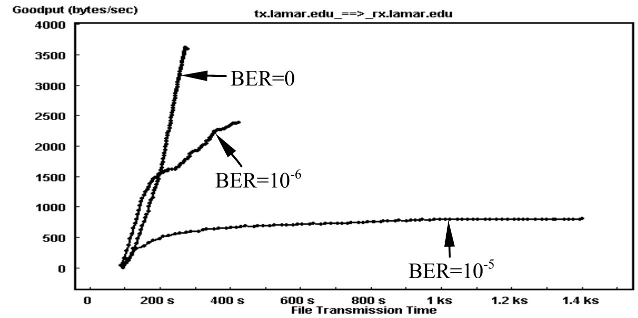
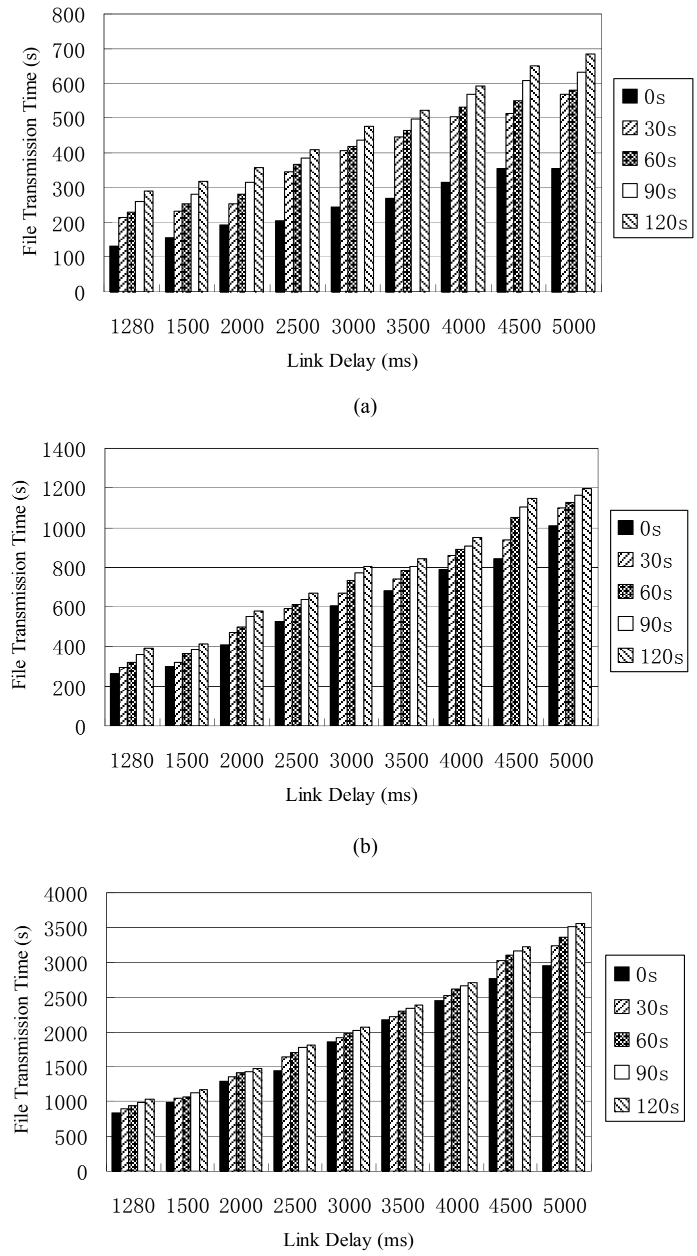


Fig. 4. Comparison of goodput performance for DTN transmissions over a cislunar channel with a link delay of 2000 ms without link disruptions at BERs of 0, 10^{-6} and 10^{-5}.



(c)

Fig. 5. File transfer time for DTN transmissions over a cislunar channel with different link delays and link disruptions. (a) BER=0. (b) BER=10^{-6}. (c) BER=10^{-5}.

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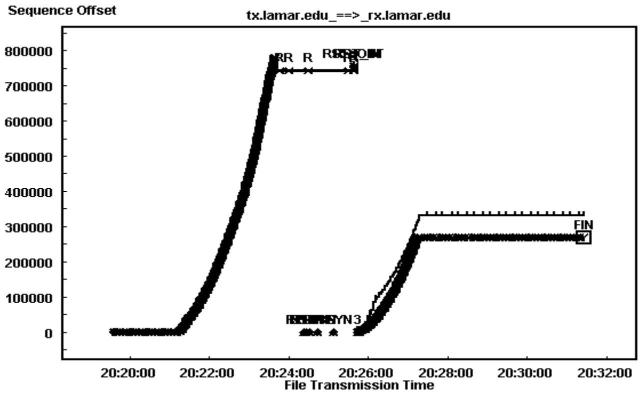
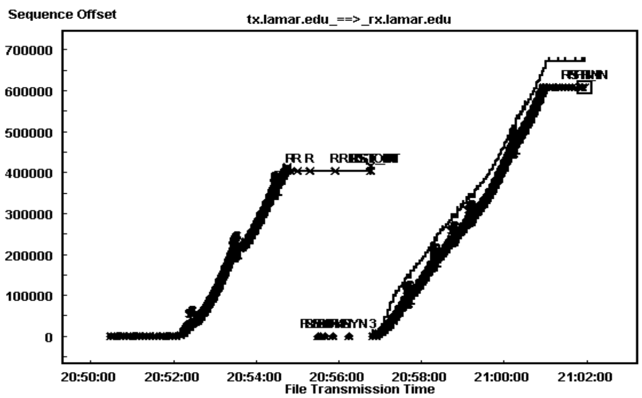
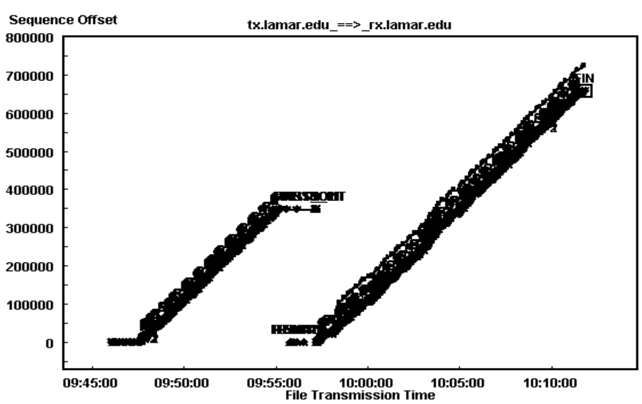


(a)

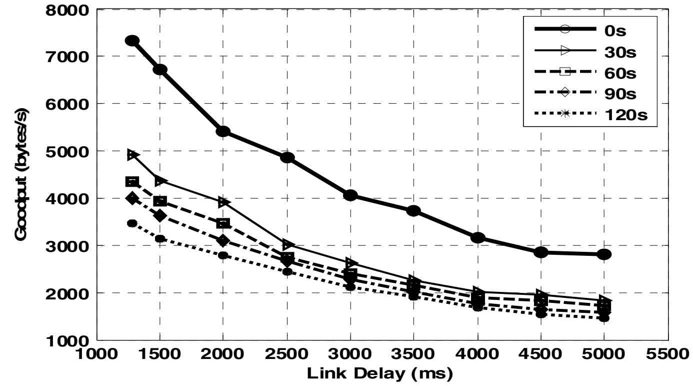


(b)

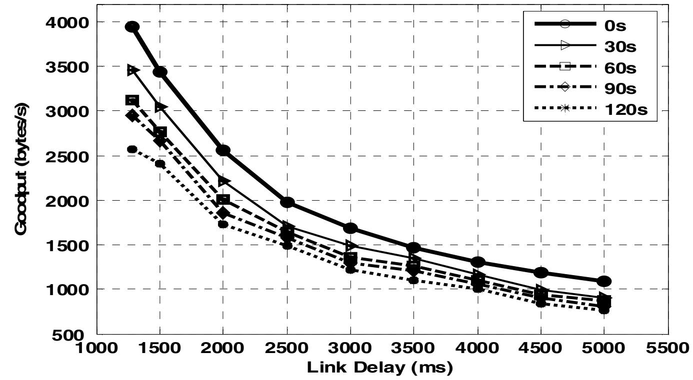


(c)

Fig. 6. Comparison of TSGs for DTN transmissions over a cislunar channel with a link delay of 2000 ms and link disruption of 120 seconds at different BERs. (a) BER=0. (b) BER=10^{-6}. (c) BER=10^{-5}.



(a)



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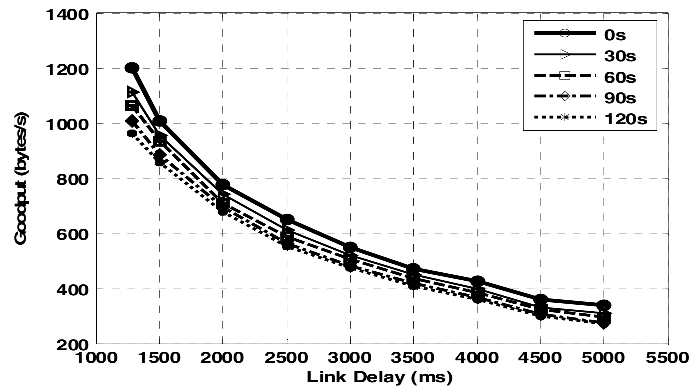

(c)

Fig. 7. Comparison of TSGs for DTN transmissions over a cislunar channel with a link delay of 2000 ms and link disruption of 120 seconds at different BERs. (a) BER=0. (b) BER=10^{-6}. (c) BER=10^{-5}.

the TSGs for the DTN transmissions without link disruption in Fig. 3, a major difference is that each transmission in Fig. 6 is divided into two separate segments by the long link disruption of 120 seconds. During the entire link disruption, the transmission of new packets is suspended and is not resumed until the disruption ends. In addition, we see MX performs retransmission of a particular segment at an exponential pace during the link disruption. When the link is disrupted, the last packet sent prior to the outage was already on the way. Because of the link disruption, MX does not receive the acknowledgment for it. Therefore, MX resends this packet. After about five trials of retransmissions at an exponential pace without any response received, MX gives up. In addition to the exponential retransmission of the last packet sent prior to the disruption, clusters of SYN packets are transmitted during link disruption at an exponential pace to probe the link connectivity. With link disruption, the sender cannot receive the ACK for the data packet sent at last, so it considers the link interrupted and sends SYN packets to request a new connection as a feature of TCP. Each cluster consists of one

SYN packet followed by five RSYN packets (i. e., Reset SYN packets), with the time intervals between two probes within each cluster also increasing exponentially. Once the link is resumed, MX starts transmitting the rest data until the whole file is sent out. Similar to the transmissions without link disruption in Fig. 3, the one-byte keep-alive probing packets are sent prior to and after data transmission to prevent a long idle connection.

In Fig. 7, we compare the goodput for the DTN protocol to transmit the 1 Mbyte file over cislunar channels with all five link disruptions at three BERs. For a transmission with a particular link disruption time, we see a roughly exponential decrease in goodput along with a linear increase in link propagation delay. For each BER, the differences in goodput among the transmissions with a different link disruption decreases along with the increase in link delay. Along with the increase in BER, the differences in goodput among the transmissions with different link disruptions also decrease and they tend to merge at the delay of 5000 ms and BER of 10^{-5}.

IV. CONCLUSIONS

When DTN runs over a long-delay cislunar channel without any link disruption, the ACK-clocked transmission mechanism in TCP-based DTN-2 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. The change in channel quality (mainly BER) has much less significant impact on the goodput for DTN transmissions with a long link delay than with a short link delay. For the transmissions with all three BERs, their goodput decreases exponentially with an additive increase in link delay, with the decreasing rate much higher at a low BER than at a high BER. The DTN protocol is effective in handling a link disruption (30 sec~120 sec) experienced in data transmission over a cislunar channel, even with the existence of a very long link delay and a high channel BER. There is a roughly exponential decrease in goodput along with the linear increase in link propagation delay.

According to the design of DTN protocol, we can choose to run it over UDP. With DTN version 2.5.0, we can not send a file larger than 64000 bytes with UDP. As future work, we intend to evaluate the performance of DTN over UDP with a much larger file with the updated version of DTN when it becomes available.

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