2019 IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)

Effect of Link Disruption on BP/LTP over a Relay-based Communication Architecture for International Space Station

Yan Zhou[1], Ruhai Wang[2], Lu Liu[1], Kanglian Zhao[3], Wenfeng Li[3], Xiangyu Lin[4], and Juan A. Fraire[5]
[1]School of Electronics and Information Engineering, Soochow University, Suzhou, 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, Nanjing, Jiangsu, P. R. China
[4]Beijing Institute of Spacecraft System Engineering, Beijing, P. R. China
[5]Universidad Nacional de Cordoba - CONICET, Córdoba, Argentina

***Abstract*—Delay-/disruption-tolerant networking (DTN) is developed for reliable data delivery in challenging communication environments characterized by a very long propagation delay and/or lengthy, random link disruption and highly lossy data links. Space-based networks and deep-space communication scenarios are typical of this type of communication environment. Bundle protocol (BP) and Licklider transmission protocol (LTP) were developed as the main protocols of DTN for reliable data transmission in space. Some studies have been done in evaluating the transmission performance, mainly throughput/goodput, on the use of BP/LTP for reliable file delivery in deep-space communication scenarios. The National Aeronautics and Space Administration (NASA) has also demonstrated DTN and implemented the use of its BP protocol on the International Space Station (ISS) for data delivery to the earth ground station. However, a little work has been done in analyzing the performance of BP/LTP for reliable data/file delivery from the ISS to the ground stations, especially in presence of link disruption. In this paper, analytical modeling and the numerical evaluation results are presented to study the effect of link disruptions on the use of BP/LTP for reliable file delivery over a relay-based communication architecture between the ISS and the ground stations.**

***Index Terms*—DTN, bundle protocol (BP), Licklider transmission protocol (LTP), space networks, satellite and space communications, international space station (ISS)**

I. Introduction

Proposed as a networking architecture in challenging communication environments, delay-/disruption-tolerant networking (DTN) [1, 2] is intended for reliable data and file delivery over a highly lossy communication channel characterized by a very long propagation delay and/or lengthy and random link disruption. DTN was intended for effective data delivery and to provide highly efficient communication service in challenging networking environments such as the harsh deep-space communication environment where traditional terrestrial network protocols (i.e., TCP/IP) typically do not work effectively. Bundle protocol (BP) [3] was developed as the main protocol of DTN for reliable data transmission in networking scenarios characterized by a long propagation delay, channel asymmetry, and link disruptions.

DTN data units, termed as BP *bundles*, convey the application data or file to be delivered at the end-to-end basis. Multiple "convergence layer adapters" (CLAs) [3] and the associated data transport protocols are proposed to work with BP, right underneath BP layer, for transport of bundles. The CLA proposed to work over harsh space communication link, Licklider transmission protocol (LTP) [4], is one of the main CLAs of DTN. This protocol stack is generally named as BP/LTPCL or simply, BP/LTP.

Extensive studies have been done in evaluating the transmission performance, mainly the throughput and/or goodput, on the use of BP and LTP protocols for reliable file delivery in cislunar and deep-space scenarios [5-8]. In addition to the application for deep-space communications that are typical of extremely long link delays, DTN and BP are also widely recognized by the community for its effective tolerance in scenarios typical of frequent and random intermittent link connectivity, although the link delay is not very long [9, 10]. The National Aeronautics and Space Administration (NASA) has also demonstrated DTN and implemented the use of its BP protocol on the International Space Station (ISS) for reliable data delivery service with respect to the payload and operations community [11, 12]. However, a little work has been done in analyzing the performance of BP/LTP for reliable data/file delivery from the ISS to the ground stations, especially in presence of link disruption.

It is broadly recognized that the relay-based communication architecture should be employed for effective data transmission in space communications in presence of intermittent link connectivity. The scenarios range from the near-earth ISS to the deep-space interplanetary internet. In this paper, analytical modeling and the numerical evaluation results are presented to study the effect of link disruptions on the use of BP/LTP for reliable file delivery between the ISS and the ground stations over a relay-based communication architecture.

In Section II, we revisit the concept of link disruption which is evitable in space communications, leading to an introduction of the relay-based communication architecture. In Section III, we present analytical modeling of the effect of link disruption on the transmission performance of BP/LTP for the ISS over the relay-based communication architecture. The numerical evaluation results are presented in Section IV. Based on the

978-1-7281-1545-0/19/$31.00 ©2019 IEEE
DOI 10.1109/SMC-IT.2019.00017

evaluation results, a summary and conclusions are presented in Section V, followed by a suggestion for future work at the end.

II. LINK DISRUPTIONS AND RELAY-BASED SPACE COMMUNICATIONS

While a very long propagation latency is inevitable in deep-space communications due to the long physical distance, link disruptions in deep-space scenarios occur either periodically or randomly. The link disruption events in deep-space communications may be caused either by spacecraft rotating or by the limited contact time. Taking the Mars exploration mission as an example [13], Mars having the rover landed on its surface may periodically "turns its back" with respect to the earth. This leads to periodic and lengthy link disruption in data delivery over the direct-to-earth communication channel.

It is broadly recognized that the relay-based communication architecture should be employed for more contact times and effective data transmission in space communications in presence of intermittent link connectivity. In recent deep-space missions with Mars Exploration Rovers, almost all the scientific data were delivered to the earth via the relaying spacecrafts in the Mars orbit. These flight missions have demonstrated that data return to the earth in deep-space missions can be significantly increased using the relaying spacecrafts. It is expected that similar performance improvement can be achieved for cislunar communications as well via the Moon's orbiting spacecrafts [9].

In comparison to the deep-space and cislunar communications, the relay-based communication architecture is even more widely adopted in the near-earth space flight missions (e.g., the ISS) for delivery of scientific data to the earth [10]. As a huge near-earth spacecraft station orbiting at approximately 300 km and travelling at around 17,000 mph, the ISS communicates with the earth ground station periodically with the direct-to-earth communication channel periodically disrupted for most of the time. To improve the data transmission efficiency, the primary data downlink paths of the ISS are designed to relay via the Tracking and Data Relay Satellite System (TDRSS) [14] Ku-band system operating at the geo-stationary earth orbit (GEO). The powerful TDRSS acts as bent-pipe relays to the ISS for effective data delivery to the earth.

Even with the widely adopted relay-based space communication, the contact windows of TDRSS to the earth ground station are not aligned all the time of data delivery. In this case, the data delivery system has to employ DTN's "store-and-forward" model for which the scientific application data bytes are stored in the persistent memory until the next-hop data link is available.

III. ANALYTICAL MODELING OF THE EFFECT

In this section, we present analytical modeling of the effect of link disruption on the transmission performance of BP/LTP over the relay-based communication architecture for the ISS. The analysis is made for the effect of link disruption during file transfer in three different cases: (1) link disruption occurred over the link from the ISS to the relaying GEO-satellite; (2) link disruption occurred over the link from the relaying GEO-satellite to the ISS (with transmission of the RSs affected); and (3) link disruption over the link from the relaying GEO-satellite to the earth ground station.

A. Effect of link disruption over the link from the ISS to the relaying GEO-satellite

When the transmission of data blocks over the link from the ISS to the relaying GEO-satellite is interrupted by link disruption, the transmission is considered failed. Or, simply, the block of data is not delivered successfully at the receiver. However, the part of the data transmitted after the disruption ends can be successfully delivered. Therefore, the total file delivery time, $T_{delivery}$, can be approximated based on the estimated number of transmission efforts affected by the duration of link disruption, i.e.,

$$T_{delivery} = T_{block} \times n + T_{break} + (T_{owlt} + T_{rs}) \quad (1)$$

in which

T_{block} is the LTP block transmission time
n is the number of blocks that conveys the entire file
T_{break} is the link break time
T_{owlt} is the one-way-light-time
T_{rs} is the RS transmission time.

If the duration of link disruption exceeds the configured RTO timer interval of the sent CP segment, the total file delivery time can be formulated by estimating the number of transmission efforts that the CP segment is sent, i.e.,

$$T_{delivery} = T_{block} \times n + T_{break} + T_{rto-cp} \times N \quad (2)$$

in which T_{rto-cp} is RTO timer interval for the CP segment and N is the number of transmission efforts affected by link disruption.

B. Effect of link disruption over a link from the relaying GEO-satellite to the ISS (with transmission of the RSs affected)

In this case, what is affected by link disruption is the returning process of RS from the relaying GEO-satellite to the ISS. This is different from the first case in which the transmission of data blocks is affected. Generally, the RS is to confirm the receipt of a CP data segment, and any byte loss of the CP segment indicates the loss of the entire segment meaning the transmission failure of the CP segment.

When the transmission of an RS segment is interrupted by link disruption, it actually means that additional time is needed to wait for another successful RS transmission. Therefore, the total file transmission time can be formulated based on the number of times the link disruption affects the RS transmission.

If the RS is retransmitted only one time, the file delivery time can therefore be formulated as

$$T_{delivery} = T_{block} \times n + T_{rs} + RTO_{rs} \quad (3)$$

It is reasonable to formulate the RTO timer interval of an RS segment as

$$RTO_{rs} = 2T_{owlt} + T_{rs} \tag{4}$$

while T_{rs} is the transmission time of RS, i.e.,

$$T_{rs} = \frac{L_{rs}}{R_{data}} \tag{5}$$

in which L_{rs} is the length of RS segment and R_{data} is the data link rate.

Plugging the formulas of RTO_{rs} and T_{rs} into (3), the file delivery time can therefore be reformulated as

$$T_{delivery} = T_{block} \times n + T_{rs} + 2T_{owlt} + \frac{L_{rs}}{R_{data}} \tag{6}$$

If the RS is retransmitted more than one time, the file delivery time can then be written as

$$T_{delivery} = T_{block} \times n + T_{rs} + (2T_{owlt} + \frac{L_{rs}}{R_{data}}) \times n_{rs} \tag{7}$$

in which n_{rs} is the number of RS transmission efforts.

C. Effect of link disruption over a link from the relaying GEO-satellite to the earth ground station

After the ISS finish transmitting data to the relaying GEO-satellite, the data is stored in the relay node which then forwards the blocks to the earth ground station. If the link disruption occurs over the second link, the data transmission efficiency is affected, and it is analyzed in this subsection.

Because the relay GEO-satellite is stationary with respect to the ground station, the link interruption caused by the ISS to the earth movement is not considered here. Therefore, the effect of the link interruption on the file delivery time of BP is similar to the earth-moon transmission scenario, and it can be analyzed in two subcases:

1) *An interruption occurring during data transmission from GEO-satellite to the earth ground station*

$$T_{delivery} = T_{block} \times n + (N_{RTO} - 1) \times T_{RTO} + T_{break} \tag{8}$$

in which N_{RTO} is the number of times that the RTO timer expires.

2) *An interrupt occurring when RS is sent from earth ground station to the GEO-satellite*

$$\begin{aligned} T_{delivery} &= T_{block} \times n + C \times RTO_{rs} \\ &= T_{block} \times n + C \times (2T_{owlt} + \frac{L_{rs}}{R_{data}}) \end{aligned} \tag{9}$$

in which C is the number of RS transmission efforts.

IV. NUMERICAL EVALUATION RESULTS

In this section, the numerical evaluation results of the effect of link disruptions on BP/LTP for reliable file delivery over a relay-based communications architecture are presented. As discussed, two data links are involved for the end-to-end delivery between the ISS and the ground stations. As the link from the ISS to the relaying GEO-satellite is more likely disrupted than the link from the relaying GEO-satellite to the earth ground station, the preliminary evaluation results are presented in this section only for file transfer of BP/LTP over

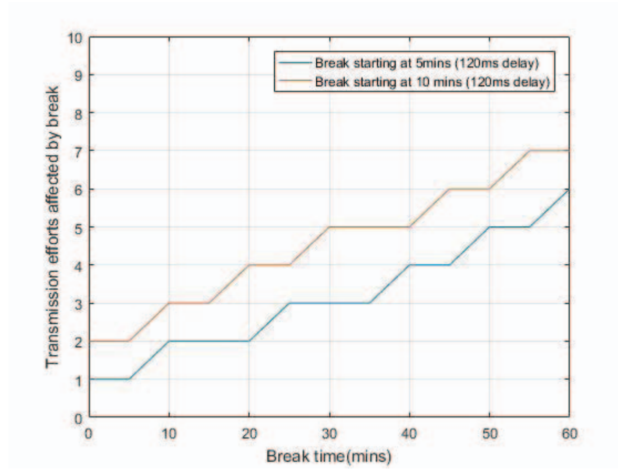

Fig. 1. A comparison of the number of transmission efforts of BP affected by the various link break intervals for successful delivery of a 45-Mbytes file between two settings of link break starting time at the BER of 0.

the first data link with no link disruption experienced over the second link.

With the configuration of BP/LTP stack, LTP is in charge of data transmission reliability in case of data loss and corruption events. Therefore, the BP custody transfer option is disabled. A file of 45 Mbytes is transmitted as the original application data for the evaluation. The two-way transmission channels between the ISS and the relaying GEO-satellite are configured to have a channel-rate asymmetry ratio of 300/1 with the data channel rate of 2 Mbps and the ACK channel rate of 6.78 Kbyte/sec. Three different channel noise (or loss) rates are presented in a form of channel bit-error-rate (BER) ranging from 0 to 10^{-5}. The one-way link propagation delay is configured to be 120 ms for each link.

The effect of various link break (or disruption) intervals ranging from 0 to 60 minutes is studied. In additional to the link break intervals, two different starting times, five minutes and ten minutes, are configured for each link break interval. In other words, the link break event is introduced to the bundle transmission over data link with two different starting times. One is to start link break five minutes later after the bundle transmission starts, and another is to have link break started ten minutes later after the transmission starts.

In Fig. 1, we present, in a comparative manner, the number of transmission efforts affected by the various link breaks (i.e., the breaks with different intervals) for successful delivery of a 45-Mbytes file for two settings of link break starting time. As the baseline evaluation, the channel quality is assumed to be ideal by configuring the BER to be 0.

It is observed that the number of transmission efforts affected by the link break events for the file transmission increase along with the increase of the break intervals for both transmissions regardless of the setting of link break starting time. The number of efforts is in a range of one to seven. That is reasonable because the longer link break interval is introduced, the longer idle time of link unavailability for data transmission is. This leads to a situation for which more retransmission efforts are affected by the link break because of frequent RTO timer expirations.

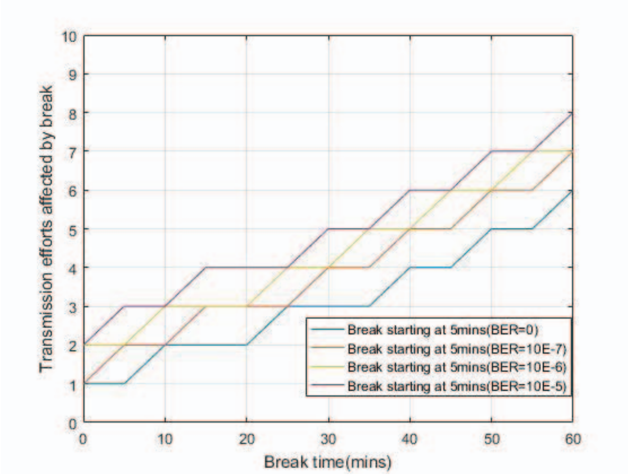

Fig. 2. A comparison of the number of transmission efforts of BP affected by the various link break intervals for successful delivery of a 45-Mbytes file among four different settings of channel BER.

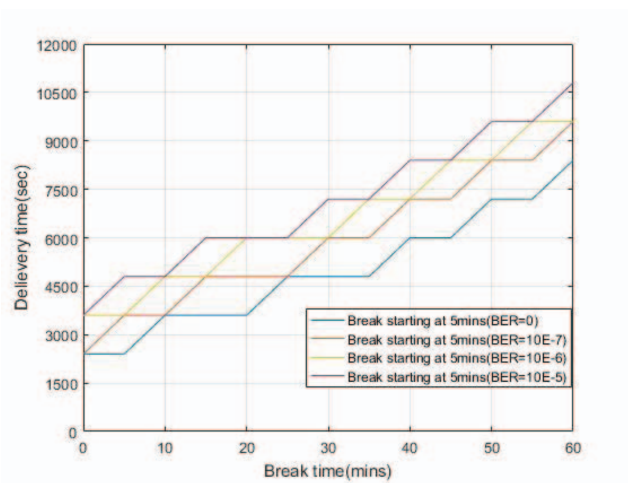

Fig. 3. A comparison of the total file delivery time of BP (with link break experienced during file delivery) among four different settings of channel BER for successful delivery of a 45-Mbytes file.

Even though the variation trends along with the increase of the break intervals are the same for both settings, both transmissions have a different number of transmission efforts affected by the link break for each of the link break intervals configured (at the x-axis). This is because of the difference in link break starting time. The transmission with the break starting time of 10 min consistently has one or two more efforts affected by the link break than other.

In Fig. 2, a similar comparison for the number of transmission efforts affected by the link break is presented among four different settings of channel BER. Same as the variation trend in Fig. 1, regardless of the channel BER, the number of transmission efforts affected by the link break increases along with the increase of the break intervals for all four transmissions, as explained. It is also observed that the transmission with a higher BER has additional efforts affected by the link break. For example, the transmission with a BER of

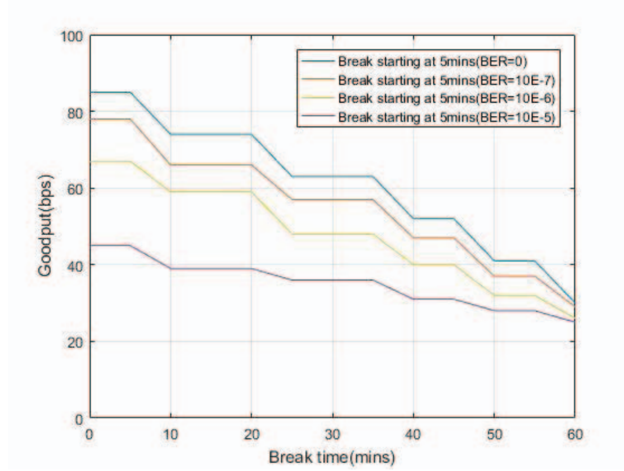

Fig. 4. A comparison of goodput performance of BP (with link break experienced during file delivery) among four different settings of channel BER for successful delivery of a 45-Mbytes file.

10^{-5} consistently has one or more efforts affected than the one with a BER of 0 for any link break event. This is reasonable because a higher BER is introduced during bundle transmission, more bundles are corrupted, and thus more transmission efforts are affected by the break event.

Continuing with the discussion on the comparison of the number of transmission efforts affected by the link break in Fig. 2, additional transmission efforts affected by the link break leads to an increase in the total number of transmission efforts required for successful file delivery. As the propagation delay in the GEO-based relay communication is very long compared to the file transmission time, the total number of transmission efforts primarily determine the total file delivery time. In other words, more transmission efforts are experienced, the longer the total file delivery time is for the end-to-end file delivery from the ISS to the earth ground station. This can be verified by comparing the total file delivery time for all four transmissions with different BERs which is illustrated in Fig. 3. As observed, the variation trend along with the increase of the link break interval matches that in Fig. 2. The relationships among all four transmissions are also the same as those presented in Fig. 2.

Fig. 4 presents a comparison of the goodput performance of BP for all four transmissions in Fig. 3. Corresponding to the increasing trend of the total file delivery time in Fig. 3, the goodput show consistent degradation with the increase in link break for each of four transmissions. This is reasonable because the goodput performance is inversely proportional to the total file delivery time. In comparison, corresponding to the differences of total file delivery time in Fig. 3, the transmission done with a BER of 0 shows the highest goodput while the one with a BER of 10^{-5} shows the lowest goodput. This is because the transmission with a BER of 10^{-5} has the longest file delivery time while the one with a BER of 0 has the shorted file delivery time.

It is also observed that the goodput performance of all four transmissions tends to get merged along with an increase in link break interval in Fig. 4. This indicates that if a very long link break event is experienced during file transmission, its effect is dominating to the overall transmission efficiency compared to the effect of channel error. This is because a long link break leads to a long interval of link unavailability for data transmission.

V. Summary and Conclusions

In this paper, analytical modeling and the numerical evaluation results are presented to study the effect of link disruptions on the use of BP/LTP for reliable file delivery over a relay-based communications architecture between the ISS and the ground stations. The main contribution of this paper is a solid analysis of the effect of link disruption happened during file transmission in three different cases: (1) link disruption occurred during file transfer over the link from the ISS to the relaying GEO-satellite; (2) link disruption occurred over a link from the relaying GEO-satellite to the ISS; and (3) link disruption occurred during file transfer over a link from the relaying GEO-satellite to the earth ground station. According to the numerical evaluation results of the model in the first case, the number of transmission efforts affected by the link break event for successful file delivery increase along with the increase of the break intervals, regardless of the setting of link break starting time. However, the effect of the equal link disruption interval on BP/LTP can be different depending on the specific time the link disruption starts because of the difference in the total number of transmission efforts taken. In addition, if a very long link break event is experienced during file transmission, its effect is dominating to the overall transmission efficiency compared to the effect of channel error. This is because a very long link break leads to a long interval of link unavailability for data transmission.

VI. Future Work

In this paper, analytical modeling and numerical evaluation results are presented and discussed to study the effect of link disruptions on the use of BP/LTP over a relay-based communications architecture between the ISS and the ground stations. The preliminary numerical results presented in this paper are reasonable with respect to the transmission mechanisms of the BP/LTP for reliable file delivery according to the analysis. It is expected that as the major future work, the built analytical models are verified or validated through realistic file transfer experiments using an emulation-based experimental testbed by running the BP/LTP protocol suite.

References

[1] S. Burleigh *et al*., "Delay-tolerant networking: An approach to interplanetary Internet," *IEEE Communications Magazine*, vol. 41, no. 6, pp. 128–136, Jun. 2003.

[2] 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.

[3] K. Scott and S. Burleigh, "Bundle protocol specification," IETF Request for Comments RFC 5050, November 2007, [Online]. Available: http://www.ietf.org/rfc/rfc5050.txt.

[4] M. Ramadas, S. Burleigh and S. Farrell, "Licklider Transmission Protocol—Specification," IETF Request for Comments RFC 5326, September 2008, [Online]. Available: http://www.ietf.org/rfc/rfc5326.txt?number=5326.

[5] K. Zhao, R. Wang, S. 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.

[6] 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.

[7] 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.

[8] Bin Cao, R. Wang, Alaa Sabbagh, Siwei Peng, Kanglian Zhao, Juan A. Fraire, Guannan Yang, and Yue Wang, "Expected File-Delivery Time of DTN Protocol over Asymmetric Space Internetwork Channels," In *Proceedings of* the 6th *IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) 2018*, Huntsville, AL, USA, Dec. 11-13, 2018.

[9] M. Feldmann, J. A. Fraire and F. Walter, "Tracking Lunar Ring Road Communication," *2018 IEEE International Conference on Communications (ICC)*, Kansas City, MO, 2018, pp. 1-7.

[10] J. A. Fraire, P. G. Madoery, J. M. Finochietto, P. A. Ferreyra and R. Velazco, "Internetworking approaches towards along-track segmented satellite architectures," *2016 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, Aachen, 2016, pp. 123-128.

[11] A. Schlesinger, B. Willman, L. Pitts, S. Davidson, W. Pohlchuck, "Delay/Disruption Tolerant Networking for the International Space Station (ISS)," In *Proceedings of* the *2017 IEEE Aerospace Conference*, Big Sky, MT, USA.

[12] A. Jenkins, S. Kuzminsky, K. Gifford, R. Pitts, K. Nichols, "Delay/Disruption-Tolerant Networking: Flight test results from the international space station," In *Proceedings of the 2010 IEEE Aerospace Conference* - Big Sky, MT, USA.

[13] NASA's Mars Science Laboratory, Jet Propulsion Laboratory, California Institute of Technology, CA, Accessed in June 2016, [Online]. Available: http://mars.nasa.gov/msl/mission/communicationwithearth/data/.

[14] J. Teles, M. Samii, and C. Doll, "Overview of TDRSS," *Adv. Space Res*., vol. 16, No. 12, 1995, pp. 67-76.