Received March 29, 2018, accepted May 6, 2018, date of publication May 10, 2018, date of current version June 5, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2834929

Modeling Disruption Tolerance Mechanisms for a Heterogeneous 5G Network

RUHAI WANG[1,2], (Senior Member, IEEE), ALAA SABBAGH[2], SCOTT C. BURLEIGH[3], MAHJABEEN JAVED[2], SHUSHI GU[4], JIAN JIAO[4], (Member, IEEE), AND QINYU ZHANG[4], (Senior Member, IEEE)

[1]School of Electronics and Information Engineering, Soochow University, Suzhou 215006, China
[2]Phillip M. Drayer Department of Electrical Engineering, Lamar University, Beaumont, TX 77710, USA
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[4]Communication Engineering Research Centre, Harbin Institute of Technology, Shenzhen 518055, China

Corresponding author: Jian Jiao (jiaojian@hit.edu.cn)

This work was supported in part by the National Natural Sciences Foundation of China under Grant 61771158, Grant 61701136, and Grant 61525103, in part by the China Postdoctoral Science Foundation under Grant 2018M630357, and in part by the Shenzhen Basic Research Program under Grant JCYJ20170811154309920, Grant JCY2017081114233370, Grant ZDSYS20170728090330586, and Grant JCYJ20160328163327348.

ABSTRACT Delay/disruption tolerant networking (DTN) was proposed as an internetworking architecture to accommodate the frequent and lengthy link disruptions and/or long propagation delays that are typical of a challenging communication environment. The challenging problems of reliable data delivery and effective mission control that are critical in space explorations are a typical application scenario of the DTN technology. Because space communications must integrate seamlessly with terrestrial communications to support efficient flight operations, DTN is designed as an overlay network architecture; as such, it innately supports the highly heterogeneous networks that will be built on 5G technology. In the absence of reliable underlying links, the reliable data delivery services of DTN rely heavily on the custody transfer feature of its core bundle protocol (BP). Little work has been done in theoretical analysis of the performance of BP custodial transfer in a space communication environment in presence of link disruptions. In this paper, we present a study of BP for reliable data delivery in space communications characterized by multiple link disruption events, accompanied by an extremely long propagation delay and data loss. An analytical model is built to estimate the bundle delivery time and transmission goodput performance of BP for bundle delivery over a space channel in the presence of multiple link disruptions. The model is validated by running data-flow experiments using a testbed infrastructure.

INDEX TERMS DTN, 5G, heterogeneous networks, space-terrestrial networks, bundle protocol (BP), intermittent connectivity.

I. INTRODUCTION

A. RESEARCH BACKGROUND

Space communications are characterized by extremely long signal propagation delay and variable and lengthy link disruptions, together with lossy data links and highly asymmetric channel rates. Long propagation latency is inevitable in space communications due to the limit on the speed of light and the extremely long interplanetary distance between the data source and data destination. While the data destination is generally a ground station on Earth, the data source may be on a different planet such as Mars or a planet which is even farther away. Link disruptions (or outages) in the end-to-end space communications are generally predictable but may vary in length significantly. They generally occur due to such factors as spacecraft movement and/or limited relay transit duration.

Referring to a Mars mission as a typical space communication scenario [1], Mars periodically ‘‘turns its back’’ to Earth, taking any rover on its surface (operating as the data source) with it and therefore leading to disruption in data delivery over the direct-to-Earth communication channel. Even with a widely adopted relay-based cis-Martian communication architecture, the contact windows of rover to orbiter and of orbiter to Earth ground station are not aligned most of the time; this leads to frequent link disruptions. The link disruption results in intermittent link connectivity for data delivery which generally severely degrades the data transmission performance, especially in space communications for which each round-trip takes at least eight minutes.

These formidable challenges of the inevitable long link delay and frequent link disruptions need to be adequately addressed in order to achieve 5G network that is capable of highly efficient and reliable data delivery without any geographical limitations. It is of paramount significance that 5G wireless networks demonstrate high levels of efficiency for a global and universal mode of continuous communication to be possible. Delay/disruption tolerant networking (DTN) [2], [3] was proposed as a networking architecture to accommodate the frequent and lengthy link disruptions and/or long link delays that are typical of space communications. Since the primary goal behind DTN is to solve the issues that arise in heterogeneous networks regarding connectivity, work regarding the integration of DTN and 5G network is crucial. In other words, DTN will be a critically important element in implementing 5G network because of its disruption-tolerant inter-connectivity capability among heterogeneous networks. Because space communications and satellite networks must integrate seamlessly with terrestrial communications to support efficient flight operations, DTN is designed as an overlay network architecture. As such, it innately supports the highly heterogeneous networks that will be built on 5G technology. DTN is recognized by the National Aeronautics and Space Administration (NASA) as the only candidate network communication technology that approaches the level of maturity required for heterogeneous space networks [4].

Proposed to serve as the core internetworking protocol of DTN, bundle protocol (BP) [5], [6] is designed to be able to withstand intermittent data link connectivity for delivery of DTN data units, bundles, using its ''store-and-forward'' procedures and ''custody transfer'' option. Residing immediately under the BP layer in the DTN protocol stack, a ''convergence layer adapter'' (CLA) [7] is designed to send and receive bundles on behalf of BP, using the underlying data transport protocols. CLAs themselves may perform reliable data delivery, making BP custody transfer unnecessary, but many CLAs are not reliable. A user datagram protocol (UDP)-based CLA (or simply, UDPCL) [8] is one of the broadly supported DTN CLAs under BP, and it is designed mainly for use of BP over dedicated private links. The Consultative Committee for Space Data Systems (CCSDS) ''solar system internetwork'' (SSI) architecture [9] is predicated on the use of BP in space communications but a variety of different protocol stack configurations are contemplated.

While DTN is referred to either as delay-tolerant networking or as disruption-tolerant networking, they are two different terms for the same architecture and protocols. From a perspective of the end-to-end data transfer over physical communication channels, delay and disruption can actually have the same effect. It is generally acceptable that ''delay'' includes ''disruption''. The ''delay'' that DTN is designed to tolerate is round-trip delay, and that can result either from long signal propagation times, from transient lapses in connectivity, or both; that is, ''delay'' includes ''delay caused by disruption''.

In order to tolerate the extremely long delay, disruption or both in space communications, the network system has to employ a ''store-and-forward'' model for which the science application data bytes are stored in persistent memory until the next-hop data link is available. This is the scenario in which we assume BP over unreliable convergence-layer protocols (which we will henceforth in this paper, unless otherwise specified, refer to simply as ''BP'') will operate for reliable data delivery, using its store-and-forward mechanism and custody transfer option to ensure that no bundles are lost. This serves as the basis for our analysis of its performance in the presence of link disruptions.

DTN's BP has already been adopted by the NASA for disruption-tolerant data delivery service from the International Space Station (ISS) to an Earth ground station [10]. Given this deployment and the current pace of CCSDS standardization progress [6], [9], it is expected that BP is likely to be deployed in future space missions. However, there is a lack of analytical understanding of the performance of BP in presence of link disruptions.

Bezirgiannidis *et al.* [11] presented a useful method of estimating data bundle delivery time in space internetworking using the contact graph routing (CGR) computation algorithm. However, link disruption is not considered in the analytical performance formulation and experimental verification of this work.

Recently, Sabbagh *et al.* [12], Zhao *et al.* [13], [14], and Jiao *et al.* [15] did some studies on performance analysis of DTN protocols for data transmission in space. In [12] and [13], the team developed analytical models for the performance of BP. While the work in [12] focuses on an analysis of BP over space channels characterized by highly asymmetric rates, the study in [13] focuses on the transmission performance and memory dynamics of BP in presence of a link break. Zhao *et al.* [14] presented a study of memory dynamics for Licklider transmission protocol (LTP)-based transmission. In [15], Wang's team showed how to ensure successful file transfers in space-vehicle communications within a single round-trip interval using BP. However, in all these studies, link disruption is either ignored or else assumed to be an invariable offset to the data or file delivery time. In other words, the manner in which link disruption affects the transmission efficiency and performance of BP is not investigated in these studies. A solid study of BP, especially in a theoretical manner, to derive an analytical understanding of its performance for reliable data delivery in presence of link disruptions is needed.

B. CONTRIBUTIONS AND NOVELTY

In this paper, we present a study of the transmission performance of BP for reliable data delivery in a space communication scenario characterized by multiple link disruption events, accompanied by an extremely long propagation delay and a high rate of data loss. The main contributions and

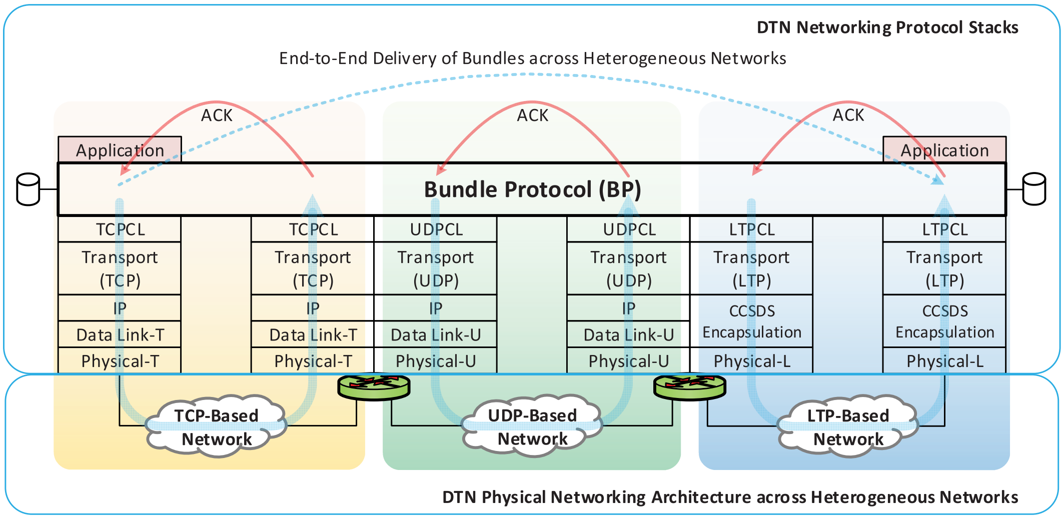


FIGURE 1. A general DTN architecture for end-to-end reliable data delivery among heterogeneous networks [12].

novelty of this paper are the development of an analytical model to estimate the bundle delivery time and goodput performance of BP in presence of multiple link disruption events and the experimental validation of the model using a PC-based testbed. To the best of our knowledge, this is the first set of analytical development in studying BP in space communications in presence of multiple link disruptions.

The remainder of the paper is organized as follows. In Section II, an overview of BP and its operation with respect to a space communication scenario are provided. Analytical modeling is presented in Section III for estimating the transmission performance of BP in presence of multiple link disruption events. The numerical results of the experiments and the model are presented in Section IV for model validation. The conclusions are drawn in Section V.

II. BP AND ITS OPERATION IN HETERGENEOUS SPACE COMMUNICATIONS

As mentioned, strengthening of terrestrial-space integrated infrastructure and space communication networks will lead to the establishment of a more resilient and robust 5G network with greater coverage. DTN is a networking architecture developed to interoperate across heterogeneous networks and protocols to accommodate long link delay and frequent, lengthy link disruptions caused by any factors that are common in 5G. A general DTN physical networking architecture and protocol stacks are presented in Fig. 1 to demonstrate the concept of BP and its application for interrogation among highly heterogeneous networks. The figure shown is a recreation of the architecture and protocol stacks presented in [12]. As the main protocol of DTN, BP was proposed to provide end-to-end data delivery services in a networking environment characterized by extremely long link delays and/or lengthy link disruptions that occur at either scheduled or random intervals. BP forms a store-and-forward overlay network by interoperating across highly heterogeneous networks as IP does. To do so, BP spans all the involved heterogeneous networks and operates on top of each local internet's data transport protocol through the interfacing CLA. These heterogeneous networks may adopt absolutely different sets of network and data transport protocols, each one individually suited to its local service area.

To withstand intermittent link connectivity and lengthy link delay, BP is designed to be able to make use of both scheduled connectivity and opportunistic contacts for data delivery, together with custody-based retransmission. To implement the custody-based store-and-forward transmission capability of BP, a bundle node needs memory for data storage. Unlike the momentary packet storage adopted for the terrestrial Internet, BP bundles are typically stored in permanent nonvolatile memory to enable delay and/or disruption tolerance. If a bundle is designated to be "custodial", it cannot be discarded immediately upon transmission. A "custodial" bundle can only be discarded by a bundle node when either its custody has been accepted by other nodes or the life time of the bundle has expired.

When a sending node sends data bundles to the next node, it starts a custody-retransmission time-out (RTO) timer for each bundle. As soon as a bundle has arrived at a receiving node, the receiver sends a custody acknowledgment (CA) in response to it, confirming that it has (or possibly has not, a variation we do not investigate in this paper) taken custody of the received bundle. BP follows the "one CA per bundle" policy, i.e., an entire bundle is acknowledged by a single CA. If no CA is returned for a bundle by the time the bundle RTO timer expires, the bundle is retransmitted. Either bundles or acknowledgements may be lost in the channel, resulting in retransmission.

The bundle transmission/retransmission and bundle-based acknowledgment mechanisms control the reliable data

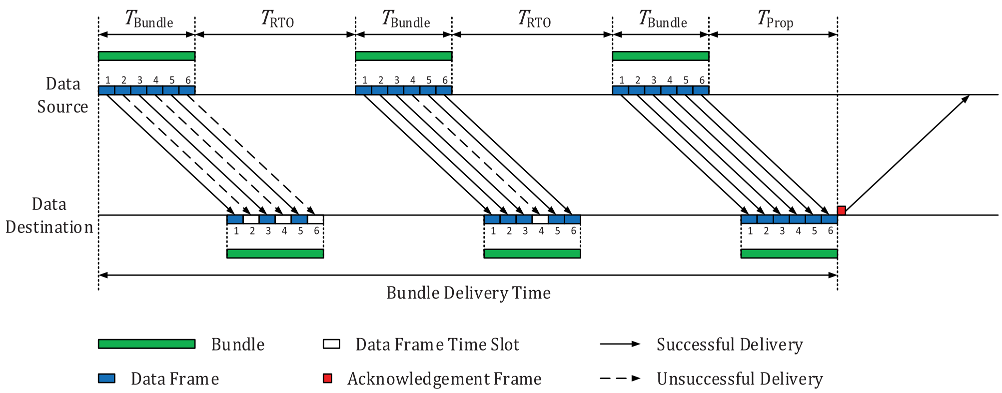


FIGURE 2. An illustration of a reliable bundle delivery scenario of BP over a lossy channel.

delivery process of BP. To illustrate the basic operation of BP following these mechanisms, a simple scenario of BP bundle delivery over a lossy channel is presented in Fig. 2. In this scenario, BP delivers a bundle, conveyed by six data packets that are encapsulated as six frames at the link layer, from the data source node directly to the destination node (i.e., with no intervening forwarding node involved).

The data bytes of the bundle conveyed in six frames are transmitted by the source node in the initial transmission effort. Let T_{Bundle} be the bundle transmission time which is determined by the bundle size and channel rate. As the retransmission is done on a bundle basis, the custodial RTO timer for the bundle starts as soon as the entire bundle is transmitted. Assume that due to the presence of channel error, the second, fourth, and sixth frames are corrupted during transmission and could not be successfully delivered to the destination node. Because the bundle delivery has failed, the corresponding CA is not sent by the destination node. Therefore, upon the expiration of the custodial RTO timer with the length of T_{RTO}, the bundle is retransmitted, leading to the second transmission effort.

Assume that during the second transmission effort of the bundle, the data byte(s) conveyed by the fourth frame are corrupted. This results again in no CA confirmation being received by the source node by the time the bundle RTO timer expires and thus, a need for another (third) transmission attempt, as illustrated. If all the data bytes of the entire bundle are successfully delivered during the third attempt, the CA, encapsulated in a single frame at the link layer, is sent by the destination in response to it. The CA confirms the successful receipt of the bundle. By this, the entire bundle is successfully delivered to the destination.

As illustrated, due to the severe data losses caused by the high error rate of the space channel, it takes BP in total three transmission efforts to secure the successful delivery of the bundle. Each effort consumes the length of time denoted by the bundle RTO timer, T_{RTO}. The RTO timer is commonly configured to be twice the one-way signal propagation time from the source to the destination, which is denoted as T_{Prop} as shown in the last transmission effort in Fig. 2. The total bundle delivery time is the time that elapses from the transmission starting point at the source node to the successful delivery of the entire bundle at the destination, which is the point at which all of the data bytes in all the frames have been received. Obviously, the total number of transmission efforts contributes significantly to the bundle delivery time, especially for space communications in which signal propagation delay dominates each transmission effort. The bundle transmission time, T_{Bundle}, is actually trivial in comparison to the lengthy space propagation delay. Therefore, the transmission performance of BP (mainly the bundle delivery efficiency) in space communications is dominated by the total number of transmission efforts taken for the successful delivery of a bundle and the inevitable lengthy propagation delay.

In the general case, let N_{TE} be the number of transmission efforts needed for successful delivery of an entire bundle. Then, if the processing time, queuing time, and other incidental time intervals are ignored for simplicity, the total bundle delivery time of BP over a single space data link, denoted as T_{BD}, can be approximated as

$$T_{BD} = N_{TE} T_{Bundle} + (N_{TE} - 1)\, T_{RTO} + T_{Prop}. \qquad (1)$$

III. PERFORMANCE MODELING OF BP IN PRESENCE OF MULTIPLE LINK DISRUPTIONS

In this section, an analytical model is derived for estimating the transmission performance (mainly bundle delivery time) of BP in a space communication scenario in presence of multiple link disruption events. The notations used during the derivation of the model are presented in Table 1.

The bundle delivery time of BP over a single space communication link including the effects of link disruption event(s), $T_{Bundle-delivery}$, can be simply written as a sum of the bundle delivery time without link disruption involved, $T_{W/O\,break}$, and the total effect of the disruption event(s) on bundle

TABLE 1. Notations.

Symbol	Definition
T_{Bundle}	Bundle transmission time.
T_{RTO}	Length of the retransmission time-out timer (RTO) for BP transmission.
T_{Prop}	Link propagation time.
T_{BD}	Total bundle delivery time.
N_{TE}	Number of transmission efforts needed for successful delivery of an entire bundle.
$T_{Bundle-delivery}$	Bundle delivery time of BP.
$T_{W/O\,break}$	Bundle delivery time without link disruption experienced.
$T_{Break-effect}$	Total effect of the disruption event(s) on bundle delivery time.
P_{Bundle}	Bundle transmission error rate.
N_{Link}	Number of data links involved for bundle delivery.
T_{Break}	Duration of link disruption.
N_{Break}	Number of link disruption events experienced during bundle delivery.
p	Probability of channel bit error (i.e., BER).
L_{Bundle}	Length of a data bundle.
GPT_{BP}	Goodput for bundle delivery of BP.

delivery time, $T_{Break-effect}$, i.e.,

$$T_{Bundle-delivery} = T_{W/O\,break} + T_{Break-effect}. \quad (2)$$

The bundle delivery time without link disruption involved is the total time that all required transmission efforts consume in repetitively transmitting the entire bundle over a consistently connected (non-disrupted) link until the all data bytes of the bundle have been delivered without error, i.e., the total bundle delivery time depicted in Fig. 2 or simply, T_{BD} in (1). Therefore, $T_{W/O\,break}$ for bundle delivery over a single space data link without link disruption involved in (2) can be formulated as

$$T_{W/O\,break} = N_{TE}T_{Bundle} + (N_{TE} - 1)\,T_{RTO} + T_{Prop}. \quad (3)$$

The number of transmission efforts needed for successful delivery of a bundle, N_{TE} in (3), can be formulated as $N_{TE} = \lceil \frac{1}{1-P_{Bundle}} \rceil$ in which P_{Bundle} is the bundle transmission error rate, as a representation of channel quality.

If the bundle delivery from the source node to the destination node involves multiple data links in sequence, i.e., N_{Link} links, the formula for the bundle delivery time can be extended to

$$T_{Bundle-delivery} = \sum_{i=1}^{N_{Link}} \Big(N_{TE_i}T_{Bundle_i} + (N_{TE_i}-1)T_{RTO_i} + T_{Prop_i}\Big) + T_{Break-effect}. \quad (4)$$

As a special case, if the multiple data links involved for the end-to-end bundle delivery are identical with respect to the propagation delay, data rate and channel quality, the bundle delivery time in (4) can be presented in a more concise form as

$$T_{Bundle-delivery} = N_{Link}\Big(N_{TE}T_{Bundle} + (N_{TE}-1)T_{RTO} + T_{Prop}\Big) + T_{Break-effect}. \quad (5)$$

If bundle delivery experiences link disruption, the bundle transmission time and propagation time over the data link are wasted with respect to the bundle delivery efficiency but they are counted as part of the total effect on bundle delivery time. Therefore, the total effect of a single link disruption event on the bundle delivery time, $T_{Break-effect}$, can be approximated as

$$T_{Break-effect} = T_{Bundle} + T_{Prop} + T_{Break}. \quad (6)$$

in which T_{Break} is the link disruption duration.

For a bundle delivery scenario characterized by multiple link disruption events, i.e., N_{Break} events, which we focus on in this paper, the total effect of link disruptions on bundle delivery time can be written as

$$T_{Break-effect} = \sum_{j=1}^{N_{Break}} T_{Break_j-effect}. \quad (7)$$

$T_{Break-effect}$ is derived by different formulas for different cases depending on the number of data links involved in the end-to-end bundle delivery:

Case 1: For bundle delivery over a single data link, i.e., one-hop delivery,

$$\begin{aligned} T_{Break-effect} &= \sum_{j=1}^{N_{Break}} T_{Break_j-effect}, \\ &= \sum_{j=1}^{N_{Break}} \left(T_{Bundle} + T_{Prop} + T_{Break_j}\right), \\ &= \sum_{j=1}^{N_{Break}} T_{Break_j} + N_{Break}\left(T_{Bundle} + T_{Prop}\right). \end{aligned} \quad (8)$$

Case 2: For bundle delivery over N_{Link} data links,

$$\begin{aligned} T_{Break-effect} &= \sum_{j=1}^{N_{Break}} T_{Break_j-effect}, \\ &= \sum_{j=1}^{N_{Break}} \left(T_{Break_j} + T_{Bundle_{Dj}} + T_{Prop_{Dj}}\right) \end{aligned} \quad (9)$$

in which D_j refers to the data link over which the jth link disruption event occurs.

Case 3: For bundle delivery over N_{Link} data links that are identical with respect to the propagation link delay, data rate and channel quality:

Because the link features are identical, identical propagation times across all the links, i.e., $T_{prop_{Dj}} = T_{prop}$, and identical bundle transmission times apply to every link, i.e., $T_{Bundle_{Cj}} = T_{Bundle}$. Therefore, $T_{Break-effect}$ in (9) can be further written as

$$\begin{aligned} T_{Break-effect} &= \sum_{j=1}^{N_{Break}} T_{Break_j-effect}, \\ &= \sum_{j=1}^{N_{Break}} \left(T_{Break_j} + T_{Bundle_{Dj}} + T_{Prop_{Dj}}\right), \\ &= \sum_{j=1}^{N_{Break}} \left(T_{Break_j} + T_{Bundle} + T_{Prop}\right), \\ &= \sum_{j=1}^{N_{Break}} T_{Break_j} + N_{Break}\left(T_{Bundle} + T_{Prop}\right). \end{aligned} \tag{10}$$

As a special case of each of Case 1, Case 2 and Case 3, if all the N_{Break} link disruption events are identical with respect to the length of disruption, i.e., T_{Break_j} is equal for all the js, the formulas of the total effect of link disruptions on bundle delivery time can be presented in a more concise form as

$$T_{Break-effect} = \begin{cases} N_{Break}(T_{Break} + T_{Bundle} + T_{Prop}), \\ \quad \text{Case 1 (i.e., over single link);} \\ N_{Break}T_{Break} + \sum_{j=1}^{N_{Break}} \left(T_{Bundle_{Dj}} + T_{Prop_{Dj}}\right), \\ \quad \text{Case 2 (i.e., over multiple links);} \\ N_{Break}(T_{Break} + T_{Bundle} + T_{Prop}), \\ \quad \text{Case 3 (i.e., over multiple ``idential'' links).} \end{cases} \tag{11}$$

With the formulas of $T_{Break-effect}$ derived in different cases, the earlier derived formulas of bundle delivery time can be rewritten:

Case I: For bundle delivery over a single space data link in presence of multiple link disruption events,

$$\begin{aligned} T_{Bundle-delivery} &= N_{TE}T_{Bundle} + (N_{TE}-1)T_{RTO} \\ &\quad + T_{Prop} + \sum_{j=1}^{N_{Break}} T_{Break_j} + N_{Break}(T_{Bundle} + T_{Prop}), \\ &= N_{TE}T_{Bundle} + (N_{TE}-1)T_{RTO} + (N_{Break}+1)T_{Prop} \\ &\quad + \sum_{j=1}^{N_{Break}} T_{Break_j}. \end{aligned} \tag{12}$$

Case II: For bundle delivery involving multiple data links in presence of multiple link disruption events,

$$\begin{aligned} T_{Bundle-delivery} &= \sum_{i=1}^{N_{Link}} \left(N_{TE_i}T_{Bundle_i} + \left(N_{TE_i}-1\right)T_{RTO_i} + T_{Prop_i}\right) \\ &\quad + \sum_{j=1}^{N_{Break}} \left(T_{Break_j} + T_{Bundle_{Dj}} + T_{Prop_{Dj}}\right). \end{aligned} \tag{13}$$

Case III: As a special case of Case II, for bundle delivery involving multiple data links in presence of multiple link disruption events, if these data links are identical with respect to the propagation delay, data rate and channel quality,

$$\begin{aligned} &T_{Bundle-delivery} \\ &\quad = N_{Link}\left(N_{TE}T_{Bundle} + (N_{TE}-1)T_{RTO} + T_{Prop}\right) \\ &\qquad + \sum_{j=1}^{N_{Break}} T_{Break_j} + N_{Break}\left(T_{Bundle} + T_{Prop}\right), \\ &\quad = \left(N_{Link}N_{TE} + N_{Break}\right)T_{Bundle} + \sum_{j=1}^{N_{Break}} T_{Break_j} \\ &\qquad + N_{Link}\left(N_{TE}-1\right)T_{RTO} + \left(N_{Link} + N_{Break}\right)T_{Prop}. \end{aligned} \tag{14}$$

For bundle delivery experiencing multiple link disruptions, if these disruption events are identical with respect to the length of disruption, the formulas for bundle delivery time can be rewritten as:

In *Case I:*

$$\begin{aligned} T_{Bundle-delivery} &= (N_{TE} + N_{Break})T_{Bundle} + N_{Break}T_{Break} \\ &\quad + (N_{TE}-1)T_{RTO} + (N_{Break}+1)T_{Prop}. \end{aligned} \tag{15}$$

In *Case II:*

$$\begin{aligned} &T_{Bundle-delivery} \\ &\quad = N_{Break}T_{Break} + \sum_{i=1}^{N_{Link}} \\ &\qquad \times \left(N_{TE_i}T_{Bundle_i} + \left(N_{TE_i}-1\right)T_{RTO_i} + T_{Prop_i}\right) \\ &\qquad + \sum_{j=1}^{N_{Break}} \left(T_{Bundle_{Dj}} + T_{Prop_{Dj}}\right). \end{aligned} \tag{16}$$

In *Case III:*

$$\begin{aligned} T_{Bundle-delivery} &= (N_{Link}N_{TE} + N_{Break})T_{Bundle} \\ &\quad + N_{Link}(N_{TE}-1)T_{RTO} + N_{Break}T_{Break} \\ &\quad + (N_{Link} + N_{Break})T_{Prop}. \end{aligned} \tag{17}$$

IV. EXPERIMENTS AND MODEL VALIDATION

In this section, we present sample experimental results for the transmission performance of BP in a relay-based heterogeneous space networking scenario in presence of multiple link disruption events. These results are presented in a comparative manner to validate the analytical model built in Section III. The results are measured from data flow experiments conducted using a testbed. The experimental setup and configurations are briefly described before the numerical results are presented.

A PC-based space communication and networking testbed (SCNT) [16] was adopted as an emulated space communication architecture for data delivery experiments to validate the analytical model and performance evaluation. The DTN/BP protocol stack is configured as BP/UDPCL/UDP/IP with Ethernet serving at data link layer. For reliable bundle delivery service over a lossy space link in presence of link disruptions, the BP custody transfer option is enabled. The implementations of BP and the related protocols were provided by the Interplanetary Overlay Network (ION) distribution V3.6.0b [17] which was the latest BP implementation available at the time these experiments were conducted and was developed by the Jet Propulsion Laboratory (JPL), California Institute of Technology. ION is a suite of DTN communication protocol implementations developed for mission operation communications across an end-to-end space, interplanetary link. The experimental evaluations done in [12]–[15] and [18] indicate that the relay-based SCNT infrastructure works effectively for performance evaluation of a protocol suite based on data-flow experiments.

A one-way link delay of 10 minutes was introduced to emulate inevitable signal propagation delay in the space communication channel. This results in a round-trip time (RTT) of 20 minutes (i.e., 1200 sec) for a general end-to-end bundle delivery scenario. Given that the RTT interval was around 1200 sec, a bundle custodial retransmission RTO timer having the same interval was configured for the experiments.

For the purposes of this study, two link disruption events are introduced in the course of bundle transmission. In addition, the duration of each link disruption in realistic space flight missions can be arbitrarily long. However, the intent of the proposed experimental work is to validate the analytical model; for this purpose, the exact number of link disruption events and the exact length of each link disruption are not important. In other words, the model is expected to be valid regardless of the number of link disruption events and the lengths of the link disruptions imposed during bundle delivery.

The data delivery experiments were conducted with six different bundle sizes: 20 Kbytes, 28 Kbytes, 36 Kbytes, 44 Kbytes, 52 Kbytes, and 60 Kbytes. The MTU size at the link layer (Ethernet) is 1500 bytes which is a commonly used size for Ethernet. Degraded channel quality is emulated by introducing a BER of 5×10^{-6} to the experiments with all the bundle sizes. This error rate is among the commonly anticipated transmission conditions over space and space communication channels [19], [20], and it is expected to result in a practical data loss rate for data delivery over a space channel. Given a channel BER representing the channel quality, the transmission error (loss) probability of a bundle, P_{Bundle}, can be easily derived as $P_{Bundle} = 1-(1-p)^{8\times L_{Bundle}}$ in which p serves as the BER and L_{Bundle} is the length of a data bundle for the end-to-end delivery. The channel data rate is configured to be 2 Mbit/s. Again, these bundle delivery experiments were designed simply to validate the model; the exact numerical values of bundle size, channel BER and data rate are not important with respect to the objective of this study.

In Fig. 3, a comparison of the bundle delivery time predicted by the model and collected from the sample experiments is presented for data transmission over a heterogeneous space networking channel with two link disruptions experienced. For the two link disruption events, one link disruption is configured to have a duration of 8 minutes and starting time of 7 minutes after the start of the experiment, and another has a duration of 28 minutes and starting time of 27 minutes after the start of the experiment. The bundle delivery time predicted by the analytical model corresponding to this experimental configuration is (13) in Section III.

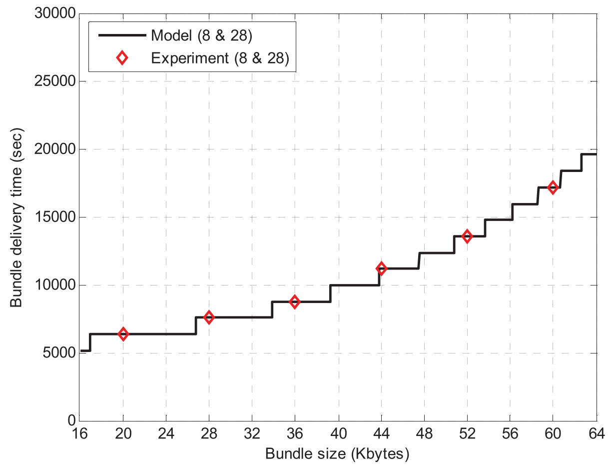


FIGURE 3. **A comparison of the bundle delivery time predicted by the model and collected from the sample experiments for data transmission over a heterogeneous space networking channel with two link disruptions experienced: a link disruption with a duration of 8 minutes and starting time of 7 minutes, and another with a duration of 28 minutes and starting time of 27 minutes.**

An important observation in Fig. 3 is that the numerical average results of the bundle delivery time measured in the experiments fit the predictions of the model for all the bundle sizes studied in this experiment. This indicates that the analytical model is validated by realistic data-flow experiments over the testbed. Therefore, the model can be adopted to predict the performance of BP in bundle delivery in space communications in presence of multiple link disruptions.

With respect to the performance variation trend of BP in response to the variations of bundle size, it is observed from Fig. 3 that the bundle delivery time, from both the model and the experiments, overall increases along with an increase in bundle size. This performance trend is due mainly to the variation of bundle size which results in the variation of data loss rate and thus, the differences in the number of transmission efforts needed for successful delivery of a bundle. That is, given a channel BER of 5×10^{-6}, the larger the bundle is, the more likely the bundle is to be corrupted by channel error, resulting in a higher chance of data loss and need for retransmission. Given that BP transmission is performed on a whole-bundle basis of, this leads to a need of additional bundle transmission efforts (or rounds) for successful delivery of a larger bundle. More transmission efforts surely lead to an increase in the total bundle delivery time because each additional transmission effort results in extra time equivalent to a transmission round, the duration of the RTO timer (which

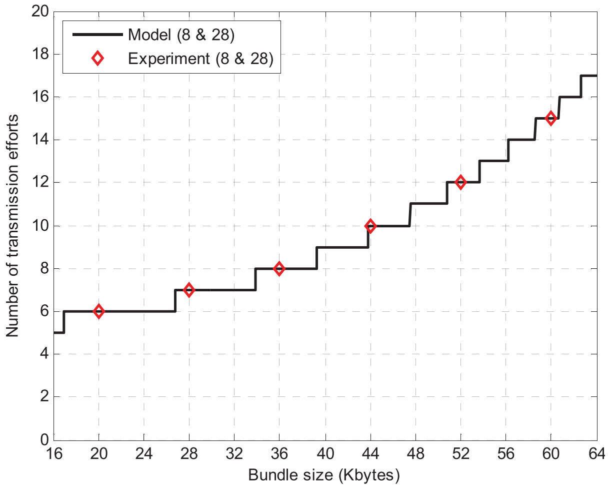


FIGURE 4. **A comparison of the number of transmission efforts (i.e., attempts) taken for successful delivery of a bundle, predicted by the model and collected from the sample experiments, for data transmission over a heterogeneous space networking channel with two link disruptions experienced: a link disruption with a duration of 8 minutes and starting time of 7 minutes, and another with a duration of 28 minutes and starting time of 27 minutes.**

is longer than 1200 sec in this study), to accomplish the bundle delivery, as illustrated in Fig. 2.

An overall trend is that the delivery time increases in a faster rate for larger bundles than for small bundles. In other words, the bundle delivery time overall increases exponentially with increasing bundle size. This is due mainly to the exponential effect of the bundle size L_{Bundle} on the bundle transmission error rate P_{Bundle} and the number of transmission efforts N_{TE}, as formulated as $P_{Bundle} = 1 - (1 - p)^{8 \times L_{Bundle}}$ and $N_{TE} = \lceil \frac{1}{1-P_{Bundle}} \rceil$. The combination of these two factors ultimately results in the exponential effect of bundle size on bundle delivery time according to (13). The staircase increase pattern of the bundle delivery time in Fig. 3 is caused by the increase of the needed number of transmission efforts along with the increase of the bundle size.

The aforementioned performance connection can be verified by comparing the bundle delivery time of BP with the corresponding number of transmission efforts taken for successful delivery of the bundle. Fig. 4 illustrates a comparison of the corresponding number of transmission efforts (or attempts) predicted by the model and collected from the experiments at various bundle sizes. It is observed that the overall pattern of increase in the bundle delivery time in Fig. 3 is matched by the increase in the number of transmission efforts resulting from the similar exponential trend and staircase pattern of the increase in bundle size. In addition, similar to the observation of bundle delivery time in Fig. 3, the number of transmission efforts measured in the experiments fit the predictions of the model for all the bundle sizes examined. This is a strong indication, from a different aspect of performance measures, that the analytical model is validated. Numerically, it takes BP six, seven, eight, ten, twelve and fifteen transmission efforts in successful delivering the entire bundle for each of the bundle sizes of 20 Kbytes, 28 Kbytes, 36 Kbytes, 44 Kbytes, 52 Kbytes, and 60 Kbytes, respectively. Because the round-trip propagation delay is overwhelmingly longer than the transmission time of a bundle, the bundle delivery time is primarily determined by the total number of transmission efforts together with the two link disruption events. Therefore, both measures consistently have the same increasing pattern along with the increase in the bundle size.

The number of transmission efforts taken for successful delivery of the entire bundle in experimental transmission is explicitly shown by the throughput performance traces measured from the real-time data flow traffic using a widely-used network protocol analyzer, Wireshark [21]. Fig. 5 shows the dynamic throughput trace at the sender in delivering a bundle of 20 Kbytes for which the transmission performance is reported in Fig. 3 and Fig. 4. The trace illustrates the data traffic measured at the sender since the transmission began. As discussed, two link disruption events are introduced during the bundle delivery, and they include a disruption with a duration of 8 minutes and another with a duration of 28 minutes.

For the throughput trace in Fig. 5, because BP delivery time (as shown on the x-axis) is extremely long - more than 6600 seconds for 20 Kbytes as shown in Fig. 3 - each transmission of the bundle is represented only as a single throughput impulse. While we are not interested in the numerical throughput performance for each impulse, the number of these impulses and their patterns at both the sender and receiver, comparatively, are our focus. These impulses and patterns provide information on the total number of transmission efforts made by BP and how the two ends interacted in ensuring successful delivery of the bundle at the receiver.

As observed from the trace at the sender in Fig. 5, the bundle is transmitted at the beginning by the sending node. As soon as the entire bundle is sent out, the custodial RTO timer (with the length of 20 minutes) for the bundle starts. (This is not shown on the throughput trace in Fig. 5 by Wireshark.) As mentioned, the first link disruption with a duration of 8 minutes is introduced seven minutes later after the transmission starts. Because of the link disruption that led to unavailability of the data channel for bundle delivery, the data bytes of the bundle transmitted by the sender do not arrive at the receiver. Because the bundle is not successfully delivered, its corresponding CA is not sent in response by the receiving node. Therefore, upon the expiration of the custodial RTO timer of 20 minutes, the bundle is retransmitted, shown as the second throughput impulse in Fig. 5. Because of the introduction of the second link disruption starting at 27 minutes after the transmission starts and having a long duration of 28 minutes, the retransmission effort of bundle delivery fails again, leading to more retransmission efforts with each of them made upon the expiration of the custodial RTO timer.

Note that with a channel BER of 5×10^{-6} introduced during bundle delivery, some of the retransmission efforts

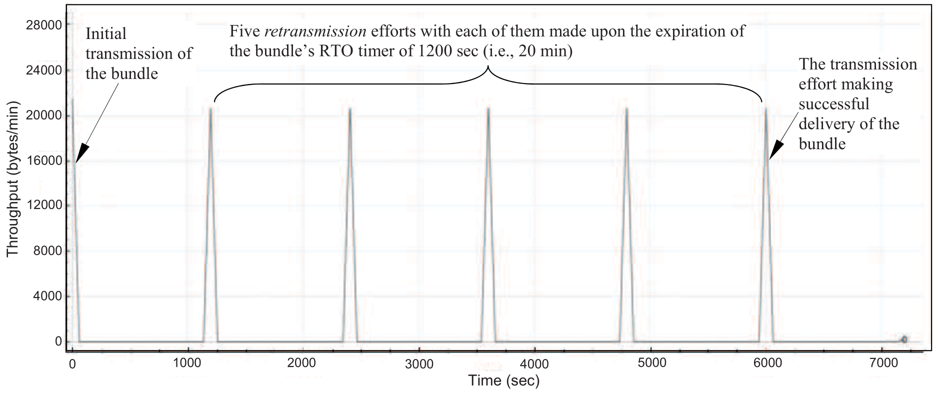


FIGURE 5. Dynamic data traffic (throughput) trace measured at the *sender* for delivery of a bundle of 20 Kbytes over a heterogeneous space networking channel.

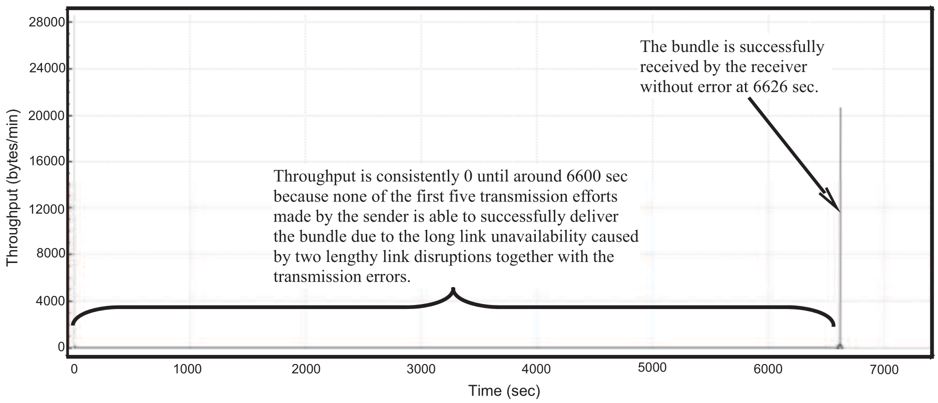


FIGURE 6. Dynamic data traffic (throughput) trace measured at the *receiver* for delivery of a bundle of 20 Kbytes over a heterogeneous space networking channel.

observed in Fig. 5 are due in part to the data losses caused by the transmission errors. But the effect of the transmission errors to the bundle delivery is actually the same as that of the link disruption - retransmission upon the expiration of the custodial RTO timer. As observed from the entire transmission trace, six transmission efforts are made in total, including the initial transmission and the following five retransmission efforts made periodically, to ensure the successful delivery of the entire bundle. The last effort is made at about 6026 seconds after the start of the experiment, around 100 minutes. This is reasonable given that five retransmission efforts are made with each of them made upon the expiration of the bundle's 20 - minute RTO timer.

Fig. 5 indicates that six transmission efforts are taken in total for the successful delivery of the entire bundle. This is an indication that all the first five efforts do not succeed, leading to failure of the bundle delivery at the receiver for each effort. The only effort which made the successful delivery is the last (the sixth) effort. This can be easily seen by checking the transmission trace measured at the receiver. Fig. 6 illustrates the corresponding throughput trace at the receiver measured for the same bundle delivery with a bundle size of 20 Kbytes.

As observed, since the transmission starts, the throughput performance is consistently 0 until around 6600 seconds. This is because out of the first five transmission efforts spanning more than 6000 seconds, none of them is able to successfully deliver the bundle at the receiver without error due to the link unavailability caused by the lengthy disruptions together with the transmission errors.

The traffic analysis provided by *Wireshark* shows that the only impulse of the throughput trace at the receiver is measured at 6626 seconds. This is an indication that the bundle is successfully delivered at the receiver 6626 seconds later since the transmission started. This is reasonable given that the bundle is transmitted under the sixth transmission effort by the sender around 6026 seconds as shown in Fig. 5 and the one-way propagation delay from the sender to the receiver is 10 minutes, i.e., (6026+600) = 6626 seconds.

As discussed, the bundle delivery time increases along with an increase in bundle size because of the resulting increase in the number of transmission efforts needed for successful delivery of the bundle. Fig. 7 shows a dynamic throughput trace at the sender illustrating the data traffic measured in delivering a much larger bundle, 44 Kbytes. As for the

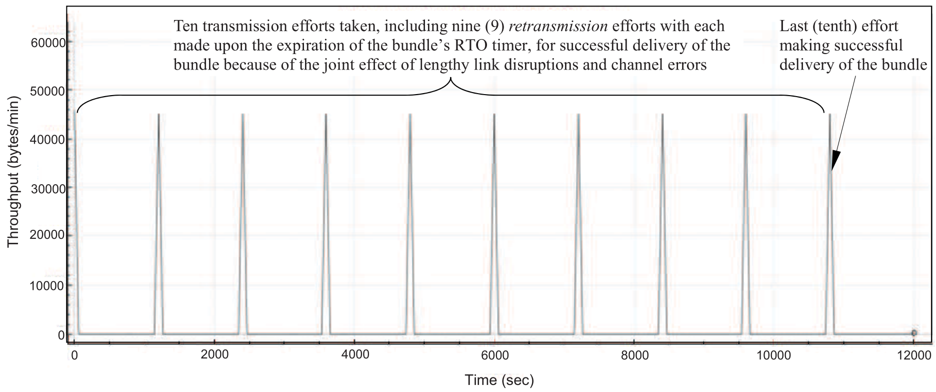


FIGURE 7. Dynamic data traffic (throughput) trace measured at the *sender* for delivery of a bundle of 44 Kbytes over a heterogeneous space networking channel.

transmission with a bundle of 20 Kbytes in Fig. 5, two link disruptions (with durations of 8 minutes and of 28 minutes) are introduced during the bundle delivery. The traffic pattern is very similar to the one observed in Fig. 5 because of the same transmission control strategy, i.e., retransmission upon the expiration of the bundle's custodial RTO timer with the length of 20 minutes. The only difference is that it takes several more transmission efforts and therefore total transmission time is much longer. The fact that several more transmission efforts are taken is because the bundle size, 44 Kbytes, is much larger than 20 Kbytes. As discussed, the bundle size L_{Bundle} has an exponential effect on the bundle transmission error rate P_{Bundle}. Because the BP retransmission is done on a bundle basis, a transmission error experienced by any data byte of the bundle results in retransmission of the entire bundle. This leads to an exponentially larger number of retransmission efforts for a large bundle than a small bundle.

The trace in Fig. 7 shows that ten transmission efforts are taken in total for the successful delivery of the bundle of 44 Kbytes, which is identical to the numerical result of the model in Fig. 4. This indicates that the bundle delivery attempts made by all the first nine efforts fail because of the joint effect of lengthy link disruptions and channel transmission errors. The only effort which leads to the successful delivery is the tenth effort which is made around 10800 seconds. This is reasonable given that following the initial transmission, nine retransmission efforts are made with each of them made upon the expiration of the bundle's RTO timer of length of 20 minutes, i.e., (1200 × 9) seconds.

The throughput trace measured at the receiver was very similar to the trace for the bundle of 20 Kbytes shown in Fig. 6, with the only difference observed in the throughput pulse of the bundle indicating that the bundle was received much later. Therefore, this finding is not presented to avoid duplication. As a matter of fact, the performance trace is consistently 0 until the end of bundle delivery showing a single impulse. The total bundle delivery time is much longer, around 11400 seconds, which is correct according to (10800+600) where 10800 seconds is the time at which

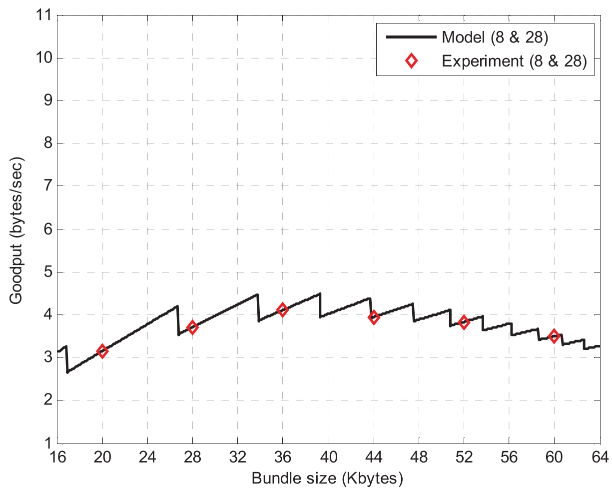


FIGURE 8. A comparison of goodput performance predicted by the model and collected from the sample experiments for data transmission over a heterogeneous space networking channel with two link disruptions experienced: a link disruption with a duration of 8 minutes and starting time of 7 minutes, and another with a duration of 28 minutes and starting time of 27 minutes.

the last transmission effort was made by the sender. This is exactly equal to the performance for the bundle of 44 Kbytes as reported in Fig. 3.

Such an extremely long bundle delivery time in space communications (or heterogeneous space networks) surely leads to very low transmission efficiency. As observed, the throughput traces at the sender and receiver serve as a good indication of the end-to-end dynamic data flow traffic over the channel. Goodput performance is widely recognized as a better measure of data transmission efficiency for a protocol from a user's application point of view. Goodput is defined as the ratio of delivered unique data bytes to the total data delivery time. Therefore, the goodput for bundle delivery of BP in space communications can be easily formulated as

$$GPT_{BP} = \frac{L_{Bundle}}{T_{Bundle-delivery}}. \tag{18}$$

Fig. 8 presents a comparison of the goodput performance of BP between the model and the experiments for the same transmission scenarios presented in Fig. 3 and Fig. 4. It is observed that the goodput performance of BP is extremely low, varying in a range of 2.5 bytes/sec to 4.5 bytes/sec. This is due mainly to the very long space channel RTT of 20 min and the two link disruptions with durations of 8 minutes and 28 minutes that jointly lead to the extremely long bundle delivery time. However, the numerical values of the goodput measured in the experiments fit well the predictions of the model. This indicates that the analytical model derived for the goodput performance of BP is valid.

The sawtooth pattern of the goodput in Fig. 8 is caused by the staircase pattern of the bundle delivery time in Fig. 3. Specifically, the linear-increase section for each "tooth" of the goodput is because of the increment of the bundle size L_{Bundle} (i.e., data bytes carried) on the x-axis with no change of the corresponding bundle delivery time on the y-axis as observed in Fig. 3. The sudden drop of the goodput is because of the sudden increase of the bundle delivery time in Fig. 3 caused by the increase of the number of transmission efforts formulated as the ceiling function, and each additional effort increases the bundle delivery time for 20 minutes, i.e., according to the following connection between GPT_{BP} and N_{TE}:

$$GPT_{BP} = \frac{L_{Bundle}}{\sum_{i=1}^{N_{Link}}\left(P_{N_{Link}}(i)\right) + \sum_{j=1}^{N_{Break}}\left(Q_{N_{Break}}(j)\right)}. \quad (19)$$

with $P_{N_{Link}}(i) = N_{TE_i}T_{Bundle_i} + \left(N_{TE_i} - 1\right)T_{RTO_i} + T_{Prop_i}$, $Q_{N_{Break}}(j) = T_{Break_j} + T_{Bundle_{Dj}} + T_{Prop_{Dj}}$, and $N_{TE_i} = \lceil \frac{1}{1-P_{Bundle_i}} \rceil$.

To study the bundle delivery performance of BP experiencing multiple link disruptions that are identical with respect to length, the experiments were also run with two link disruptions of the same duration, 9 minutes. As was done for the first set of experiments, the two link disruptions were introduced at the starting times of 7 minutes and 27 minutes. According to the comparison results between the model and the experiment data, the observed performance pattern and trend were very similar to those in Figs. 3 and 4. Therefore, they are not presented here. As a sample of transmission efficiency, Fig. 9 presents their comparison of goodput performance. Similar to the goodput comparison in Fig. 8, the numerical values measured in the experiments fit well the predictions of the model with similar variation pattern. The goodput is extremely low at each bundle size but slightly higher than that presented in Fig. 8. This is because the duration of the introduced link disruptions, i.e., a total of eighteen (2 × 9) minutes, is much shorter than thirty-six (8+28) minutes in the first set of experiments.

Although the overall goodput performance is extremely low due to the joint effect of the very long propagation delay and the lengthy duration of the two link disruptions, it shows minor variation with variation in bundle size. The best goodput performance is given by a bundle size in a range of 30 Kbytes - 40 Kbytes. It is observed that out of the

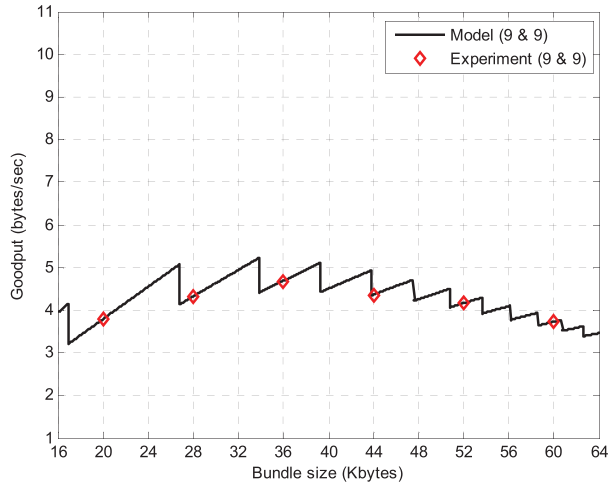


FIGURE 9. A comparison of goodput performance predicted by the model and collected from the sample experiments for data transmission over a heterogeneous space networking channel with two link disruptions that are identical with respect to the length and each disruption having the same duration, 9 minutes.

six bundle sizes studied in these experiments, the bundle with a length of 36 Kbytes outperforms others, and BP shows minor goodput degradation with either increase or decrease of bundle size from this figure. The performance degradation with the larger bundle occurs because of the significant increase of the bundle delivery time caused by the additional number of transmission efforts taken for successful delivery of a large bundle, as discussed.

Goodput performance degrades with decrease of bundle size below 36 Kbytes for a different reason. BP shows performance degradation with a small bundle (e.g., 20 Kbytes) because a small number of data bytes are delivered at the cost of the quite long bundle delivery time. For example, the bundle delivery time for the bundle of 20 Kbytes is not much shorter in comparison to that for the bundle of 36 Kbytes. The long bundle delivery time is due to the joint effect of the lengthy duration of link disruptions and the large number of transmission efforts together with the extremely long round-trip delay of 20 minutes. The lengthy duration of two link disruptions contributes, as a fixed time offset of 36 minutes, to the total delivery time of a small bundle, just as for the transmissions of the large and medium-size bundles. But it leads to minor performance degradation according to (18) because a smaller number of data bytes are delivered to the destination.

V. CONCLUSIONS

In this paper, analytical modeling is presented to study the transmission performance of the main protocol of DTN, BP, in a heterogeneous space networking system characterized by multiple link disruption events together with lengthy link delay and data loss. This use case can be viewed as an expression of the extreme worst-case operating conditions that a heterogeneous network built on 5G technology would be likely to encounter. Data flow experiments using a PC-based testbed infrastructure were conducted to validate the model.

According to the results of this study, the analytical model presented in this paper is valid regardless of the number of link disruption events, the durations of the link disruption, the number of data links, and the sizes of the bundles. Therefore, it is concluded that the model can predict the transmission performance of BP in space communications experiencing multiple link disruptions, including the total bundle delivery time, total number of transmission efforts taken for bundle delivery, and goodput performance.

The study indicates that for data delivery of BP over a lossy space channel in presence of multiple link disruptions, the bundle delivery time is primarily determined by the total number of transmission efforts taken for successful bundle delivery together with the duration of link disruptions. The curves for bundle delivery time and the number of transmission efforts are similar, varying with variation in bundle size. It is found that both measures tend to increase exponentially with increasing bundle size due mainly to the exponential effect of bit errors on the total number of transmission efforts. Although the goodput performance of BP in space was shown to be very low under these conditions due to the extremely long bundle delivery time, bundle sizes in a certain range tend to achieve better performance than other bundles. For the experiments at a BER of 5×10^{-6} presented in this study, the best goodput performance is achieved by a bundle size in a range of 30 - 40 Kbytes. Either increasing or decreasing bundle size outside of this range results in some performance degradation, for the reasons explained in Section IV.

ACKNOWLEDGMENT

The research described in this paper was performed in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). Government sponsorship is acknowledged.

REFERENCES

[1] NASA's Mars Science Laboratory. *Jet Propulsion Laboratory, California Institute of Technology, CA*. Accessed: Aug. 2017. [Online]. Available: http://mars.nasa.gov/msl/mission/communicationwithearth/data/

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

[3] *Rationale, Scenarios, and Requirements for DTN in Space*, document CCSDS 734.0-G-1, CCSDS, Aug. 2010. [Online]. Available: https://public.ccsds.org/Pubs/734x0g1e1.pdf

[4] The Space Internetworking Strategy Group (SISG), "Recommendations on a strategy for space Internetworking," Interagency Oper. Advisory Group, NASA Headquarters, Washington, DC, USA, Tech. Rep. IOAG.T.RC.002.V1, Aug. 2010.

[5] K. Scott and S. Burleigh, *Bundle Protocol Specification*, document RFC 5050, IETF Request for Comments, Nov. 2007. [Online]. Available: http://www.ietf.org/rfc/rfc5050.txt

[6] *CCSDS Bundle Protocol Specifications*, document CCSDS 734.2-B-1, CCSDS, September 2015. [Online]. Available: https://public.ccsds.org/Pubs/734x2b1.pdf

[7] Z. Bian, R. Wang, K. Zhao, D. Bian, Z. Xie, and Y. Qian, "Bundle protocol for data delivery over highly asymmetric deep-space channels," *IEEE Netw.*, vol. 30, no. 5, pp. 68–73, Sep./Oct. 2016.

[8] H. Kruse and S. Ostermann, *UDP Convergence Layers for the DTN Bundle and LTP Protocols*, document draft-irtf-dtnrg-udp-clayer-00, IETF DTNRG IRTF Research Group, Nov. 2008. [Online]. Available: http://tools.ietf.org/html/draft-irtf-dtnrg-udp-clayer-00

[9] *Solar System Internetwork (SSI) Architecture*, document CCSDS 730.1-G-1, CCSDS, Jul. 2014. [Online]. Available: https://public.ccsds.org/Pubs/730x1g1.pdf

[10] NASA Technologies. (Jun. 21, 2016). *New Solar System Internet Technology Debuts on the International Space Station*. [Online]. Available: http://www.nasa.gov/feature/new-solar-system-internet-technology-debuts-on-the-international-space-station

[11] N. Bezirgiannidis, S. Burleigh, and V. Tsaoussidis, "Delivery time estimation for space bundles," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 49, no. 3, pp. 1897–1910, Jul. 2013.

[12] A. Sabbagh, R. Wang, K. Zhao, and D. Bian, "Bundle protocol over highly asymmetric deep-space channels," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2478–2489, Apr. 2017.

[13] K. Zhao, R. Wang, S. C. Burleigh, A. Sabbagh, W. Wu, and M. De Sanctis, "Performance of bundle protocol for deep-space communications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 52, no. 5, pp. 2347–2361, Oct. 2016.

[14] K. Zhao, R. Wang, S. C. Burleigh, M. Qiu, A. Sabbagh, and J. Hu, "Modeling memory-variation dynamics for the Licklider transmission protocol in deep-space communications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 51, no. 4, pp. 2510–2524, Oct. 2015.

[15] J. Jiao *et al.*, "Reliable deep-space file transfers: How data transfer can be ensured within a single round-trip interval," *IEEE Veh. Technol. Mag.*, vol. 12, no. 4, pp. 86–94, Dec. 2017.

[16] R. Wang, S. C. Burleigh, P. Parik, C.-J. Lin, and B. Sun, "Licklider Transmission Protocol (LTP)-based DTN for cislunar communications," *IEEE/ACM Trans. Netw.*, vol. 19, no. 2, pp. 359–368, Apr. 2011.

[17] S. Burleigh. (Aug. 2017). Interplanetary Overlay Network Design and Operation V3.6.0b. JPL D-48259, Jet Propulsion Laboratory, California Institute of Technology, CA, USA. Accessed: Oct. 2017. [Online]. Available: http://sourceforge.net/projects/ion-dtn/files/latest/download

[18] 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 Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2536–2550, Mar. 2017.

[19] R. C. Durst, G. J. Miller, and E. J. Travis, "TCP extensions for space communication," *Wireless Netw.*, vol. 3, no. 5, pp. 389–403, Oct. 1997.

[20] N. Aeronautics and S. Administration. (Aug. 2012). Space Network Users, Guide (SNUG) Revection 10, Goddard Space Flight Center, Greenbelt, MD, USA. Accessed: Nov. 2016. [Online]. Available: http://esc.gsfc.nasa.gov/assets/files/450-SNUG.pdf

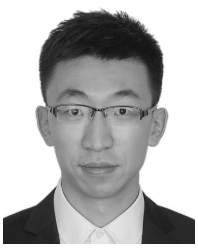
[21] *Wireshark (2.4.4)*. Accessed: Jan. 2018. [Online]. Available: https://www.wireshark.org/

RUHAI WANG (M'03–SM'17) received the Ph.D. degree in electrical engineering from New Mexico State University in 2001. He is currently a Professor with the Phillip M. Drayer Department of Electrical Engineering, Lamar University, Beaumont, TX, USA. He also serves as a Principal Scientist with Nanjing University and the Chair Professor with Soochow University, China. He has authored or co-authored nearly 100 research papers in international journals and conferences proceedings. His current research interests include space communications and networks.

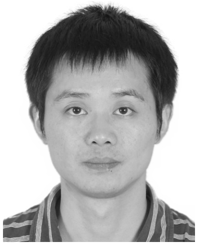
ALAA SABBAGH received the bachelor's degree in electrical engineering and the master's degree in communications engineering from Al-Baath University, Homs, Syria, in 2009 and 2013, respectively, and the Doctoral degree from Lamar University, Beaumont, TX, USA, in 2016. He is currently an Instructor with the Florence–Darlington Technical College, Florence, SC, USA. His research interests include computer networks, cyber security, space communications, and networks.

SCOTT C. BURLEIGH is currently a Principal Engineer with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. As a participant in CCSDS, he has co-authored the specifications for the CCSDS file delivery protocol and the asynchronous message service, while as a member of the DTN Research Group, IRTF, he has co-authored the specifications for the DTN BP (RFC 5050) and the DTN LTP for delay-tolerant ARQ (RFC 5326). He has developed implementations of these protocols that are designed for integration into deep space mission flight software, with the long-term goal of enabling deployment of a delay-tolerant interplanetary Internet.

MAHJABEEN JAVED received the bachelor's degree in electrical engineering from The Reaud Honors College, Lamar University, Beaumont, TX, USA, in 2018. She is currently a Research Assistant with the Computer Networking Research Laboratory, Phillip M. Drayer Department of Electrical Engineering, Lamar University. Her research interests involve computer networks, cyber security, fabrication and processing of biomedical smart devices, and smart materials.



SHUSHI GU received the M.S. and Ph.D. degrees in communication engineering from the Harbin Institute of Technology (HIT) in 2012 and 2016, respectively. He is currently a Post-Doctoral Research Fellow with the Communication Engineering Research Centre, Shenzhen Graduate School, HIT, Shenzhen, China. His current interests include erasure codes, network and channel coding, space information networks, and distributed storage system.



JIAN JIAO (M'16) received the M.S. and Ph.D. degrees in communication engineering from the Harbin Institute of Technology (HIT) in 2007 and 2011, respectively. From 2011 to 2015, he was a Post-Doctoral Research Fellow with the Communication Engineering Research Centre, Shenzhen Graduate School, HIT, Shenzhen, China. From 2016 to 2017, he was a China Scholarship Council Visiting Scholar with the School of Electrical and Information Engineering, University of Sydney, Sydney, Australia. Since 2017, he has been an Assistant Professor with the Department of Electrical and Information Engineering, HIT. His current interests include error control codes, space information networks, random multiple access, and machine-to-machine communications. He received the Shenzhen High Level Talent Program Award in 2015.

QINYU ZHANG (M'08–SM'12) received the bachelor's degree in communication engineering from the Harbin Institute of Technology (HIT) in 1994, and the Ph.D. degree in biomedical and electrical engineering from the University of Tokushima, Japan, in 2003. From 1999 to 2003, he was an Assistant Professor with the University of Tokushima. From 2003 to 2005, he was an Associate Professor with the Shenzhen Graduate School, HIT, where he was also the Founding Director of the Communication Engineering Research Center, School of Electronic and Information Engineering. Since 2005, he has been a Full Professor and the Dean of the EIE School, HIT. His research interests include aerospace communications and networks, wireless communications and networks, cognitive radios, signal processing, and biomedical engineering. He has been a TPC Member of INFOCOM, ICC, GLOBECOM, WCNC, and other flagship conferences in communications. He received three scientific and technological awards from governments and received the National Science Fund for Distinguished Young Scholars, the Young and Middle-Aged Leading Scientist of China, and the Chinese New Century Excellent Talents in University. He is on the Editorial Board of some academic journals, such as the *Journal on Communications*, the *KSII Transactions on Internet and Information Systems*, and *Science China: Information Sciences*. He was the TPC Co-Chair of the IEEE/CIC ICCC'15, the Symposium Co-Chair of the IEEE VTC'16 Spring, an Associate Chair for Finance of ICMMT'12, and the Symposium Co-Chair of CHINACOM'11. He was the Founding Chair of the IEEE Communications Society Shenzhen Chapter.