A Study of Licklider Transmission Protocol in Deep-Space Communications in Presence of Link Disruptions

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Delay/disruption-tolerant networking (DTN) is widely recognized as a key internetworking technology for implementing a space system of systems (SoS). Aimed at being the main data transport protocol of DTN, Licklider transmission protocol (LTP) is expected to provide reliable data transmission service in a challenging space SoS networking environment regardless of random link disruptions. In this article, a study of LTP in deep-space communication networks in presence of link disruptions is presented. An analytical framework is developed for the effect of multiple random link disruptions on LTP's reliable data delivery in deep-space networks. The study indicates that the models accurately predict the transmission performance of LTP over a deep-space communication channel in presence of multiple link disruptions. A threshold interval value, obtained from the analytical modeling results, is proposed as a means of determining the reducibility of two successive link disruptions to a single disruption; that threshold value is verified by the experiments.

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I. INTRODUCTION

A. Background

Space system of systems (SoS) is defined as a network of assets on Earth, in orbit around Earth, in orbit around solar system bodies, and on the surface of solar system bodies that are interconnected and/or interoperated to perform a mission [1]. Delay/disruption-tolerant networking (DTN) [2] is developed as a key internetworking technology for implementing a space SoS and integrating the Earth system, space system, and deep-space system for reliable data transmission [3]. Targeted at the main transport protocol of DTN, Licklider transmission protocol (LTP) [4] is expected to provide a reliable data delivery service in a space SoS, especially in deep-space communication networks, regardless of presence of random link disruptions and/or extremely long propagation delays. LTP is one of the transport protocols that are expected to be operable under bundle protocol (BP) [5], the core "overlaying" protocol of DTN. For the details of DTN approach and its operation methods to deep-space networking, refer to [2] and [3].

The basic protocol data unit of LTP is termed a *block*. To meet various application requirements and user transmission services, selective block transmission mechanisms are provided by LTP: LTP service with respect to any single block can be reliable, unreliable, or both [4]. That is, LTP may transmit an entire block either reliably (in the manner of TCP) or unreliably (in the manner of UDP), or alternatively it may transmit part of a block reliably and the rest unreliably. Reliable transmission of a single block is effected by designating all the data bytes of a block as "red" data, while designating the entire block as "green" data effects unreliable transmission service. To apply both transmission services to a single LTP data block, the part of the block that requires reliable transmission is designated the "red" part, and the rest is designated to be "green."

It is commonly recognized that extremely long signal propagation delays, lengthy and frequent link disruptions, high data loss rates (i.e., high bit error rates), and highly asymmetric channel rates are the major factors that degrade data transmission performance in a space SoS network. Link disruption events occur periodically and/or randomly because of interruptions in transit capability between the data source node and the ground destination node, caused by satellite/planet rotations, the sun storm, or the asteroid interference.

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B. Related Work

Some efforts have been made jointly by the NASA's Jet Propulsion Laboratory (JPL) and other academic groups to exercise LTP [6], [7], [8], [9], [10], [11], [12], [13], [14] and BP [15], [16], [17], [18], [19], [20], [21], [22], [23] in space. However, in most of the LTP studies, the effect of link disruption either is ignored or is assumed to constitute an invariable offset to the delivery time, i.e., the link disruption duration is simply added to the total file/data delivery time without a detailed analysis of how it really affects the data block delivery and transmission performance. Furthermore, simply adding the disruption duration to the baseline delivery time is a very rough approximation of the block delivery time, which may not accurately characterize the performance of LTP.

In [14], a theoretical framework for the effect of a single link disruption event is presented for LTP in Mars communications. Also, for most of these studies on LTP [6], [7], [8], [9], [10], the effect of only a single link disruption is considered. Because of the extremely long physical distance spanning multiple systems integrated in a space SoS, there is a chance that multiple link disruptions may occur during a given block transfer. A single recent study has examined the effect of multiple random link disruptions on LTP specifically for Mars communications [13]. However, in [13], preliminary experimental results are presented. A solid theoretical analysis is needed to account for the experimental results and conclusions presented. Formal comparisons between LTP and other similar deep space communication techniques (e.g., enhanced TCP, UDP, or a hybrid of them) have been done extensively. They are done from various aspects, including the effects of link disruptions, lengthy propagation delays, high data loss rates, and asymmetric channels to their transmission performance. As this study focuses on a different research problem, there is no need to repeat similar comparisons in this article. For the detailed comparison results, refer to [7], [10], and [21].

Energy consumption is consistently considered as an important factor in data routing and forwarding in DTN. In [24], an incentive scheme is developed based on energy spent by the vehicular DTN node for forwarding data successfully. A secure routing mechanism is presented based on the trust value of the vehicular DTN nodes.

C. Contributions and Significance of This Study

In this article, a study of the effect of multiple link disruption events on LTP, as an extension of [14], is presented, carrying out an analysis of LTP data block transfer experiencing multiple link disruptions with each individual disruption having a random starting time and random duration. The study focuses on analyzing how multiple link disruptions can affect:

1) the number of checkpoint (CP) and report segment (RS) transmission attempts and retransmission attempts required (as caused by the link disruptions);
2) the consequent round-trip time (RTT) of data exchange;
3) the data block delivery time;
4) the resulting goodput performance of LTP for reliable data block delivery over unreliable deep-space channels.

Realistic data block transmission experiments using a PC-based experimental infrastructure are conducted to validate the analytical models.

To the best of our knowledge, this article presents the first analytical framework for this problem in conjunction with experimental results for the effect of multiple link disruptions on reliable data delivery of LTP in deep-space communications. In order to model the time effect of multiple link disruptions on LTP block transfer, one of the key contributions of this works is to consider the interaction between two successive disruption events. The quantitative results collected using both the analytical framework and experimental methods are useful in characterizing the operation and transmission performance of LTP in presence of multiple link disruptions. As explained later in this article, the operational advantages of deploying LTP in DTN are clear. Note that effective network management capability is critical to the realization of these advantages, as only LTP "engines" that are intelligently configured can successfully cope with random link disruptions.

The rest of this article is organized as follows. Section II provides an overview of the reliable transmission of LTP. In Section III, the essential time components of LTP are introduced. Section IV is dedicated to analytical modeling for the effect of the link disruptions, followed by an overview of the experimental infrastructure in Section V. The model validation and performance evaluation are presented in Section VI. Finally, Section VII concludes this article.

II. OVERVIEW OF RELIABLE DATA TRANSMISSION IN LTP

As this study is mainly concerned with the reliable transmission service of LTP in presence of multiple link disruptions, we only present an overview of the transmission of a block when it is configured to be entirely "red." For the transmission of a "green" block or a mix of "green" and "red" parts of a block, refer to [4].

As soon as a "red" block transfer request was received from the client, the sending LTP engine checks the data block size with respect to the underlying link maximum transfer unit (MTU) size for transmission. As necessary, the block is segmented as multiple red LTP data segments so that each of them can be fit within a link-layer frame MTU. The last segment of the block is flagged by the sender as an asynchronous CP. The CP segment also serves as the end of red part (EORP) and the end of block (EOB). Following the segmentation and flagging process, all the segments of the block are queued for transmission in order. As soon as the queued CP/EORP/EOB segment is transmitted, the retransmission timeout timer of the CP segment, termed the *CP timer*, is started at the sender. Similar to the operation

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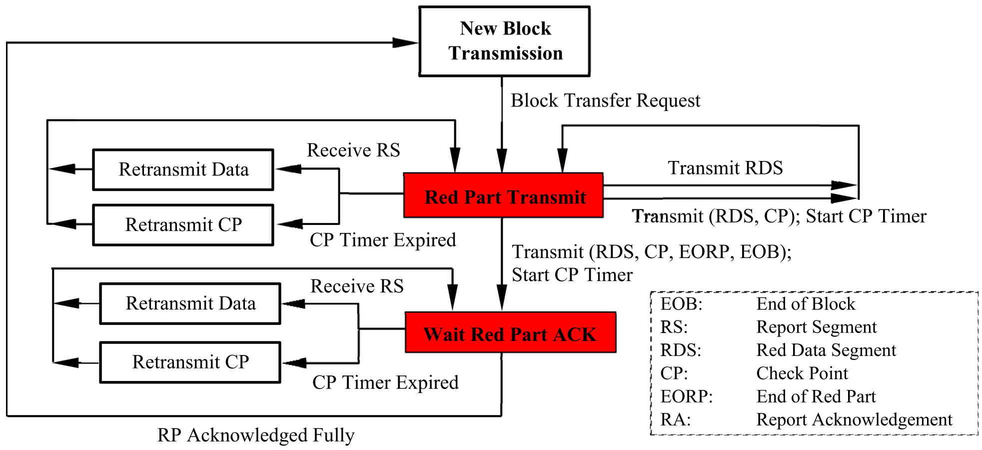

Fig. 1. LTP sending states and operating procedures for transmission of "red" part of a block [4].

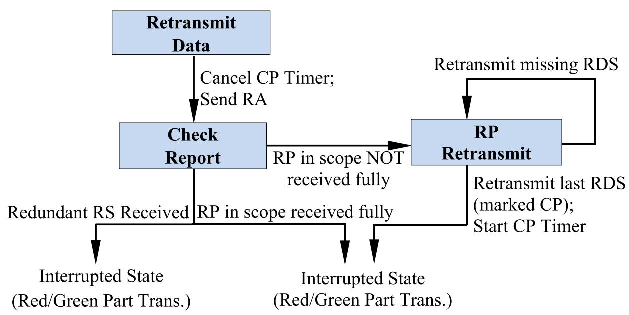

Fig. 2. Flowchart depicting how the transmission of a single LTP block can be concluded when the sender is "interrupted" by an RS [4].

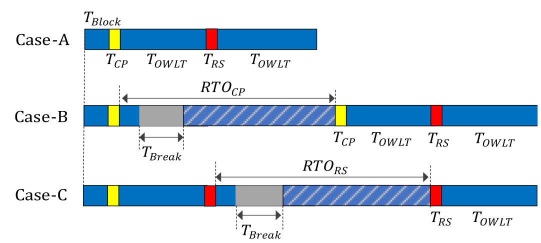

Fig. 3. Time components involved in general LTP transmission without and with single link disruption occurred.

of the RTO timer of a TCP segment, the CP segment (not the entire block) is retransmitted if the acknowledging RS is not received from the LTP receiver upon expiration of the CP timer.

The RS segment is sent by the receiving LTP in response to the reception of the CP segment to report the delivery status of the entire block; the RS requests retransmission of any data segments that were not successfully received. If all the red data segments are reported (by the received RS) to have been successfully received, a report acknowledgment segment is sent by the sender in response to the RS. However, if any segment is reported lost (that is, not delivered), it is retransmitted immediately. The last one of the retransmitted segments of the block is again flagged as a CP, which requests another RS reporting on the delivery status of those retransmitted segments. The process repeats until all the segments of the original block are successfully delivered at the receiver. Note that the LTP sender can also be interrupted by an expiration of a previously set CP timer [4]. If this occurs, the CP segment needs to be retransmitted with a new timer started.

Fig. 1 shows a flowchart of LTP sending states and the corresponding operating procedures illustrating the reliable transmission algorithms for "red" part of a block. It is transcribed from the LTP sender state transmission diagram in request for comments 5326 [4] with some modifications made. The chart is modified so that only the states related to the transmission of "red" data are shown. As illustrated, the two states are the Red Part Transmit and the Wait Red Part ACK. Referring to each state, the data transmission procedures and sequences of LTP are illustrated together with the interactions with the associated receiver.

Fig. 2 presents another flowchart depicting how the transmission of a single block can be concluded when the LTP sender is in one of two "red" states but is "interrupted" by an RS from the receiver. The operational process for the retransmission of the red data segments as requested by the RS is also illustrated. Refer to [4] for a detailed explanation of the associated transmission algorithms in the chart.

III. Essential Time Components in a General LTP Transmission Scenario

Fig. 3 illustrates the essential time components involved in a general LTP transmission scenario without and with link disruption experienced. All the involved time terms are defined in Table I. Case-A shows basic time components in the case of no disruption. In comparison, Case-B shows the time components experienced when a link disruption occurs during block transmission, and Case-C shows the time components experienced when a link disruption occurs right during RS transmission (after the block is delivered).

Taking the time components involved for LTP transmission in Case-A, the baseline RTT for LTP block delivery without link disruption presence, termed RTT_0, can be estimated as a sum of the basic time components involved

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TABLE I
Notations for Analytical Modeling

Symbol	Definition
RTT_0	Baseline RTT for block delivery w/o disruption
T_{Block}	LTP data block transmission time
T_{OWLT}	One-way-light time between source and destination
T_{RS}	Transmission time of an RS
T_{CP}	Transmission time of a CP segment
RTO_{CP}	CP retransmission timeout timer
RTO_{RS}	RS timeout retransmission timer
T_{Break}	Time duration of a link disruption
$\Delta RTT_{Disrupt}$	RTT increment resulting from a link disruption
N_{CP}	CP retransmissions attempts due to link disruption
x	Link disruption starting time
N_{RS}	RS retransmission attempts due to link disruption
L_{CP}	Length of a CP segment
x_i	Starting time of the ith link disruption
T_{Break_i}	Duration of the ith link disruption
X_{i_end}	End of the ith link disruption
ΔT	Time interval between adjacent link disruptions
TH_i	Threshold time point at which adjacent link disruptions can be equated
$\Delta RTT_{Disrupt}(T_{Break\_i})$	RTT increment due to the ith link disruption
N_{CP-i}	CP retransmission attempts made during the ith link disruption
N_{CP-Eq}	CP retransmission attempts made during an equated link disruption
RTT_{cp}	RTT for retransmission of a CP
T_{Case-i}	Block delivery time in Case i
N_{RS-i}	RS (re)transmission attempts made during the ith disruption
N_{Case-i}	Extra CP transmission attempts made due to both disruptions in Case i
L_{Block}	Length of an LTP data block
GP_{Case-i}	Goodput for block transfer in Case i
T_{Break_Eq}	Duration of an equated single disruption
N_{RS-Eq}	RS retransmission attempts made during an equated disruption
$\Delta RTT_{Disrupt\_total}$	Time effect of an equated disruption on block delivery

in block delivery. These time components include the LTP data block transmission time, the one-way-light time between source and destination, and transmission time of an acknowledging RS, i.e., the length of RTT_0 is equal to $(T_{Block} + 2T_{OWLT} + T_{RS})$.As discussed, the last segment of the block is flagged by the sender as an asynchronous CP. Therefore, T_{Block} includes the transmission time of a CP segment T_{CP}.

The effect of link disruption mainly refers to the unavailability of link for transmission of data segments over the data link and acknowledging RS over the ACK link, which results in a loss of data block or RS and their retransmissions. As shown in the flowchart in Fig. 1, a corresponding RTO timer is set for each of a data block and an RS to control their individual retransmission. The timeout timer for a block is set for the last segment, i.e., the CP segment. The timer lengths are termed RTO_{CP} and RTO_{RS}, as shown in Fig. 3. The CP segment of a block is retransmitted upon expiration of the RTO_{CP} timer. From a perspective of time, the loss of a CP segment generally occurs in the first T_{OWLT} period. Case-B in Fig. 3 shows a scenario in which the CP segment is lost in the first T_{OWLT} period due to the link disruption having a length of T_{Break}, which results in its retransmission upon an expiration of the RTO_{CP} timer. The retransmission event leads to another period of transmission/delivery time of the CP and RS.

Case-C in Fig. 3 shows a scenario in which an RS segment is lost in the second T_{OWLT} period due to the disruption, resulting in its retransmission upon an expiration of the RTO_{RS} timer. As observed, the RS loss generally occurs in the second T_{OWLT} period because it is only transmitted in response to arrival of a data block which already propagated for the T_{OWLT} period. In comparison, the extra period of transmission/delivery time of the RS segment is only around half of the extra period in Case-B. This is because the loss of an RS does not entail retransmission of the CP segment.

Based on essential time components contributed to the block delivery time illustrated in Case-B and Case C in Fig. 3, it is obvious that the time effect of link disruption on LTP is mainly caused by the length of the disruption and the resulted losses of the CP/RS segments. If any non-CP segments of the block are lost, even though the retransmission of them is needed, there is no need to wait until the expiration of the RTO_{CP} timer. As soon as the corresponding RS is received, they are retransmitted. In this case, the extra period of transmission/delivery time of the CP and RS segments is not needed. For the RS transmission, as the RS is only a single and very small segment (only about a dozen bytes long), a loss of any of its bytes has the same time effect to the block delivery time.

Therefore, according to the aforementioned discussion, the analysis of the time effect of a single link disruption on LTP block delivery for reliable data delivery can be divided into two different cases: the case of CP loss that occurs during the first T_{OWLT} period (i.e., $0 \sim (T_{Block} + T_{OWLT}))$ and the case of RS loss occurred during the second T_{OWLT} period (i.e., $(T_{Block} + T_{OWLT}) \sim \mathrm{RTT}_0)$).

IV. ANALYTICAL MODELING FOR THE EFFECT OF MULTIPLE LINK DISRUPTIONS ON LTP

For analysis of the time effect of multiple link disruptions on LTP block transfer, the key is to consider the interaction between two successive disruption events. If the successive disruption events do not interact with each other, they must be considered as multiple individual disruption events. However, if the successive disruption events interact with each other, their interactions have to be studied when the total effect of all the disruptions is modeled. The notations used for the entire modeling process are listed in Table I.

Fig. 4 illustrates an LTP block transmission scenario with more than one link disruption occurred on the links. For the sake of simplicity, only two link disruption events are considered. But the analysis is applicable to a scenario of having any number of link disruptions, as will be discussed at the end of this section.

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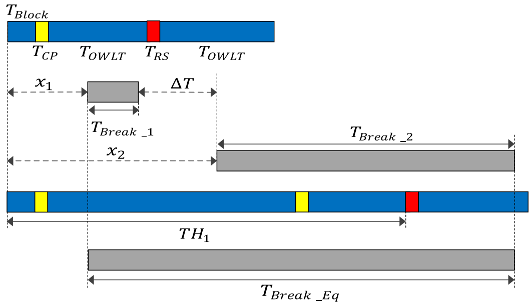

Fig. 4. Time components involved in general LTP transmission with more than one link disruption occurred.

For the first disruption, let x_1 be the disruption starting time and let T_{Break_1} be the length of the disruption. Similarly, for the second disruption, let x_2 and T_{Break_2} be the disruption starting time and the length of the disruption, respectively. According to the illustration in Case-B in Fig. 3, for LTP data transfer in presence of a single link disruption, the effect of the disruption to block delivery time ends at $(T_{Block} + \text{RTO}_{CP})$, i.e., prior to the CP segment retransmission starting point. As a result, the RTT interval is equivalent to $(\text{RTT}_0 + \text{RTO}_{CP})$. Assume that the second disruption (i.e., the one starting at x_2 shown in Fig. 4) occurs prior to the end of the time effect of the first disruption. Then, even though the effect of the first disruption is concluded, the lost CP segment cannot be retransmitted because the data link is still unavailable due to the second disruption. In other words, the sender has to wait until the time effect of the second disruption ends. This implies that the total effect of both link disruption events is equivalent to the effect of a single disruption having a length of T_{Break_Eq}.

Therefore, in order to simplify the analysis of the time effect of multiple link disruption events, it is proposed in this study to *reduce* multiple disruption events to smaller numbers of events for analysis of the time effect. Whether or not two successive disruptions can be, in effect, reduced to a single disruption depends on the starting time and duration of the "next" (that is, second) link disruption. If the "next" link disruption occurs before the time effect of the "current" disruption ends (as shown in Fig. 4), the two disruption events can be reduced to a single one. If the "next" link disruption occurs after the time effect of the "current" disruption ends, they do not interact with each other, and therefore, they cannot be reduced to a single disruption event. In this case, the effect of each link disruption has to be analyzed separately.

To investigate whether or not two successive disruptions can be reduced as a single one, the key is the analysis of the time interval from the end of the time effect of the first disruption to the RTT. Denote the interval between the ending time of the first disruption and the starting time of the second disruption as ΔT. Referring to the scenario having two link disruption events in Fig. 4, ΔT can be formulated as

$$\Delta T = x_2 - X_{1\_end} \tag{1}$$

where X_{1_end} is the end of the first disruption. According to the discussion in Section III, the time effect of a link disruption on LTP block delivery is different depending on the CP segment loss or the RS loss due to the disruption, and each of the loss events occurs during a different time period. Therefore, the analysis of the time effect of multiple link disruption is also divided into two cases.

1) In case of CP loss caused by first link disruption (i.e., $0 < \boldsymbol{x}_1 < \boldsymbol{T_{Block}} + \boldsymbol{T_{OWLT}}$)

A scenario of the CP loss caused by the first link disruption is illustrated in Fig. 4. As illustrated by the third time bar in Fig. 4, if the first link disruption causes the CP loss, the RTT will go through a period of $(2T_{OWLT} + T_{RS})$ beyond the end of the effect of the first disruption. For the period of $(2T_{OWLT} + T_{RS})$, the period of T_{OWLT} is the time taken for the propagation of the retransmitted CP segment while the remainder of $(T_{OWLT} + T_{RS})$is for the transmission and propagation of the corresponding RS. Therefore, if the second link disruption occurs during the period of T_{OWLT} out of $(2T_{OWLT} + T_{RS})$, it will again result in unavailability of data link for the propagation of the retransmitted CP segment, meaning that the CP segment is lost again. This implies that in case the second link disruption occurs during the period of T_{OWLT}, the two link disruption events can be reduced to a single effective disruption, as discussed earlier.

In contrast, if the second link disruption occurs during the period of $(T_{OWLT} + T_{RS})$ out of $(2T_{OWLT} + T_{RS})$, the disruption only affects the RS transmission. The retransmission of the CP segment is not affected as it has been completed by the time the disruption occurs. In this case, the time effect of the second disruption can be estimated according to the method discussed earlier for the loss of an RS caused by a single link disruption. In other words, the two disruptions cannot be reduced to a single disruption event.

In summary, for LTP block transmission in presence of two link disruptions, after the effect of the first link disruption ends, if the second disruption event occurs during the period of T_{OWLT}, these two disruptions can be reduced to a single effective disruption. Otherwise, they cannot.

2) In case of RS loss caused by first link disruption (i.e., $\boldsymbol{T_{Block}} + \boldsymbol{T_{OWLT}} < \boldsymbol{x}_1 < \boldsymbol{RTT}_0$)

As discussed, an RS is sent by the receiver in response to the receipt of a CP segment. For a transmission scenario of RS loss caused by the first link disruption, the transmission of the CP segment is not affected because the CP has already been delivered at the receiver when the disruption occurs. Instead, the disruption only affects the transmission of the RS over the ACK channel. Because it takes a timer interval of $(T_{Block} + T_{OWLT})$ to successfully deliver the block at the receiver, the first link disruption necessarily occurs in a time range of $(T_{Block} + T_{OWLT}) \sim \text{RTT}_0)$). In this case, the RTT will be extended by a period of T_{OWLT} beyond the end of the effect of the first disruption. If the second link disruption occurs during this period of T_{OWLT} , the disruption only affects the RS transmission as the first disruption does. It is obvious that if the second link disruption occurs prior to the end of

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RTT interval for the first disruption, the first and second link disruptions can be reduced as a single disruption.

Therefore, in order to determine whether or not two successive link disruption events can be reduced to a single one, there is a need to determine a threshold time point beyond which two disruptions can be reduced to a single disruption in each of two cases. Denote such a threshold time point (beyond which two disruptions can be reduced to a single one) as TH_1 which can be formulated in each of two cases.

Case 1: *In case of CP loss caused by first link disruption* (i.e., $0 < x_1 < T_{Block} + T_{OWLT}$)

In the case of CP loss caused by the first link disruption (i.e., $0 < x_1 < T_{Block} + T_{OWLT}$), TH_1 is the threshold time point at which the second link disruption occurs within the period of T_{OWLT} after the effect of the first link disruption end, as shown in Fig. 4. TH_1 can be formulated as

$$\mathrm{TH}_1 = T_{Block} + \Delta\mathrm{RTT}_{Disrupt}\left(T_{Break\_1}\right) + T_{OWLT} \tag{2}$$

in which $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1})$ is the RTT increment resulting from the first link disruption to the baseline RTT. Let N_{CP-1}be the number of CP retransmission attempts made during the first link disruption event. As illustrated in Case-B in Fig. 3, the time increment resulting from a link disruption to the estimated RTT can be written as $(x + T_{Break} - T_{Block} + T_{CP})$. As it takes the sender a time period of RTO_{CP} to make each CP retransmission attempt, N_{CP-1}can be formulated as

$$N_{CP-1} = \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil. \tag{3}$$

Then, $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1})$ can be formulated as

$$\begin{aligned}\Delta\mathrm{RTT}_{Disrupt}\left(T_{Break_1}\right) &= N_{CP-1} \times \mathrm{RTO}_{CP} \\ &= \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP}.\end{aligned} \tag{4}$$

With the formula of $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1})$ derived, TH_1 can be rewritten as

$$\begin{aligned}\mathrm{TH}_1 = T_{Block} &+ \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} \\ &+ T_{OWLT} \quad X_{1\_end} > T_{Block}.\end{aligned} \tag{5}$$

For $0 < (x_1 + T_{Break\_1}) < T_{Block}$, it is obvious that $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1}) = 0$. This means that the first link disruption does not affect the CP segment transmission, which makes the second link disruption the only disruption event occurred during block delivery. In other words, it is the same as the case of a single disruption, and therefore, it is ignored in this study.

With the formulas for TH_1 derived, in the case that two link disruptions can be reduced to one, the threshold time point at which the second link disruption affects the transmission of the RS can be formulated as

$$\mathrm{TH}_2 = \mathrm{TH}_1 + T_{RS} + T_{OWLT}. \tag{6}$$

Similarly, the threshold time point that determines whether or not the second link disruption affects the retransmission of the data block and the CP segment can be formulated as

$$\mathrm{TH}_3 = \mathrm{TH}_2 + T_{Block} + T_{OWLT}. \tag{7}$$

If the second link disruption starts prior to the threshold time point TH_1, i.e., $x_2 < \mathrm{TH}_1$, it means that the second disruption event occurs before the time effect of the first disruption ends. In this case, the second disruption can be considered as an extension of the first disruption, and the two disruption events can be reduced to a single disruption event. Denote the number of CP retransmission attempts made during the reduced link disruption event as N_{CP-Eq}, and it can be formulated as

$$\begin{aligned}N_{CP-Eq} &= \left\lceil \frac{X_{2\_end} - (T_{Block} - T_{CP})}{\mathrm{RTO}_{CP}} \right\rceil \\ &= \left\lceil \frac{X_{2\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil\end{aligned} \tag{8}$$

where X_{2_end} is the end of the second disruption. The RTT for CP retransmission can be written as

$$\mathrm{RTT}_{CP} = T_{CP} + 2T_{OWLT} + T_{RS}. \tag{9}$$

Denote the block delivery time taken for successful block delivery in Case 1 as T_{Case-1}, which can be approximated as (in the case that two link disruptions can be reduced to one)

$$\begin{aligned}T_{Case-1} &= T_{Block} - T_{CP} + N_{CP-Eq} \times \mathrm{RTO}_{CP} \\ &\quad + \mathrm{RTT}_{CP} + \mathrm{RTT}_0 \\ &= T_{Block} - T_{CP} \\ &\quad + \left\lceil \frac{X_{2\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \\ &\quad \times \mathrm{RTO}_{CP} + \mathrm{RTT}_{CP} \\ &\quad + \mathrm{RTT}_0, \quad x_2 < \mathrm{TH}_1.\end{aligned} \tag{10}$$

If two successive link disruptions cannot be reduced to one, the number of CP retransmissions made during the first link disruption event is N_{CP-1} which is derived in (3). In case of either $\mathrm{TH}_1 < x_2 < \mathrm{TH}_2$ or $x_2 > \mathrm{TH}_3$, the RS transmission/retransmission attempt is affected by the second link disruption. Let N_{RS-2} be the number of RS (re)transmission attempts made during the second link disruption event; it can be formulated as

$$N_{RS-2} = \begin{cases} \left\lceil \frac{X_{2\_end} - \mathrm{TH}_1}{\mathrm{RTO}_{RS}} \right\rceil, & \mathrm{TH}_1 < x_2 < \mathrm{TH}_2 \\ 0, & \mathrm{TH}_2 < x_2 < \mathrm{TH}_3 \\ \left\lceil \frac{X_{2\_end} - \mathrm{TH}_3}{\mathrm{RTO}_{RS}} \right\rceil, & x_2 > \mathrm{TH}_3 \end{cases}. \tag{11}$$

In the case of $\mathrm{TH}_2 < x_2 < \mathrm{TH}_3$, the CP segment retransmission attempt is affected by the second link disruption. Let N_{CP-2} be the number of CP retransmissions made during the second link disruption event; it can be formulated as

$$N_{CP-2} = \left\lceil \frac{X_{2\_end} - \mathrm{TH}_2}{\mathrm{RTO}_{CP}} \right\rceil, \quad \mathrm{TH}_2 < x_2 < \mathrm{TH}_3. \tag{12}$$

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If two link disruptions cannot be reduced to a single effective disruption event, the block delivery time is presented as (13) shown at the bottom of the next page.

With the formulas of N_{RS-2}, N_{CP-1}, and N_{CP-2} plugged in, the block delivery time in Case 1 if two sequential link disruptions are not reducible is presented as (14) shown at the bottom of this page.

Denote the extra transmission attempts made at the sender due to both link disruptions in Case 1 as N_{Case-1}. With the block delivery time formulated, N_{Case-1} can be simply written as

$$N_{Case-1} = \left\lceil \frac{T_{Case-1}}{\mathrm{RTO}_{CP}} \right\rceil. \tag{15}$$

Goodput performance is commonly recognized as a good measure of data transmission effectiveness for a networking protocol. Goodput is defined as the ratio of the application data size for transmission to the data delivery time. Let L_{Block} be the length of data block for transmission. Denote the goodput for block transfer in Case 1 as GP_{Case-1}, which can be formulated as the ratio of the LTP data block size to the total data delivery time. In a compact form, GP_{Case-1} in all the subcases can be presented as (16) shown at the bottom of this page.

Case 2: *In case of RS loss caused by first link disruption* (i.e., $T_{Block} + T_{OWLT} < x_1 < \mathrm{RTT}_0$)

In the case of RS loss caused by first link disruption (i.e., $T_{Block} + T_{OWLT} < x_1 < \mathrm{RTT}_0$), the threshold time point TH_1 can be presented as

$$\begin{aligned}\mathrm{TH}_1 &= T_{Block} + T_{OWLT} + T_{RS} \\ &\quad + \Delta\mathrm{RTT}_{Disrupt}\left(T_{Break_1}\right) + T_{OWLT} \\ &= \mathrm{RTT}_0 + \Delta\mathrm{RTT}_{Disrupt}\left(T_{Break\_1}\right).\end{aligned} \tag{17}$$

Let N_{RS-1} be the number of RS retransmissions occurring during the first link disruption event. Then, as done for N_{CP-1} in (3), N_{RS-1} can be formulated as

$$N_{RS-1} = \left\lceil \frac{X_{1\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil. \tag{18}$$

Similarly, $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1})$ can be formulated as

$$\begin{aligned}\Delta\mathrm{RTT}_{Disrupt}\left(T_{Break_1}\right) &= N_{RS-1} \times \mathrm{RTO}_{RS} \\ &= \left\lceil \frac{X_{1\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}.\end{aligned} \tag{19}$$

With the formula of $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_1})$ plugged in, TH_1 can be rewritten as

$$\mathrm{TH}_1 = \mathrm{RTT}_0 + \left\lceil \frac{X_{1\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}. \tag{20}$$

Similar to Case 1, if the second link disruption starts prior to the threshold time point TH_1, i.e., $x_2 < \mathrm{TH}_1$, the two disruption events can be effectively reduced to a single disruption. Denote the duration of the reduced single disruption event as T_{Break_Eq}, which can be written as

$$T_{Break\_Eq} = X_{2\_end} - x_1. \tag{21}$$

Denote the block delivery time taken for successful block delivery in Case 2 as T_{Case-2}. Let N_{RS-Eq} be the number of RS retransmissions made during the reduced link disruption event. Then, in the case that two link disruptions can be reduced to a single link disruption event, T_{Case-2} can be approximated as

$$T_{Case-2} = \mathrm{RTT}_0 + N_{RS-Eq} \times \mathrm{RTO}_{RS} \tag{22}$$

and N_{RS-Eq} can be formulated as

$$N_{RS-Eq} = \left\lceil \frac{X_{2\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil. \tag{23}$$

$$T_{Case-1} = \begin{cases} T_{Block} - T_{CP} + N_{CP-1} \times \mathrm{RTO}_{CP} + N_{RS-2} \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0, & \mathrm{TH}_1 < x_2 < \mathrm{TH}_2 \\ 2\left(T_{Block} - T_{CP} + \mathrm{RTT}_{CP}\right) + \left(N_{CP-1} + N_{CP-2}\right) \times \mathrm{RTO}_{CP} + \mathrm{RTT}_0, & \mathrm{TH}_2 < x_2 < \mathrm{TH}_3 \\ T_{Block} - T_{CP} + N_{CP-1} \times \mathrm{RTO}_{CP} + N_{RS-2} \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0, & x_2 > \mathrm{TH}_3 \end{cases}. \tag{13}$$

$$T_{Case-1} = \begin{cases} T_{Block} - T_{CP} + \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} + \left\lceil \frac{X_{2\_end} - \mathrm{TH}_1}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0, & \mathrm{TH}_1 < x_2 < \mathrm{TH}_2 \\ 2\left(T_{Block} - T_{CP} + \mathrm{RTT}_{CP}\right) + \left(\left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil + \left\lceil \frac{X_{2\_end} - \mathrm{TH}_2}{\mathrm{RTO}_{CP}} \right\rceil\right) \times \mathrm{RTO}_{CP} + \mathrm{RTT}_0, & \mathrm{TH}_2 < x_2 < \mathrm{TH}_3 \\ T_{Block} - T_{CP} + \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} + \left\lceil \frac{X_{2\_end} - \mathrm{TH}_3}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0, & x_2 > \mathrm{TH}_3 \end{cases}. \tag{14}$$

$$\mathrm{GP}_{Case-1} = \frac{L_{Block}}{T_{\mathrm{Case}-1}} = \begin{cases} \frac{L_{Block}}{T_{Block} - T_{CP} + \left\lceil \frac{X_{2\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0}, & x_2 < TH_1 \\ \frac{L_{Block}}{T_{Block} - T_{CP} + \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} + \left\lceil \frac{X_{2\_end} - \mathrm{TH}_1}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0}, & \mathrm{TH}_1 < x_2 < \mathrm{TH}_2 \\ \frac{L_{Block}}{2\left(T_{Block} - T_{CP} + \mathrm{RTT}_{CP}\right) + \left(N_{\mathrm{CP}-1} + N_{\mathrm{CP}-2}\right) \times \mathrm{RTO}_{CP} + \mathrm{RTT}_0}, & \mathrm{TH}_2 < x_2 < \mathrm{TH}_3 \\ \frac{L_{Block}}{T_{Block} - T_{CP} + \left\lceil \frac{X_{1\_end} - T_{Block} + T_{CP}}{\mathrm{RTO}_{CP}} \right\rceil \times \mathrm{RTO}_{CP} + \left\lceil \frac{X_{2\_end} - \mathrm{TH}_3}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS} + \mathrm{RTT}_{CP} + \mathrm{RTT}_0}, & x_2 > \mathrm{TH}_3 \end{cases}. \tag{16}$$

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If the second link disruption starts after the threshold time point TH_1, i.e., $x_2 > \mathrm{TH}_1$, the RS is successfully delivered to the sender prior to the start of the second link disruption. This implies that the second link disruption has no effect to the block delivery, and only the first disruption affects the block delivery. Therefore, the block delivery time can be approximated as

$$T_{Case-2} = \mathrm{RTT}_0 + N_{RS-1} \times \mathrm{RTO}_{RS}. \tag{24}$$

With the formulas of N_{RS-Eq} and N_{RS-1} plugged in, T_{Case-2} can be formulated as

$$T_{Case-2} = \begin{cases} \mathrm{RTT}_0 + \left\lceil \frac{X_{2\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}, & x_2 < \mathrm{TH}_1 \\ \mathrm{RTT}_0 + \left\lceil \frac{X_{1\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}, & x_2 > \mathrm{TH}_1 \end{cases}. \tag{25}$$

Similar to Case 1, the extra transmission attempts made at the sender due to two link disruptions in Case 2 can be simply written as

$$N_{Case-2} = \left\lceil \frac{T_{Case-2}}{\mathrm{RTO}_{CP}} \right\rceil. \tag{26}$$

Denote the goodput for block transfer in Case 2 as GP_{Case-2} , it can be formulated in each of its subcases as

$$\mathrm{GP}_{Case-2} = \frac{L_{Block}}{T_{Case-2}} = \begin{cases} \frac{L_{Block}}{\mathrm{RTT}_0 + \left\lceil \frac{X_{2\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}}, & x_2 < \mathrm{TH}_1 \\ \frac{L_{Block}}{\mathrm{RTT}_0 + \left\lceil \frac{X_{1\_end} - T_{Block} - T_{OWLT}}{\mathrm{RTO}_{RS}} \right\rceil \times \mathrm{RTO}_{RS}}, & x_2 > \mathrm{TH}_1 \end{cases}. \tag{27}$$

The aforementioned analysis in the case of two link disruption events can be expanded to a case with multiple (e.g., n) link disruption events experienced. Let TH_{n-1} be the threshold time point at which the nth link disruption occurs within the period of T_{OWLT} after the effect of the first $(n-1)$ link disruption events end. For $x_n < \mathrm{TH}_{n-1}$, the duration of the single disruption event to which all n disruption events can be reduced is approximated as

$$T_{Break\_Eq} = x_n + T_{Break\_n} - x_{n-1} \tag{28}$$

and the total time effect of the reduced single disruption event on block delivery can be written as

$$\Delta\mathrm{RTT}_{Disrupt\_total} = \Delta\mathrm{RTT}_{Disrupt}\left(T_{Break\_Eq}\right). \tag{29}$$

For $x_n > \mathrm{TH}_{n-1}$, these n link disruption events cannot be reduced to a single disruption event. Therefore, each of these n disruption events has to be considered as an individual disruption event. Let T_{Break_i} be the duration of the ith link disruption and $\Delta\mathrm{RTT}_{Disrupt}(T_{Break\_i})$ be the time effect of the ith link disruption on block delivery; the total time effect of all n link disruption events on block delivery can then be written as

$$\Delta\mathrm{RTT}_{Disrupt\_total} = \sum_{i=0}^{n} \Delta\mathrm{RTT}_{Disrupt}\left(T_{Break\_i}\right). \tag{30}$$

In the case of multiple link disruption events experienced by block transfer, the formulas for the block delivery time, the number of CP/RS retransmissions made during the individual link disruption, the total extra transmission attempts made due to multiple link disruptions, and the goodput are similar to those presented for two link disruptions. The only difference is in the numerical values of the transmission attempts taken. Therefore, those formulas are not presented for the sake of simplicity.

V. OVERVIEW OF EXPERIMENTAL INFRASTRUCTURE AND CONFIGURATIONS

The PC-based space communication and networking testbed used in [6], [7], [8], [9], and [10] was adopted as the infrastructure for the data block delivery experiments in this article. The testbed was validated. As the testbed was extensively described in the previous work [10], it is not discussed in detail here. The interplanetary overlay network distribution v4.1.1 [24] developed by the NASA's JPL was adopted as the LTP protocol implementation for the experiments.

For the protocol configuration, LTP was configured to operate under the overlaying BP (i.e., BP/LTP). The BP custody transfer option was disabled so that the effect of BP reliability service on LTP transmission was removed. By this, the sole reliable data delivery service of LTP can be evaluated. To configure for the reliable transmission service of LTP, all the data bytes of the LTP block were designated as "red" data. Each LTP data block was configured to contain 40 bundles with each bundle having 5 kb of data, i.e., 40 bundles/block.

With respect to the space channel configurations, a one-way link delay of 10 min (600 s) was introduced to emulate the inevitable link propagation delay on each of the downlink and uplink channels. This delay setting is typical for Mars–Earth communication systems. The effect of channel-rate asymmetry on file transmission was also integrated into the experiments. The channel asymmetry was implemented by configuring a downlink channel rate of 250 kb/s and an uplink channel rate of 25 kb/s, leading to a channel ratio of 10/1.

For the sake of simplicity, the experiments were configured to affect two link disruption events for each data block transfer. However, even though the experiments were only configured to run with two link disruptions, the discussions are expected to be applicable to block transfers experiencing multiple link disruptions, as discussed in Section IV. In other words, if the analytical models are validated by experiments based on two link disruptions, those findings should also be applicable in a scenario characterized by more than two disruptions.

VI. PERFORMANCE EVALUATION AND MODEL VALIDATION

Table II lists the link disruption starting times for the first and second link disruptions and the durations of both disruptions for all experiments. Due to the paper length

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TABLE II
Setting Up of Link Disruptions for the Experiments

Block Transfer	First disruption Starting Time (min)	Second disruption Starting Time (min)	Disruption Duration (min)	Time Intervals (min)
Set 1	7	22, 27, 32, 37, 42, and 47	10	5, 10, 15, 20, 25 and 30
Set 2	13	28, 33, 38, 43, 48, and 53		

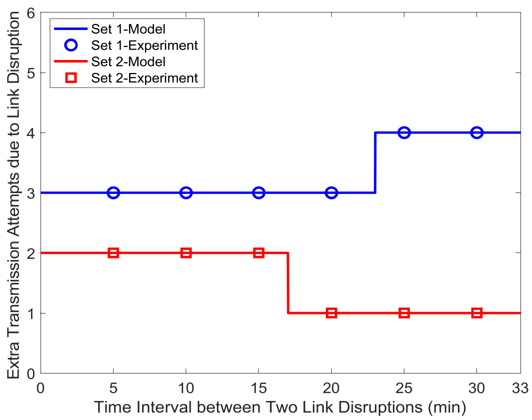

Fig. 5. Comparison of the extra number of transmission attempts entailed in successful block delivery.

limit, only two sets of the experiments are presented, named Set 1 and Set 2. These sets of experiments are sufficient to clarify the time effect of multiple link disruptions on LTP and to validate the models. Set 1 and Set 2 are different with respect to their link disruption starting times following the beginning of the transmission—7 min for Set 1 and 13 min for Set 2. Set 1 corresponds to the modeling Case 1 in which the first link disruption causes CP segment loss (i.e., with $0 < x_1 < T_{Block} + T_{OWLT}$). In contrast, Set 2 corresponds to the modeling Case 2 in which the first link disruption causes RS loss (i.e., with $T_{Block} + T_{OWLT} < x_1 < \mathrm{RTT}_0$).

It was found that the time interval between two link disruption events is the key for computing the threshold time point [i.e., TH_1 formulated in (5) and (20)], which determines whether or not two disruption events can be reduced to a single effective disruption event. Therefore, while the starting time for the first link disruption event was fixed (7 min for Set 1 and 13 min for Set 2), various starting times were configured for the second link disruption event (i.e., x_2), as given in Table II. The durations of both link disruption events were the same: 10 min. This led to six different time intervals between two link durations for each set of the experiments—5, 10, 15, 20, 25, and 30 min. As a clarification, the first time interval of 5 min occurred at time (22−(7+10)) for Set 1 and at time (28−(13+10)) for Set 2.

Fig. 5 presents a comparison of the extra number of transmission attempts entailed in successfully delivering a block as a function of the time interval between two link disruption events. The comparison is made between Set 1 and Set 2 for both the models and experiments. The discussion is divided into two cases in consideration of the two sets of experiments.

A. Extra Transmission Attempts Due to Link Disruption in Set 1

It is observed in Fig. 5 that the block transfer in Set 1 consistently has three extra transmission attempts for the time interval shorter than 23 min, increasing to four thereafter. The variation in the number of extra transmission attempts is reasonable. According to the analysis in Section IV, the numerical value of the threshold time point TH_1 in Set 1 is around 40 min. It was concluded that if $x_2 < \mathrm{TH}_1$, both link disruption events can be reduced to a single effective disruption event; otherwise, they need to be processed as two independent disruption events. Considering the numerical values of x_2 of Set 1 in Table II, the experiments in which the second disruption started at 22, 27, 32, and 37 min enabled reduction of the successive disruption events into a single disruption event, while those in which the second disruption started at 42 and 47 min did not.

The second disruption starting times of 22, 27, 32, and 37 min correspond to the time intervals (from the first disruption) of 5, 10, 15, and 20 min in Fig. 5, and the starting times of 42 and 47 min correspond to the time intervals of 25 and 30 min. This implies that the second disruptions beginning at time intervals of 5–20 min could in each case enable disruption reduction to a single disruption event. In contrast, the second disruptions beginning at time intervals of 25 and 30 min were not amenable to reduction of both disruptions to a single disruption event, and therefore, each of them had to be processed as a separate disruption event after the effect of the first disruption ended.

With respect to the numerical values of the extra transmission attempts in Set 1, they are three and four before and after when time interval reaches 23 min, respectively, as shown in Fig. 5. As mentioned, for all the block transfers in Set 1, the data segments (including the CP segment) are lost during the initial transmission due to the first link disruption. All the segments need to be retransmitted for the successful delivery of an entire block. For the transfers at time intervals of 5–20 min, the two successive link disruption events interact with each other and, therefore, may be reduced to a single long disruption in each case. In this event, because the first (initial) transmission of the block fails and the CP is lost, no RS is sent in response to the receiver. Therefore, upon expiration of the CP's RTO timer (i.e., RTO_{CP}) at the sender, the second CP transmission attempt is made at 20 min. But the second attempt fails again because the link is not yet available.

However, when the third CP transmission attempt is made at 40 min, the reduced effect of both link disruptions ends, which led to a successful delivery of the CP segment at 50 min. In response to the receipt of the CP segment, an RS is sent by the receiver. As soon as the RS arrives at the sender at 60 min, acknowledging the incomplete reception of the block, the entire block is retransmitted by the sender (the fourth attempt). The block is successfully delivered to

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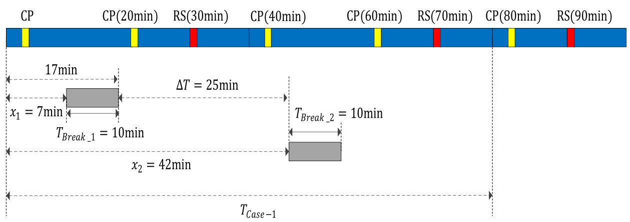

Fig. 6. Block transfer scenario in Set 1 illustrating the transmission attempts of CP and RS segments with respect to the link disruption time interval of 25 min.

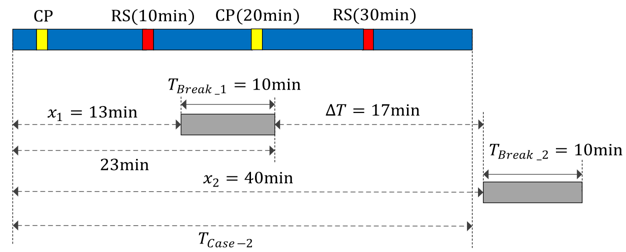

Fig. 7. Block transfer scenario in Set 2 illustrating the transmission attempts of CP and RS segments with respect to the time interval of 17 min.

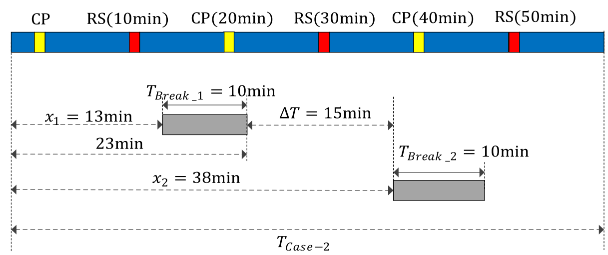

Fig. 8. Block transfer scenario in Set 2 illustrating the transmission attempts of CP and RS segments with respect to the time interval of 15 min.

the receiver at 70 min. Out of all four attempts made by the sender for a successful block delivery, the first three failed due to the disruptions, and only the last one was successful. This implies that three extra transmission attempts were made due to the effect of two link disruptions, as observed in Fig. 5.

For the block transfers at time intervals of 25 and 30 min, the situation is different. Taking the case of 25 min for discussion, Fig. 6 presents the detailed block transfer scenario in Set 1 with the first disruption starting at 7 min, illustrating the *transmission* attempts of CP segments (at sender) and RS (at receiver) with respect to the time interval of 25 min between two link disruptions. The scenario is self-explained. Unlike the scenarios with time intervals of 5–20 min, the second CP transmission attempt performed by the sender at 20 min is successfully delivered. This is because of the long-time interval of 25 min between the two disruptions. As observed, the link is available from 17 to 42 min, providing enough time for the CP segment to propagate through the link and arrive at the receiver at 30 min.

B. Extra Transmission Attempts Due to Link Disruption in Set 2

Unlike the variation in Set 1, the transfer in Set 2 in Fig. 5 shows an opposite variation trend. There are consistently two extra transmission attempts for the time intervals shorter than 17 min, dropping to one extra transmission attempt thereafter. Similarly, it is found that the numerical value of the threshold time point TH_1 in Set 2 is 40 min. In view of to the listed second disruption starting times in Set 2 in Table II, we find that the second disruptions started at 28, 33, and 38 min enable reduction to a single disruption event, while those started at 43, 48, and 53 min do not. The starting times of 28 min, 33 min, and 38 min correspond to the time intervals (from the first disruption) of 5 min, 10 min, and 15 min, and the starting times of 43 min, 48 min, and 53 min correspond to the time intervals of 20 min, 25 min, and 30 min, respectively. That is why the difference in the extra transmission attempts is observed at the time interval of 17 min in Set 2 in Fig. 5.

Fig. 7 presents the detailed block transfer scenario in Set 2, illustrating the transmission attempts of CP and RS segments with respect to the time interval of 17 min. During the entire block transfer process, the CP segment is only retransmitted once (at 20 min) following the initial block transmission. That is why the numerical value of the extra transmission attempt in Set 2 in Fig. 5 is consistently 1 for those transfers with the time intervals of 20–30 min. In contrast, for the block transfers with the time intervals of 5, 10, and 15 min, the duration of link availability between the two disruption events is too short for the RS resent at 30 min to be successfully delivered to the sender. This is because the link has to be consistently available for 10 min (i.e., until the time of 40 min) for the RS to arrive at the sender. But the second disruptions at time intervals of 5–15 min preclude this length of link availability.

Taking the case with the longest time interval (15 min) for discussion, Fig. 8 illustrates the transmission attempts of CP and RS segments for the block transfer with respect to two link disruptions. As observed, for the RS resent at 30 min, because of the short time interval of 15 min between the two disruptions, the link is only available up to the time of 38 (= 23+15) min. In other words, the retransmission attempt of the RS fails again. In this case, the CP segment is re-resent by the sender at the time of 40 min. (The first retransmission attempt for the CP segment was made at 20 min.) This leads to two extra transmission attempts as observed in Fig. 5. The resent CP is lost again due to the second link disruption. The block transfer is not concluded until after the second link disruption ends; the RS resent by the receiver at 50 min arrives at the sender at 60 min.

C. Numerical Results of RTT and Goodput Performance

The time effect of link disruption events on reliable block transfer can also be observed from variation in the RTT. Fig. 9 presents a comparison of the numerical values of RTT for the models and experiments in both sets of the transfers. The numerical value of the RTT for each block transfer is measured as the time difference between

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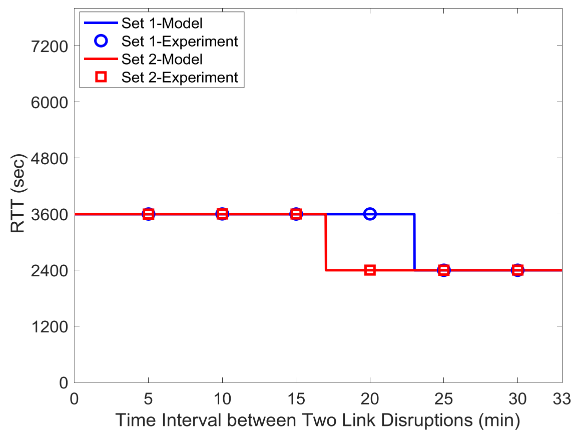

Fig. 9. Comparison of the numerical values of RTT between two sets.

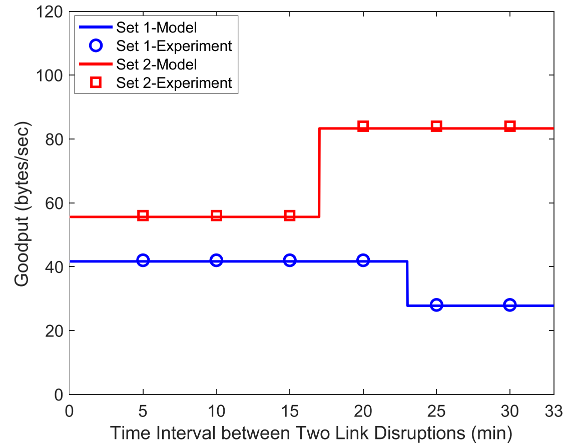

Fig. 10. Comparison of goodput performance between two sets.

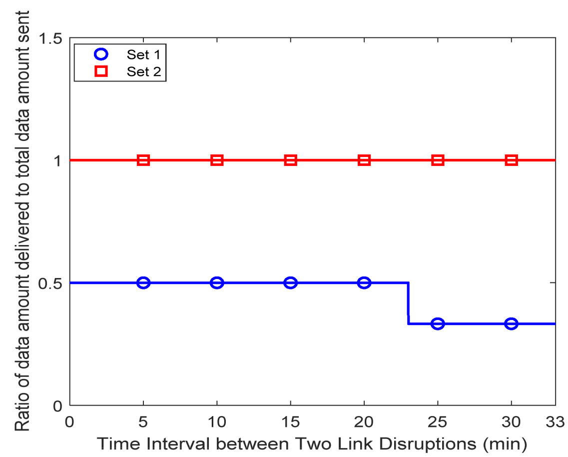

Fig. 11. Comparison of the ratio of data amount delivered to total data amount sent between two sets.

the *first reception of an RS* from the receiver and the *first transmission of the CP* segment (i.e., the initial transmission of the block). Comparing the block transfers in Set 1 and Set 2, even though they consistently have different numbers of extra transmission attempts, most of their numerical values of RTT are equal, as shown in Fig. 9. The numerical values of the measured RTT, either 3600 sec or 2400 sec, and the difference in the variation trends between Set 1 and Set 2 in Fig. 9 can be explained based on the time at which the link is available for transmission of the RS in response to receipt of the CP segment. The link availability is mainly determined by the length of both link disruptions and the starting time of the second disruption; taken together these parameters determine whether or not two link disruptions can be effectively reduced to a single disruption event.

For all the block transfers with the time intervals of 5, 10, 15, and 20 min (i.e., shorter than 23 min) in Set 1, it is clarified in Section VI-A that the RTT measured for the block transfer is 60 min (i.e., 3600 s). This is exactly the numerical values of their RTT shown in Fig. 9. The RTT value of 60 min implies that the two disruption events may be reduced to a single disruption, which is true according to the earlier analysis.

In comparison, the block transfers with the time intervals of 25 and 30 min (i.e., longer than 23 min) in Set 1 have much shorter RTT. As illustrated in Fig. 6, the first RS is sent to the receiver at 30 min, and it is successfully delivered to the sender at 40 min. Therefore, the RTT measured for the block transfers with time intervals of 25 min and 30 min in Set 1 is 40 min (i.e., 2400 s). This RTT length is 20-min shorter than that of the transfers having the time intervals less than 23 min, as illustrated in Fig. 9. For all the block transfers with time intervals of 5, 10, and 15 min (i.e., shorter than 17 min) in Set 2, it is shown in Fig. 8 that the RS resent by the receiver at 50 min arrives at the sender at 60 min as the first RS acknowledging the receiving status of the block. This leads to the numerical value of 60 min (3600 s) for the RTT, which is equal to the RTT for the block transfer with the time intervals of 5–20 min in Set 1, as shown in Fig. 9.

The increase in the total number of transmission attempts leads to an increase in the block delivery time. The goodput performance for the block transfer in both Set 1 and Set 2 is expected to be inversely proportional to the extra number of transmission attempts as shown in Fig. 5. This is exactly what the goodput performance comparison in Fig. 10 shows with respect to the goodput variation trend for both Set 1 and Set 2 and the relationship between two sets. For the block transfers in Set 1, corresponding to the increase in required transmission attempts from three to four at the time point of 23 min, goodput performance shows a decrease of around 15 bytes/s. Similarly, for the transfers in Set 2, in response to the decrease in required transmission attempts at 17 min, the goodput shows an increase around 30 bytes/s.

To have a measure of the link utilization affected by link disruption, Fig. 11 presents a comparison of the ratio of data volume delivered to total data volume sent in transmitting a data block for two sets of experiments. This ratio reflects the impact of link disruptions on the amount of transmitted data—the lower the ratio, the greater the amount of data caused by retransmission and the lower the link utilization. Since the size of the retransmitted CP and RS segments is very small compared to the size of an entire block, the effect of the additional data volume caused by the retransmitted CP and RS segments can be ignored. This implies that a

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decrease in the ratio in Fig. 11 is mainly caused by the retransmissions of the data block.

For the block transfers in Set 1, with a disruption time interval of 23–33 min configured, the retransmission of the data block at 40 min is affected by the second link disruption, as shown in Fig. 6. In other words, it takes three transmissions in total for a successful delivery of the LTP data block. This implies that the ratio is about 1/3. However, with a time interval of 0–23 min, the second link disruption only affects the retransmitted CP or RS segments. This leads to a ratio of 1/2, as shown in Fig. 11. For Set 2, the data block is successfully delivered to the receiver for the first time, and link disruption only affects the CP and RS segments. This implies that the ratio is consistently equal to 1 (100%) in this case.

VII. CONCLUSION

In this article, an analytical framework is developed to model the effect of multiple link disruptions on LTP's reliable data delivery in space SoS. Realistic block transmission experiments indicate that the framework and models in this study accurately predict the performance of LTP in presence of multiple link disruptions with various starting time and durations. The study indicates that the key to analyzing the effect of multiple link disruptions on LTP is to determine whether or not two successive link disruption events can be reduced to a single one. A time point is determined, based on the analytical modeling results, as a threshold interval to check if two successive link disruptions are reducible to a single disruption, and it is verified by the experiments. The threshold is mainly determined by the starting time and duration of link disruption events. If the "next" disruption event starts prior to the determined threshold time point, it interacts with the "previous" disruption, and therefore, the two disruptions can in effect be reduced to a single disruption. Otherwise, each of the disruptions has to be considered as an individual disruption. It is also found that, for block transfers that experience multiple link disruption events, the earlier the first disruption starts, the greater the number of transmission attempts that will likely be needed for successful delivery of the entire block. As a result, the data block delivery time increases and goodput performance drops.

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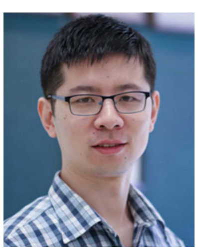

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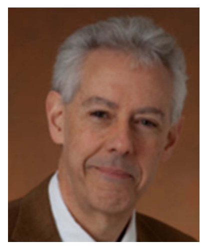

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